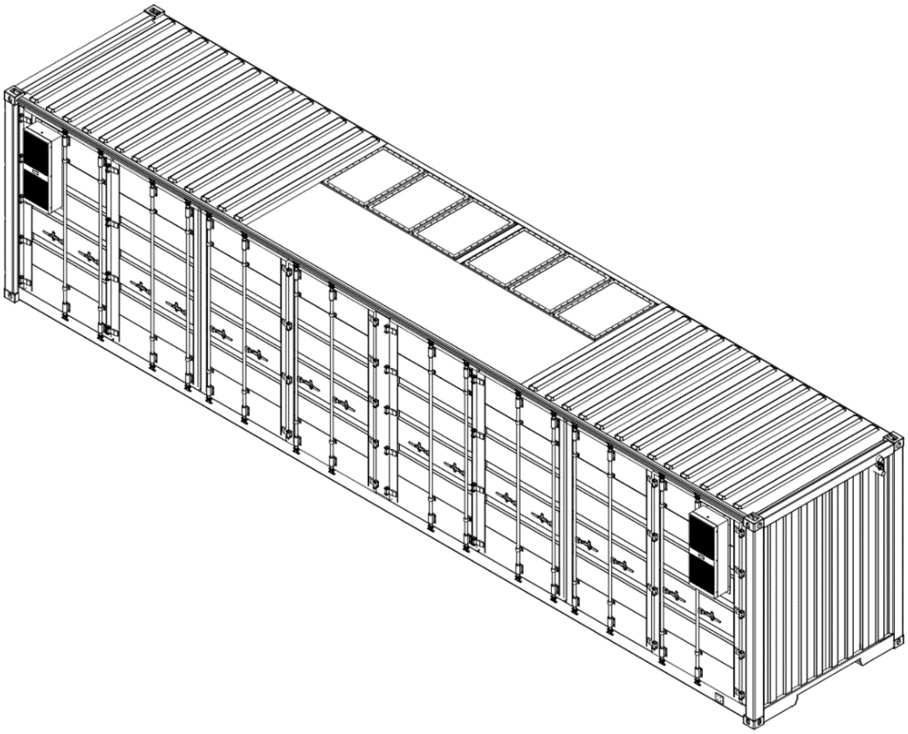
COFFMAN ENGINEERS

Draft Preliminary HMA Report

Rancho Viejo Solar Utility BESS

August 13, 2024
Revision A



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Draft Preliminary HMA
Rancho Viejo

August 13, 2024
Revision A

Coffman Project Number: 241470

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Revision History		
Revision	**Date**	**Description of Revision**
A	7/24/2024	Preliminary HMA 1st Draft
A1	8/13/2024	Preliminary HMA Revised Draft

EXECUTIVE SUMMARY

This Hazardous Mitigation Analysis (HMA) evaluates the conformance of the AES Rancho Viejo Solar Utility Battery Energy Storage System (BESS) project site with respect to the HMA requirements of NFPA 855, *Standard for the Installation of Energy Storage Systems* and IFC, *International Fire Code*.

ANALYSIS FAILURE MODES

The failure modes considered in this analysis are based on the specific failure modes required to be evaluated when completing an HMA per the 2021 edition of IFC and the 2023 edition of NFPA 855. The failure modes analyzed are as follows and discussed further in Appendix A for how they directly correspond to the failure modes within the two codes:

1. A thermal runaway or mechanical failure 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.
3. Failure of a required protection system including, but not limited to, ventilation (HVAC), exhaust ventilation, smoke detection, fire detection, fire suppression, or gas detection.
4. Voltage surges on the primary electric supply.
5. Short circuits on the load side of the ESS.

ANALYSIS ACCEPTANCE CRITERIA

The acceptance criteria used in this analysis aligns to the HMA approval criteria listed in the 2021 edition of IFC and the 2023 edition of NFPA 855. The acceptance criteria applied in this analysis is described below and in further detail in Appendix A for how it directly corresponds to the criteria within the two codes:

1. Fires and products of combustion will not prevent occupants from evacuating to a safe location.
2. Deflagration hazards will be addressed by an explosion control or other system.

ANALYSIS APPROACH

This evaluation implements a bowtie methodology to holistically evaluate the CEN BESS enclosure against the identified acceptance criteria. This hazard model follows the guidance provided in NFPA 855 Section G.4. Bow tie modeling is a common hazard mitigation analysis tool used in the maritime, oil and gas, and utility industries. The strength of the bowtie approach comes from its visual nature, which evaluates the chronological pathways leading from threats to critical hazard events to consequences with the associated mitigative and preventative barriers in place to reduce or eliminate the said consequences.

ANALYSIS APPROVAL

Demonstration of conformance with the acceptance criteria is as described below:

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

   The CEN enclosure features a sufficient quantity of safety barriers to limit the rate of propagation of an escalating fire or thermal runaway event and provide adequate situational awareness to facility occupant to permit evacuation to a safe location.

2. Deflagration hazards will be addressed by an explosion control or other system.

   This analysis has identified that a propagating cell failure event poses a deflagration hazard. The CEN enclosure will be equipped with a NFPA 68 compliant deflagration venting system to release *the combustion gases and pressure resulting from a deflagration within the enclosure so that structural and mechanical damage is minimized.*

Conformance with acceptance criteria described above is intended to demonstrate compliance with the HMA requirements of NFPA 855 and the IFC.

MAJOR ANALYSIS ASSUMPTIONS AND LIMITATIONS

This hazard study documented in this report is subject to the following major assumptions and limitations:

- **Unknown Failure Modes –** Major BESS failures modes not known by industry at the time of this analysis and not otherwise considered in this report may exist.
- **Outside Event effecting more than one unit** – The compounding effect of failure modes affect more than one enclosure at a time is not directly considered.
- **Hazards during Construction, Shipping and Storage** – The hazards associated with the construction, off-site storage and shipping of the BESS enclosures are not evaluated.
- **Continued Maintenance** – All BESS systems are assumed to be inspected, tested and maintained to minimum standards.
- **Installed per code –** Protection systems inside the BESS enclosure and site wide protection systems are assumed to be installed and maintained per minimum regulatory requirements. Coffman is not scoped to verify code compliance within the BESS enclosure.

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ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
AES	AES Clean Energy
AHJ	Authority Having Jurisdiction
BESS	Battery Energy Storage System
BCU	Battery Control Unit
BMS	Battery Management System
CID	Current Interrupt Device
DC	Direct Current
ESS	Energy Storage System
FACP	Fire Alarm Control Panel
FEMA	Failure Modes and Effects Analysis
HMA	Hazard Mitigation Analysis
HRR	Heat Release Rate
HVAC	Heating, Ventilation & Air Conditioning
IDLH	Immediately Dangerous to Life or Health
IFC	International Fire Code
IP	Ingress Protection
LFL	Lower Flammability Limit
NFPA	National Fire Protection Association
PLC	Programmable Logic Controller
ROCC	Remote Operations Control Center
SCADA	Site Supervisory Control and Data Acquisition
SME	Subject Matter Expert
SOC	State of Charge
SOH	State of Health
UPS	Un-interruptible Power Supply
VRLA	Valve-Regulated Lead Acid

1.0 INTRODUCTION

This Hazard Mitigation Report has been prepared by Coffman Engineers, Inc. (Coffman) to evaluate the conformance of the AES Rancho Viejo Solar Utility Battery Energy Storage System (BESS) project site against the Hazardous Mitigation Analysis (HMA) requirements of the National Fire Protection Association (NFPA) 855, *Standard for the Installation of Energy Storage Systems* (2023 edition), and the *International Fire Code* (2021 edition). This evaluation assesses the anticipated overall effectiveness of the provided protective barriers to prevent and mitigate the consequences of a battery related failure.

This analysis is based on conversations with AES Clean Energy (AES) personnel as well as the provided drawings and documents listed in the Referenced Documents section at the end of this report.

1.1 APPLICABLE CODES AND STANDARDS

This analysis evaluates the AES Rancho Viejo Solar Utility site against the requirements found in the codes and standards referenced below:

- *International Fire Code* (IFC), 2021 edition, as adopted by Sante Fe County Ordinance 2023-06
- *Sante Fe County Ordinance 2023-06 as adopted by the Board of County Commissioners*
- *Sante Fe County Ordinance 2023-09 as adopted by the Board of County Commissioners*
- *International Wildland Urban-Interface Code* (IWUIC), 2021 edition, as adopted by Sante Fe County
- NFPA 855, *Standard for the Installation of Energy Storage System*, 2023 edition
- NFPA 68, *Explosion Protection by Deflagration Venting*, 2013 edition
- NFPA 72, *National Fire Alarm and Signaling Code*, 2019 edition
- NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems*, 2018 edition
- UL 9540A, *Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems*, 4th Edition, November 12, 2019

1.2 OTHER REFERENCED CODES, STANDARDS AND RECOMMENDED PRACTICES

The following industry standards and recommended practices are referenced throughout this report in addition to the adopted codes and standards referenced above.

- ISO IEC 31010, *Risk Assessment Techniques*, 2019 edition

1.3 ANALYSIS GOALS AND OBJECTIVES

In accordance with NFPA 855 Section 9.4.1 and IFC Section 1207.5, an approved HMA is required to permit outdoor lithium-ion Energy Storage Systems (ESS) installations with a capacity exceeding 600 kWh. The objective of this HMA is to evaluate the consequences of the site-specific failure modes.

The single mode failure modes considered in this analysis are described in Table 1, below. The failure modes described in the table align to the single mode failure modes listed in the 2023 edition of NFPA 855 and the 2021 editions of the IFC. See Appendix A for a detailed description of how the selected failure modes correlate to specific IFC and NFPA 855 requirements.

Table 1: Analysis Failure Modes	
Failure Mode	**Failure Mode Description**
1	A thermal runaway or mechanical failure 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 detection, fire suppression, or gas detection.
4	Voltage surges on the primary electric supply.
5	Short circuits on the load side of the ESS.

The acceptance criteria applied in this analysis is described in Table 2. The acceptance criteria described in the table aligns to the HMA approval criteria listed in the 2023 edition of NFPA 855 and the 2021 edition of the IFC. See Appendix A for a detailed description of how the selected acceptance criteria correlate to specific IFC and NFPA 855 requirements.

Table 2: Analysis Acceptance Criteria	
Acceptance Criteria	**Acceptance Criteria Description**
1	Fires and products of combustion will not prevent occupants from evacuating to a safe location
2	Deflagration hazards will be addressed by an explosion control or other system

2.0 SITE DESCRIPTION

2.1 SITE INFORMATION

The AES-Rancho Viejo Solar Utility BESS project site is located in Santa Fe County, New Mexico. A site plan of the battery energy storage system layout is shown in **Figure 1**.

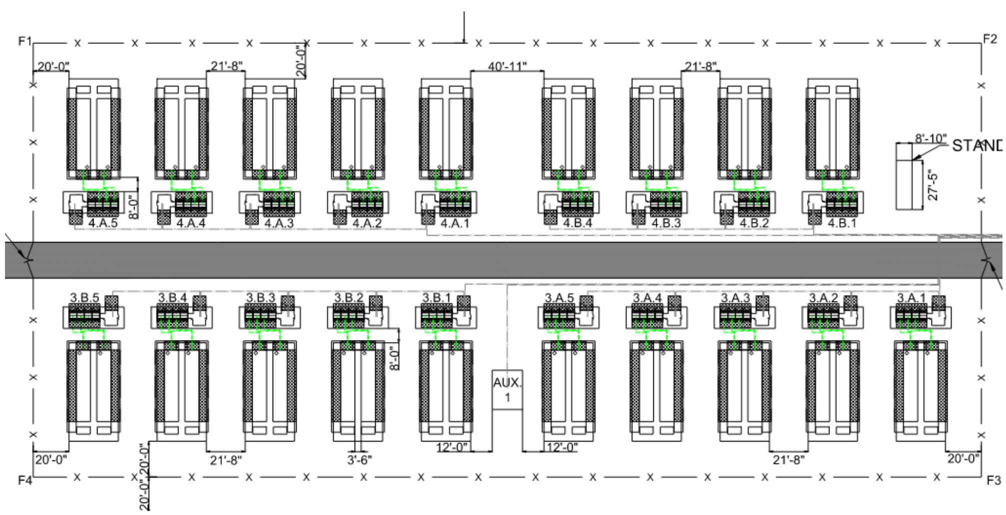

Figure 1 - Rancho Viejo BESS Site Plan

The site will include CEN enclosures manufactured by AES containing lithium-ion battery technology. The energy storage system proposed for this project is the Samsung SDI / E5S ESS. The details of the Rancho Viejo BESS facility are summarized in Table 3 below.

Table 3: CEN BESS System Specification Summary	
Owner:	AES
Overall BESS Capacity:	48 MW for 4 hours / 192 MWh
Number of BESS Enclosures:	38
Total Site Area:	2.94 Acres

2.2 FIRE DEPARTMENT ACCESS

Fire department roads will be provided on site to meet the spatial criteria of the IFC as noted below and shown in **Figure 2**:

- Unobstructed width of at least 20 feet
- Unobstructed vertical clearance of 13 feet 6 inches
- Dead ends more than 150 feet will be provided with an approved turn around area

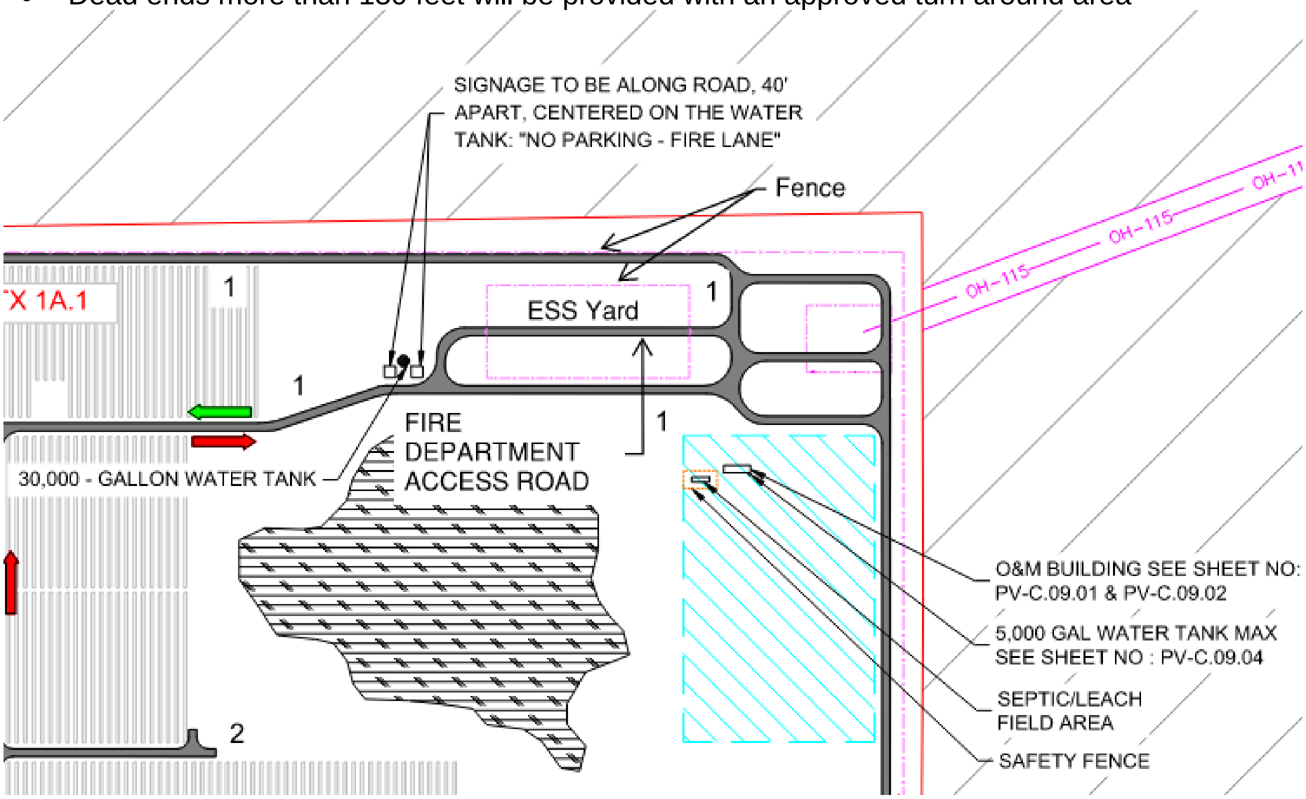

Figure 2 - Fire Department Features Site Map

2.3 LOCAL CLIMATE CONDITIONS

ASHREA data for the nearest airport at Albuquerque International shows a 1% extreme wind speed of 28.2 mph and 0.4% annual occurrence high temperature of 95.2º F. The overall site is relatively flat and does not pose additional risks.

3.0 ENERGY SYSTEM DESCRIPTION

The CEN enclosure is an 8,068 kWh lithium-ion BESS. The CEN enclosure utilizes lithium-ion cells manufactured by Samsung featuring lithium nickel cobalt aluminum oxide chemistry. The CEN enclosure is a non-walk-in style ground mounted outdoor BESS enclosure. Primary equipment included within the enclosure includes lithium-ion battery modules, DC disconnect switch, control and communications panel, AC/DC electrical panel, dehumidifiers, chilled water-cooling lines, and a fire suppression system. An image of the CEN enclosure is shown in Figure 3 – CEN BESS Enclosure (Exterior View)and Figure 4, below. The CEN enclosure specifications are summarized in Table 4.

Table 4: E5S BESS System Specification Summary			
ESS System Manufacturer:		AES	
ESS Model #:		AES Spec CEN-E5S	
ESS Electrical Ratings:		8,068 kWh	
ESS Max Voltage:		1494 Vdc	
ESS Enclosure Dimensions:		40’-0” (L) x 8’-0” (W) x 9’-6” (H)	
ESS Layout / Construction:		Non-Occupiable, Non-Walk-in, Non-Combustible 252 Modules per enclosure	
Cell		**Module**	
Manufacturer:	Samsung SDI CO LTD	Manufacturer:	Samsung SDI CO LTD
Model No:	CP1495L101A	Model No:	E5S (MS3204L101A)
Electrical Rating:	3.68 Vdc, 145 Ah	Electrical Rating:	110.4 Vdc, 290 Ah
Chemistry:	$LiNiCoALO_2$	Cells per Module:	60
Format:	Prismatic	Module Dimensions:	388 x 1751 x 155 mm

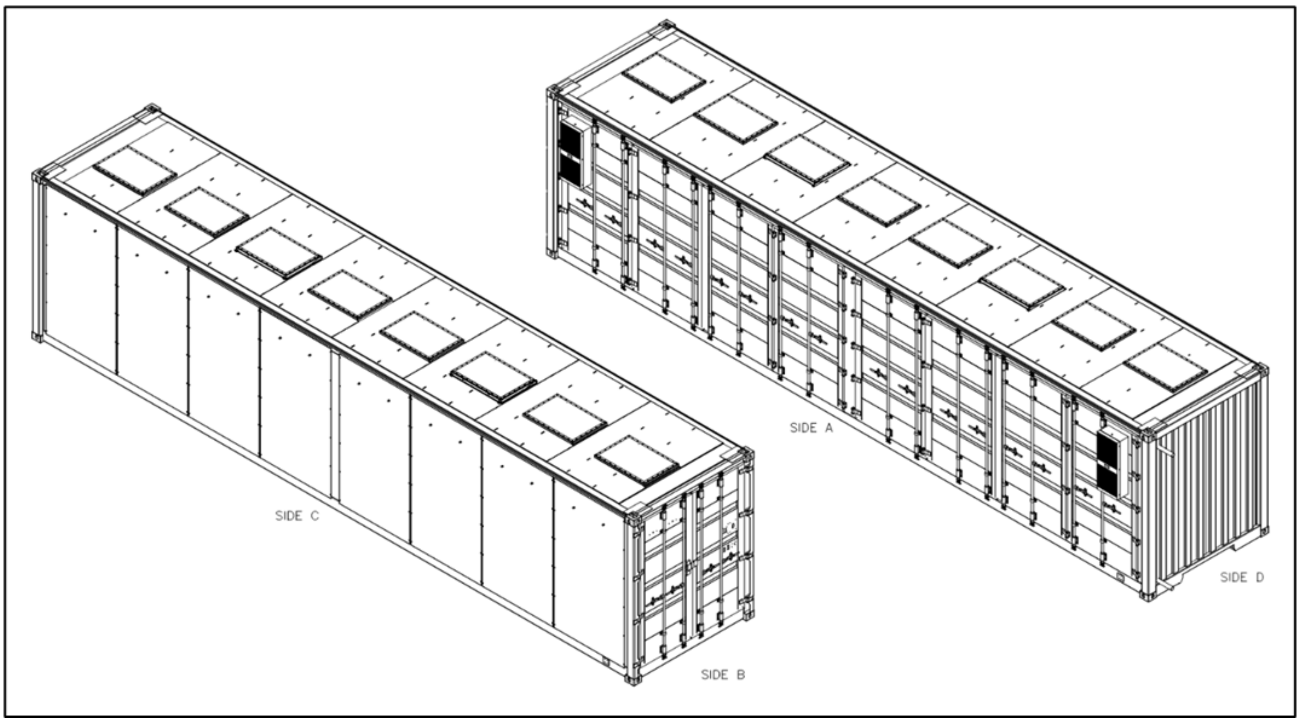

Figure 3 – CEN BESS Enclosure (Exterior View)

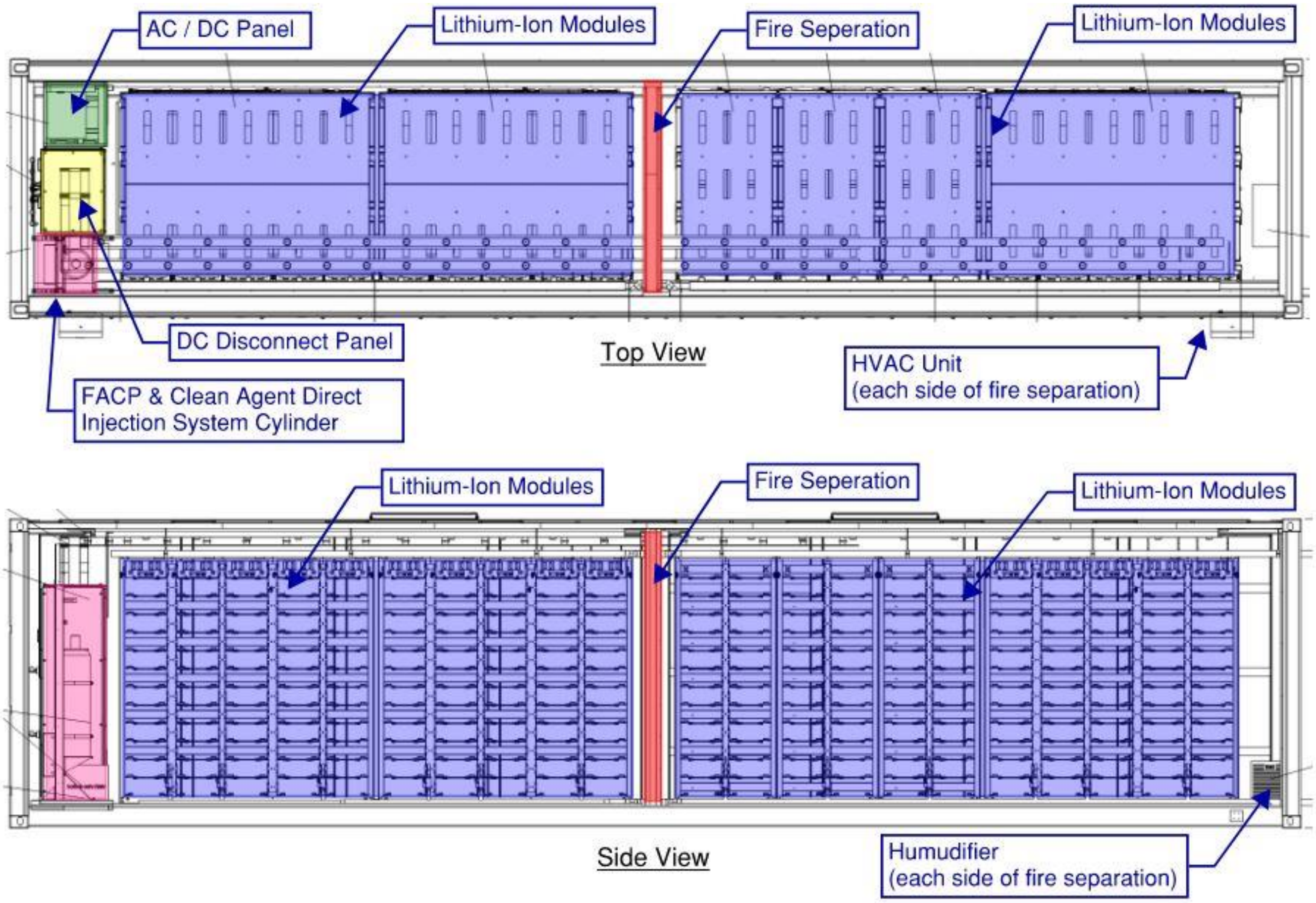

Figure 4 – CEN BESS Enclosure (Internal View)

3.1 ESS ENCLOSURE AND EQUIPMENT DESCRIPTION

The CEN enclosure consists of a 40’-0” long x 8’-0” wide x 9’-6” high, IP 55 rated, ISO container (See Figure 3). The enclosure features openable doors three sides. Deflagration panels are provided on the enclosure roof. The enclosure is subdivided by a fire separation constructed utilizing a metal faced mineral wool panel. The ceiling, wall and door panels are equipped with an FM Global approved Class 1 insulation material.

The enclosure contains 252 lithium-ion battery modules, each containing 60 cells. The modules are located on racks as shown in Figure 4. Each battery rack includes 12 battery modules and a battery control unit (BCU). The BCU contains the battery management system (BMS), contactor and fuse for the respective battery rack.

A DC disconnect switch panel containing the main DC fuses and disconnect switch is located on side B of the enclosure (See Figure 4). Also located on side B of the enclosure is an AC/DC electrical panel and an 1800 W un-interruptible power supply (UPS). The UPS is equipped with valve-regulated lead acid (VRLA) batteries. The fire alarm control panel (FACP) and fire suppression tank are also located in this area.

The enclosure is provided with humidifier and externally mounted HVAC units. Heating within the enclosure is provided by electric resistance heating. Cooling to the battery modules is provided by a liquid cooling system connected to a remote external chiller. The cooling system utilizes a 50/50 ethylene glycol mixture. No flammable refrigerants will be used within the enclosure.

3.2 FIRE AND THERMAL RUNAWAY SAFETY FEATURES

The CEN enclosure will include the following fire and thermal runaway features.

3.2.1 Battery Management System

The CEN enclosure includes an integrated BMS. The BMS system monitors state of charge (SOC), rate of charge/discharge, state of health (SOH), voltage and temperature. The BMS is capable of disconnecting individual battery racks when faults are detected. BMS data is communicated via a programmable logic controller (PLC) and site supervisory control and data acquisition (SCADA) system to an off-site Remote Operations Control Center (ROCC).

3.2.2 Deflagration Protection System

The CEN enclosure is equipped with six roof mounted deflagration panels to provide pressure relief from overpressure events related to the ignition of flammable gases released during lithium-ion thermal runaway. The deflagration protection system has been designed in accordance with the 2023 edition of NFPA 68.

3.2.3 Smoke Detection

A smoke detection system is provided in the enclosure. A photoelectric smoke detector is provided at the roof level of the enclosure above each battery rack. Enclosure smoke detectors are monitored by the enclosure FACP. Alarm signals are communicated to the ROCC via the site SCADA system as well as communicated directly to the site FACP.

3.2.4 Gas Detection

The enclosure is provided with carbon monoxide and lower explosive limit (LEL) flammable gas detection. LEL gas detection is accomplished utilizing catalytic bead detectors which are sensitive to both hydrogen and hydrocarbon gases. Alarm signals are communicated to the ROCC via the site SCADA system as well as communicated directly to the site FACP.

3.2.5 Facility Occupant Notification

A combination horn/strobe is located on the exterior of each CEN enclosure for notifying nearby facility occupants of a hazardous condition within the enclosure. Activation of the notification device occurs upon detection of a low gas level, activation of a single smoke detector or discharge of the thermal runaway propagation suppression system.

3.2.6 Thermal Runaway Propagation Suppression System

A direct injection clean agent system is provided to limit propagation of a thermal runaway event. The system utilizes Novec 1230 (FK 5-1-12) clean agent. The system includes a pressurized storage cylinder and piping network to discharge agent directly above each cell vent area. The system is intended to cool a thermal runaway event, extinguish flames generated by an exothermic reaction, and limit propagation to adjacent cells by keeping cell surfaces below critical onset temperatures. The direct injection system is configured to be released by the FACP upon activation of two or more smoke detectors or activation of the manual pull releasing station located on the exterior of the enclosure. The effectiveness of the direct injection system was evaluated as a part of the installation level UL9540a test discussed in Section 4.0.

3.2.7 Electrical Fault Protection

Each module is equipped with a fusible link. Fuses are present on both the positive and negative terminals of each battery rack. Additionally, fuses are provided for each enclosure DC connection.

3.2.8 Emergency Stop

Final details to include details of how e-stop will be accomplished will be provided in final HMA report.

3.2.9 Site Specific Protections

The following features related to the project site provide additional protection:

3.2.9.1 Facility Layout

As shown in **Figure 5** below, the CEN enclosures are grouped in side-by-side pairs with 3.5 feet of space between each enclosure. Each pair is then spaced 29.67 feet from the next pair in groups totaling 5 pairs (10 CEN enclosures) with the exception of the top right group which includes only 4 pairs (8 CEN enclosures). The site consists of 4 total groups of enclosures separated by a minimum of 48 feet of space between them. If a fire evolves to the point it spreads beyond an enclosure, it is highly likely the pair will become involved. It is recommended that defensive firefighting be provided to mitigate further spread to adjacent pairs of enclosures. The additional separation between the pairs and the groups of enclosures helps to mitigate the potential for fire to spread throughout the site.

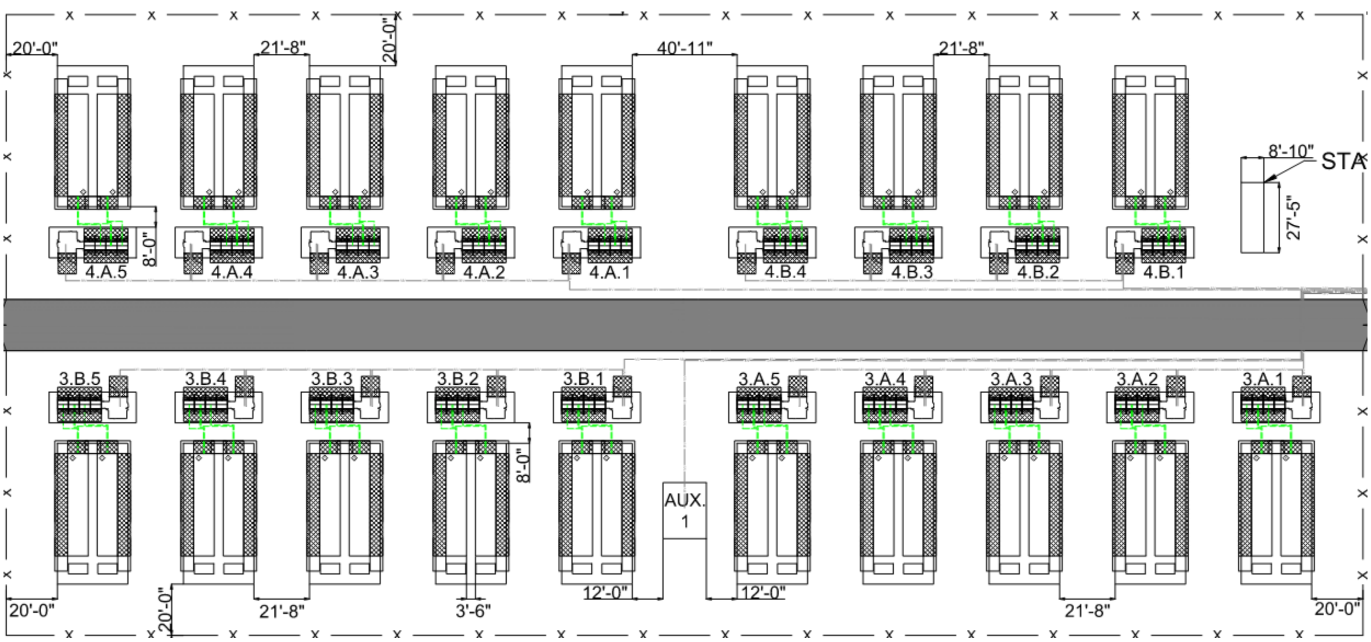

Figure 5 - E5N Enclosure Spacing

3.2.9.2 Vegetation Control

There will be a minimum 10-foot clearance between each side of the outdoor BESS units and combustible vegetation and other combustible growth as required by NFPA 855 section 9.5.2.2.

In accordance with 2021 IWUIC and Sante Fe County Ordinance 2023-06, a defensible space of 30 feet is required around the BESS enclosure structures given a moderate hazard classification as determined using the Santa Fe County Community Wildfire Protection Plan map. This may require modifications to the surrounding fuels such as vegetation to maintain the space in accordance with the requirements of IWUI Section 603. This will limit the potential for wildfires from surrounding areas to affect the BESS enclosures and vice versa. Additional defensible space can be provided around the BESS yard for additional protection beyond the code requirements.

3.2.9.3 Fire Water

The water supply at the Rancho Viejo site will be provided by a NFPA 1142 code compliant ground level water storage tank. The water tank will be provided with a water level gauge. The tank will be located west of the BESS field as shown in Figure 2. The water storage tank will be provided with a fire hose connection for fire department use; however, the site will not have any fire hydrants on the public water system. The water tank will have a 29,093-gallon nominal capacity.

The water supply is intended to provide fire flow to protect the energy storage system from incidental fire exposure from a non-energy storage system source or for defensive cooling of nearby equipment from an energy storage system related fire event. See below for three different fire scenarios analyzed to determine the appropriate water tank size to provide an adequate supply for emergency responders.

Fire Scenario #1 – Power Conversion System (PCS) Fire Incident
In this scenario, it is proposed that a fire is developing from a single PCS. It is assumed a PCS fire will require the same water supply as a transformer fire. FM Global DS 5-4, section 2.3.2.3 suggests a 1-hour hose stream flowing at 250 gpm for transformers holding FM approved liquids or up to 1,000 gallons of mineral oil. See below for the recommended fire water storage required for a PCS fire.

250 gpm x 60 minutes = 15,000 gallons of fire water

Fire Scenario #2 – Exposure Fire Incident
In an exposure fire incident, it is expected that a fire is emanating from a car or non-PCS equipment. In this scenario, two (2) handlines flowing at 200 gpm for 1-hour will have the capability to suppress a large exposure fire. See below for the recommended fire water storage required for an exposure fire:

200 gpm x 2 handlines x 60 minutes = 24,000 gallons of fire water

Fire Scenario #3 – BESS Fire Incident
In this scenario, it is proposed a fire originates from an BESS enclosure. The water volumes calculated above could assist emergency responders in intermittently cooling nearby exposures, control smoke, or extinguish small vegetation fires. For example, 24,000 gallons of fire water could intermittently (50% of the time) provide one (1) handline flowing at 200 gpm for 4-hours to cool nearby exposures. Alternately, if a fog nozzle is utilized, 24,000 gallons of fire water could provide two (2) handlines flowing 100 gpm intermittently (50% of the time) for a duration of 4-hours.

3.2.9.4 Site-Wide Fire Alarm System

While each individual CEN enclosure is installed with a FACP to monitor the local conditions and activate the internal suppression system, the site will also be provided with a site-wide fire alarm system and FACP capable of monitoring and reporting signals from each enclosure. The site-wide fire alarm system will be designed in accordance with NFPA 72 and will be capable of notifying the fire department during a fire event at an enclosure so that a response can be initiated. The fire alarm system will also be capable of notifying occupants within the BESS yard to alert them of a potential hazard.

3.2.9.5 Fire Department Response

The fire department will be automatically notified of an event at the project site via the FACP to assist in reducing the overall response time.

4.0 FIRE TESTING REVIEW

Full-scale fire testing provides a basis for the evaluation of thermal runaway fire propagation and the effectiveness of the fire protection strategy in mitigating potential harmful conditions arising from a thermal runaway event.

4.1 UL9540A TESTING

The CEN BESS system has been subject to testing utilizing the methods of UL 9540A at the cell, module, unit and installation levels. The UL 9540A test results are summarized below. Refer to the UL 9540A Cell, Module and Unit level test reports for detailed information. Full UL 9540A test reports are provided for review in Appendix F.

- **Cell Level Testing** – Cell level testing indicates that [redacted] of gas may be released per cell when thermal runaway occurs. Testing indicates that the gas is primarily composed of [redacted] with a LFL of [redacted] at ambient temperature. Refer to the *UL 9540A Cell Level Report* for detailed gas composition data. The average cell surface temperature at thermal runaway was [redacted]. The cell vent gas fundamental burning velocity, S_u, was determined to be [redacted] with a maximum pressure, P_{max}, of [redacted].

- **Module Level Testing** – Module level testing demonstrated that thermal runaway initiation of a single cell is capable of propagation throughout a majority of the cells within the module. The testing resulted in flaming combustion, flying debris, explosive discharge of gas and sparks or electrical arcs. A peak heat release rate (HRR) of [redacted] was achieved during testing.

- **Unit Level Testing** – Unit level testing did not result in propagation of a thermal runaway event from the failure of a single cell. External flaming combustion was observed with a peak HRR of [redacted]. Release of flammable gas with an associated explosion was not observed. The maximum enclosure wall surface temperature observed was [redacted].

- **Installation Level Testing** – The installation level test is intended to collect information regarding the performance of the ESS's fire protection features. The installation level test included the operation of the direct injection clean agent cooling system. The installation level test did not result in propagation of a thermal runaway event from the failure of a single cell. No flaming or flying debris was observed outside of the enclosure. The maximum enclosure wall surface temperature observed was [redacted].

4.2 BESPOKE FIRE AND DEFLAGRATION TESTING

Bespoke Fire and Deflagration testing was conducted for this project. Test results are being processed and updates will be provided in the final version of the HMA report. The results will be evaluated and compared to local ambient conditions.

5.0 FIRE SAFETY ANALYSIS

This fire safety analysis is intended to provide a record of the decision-making process in determining the fire prevention, fire protection and explosion prevention measures for the identified hazards associated with the CEN BESS enclosure.

5.1 ANALYSIS METHODOLOGY

This analysis implements a bowtie methodology to holistically evaluate the CEN BESS enclosure against the analysis acceptance criteria identified in Table 2. The bowtie hazard assessment model developed in this analysis is described in ISO IEC 31010 Section B.21 and NFPA 855 Section G.4.

Bow tie modeling is a common hazard mitigation analysis tool used in the maritime, oil and gas, and utility industries. The strength of the bowtie approach comes from its visual nature, which evaluates the chronological pathways leading from threats to critical hazard events to consequences with the associated mitigative and preventative barriers in place to reduce or eliminate the said consequences. In this analysis, many of these threats parallel the hazards addressed by the fire code, such as unexpected thermal runaway.

As all threats and consequences tie into a single hazard event, the shape of the model resembles a bow tie. The length of the pathway on either side is dependent on the number of barriers that exist to prevent that threat from reaching the hazard event or the hazard event from devolving into the full consequence.

When assessed, the strength of each barrier is assessed in a qualitative manner. Barrier strength may vary depending upon the nature and stage of failure being assessed.

Refer to Appendix B for a full general description of the Bowtie methodology.

5.2 BOW TIE MODEL DEVELOPMENT

The bow tie model described in this section was used to evaluate the failure modes found in Table 1 against the noted analysis acceptance criteria found in Table 2.

5.2.1 Hazard and Top Event

The primary hazard of concern in this analysis is the considerable amount of energy contained with the BESS enclosure.

The top event is the moment when control over the hazard or its containment is lost. The central hazard event used in this analysis is defined as a single cell failure which begins to propagate through the system. This propagation may occur as the initiation of thermal runaway in adjacent cells or damage to adjacent equipment inside or outside the enclosure, or harm to personnel.

5.2.2 Threats and Preventative Barriers

The threats are arranged into four separate categories (primarily for presentation purposes), these include, threats resulting from thermal runaway or mechanical failure events, control and prevention system failure events, external impact failure events and electrical failures.

Table 5 and Table 6, below provides a brief summary of the threats and associated preventative barriers considered in this analysis. See Appendix C for a detailed review of each threat and preventative barrier. The resulting bow tie diagrams can be found in Appendix E. An assessment of the general strength of each individual barrier is also provided. While a general assessment is provided, the criticality and effectiveness of the barriers may vary based on the associated threat pathway.

Table 5: Threat Summary

Threat	Threat Description	Threat Category
Single-Cell Thermal Runaway	A single cell has entered thermal runaway resulting in flames and combustion or production of flammable gases.	Thermal Runaway & Mechanical Failure
Multi-Cell Thermal Runaway	Multiple cells have entered thermal runaway.	Thermal Runaway & Mechanical Failure
Internal Defect / Failure (No Thermal Runaway)	A cell has failed as a result of an internal defect, creating a short circuit, open circuit, or other electrical condition or off-gas but not entering thermal runaway.	Thermal Runaway & Mechanical Failure
Hazardous Temperature Condition (Cell)	High temperature at the cell level during normal operations without thermal runaway.	Thermal Runaway & Mechanical Failure
Hazardous Temperature Condition (Module)	High temperature in the module during normal operation without failure / thermal runaway.	Thermal Runaway & Mechanical Failure
Hazardous Temperature Condition (Enclosure)	High temperature in the room or enclosure during normal operations	Thermal Runaway & Mechanical Failure
Electrical Hotspot / Loose Connection	Loose connections in the system may increase resistance and cause hotspots. Hotspots may form in other ways for unknown reasons. These hotspots will then conduct via bus bars or mechanical contact into cells.	Thermal Runaway & Mechanical Failure
Impact	Something has struck, sharply or as blunt force, the battery system, causing mechanical damage or deformation.	External Impact Failures
Water Damage (Flooding)	The system is flooded with water as a result of cooling system failure.	External Impact Failures
Water Damage (Condensation)	The system is subject to uncontrolled condensation of water via dehumidifier failure, internal condensation of moisture, or from natural reasons.	External Impact Failures
External Fire Impingement	An external fire that is impinging on the system from outside the containment.	External Impact Failures
Dust / Dirt / Particulate Accumulation	Accumulation of dust, dirt, or particulate that results in an adverse condition inside the system.	External Impact Failures
Human Factors	An adverse condition caused by the result of human interaction, error, or imperfection.	External Impact Failures
Module Cooling or HVAC System Failure	Mechanical or electrical failure of the module cooling or enclosure HVAC system resulting in high temperatures throughout system.	Control & Prevention System Failure
Sensor Failure	A sensor inside the system fails, resulting in incorrect reporting of system properties.	Control & Prevention System Failure
BMS Failure	Cell / module level monitoring and control fails, resulting in inability to shut down, report adverse conditions, properly monitor, balance, or protect the system resulting in an adverse condition.	Control & Prevention System Failure
Enclosure PLC Failure	Failure of the enclosure PLC controller resulting in adverse condition to the system or inability to detect or protect against adverse conditions under its purview.	Control & Prevention System Failure

Table 5: Threat Summary		
Threat	**Threat Description**	**Threat Category**
Site Control / Balance of Plant / PLC Failure	Failure of the master site controller or other balance of system controller resulting in adverse condition to the system or inability to detect or protect against adverse conditions under their purview.	Control & Prevention System Failure
Shutdown / Isolation Failure	Failure of the system to shut down or isolate itself when an adverse condition is detected.	Control & Prevention System Failure
Hazardous Voltage Condition	This could include high line voltages, floating ground issues, or other high voltage issues at the cell, module, or rack level.	Electrical Failure
Ground Fault / Isolation Fault	This could include localized shorting of cells, shorting between modules, shorting of entire racks or systems and ground fault shorting.	Electrical Failure

Table 6: Preventative Barrier Summary	
Barrier	**Preventative Barrier Description**
Passive Module Protections	Module fuses which may open the circuit in the case of failure as well as the general resilience of design to withstand adverse electrical conditions.
Liquid Cooling System	The liquid cooling system is an active cell protection which may prevent thermal runaway propagation.
Enclosure Dehumidification System	The enclosure's dehumidification system acts to prevent the buildup of condensation that may pose a short circuit hazard.
Direct Injection Clean Agent System	The direct injection clean agent system is an active cell protection which may prevent thermal runaway propagation.
Cell Thermal Abuse Tolerance	Ability of the cells to withstand thermal abuse without going into failure themselves.
Cell Quality Control	Overall quality of the cell such that internal defects are minimized, and cells maintain rigidity and shape during operations. Also includes tight tolerances with respect to degradation and new capacity.
BMS Control	Includes monitoring and shutdown/isolation capabilities of the affected BMS / module or system.
Temperature Monitoring and Alarms	Thermal monitoring within the enclosure.
System Shutdown / Disconnect	Ability of system to actively shut itself down or disconnect itself. This is the aggregate of the BMS ability as well as physical disconnects and the Balance of System controller's ability to shut down.
Preventative Maintenance and Commissioning	Proper maintenance and monitoring of the system in conjunction with adequate commissioning and site acceptance testing to reduce likelihood of loose connections or other transportation- or construction-related defects.
Passive Circuit Protection and Design	Breakers and fuses which may open the circuit in the case of failure as well as general resilience of design to withstand adverse electrical conditions.
Cell Electrical Abuse Tolerance	Ability of the cell to withstand electrical abuse such as overcharge, over discharge, high currents, or other adverse electrical abuse.
Redundant Failure Detection / System Intelligence	The ability of the system to determine a sensor has failed, to operate safely without that sensor to shut down, or operate safely indefinitely without sensor. This may include Checksums, additional sensors, or the ability to pull data from other sensors.

Table 6: Preventative Barrier Summary	
Barrier	**Preventative Barrier Description**
Human Factors / Process Control	Quality control or other processes put in place to prevent mishandling of systems that may result in adverse or hazardous conditions or mishandling.
Enclosure / Structural Resiliency	Resiliency of the system and enclosure of the system to withstand impacts or strikes.
Module Resiliency	Resiliency of the individual modules to withstand impacts, shocks, or other mechanical abuse.
Cell Physical Abuse Tolerance	Ability of the cell to withstand thermal, physical, or mechanical abuse.
Humidity Monitoring	Monitoring within the enclosure which may detect high humidity, water condensation or water leakage.
System Maintenance	Proper preventative maintenance to minimize the impact of adverse, long term or slow acting environmental effects resulting in degradation.
SME Training	Proper training procedures, availability of subject matter expertise and system competence, and clear jurisdictional hierarchy for managing situations.
Voltage Monitoring	Overall effectiveness of the voltage monitoring scheme of the system. Includes resilience to errors, error checking, and other measurement intelligence.
Insulation Monitoring	Continual, or active, monitoring of insulation integrity, ground versus float voltage, and other practices to prevent insulation or isolation degradation.

5.2.3 Consequences and Mitigative Barriers

Table 7 and Table 8, below provides a brief summary of the consequences and associated mitigative barriers considered in this analysis. See Appendix D for a detailed review of each consequence and mitigative barrier. The resulting bow tie diagrams can be found in Appendix E. An assessment of the general strength of each individual barrier is also provided. While a general assessment is provided, the criticality and effectiveness of the barriers may vary based on the associated consequence pathway.

Table 7: Consequence Summary	
Consequence	**Consequence Description**
Cell / Module Combustion	A battery cell or module has failed and is now producing flame or combusting.
Multi-Module / Rack Fire	Multiple modules have begun producing flame or combusting.
Fire Spread Beyond Enclosure Fire Partition	A fire within the system has spread from one side of the enclosure fire separation to the modules/rack and equipment on the opposite side within the same enclosure.
Fire Spread Beyond Enclosure	A fire within the system has spread beyond the enclosure to adjacent BESS enclosures or other structures.
Cell Off-Gassing / Explosions	A cell or multiple cells have failed or entered thermal runaway and is now producing off-gas.
Accumulation of Off-Gasses / Delayed Explosions	A cell or multiple cell failure which may or may not have propagated has resulted in the accumulation of potentially explosive off-gas within the enclosure.
Balance of System Fire	A fire that either is initiated in or results in the involvement of a balance of system fire such as wire insulation, electrical components, or plastic inside the system.
Environmental / HAZMAT Issues	A large-scale system fire has resulted in an environmental or hazardous material incident which requires hazardous material response.

Table 8: Mitigative Barrier Summary	
Barrier	**Mitigative Barrier Description**
Enclosure Smoke Detection	Activation of the enclosure's smoke detection system and communication via the FACP. System activation provides both situational awareness to facility operators, personnel in the vicinity of the enclosure, and first responders as well as activation of the enclosure's direct injection clean agent system.
Enclosure Gas Detection System	Activation of the enclosure's gas detection system and communication of alarm signal to the SCADA system. System activation provides situational awareness to facility operators, personnel in the vicinity of the enclosure and first responders.
Occupant Notification	Activation of the alarm notification device on the exterior of the enclosure and activation of the facility's site wide alarm system if provided.
BMS Data Availability	Includes BMS measurements available to first responders, Facility Operations Center or other SMEs. Effectiveness based on what is detected and how well, how this information is being conveyed, and robustness of sensors in case of failure.
Direct Injection Clean Agent System	Activation of the direct injection clean agent system may limit or reduce the rate of a propagating thermal runaway event.
Deflagration Protection	Activation of the enclosures deflagration venting system.
Thermal Isolation (Enclosure Insulation)	Passive thermal propagation protection provided by insulation installed on the boundaries of the enclosure.
Thermal Isolation (Enclosure Fire Separation)	Passive thermal propagation protection provided the enclosure's fire separation.
Thermal Isolation (Module / Rack Separation)	Passive thermal propagation protection provided by physical separation between modules within a rack and physical separation between racks within the enclosure.
Facility Design and Siting	Placement of the facility such that adverse environmental effects such as flooding, vehicle impact, and fire impingement are mitigated or avoided. The strength of this barrier is dependent upon the site-specific aspects of the facility layout.
Emergency Response Plan / First Responders	System operator plan to handle any and all emergency events. A site-specific emergency response plan should be developed. Effectiveness based on level of the subject matter expert (SME) / first responder training, knowledge of the specific BESS undergoing failure, coordination with fire department, etc.
Fire Service Response	Fire department response including active firefighting suppression. Effectiveness based on level of department knowledge and training to effectively respond both offensively and defensively during an BESS incident.

5.3 FAULT CONDITION ANALYSIS

The fault condition analysis below uses the four bow tie diagrams shown below as Figure 6 through Figure 9 for evaluation of the failure modes against the acceptance criteria identified in Table 2. See Appendix E for enlarged versions of the bow tie diagrams.

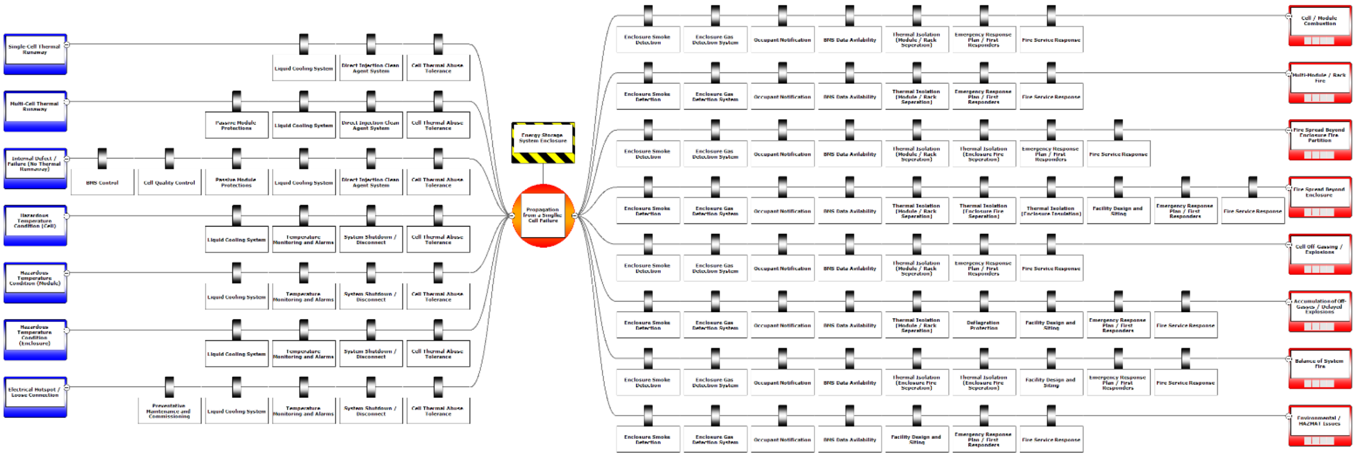

Figure 6 – Thermal Runaway and Mechanical Failure Bow Tie Diagram

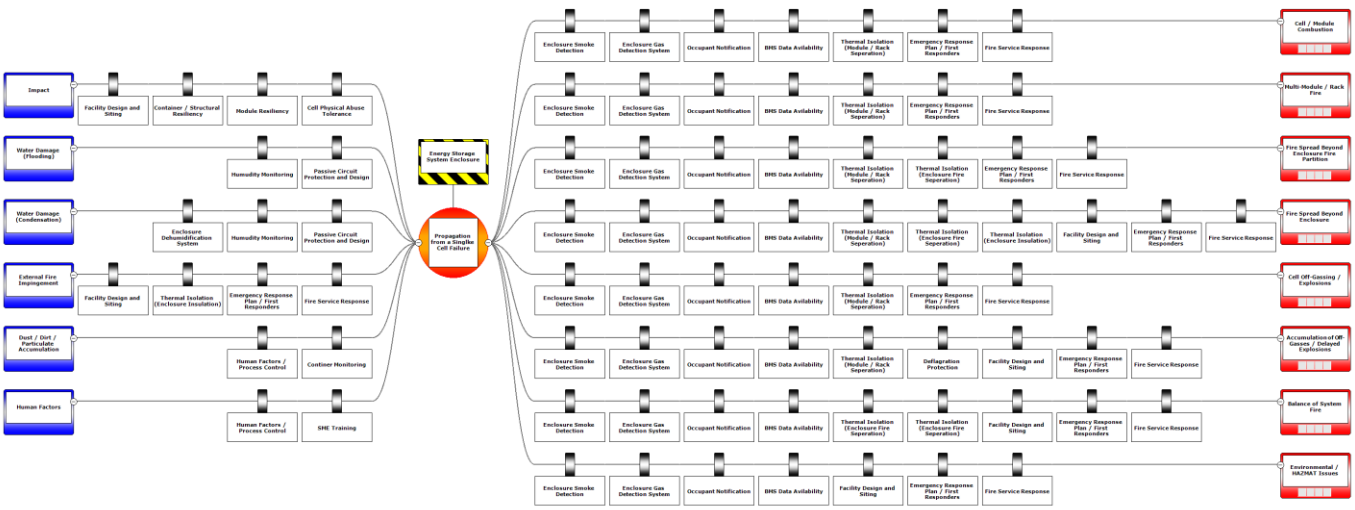

Figure 7 – External Impact Failures Bow Tie Diagram

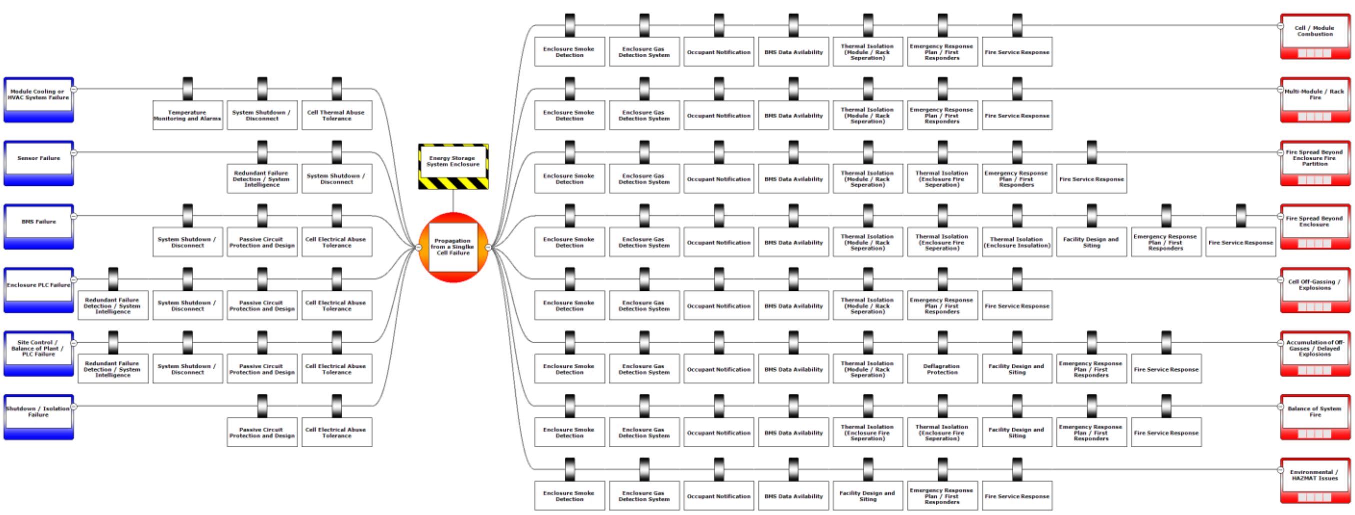

Figure 8 – Control and Prevention System Failure Bow Tie Diagram

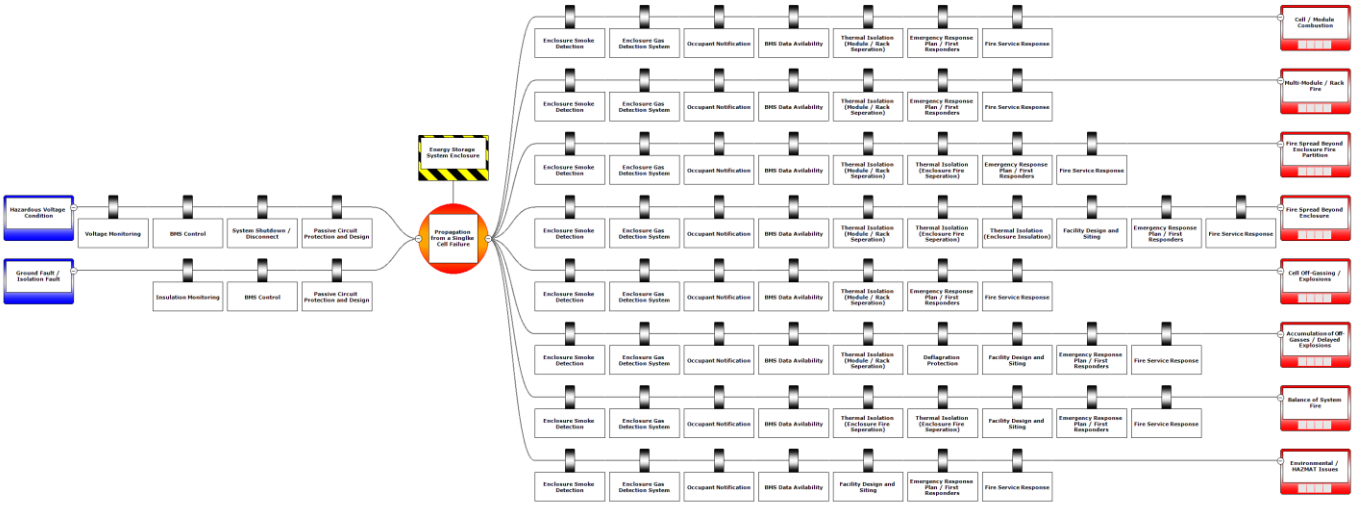

Figure 9 – Electrical Failure Bow Tie Diagram

5.3.3 Failure Mode 1: Single BESS unit Thermal Runaway or Mechanical Failure

Failure Mode 1 considers a thermal runaway or mechanical failure in a single BESS unit. The analysis for this failure mode primarily uses the thermal runaway & mechanical failure (see Figure 6), and the external impact threat pathway (see Figure 7) bow tie diagrams.

The threats identified in Figure 6 and Figure 7 can lead to a thermal runaway event in a single or group of cells due to a direct cell failure or indirectly from other root causes. Specific threats include conditions arising from within the enclosure such as internal cell defects and high heat conditions as well as conditions arising externally such as impacts from external fire events and flooding. Other conditions that may lead to a propagating cell failure event via electrical, control system and prevention system failures are examined in subsequent report sections.

Several active and passive barriers act to prevent a propagating cell failure scenario from developing from these threats. Key preventative barriers in the CEN enclosure product design include, passive module protections, cell thermal abuse tolerance, liquid cooling system, direct injection clean agent system, BMS control system, passive circuit protection, enclosure monitoring system and the enclosure insulation. Other key preventative barriers that may be present or in varying strengths depending upon the final site installation include, system shut down capability, facility design and siting, emergency planning and fire service response.

Once a propagating failure event has occurred, the smoke detection, gas detection and BMS data availability mitigation barriers act to provide situational awareness to facility operators and emergency responders. The strength of these barriers will be dependent upon site installation conditions. The enclosure, fire separation and module thermal isolation barriers act to limit the propagation of the escalating event. The deflagration protection barrier mitigates the possible effects of explosions. The facility siting, emergency response/planning and fire service response barriers are anticipated to provide additional barriers to mitigate an incident depending upon final site conditions.

During a thermal runaway event, several of the provided safety barriers would be expected to slow the growth of a failure event (i.e. thermal isolation, direct injection clean agent system, etc.). The slower rate of propagation with these barriers in effect acts to increase the effectiveness of the smoke and gas detection systems by providing an increased amount of time for event detection prior to the development of untenable conditions adjacent to the enclosure. With the situational awareness provided by activation of the occupant notification appliances located on the exterior of the enclosure, sufficient time is anticipated to be provided to allow for evacuation of facility occupants to a safe location. The final site installation and operation conditions may act to further multiply the effectiveness of this barrier, such as occupant evacuation training and a site wide fire/emergency notification system.

The accumulation of cell off-gas from a thermal runaway event presents an explosion hazard. This hazard is specifically evaluated in the bow tie model as a possible consequence. The provided deflagration venting system provides a strong barrier to mitigate the effects of deflagration events resulting from a thermal runaway event of up to three cells. Given the previously mentioned safety barriers which act to reduce the rate of propagation of an escalating event, the proposed deflagration system is deemed to be adequate. The gas detection system has the capability to provide situational awareness of internal conditions to emergency and fire service responders.

5.3.2 Failure Mode 2: Failure of a Required Protection System not Covered by Product Listing FMEA

This failure mode considers the 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 analysis for Failure Mode 2 uses the control and prevention system failure threat pathway bow tie diagram (see Figure 8).

Specific threats analyzed for this failure mode included cooling system failure, sensor failure, BMS failure, site control / PLC failure and shutdown isolation failure. While none of these threats lead directly to the failure of a cell, they can serve as precursor events to cell failure.

The safety barriers preventing the threats considered in this failure mode from escalating to a propagating cell failure event primarily include cell electrical and thermal abuse tolerance, passive circuit protection and design, and system shutdown / disconnect capability. The effectiveness of the system shutdown / disconnect capability may be subject to site conditions.

The mitigative barriers available once a propagating event has begun are typical to those discussed in the Failure Mode 1 section above.

The assessment of the identified safety barriers to limit the possible consequences to what is specified in the analysis acceptance criteria is typical to the discussion found in the Failure Mode 1 section above.

5.3.3 Failure Mode 3: Failure of a Required Protection System

Failure Mode 3 considers the failure of a required protection system. The analysis for this failure mode primarily uses the thermal runaway & mechanical failure (see Figure 6), and the external impact threat pathway (see Figure 7) bow tie diagrams.

For this failure mode, the consequences are evaluated with required protection systems assumed to have failed and be out of service. The model was separately evaluated assuming failures of the enclosure smoke detection system, enclosure gas detection system, deflagration protection system and direct injection clean agent system. Simultaneous multiple system failures are not considered. Failure of any of the above listed system is not anticipated to immediately create a hazardous condition, rather, failure of a required protection system will reduce the ability to prevent or mitigate hazardous conditions developing from a fire or thermal runaway event.

A failure of the smoke detection system would be expected to lead to a failure of the direct injection clean agent system and in a possible reduction in the overall situational awareness during an emergency. In this case, the gas detection system and BMS data safety barriers act to provide a degree of continued situational awareness. Activation of the gas detection system is expected to occur during a fire or thermal runaway incident and provide activation of the occupant notification system even if a failure occurs in the smoke detection system. The direct injection clean agent system may be released using the manual pull station on the outside of the enclosure if the smoke detection system is not functioning. The strength of the gas detection and direct injection clean agent system barrier is conditional based on the quality and use of the emergency plan, and the quality of communication between the ROCC and on-site personnel. Other safety barriers such as thermal abuse tolerance and thermal isolation are expected to continue at their previous performance level.

Failure of the gas detection system is not anticipated to result in a significant reduction in safety as this system primarily provides situational awareness. The deflagration prevention system, which uses a passive deflagration vent design, is expected to continue providing a strong safety barrier against explosion type hazard when gas detection system failure occurs.

The deflagration prevention system uses a NFPA 68 compliant passive vent design that does not rely upon electrical or mechanical systems to maintain safety. The passive design is expected to have greater availability as compared to active system designs which use ventilation or other methodologies to maintain safety. If the deflagration prevention system fails, the gas detection system would be expected to provide a degree of situational awareness regarding an escalating flammable gas event within the enclosure.

The direct injection clean agent system is treated as a preventative barrier within this analysis. All threat pathways considered in this failure mode feature multiple additional preventative and mitigative barriers.

The CEN enclosure is evaluated to include a sufficient quantity of safety barriers, such that the failure of any one of the required protection systems is not expected to result in a situation where the rate of event propagation will prevent the evacuation of facility occupants to a safe location.

This can also include the failure of site-wide fire alarm monitoring and reporting, however a system installed in accordance with NFPA 72 helps to mitigate the potential for a failure in which the fire department is not made aware.

5.3.4 Failure Mode 4: Primary Electric Supply Voltage Surges

The analysis for Failure Mode 4 uses the Hazardous Voltage Condition pathway on the electrical system failure threat bow tie diagram (see Figure 9).

The primary safety barriers expected to prevent a propagating cell failure are voltage monitoring and BMS control. The system shutdown and passive circuit protection barriers are expected to also provide preventative barriers. The effectiveness of the system shutdown / disconnect capability may be subject to site conditions.

The mitigative barriers available once a propagating event has begun are typical to those discussed in the Failure Mode 1 section above.

The assessment of the identified safety barriers to limit the possible consequences to what is specified in the analysis acceptance criteria is typical to the discussion found in the Failure Mode 1 section above.

5.3.5 Failure Mode 5: Load Side Short Circuits

The analysis for Failure Mode 5 uses the Ground Fault / Isolation Fault pathway on the electrical system failure threat bow tie diagram (see Figure 9).

The primary safety barriers expected to prevent a propagating cell failure are BMS control and passive circuit protection barriers. Insulation monitoring can also serve to prevent this type of failure.

The mitigative barriers available once a propagating event has begun are typical to those discussed in the Failure Mode 1 section above.

The assessment of the identified safety barriers to limit the possible consequences to what is specified in the analysis acceptance criteria is typical to the discussion found in the Failure Mode 1 section above.

6.0 ANALYSIS APPROVAL

The acceptance criteria applied in this analysis aligns to the HMA approval criteria listed in the 2023 edition of NFPA 855 and the 2021 edition of the IFC. Conformance with the specified acceptance criteria is demonstrated in Table 9 below.

Table 9: Compliance with Analysis Acceptance Criteria

Acceptance Criteria	Acceptance Criteria and Demonstration of Compliance	
1	Requirement:	Fires and products of combustion will not prevent occupants from evacuating to a safe location
	Conformance:	The CEN enclosure features a sufficient quantity of safety barriers to limit the rate of propagation of an escalating fire or thermal runaway event and provide adequate situational awareness to facility occupants to permit evacuation to a safe location.
2	Requirement:	Deflagration hazards will be addressed by an explosion control or other system
	Conformance:	This analysis has identified that a propagating cell failure event poses a deflagration hazard. The CEN enclosure will be equipped with a NFPA 68 compliant deflagration venting system to release the combustion gases and pressure resulting from a deflagration within the enclosure so that structural and mechanical damage is minimized.

7.0 ANALYSIS ASSUMPTIONS AND LIMITATIONS

The analysis presented in this analysis is limited by the following key assumptions:

- **Unknown Failure Modes** – While large-scale fire testing and commitment of considerable resources to the study of energy storage safety issues has drastically improved the industry's understanding of failure modes, threats, consequences and general safety, many failure modes and corresponding responses remain uncharacterized. Unknown failures may also potentially arise not otherwise considered in this analysis. The conclusions of this analysis should be re-evaluated as such failure modes become known to the industry.

- **Outside Event effecting more than one unit** – Several of the identified failure modes may affect multiple enclosures simultaneously, examples include flooding, external fires and voltage surges. The effectiveness of some safety barriers may be degraded when multiple events are occurring simultaneously and thus may not perform at the same strength as compared to when preventing or mitigating a single event. While this analysis does not directly consider events affecting more than a single unit at a time, it can be assumed that the risk of event propagation will be increased as more enclosures are involved.

- **Hazards during Construction, Shipping and Storage –** This analysis does not evaluate the hazards associated with the construction, off-site storage and shipping of the BESS enclosures. Other hazards may exist during these phases that are not present during operation of the enclosure.
- **Continued Maintenance** – All BESS systems are assumed to be inspected, tested and maintained in accordance with the original equipment manufacturer's instructions and as required by regulatory requirements. A lack of inspection, testing and maintenance of BESS subsystems can be expected to have a detrimental effect on the strength of the provided safety barriers.
- **Installed per code** – All life safety, fire protection and explosion systems are assumed to be installed and maintained in accordance with the applicable installation standards as required by the IFC. This report does not specifically evaluate the compliance of any protection systems to applicable installation standards.

8.0 REFERENCED DOCUMENTATION

In addition to the code documents listed in this report, other documents reviewed as part of this report were all provided by the project team. These documents include:

- *AES CEN Project BESS Container General and Internal Arrangement* drawings, CEN Solutions, Revision 0, Dated January 3, 2024
- *McFarland B – BESS Signals Logic Specific Project Procedure*, CEN Solutions, Revision 3, Dated October 16, 2023
- *30% Electrical Documents for Rancho Viejo Solar Utility BESS*, PVInsight Inc., Revision 3, Dated 07/02/2024
- *30% Civil Documents for Rancho Viejo Solar Utility BESS*, PVInsight Inc., Revision 3, Dated 07/02/2024
- *30% Structural Documents for Rancho Viejo Solar Utility BESS*, PVInsight Inc., Revision 2, Dated 03/04/2024
- *UL 9540A Report – Cell Level Report* (Project No. 4790746849), Dated July 7, 2023
- *UL 9540A Report – Module Level Report* (Project No. 4790351859), Dated July 10, 2023
- *UL 9540A Report – Unit Level Report* (Project No. 4790648531), Dated July 6, 2023
- *UL 9540A Report – Installation Level Report* (Project No. 4790648557), Dated July 7, 2023
- *Bespoke Fire Testing Reports to be added*

9.0 QUALIFICATIONS AND LIMITATIONS STATEMENT

The opinions and recommendations made in this report have been rendered using our professional judgment after our visual inspection and an evaluation of the information obtained from the documents provided to Coffman. The information contained within this report is specific to this project and should not be applied to any other facility or operation. We assume no liability for the work, opinions or reports of any other independent consulting firm engaged to do so. The analysis detailed in this report is based upon our engineering judgment using codes, standards, and research publicly available to-date relative to lithium-ion batteries. The recommendations in this report are advisory in nature. It is the sole responsibility of the client to implement the conclusions and recommendations contained herein.

APPENDIX A – NFPA 855 AND IFC HAZARDOUS MITIGATION ANALYSIS REQUIRMENTS

A1. INTRODUCTION

This Appendix compares the HMA failure mode and analysis approval requirements as found in the below listed codes to the failure modes and approval requirements selected for the analysis contained in this Fire Safety Technical Report.

- *International Fire Code* (IFC), 2021 edition
- NFPA 855, *Standard for the Installation of Energy Storage System*, 2023

A1.1. FAILURE MODES

The single mode failure modes considered in this analysis are described in Table 1. Table 2 below, relates the failure mode requirements as found in NFPA 855 and the IFC to the failure mode requirements applied to this analysis.

Table 1: Analysis Failure Modes

Failure Mode	Failure Mode Description
1	A thermal runaway or mechanical failure 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 detection, fire suppression, or gas detection.
4	Voltage surges on the primary electric supply.
5	Short circuits on the load side of the ESS.

Table 2: NFPA 855 and IFC Failure Mode Requirements

Code or Standard	Failure Mode Description	As Applied in This Analysis
NFPA 855 (2023 edition) Section 4.4.2.1	(1) A thermal runaway or mechanical failure in a single ESS unit.	Addressed in this analysis as Failure Mode #**1** (See Table 1).
	(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).	Addressed in this analysis as Failure Mode #**2** (See Table 1).
	(3) Failure of a required protection system including, but not limited to, ventilation (HVAC), exhaust ventilation, smoke detection, fire detection, fire suppression, or gas detection.	Addressed in this analysis as Failure Mode #**3** (See Table 1).
IFC (2021 Edition) Section 1207.1.4.1	(1) A thermal runaway condition in a single ESS rack, module or unit.	Addressed in this analysis as Failure Mode #**1** (See Table 1).
	(2) Failure of any battery (energy) management system	Addressed in this analysis as a component of Failure Mode #**2** (See Table 1).
	(3) Failure of any required ventilation or exhaust system	Addressed in this analysis as a component of Failure Mode #**3** (See Table 1).
	(4) Voltage surges on the primary electric supply	Addressed in this analysis as Failure Mode #**4** (See Table 1).

	(5) Short circuits on the load side of the ESS	Addressed in this analysis as Failure Mode #**5** (See Table 1).
	(6) Failure of the smoke detection, fire detection, fire suppression or gas detection system	Addressed in this analysis as a component of Failure Mode #**3** (See Table 1).
	(7) Required spill neutralization not being provided or failure of a required secondary containment system	Not Applicable – Secondary containment are not required for lithium-ion battery types.

A1.2. ACCEPTANCE CRITERIA

The acceptance criteria considered in this analysis are described in Table 3. Table 4 below, relates the approval criteria requirements as found in NFPA 855 and the IFC to the acceptance criteria applied to this analysis.

Table 3: Analysis Acceptance Criteria

Acceptance Criteria	Acceptance Criteria Description
1	Fires and products of combustion will not prevent occupants from evacuating to a safe location
2	Deflagration hazards will be addressed by an explosion control or other system

Table 4: NFPA 855 and IFC Approval Criteria Requirements

Code or Standard	Approval Criteria Requirements	As Applied in This Analysis
NFPA 855 (2023 edition) Section 4.4.3	(1) Fires will be contained within unoccupied ESS rooms for the minimum duration of the fire resistance rating specified in NFPA 855 Section 9.6.4	Not Applicable – The E5S enclosure does not constitute a room, nor is the E5S enclosure intended to be used indoors.
	(2) Fires and products of combustion will not prevent occupants from evacuating to a safe location	Addressed in this analysis as Acceptance Criteria #**1** (See Table 3).
	(3) Deflagration hazards will be addressed by an explosion control or other system	Addressed in this analysis as Acceptance Criteria #**2** (See Table 3).
IFC (2021 Edition) Section 1207.1.4.2	(1) Fires will be contained within unoccupied ESS rooms or areas for the minimum duration of the fire-resistance-rated separations identified in IFC Section 1207.7.4	Not Applicable – The E5S enclosure does not constitute a room, nor is the E5S enclosure intended to be used indoors.
	(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 E5S enclosure is not intended to be used indoors.
	(3) Toxic and highly toxic gases released during fires will not reach concentrations in excess of the IDLH level in the building or adjacent means of egress routes during the time deemed necessary to evacuate occupants from any affected area	Addressed in this analysis as Acceptance Criteria #**1** (See Table 3).

	(4) Flammable gases released from ESS during charging, discharging and normal operation will not exceed 25 percent of their LFL	Not Applicable – Lithium-ion cells are hermetically sealed and do not vent under normal charging or discharging operating conditions. Flammable gases are not released during normal operations.
	(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	Addressed in this analysis as Acceptance Criteria #2 (See Table 3).

APPENDIX B – BOW TIE METHODOLOGY

B1. INTRODUCTION

This Appendix provides a general description of the bow tie methodology as a hazard analysis tool.

The bow tie methodology is common is risk and hazard studies to identify the safety barriers that can be implemented to prevent a critical event from happening and/or to mitigate its effects after it has occurred [1]. In bow tie models, a fault tree and event tree are linked to a critical event that is related to an undesirable event. In this way, bow tie models represent the relationship that exists between hazards, threats, safety prevention barriers, safety mitigation barriers and consequences.

The strength of the bowtie approach comes from its visual nature. An example of a bow tie model is given below in

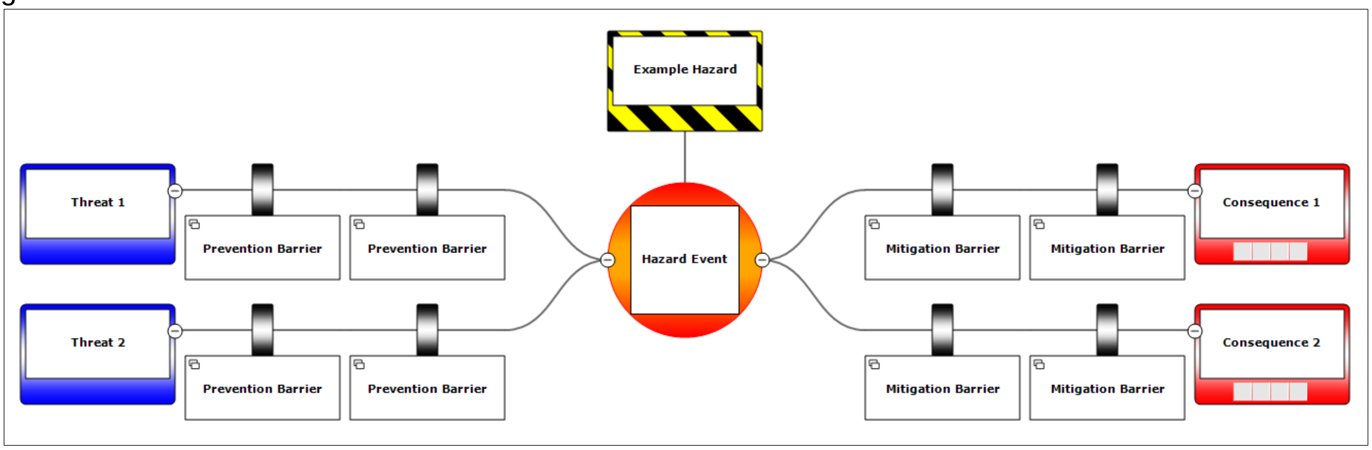

Figure **1**.

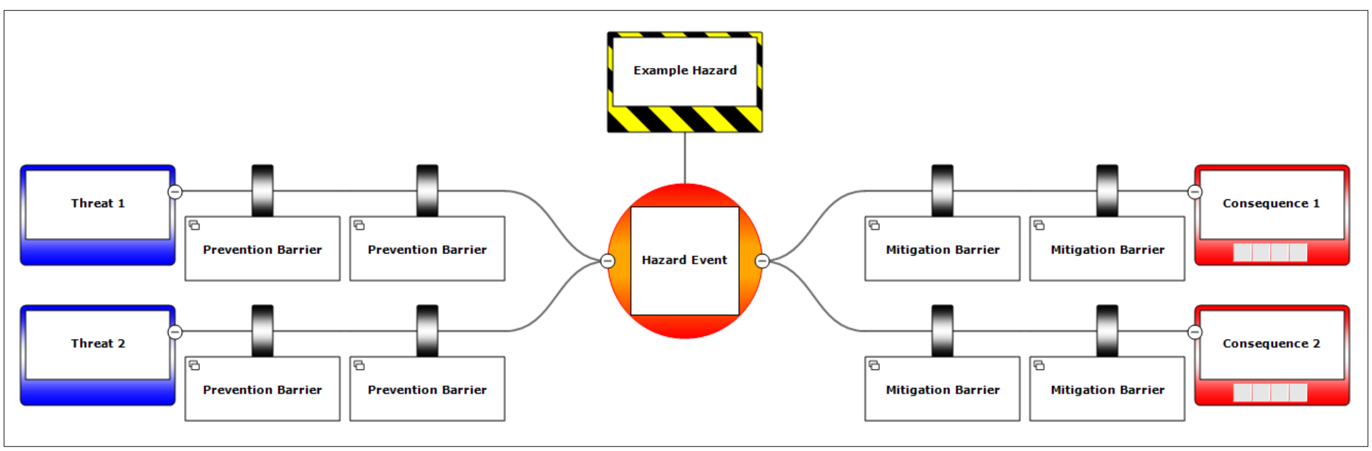

Figure 1 – Bow Tie Model Description

B2. BOW TIE ELEMENTS

Bow tie models contain the elements listed below:

- **Hazard –** The hazard is an operation, activity or material with the potential to cause harm. It is shown on bow tie model diagrams to provide clarity to the reader as to the source of risk. Hazards are part of normal business and are often necessary to run an operation.

- **Top Event –** The top event is the moment when control over the hazard or its containment is lost. While the top event may have occurred, there may still be time for barriers to act to stop or mitigate the consequences.

- **Threats –** Threats are the potential reasons for loss of control of the hazard leading to the top event. For each top event there are normally multiple threats located on the left side of the bow tie model diagram, each representing a single scenario that could directly and independently lead to the event.

- **Consequences** – Consequences are unwanted outcomes that could result from the top event and lead to damage or harm. Generally, these would be major accident events, but lesser consequences can be selected if the aim is to map the full range of important safety and environmental barriers. One top event may have multiple consequences, but normally only important consequences would be developed to show the mitigation of barriers, not trivial ones.

- **Barriers** – Barriers can be physical or non-physical measures to prevent or mitigate unwanted events. Active barriers can differ with respect to 'detect', 'decide' and 'act' components they contain and whether these components are performed by humans or executed by technology.

    - **Prevention Barriers –** A prevention barrier is a barrier that prevents the top event from occurring. A key test for a prevention barrier is that it must be capable of completely stopping the top event on its own. These barriers appear to the left of the top event on the bow tie model diagram.

    - **Mitigation Barriers** – Mitigation barriers are employed after the top event has occurred and act to prevent or reduce losses and regain control once it has been lost. These barriers appear to the right of the top event on the bow tie model diagram.

The bow tie element descriptions provided above, is based on information found in *Bow Ties in Risk Management* as developed by the Center for Chemical Process Safety [2].

B3. ADVANTAGES, DISADVANTAGES AND UNCERTAINTIES

All hazard analysis techniques are subject to certain advantages, disadvantages and uncertainties. These items are summarized below for the bow tie methodology. The summary provided below is based upon information found in *A Guide to Hazard Identification Methods* [3].

B3.1. ADVANTAGES

- **Hazard Communication** – Bow tie model diagrams communicate:
    - a clear picture of the possible consequences and the routes in which they arise
    - the necessary conditions and sequences of events for each to occur
    - the relative importance of each safety barrier and the consequence of failure
    - the points where additional safety barriers are needed
    - the conditions requiring further in-depth analysis

- **Facilitate hazard-event-consequences Understanding** – The analysis and its visual representation can help all concerned with the safety of a facility to recognize the sequence that could lead to catastrophic events and to appreciate maintaining preventative and mitigation barriers.

- **AHJ Communication** – Regulatory authorities can be assured that a full analysis has been carried out and that hazards are understood and satisfactorily controlled.

B3.2. DISADVANTAGES

- **Requires Detailed Process Understanding –** The analyst needs to be skilled in the use of bow ties, particularly in determining the degree of detail to be included and have a detailed understanding of the system under analysis.
- **Poor Data** – The value of a study will be limited if the available data is of poor quality and lacks robustness or relevance. Imprecise data leads to imprecise predictions.
- **Treat with Care** – All results must be treated with care.

B3.3. UNCERTAINTIES

- **Common Mode Failures** – It is essential that full allowance is made for common mode failures and it may be necessary to make an arbitrary allowance for the possibility of these events.

B4. APPENDIX B REFERENCES

[1] S. Mannan, Lees' Loss Prevention in the Process Industries, Waltham, MA: Elservier, 2012.
[2] Center for Chemical Process Safety of the American Institute of Chemical Engineers, Bow Ties in Risk Managment, Hoboken, NJ: John Wiley & Sons, Inc., 2018.
[3] F. Crawley, A Guide to Hazard Identification Methods, Cambridge, MA: Elsevier, Inc., 2020.

APPENDIX C – THREAT AND PREVENTATIVE BARRIER DESCRIPTIONS

Table 1: Detailed Threat Descriptions		
Threat	**Threat Description**	**Threat Category**
Single-Cell Thermal Runaway	*A single cell has entered thermal runaway resulting in flames and combustion or production of flammable gases.* This scenario may occur as a result of an internal cell defect or other cause. Single cell thermal runaway events may not be readily detectable if the event scenario does not propagate beyond the initial event. If no ignition source is present, the failure may result in the generation of hazardous and flammable gases that could lead to other hazards. If an ignition source is present, the byproducts may combust and result in fire. The UL 9540A module, unit and installation level test for the E5S ESS enclosure utilizes a single cell thermal runaway event as an initiating event.	Thermal Runaway & Mechanical Failure
Multi-Cell Thermal Runaway	*Multiple cells have entered thermal runaway.* Multicell thermal runaway is a credible failure mode that may result from the overcharge of a parallel cell group or the early results of a propagating cell failure. Multicell thermal runaway may prove manageable and containable in some cases.	Thermal Runaway & Mechanical Failure
Internal Defect / Failure (No Thermal Runaway)	*A cell has failed as a result of an internal defect, creating a short circuit, open circuit, or other electrical condition or off-gas but not entering thermal runaway.* In this instance an internal cell defect does not result in thermal runaway but results in the electrical failure of the cell. This may be by reducing the capacity of the cell relative to its neighbors, creating a dead short or creating an open circuit event.	Thermal Runaway & Mechanical Failure
Hazardous Temperature Condition (Cell)	*High temperature at the cell level during normal operations without thermal runaway.* This hazardous temperature threat is a condition in which cells within a module are exposed to high temperatures just short of thermal runaway. This may be the result of hotspots, an HVAC failure, heavy operation, excessive degradation or increased impedance. Regardless of cause, high cell temperatures pose an increased likelihood of thermal runaway or increasing cell degradation.	Thermal Runaway & Mechanical Failure
Hazardous Temperature Condition (Module)	*High temperature in the module during normal operation without failure / thermal runaway.* At the module level, poor performance of cooling systems may result in cases where a module, sets of modules, or entire racks operate at elevated or uneven temperatures relative to other modules or racks within a system. Cells with manufacturing defects or other environmental considerations may also result in elevated cell and module temperatures.	Thermal Runaway & Mechanical Failure
Hazardous Temperature Condition (Enclosure)	*High temperature in the enclosure during normal operations.* The largest scale of hazardous temperature condition, dangerously elevated container temperatures pose serious risk to system safety. High temperatures throughout the entire enclosure will equate to high temperatures throughout all modules and thus cells, further increasing	Thermal Runaway & Mechanical Failure

Table 1: Detailed Threat Descriptions		
Threat	**Threat Description**	**Threat Category**
	the risk of thermal runaway. Non-uniform thermal management means hot spots may be even hotter than usual. These events may be caused by HVAC failures but may also be the result of poor thermal management of co-located power electronics, intense duty cycles, or environmental conditions such as record high ambient temperatures or fire impingement.	
Electrical Hotspot / Loose Connection	*Loose connections in the system may increase resistance and cause hotspots. Hotspots may form in other ways for unknown reasons. These hotspots will then conduct via bus bars or mechanical contact into cells.* Electrical hotspots within a device may propagate through thermally conductive busbars and materials, resulting in the direct heating of cells. Management of this threat pathway involves proper engineering practices for thermal design, proper commissioning, and maintenance practices to insure proper electrical connections, adequate active or passive thermal monitoring, alarms to stop operation if such conditions are reached and an ability to properly shutdown the system.	Thermal Runaway & Mechanical Failure
Impact	*Something has struck the battery system, sharply or as blunt force, causing mechanical damage or deformation.* This is defined as something striking a system (e.g., inadvertent forklift strike or a vehicle hitting the system as part of a deliberate attack). As physical damage to the batteries can result in either immediate or delayed cell failure and fire, such an event may pose grave risk if unmanaged. The risk of this threat is likely to be greater during maintenance activities when other protection systems are not in service. Maintenance activity-related scenarios fall beyond the scope of this analysis.	External Impact Failures
Water Damage (Flooding)	*The system is flooded with water as a result of liquid cooling system failure.* A failure of the cooling system may lead to flooding of the enclosure. This damage poses two risks, one from the risk of short circuit, and the other from degradation to components and corrosion from exposure to water.	External Impact Failures
Water Damage (Condensation)	*The system is subject to uncontrolled condensation of water via dehumidifier failure, internal condensation of moisture, or from natural reasons.* Whether this is condensate building on cool surfaces which falls onto the system, or the formation of condensate on sensitive parts, the presence of water and moisture within electrical systems is not best practice in these systems (outside of intentional liquid cooling systems or those rated for damp environments). The E5S enclosure includes two separate dehumidifiers which act to reduce the probability of a complete failure of the dehumidifier system.	External Impact Failures
External Fire Impingement	*An external fire that is impinging on the system from outside the containment.* Systems built near combustible materials or equipment are at risk of being exposed to fire should these flammable structures become	External Impact Failures

Table 1: Detailed Threat Descriptions		
Threat	**Threat Description**	**Threat Category**
	involved in fire (examples include power transformers and wildfire threats). The site plan shows that the PCS units are located 8 ft from each pair of enclosures and could pose a potential fire hazard risk to the enclosures. There is also a standby generator located 21 ft from one of the enclosures.	
Dust / Dirt / Particulate Accumulation	*Accumulation of dust, dirt, or particulate that results in an adverse condition inside the system.* Dependent on location and maintenance, the accumulation of dust, dirt, or other particles may result in eventual failure. Examples include reducing the effectiveness of thermal management, causing failure of moving parts or switches, or creating electrical shorts.	External Impact Failures
Human Factors	*An adverse condition caused by the result of human interaction, error, or imperfection.* This broad reaching category is intended to cover any accident directly attributable to human intervention. Human factors include any and all variables that humans induce in the systems they interact with. Examples include a visitor bumping into a button, switch, or wire; a technician dropping a wrench on terminals; and an operator missing a warning signal.	External Impact Failures
Module Cooling or HVAC System Failure	*Mechanical or electrical failure of the module cooling or enclosure HVAC system resulting in high temperatures throughout system.* HVAC system failures are a common occurrence in ESS installations. A failure of the module cooling system or the HVAC system may create clear temperature gradients across the system. The systems provide degree of redundancy to each other.	Control & Prevention System Failure
Sensor Failure	*A sensor inside the system fails, resulting in incorrect reporting of system properties.* As a control system is only as effective as its ability to measure and provide feedback – the failure of a sensor may result in adverse conditions in a system unable to properly measure its own state.	Control & Prevention System Failure
BMS Failure	*Cell / module level monitoring and control fails, resulting in inability to shut down, report adverse conditions, properly monitor, balance, or protect the system resulting in an adverse condition.* Failures may be software related (e.g., hang up in operation), hardware related (e.g., failure of a balancing circuit or loss of a sensor), or a combination of both where the entire system fails.	Control & Prevention System Failure
Enclosure PLC Failure	*Failure of the enclosure PLC controller resulting in adverse condition to the system or inability to detect or protect against adverse conditions under its purview.* The E5S enclosure utilizes a PLC to communicate supervision and control signals between the battery system BMS, HVAC controller, FACP and to the master site controller. While failure of this controller itself is unlikely to result in immediate risk to the system, failure of this controller will likely compromise the ability of the system to communicate its status to the ROCC and control interactions between systems.	Control & Prevention System Failure

Table 1: Detailed Threat Descriptions		
Threat	**Threat Description**	**Threat Category**
Site Control / Balance of Plant / PLC Failure	*Failure of the master site controller or other balance of system controller resulting in adverse condition to the system or inability to detect or protect against adverse conditions under their purview.* While failure of this controller itself is unlikely to result in immediate risk to the system, failure of this controller will likely compromise the ability of the system to adequately shutdown and isolate itself as well as monitor and control interactions between systems. In some cases, if this controller is needed for intervention, failure has likely already occurred or the system is experiencing massive, system wide issues, thus the master site controller may be necessary for adequate isolation from the grid or other AC or DC sources among other actuations. The relative risk of this threat may vary on a site-by-site basis and therefore not fully addressed within the scope of this report.	Control & Prevention System Failure
Shutdown / Isolation Failure	*Failure of the system to shut down or isolate itself when an adverse condition is detected.* This may be the result of a failure of electrical or mechanical protections designed to open power circuits within the system. For the E5S enclosure this may include failure of the battery rack level contactors or other automated disconnects upstream of the enclosure. Failure of this type may require manual human intervention to accomplish system isolation. Each PCS block has a motor operated switch that is capable of disconnecting power upstream and downstream of the block. Additional information related to the relative risk of this threat will be expanded upon in the final HMA.	Control & Prevention System Failure
Hazardous Voltage Condition	*This could include high line voltages, floating ground issues, or other high voltage issues at the cell, module, or rack level.* In this case, the voltage on the batteries is increased or decreased to unsafe levels beyond the voltage limits. A number of issues could cause either scenario. Such scenarios have been directly attributed to historic large scale ESS fires.	Electrical Failure
Ground Fault / Isolation Fault	*This could include localized shorting of cells, shorting between modules, shorting of entire racks or systems and ground fault shorting.* Unintended ground faults and insulation faults resulting in shorts that produce adverse, high current events. Similar to short circuiting, these events have been directly attributed to historic large scale ESS fires.	Electrical Failure

Table 2: Detailed Preventative Barrier Descriptions	
Barrier	**Preventative Description**
Passive Module Protections	*Module fuse which may open the circuit in the case of failure as well as general resilience of design to withstand adverse electrical conditions.*

Table 2: Detailed Preventative Barrier Descriptions	
Barrier	**Preventative Description**
	In cases where the circuit is unable to adequately isolate itself, the final barrier to avoiding catastrophic failure is passive circuit elements. Passive protection is provided by the module fuse which may open individual modules prior to failure. Depending on the nature of the failure, these elements may have mixed success in achieving these goals. The final passive protection barrier resides in the module itself.
Liquid Cooling System	*The liquid cooling system is an active cell protection which may prevent thermal runaway propagation.* Active cell protections include any type of actively monitored or controlled mechanism intended to protect against the effects of thermal runaway, whether it be actively preventing the cell from entering thermal runaway or actively mitigating thermal runaway once it occurs. For the E5S enclosure, this includes the liquid cooling system.
Enclosure Dehumidification System	*The enclosure's dehumidification system acts to prevent the buildup of condensation that may pose a short circuit hazard.* The E5S enclosure is provided with two dehumidifiers, one located on each side of the fire separation. The operation of the dehumidifiers are initiated by a humidity sensor located on each side of the fire separation. Humidifiers are powered from a separate auxiliary feed and will remain powered regardless if the enclosure is disconnected from DC power.
Direct Injection Clean Agent System	*The direct injection clean agent system is an active cell protection which may prevent thermal runaway propagation.* Active cell protections include any type of actively monitored or controlled mechanism intended to protect against the effects of thermal runaway, whether it be actively preventing the cell from entering thermal runaway or actively mitigating thermal runaway once it occurs. For the E5S enclosure, this includes the direct injection clean agent systems. This system is activated by activation of two smoke detectors or by the manual release located on the outside of the E5S enclosure. The system will continue to operate, discharging agent to all cells, until the agent is exhausted. The potential effectiveness of this barrier is demonstrated in the UL 9540A installation level testing.
Cell Thermal Abuse Tolerance	*Ability of the cells to withstand thermal abuse without going into failure themselves.* Thermal abuse tolerance applies to the ability of the chemistry in question to fail when exposed to high temperatures. It is typically not considered a strong barrier without sufficient testing to demonstrate. Both the cell and module proposed for the E5S enclosure are UL 1973 listed which includes testing for thermal abuse tolerance.
Cell Quality Control	*Overall quality of the cell such that internal defects are minimized, and cells maintain rigidity and shape during operations. Also includes tight tolerances with respect to degradation.* This barrier is intended as a catch all for considerations related to cell quality. This is likely to be outside the control of the end user of the system but covers the overall reliability of the cells with respect to internal failures and faults that may result in adverse conditions.

Table 2: Detailed Preventative Barrier Descriptions	
Barrier	**Preventative Description**
BMS Control	*Includes monitoring and shutdown/isolation capabilities of the affected BMS / module or system.* BMS Control includes aspects of BMS Shutdown / Disconnect but also includes overall effectiveness of monitoring such that proactive measures may be taken, or warnings given, indicating imminent failure or adverse conditions. Utilized as a barrier on multiple threats, this barrier is evaluated differently in each case based on the algorithmic response to the threat or failure in question.
Temperature Monitoring and Alarms	*Thermal monitoring within the container.* This barrier is the ability of the battery system or BMS to detect adverse thermal conditions within itself and alarm those issues outward. Four temperature sensors are provided within each module. The BMS will initiate an automatic shutdown when a hazardous temperature condition is detected.
System Shutdown / Disconnect	*Ability of system to actively shut itself down or disconnect itself. This is the aggregate of the BMS ability as well as physical disconnects and the Balance of System controller's ability to shut down.* This barrier may be approached from two perspectives, with the first the ability of the system to truly shut off only the affected and responsible operations when such conditions are detected. This shutdown will stop ohmic and electrochemical heating thus stopping heat generation and may also increase the temperature at which thermal runaway would occur (by stopping internal heat generation). The second approach involves shutting down the entire system. The BMS system is capable of automatically disconnecting individual battery racks. Remote emergency manual system shutdown of the enclosure from the ROCC can only be accomplished using disconnects located beyond the E5S enclosure. A manual DC disconnect is also available within the enclosure. The strength of this barrier will be expanded upon in the final HMA.
Preventative Maintenance and Commissioning	*Proper maintenance and monitoring of the system in conjunction with adequate commission and site acceptance testing to reduce likelihood of loose connections or other transportation or construction defects.* Preventative Maintenance consists of the normally scheduled preplanned maintenance required for operation such as periodic inspections for function and operating limits and the necessary upkeep required for continued operation as well as the prompt repair of failures and failing components. Commissioning refers to the process of bringing the system online, performing inspections of the built system to ensure proper compliance with operating parameters, and the shakedown of “bugs” and issues from construction to normal operation. Through these processes, the system is brought to and maintained in good working order.
Passive Circuit Protection and Design	*Breakers and fuses which may open the circuit in the case of failure and general resilience of design to withstand adverse electrical conditions.* The E5S enclosure includes a passive fuse for each battery rack and at the main DC disconnect.
Cell Electrical Abuse Tolerance	*Ability of the cell to withstand electrical abuse such as overcharge, over discharge, high currents, or other adverse electrical abuse.*

Table 2: Detailed Preventative Barrier Descriptions	
Barrier	**Preventative Description**
	The ability of the individual cells to withstand electrical abuse such as short circuit, overcharge, and overcurrent events without resulting in adverse conditions. As no testing standard yet exists to quantify the ability of the cell to withstand electrical abuse, this barrier is evaluated as weak
Redundant Failure Detection / System Intelligence	*Ability of system to determine a sensor has failed, to operate safely without that sensor to shut down, or operate safely indefinitely without sensor. This may include Checksums, additional sensors, or the ability to pull data from other sensors.* This barrier is highly dependent on the sensor in question as well as the design, architecture, and operation of the system as a whole and the evaluation of the data collected within the confines of the system.
Human Factors / Process Control	*Quality control or other processes put in place to prevent mishandling of systems that may result in adverse or hazardous conditions or mishandling.* A catchall barrier that includes all possible failures and adverse conditions brought about by human interaction with the system. It also includes failures related to process and flow separate from the control system of ESS itself. This could be as simple as a technician dropping a wrench across the terminals or as complex as sophisticated maintenance procedure which fails to adequately address an otherwise trivial detail, such as failure to check the tightness of unreachable bolts or clean unexposed terminals. The relative strength of this barrier is assumed to be in alignment with industry norms.
Container / Structural Resiliency	*Resiliency of the system and container of the system to withstand impacts or strikes.* The enclosure envelope is assumed to be effective to protect against basic vandalism or low speed, accidental vehicle impacts such as construction equipment as well as high winds, hail, seismic vibrations, and other environmental forces.
Module Resiliency	*Resiliency of the individual modules to withstand impacts, shocks, or other mechanical abuse.* Similar to cell abuse tolerance, this barrier covers the overall strength and rigidity of a battery module as it relates to the ability of the module to withstand both impacts and shocks as well as the noise, vibration, and harshness.
Cell Physical Abuse Tolerance	*Ability of the cell to withstand thermal, physical, or mechanical abuse.* This barrier considers the ability of a cell to withstand physical, thermal, or mechanical damage without resulting in an adverse condition. As all lithium ion battery chemistries have shown susceptibility to physical damage such as penetration and crush, this barrier is likely to be considered weak, depending on the threat faced. The proposed cell and module have been certified to UL 1973 which includes physical abuse testing. These include vibration, shock, crush, static force, impact, and drop impact testing. The strength of this barrier is assessed as strong when the degree of abuse is within the bounds of UL testing but may be weaker when these bounds are exceeded.
Humidity Monitoring	*Monitoring within the container which may detect high humidity, water condensation or water leakage.*
System Maintenance	*Proper preventative maintenance to minimize the impact of adverse, long term or slow acting environmental effects resulting in degradation.* Includes normally scheduled maintenance required for operation including periodic inspections for function and operating limits, replacement of expendable parts, and

Table 2: Detailed Preventative Barrier Descriptions	
Barrier	**Preventative Description**
	any necessary upkeep required for continued operation. Also includes prompt repair of failures and failing components.
SME Training	*Proper training procedures, availability of subject matter expertise and system competence, and clear jurisdictional hierarchy for managing situations.* Though required by fire codes such as NFPA 855, subject matter expert (SME) remains an undefined term and the quality and title of SMEs across the industry varies wildly. In addition to the undefined term, there is no nationally recognized standard or methodology for training or credentialing subject matter experts. In some cases, the SME may be more critical to the response of an ESS emergency than the first service, because the safety of the first responders and fire fighters also depends on the SME. This role should be evaluated carefully by all stakeholders when selecting an SME.
Voltage Monitoring	*Overall effectiveness of the voltage monitoring scheme of the system. Includes resilience to errors, error checking, and other measurement intelligence.* This includes adequate measurement of voltage throughout the system coupled with checks or redundant measurements such that a sensor failure cannot drive the system to an adverse condition. This includes monitoring of module, rack, and bus levels DC voltages and any intermediary voltages.
Insulation Monitoring	*Continual, or active, monitoring of insulation integrity, ground versus float voltage, and other practices to prevent insulation or isolation degradation.* Insulation monitoring is a common electrical maintenance best practice. Degradation of insulation for any reason runs the risk of current related failures anywhere in the system. This includes not just wire insulation but isolation on components and effectiveness of ground isolation during normal operation.

APPENDIX D – CONSEQUENCE AND MITIGATIVE BARRIER DESCRIPTIONS

Table 1: Detailed Consequences Descriptions	
Consequence	**Consequence Description**
Cell / Module Combustion	*A battery cell or module has failed and is now producing flame or combusting.* A single cell failure resulting in combustion and flame is likely the result of thermal runaway. While several mitigating barriers exist to prevent this scenario from reaching its natural conclusion, should those barriers fail, it is possible this consequence will continue, evolving into any of the consequences included in this analysis. Spread to other nearby cells or modules may continue the propagation of failure throughout the system
Multi-Module / Rack Fire	*Multiple modules have begun producing flame or combusting.* Fire within multiple modules or racks. Fire at this scale may be the result of propagation from a smaller event. Fire at this scale will be more dependent on the fire department response. Defensive postures may be needed to protect external exposures. A fire of this magnitude is expected to continue burning for several hours. This fire scenario is beyond the fire events experienced in UL 9540A testing for the E5S enclosure.
Fire Spread Beyond Enclosure Fire Partition	*A fire within the system has spread from one side of the enclosure fire rated partition to the modules/rack and equipment on the opposite side within the same enclosure.* In this scenario, the fire event has spread beyond the fire partition that subdivides the E5S enclosure, subsequently involving the modules/racks and other equipment on the opposite side of the enclosure. This fire scenario is beyond the fire events experienced in UL 9540A testing for the E5S enclosure.
Fire Spread Beyond Enclosure	*A fire within the system has spread beyond the enclosure to adjacent ESS enclosures or other structures.* In this case, fire has likely compromised the entire or a large portion of the interior space of the enclosure and has now breached the container, posing immediate risk to adjacent equipment or facilities. This scenario may occur even if the fire does not compromise the enclosure fire partition. Defensive firefighting is likely required to mitigate this incident. A fire of this scale may burn for several hours or days. ASHREA data for the nearest airport at Albuquerque International shows 1% extreme wind speed shows a wind speed of 28.2 mph and high temperatures of 95.2º F. The overall site is relatively flat and a defensible space is recommended to be maintained around enclosures to reduce wildfire risk. Based on the project site plan, the E5S enclosures are grouped in side-by-side pairs with 3.5 feet of space between each enclosure. Each pair is then spaced 21.75 ft from the next pair in groups totaling 5 pairs (10 E5S enclosures). The site consists of 4 total groups of enclosures separated by a minimum of 40’ of space between them. If a fire spreads beyond an enclosure, it is highly likely the pair will become involved. It is recommended that defensive firefighting be provided to mitigate further spread to adjacent pairs of enclosures. Fire modeling is being conducted to determine the likelihood of a fire spreading beyond that. The Final HMA report will be updated to include the results of the analysis.
Cell Off-Gassing / Explosions	*A cell or multiple cells have failed or entered thermal runaway and is now producing off-gas.* UL 9540A testing indicates that the cell off gasses include hydrogen, carbon monoxide, methane and other flammable hydrocarbons. When mixed with oxygen from the air, a flammable mixture may be formed. As such, this event may pose even greater risk than a single cell combustion, as the ability of batteries to maintain high temperatures in excess of autoignition temperatures for hours is well documented and the electrical nature of the systems adds additional ignitions sources. The cells utilized for the E5S enclosure may

	possess enough electrolyte, and ultimately gas generation potential, to create a flammable environment from only a single cell.
Accumulation of Off-Gasses / Delayed Explosions	*A cell or multiple cell failure which may or may not have propagated has resulted in the accumulation of potentially explosive off-gas within the enclosure.* Even with a single cell, long after the risk of propagating failure has passed, off-gas may continue to linger in the area, especially within the enclosure. This gas may continue to pose deflagration risk. Even cooled or extinguished batteries may emit gas several hours following an event. The lack of ventilation within the enclosure means the ability to exhaust this gas without putting personnel into harm's way is practically nonexistent.
Balance of System Fire	*A fire that either is initiated in or results in the involvement of a balance of system fire such as wire insulation, electrical components, or plastic inside the system.* In this instance, a small fire results in damage to the balance of system, including wiring insulation, bus bars, plastic containment or other component or material. Such damage may pose significant risk as compromised wiring or components may result in arcing, shorting, or other high energy event or act as ignition source causing delayed fire or explosion.
Environmental / HAZMAT Issues	*A large-scale system fire has resulted in an environmental or hazardous material incident which requires hazardous material response.* Examples include toxic smoke / gas plumage, contamination of firefighting runoff water in a sensitive area, or leftover energetic hazardous materials which may require special handling. These issues may be an active concern throughout the initial fire / thermal runaway incident or may be addressed post initial incident.

Table 2: Detailed Mitigative Barrier Descriptions

Barrier	Mitigative Barrier Description
Enclosure Smoke Detection	*Activation of the enclosure's smoke detection system and communication via the Fire Alarm Control Panel (FACP). System activation provides both situational awareness to facility operators, personnel in the vicinity of the enclosure and first responders, as well as activation of the enclosure's direct injection clean agent system.* This barrier provides situational awareness of an emerging situation to facility operators and first responders. The effectiveness is based on the ability of the system and site to provide information and clarity of the failure. Poor situational awareness may weaken subsequent barriers. Effective use of the information provided by this system is dependent on proper annunciation of this data on site or the availability of this data to first responders and operations personnel. Activation of the smoke detection system will initiate the enclosure fire alarm notification device to facilitate personnel evacuation from the immediate vicinity of the enclosure. Communication of the fire alarm signal from the enclosure's FACP to the site's FACP may be used to initiate site wide notification of the fire event. Detection of smoke within the enclosure by two or more detectors will result in activation of the direct injection clean agent system. Depending upon the nature of the failure scenario, this system may act to reduce or limit the likelihood of continued propagation of a thermal event.

Enclosure Gas Detection System	*Activation of the enclosure's gas detection system and communication of alarm signal to the SCADA system. System activation provides situational awareness to facility operators, personnel in the vicinity of the enclosure and first responders.* This barrier provides situational awareness of an emerging situation to facility operators and first responders. When activated the gas detection system raises an alarm in the ROCC and will activate the enclosure fire alarm notification device to facilitate personnel evacuation from the immediate vicinity of the enclosure. Communication of gas detector data to emergency and first responders will require interface with the ROCC. The strength of this barrier may vary on a site-by-site basis and requires coordination with the team.
Occupant Notification	*Activation of the alarm notification device on the exterior of the enclosure and activation of the facility's site wide alarm system if provided.* This barrier provides situational awareness of an emerging fire or gas related situation to occupants in the area adjacent to the enclosure and in the wider facility (if a site wide occupant notification system is provided). Occupants are expected to evacuate the immediate area upon alarm system activation. The strength of this barrier may vary depending upon the quality of employee and site visitor training. The strength of this barrier may vary on a site-by-site basis and therefore not fully addressed within the scope of this report.
BMS Data Availability	*Includes BMS measurements available to first responders, ROCC, or other SMEs. Effectiveness based on what is detected and how accurate, how this information is being conveyed, and robustness of sensors in case of failure.* In the event of a failure event, BMS data may be available via the ROCC or otherwise communicated to first responders. This information may provide insight into the current conditions of the system (e.g., temperature of cells / modules, SOC, voltage trends, etc.) – provided the system is still online – or the state of the system prior to loss of measurements. This barrier provides situational awareness of an emerging situation to facility operators and first responders. The effectiveness is based on the ability of the system and site to provide information and clarity of the failure. Poor situational awareness may weaken subsequent barriers. Effective use of the information provided by this system is dependent on proper annunciation of this data on site or the availability of this data to first responders and operations personnel.
Direct Injection Clean Agent System	*Activation of the direct injection clean agent system may limit or reduce the rate of a propagating thermal runaway event.* This system is activated by smoke detector operation (two or more detectors). The direct injection clean agent may limit or reduce the rate of a previously occurring propagating thermal runaway event.
Deflagration Protection	*Activation of the enclosure's deflagration venting system.* Deflagration or explosion as a result of combustion, expansion, or detonation, poses severe risks to life and property near an ESS. UL 9540A testing indicates that the cell off gasses include hydrogen, carbon monoxide, methane and other flammable hydrocarbons. When mixed with oxygen from the air, a flammable mixture may be formed. The E5S enclosure has been provided with a deflagration vent design in accordance with the requirements of NFPA 68. The system has been subject to both UL 9540A installation level testing and bespoke deflagration testing. The system has been primarily designed to protect from an off-gassing event involving three cells.

Thermal Isolation (Enclosure Insulation)	*Passive thermal propagation protection provided by insulation installed on the boundaries of the enclosure.* The insulating panels provided on the enclosure walls is anticipated to reduce conduction to the exterior surface of the enclosure thusly retarding fire spread to adjoining enclosures. The assessed strength of this barrier for the E5S enclosure is informed by both UL 9540A and bespoke fire testing. These will be analyzed and included in the final HMA report.
Thermal Isolation (Enclosure Fire Separation)	*Passive thermal propagation protection provided the enclosure's fire separation.* The enclosure's fire separation subdivides the enclosure into two separate fire compartments. This separation provides a strong barrier to limiting a flaming fire event to half of the enclosure. The assessed strength of this barrier for the E5S enclosure is informed by bespoke fire testing. These will be analyzed and included in the final HMA report.
Thermal Isolation (Module / Rack Separation)	*Passive thermal propagation protection provided by physical separation between modules within a rack and physical separation between racks within the enclosure.* The degree of separation provided between modules within rack and between racks acts to retard the rate of thermal runaway / fire propagation. This barrier is assessed to be relatively weak for most flaming fire scenarios but stronger for non-flaming thermal runaway scenarios. The assessed strength of this barrier for the E5S enclosure is informed by both UL 9540A and bespoke fire testing. These will be analyzed and included in the final HMA report.
Facility Design and Siting	*Placement of the facility such that adverse environmental effects such as flooding, vehicle impact, and fire impingement are mitigated or avoided. The strength of this barrier is dependent upon the site-specific aspects of the facility layout.* This barrier is intended to include analysis of the system in its location with respect to localized environmental hazards, adjacent structures, fire loads, and personnel exposures, and other generic environmental threats either to the system as posed by the environment or to the environment as posed by the system. While a specific spacing may be suitable for most ESS, it may not be sufficient spacing from a large fuel storage depot or an ambulatory care facility. Further, proper siting should include the type of environment the system is built in such as a flood plain, a high traffic area, a wetland, or an area prone to fire. The E5S enclosures are grouped in side-by-side pairs with 3.5 feet of space between each enclosure. Each pair is then spaced 21.75 ft from the next pair in groups totaling 5 pairs (10 E5S enclosures). The site consists of 4 total groups of enclosures separated by a minimum of 40' of space between them. If a fire evolves to the point it spreads beyond an enclosure, it is highly likely the pair will become involved. It is recommended that defensive firefighting be provided to mitigate further spread to adjacent pairs of enclosures. The additional separation between the pairs and the groups of enclosures helps to mitigate the potential for fire to spread throughout the site. The site is considered remote and not anticipated to have public traffic that could pose physical damage risk to the enclosures.
Emergency Response Plan / First Responders	*System operator plan to handle any and all emergency events. A site-specific emergency response plan should be developed. Effectiveness based on level of the subject matter expert (SME) / first responder training, knowledge of the specific ESS undergoing failure, coordination with fire department, etc.* First responders refer to site personnel, corporate employees, local technicians, and SMEs who may be the first to detect or respond to failure or fault in the system and alert fire services. The term first responders in this case does not refer to fire fighters or other fire service personnel, but to those who will be reporting the event or directing the fire

	service in regard to the risks posed by the system. The guidance from these individuals, as well as the information contained in the emergency response plan, will serve as the initial human response to the incident and have the greatest chance of containing the incident, if it is containable, to a reduced state. Depending on time to detection, along with time to first response and fire service response, the incident may have progressed through multiple consequence pathways, as single cell failure can propagate to adjacent modules and beyond in a matter of minutes. The ERP will be reviewed and the strength of this barrier will be expanded upon in the final HMA.
Fire Service Response	*Fire department response including active firefighting suppression. Effectiveness based on level of department knowledge and training to effectively respond both offensively and defensively during an ESS incident.* This barrier includes all aspects of the fire service response including the personnel, resources, knowledge, and overall comfort level brought to bear on the scene. Current industry training and emergency response planning point toward automatic dispatch of multiple trucks or departments/stations for ESS emergencies or multiple alarms in some jurisdictions. Response time, access, fire water supply and situational awareness (e.g., Detection Systems) will act as a multipliers, resulting in decisions which may save the currently impacted or adjacent systems or result in the loss of the entire facility. SFCFD does not have a HAZMAT team but utilizes the City of Sante Fe Fire Department with a response time of 24 minutes.

APPENDIX E – BOW TIE MODEL DIAGRAMS

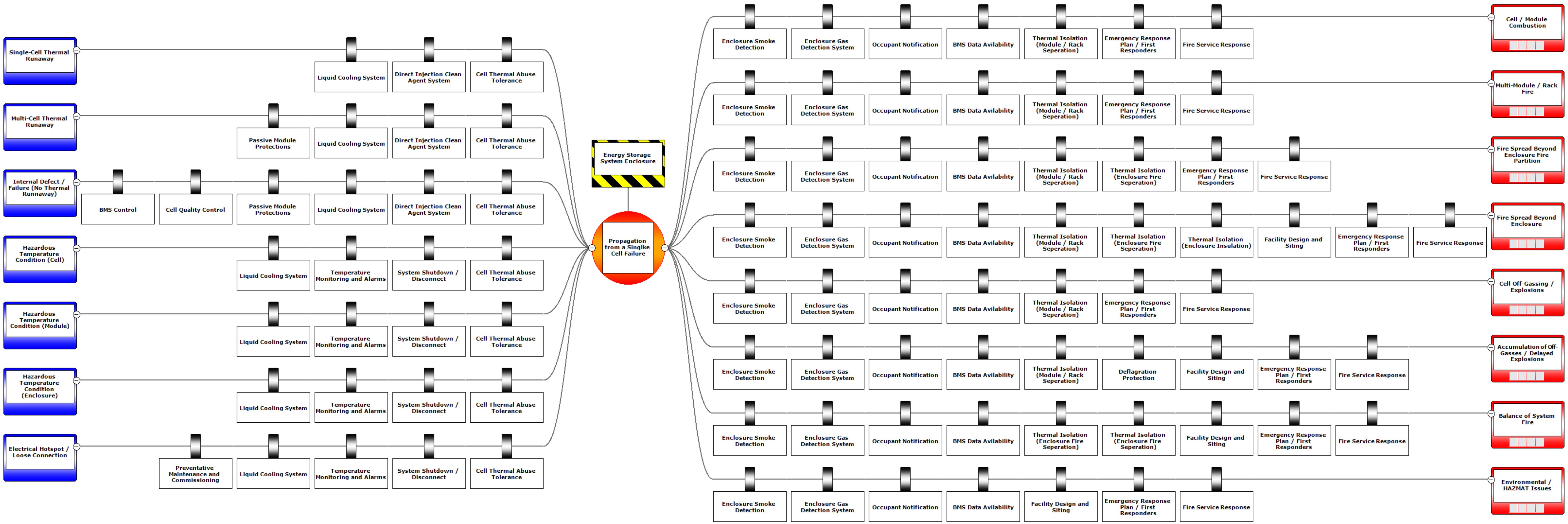

Figure E-1 – Thermal Runaway and Mechanical Failure Threat Pathways

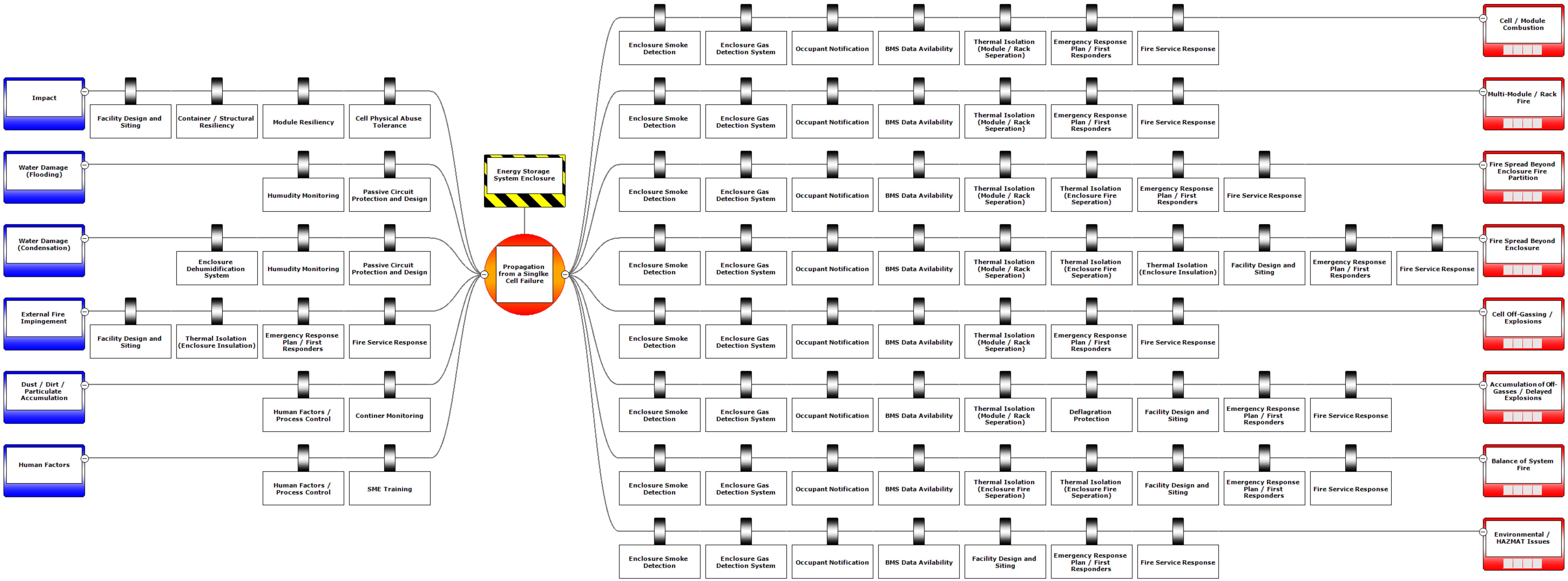

Figure E-2 – External Impact Failures Threat Pathways

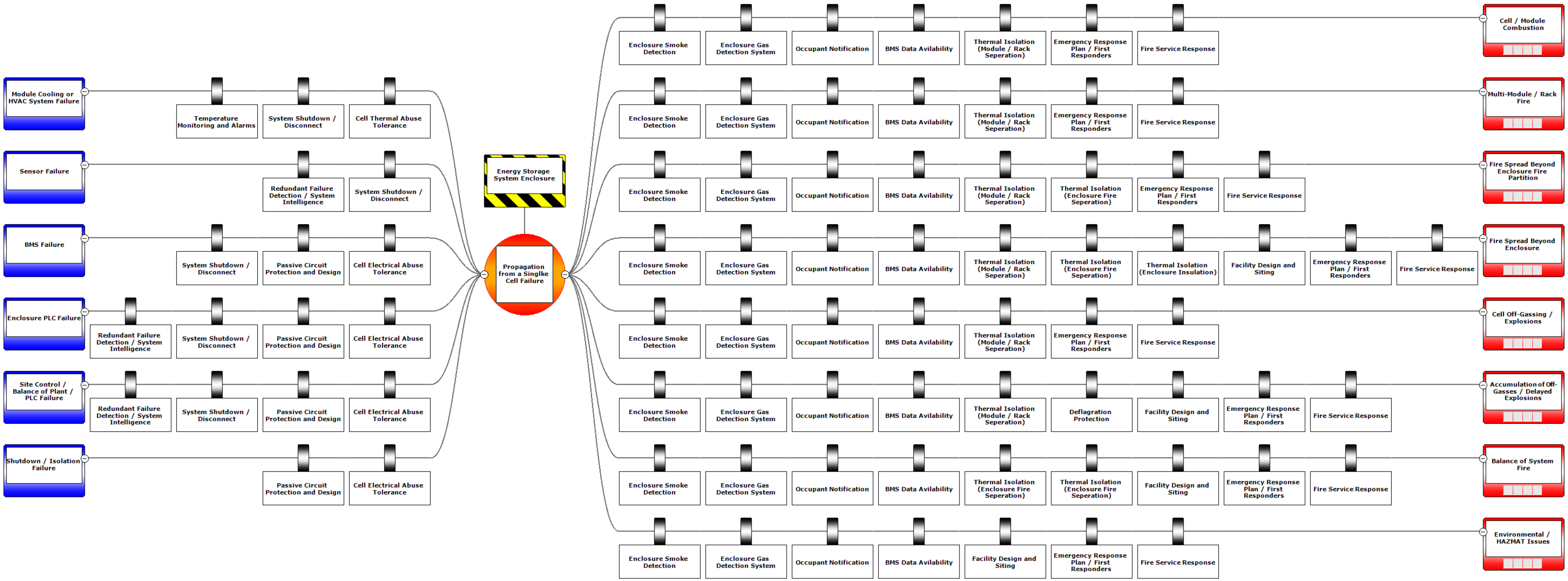

Figure E-3 – Control and Prevention System Failure Threat Pathways

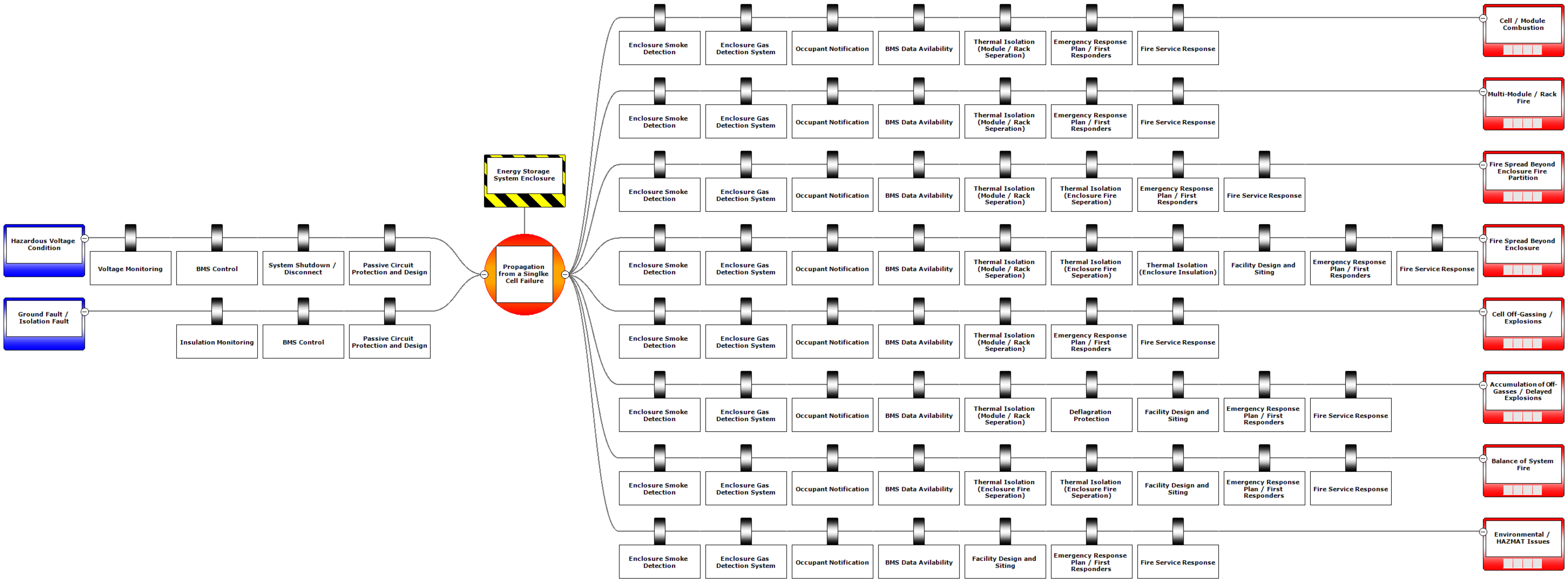

Figure E-4 – Electrical Failure Threat Pathways

APPENDIX F – UL 9540A FIRE TEST RESULTS

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FOR AUTHORIZED REVIEW ONLY