

SOLBANK 3.0 (0.5P) BESS

HAZARD MITIGATION ANALYSIS

November 7th, 2024 | Rev. 0

SUMMARY

This document serves as a product-specific* Hazard Mitigation Analysis performed for the SolBank 3.0 BESS.

*This document does not address site-specific hazards, barriers, and mitigations.



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PROJECT DESCRIPTION

Project Name	SolBank 3.0 Generic HMA
Project No.	24-20470
Prepared For	Canadian Solar 545 Speedvale Avenue West Guelph, Ontario N1K 1E6
Revision No.	Rev. 0
Date of Issue	11/7/2024

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Revision History

Revision No.	Date of Issue	Substance of Change	Prepared By	Reviewed By
Rev. 0	11/7/2024	Draft issue	A. Jakubowski	N. Petrakis

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TABLE OF CONTENTS

1	INTRODUCTION	6
1.1	Background	6
1.2	Applicable Codes and Standards	6
1.3	Summary of Findings	7
2	ENERGY STORAGE SYSTEM DESCRIPTION	9
2.1	Energy Storage System Overview	9
2.2	Fire Safety Features	10
2.2.1	Explosion Prevention System	11
2.2.2	Explosion Protection System	12
2.2.3	Battery Management System (BMS)	12
2.2.4	Fire Detection.....	12
2.2.5	Electrical Fault Protection Devices	13
2.2.6	Site Controller and Monitoring	13
2.2.7	Fire Suppression Systems	13
2.2.8	Thermal Management System.....	14
3	HAZARD MITIGATION ANALYSIS	15
3.1	HMA Methodology	15
3.2	Primary Consequences of ESS Failure and Mitigative Barriers	16
3.3	Fault Condition Analysis.....	18
3.3.1	Thermal Runaway Condition in a Single Battery Storage Rack, Module, or Unit	20
3.3.2	Failure of Any Energy Management System	22
3.3.3	Failure of Any Required Ventilation or Exhaust System.....	23
3.3.4	Failure of the Smoke Detection, Fire Extinguishing, or Gas Detection System	25
3.3.5	Voltage Surges on the Primary Electric Supply.....	27
3.3.6	Short Circuits on the Load Side of the ESS.....	28
3.3.7	Failure of Temperature Control (HVAC)	30
3.4	Analysis Approval	32
4	SUPPORTING DOCUMENTATION	35
4.1	UL 9540A Large-Scale Fire Testing	35
4.1.1	Cell Level Test	35
4.1.2	Module Level Test.....	36
4.1.3	Unit Level Test.....	38
4.2	NFPA 69 Analysis	40
4.3	Heat Flux Analysis.....	43

APPENDIX A – DETAILED HMA DIAGRAMS AND BARRIER DESCRIPTIONS	46
A.1 All Fault Conditions.....	46
A.2 Thermal Runaway Condition	47
A.3 Failure of an Energy Management System	48
A.4 Failure of a Required Smoke Detection, Fire Extinguishing, or Gas Detection System	49
A.5 Voltage Surges on the Primary Electric Supply	50
A.6 Short Circuits on the Load Side of the ESS.....	51
APPENDIX B – HMA METHODOLOGY	52
APPENDIX C – REFERENCED DOCUMENTATION	55
APPENDIX D – REFERENCED CODES AND STANDARDS.....	55

1 INTRODUCTION

1.1 Background

Energy Safety Response Group (ESRG) has been retained by Canadian Solar to perform a product-specific Hazard Mitigation Analysis (HMA) in accordance with *NFPA 855 Standard for the Installation of Stationary Energy Storage Systems (2023): §4.4.1 Hazard Mitigation Analysis* and the *2021 International Fire Code (IFC): §1207.1.4.1*. This HMA can be utilized to assess the anticipated overall effectiveness of protective barriers in place to mitigate the consequences of a battery-related failure. The analysis was performed based on the current documentation available at the time of the report.

1.2 Applicable Codes and Standards

IFC Chapter 12: §1207.1.4 and *NFPA 855: §4.4.1*, require that an approved hazard mitigation analysis (HMA) be performed where allowed as a basis for increasing the maximum allowable quantities (MAQs) of energy storage capacity (600 kWh for lithium-ion batteries). This hazard mitigation analysis is conducted in accordance with *IFC Chapter 12: §1207.1.4.1* and *NFPA 855: §4.4.2* to evaluate the consequences of the following failure modes:

- 1) *A thermal runaway condition in a single ESS rack, module, or unit.*
- 2) *Failure of any battery (energy) management system.*
- 3) *Failure of any required ventilation or exhaust system.*
- 4) *Failure of the smoke detection, fire detection, fire suppression, or gas detection system.*
- 5) *Voltage surges on the primary electric supply.*
- 6) *Short circuits on the load side of the ESS.*
- 7) *Required spill neutralization not being provided or failure of a required secondary containment system.*
- 8) *Failure of temperature control (HVAC).*

For the purposes of this report, only single failures modes shall be considered for each mode given above.

Per *IFC §1207.1.4.2, Analysis Approval*, the fire code official shall be authorized to approve the hazard mitigation analysis provided the consequences of the analysis demonstrate the following:

- 1) *Fires will be contained within unoccupied ESS rooms or areas for the minimum duration of the fire-resistance-rated separations identified in IFC §1207.7.4.*
- 2) *Fires in occupied work centers will be detected in time to allow occupants within the room or area to safely evacuate.*
- 3) *Toxic and highly toxic gases released during fires will not reach concentrations in excess of the immediately dangerous to life or health (IDLH) level in the building or adjacent*

means of egress routes during the time deemed necessary to evacuate occupants from any affected area.

- 4) *Flammable gases released from ESS during charging, discharging, and normal operation will not exceed 25 percent of their lower flammability limit (LFL).*
- 5) *Flammable gases released from ESS during fire, overcharging, and other abnormal conditions will be controlled through the use of ventilation of the gases, preventing accumulation, or by deflagration venting.*

This above analysis approval per *IFC §1207.1.4.2* also complies with the requirements set forth by *NFPA 855: §4.4.3*.

The following key codes, standards, and local requirements are referenced throughout the report:

- *International Fire Code §1207 Electrical Energy Storage Systems*, 2021 Edition
- *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 69 Standard on Explosion Prevention Systems*, 2024 Edition
- *NFPA 70 National Electric Code*, 2023 Edition
- *NFPA 72 National Fire Alarm and Signaling Code*, 2022 Edition

1.3 Summary of Findings

Based on a review of the documentation provided by Canadian Solar, ESRG finds that adequate protections are provided for the fault conditions listed per *IFC §1207.1.4.1* and *NFPA 855 §4.4.2*, as well as all analysis approval requirements per *IFC §1207.1.4.2* and *NFPA 855 §4.4.3*. Key findings of this report include:

- The SolBank 3.0 BESS is equipped with many protection features (e.g., explosion prevention, BMS control, fire detection, electrical fault protection, site controller and monitoring, and thermal management) to effectively manage all fault conditions specified in *IFC §1207* and *NFPA 855*.
- UL9540A large-scale testing was performed at the cell, module, and unit levels. Unit level testing was favorable, in which thermal runaway was limited to the initiating module. No flying debris, external flaming, explosive discharge of gases, sparks, electrical arcs, or other electrical events were observed during testing.
- An active explosion prevention system is provided for the enclosure to limit the buildup of flammable gases during a potential failure condition. A CFD analysis was performed by

TUV Rheinland and demonstrates that the system design is capable of maintaining average gas concentrations in the enclosure below 25% LFL, in accordance with the requirements of NFPA 69 *Standard on Explosion Prevention Systems*.

- A fire modeling analysis was conducted by Hazard Dynamics to evaluate the potential for fire propagation to adjacent enclosures in the event of a single burning enclosure. The models considered several wind conditions and found that, in each scenario, the heat transferred to adjacent enclosures does not cause battery temperatures to exceed the Lithium cell venting temperature.
- It is recommended that training is provided to the local fire departments to familiarize personnel with the site and hazards associated with lithium-ion ESS. First responders are instructed to stay at a safe distance in the unlikely event of a system failure.

2 ENERGY STORAGE SYSTEM DESCRIPTION

2.1 Energy Storage System Overview

The SolBank 3.0 BESS (Model S-5015-2h) is a modular, cabinetized (or non-enterable) MWh-scale system. Each individual SolBank 3.0 enclosure utilizes 48 battery modules, each consisting of 104 lithium iron phosphate (LFP) battery cells wired in series, providing a total aggregate of 2350 kW/4700 kWh (4.7 MWh) of rated DC power / usable energy capacity at beginning of life (BOL).

Each individual SolBank enclosure integrates all power electronics, controls, and safety features required to support the DC side of the BESS. All components are integrated into a 20', IP55-rated, high cube steel container (enclosure) and are accessible from the exterior through five individual access doors. The SolBank houses 12 rack-mounted battery management systems (BMS) – one for each battery string – to ensure optimal battery functionality. The BMS constantly monitors and controls battery voltages, temperatures, state of charge (SOC), and other key operating parameters. Cell-level temperature control is managed through a liquid cooling and heating system, allowing for greater heat dissipation and uniform cell temperature management.

Figure 2-2-1: SolBank 3.0 Features and Layout

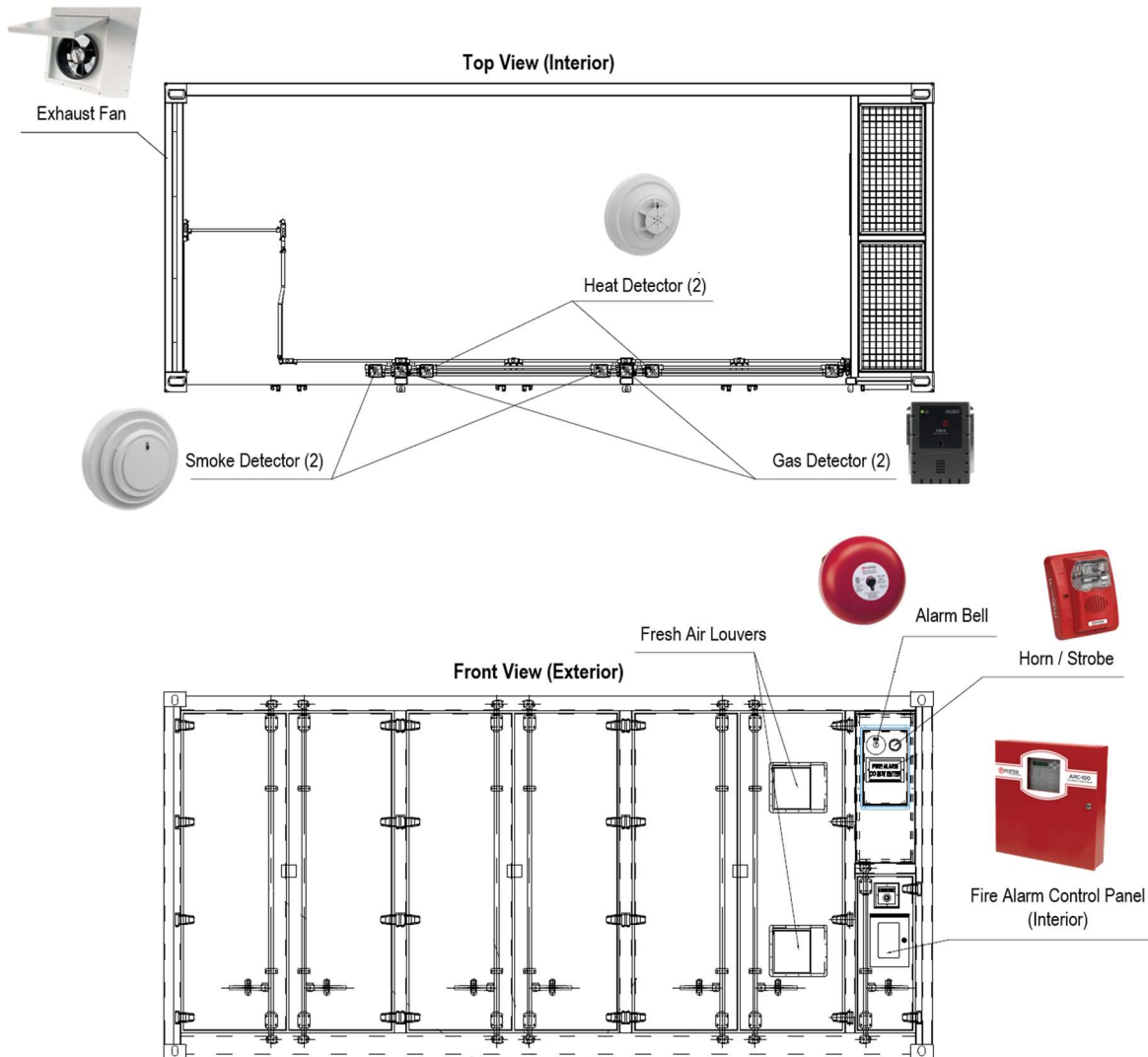


The SolBank has a variety of integrated fire safety features including automatic smoke detection, heat detection, and combustible gas detection within each enclosure. Audible (alarm bell) and audible/visual (horn/strobe) notification devices are provided on the exterior of the SolBank, with distinctive alarm patterns to indicate the different alarm levels that could be detected. An active explosion prevention system is provided, working in conjunction with the combustible gas detection system to activate early and exhaust flammable gases to maintain the enclosure environment below flammable limits during a potential failure event. These fire safety features are detailed in [Section 2.2](#).

2.2 Fire Safety Features

The SolBank 3.0 BESS is provided with several fire and operational safety features to detect and prevent failures within the system (Figure 2-2).

Figure 2-2-2: SolBank 3.0 Fire Safety Features



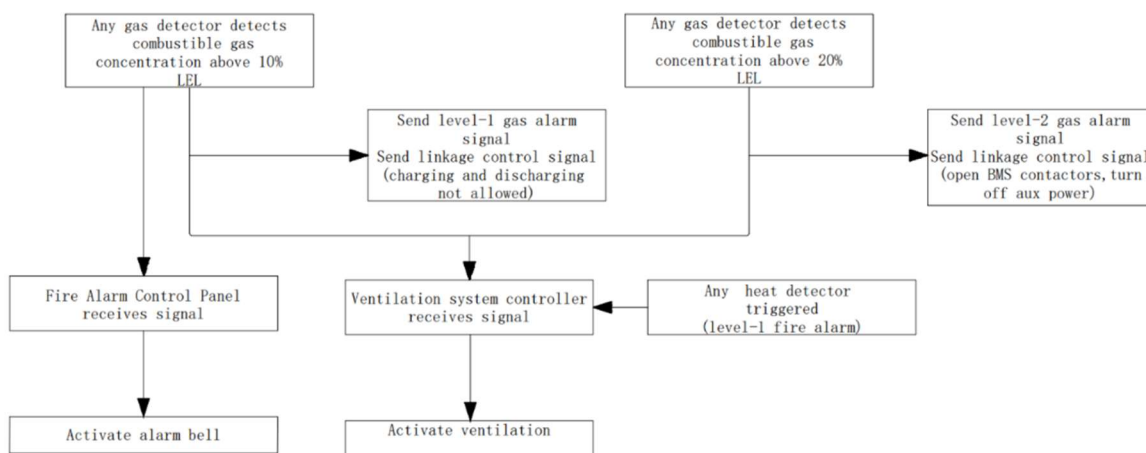
2.2.1 Explosion Prevention System

The SolBank 3.0 enclosure is equipped with an explosion prevention system designed to exhaust the flammable byproducts of cell off-gassing that may be generated during a potential failure condition. To detect flammable gases, two (2) combustible gas detectors are installed at the top interior of each cabinet and are connected to an internal, listed fire alarm control panel (FACP). The internal FACP is monitored by the SolBank 3.0 Controller to relay any alarm signals to the site energy management system (EMS). All enclosure FACP's may also be networked to a master site FACP.

The gas detectors are calibrated to activate when the concentration of hydrogen at the detector location reaches 10% of the lower flammability limit (LFL). Once activated, the combustible gas detector will send an alarm signal to the FACP, activate the alarm bell, and activate the explosion prevention system (exhaust fan and fresh air louvers). The exhaust fan is rated for a capacity of 820 CFM and is designed to maintain the concentration of combustible gases within the enclosure below 25% of the lower flammable limit (LFL), as per the requirements of NFPA 69 *Standard on Explosion Prevention Systems*. A CFD analysis performed by TUV Rheinland demonstrates that the system design is capable of meeting these requirements ([Section 4.2](#)).

The explosion prevention system logic (Figure 2-3) consists of two alarm levels: *Level 1* and *Level 2*. Gas detector activation at 10% LFL will initiate a *Level 1* alarm condition. In addition to sending an alarm signal to the FACP, activating the alarm bell, and activating the explosion prevention system, a *Level 1* gas alarm will stop battery charging and discharging processes within the enclosure. If flammable gas concentrations reach 20% LFL, it will trigger a *Level 2* alarm condition. A *Level 2* alarm condition will open BMS contactors and turn off auxiliary power, in addition to all *Level 1* alarm condition actions. A *Level 2* alarm condition will not remove auxiliary power from the explosion prevention system. Each container is also outfitted with a battery backup capable of operating the explosion prevention system if auxiliary power is lost.

Figure 2-2-3: Explosion Prevention System Logic



2.2.2 Explosion Protection System

Each SolBank 3.0 BESS enclosure may be equipped with optional deflagration venting designed in accordance with *NFPA 68 Standard on Explosion Protection by Deflagration Venting*. This option is not considered in this analysis.

2.2.3 Battery Management System (BMS)

Each SolBank BESS is outfitted with a dedicated battery management system (BMS) for each battery string, with a total of 12 rack-mounted BMS per enclosure. Each BMS works in concert with the individual battery pack battery management units (BMU) to ensure optimal battery functionality and safety. The BMS monitors and controls cell and module voltages, temperature, state of charge (SOC), and other key parameters of operation. The BMS ensures early detection of pre-fault conditions and immediate detection of fault events. If parameters exceed pre-determined permissible values, the BMS will open the integrated DC contactors to automatically disconnect the affected string and send an alarm to the site's energy management system (EMS).

Additionally, the SolBank BESS utilizes integrated position sensors on the external access doors. If an access door is opened during system operation, the SolBank will immediately shut down and each BMS will automatically isolate their respective battery string from the main system bus.

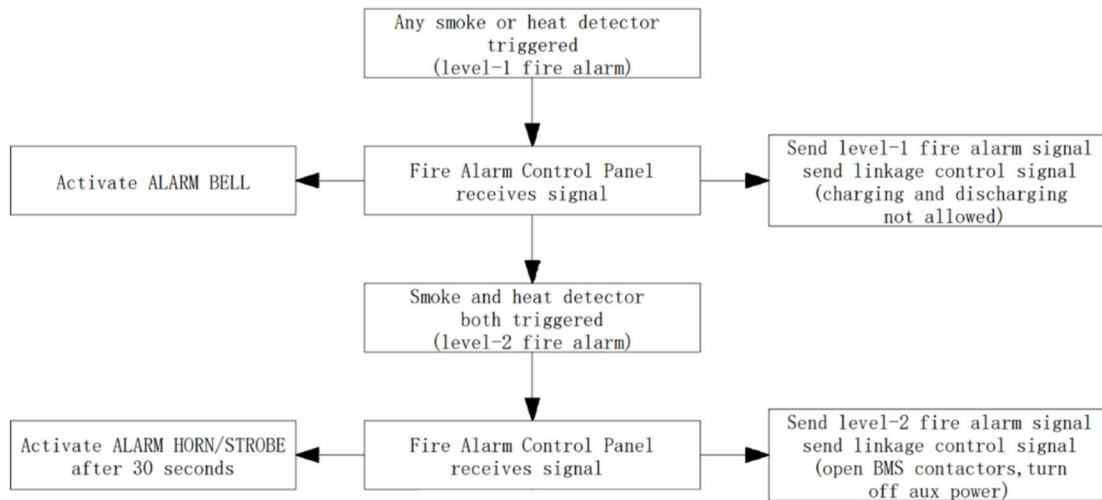
2.2.4 Fire Detection

Each SolBank BESS is equipped with two (2) smoke and two (2) heat detectors located centrally on the interior ceiling of the enclosure. The smoke detectors are calibrated to an alarm sensitivity of 3.5 %/ft and the heat detectors are calibrated to an alarm threshold of 85°C (185°F). Like the gas detectors ([Section 2.2.1](#)), the smoke and heat detectors are connected to an internal FACP which will relay alarm and supervisory signals to the site EMS via the SolBank 3.0 Controller and to a master FACP, if specified for the site.

The fire detection system logic (Figure 2-4) consists of two alarm levels: *Level 1* and *Level 2*. If the FACP receives a signal from a single detector (smoke or heat) activation, it will trigger a *Level 1* alarm condition. A *Level 1* alarm condition will activate the alarm bell and stop all charging and discharging processes within the enclosure. If the FACP receives an activation signal from both a smoke and heat detector, it will trigger a *Level 2* alarm condition. Activation of a *Level 2* alarm condition will turn off auxiliary power and open BMS contactors to automatically isolate the affected enclosure. A *Level 2* alarm condition will not remove auxiliary power from the explosion prevention system.

Backup power to the detectors is provided via battery backup within the FACP, as per the requirements of NFPA 72. The system is designed in compliance with the requirements of NFPA 72 and NFPA 70.

Figure 2-2-4: Fire Detection System Logic



2.2.5 Electrical Fault Protection Devices

In addition to BMS protections ([Section 2.2.3](#)), electrical fault protection devices are provided for the BESS and the power conversion system (PCS). The SolBank's DC junction box contains all primary DC busbars, fuses, surge protection devices (SPD), and power monitoring required to safely exchange power between the SolBank 3.0 and the PCS. All SolBank 3.0 electrical circuits are protected by properly sized overcurrent protection devices (OCPD). Site-level electrical fault protection devices are provided by the UL 1741 listed inverter, including insulation monitoring devices for ground fault protection, medium voltage (MV) switchgear, DC switch disconnectors, and Type 2 protection for AC and DC overvoltage protection. The BESS MV switchgear typically includes protection and switching equipment to sufficiently protect both the BESS facility and the grid from faults: relays, meters, breakers (motorized or non-motorized), fuses, and other distribution gear.

2.2.6 Site Controller and Monitoring

The SolBank 3.0 system is monitored and controlled by a site energy management system (EMS) or local plant controller (LPC) during normal operations. The EMS or LPC will communicate with an offsite fleet controller, SCADA operations center, or other third-party dispatch and monitoring entity to allow remote control and operations of the system. System status and alarms are communicated to the EMS and remote operations personnel. In the event of an emergency condition, the SolBank 3.0 system can be remotely shut down.

2.2.7 Fire Suppression Systems

The SolBank 3.0 enclosures may be equipped with an optional aerosol fire suppression system. However, the BESS units do not rely on any external or internal fire suppression

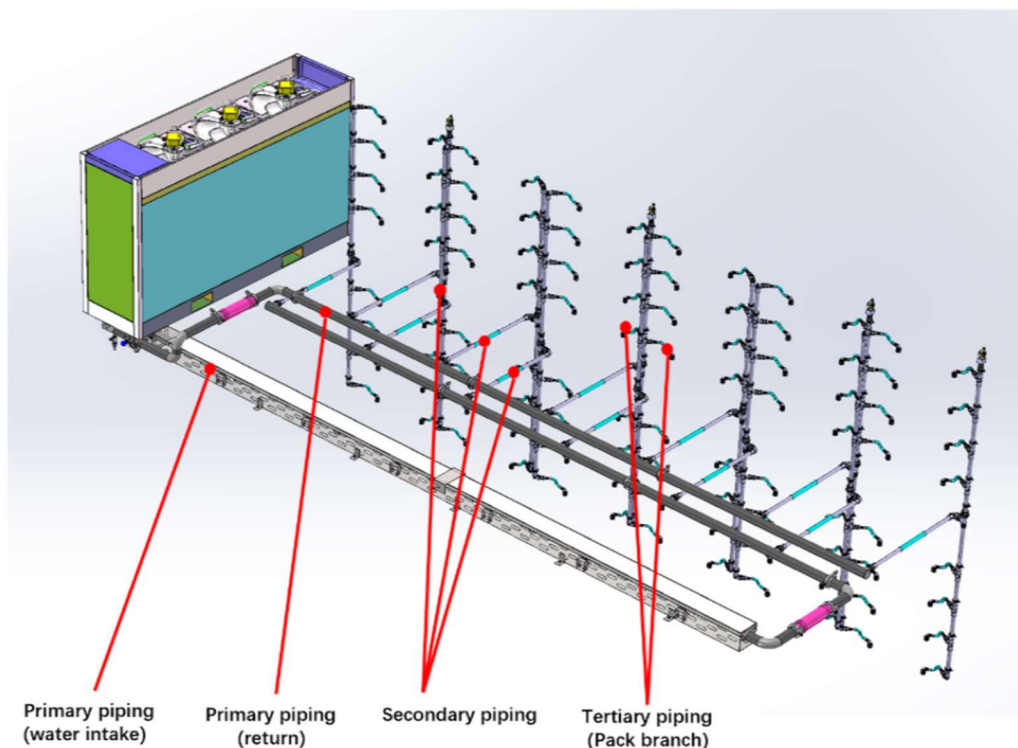
systems to mitigate a cascading thermal runaway event. Unit level testing to the UL 9540A standard indicated that thermal runaway did not propagate throughout the module and there was no module-to-module propagation. Additionally, no external flaming was observed during the test. Accordingly, the optional aerosol suppression system is not considered in this analysis.

2.2.8 Thermal Management System

Each SolBank 3.0 utilizes a liquid cooling and heating system to maintain cell temperatures between 20 – 35°C (68 – 95°F). The system distributes a temperature-regulated ethylene glycol solution throughout the enclosure, efficiently dissipating heat from battery cells when charging and discharging, while providing necessary cell heating during periods of cold weather (Figure 2-5).

The thermal management system coolant flows from a coolant reservoir to the 48 battery modules in the enclosure. After passing through each device and absorbing/releasing heat, the coolant flows back into the HVAC cabinet where it is cooled by a heat exchanger, if necessary. The cold side of the heat exchanger is supported by the SolBank's door-mounted AC system. The enclosure is continuously monitored for temperature and liquid chiller operation and will send alerts if critical levels are reached, or if there is loss of communication from the system.

Figure 2-2-5: Thermal Management System

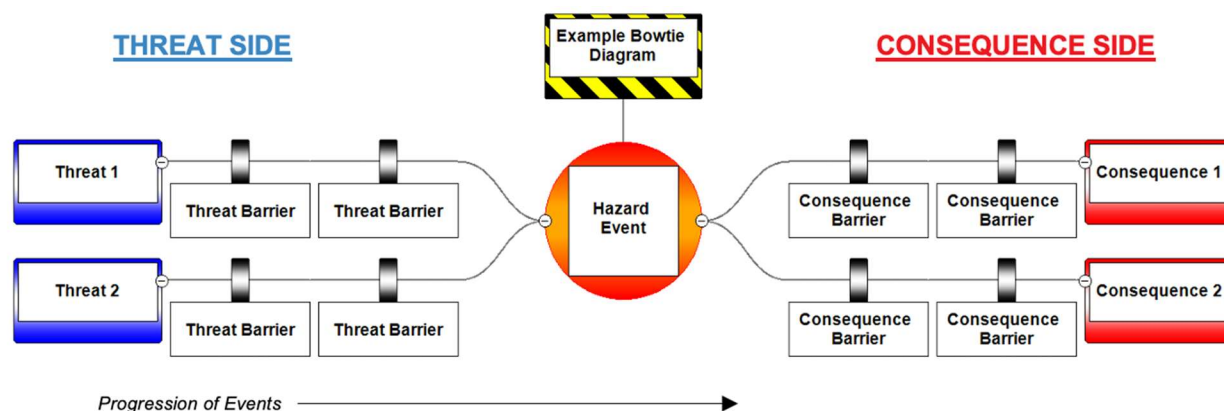


3 HAZARD MITIGATION ANALYSIS

3.1 HMA Methodology

ESRG utilizes the bowtie methodology for hazard and risk assessments, as is described in *NFPA 855 (2023 Ed.) Appendix G.3.6* and *ISO/IEC 31010 §B.21*, as it allows for in-depth analysis of 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** (Figure 3-1). This simple diagrammatic way of describing and analyzing the pathways of a risk from hazards to outcomes can be considered a combination of the logic of a fault tree analyzing the cause of an event and an event tree analyzing the consequences.

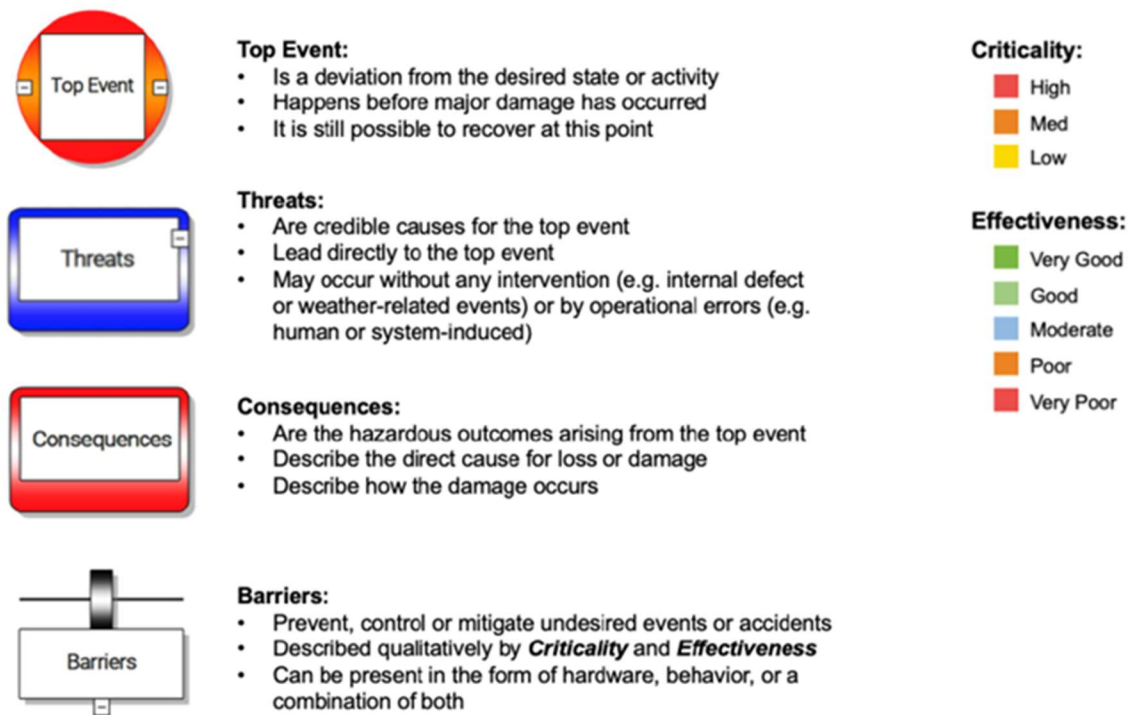
Figure 3-3-1: Example Bowtie Diagram



Each fault condition per *IFC* and *NFPA 855*, assessed in Sections 3.3.1 – 3.3.7, 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 the 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 or off-gassing leading to explosion. For more on the methodology and relevant terminology, see [Appendix B](#) of this report.

Figure 3-3-2: Bowtie Diagram Elements



3.2 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 several specific hazard scenarios, as depicted in Figure 3-3 (though other scenarios not shown may certainly also occur). These primary consequences serve as the basis for the consequence side of most of the fault condition diagrams in the following sections of this report.

While not explicitly detailed in the simplified diagram in Figure 3-3, the criticality and effectiveness of the barriers may vary based on the associated threat or consequence pathway. For example, a water-based suppression system may be more *critical* to prevent cell or module combustion from spreading and ultimately leading to fire spread beyond containment, than it is for preventing off-gassing within the enclosure, potentially leading to explosion. Similarly, the same water-based suppression system may be more *effective* for mitigating spread of fire throughout the system than it is for reducing risk of explosion.

Figure 3-3-3: Primary Consequence Diagram

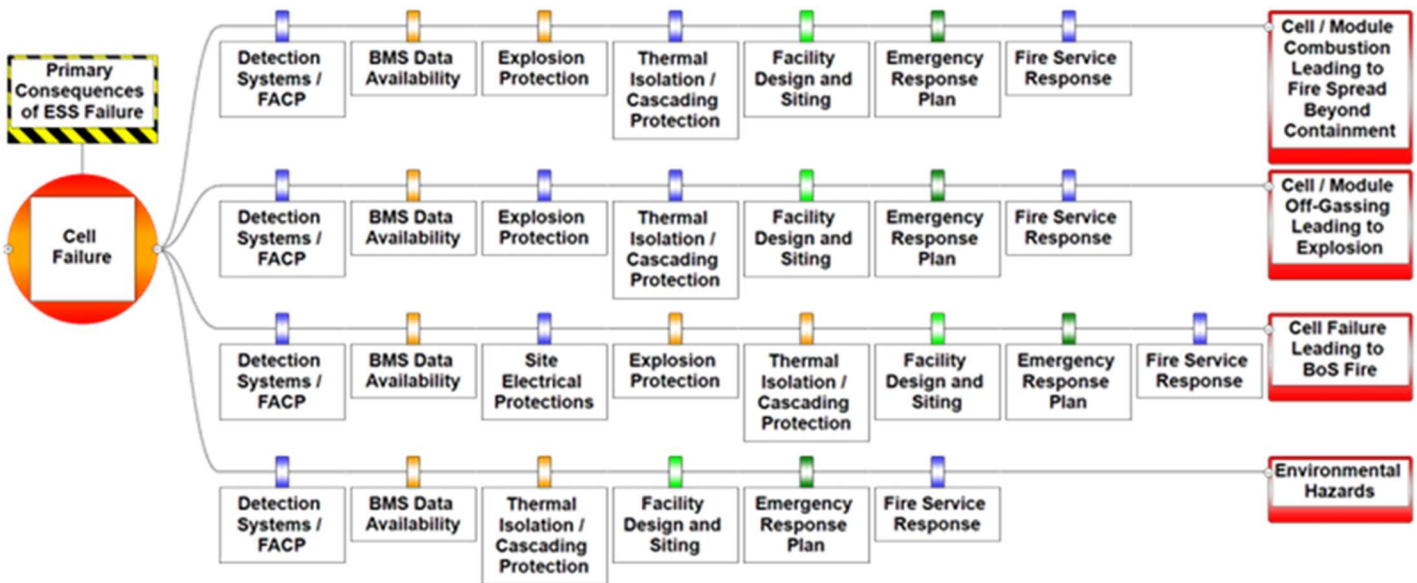


Table 3-1: Primary Consequence Barriers

PRIMARY CONSEQUENCE BARRIERS	
Battery Management System (BMS)	Each battery string is outfitted with a BMS that works with the individual battery management units (BMU). The BMS constantly monitors and controls cell voltages, current, temperature, SOC, and other operating parameters. If parameters exceed permissible values, the BMS will open the integrated DC contactors to automatically disconnect the affected string and send an alarm to the site EMS.
Fire Detection	An internal automatic smoke, heat, and combustible gas detection system is connected to an internal FACP which will relay alarm signals to the site EMS via the SolBank Controller, triggering alarm signals and respective safety responses.
Water-Based Suppression System	There is no water-based fire suppression system provided for the BESS product or for the installation. The SolBank 3.0 BESS does not rely on any internal or external fire suppression systems to mitigate a cascading thermal runaway event.
Deflagration Protection	An explosion prevention (explosion control) system is provided in each SolBank enclosure in the event flammable byproducts of cell off-gassing were to develop to detectable levels within the unit. The enclosure utilizes an 820 CFM exhaust fan and louvered intakes which automatically activate upon detection of 10% LFL (hydrogen). CFD analysis results demonstrate that the system design is capable of meeting the applicable requirements of NFPA 69.
Thermal Isolation / Cascading Protection	Passive and active thermal isolation barriers are provided, including aerogel between cells and active liquid cooling for thermal

	management. UL9540A unit level testing indicated no observation of module-to module propagation, flying debris, explosive discharge of gases, external flaming sparks, electrical arcs, or other electrical events during the test.
Electrical Fault Protection Devices	Electrical fault protection devices at the BESS include overcurrent protection and overvoltage (surge) protection devices. Site level electrical protections are provided by the UL 1741 listed inverter (PCS).
Facility Design and Siting	Proper siting based on appropriate separation distances from nearby exposures, land area and use, facility type, and other design factors may increase the strength of this barrier. Project developers using the SolBank 3.0 should follow Canadian Solar's recommended installation guidelines.
Emergency Response Plan (ERP)	A site-specific Emergency Response Plan (ERP), in accordance with the requirements of the locally adopted codes/standards, will provide an additional level of safety for individual installations utilizing the SolBank 3.0. Additionally, adequate familiarization designated subject matter experts (SMEs) and corporate first responders can greatly improve the strength of this barrier
BMS Data Availability / Remote Operations Center (ROC)	The EMS monitoring software provides the ability for the BMS / BMU data to be transmitted remotely to a remote operations center (ROC) for monitoring or to be available locally for subject matter expert (SME).
Fire Service Response	It is unknown if an adequate water supply or source will be available at most sites for firefighting purposes. As recommended in ESRG's Emergency Response Guidelines (ERG), a defensive firefighting approach shall be utilized, with water sprayed on neighboring exposures and neighboring enclosures if advised by Canadian Solar or at the discretion of the first responders. Site-specific training and installation familiarization for local responding stations may further increase the strength of this barrier, and that fire department equipment and capabilities will be strong with this familiarization.

3.3 Fault Condition Analysis

Both *IFC §1207.1.4* and *NFPA 855 §4.4.1* require that an approved hazard mitigation analysis (HMA) be performed where allowed as a basis for increasing maximum allowable quantities (MAQs) of energy storage capacity. Table 3-2 provides a summary of findings from the HMA performed in fulfillment of *IFC §1207.1.4.1* and *NFPA 855 §4.4.2.1*. Each fault condition is described in greater detail in Sections 3.3.1 – 3.3.7 of this report, accompanied by simplified bowtie diagrams for visualization of mitigative barriers. Full bowtie diagrams with barrier descriptions are provided in [Appendix A](#).

For the purposes of this report, only single failure modes shall be considered. Additionally, 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. This assessment is based on the most recent information provided by Canadian Solar at the time of this report and is subject to change prior to commissioning of the installation.

Table 3-2: Summary of IFC §1207.1.4.1 and NFPA 855 §4.4.2.1 Fault Condition Analysis

Compliance Requirement	Comments
1. Thermal runaway condition in a single ESS rack, module, or unit.	Several measures are implemented to reduce the potential of a thermal runaway event from occurring including BMS controls and an active thermal management system. Battery system subcomponents have been tested and listed to UL 1973. UL 9540A unit level testing has shown that thermal runaway can be contained within the module. Should a thermal runaway event occur, additional mitigative barriers and safety systems are in place to mitigate further failure propagation (see Section 3.3 for more on these systems).
2. Failure of any battery (energy) management system.	BMS, redundant failure detection, and several electrical shutdowns / disconnects provide protection against further failure propagation across the system.
3. Failure of any required ventilation or exhaust system.	Lithium-ion batteries do not release flammable gas during normal operations and, therefore, are not required to be provided with an exhaust ventilation system, per the installation codes/standards. The SolBank 3.0 enclosure, however, is equipped with an explosion prevention system (exhaust fan and fresh air intake activated via combustible gas detection), in the unlikely event that flammable gases develop during a failure condition. Strong facility siting and a site-specific emergency response plan (ERP) provide additional layers of protection and guidance to protect life and property.
4. Failure of the smoke detection, fire detection, fire suppression, or gas detection system.	The SolBank 3.0 does not rely on any internal or external fire suppression systems. The internal smoke, heat, and gas detection systems are connected to an internal, listed FACP. The FACP is monitored by the SolBank Controller which will relay device fault or trouble signals to the site EMS.

	Additionally, the BMS and system shutdown / disconnects may prevent cell failure from occurring. Redundant failure detection is provided by the upper controller.
5. Voltage surges on the primary electric supply.	Voltage surges on the primary electric supply are mitigated by inverter / PCS controls, voltage monitoring, and automatic disconnects provided by the BMS, as well as several passive circuit protections.
6. Short circuits on the load side of the ESS.	Short circuits on the load side of the ESS are mitigated by BMS control and subsequent safety actions as well as by passive circuit protection (fuses) and design.
7. Required spill neutralization not being provided or failure of a required secondary containment system.	Not applicable. No spillable liquid electrolyte is present.
8. Failure of temperature control (HVAC).	The SolBank BESS utilizes an active thermal management system to circulate liquid coolant throughout the enclosure to maintain battery cell temperature during charging and discharging. Operation of the thermal management system is monitored by the SolBank Controller. System failure will send fault signals to the site EMS. The active liquid cooling system is also monitored by leak and pressure sensors. The BESS will automatically shut down and isolate battery strings if abnormal temperatures are detected within the enclosure.

3.3.1 Thermal Runaway Condition in a Single Battery Storage Rack, Module, or Unit

Thermal runaway, as defined by *NFPA 855* §3.3.26, is the self-heating of an electrochemical system in an uncontrollable fashion. The cause of a thermal runaway event can range from a manufacturing 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.

Several 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 safety actions based on the fault signal received. Should a thermal runaway condition spread to a single module, rack, or unit, additional protections, including BMS control and system shutdown / disconnects, are anticipated to mitigate further propagation of failure throughout the system. UL 9540A unit level testing indicated that thermal runaway propagation was contained within the module to a limited number of cells and did not result in any external flaming or an explosive release (although flammable gases were released).

Should thermal runaway occur within a system, several key barriers are provided to mitigate against propagation of failure throughout the system leading to more severe consequences, described in detail in [Section 3.2](#) of this report.

Figure 3-3-4: Thermal Runaway Condition Diagram



Table 3-3: Thermal Runaway Condition Barriers

Barrier	Barrier Description
THREAT BARRIERS	
Battery Management System (BMS)	Each battery string is outfitted with a BMS that works with the individual battery management units (BMU). The BMS constantly monitors and controls cell voltages, current, temperature, SOC, and other operating parameters. If parameters exceed permissible values, the BMS will open the integrated DC contactors to automatically disconnect the affected string and send an alarm to the site EMS.
Thermal Management System	An active thermal management system, utilizing a liquid coolant, efficiently dissipates heat from battery cells when charging and discharging to maintain cell temperatures between 20 – 35°C (68 – 95°F).
Cell Thermal Abuse Tolerance	The cell has been tested and listed to UL 1973 in which thermal abuse tolerance was tested.

Module Thermal Abuse Tolerance	System subcomponents have been tested and listed to UL 1973 in which thermal abuse tolerance was tested.
CONSEQUENCE BARRIERS	
See Section 3.2 for list of primary consequence barriers.	

3.3.2 Failure of Any Energy 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 SolBank BESS utilizes a tiered hierarchy of controls starting at the module and string level, up to the site level (EMS).

In the event of a communication loss between the BMS/BMU and the EMS, a watchdog alarm will be activated and isolate the affected system. If a failure of the EMS were to occur, each battery string is equipped with a dedicated BMS to provide corrective actions in case of detection of abnormal operation outside of set parameters. To further isolate any failure stemming from a failure of the site EMS, passive and active electrical fault protections are provided at multiple levels, as described in [Section 2.2.5](#).

Finally, should a propagating thermal runaway occur, several key barriers are provided to mitigate against propagation of failure throughout the system leading to more severe consequences, described in detail in [Section 3.2](#) of this report.

Figure 3-3-5: Failure of an Energy Management System Diagram



Table 3-4: Failure of an Energy Management System Barriers

Barrier	Barrier Description
THREAT BARRIERS	

Energy Management System (EMS)	The site level energy management system (EMS) supervises output of all enclosures to provide isolation / protective actions in case of module or rack BMS failure.
Module BMS	The string-level BMS provides isolation / protective actions in case of site EMS failure or loss of communication.
System Shutdown / Disconnect	Multiple levels of passive and active electrical protections are provided for the system including module overcurrent protection via fuses and breakers, inverter DC and AC protections, and ground fault monitoring. Surge protection devices are provided for the SolBank. An emergency stop (E-stop) button is provided on each end of the enclosure. When the E-stop is pushed, the SolBank will immediately commence shut down, and all BMS will isolate battery strings from the main system bus.
Passive Circuit Protection and Design	Fused disconnects and DC disconnect switches, in addition to ground fault detection / interruption and overvoltage protection are provided.
Cell Electrical Abuse Tolerance	The cell has been tested and listed to UL 1973 in which electrical abuse tolerance was tested.
CONSEQUENCE BARRIERS	
See Section 3.2 for list of primary consequence barriers.	

3.3.3 Failure of Any Required Ventilation or Exhaust System

Lithium-ion technologies do not release flammable gases during normal charging or discharging operations and are therefore not required to be provided with an exhaust ventilation system. The SolBank 3.0 enclosure, however, is equipped with an explosion prevention system – activated via combustible gas detection – in the unlikely event that flammable gases develop during a failure condition.

Smoke, heat, combustible gas detection, and other failure detection systems will send notification to the FACP and/or site EMS, triggering alarm signals and respective safety systems. Should cell off-gassing occur, the enclosure is provided with fresh air intake and an 820 CFM exhaust fan which will activate to evacuate the cabinet of flammable gas buildup. This system is monitored by the SolBank Controller and, if operation of the exhaust system fails, a notification will be sent to the site EMS. Should either of these systems fail, facility siting and proper response procedures will provide a final layer of safety to ensure the protection of life and property.

Figure 3-3-6: Failure of Any Required Ventilation or Exhaust System

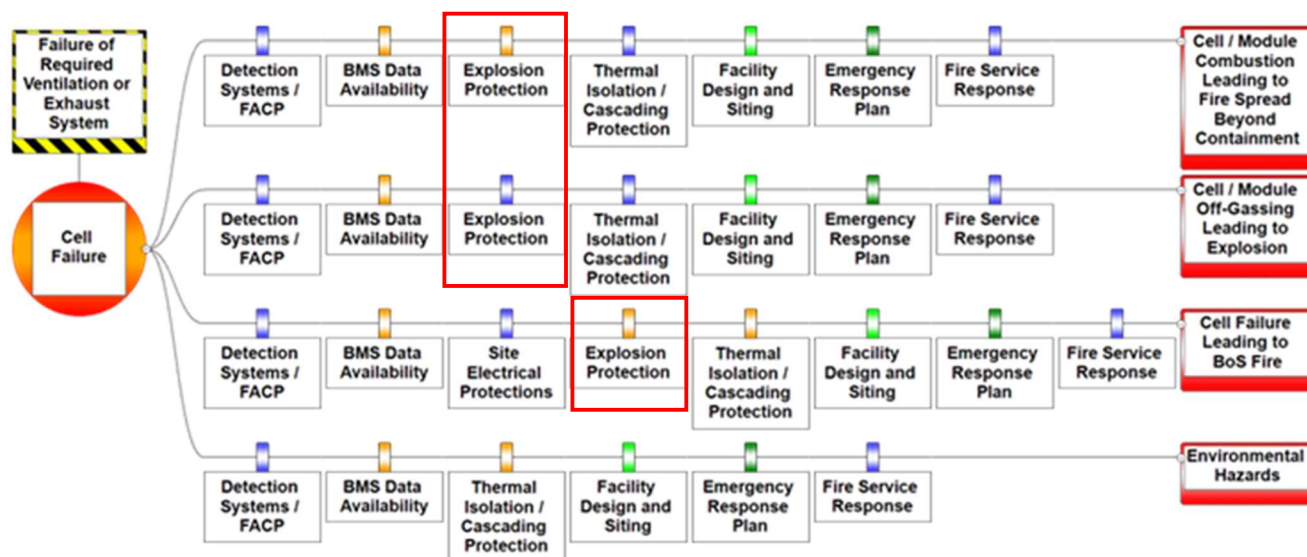


Table 3-5: Failure of Any Required Ventilation or Exhaust System

Barrier	Barrier Description
CONSEQUENCE BARRIERS	
Fire Detection	An internal automatic smoke, heat, and combustible gas detection system is connected to an internal FACP which will relay alarm signals to the site EMS via the SolBank Controller, triggering alarm signals and respective safety responses.
BMS Data Availability / Remote Operations Center (ROC)	The EMS monitoring software provides the ability for the BMS / BMU data to be transmitted remotely to a remote operations center (ROC) for monitoring or to be available locally for subject matter expert (SME).
Electrical Fault Protection Devices	Electrical fault protection devices at the BESS include overcurrent protection and overvoltage (surge) protection devices. Site level electrical protections are provided by the UL 1741 listed inverter (PCS).
Thermal Isolation / Cascading Protection	Passive and active thermal isolation barriers are provided, including aerogel between cells and active liquid cooling for thermal management. UL9540A unit level testing indicated no observation of module-to-module propagation, flying debris, explosive discharge of gases, external flaming sparks, electrical arcs, or other electrical events during the test.

Facility Design and Siting	Facility design and siting may vary on a site-by-site basis. It should be ensured that sites follow Canadian Solar's recommended guidance for siting and other installation specifications be followed.
Emergency Response Plan (ERP)	Product-level Emergency Response Guide (ERG) provided by Canadian Solar/ESRG. An additional level of safety may be provided via site-specific Emergency Response Plans (ERP) in accordance with the locally adopted codes/standards.
Fire Service Response	Site-specific training and installation familiarization for local responding stations will increase the strength of this barrier, and fire department equipment and capabilities will be strong with this familiarization.

3.3.4 Failure of the Smoke Detection, Fire Extinguishing, or Gas Detection System

The SolBank BESS does not rely on any external or internal fire suppression systems to mitigate a cascading thermal runaway event. However, several active and passive barriers are provided to mitigate the effects of a failure of a smoke, heat, or combustible gas detector within the BESS enclosures. The BMS and system shutdown / disconnects may prevent cell failure from occurring, as described previously.

The automatic smoke, heat, and combustible gas detectors are connected to a UL 864 listed fire alarm control panel (FACP), monitoring them for system integrity. In the event of a detector failure, the FACP will automatically send trouble signals to the site EMS via the SolBank Controller for personnel to investigate. Redundant failure detection is included in the form of checksums from the upper controller.

Figure 3-3-7: Failure of Smoke Detection, Fire Extinguishing, or Gas Detection System Diagram

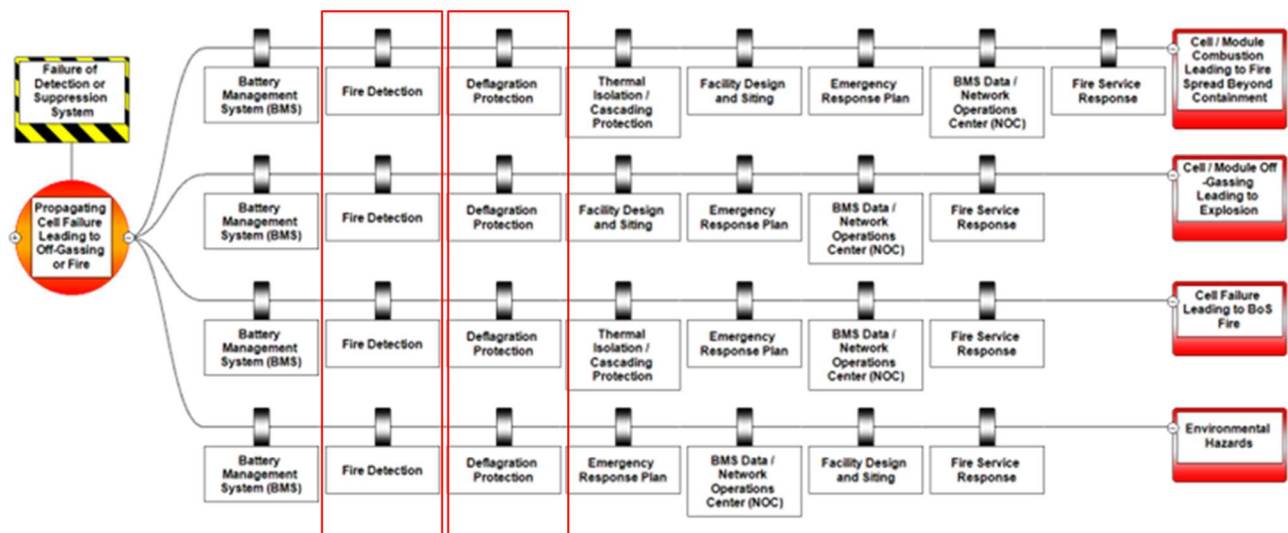


Table 3-6: Failure of Smoke Detection, Fire Extinguishing, or Gas Detection System Barriers

Barrier	Barrier Description
CONSEQUENCE BARRIERS	
Battery Management System (BMS)	Each battery string is outfitted with a BMS that works with the individual battery management units (BMU). The BMS constantly monitors and controls cell voltages, current, temperature, SOC, and other operating parameters. If parameters exceed permissible values, the BMS will open the integrated DC contactors to automatically disconnect the affected string and send an alarm to the site EMS.
Fire Detection	An internal automatic smoke, heat, and combustible gas detection system is connected to an internal FACP which will relay alarm signals to the site EMS via the SolBank Controller, triggering alarm signals and respective safety responses. If the single failure mode is the failure of a smoke, heat, or gas detector, this barrier may be weakened.
Deflagration Protection	An explosion prevention (explosion control) system is provided in each SolBank enclosure in the event flammable byproducts of cell off-gassing were to develop to detectable levels within the unit. The enclosure utilizes an 820 CFM exhaust fan and louvered intakes which automatically activate upon detection of 10% LFL (hydrogen). CFD analysis results demonstrate that the system design is capable of meeting the applicable requirements of NFPA 69. If the single failure mode is the failure of the gas detection system, this barrier may not be available.
Thermal Isolation / Cascading Protection	Passive and active thermal isolation barriers are provided, including aerogel between cells and active liquid cooling for thermal management. UL9540A unit level testing indicated no observation of module-to-module propagation, flying debris, explosive discharge of gases, external flaming sparks, electrical arcs, or other electrical events during the test.
Facility Design and Siting	Facility design and siting may vary on a site-by-site basis. It should be ensured that sites follow Canadian Solar's recommended guidance for siting and other installation specifications be followed.
Emergency Response Plan (ERP)	Product-level Emergency Response Guide (ERG) provided by Canadian Solar/ESRG. An additional level of safety may be provided via site-specific Emergency

	Response Plans (ERP) in accordance with the locally adopted codes/standards.
BMS Data Availability / Remote Operations Center (ROC)	The EMS monitoring software provides the ability for the BMS / BMU data to be transmitted remotely to a remote operations center (ROC) for monitoring or to be available locally for subject matter expert (SME).
Fire Service Response	Site-specific training and installation familiarization for local responding stations will increase the strength of this barrier, and fire department equipment and capabilities will be strong with this familiarization.

3.3.5 Voltage Surges on the Primary Electric Supply

Voltage surges on the primary electric supply are expected to be largely mitigated by voltage monitoring and corrective actions taken by the BMS / BMU. The SolBank BESS cabinet is provided with overvoltage and surge protection devices that will protect the equipment in the event of a voltage spike.

Should corrective actions triggered by the BMS fail to prevent further propagation of failure, several additional electrical fault protections are provided, as are briefly described in [Section 2.2.5](#).

Figure 3-3-8: Voltage Surges on the Primary Electric Supply Diagram



Table 3-7: Voltage Surges on the Primary Electric Supply Barriers

Barrier	Barrier Description
THREAT BARRIERS	
Voltage Monitoring	Voltage is monitored by the BMS/BMU, triggering fault and alarm monitor indicators, and potential system disconnect or other corrective actions if operating out of normal parameters.

System Shutdown / Disconnect	Multiple levels of passive and active electrical protections are provided for the system including module overcurrent protection via fuses and breakers, inverter DC and AC protections, and ground fault monitoring. Surge protection devices are provided for the SolBank. An emergency stop (E-stop) button is provided on each end of the enclosure. When the E-stop is pushed, the SolBank will immediately commence shut down, and all BMS will isolate battery strings from the main system bus.
Battery Management System (BMS)	Each battery string is outfitted with a BMS that works with the individual battery management units (BMU). The BMS constantly monitors and controls cell voltages, current, temperature, SOC, and other operating parameters. If parameters exceed permissible values, the BMS will open the integrated DC contactors to automatically disconnect the affected string and send an alarm to the site EMS.
Inverter / PCS Controls	Site level electrical protections are provided by the UL 1741 listed inverter.
Passive Circuit Protection / Design	Fused disconnects and DC disconnect switches, in addition to ground fault detection / interruption and overvoltage protection are provided.
System Electrical Abuse Tolerance	The system is anticipated to be listed to UL 9540, in which system electrical abuse tolerance is tested.
CONSEQUENCE BARRIERS	
See Section 3.2 for list of primary consequence barriers.	

3.3.6 Short Circuits on the Load Side of the ESS

Like the electrical mitigations for voltage surge on the primary electric supply described in [Section 3.3.5](#), short circuits on the load side of the energy storage system are managed by the BMS and system shutdown, as well as passive circuit protections.

Finally, as is consistent across all previous fault conditions, should 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, which are described in detail in [Section 3.2](#) of this report.

Figure 3-3-9: Short Circuits on the Load Side of the ESS Diagram



Table 3-8: Short Circuits on the Load Side of the ESS Barriers

Barrier	Barrier Description
THREAT BARRIERS	
Battery Management System (BMS)	Each battery string is outfitted with a BMS that works with the individual battery management units (BMU). The BMS constantly monitors and controls cell voltages, current, temperature, SOC, and other operating parameters. If parameters exceed permissible values, the BMS will open the integrated DC contactors to automatically disconnect the affected string and send an alarm to the site EMS.
Voltage Monitoring	Voltage is monitored by the BMS/BMU, triggering fault and alarm monitor indicators, and potential system disconnect or other corrective actions if operating out of normal parameters.
System Shutdown / Disconnect	Multiple levels of passive and active electrical protections are provided for the system including module overcurrent protection via fuses and breakers, inverter DC and AC protections, and ground fault monitoring. Surge protection devices are provided for the SolBank. An emergency stop (E-stop) button is provided on each end of the enclosure. When the E-stop is pushed, the SolBank will immediately commence shut down, and all BMS will isolate battery strings from the main system bus.
Passive Circuit Protection / Design	Fused disconnects and DC disconnect switches, in addition to ground fault detection / interruption and overvoltage protection are provided.

System Electrical Abuse Tolerance	The system is anticipated to be listed to UL 9540, in which system electrical abuse tolerance is tested.
CONSEQUENCE BARRIERS	
See Section 3.2 for list of primary consequence barriers.	

3.3.7 Failure of Temperature Control (HVAC)

The SolBank 3.0 is equipped with an active thermal management system which circulates a liquid coolant throughout the enclosure to maintain battery cell temperatures when charging and discharging. The coolant system is monitored by leak and pressure sensors and operation of the liquid chiller is monitored by the SolBank Controller. If critical temperatures or potential failure of the liquid chiller are detected, the output of that enclosure will be shut down immediately to prevent overheating. Additionally, a notification will be sent to the EMS.

Should failure propagate throughout all “threat” side barriers, leading to cell or module thermal runaway, additional systems are in place to prevent further failure leading to more severe events such as a fully developed fire in the battery system or deflagration.

Smoke, heat, combustible gas, and other failure detection systems will send notifications to the FACP and/or site EMS, triggering alarm signals and respective safety systems. Should cell off-gassing occur, the enclosure is provided with fresh air intake and an 820 CFM exhaust fan, which will activate to evacuate the cabinet of flammable gas buildup. This system is monitored by the SolBank Controller and, if operation of the exhaust system fails, a notification will be sent to the site EMS. Should either of these systems fail, facility siting and proper response procedures will provide a final layer of safety to ensure the protection of life and property.

Figure 3-3-10: Failure of Temperature Control Diagram

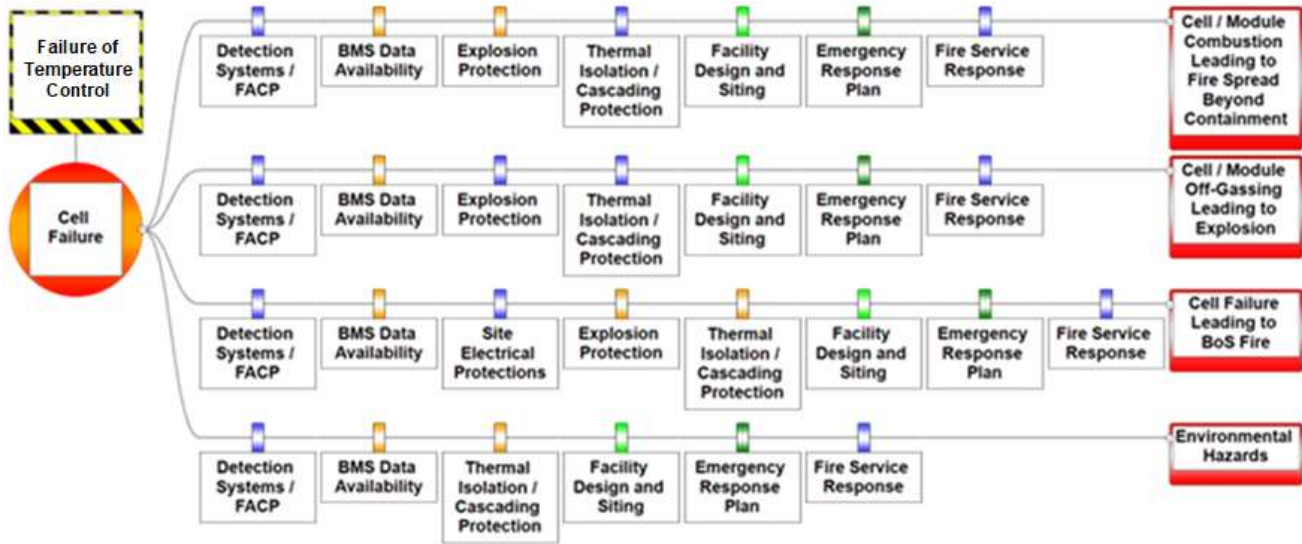


Table 3-9: Failure of Temperature Control Barriers

Barrier	Barrier Description
CONSEQUENCE BARRIERS	
Fire Detection	An internal automatic smoke, heat, and combustible gas detection system is connected to an internal FACP which will relay alarm signals to the site EMS via the SolBank Controller, triggering alarm signals and respective safety responses.
BMS Data Availability / Remote Operations Center (ROC)	The EMS monitoring software provides the ability for the BMS / BMU data to be transmitted remotely to a remote operations center (ROC) for monitoring or to be available locally for subject matter expert (SME).
Deflagration Protection	An explosion prevention (explosion control) system is provided in each SolBank enclosure in the event flammable byproducts of cell off-gassing were to develop to detectable levels within the unit. The enclosure utilizes an 820 CFM exhaust fan and louvered intakes which automatically activate upon detection of 10% LFL (hydrogen). CFD analysis results demonstrate that the system design is capable of meeting the applicable requirements of NFPA 69.

Electrical Fault Protection Devices	Electrical fault protection devices at the BESS include overcurrent protection and overvoltage (surge) protection devices. Site level electrical protections are provided by the UL 1741 listed inverter (PCS).
Thermal Isolation / Cascading Protection	Passive and active thermal isolation barriers are provided, including aerogel between cells and active liquid cooling for thermal management. UL9540A unit level testing indicated no observation of module-to-module propagation, flying debris, explosive discharge of gases, external flaming sparks, electrical arcs, or other electrical events during the test.
Facility Design and Siting	Facility design and siting may vary on a site-by-site basis. It should be ensured that sites follow Canadian Solar's recommended guidance for siting and other installation specifications be followed.
Emergency Response Plan (ERP)	Product-level Emergency Response Guide (ERG) provided by Canadian Solar/ESRG. An additional level of safety may be provided via site-specific Emergency Response Plans (ERP) in accordance with the locally adopted codes/standards.
Fire Service Response	Site-specific training and installation familiarization for local responding stations will increase the strength of this barrier, and fire department equipment and capabilities will be strong with this familiarization.

3.4 Analysis Approval

Per *IFC §1207.1.4.2, Analysis Approval*, the fire code official shall be permitted to approve the hazard mitigation analysis provided the consequences of the analysis demonstrate the following:

- 1) *Fires will be contained within unoccupied ESS rooms or areas for the minimum duration of the fire-resistance-rated separations identified in IFC §1207.7.4.*
- 2) *Fires in occupied work centers will be detected in time to allow occupants within the room or area to safely evacuate.*
- 3) *Toxic and highly toxic gases released during fires will not reach concentrations in excess of the immediately dangerous to life or health (IDLH) level in the building or adjacent means of egress routes during the time deemed necessary to evacuate occupants from any affected area.*
- 4) *Flammable gases released from ESS during charging, discharging, and normal operation will not exceed 25 percent of their lower flammability limit (LFL).*

- 5) *Flammable gases released from ESS during fire, overcharging, and other abnormal conditions will be controlled through the use of ventilation of the gases, preventing accumulation, or by deflagration venting.*

Table 3-10: Summary of Analysis Approval

Compliance Requirement	Comments
1. Fires will be contained within unoccupied ESS rooms or areas for the minimum duration of the fire-resistance-rated separations identified in IFC §1207.7.4.	Not applicable. The SolBank BESS enclosures are of non-combustible construction and are outdoor, standalone, ground-mounted systems.
2. Fires in occupied work centers will be detected in time to allow occupants within the room or area to safely evacuate.	Not applicable. The SolBank BESS enclosures are not enterable and therefore, will never be occupied.
3. Toxic and highly toxic gases released during fires will not reach concentrations in excess of the immediately dangerous to life or health (IDLH) level in the building or adjacent means of egress routes during the time deemed necessary to evacuate occupants from any affected area.	The SolBank 3.0 is a non-enterable enclosure and is not intended to be installed within any buildings. UL 9540A (4th Ed.) does not require the measurement of toxic gases (only flammable gases) and limited information on toxic gases released for the specific battery system is available. In extensive experience performing large-scale fire testing of li-ion batteries, ESRG has found that measured proprietary gas data indicate that toxicity levels are much in line with that of typical structure fires.
4. Flammable gases released from ESS during charging, discharging, and normal operation will not exceed 25 percent of their lower flammability limit (LFL).	Not applicable. Lithium-ion batteries do not release flammable gases during charging, discharging, or normal operation.
5. Flammable gases released from ESS during fire, overcharging, and other abnormal conditions will be controlled through the use of ventilation of the	UL9540A testing shows that the system can potentially release flammable gases during failure and abnormal conditions. The SolBank 3.0 BESS is provided with an active explosion prevention system (fresh air intake and exhaust

gases, preventing accumulation, or by deflagration venting.	fan). This system will ensure that any flammable gases developed within the BESS enclosure during a failure event will be exhausted, and the enclosure will remain below flammability limits.
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4 SUPPORTING DOCUMENTATION

The following key supporting documents were provided by Canadian Solar and reviewed as a basis for this hazard mitigation analysis.

4.1 UL 9540A Large-Scale Fire Testing

4.1.1 Cell Level Test

UL 9540A (4th Ed.) cell level testing was conducted on the Hithium Model LFP71173207 3.2V, 314Ah, lithium iron phosphate (LFP) cell by TUV Rheinland with report issued December 6, 2023 (Report No. CN23F118 001) [1].

Thermal runaway at the cell level was achieved via external film heaters with a 4°C/min to 7°C/min thermal ramp. Cell venting occurred at an average of 203.7°C over five test samples, with average onset of thermal runaway at 295.7°C, during which approximately 130 L of gas were released. Gas analysis was provided to determine the lower flammability limit (LFL), burning velocity, and maximum pressure (Table 5-1).

As common in lithium-ion cell level tests, the vent gases produced during thermal runaway presented a flammability hazard when mixed with air at both ambient and cell venting temperatures. Therefore, the performance criteria of cell level testing in accordance with §7.7 of UL 9540A (4th Ed.) were not met, and module level testing was required to be conducted.

Table 4-1: Cell Level Test Results

Avg. Cell Surface Temperature at Venting (°C)	203.7
Avg. Cell Surface Temperature at Thermal Runaway (°C)	295.7
Gas Volume (L)	130
Lower Flammability Limit (LFL) at Ambient Temperature	8.1%
Lower Flammability Limit (LFL) at Venting Temperature	6.5%
Burning Velocity, S_u (m/s)	0.779
Maximum Pressure, P_{max} (MPa)	0.78

Table 4-2: Cell Level Gas Composition

Gas Component	Concentration (Vol. %)
Methane (CH ₄)	3.671
Ethane (C ₂ H ₆)	0.548

Ethylene (C ₂ H ₄)	1.389
Propane (C ₃ H ₈)	0.18
Propylene (C ₃ H ₆)	0.745
C ₄ (Total)	0.288
C ₅ (Total)	0.241
Carbon Monoxide (CO)	16.202
Carbon Dioxide (CO ₂)	26.861
Hydrogen (H ₂)	49.875
Total	100

Figure 4-1: Cell Level Test Setup (Left) and Cell After Test (Right)



4.1.2 Module Level Test

UL 9540A (4th Ed.) module level testing was conducted on the CSI-SolBank-P-104.5-2h-H module by TUV Rheinland with report issued June 28, 2024 (Report No. CN248UKE 001) [2].

As with cell level testing, thermal runaway at the module level was initiated via external heaters with a 4°C/min to 7°C/min thermal ramp. A total of five cells underwent thermal runaway (thermal runaway was initiated in three cells and propagated to two adjacent cells). White smoke was observed during testing. No flying debris, explosive discharge of gases, or external flaming were observed. Additionally, no sparks, electrical arcs, or other electrical events were observed during testing.

As the module level performance criteria in accordance with §8.4 of UL 9540A (4th Ed.) were not met, unit level testing was required to be conducted on a complete unit employing the CSI-SolBank-P-104.5-2h-H modules.

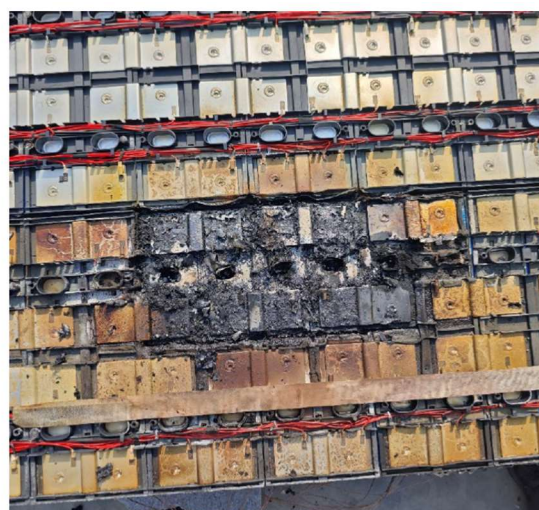
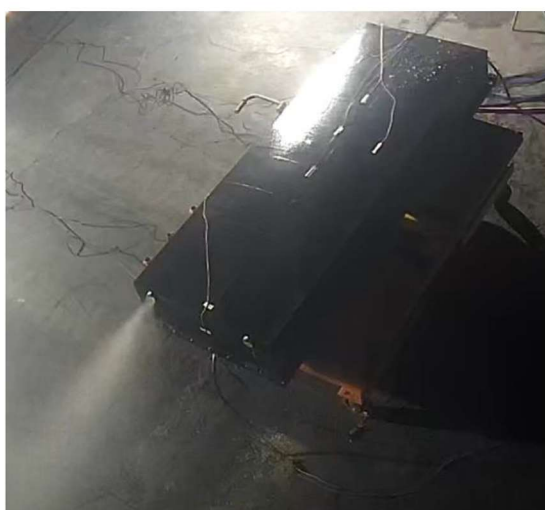
Table 4-3: Module Level Test Results

Weight Before Test (kg)	662.0 (with thermocouples)
Weight After Test (kg)	652.5 (with thermocouples)
Weight Loss (kg)	9.5
Peak Chemical Heat Release Rate, HRR (kW)	No flaming observed
Total Heat Release (MJ)	No flaming observed
Maximum Smoke Release Rate, SRR (m ² /s)	0.126
Total Smoke Released (m ²)	35.058

Table 4-4: Module Level Gas Composition and Volume

Gas Compound	Gas Type	Total Volume of Gas (L)	
		Pre-Flaming (L)	Post-Flaming (L)
Total Hydrocarbons (Propane Equivalent)	Hydrocarbons	285.55	No flaming
Carbon Monoxide (CO)	Carbon Containing	157.10	No flaming
Carbon Dioxide (CO ₂)	Carbon Containing	388.98	No flaming
Hydrogen (H ₂)	Hydrogen	262.16	No flaming
Note: 1) The collection time is from 15:45 to 20:40.			

Figure 4-2: Module Level Smoke Release (Left) and Module After Test (Right)



4.1.3 Unit Level Test

UL 9540A (4th Edition) unit level testing was conducted on the SolBank battery rack CSI-SolBank-R-418-2h-H 1331.2 V, 418 kWh unit by TUV Rheinland with report issued June 28, 2024 (Report No. CN24M32L 001) [3].

During testing, target racks were installed above and adjacent to an initiating rack and thermal runaway was achieved via external film heating, as in cell and module level tests. Observations from the test indicate that five cells underwent thermal runaway (three initiating cells propagated to two adjacent cells). The thermal runaway did not propagate throughout the module, and there was no module-to-module propagation. No flying debris, explosive discharge of gases, external flaming, sparks, electrical arcs, or other electrical events were observed during the test.

Unit level testing results met all applicable requirements set forth in UL 9540A (4th Ed.), Table 9.1. Therefore, installation level testing was not required.

Table 4-5: Unit Level Test Results

Weight Before Test (kg)	661.0 (with thermocouples)
Weight After Test (kg)	659.0 (with thermocouples)
Weight Loss (kg)	2.0
Peak Chemical Heat Release Rate, HRR (kW)	No flaming observed
Peak Convective Heat Release Rate, HRR (kW)	No flaming observed
Total Heat Release (MJ)	No flaming observed
Maximum Smoke Release Rate, SRR (m ² /s)	0.351
Total Smoke Released (m ²)	79.570

Table 4-6: Unit Level Gas Composition and Volume

Gas Compound	Gas Type	Total Volume of Gas (L)	
		Pre-Flaming (L)	Post-Flaming (L)
Total Hydrocarbons (Propane Equivalent)	Hydrocarbons	268.04	No flaming
Carbon Monoxide (CO)	Carbon Containing	104.63	No flaming
Carbon Dioxide (CO ₂)	Carbon Containing	427.33	No flaming
Hydrogen (H ₂)	Hydrogen	174.19	No flaming
Note: 1) The collection time is from 21:13 to 02:20.			

Figure 4-3: Unit Level Test Setup

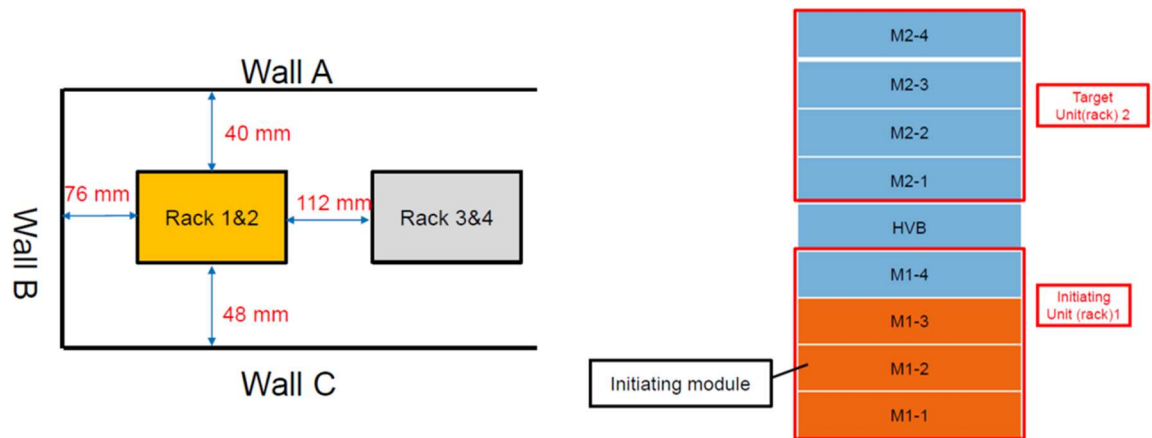


Figure 4-4: Unit Level Smoke Release



Figure 4-5: Initiating Module After Test (Rack 1)



4.2 NFPA 69 Analysis

A three-dimensional computational fluid dynamics (CFD) analysis was performed by TUV Rheinland to evaluate the design and anticipated performance of the SolBank 3.0 explosion prevention system. The analysis utilized UL 9540A test data to demonstrate that the system design successfully reduces the concentration of combustible gases in the container to less than 25% of the gas mixture lower flammability limit (LFL). In the issued report, TUV concluded that the SolBank 3.0 explosion prevention system can reduce the combustible concentration in the container with five cells in a module undergoing thermal runaway [4]. TUV found that the system mitigates the explosion risk to a substantially low and manageable level, and meets the intent of NFPA 69, Chapter 8: *Deflagration Prevention by Combustible Concentration Reduction*.

Key assumptions and observations from the TUV report are summarized below:

- The model assumes a constant gas release rate of 116.5 LPM based on maximum values in raw test data from the module level test. The composition of the gas was obtained from the cell level test report.
- The container is fitted with one exhaust fan with a rated flow rate of 1393.34 m³/h (820 CFM), though the model assumes a flow rate of 1019.52 m³/h (600 CFM) as a conservative measure. The exhaust fan and motorized inlet louvers are activated when the gas concentration at either detector reaches 10% LFL, based on the hydrogen component. Activation time includes a 5s lag time to account for the fan ramping up.
- A total of three gas dispersion scenarios were analyzed, each considering a different leakage position (Figure 5-6). As a conservative measure, gas release was initiated at the lowest module to maximize the necessary time for released gas to reach the detectors.

- All scenarios with the extraction fan activated can reduce the flammable volume of gas and are able to keep the flammable gas concentration below 25% LFL in the container (Table 5-7 and Figure 5-7).
- The explosion prevention system was found to comply with the applicable requirements of NFPA 69.
- It is noted that small pockets of gas are seen to exceed 25% LFL throughout the process, though the requirements for average enclosure concentrations per NFPA 69 are met (Figure 5-8).

Figure 4-6: Gas Leakage Locations

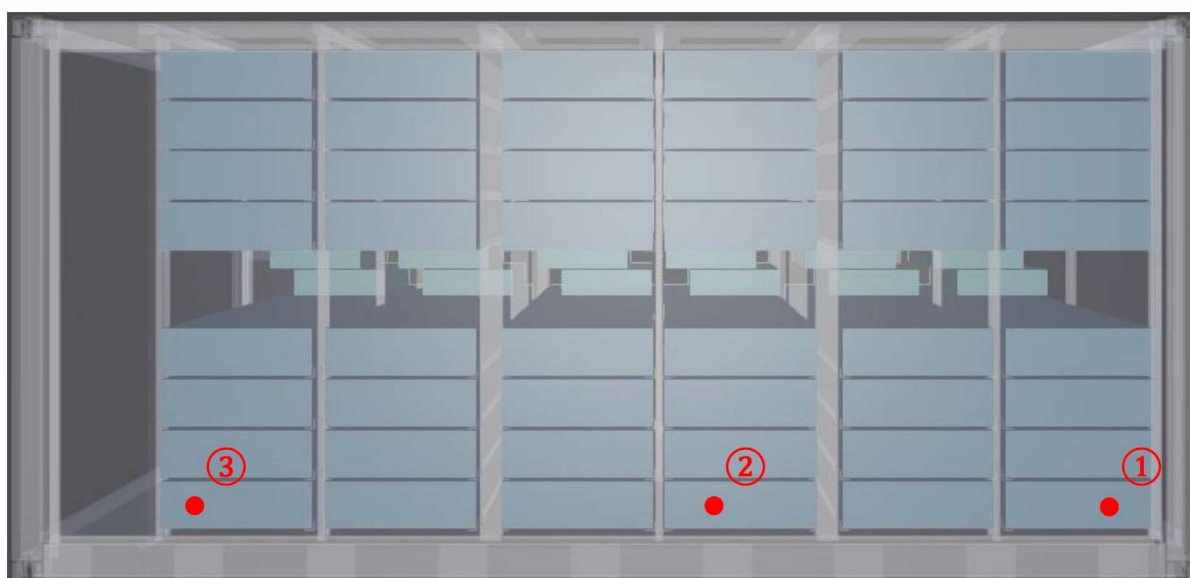


Table 4-7: Maximum Average Gas Concentrations

Scenario	Maximum Average Gas Concentration	
	Vol. %	% of LFL
1	0.495%	7.62%
2	0.514%	7.91%
3	0.574%	8.83%

Figure 4-7: Average Gas Concentrations

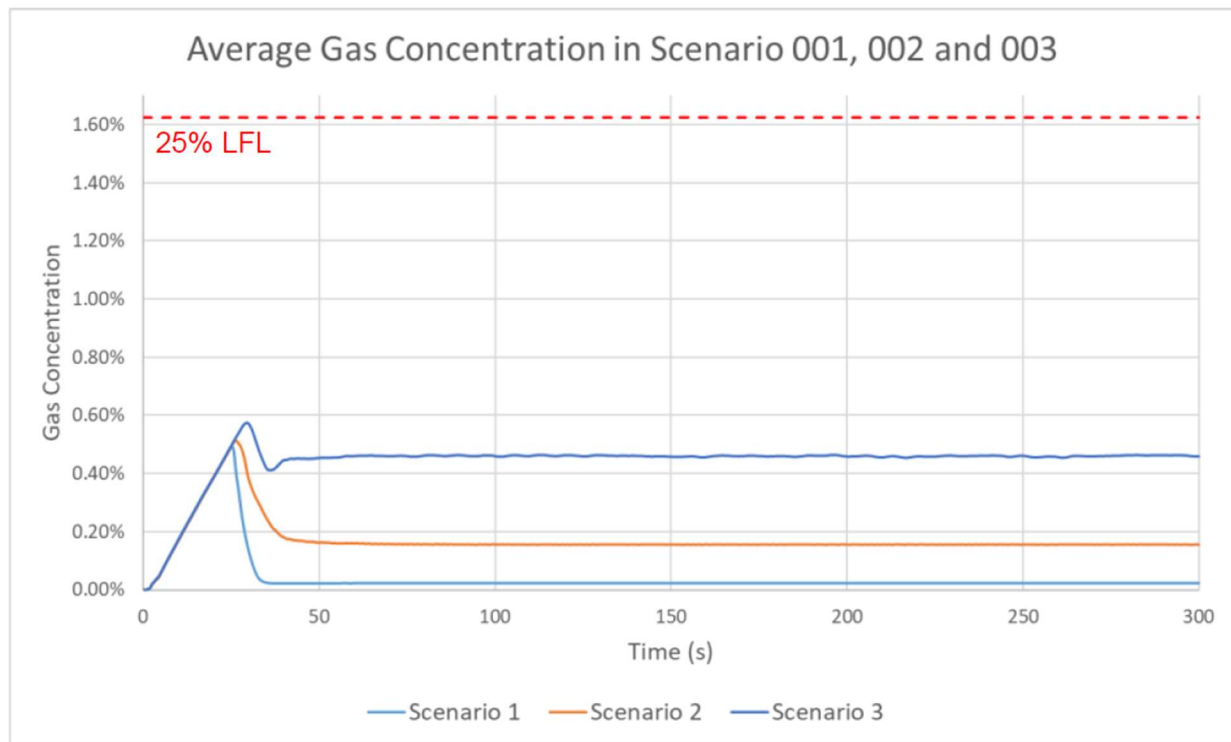
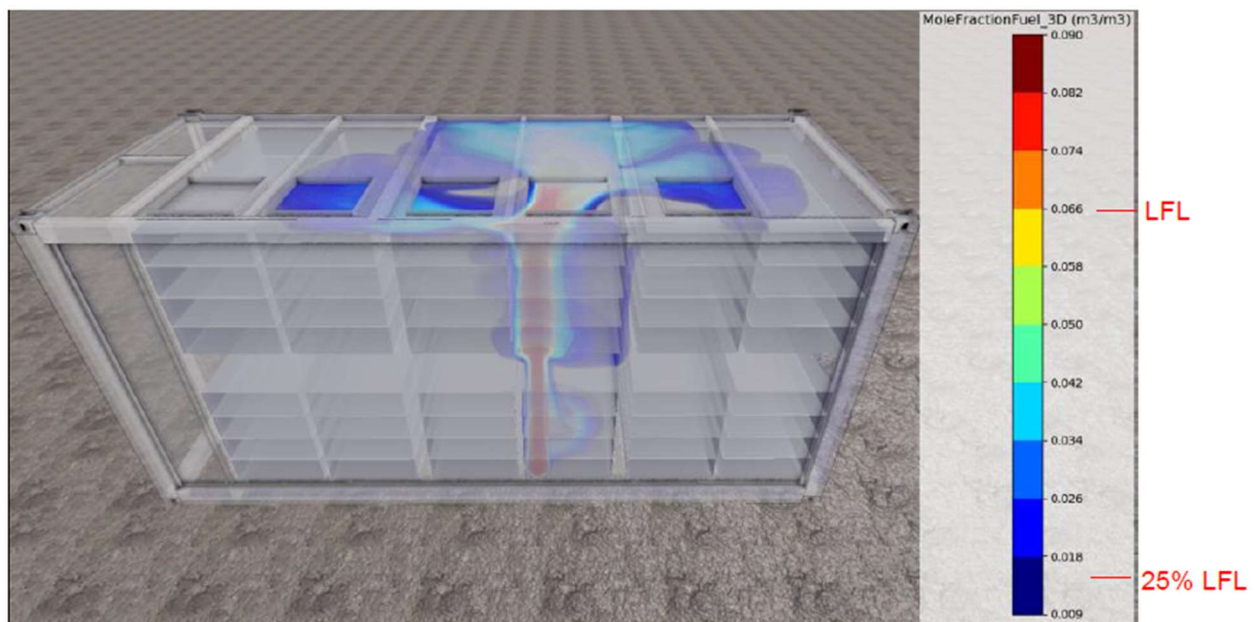


Figure 4-8: Maximum Average Gas Concentration (Scenario 2)



4.3 Heat Flux Analysis

A three-dimensional computational fluid dynamics (CFD) fire modeling analysis was performed for the SolBank 3.0 energy storage system by Hazard Dynamics [5]. The purpose of the analysis was to evaluate the potential for fire propagation to adjacent enclosures in the event of a single burning enclosure. The modeled scenarios considered (1) a single-enclosure fire with no wind, (2) a single-enclosure fire with 20 mph wind from the north, (3) a single-enclosure fire with 20 mph wind from the south, and (4) a single-enclosure fire with 20 mph wind from the east.

For each model considered, the internal temperatures of the enclosures adjacent to the burning enclosure were estimated using Fire Dynamics Simulator (FDS) software. Internal temperatures were compared to the cell vent temperatures – from UL 9540A data – to assess the possibility of thermal runaway propagation. Additionally, the external temperatures and heat fluxes on adjacent enclosures were modeled to assess the possibility of fire propagation through flammable components of the enclosure construction.

Key observations from the Hazard Dynamics report are summarized below:

- The SolBank 3.0 incorporates design features intended to isolate exposed components to prevent spread to the battery compartment. Some of these methods include a thermal barrier between the cooling unit and battery cavity, V-0 fire-rated weather stripping, and door designs that offer an additional steel layer behind the weather stripping.
- Fire modeling results show that for a no-wind scenario, flames generally rise vertically and have limited impacts on nearby enclosures (Figure 4-9). In this scenario, the heat transferred to adjacent enclosures does not cause internal temperatures to exceed the Hithium cell venting temperature (Figure 4-10). It is possible that, in this scenario, the flames may melt or burn weatherstripping or chiller components. The system incorporates design features which are intended to prevent these exterior components from causing fire spread into the battery compartment.

Figure 4-9: View of Fire Model (No Wind)

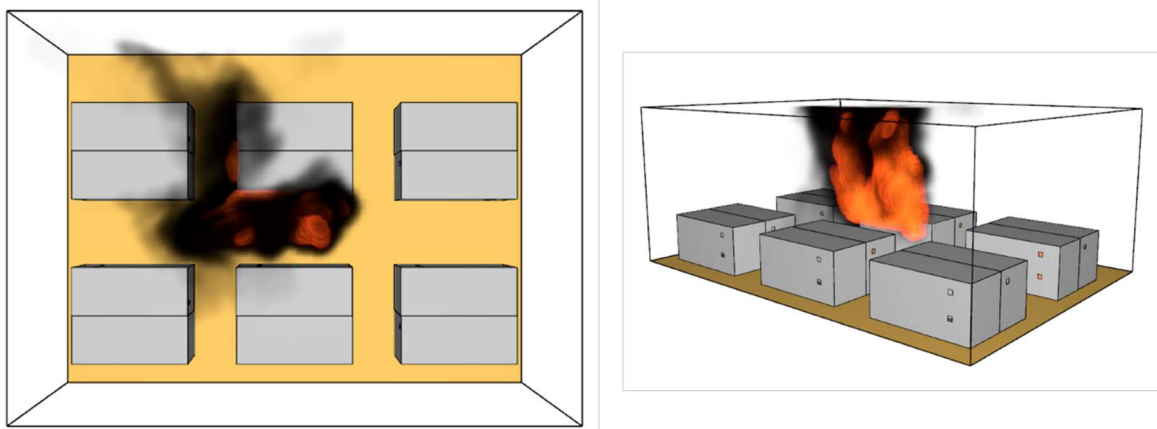
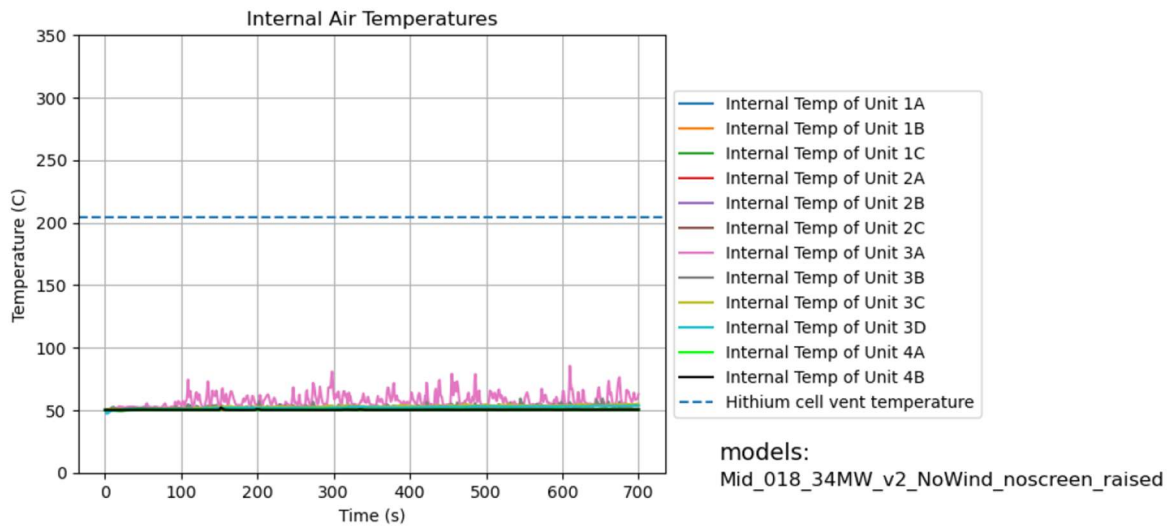


Figure 4-10: Internal Temperatures of Adjacent Enclosures (No-Wind Model)



- Fire modeling results show that for 20 mph winds from three major directions, flames are driven by the wind to lean and have a greater impact on adjacent enclosures (Figure 4-11). In these scenarios, the heat transferred to adjacent enclosures does not cause battery temperatures to exceed the Hithium cell venting temperature (Figure 4-12). As with the no-wind scenario, the flames may melt or burn weatherstripping or chiller components. The system incorporates design features which are intended to prevent these exterior components from causing fire spread into the battery compartment.

Figure 4-11: View of Fire Model (20 mph Northerly Wind)

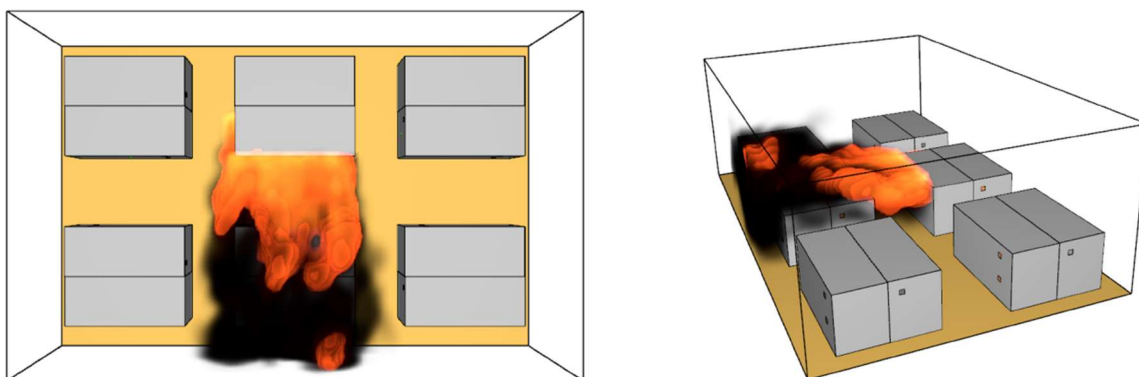
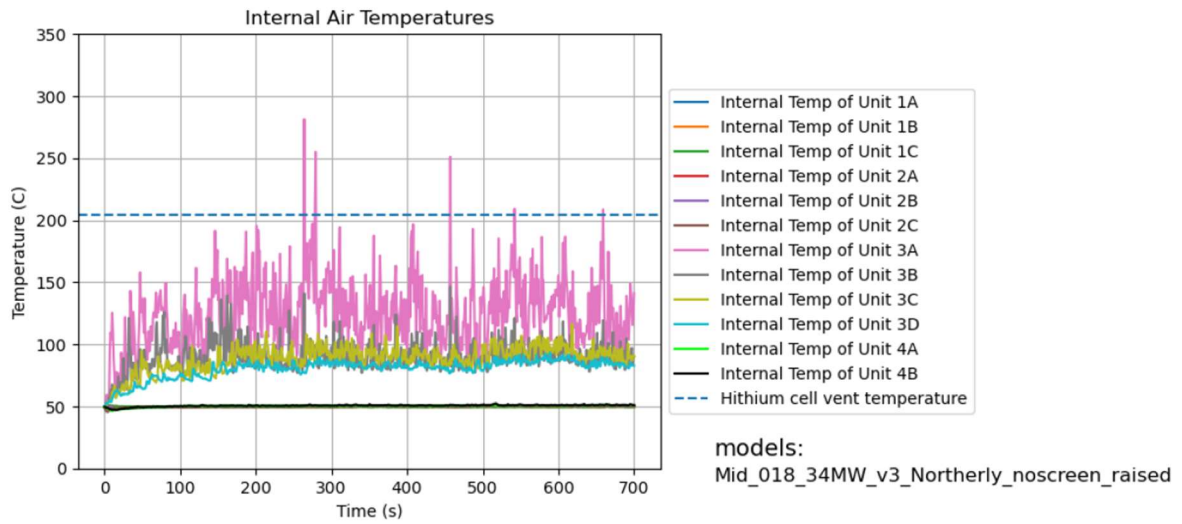


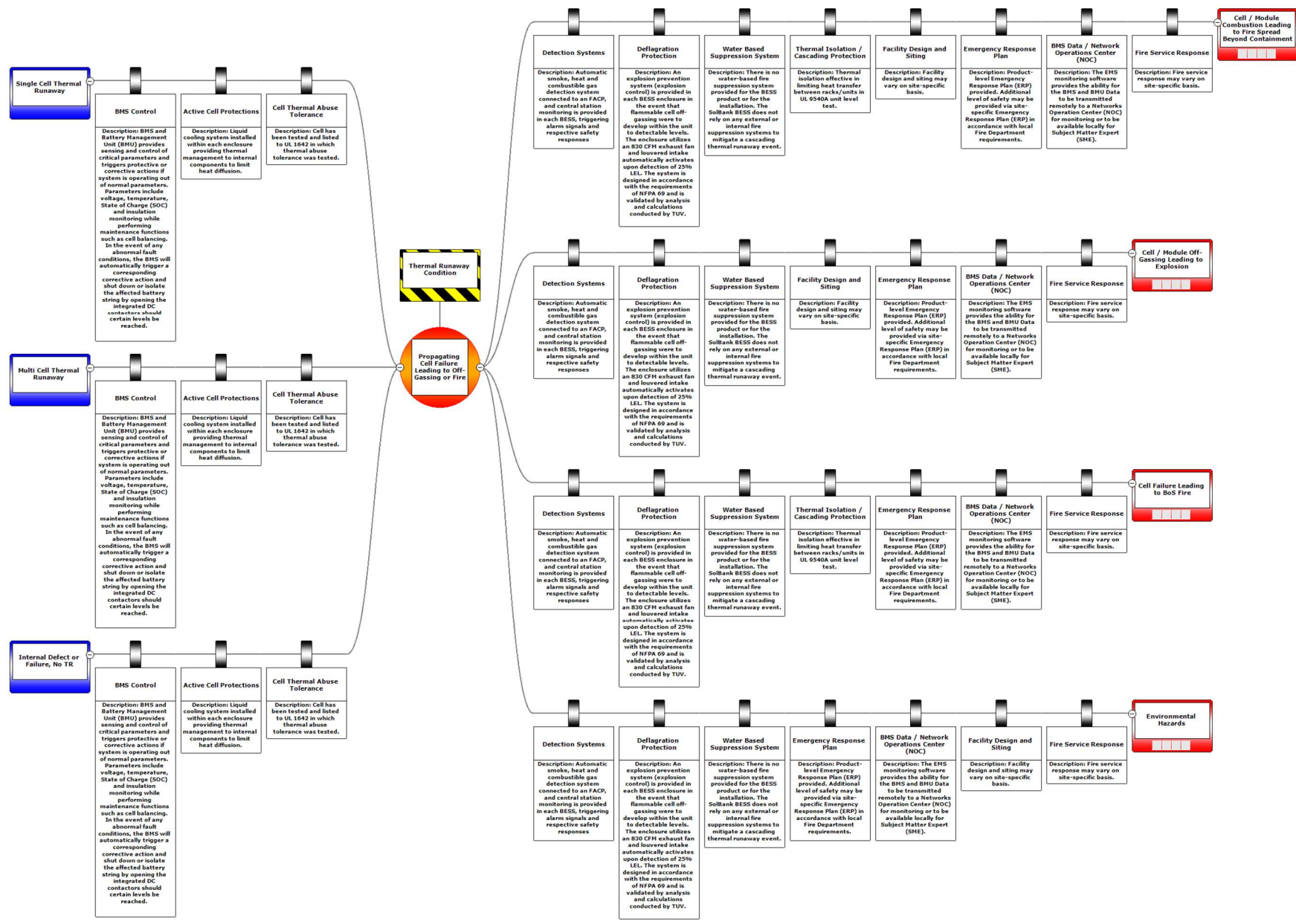
Figure 4-12: Internal Temperatures of Adjacent Enclosures (20 mph Northerly Wind Model)



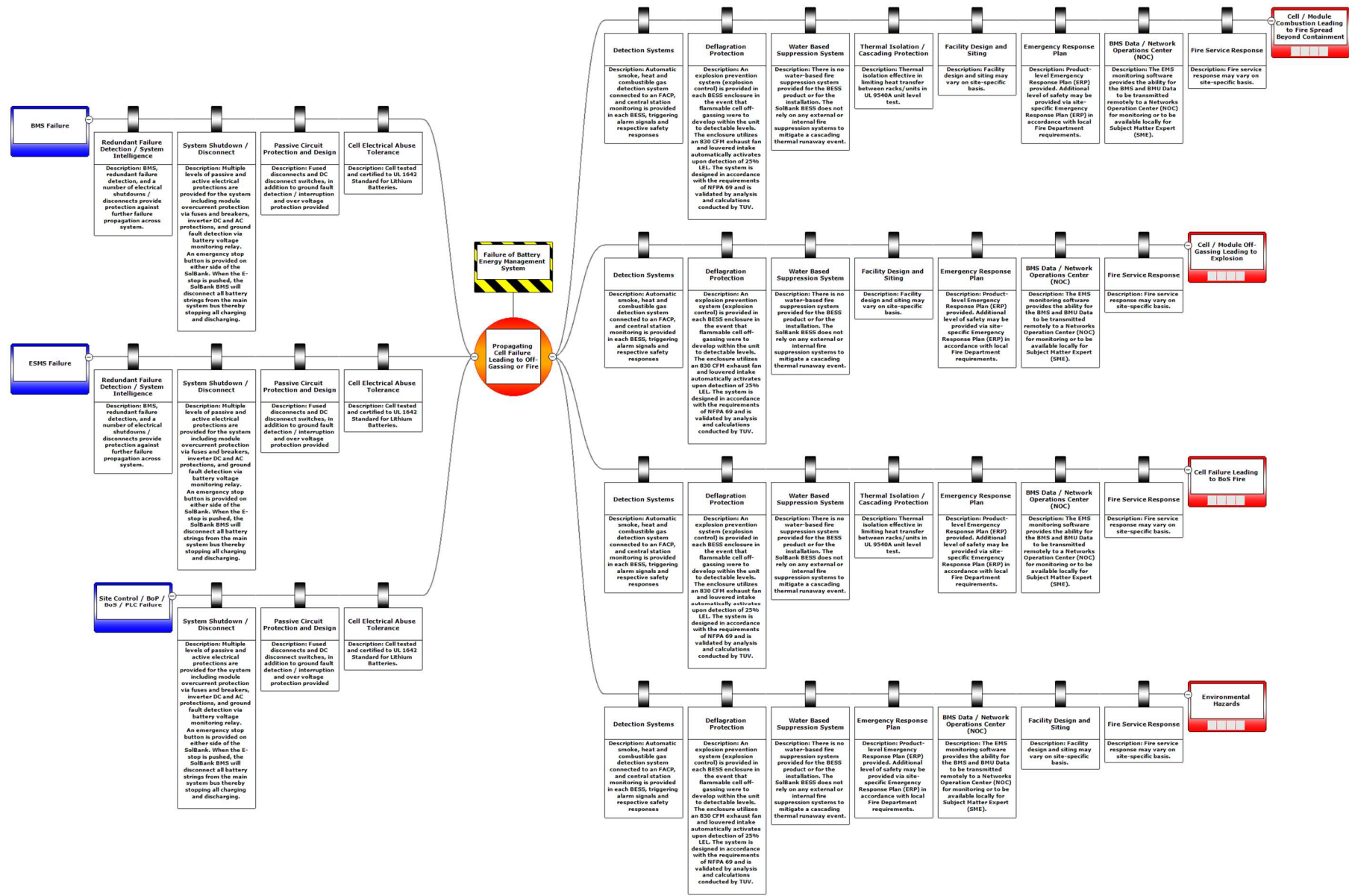
A.1 All Fault Conditions



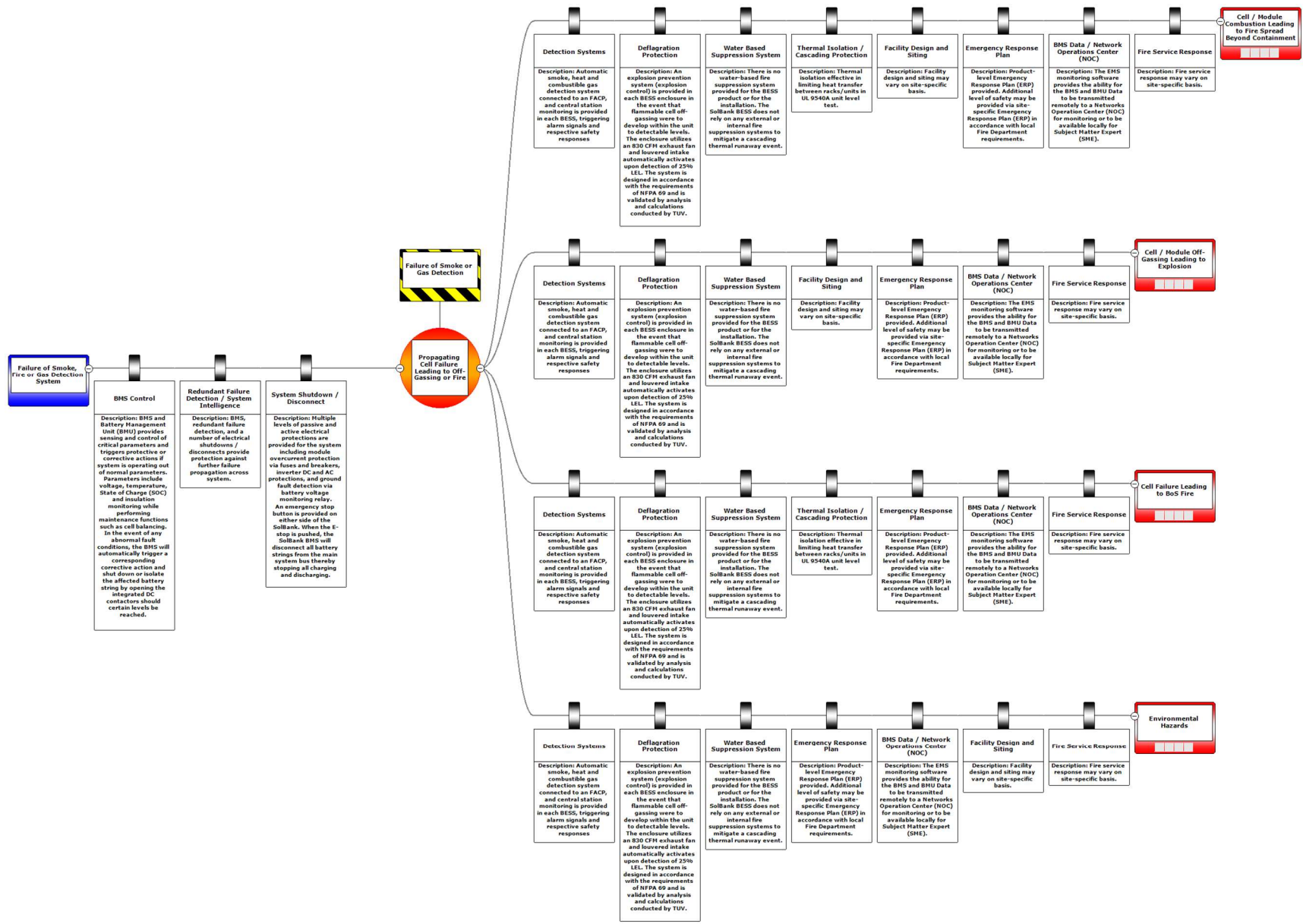
A.2 Thermal Runaway Condition



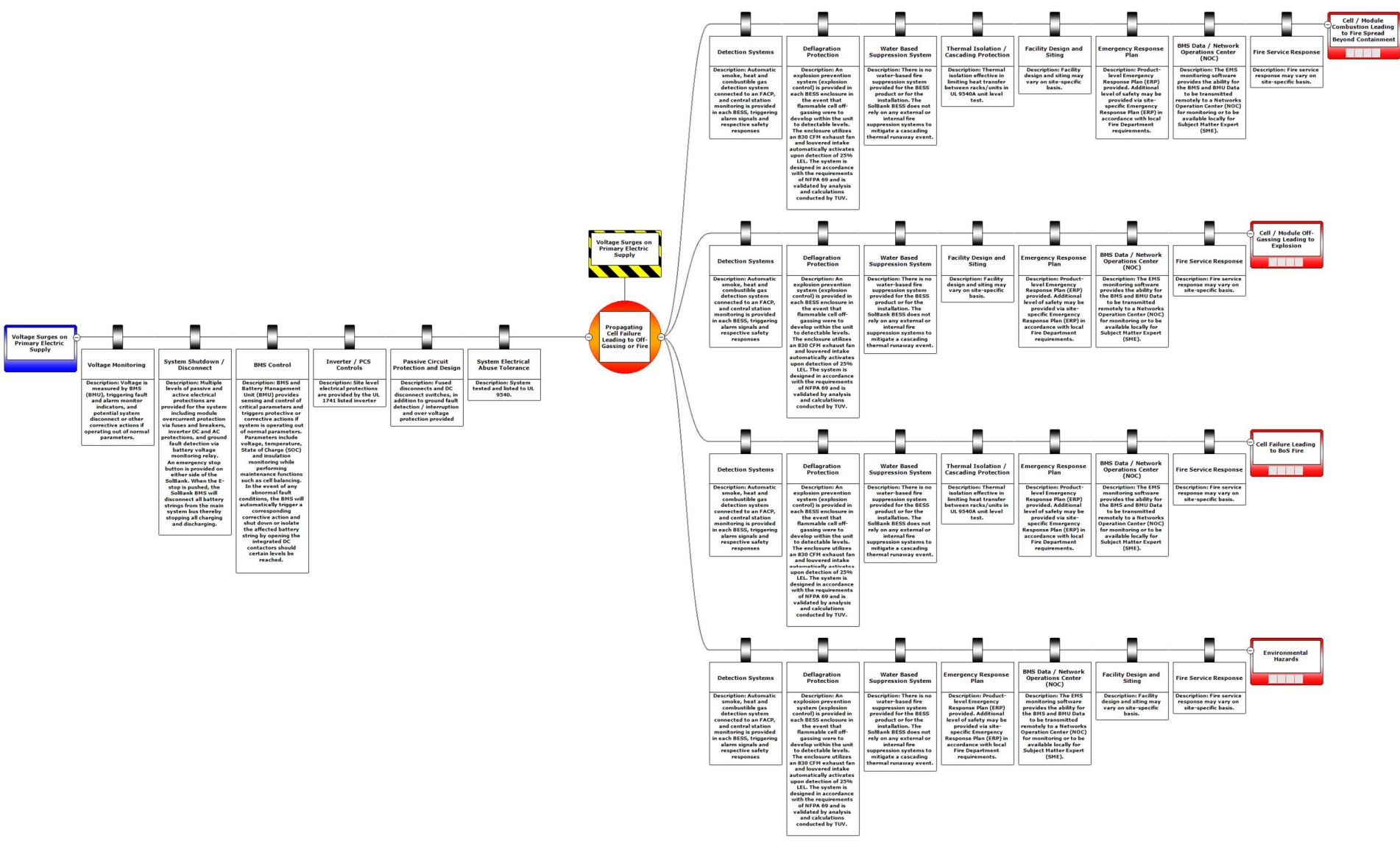
A.3 Failure of an Energy Management System



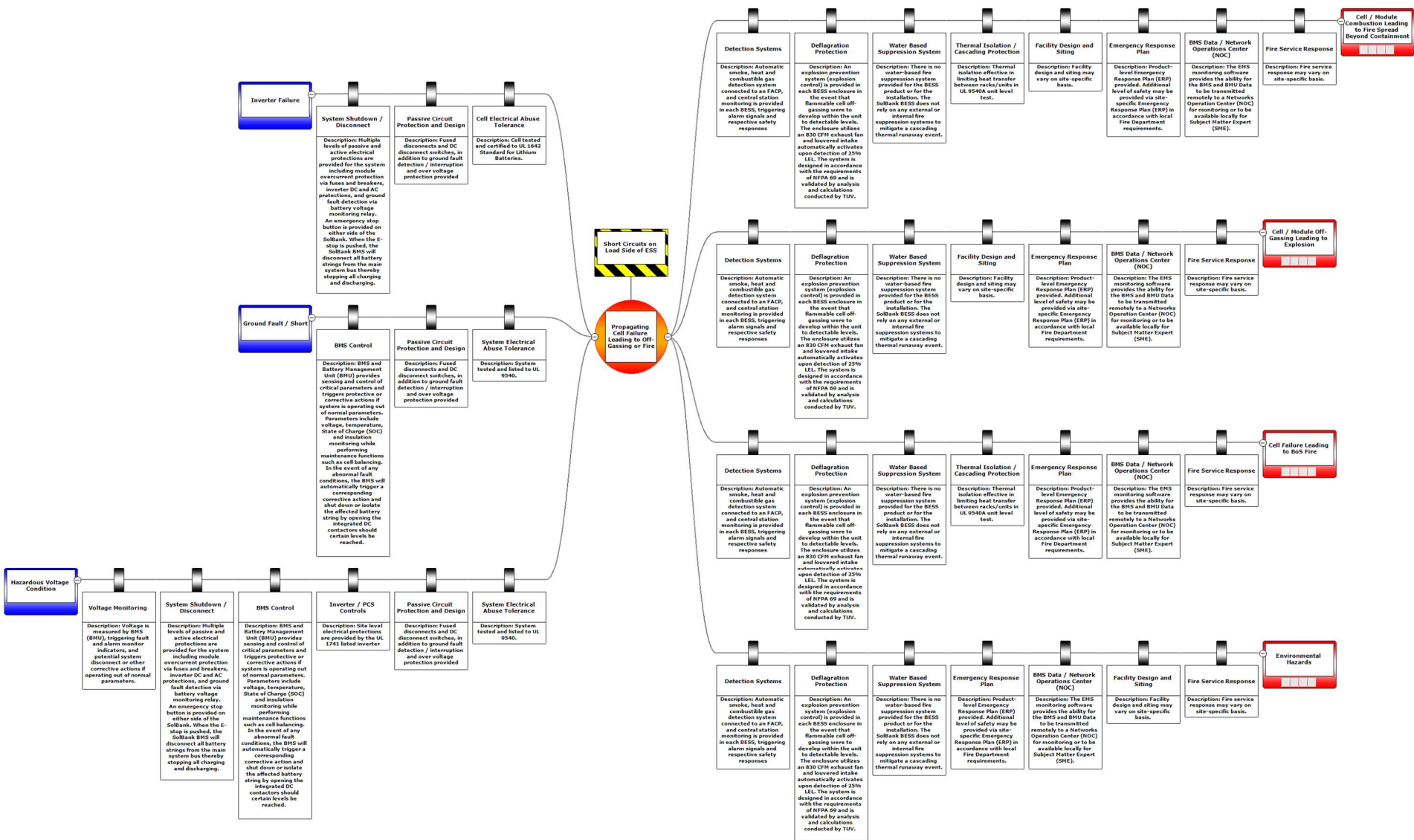
A.4 Failure of a Required Smoke Detection, Fire Extinguishing, or Gas Detection System



A.5 Voltage Surges on the Primary Electric Supply



A.6 Short Circuits on the Load Side of the ESS

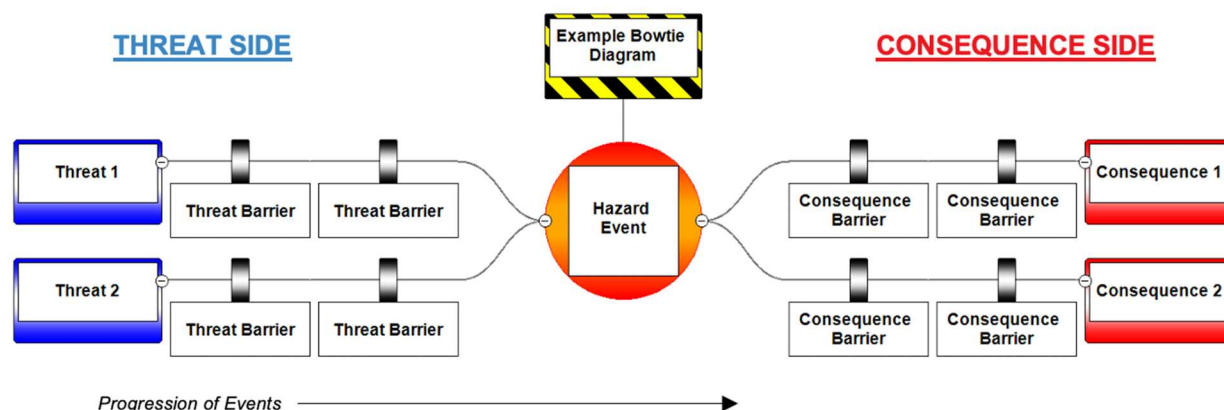


APPENDIX B – HMA METHODOLOGY

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 *NFPA 855 (2023 Ed.) Appendix G.3.6* and *ISO/IEC 31010 §B.21*, as it allows for in-depth analysis of 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 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 shows a single risk or consequence and all the barriers in place to stop it without the need for complex, numerical tables for threat pathways. 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 while it is still possible to prevent further damage.

- **Threats**

There 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 top event. Examples of threats are hazardous temperature conditions, BMS failure, and water damage from

condensation, each leading to cell failure (the top event for many of the 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). At times, 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 in this analysis 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 top event. For the models included in this analysis, the top 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 top 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 included models identify a set of common consequences representing areas of key concern to utilities, energy storage system operators, and first responders.

- **Barriers**

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 to maintain a desired state. Barriers can be included as proactive threat barriers or reactive consequence barriers.

Each barrier in these models is 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. However, 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 several 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.

APPENDIX C – REFERENCED DOCUMENTATION

- [1] 14-Hithium-314Ah-UL9540A Report.pdf
- [2] CN248UKE 001_UL 9540A_Module_TR_extsigned.pdf
- [3] CN24M32L 001_UL 9540A_unit_TR_extsigned.pdf
- [4] CN24SBF7 001_Hithium Cell_NFPA 69_TR_extsigned.pdf
- [5] HD_24018_ESRG_CSI_Solbank3.0_Fire-1.0-10_24_2024.pdf

APPENDIX D – REFERENCED CODES AND STANDARDS

- *International Fire Code §1207 Electrical Energy Storage Systems*, 2021 Edition
- *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 69 Standard on Explosion Prevention Systems*, 2024 Edition
- *NFPA 70 National Electric Code*, 2023 Edition
- *NFPA 72 National Fire Alarm and Signaling Code*, 2022 Edition