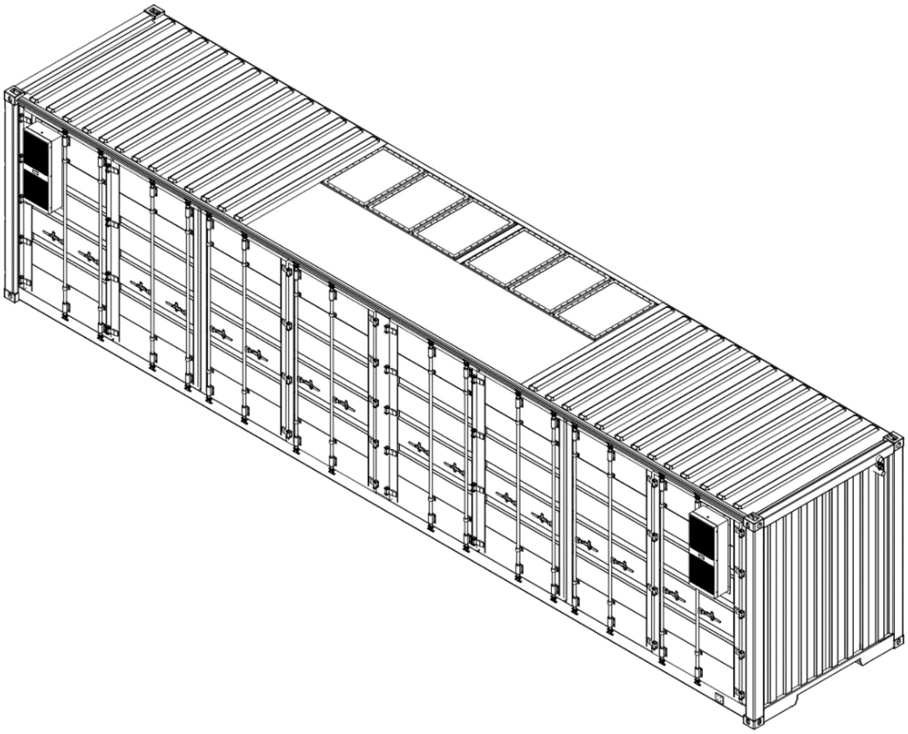
Draft Preliminary HMA Report

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**.

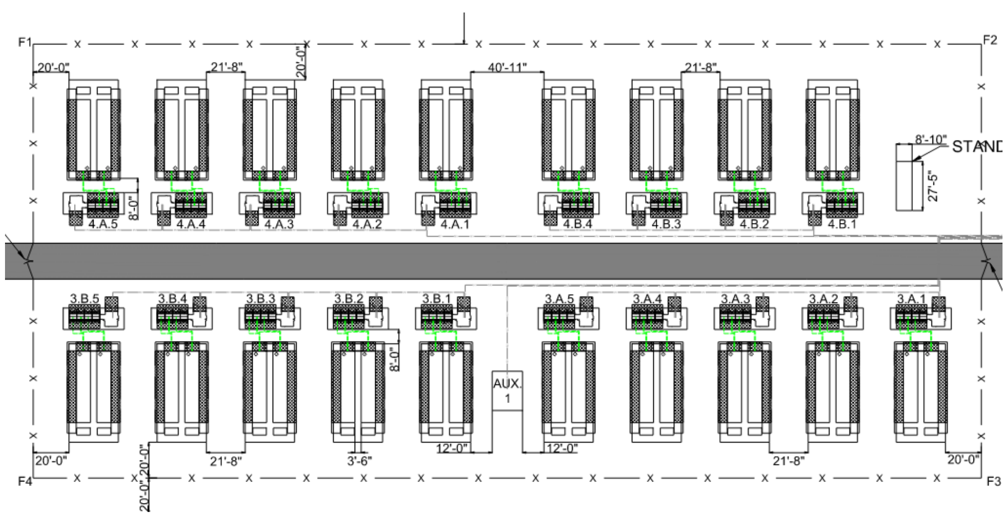

Figure 1 - Rancho Viejo BESS Site Plan

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

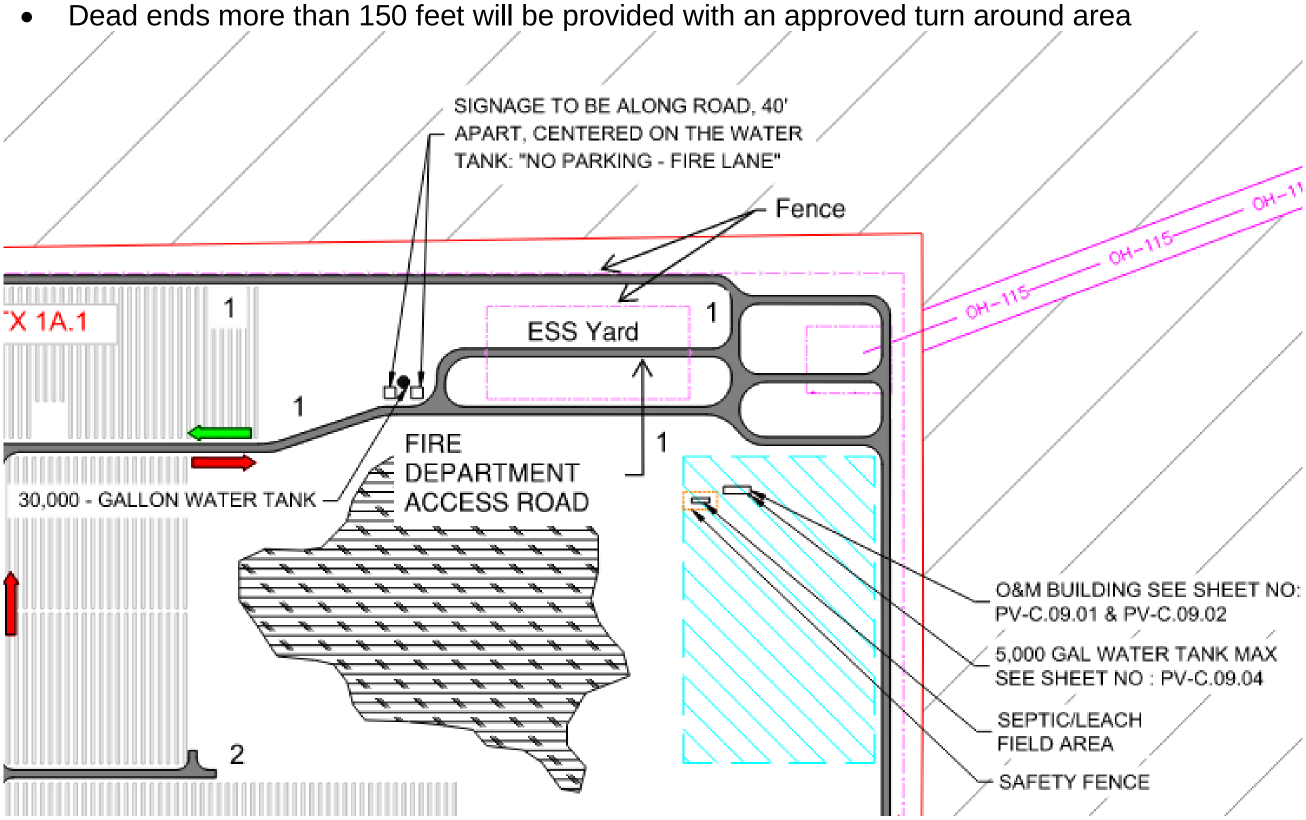

Figure 2 - Fire Department Features Site Map

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

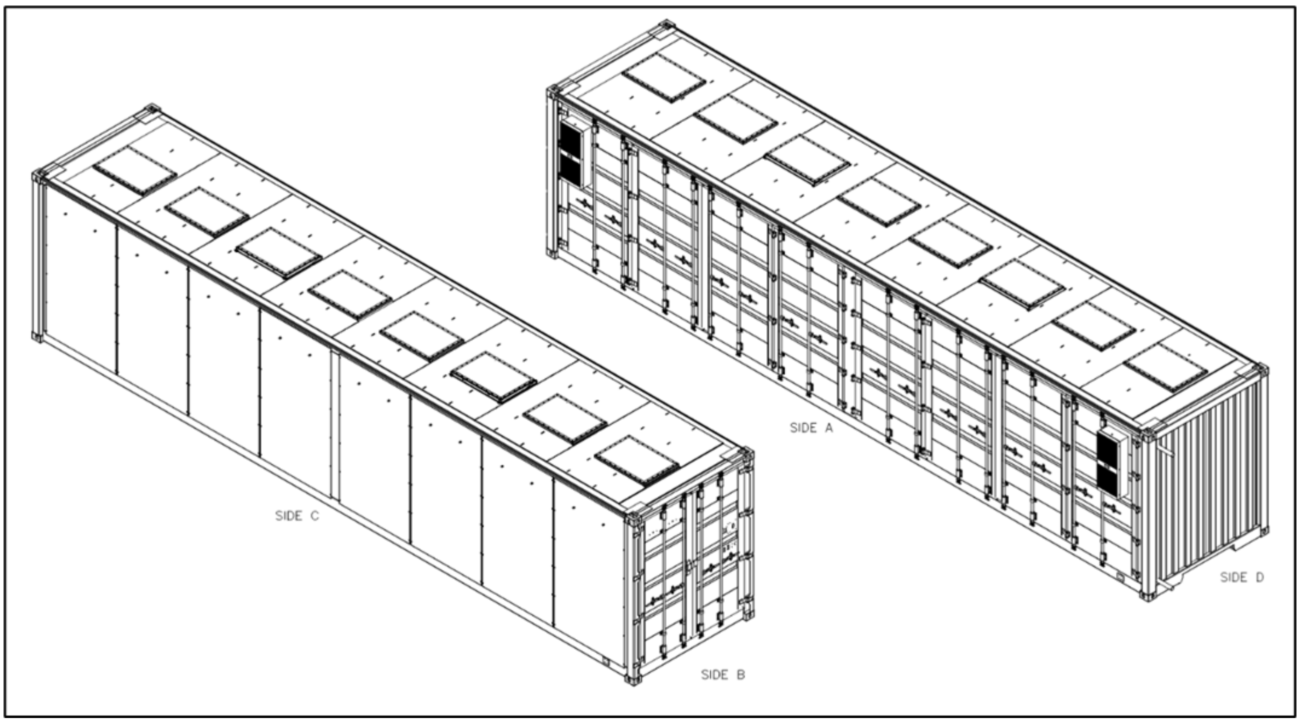

Figure 3 – CEN BESS Enclosure (Exterior View)

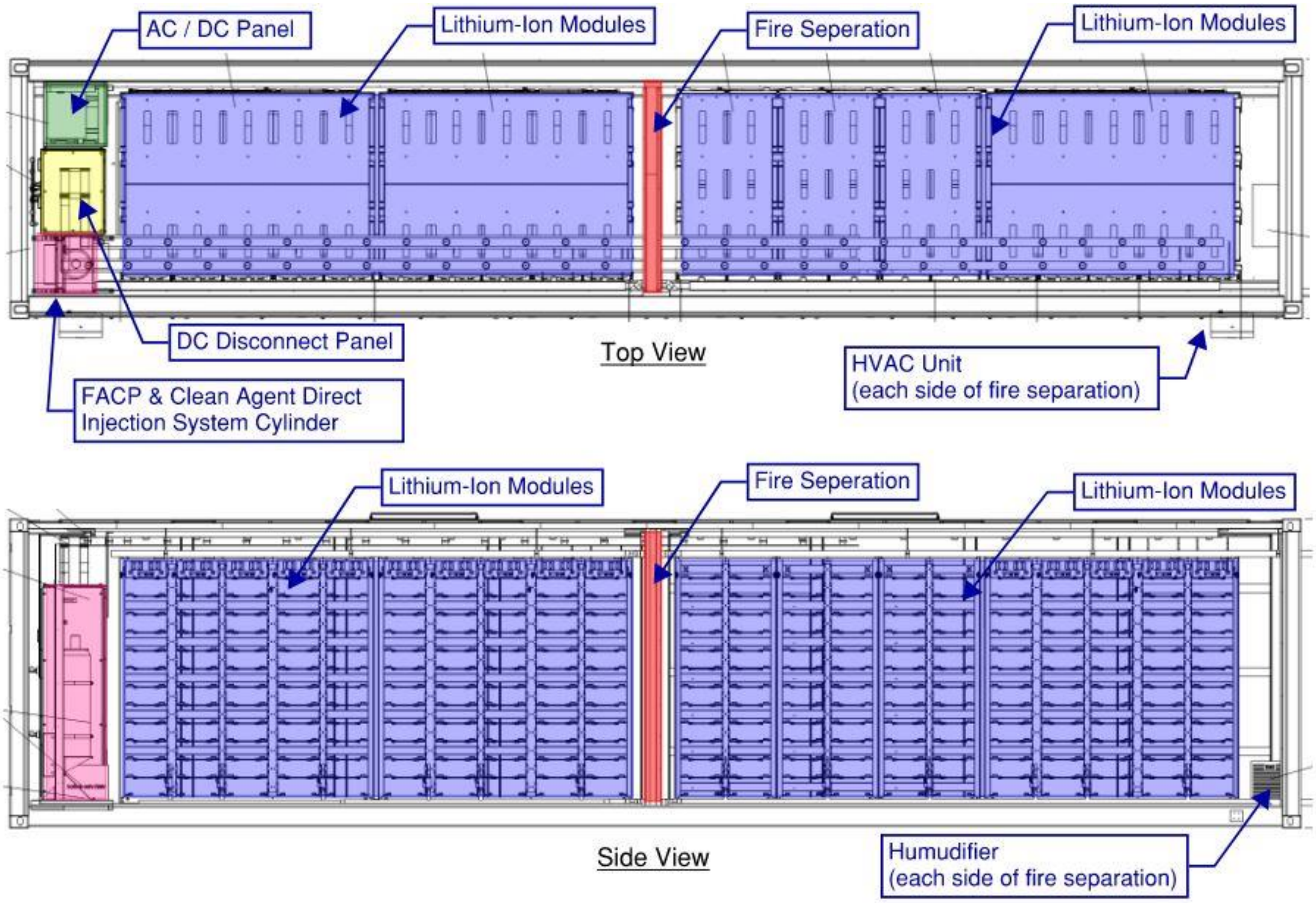

Figure 4 – CEN BESS Enclosure (Internal View)

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.

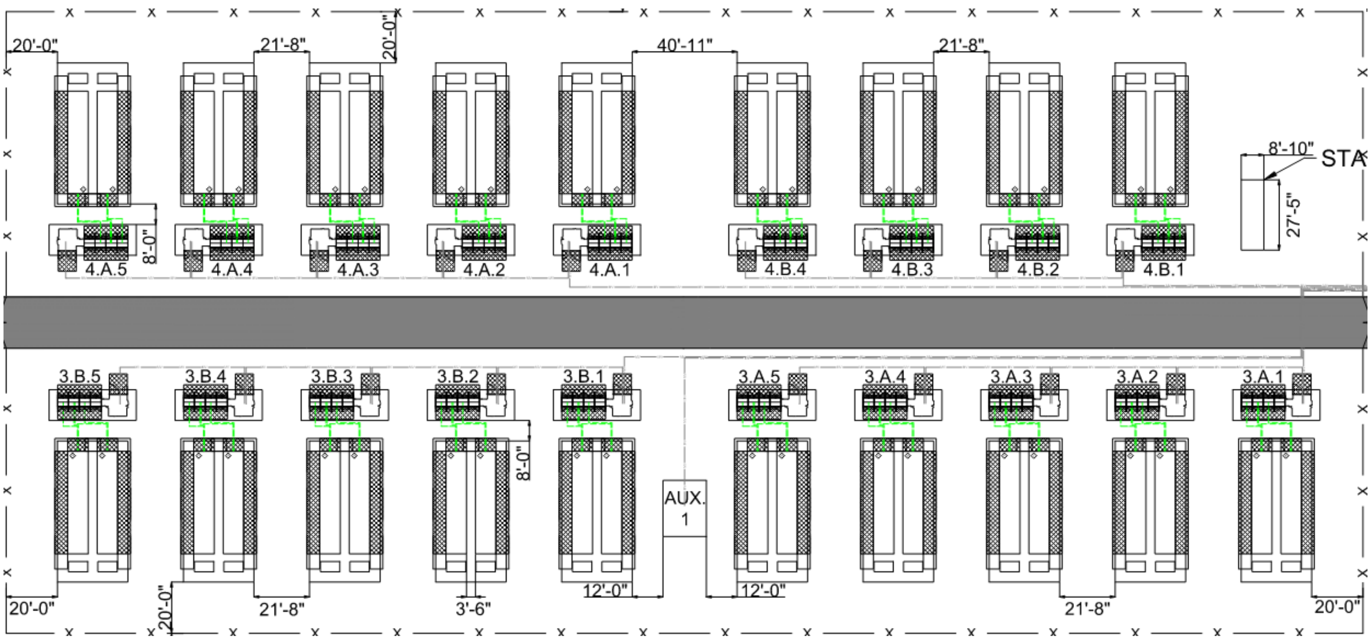

Figure 5 - E5N Enclosure Spacing

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 423 L of gas may be released per cell when thermal runaway occurs. Testing indicates that the gas is primarily composed of hydrogen (32.7%), carbon monoxide (40.9%), methane (15.43%) and carbon dioxide (9.2%) with a LFL of 8.04% 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 178°C. The cell vent gas fundamental burning velocity, S_u, was determined to be 88.40 cm/s with a maximum pressure, P_{max}, of 105.3 psig.

- **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 3935 kW 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 426.1 kW. Release of flammable gas with an associated explosion was not observed. The maximum enclosure wall surface temperature observed was 169°C.

- **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 670°C.

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.

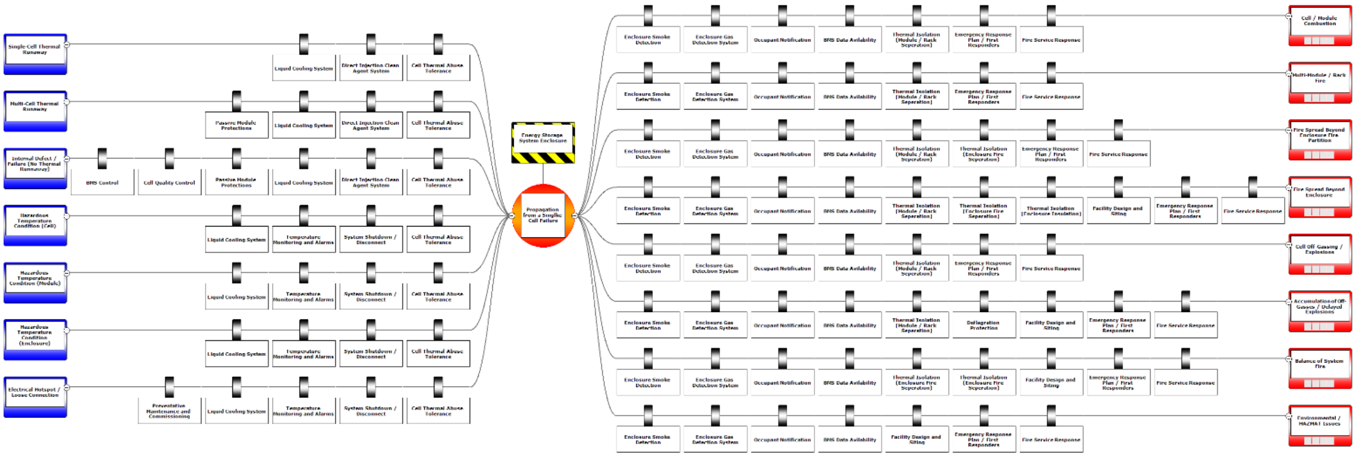

Figure 6 – Thermal Runaway and Mechanical Failure Bow Tie Diagram

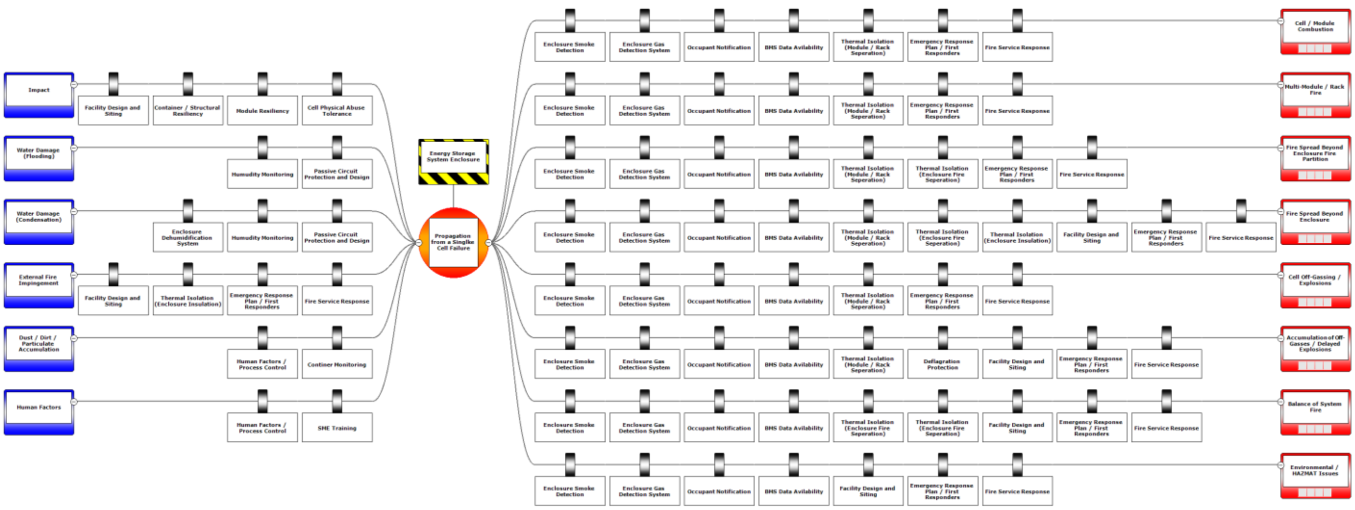

Figure 7 – External Impact Failures Bow Tie Diagram

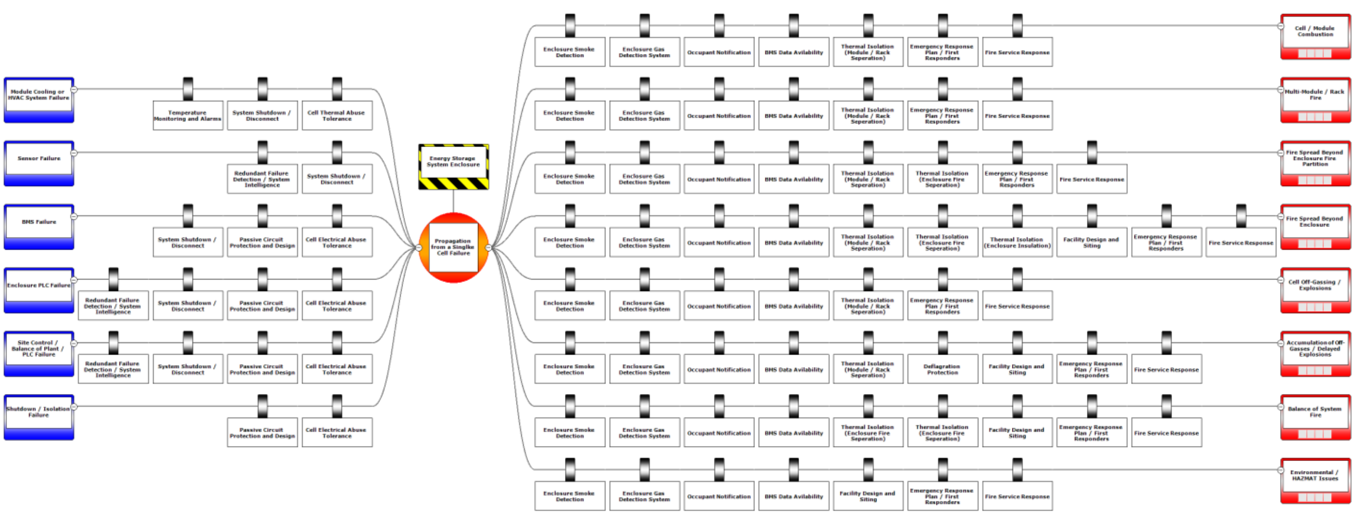

Figure 8 – Control and Prevention System Failure Bow Tie Diagram

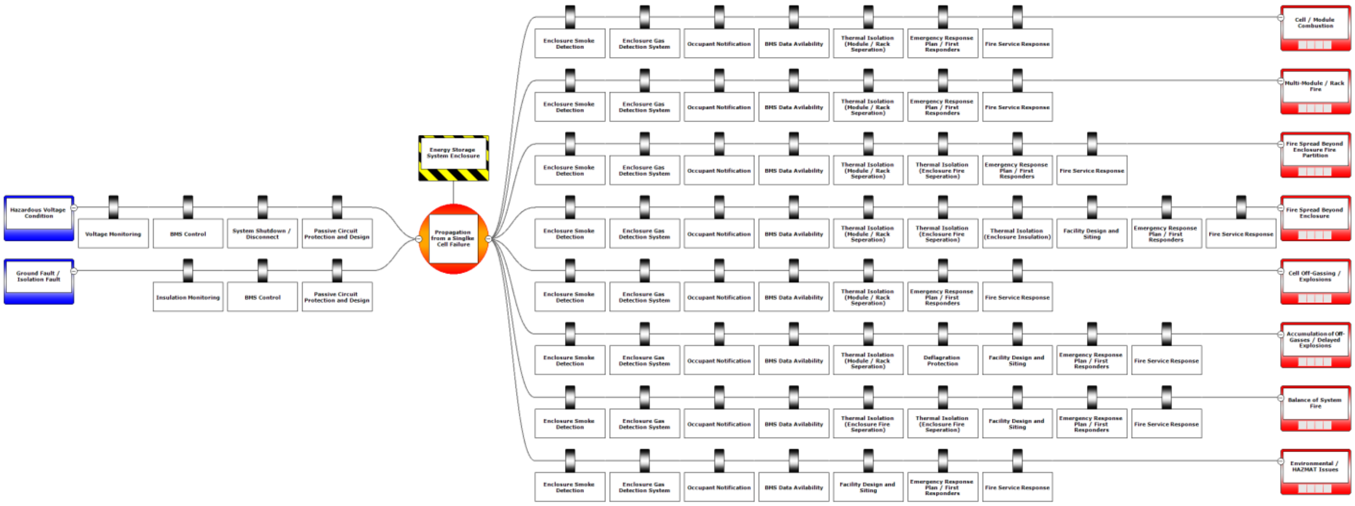

Figure 9 – Electrical Failure Bow Tie Diagram

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

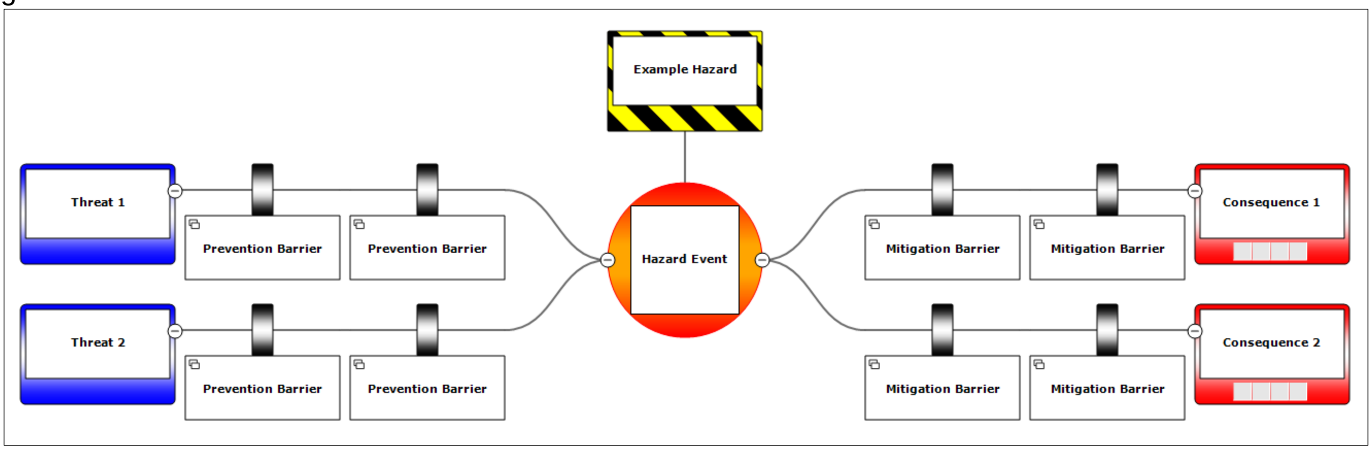

Figure **1**.

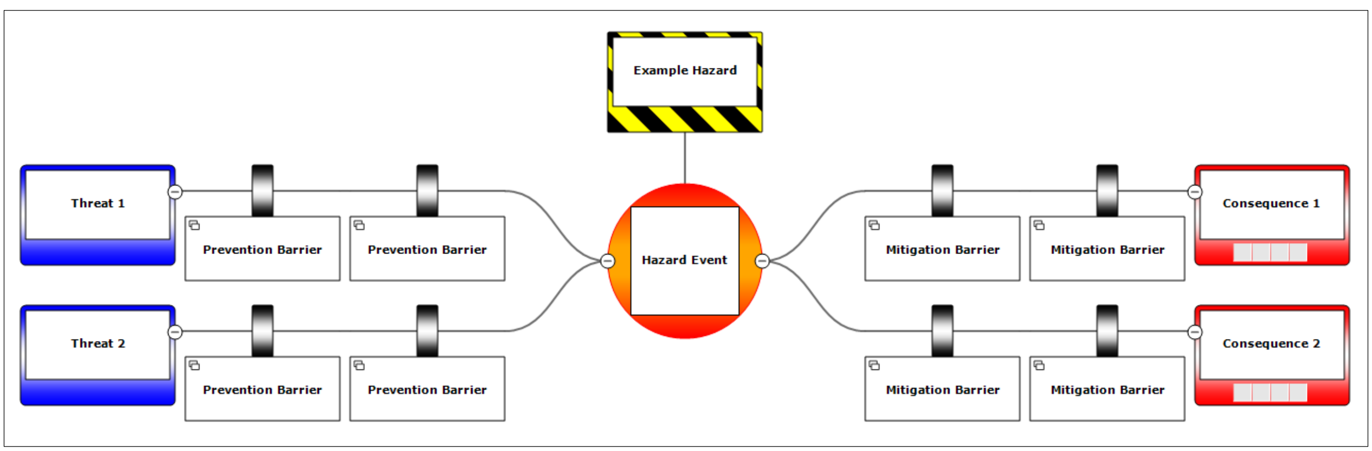

Figure 1 – Bow Tie Model Description

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

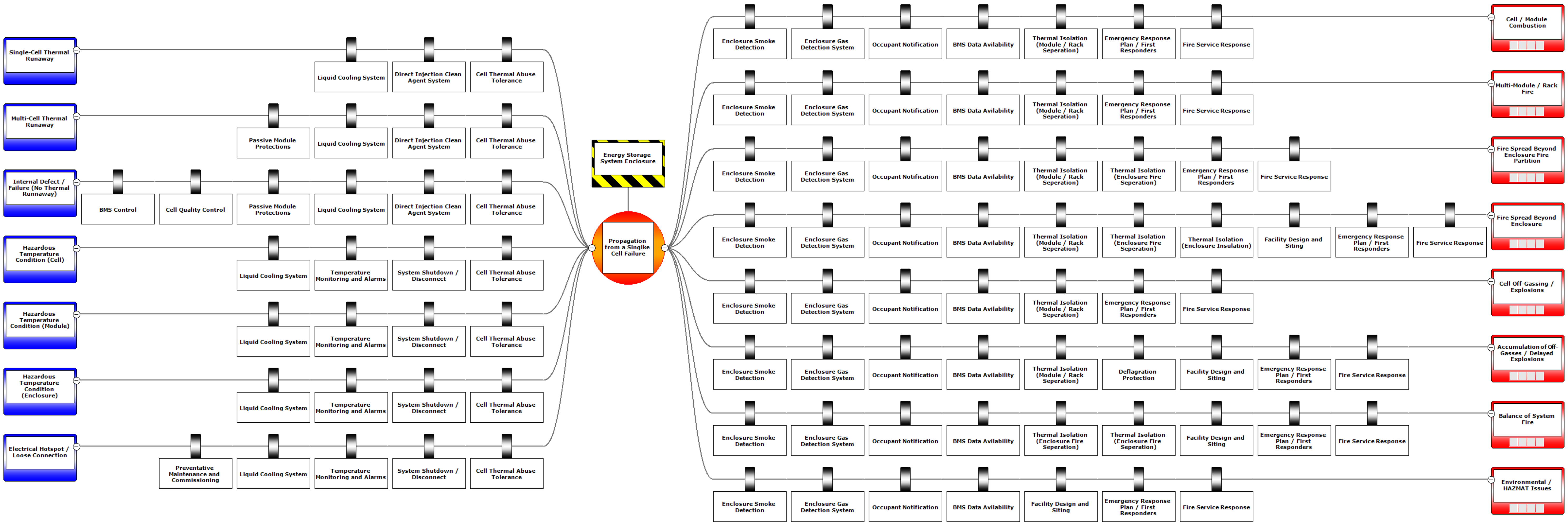

Figure E-1 – Thermal Runaway and Mechanical Failure Threat Pathways

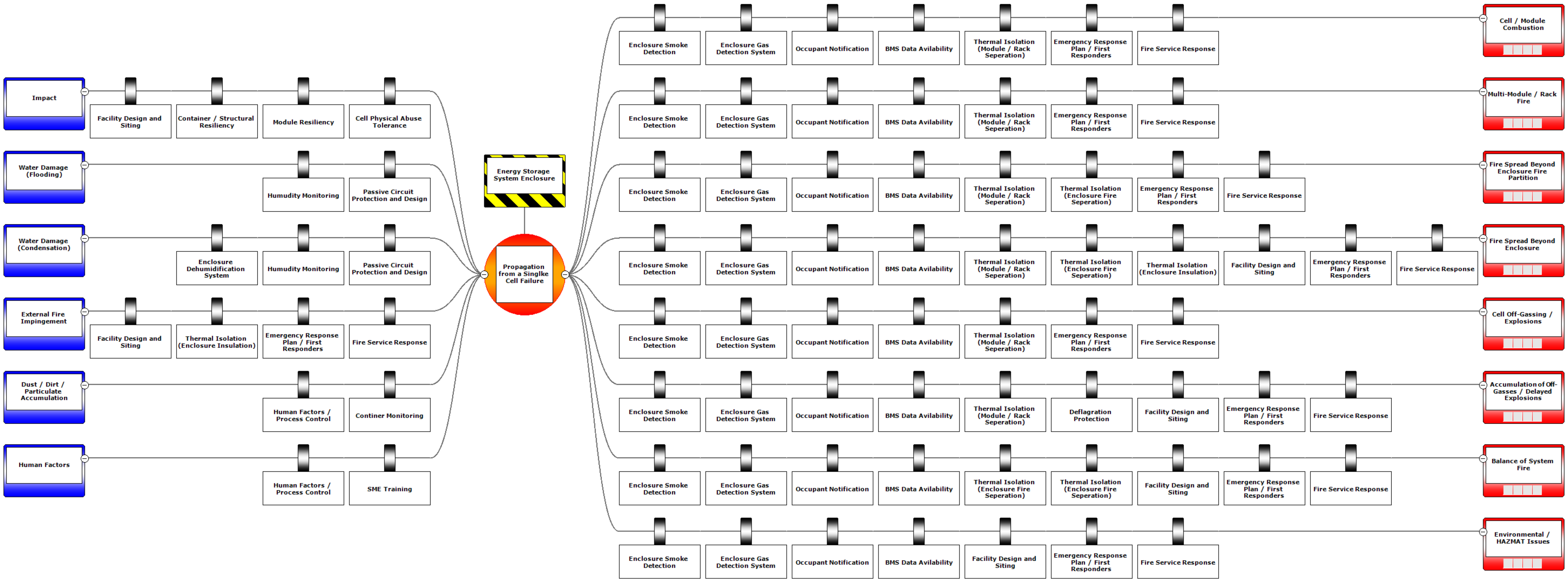

Figure E-2 – External Impact Failures Threat Pathways

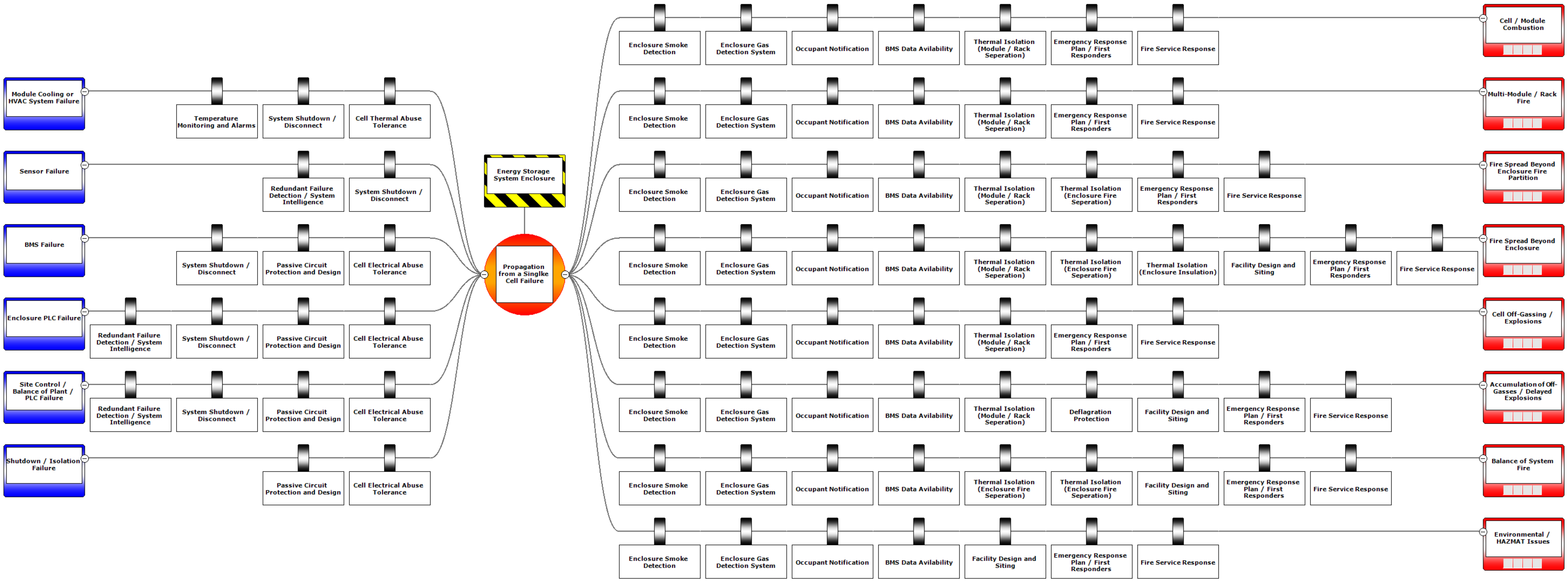

Figure E-3 – Control and Prevention System Failure Threat Pathways

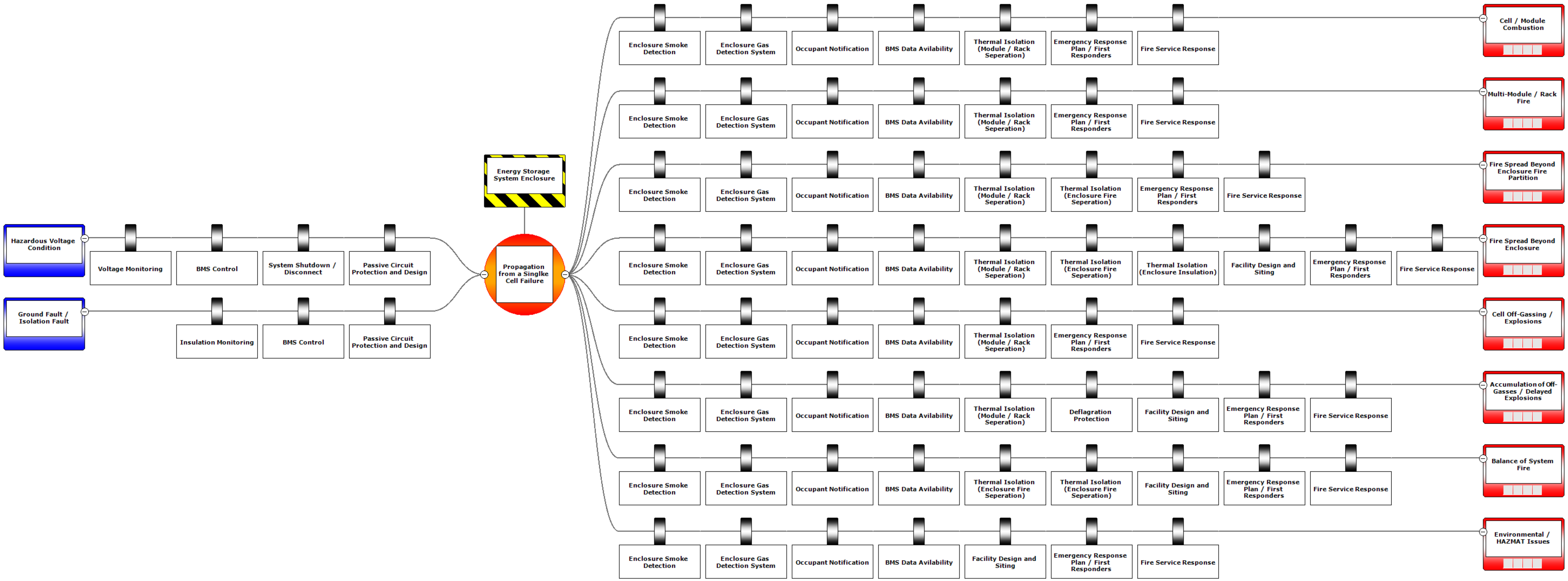

Figure E-4 – Electrical Failure Threat Pathways

APPENDIX F – UL 9540A FIRE TEST RESULTS

CELL TEST REPORT
ULL 9540A
Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems (AACD)

Project Number..............................:	**4790746849**
Date of issue ....:	**2023-07-07**
Total number of pages...................:	**34**
UL Report Office ....:	UL Solutions
Applicant's name...........................:	SAMSUNG SDI CO LTD
Address ....:	428-5 GONGSE-DONG GIHEUNG-GU YONGIN-SI, GYEONGGI-DO 446-577 Republic of Korea
Test specification:	4th Edition, Section 7, November 12, 2019
Standard ....:	UL 9540A, Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems
Test procedure ....:	7.1, 7.2, 7.3.1, 7.4, 7.6.1, 7.7
Non-standard test method ....:	N/A

General disclaimer:

The test results presented in this report relate only to the sample tested in the test configuration noted on the list of the attachments.

UL LLC did not select the sample(s), determine whether the sample(s) was representative of production samples, witness the production of the test sample(s), nor were we provided with information relative to the formulation or identification of component materials used in the test sample(s).

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Cell level information	
Model No ....:	CP1495L101+
Ratings (Vdc, Ah) ....:	3.68 Vdc, 145 Ah
Chemistry of test item………………:	$LiNiCoAlO_2$
Original Equipment Manufacturer (OEM):	SAMSUNG SDI CO LTD
Branding Manufacturer (if not OEM):	N/A
Was the cell certified? …………………………..:	Yes
Standard test item certified to …………..:	UL 1973 (File Number: MH64496)
Organization that certified test item …….:	UL
Average cell surface temperature at gas venting, °C:	166
Average surface temperature at thermal runaway, °C:	178
Gas Volume (L):	423
Lower flammability limit (LFL), % volume in air at the ambient temperature	8.04
Lower flammability limit (LFL), % volume in air at the venting temperature	6.74
Burning velocity (S_u) cm/s:	86.40
Maximum pressure (P_{max}) psig:	105.3

Cell Gas composition

Gas	Measured %
Hydrogen	32.7 %
Carbon monoxide	40.9 %
Methane	15.43 %
Ethylene	0.56 %
Ethane	1.06 %
Carbon dioxide	9.2 %
Propene (Propylene)	0.04 %
Propane	0.03 %
C4 Total	0.05 %
C5 Total	0.01 %
Benzene	0.06 %
Total	**100 %**

Cell failure test method performed (summary of method and test clause):

- ☒ External heating using thin film with 4°C to 7°C thermal ramp.
- ☐ Nail Penetration
- ☐ Overcharge
- ☐ External short circuit (***X*** Ω *external resistance*)
- ☐ Flow Battery with 2 active electrolyte methods
- ☐ Flow Battery with 1 active electrolyte methods
- ☐ Others

Description of method used to fail cells if other than external thin film heater with thermal ramp, : **N/A**		
Summary of testing:		
~~**Performance Criteria in accordance with Clause 7.7 and Figure 1.1:**~~ ~~[ ] Thermal runaway was not induced in the cell; and~~ ~~[ ] The cell vent gas did not present a flammability hazard when mixed with any volume of air, as determined in accordance with ASTM E918 at both ambient and vent temperatures.~~		
Necessity for a module level test		
[X] The performance criteria of the cell level test as indicated in 7.7 of UL 9540A 4th edition has not been met, therefore a module level testing in accordance with UL 9540A will need to be conducted on a complete module employing this cell. **[ ]** The performance criteria of the module level tests as indicated in 7.7 of UL 9540A 4th edition has been met, therefore a module level testing in accordance with UL 9540A need not be conducted.		
Testing Laboratory information		
Testing Laboratory and testing location(s):		
Testing Laboratory:	SAMSUNG SDI CO LTD	
Testing location/ address .... :	Samsung Sdi Samnam Myeon Ulju Gun Ulsan 689-701 Republic of Korea	
Tested by (name, signature)....................... :	YongHee Yun	
Witnessed by (for 3rd Party Lab Test Location) (name, signature) .... :	BeomSeok Hong	
Project Handler (name, signature)............. :	BeomSeok Hong	
Reviewer (name, signature) …………….:	Sean Yang	
Gas Analysis Testing Laboratory:		
Burning velocity Testing location/ address.. :	UL Solutions / 333 Pfingsten Road Northbrook, IL 60062 USA	
Lower Flammability Limit and Explosion Severity Testing location/ address... :	UL Solutions / 333 Pfingsten Road Northbrook, IL 60062 USA	
Project Handler (name, signature)............ :	Robert Hollis	
Reviewer (name, signature) …………….:	Chris Jones	

List of Attachments (including a total number of pages in each attachment):
Attachment A: Cell Conditioning (Charge/discharge) Profiles - (*Pages **16** through **20***)
Attachment B: Cell Instrumentation Photos - (*Pages **21** through **22***)
Attachment C: Cell Temperature Profiles during testing - (*Pages **23** through **25***)
Attachment D: Cell Testing Photos - (*Pages **26** through **30***)
Attachment E: Cell Test Datasheets - (*Pages **31** through **31***)
Attachment F: Cell vent gas test chamber photo and profile of chamber gas analysis (O_2 and Pressure) – (*Pages **32** through **33***)
Attachment G: Certification Requirement decisions - (*Pages* **34** *through* **34)**

Photo of cell:

<Top>

<Overall>

Test Item Charge/Discharge Specifications:	
• **Charge current, A:**	47.3
• **Standard full charge voltage, Vdc:**	4.15
• **Charge temperature range, °C:**	0 to 60
• **End of charge current, A:**	29
• **Discharge current, A:**	47.3
• **End of discharge voltage, Vdc:**	2.7
• **Discharge temperature range, °C:**	0 to 60

Test item particulars ....:	
Possible test case verdicts:	
- test case does not apply to the test object...........:	N/A
- test object does meet the requirement ....:	P (Pass)
- test object does not meet the requirement...........:	F (Fail)
- test object was completed per the requirement...:	C(Complete)
- test object was completed with modification……:	M(Modification)
Testing..:	
Date of receipt of test item ....:	2023-02-21
Date (s) of performance of tests ....:	2023-02-21 to 2023-02-22, 2023-03-27 to 2023-03-28

General remarks:

"(See Enclosure #)" refers to additional information appended to the report.
"(See appended table)" refers to a table appended to the report.

Throughout this report a point is used as the decimal separator.

Manufacturer's Declaration of samples submitted for test:	
The applicant for this report includes samples from more than one factory location and a declaration from the Manufacturer stating that the sample(s) submitted for evaluation is (are) representative of the products from each factory has been provided ....:	☒ **Yes** ☐ **Not applicable**
Name and address of factory (ies) .... :	1. SAMSUNG SDI CO LTD 163 Bangudae-ro, Ulju-gun,Ulsan, Ulsan, 689-701, Republic of Korea 2. Samsung SDI-ARN(XI'AN) Power Battery Co Ltd No 2655 BiYuan 3rd road, Xi'an, Shaanxi Sheng, 710399,China

General product information and other remarks:

CP1495L101+ is a rechargeable li-ion battery cell manufactured by SAMSUNG SDI CO LTD. The cell is rated for 3.68 Vdc, 145 Ah. See table Critical components information for details.
The suffix "+" is a placeholder to identify the customer of Samsung SDI, who purchases the cell tested in this report. Samsung SDI confirmed that cells with different suffixes will have the same cell design. The sample tested was CP145L101A.

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

5.0	**CONSTRUCTION**		**Verdict**
5.1. 5.4	**Cell/Stack Construction**		—
5.1.1, 5.4.1	Generic Chemistry:	Li-ion ($LiNiCoAlO_2$)	—
	Electrolyte Chemistry:		—
	Flow Battery Electrolyte No. 1 Chemistry:	N/A	—
	Max volume of system electrolyte No. 1, L:	N/A	—
	Flow Battery Electrolyte No. 2 Chemistry:	N/A	—
	Max volume of system electrolyte No. 2, L:	N/A	—
	Separator Melt Temperature, °C:		—
	Format: Cylindrical /Prismatic /Pouch Flow Battery Stack	Prismatic	—
	Overall Dimensions, mm		—
	Cell Weight, g		—
5.1.2	Cell Certification:	Certified	—
	Standard Used for Cell Certification:	UL 1973 , Appendix E File Number: MH64496	—
	Organization that Certified Cell:	UL Solutions	—
5.1.1, 5.4.1	Cell/Stack Ratings: • Nominal Voltage, Vdc •Nominal Capacity, Ah	3.68 Vdc 145 Ah	— —
5.4.1	Flow Battery: No. of Cells per Stack:	N/A	—
	Flow battery system manufacturer:	N/A	—
	Flow battery system model:	N/A	—
	Flow battery system ratings, Vdc, Ah:	N/A	—
5.4.2	Flow battery system certified to UL 1973:	N/A	—
	Organization that certified flow battery system:	N/A	—
6.0	**PERFORMANCE**		**Verdict**
6.1	**General**		
7.2	**Samples**		
7.2.1	Samples conditioned through charge discharge cycling a minimum of 2 cycles.	See Attachment A for profiles See Table 1 for specifications	C
7.2.2	100% SOC and stabilize from 1h to 8 h before testing		

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

7.2.3	Pouch Cells constrained per end use during testing.		C
7.3	**Determination of thermal runaway methodology**		
7.3.1	**General**		
7.3.1.1	Ambient indoor laboratory conditions: 25 ±5°C (77 ±9°F) ≤50 ±25% RH at the initiation of the test.	See Attachment C and E	M
7.3.1.2	Heat the cell to thermal runaway by externally applied flexible film heaters	See Attachment B	C
	Heater Dimension	98.85 mm x 157 mm	
	A surface heating rate of 4° C (7.2° F) to 7° C (12.6° F) per minute was applied to the cell.	See Attachment C, D, and E See Table 4.	C
	Maximum surface end point temperature, °C	In accordance with Certification Requirement Decision dated on 2020-05-20, no holding temperature used for the test. Please refer to Attachment G.	M
	The following method(s) was employed to cause thermal runaway: ☐ Mechanical (e.g. nail penetration); ☐ Electrical stress in the form of overcharging, ☐ Electrical stress in the form of over discharging ☐ Electrical stress in the form of external short-circuiting ☐ Use of alternate heating sources (e.g. oven). ☐ Other (explain)	Only external heating using film heaters was used.	N/A
7.3.1.3	Detail of test method when using another cell abuse method to initiate thermal runaway	See Attachment E	N/A
7.3.1.4	Monobloc batteries such as a lead acid battery		N/A
7.3.1.5	Estimated surface temperature at which internal short circuiting within the cell will occur that could lead to a thermal runaway condition.		N/A
7.3.1.6	The cell was heated until thermal runaway has occurred.	Refer to Attachment C	C
	Another external heating method was used to cause cell thermal runaway		N/A
7.3.1.7	The cell's exterior surface temperature was measured	See Attachment B	C
7.3.1.8	The temperature at which the cell case vents due to internal pressure rise was documented.	See Table 3 and 4 See Attachment C, D and E	C

Clause	Requirement + Test	Result - Remark	Verdict
7.3.1.9	The temperature at the onset of thermal runaway was documented.	See Table 3 and 4 See Attachment C, D and E	C
	If cell venting occurs first, the cell was heated continuously until thermal runaway occurs.	See Attachment C	C
7.3.1.10	When using methods other than the heater method, the stresses were applied to the cell until thermal runaway occurs.		N/A
7.3.1.11	3 additional samples were tested using the same method and exhibited thermal runaway	See Table 3, 4 and 5 See Attachment C, D and E	C
7.4	**Cell vent gas composition test**		
7.4.1	Cell vent gas was generated and captured by forcing a cell into thermal runaway with the methodology developed in 7.3, inside a pressure vessel	Size of pressure vessel used: 82 L Refer to Attachment F	C
	The test was initiated with an initial condition of atmospheric pressure and less than 1% oxygen by volume.	Refer to Attachment F Atmospheric pressure (psig): 0.96	C
		Oxygen concentration measured (% volume): < 0.55	
		Inert gas used: Nitrogen	
7.4.2	Cell vent gas composition was determined using Gas Chromatography (GC)	Refer to Table 8 Refer to Attachment F	C
	Hydrogen gas was measured	Refer to Table 8	C
	The initial atmospheric conditions prior to testing were noted.	Refer to Table 3 Refer to attachment C and F	C
7.4.3	The lower flammability limit of the cell vent gas was determined on samples of the synthetically replicated gas mixture in accordance with ASTM E918, testing at both ambient and cell vent temperatures.	Refer to Table 9 and 10	C
7.4.4	The gas burning velocity of the synthetically replicated cell vent gas was determined in accordance with the Method of Test for Burning Velocity Measurement of Flammable Gases Annex in ISO 817.	Refer to Table 9 and 10	C
7.4.5	P_{max} of the synthetically replicated cell vent gas was determined in accordance with EN 15967.	Refer to Table 9 and 10	C
7.6	**Cell Level Test Report Information**		

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict
7.6.1	Minimum information provided in the report for items a) through m)		C
7.6.2	Minimum information of items a) through k) was provided in the report for flow battery		N/A
7.7	**Performance – cell level test**		
7.7.1	a) Thermal runaway cannot be induced in the cell; and	Thermal runaway was achieved in all five cells by external heat applied by external heating Refer to attachment C and D.	F
	b) The cell vent gas does not present a flammability hazard when mixed with any volume of air, at both ambient and vent temperatures.	Cell vent gas found to be flammable. Refer to table 8.	F

Table 1 – Specified conditioning parameters			
Charging:		Discharging	
Current (CC), A	47.3	Current (CC), A	47.3
Standard full charge voltage, Vdc	4.15	Voltage at start of discharge, Vdc	4.15
End of charge current, A	29	End of discharge voltage, Vdc	2.7
Charging Test Ambient, °C	0 to 60	Discharging Test Ambient, °C	0 to 60
Refer to Attachment A for charge/discharge profiles for each cell.			

Table 2 – Charge completion and cell test initiation times		
Cell Test Number	**Charge Completion Date and Time**	**Cell test Date and Time**
1	2023-02-21, 08:29:14	2023-02-21, 11:46:21
2	2023-02-21, 08:31:03	2023-02-21, 14:39:22
3	2023-02-21, 08:30:05	2023-02-21, 16:36:00
4	2023-02-22, 07:10:18	2023-02-22, 09:59:16
5	2023-03-28, 08:19:16	2023-03-28, 13:12:52

Table 3 - Test Initiation Details					
	Cell Test 1	**Cell Test 2**	**Cell Test 3**	**Cell Test 4**	**Cell Test 5**
Test Date	2023-02-21	2023-02-21	2023-02-21	2023-02-22	2023-03-28
Test Start Time	11:46:21	14:39:22	16:36:00	09:59:16	13:12:52
Initial Lab Temperature	20.6	20.0	20.4	21.5	21.3
Initial Relative Humidity	27.1	51.4	41.0	38.5	36.0

Table 4 - Thermal Runaway Results					
	Cell Test 1	**Cell Test 2**	**Cell Test 3**	**Cell Test 4**	**Cell Test 5**
OCV at start of test, Vdc	4.10	4.11	4.10	4.10	4.12
Average Heating Rate, °C/min	5.51	5.59	5.66	5.58	5.58
Venting Time after the test start (hh:mm:ss)	00:39:54	00:39:13	00:39:40	00:38:40	00:38:36
Venting Temperature, °C	163	163	166	168	164
Thermal Runaway Time after the test start (hh:mm:ss)	00:43:53	00:42:56	00:39:41	00:42:21	00:42:00
Thermal Runaway Temperature, °C	177	176	166	184	186
Refer to Attachment C for surface temperature profiles during testing See attachment E for datasheets Temperatures indicated above are taken from the thermocouple located on the side of the cell that is not covered by the heater.					

Table 5 – Average Vent and Thermal Runaway Temperatures	
Average of Cell Vent Temperatures, °C	166
Average of Cell Thermal Runaway Temperatures, °C	178
#Averages of cell tests other than the gas analysis test (Cell test 5)	

Table 6 – Parameters Flow Battery	
Single Electrolyte Flow Battery:	N/A
• Volume of Electrolyte Used for Flammability Determination, L	N/A
• Percentage of metal particles representative of fully charged electrolyte (% per volume of test electrolyte)	N/A
• Maximum volume of electrolyte for planned system, L	N/A
Two Electrolyte Flow Battery:	N/A
• Volume of Electrolyte No. 1 Used for Flammability Determination, L	N/A
• Volume of Electrolyte No. 2 Used for Flammability Determination, L	N/A
• Max. volume of electrolyte No. 1 in system, L	N/A
• Max. volume of electrolyte No. 2 in system, L	N/A
Two Electrolyte Flow Battery: Method for charging electrolytes to activate them	N/A
Electrolyte viscosity at 25°C (77°F), m^2/sec of Electrolyte 1	N/A
Electrolyte viscosity at 25°C (77°F), m^2/sec of Electrolyte 2	N/A
ASTM Method to Determine Flash Point:	N/A
Abnormal test methods used for single electrolyte flow battery:	N/A
Abnormal test methods used for two electrolyte flow battery:	N/A
Representative flow battery system used for abnormal testing:	N/A
• Manufacturer:	N/A
• Model No.:	N/A
• Electrical Ratings, Vdc, Ah	N/A
• Total Electrolyte No. 1 Contained, L	N/A
• Total Electrolyte No. 2 Contained, L	N/A

Table 7 – Results of Flammability Testing of Flow Battery Electrolyte	
Flash Point Determined:	N/A
Flash Point Temperature of electrolyte 1, °C:	N/A
Test temperature of electrolyte 1,° C:	N/A
Flash point temperature of electrolyte 2, °C:	N/A
Test temperature of electrolyte 2, °C:	N/A
Two electrolyte flow battery: Maximum temperature measured when mixing electrolytes, °C:	N/A
Maximum electrolyte temperature measured during abnormal testing, °C: • Short circuit test from UL1973:	N/A
• Overcharge test from UL 1973:	N/A

Table 8 – Results of Gas Analysis (Excluding O_2 and N_2)			
Gas		**Measured %**	**Component LFL[1]**
Hydrogen	**H2**	32.70 %	4.0 %
Carbon monoxide	**CO**	40.90 %	10.9 %
Carbon dioxide	**CO2**	9.20 %	--
Methane	**CH4**	15.43 %	4.4 %
Ethane	**C2H6**	1.06 %	2.4 %
Ethylene	**C2H4**	0.56 %	2.4 %
Propane	**C3H8**	0.03 %	1.7 %
Propene (Propylene)	**C3H6**	0.04 %	2.0 %
C4 Total[2]	**--**	0.05 %	--
C5 Total	**--**	0.01 %	--
Benzene	**C6H6**	0.06 %	1.2 %
Total	**--**	100 %	--

Table 9 – Gas composition excluding the constituents with boiling points higher than 60°C[3]			
Gas		**Measured %**	**Component LFL**
Hydrogen	**H2**	32.71	4.0
Carbon monoxide	**CO**	40.91	10.9
Carbon dioxide	**CO2**	9.20	--
Methane	**CH4**	15.43	4.4
Ethane	**C2H6**	1.06	2.4
Ethylene	**C2H4**	0.56	2.4
Propane	**C3H8**	0.03	1.7
Propene (Propylene)	**C3H6**	0.04	2.0
C4 Total[2]	**--**	0.05	--
C5 Total	**--**	0.01	--
Total	**--**	100.00	--

[1] Extracted LFL values from ISO 10156-2017

[2] Average of n-Butane, 1-Butene, cis-Butene, trans-Butene

[3] The constituents with a higher boiling point were excluded for the flammability characteristic analysis as these components will turn into a liquid state at room temperature and will not release from the gas bottle as a homogenous mixture.

Table 10 – Properties of Vent Gas Analysis	
Lower Flammability limit at Ambient Temperature, 25°C (% vol in air)	8.04
Lower Flammability limit at Vent Temperature, [166 °C] (% vol in air)	6.74
Flow Batteries, LFL scaled to maximum electrolyte volume of system, 25°C (% vol in air)	N/A
Flow Batteries, LFL scaled to maximum electrolyte volume of system, [°C] (% vol in air)	N/A
Burning Velocity Measurement, S_u cm/sec	86.40
Maximum Pressure P_{max}, psig	105.3

	TABLE: Critical components information				
Object / part No.	**Manufacturer/ trademark**	**Type / model**	**Technical data**	**Standard**	**Mark(s) of conformity**
Cell Model	SAMSUNG SDI CO LTD	CP1495L101+	3.68 Vdc, 145 Ah	UL 1973 , Appendix E UL 9540A	UL (MH64496) Tested within appliance
Cell case	--	--	Al, (0.6 ~ 1.2) mm	--	--
Electrolyte	--	--	LiPF6 salt, EC/EMC/DMC mixture	--	--
Separator	--	--	Ceramic / PE, Thickness: 16 µm	--	--
Insulation	--	--	PET, Thickness: 0.1 mm	--	--
Anode	--	--	Graphite	--	--
Cathode	--	--	NCA	--	--
Cu Foil (for Anode)	--	--	Cu, 8 µm	--	--
Al Foil (for Cathode)	--	--	Al, 12 µm	--	--
Vent or pressure release mechanism	--	--	Notch Type	--	--

~~**List of test equipment used:**~~

~~A completed list of used test equipment shall be provided in the Test Reports when a Customer's Testing Facility has been used.~~

Clause	Measurement / testing	Testing / measuring equipment / material used, (Equipment ID)	Range used	Last Calibration date	Calibration due date

Attachment A: Cell Conditioning (Charge/discharge) Profiles - (*Pages **16** through **20***)

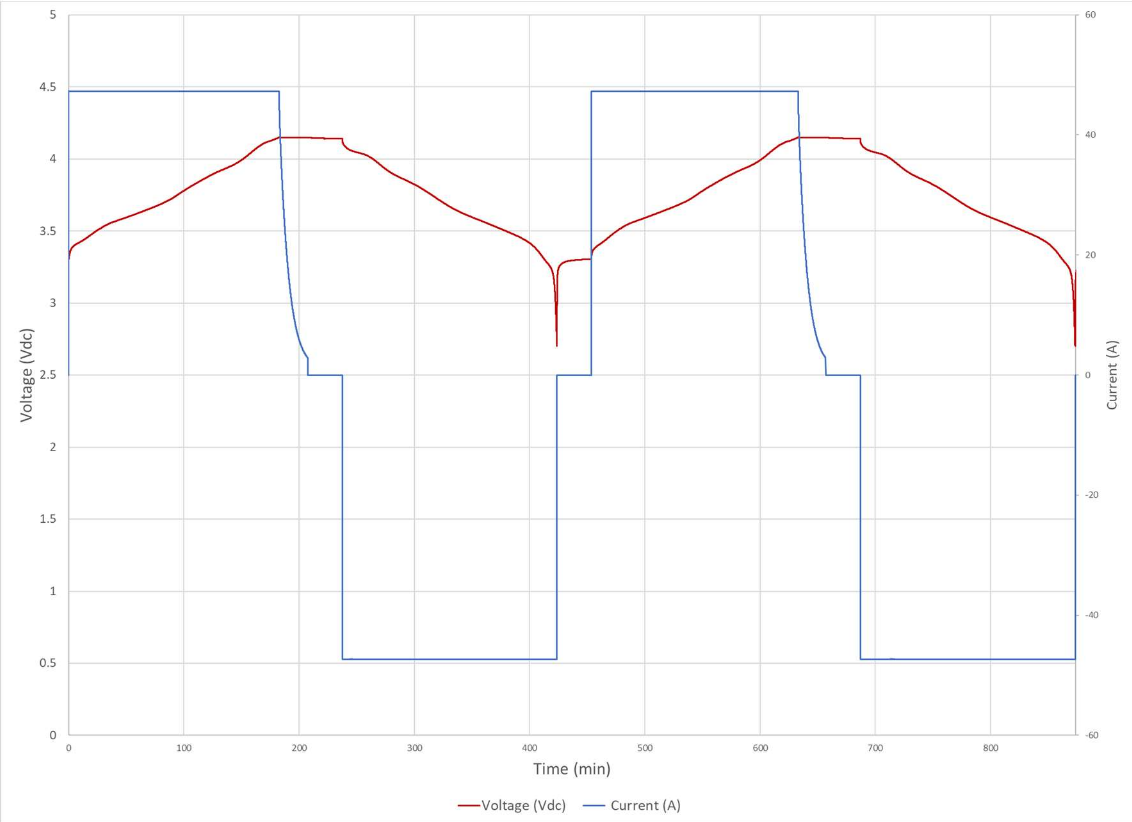


Figure A1: Sample 1 - Cell Conditioning Profile

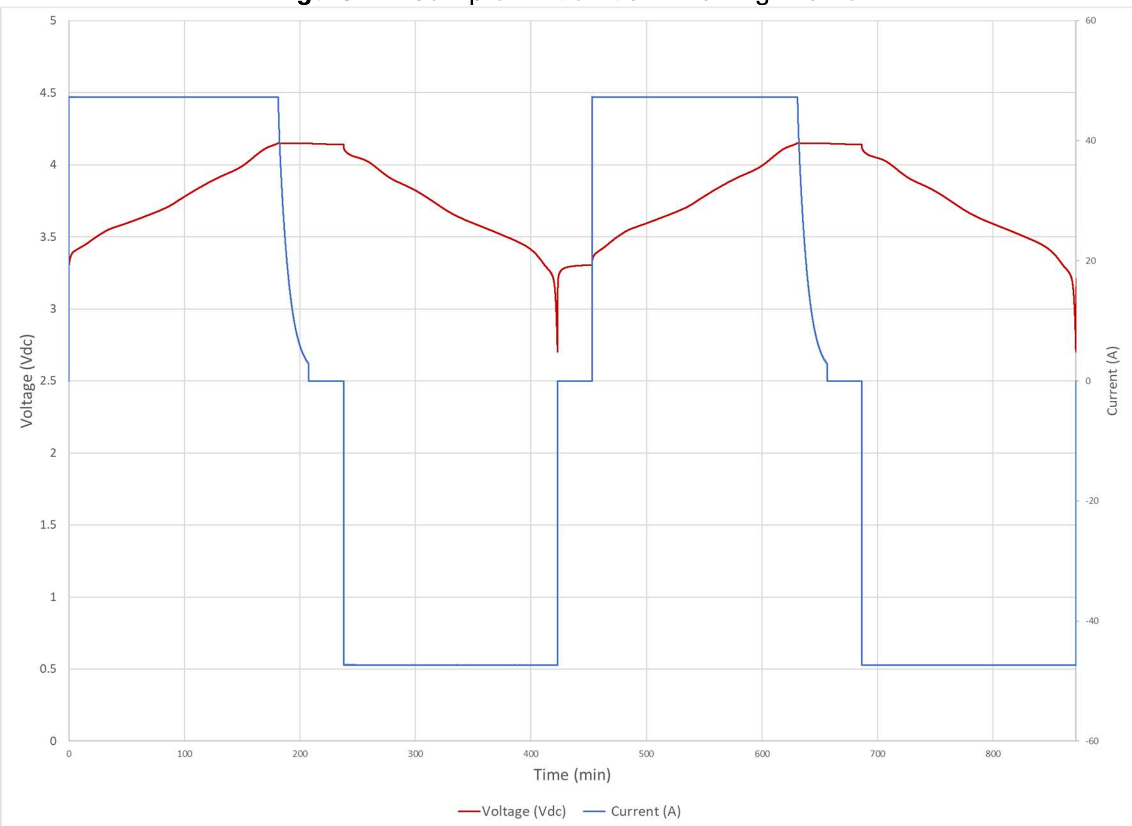


Figure A2: Sample 2 - Cell Conditioning Profile

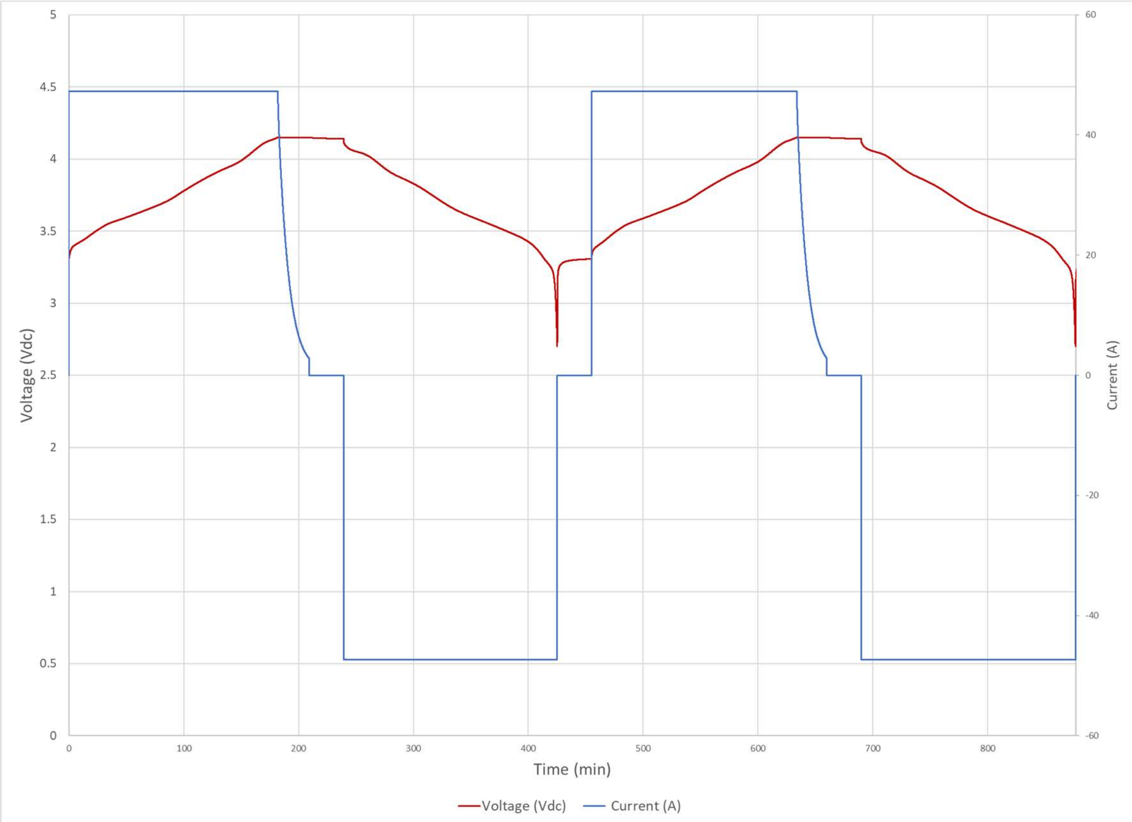


Figure A3: Sample 3 - Cell Conditioning Profile

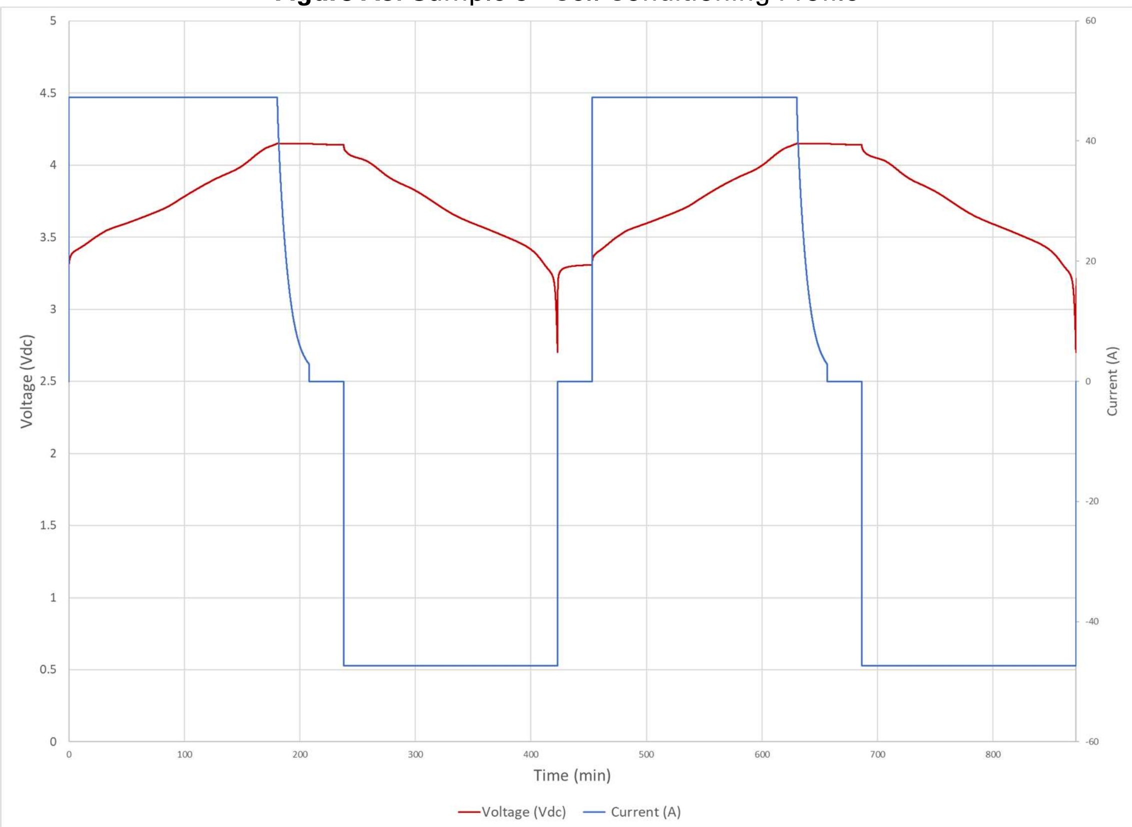


Figure A4: Sample 4 - Cell Conditioning Profile

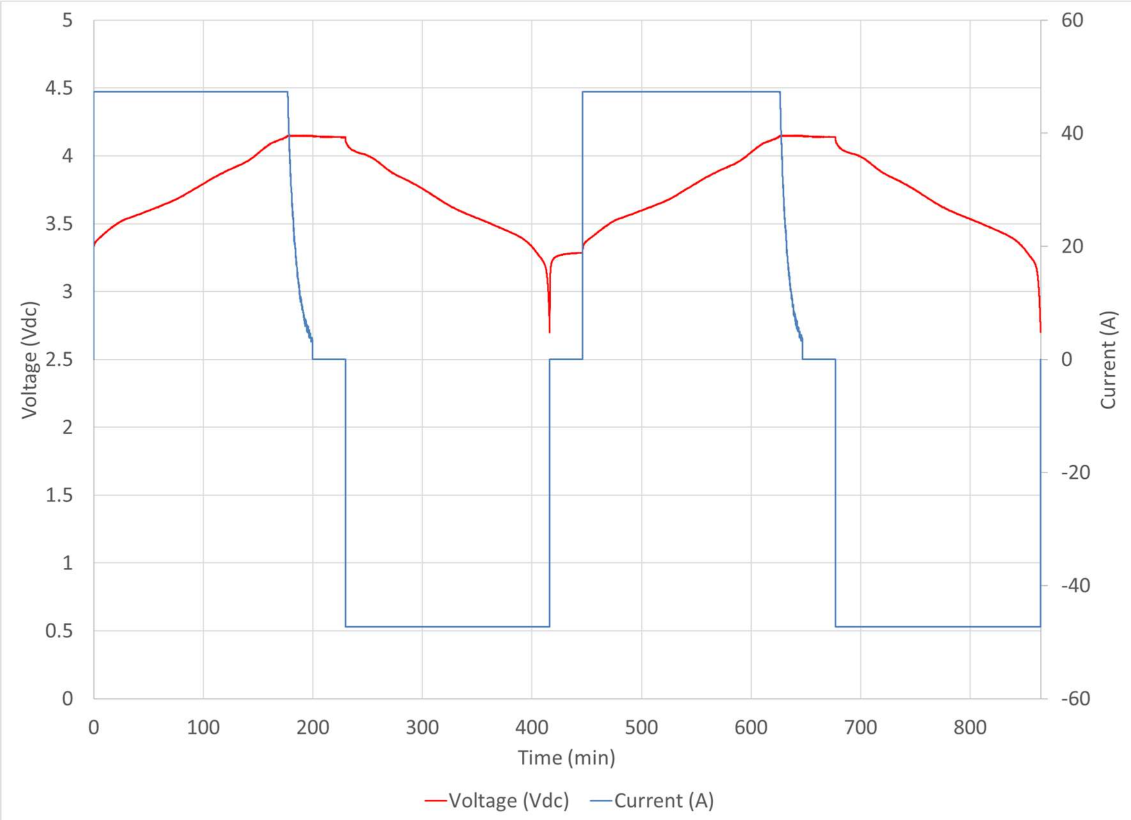


Figure A5: Sample 5 - Cell Conditioning Profile

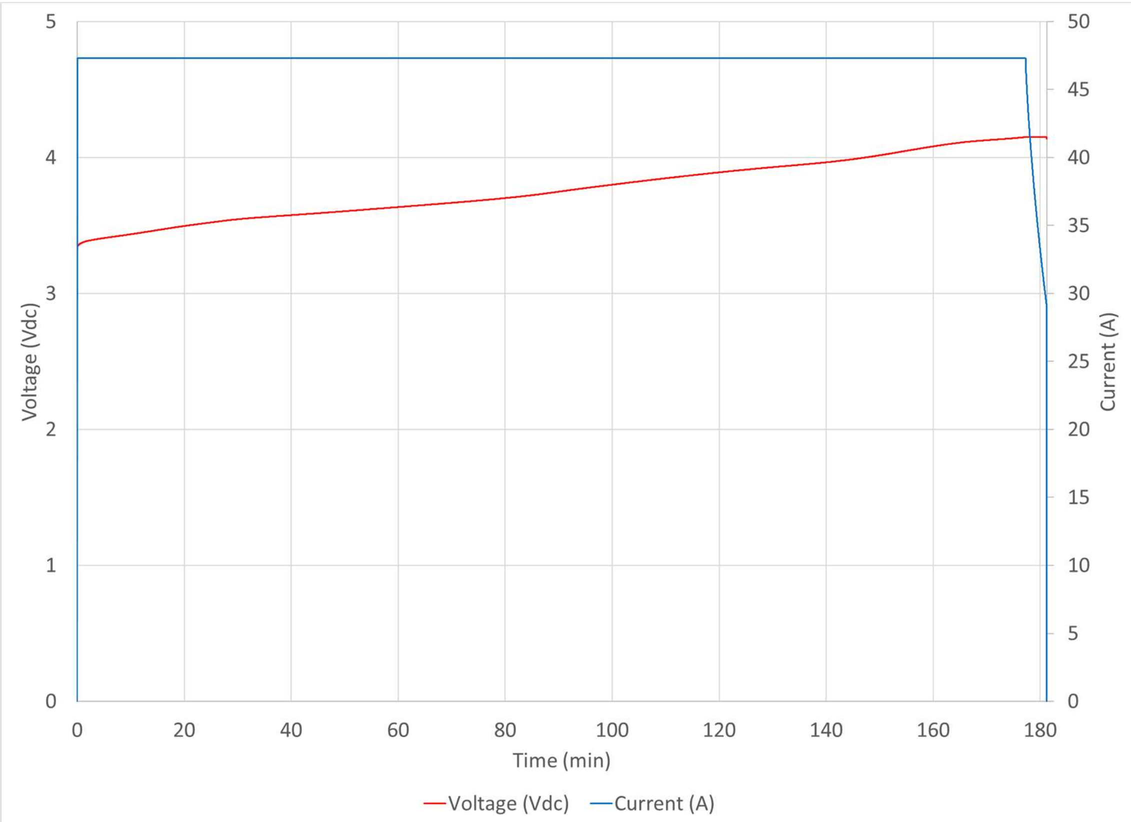


Figure A6: Sample 1 Charging and Top-off Profile

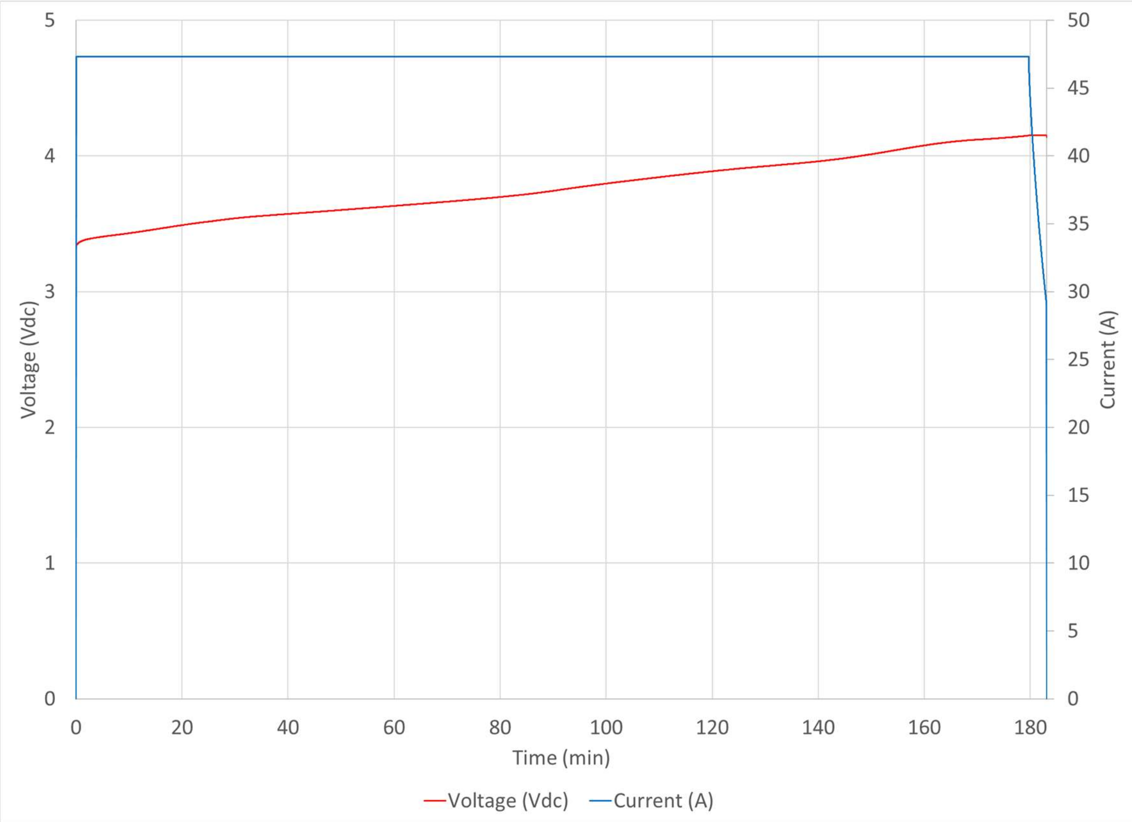


Figure A7: Sample 2 Charging and Top-off Profile

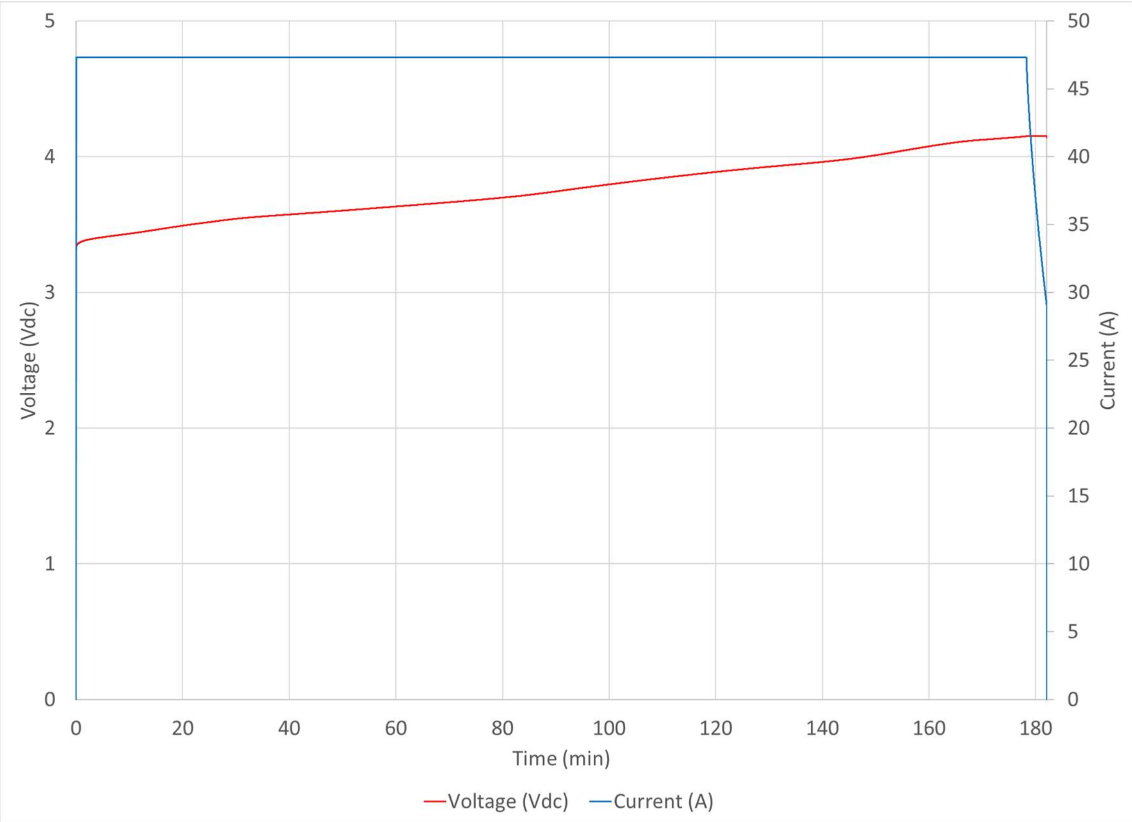


Figure A8: Sample 3 Charging and Top-off Profile

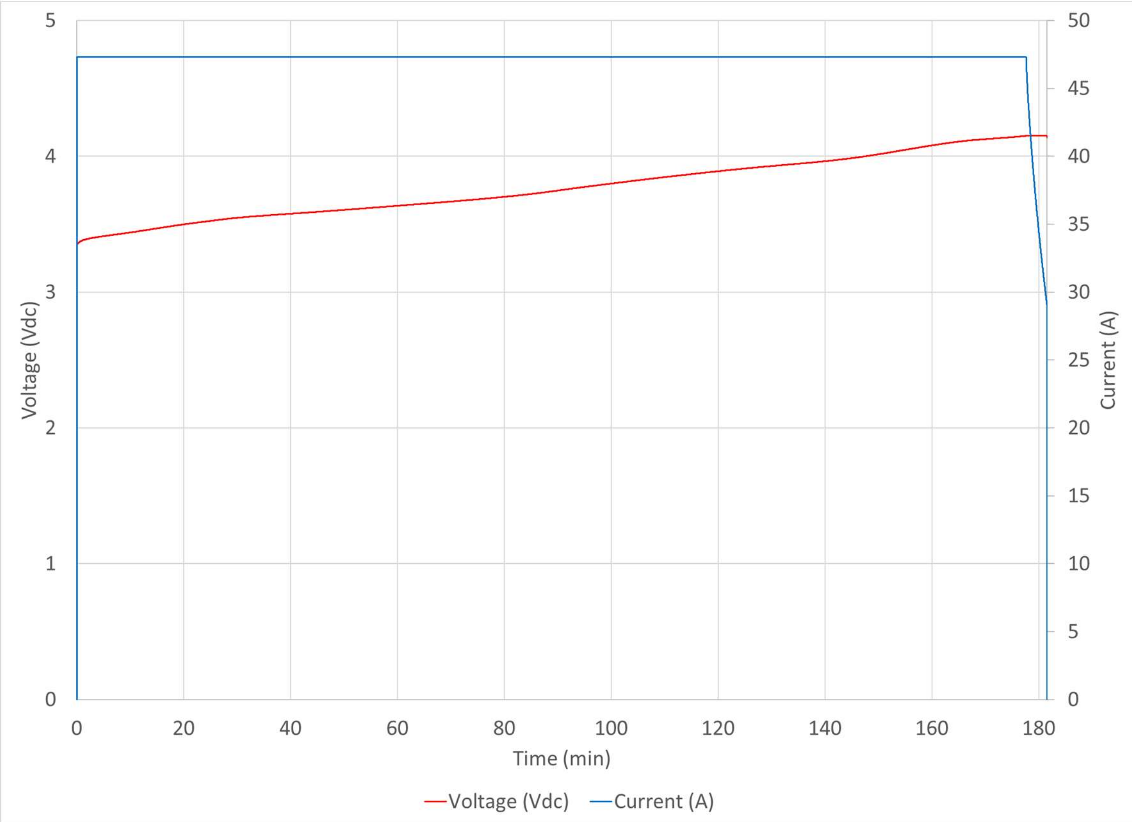


Figure A9: Sample 4 Charging and Top-off Profile

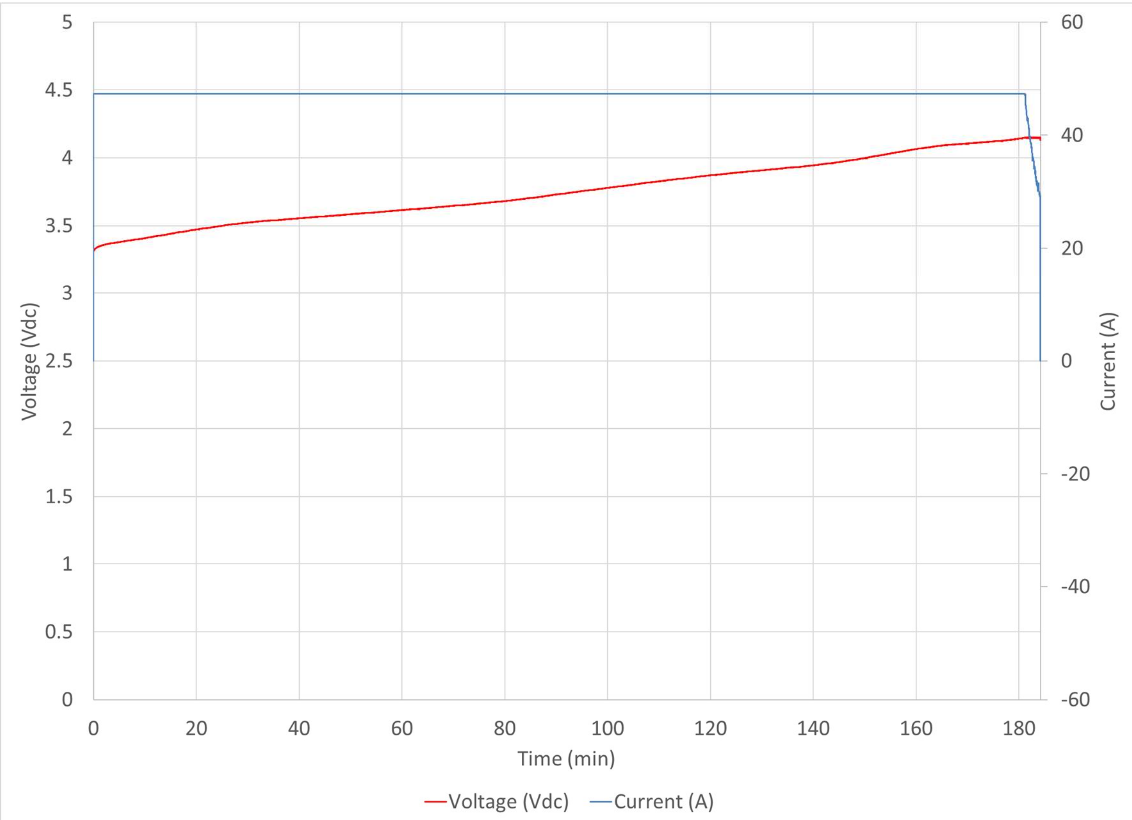
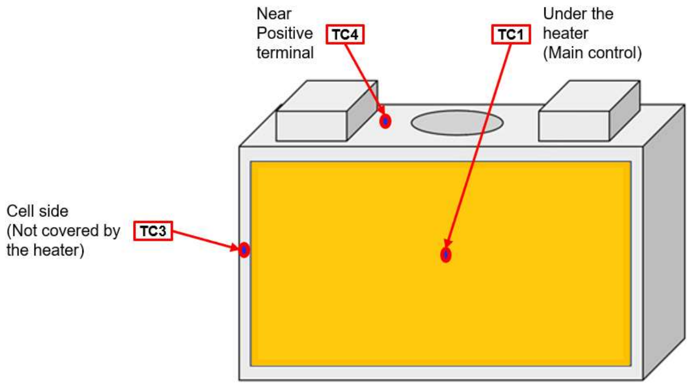


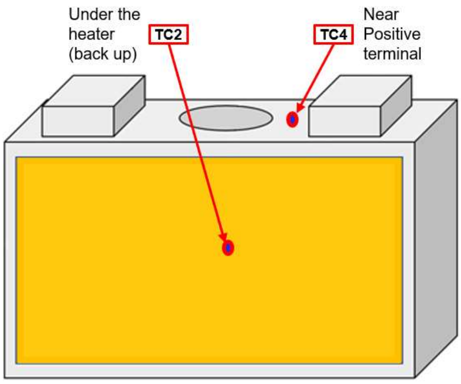
Figure A10: Sample 5 Charging and Top-off Profile

Attachment B: Cell Instrumentation Photos - (*Pages **21** through **22***)

Initiating Cell (Normal Thermal Runaway and Gas Chamber)

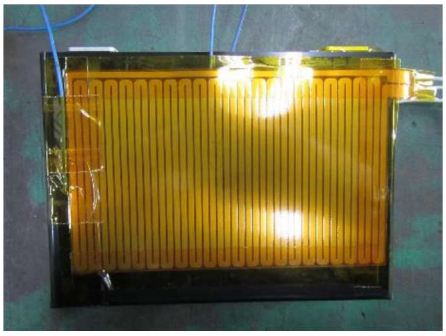
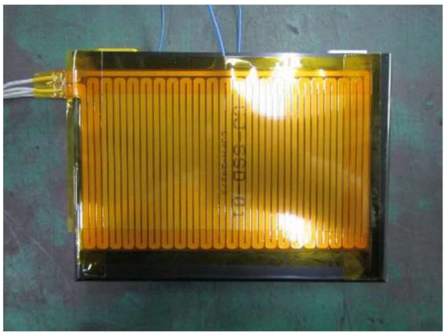
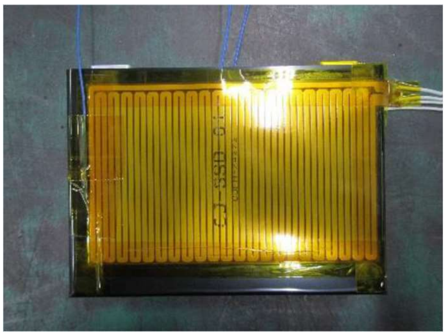
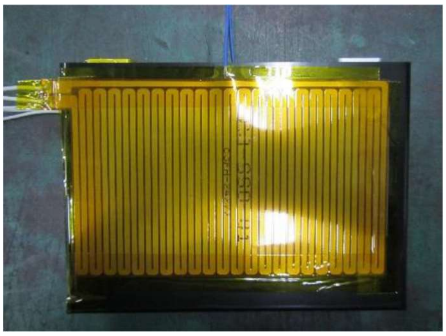
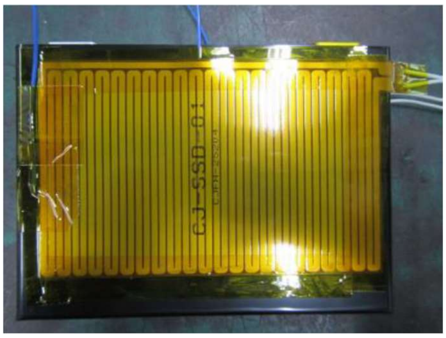
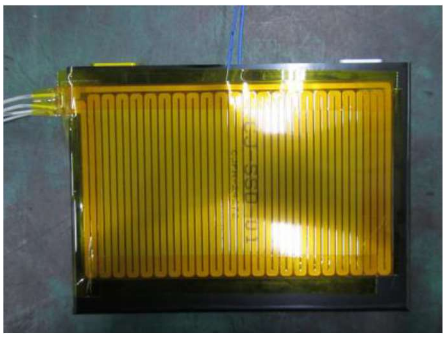
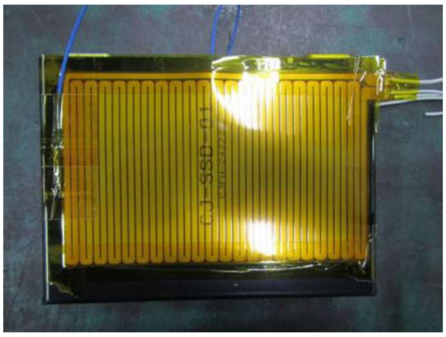
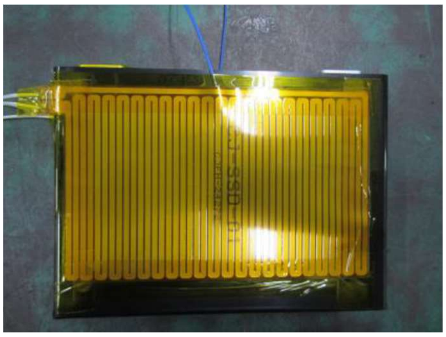
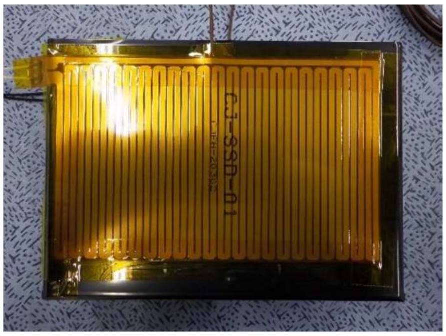


<Front>



<Back>

TC No.	Descriptions
TC1	Under the heater (Main control)
TC2	Under the heater (back up)
TC3	Cell side
TC4	Near Positive terminal

Front	Back	
		**Figure B1:** Sample No. 1
		**Figure B2:** Sample No. 2
		**Figure B3:** Sample No. 3
		**Figure B4:** Sample No. 4
		**Figure B5:** Sample No. 5

Attachment C: Cell Temperature Profiles during testing - (*Pages **23** through **25***)

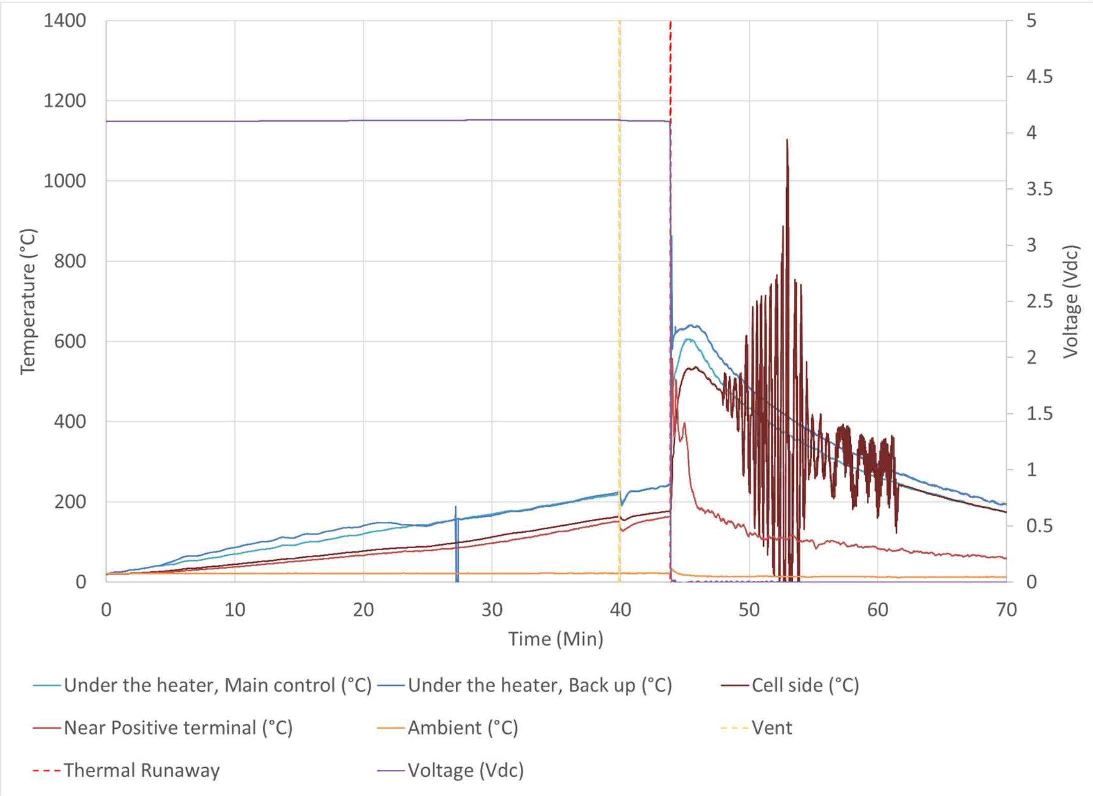


Figure C1: Sample 1 - Thermal Runaway & Vent Temperature

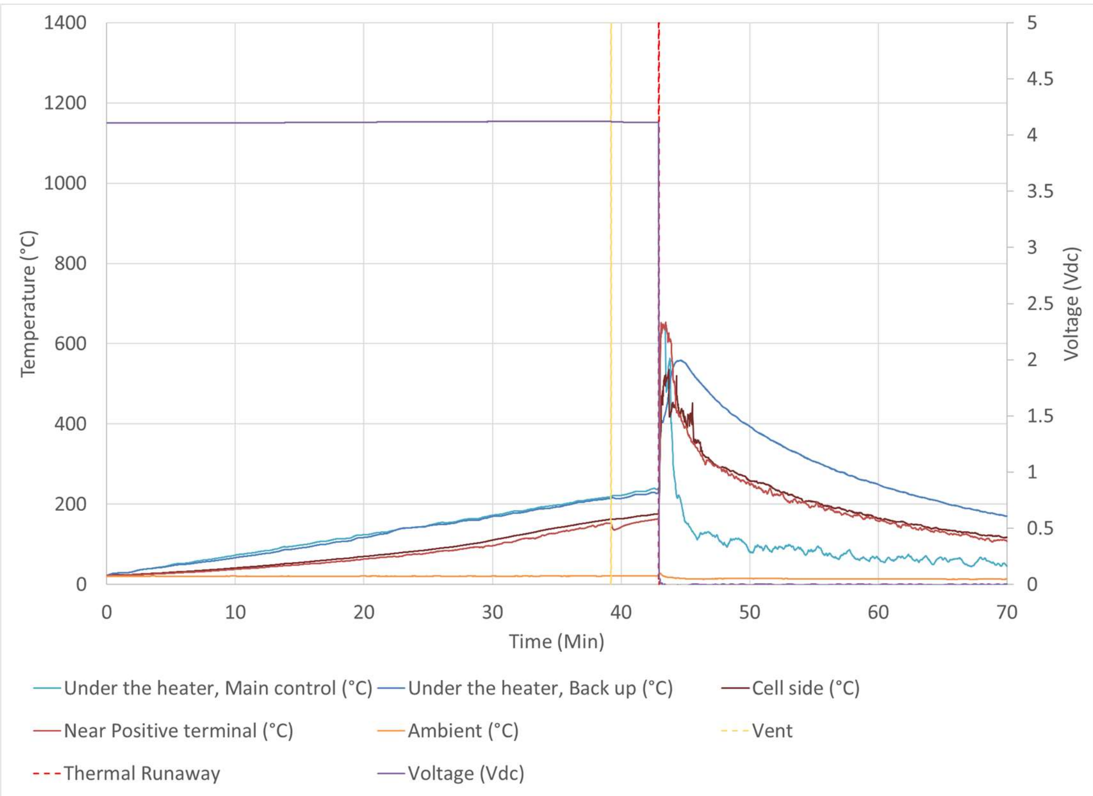


Figure C2: Sample 2 - Thermal Runaway & Vent Temperature

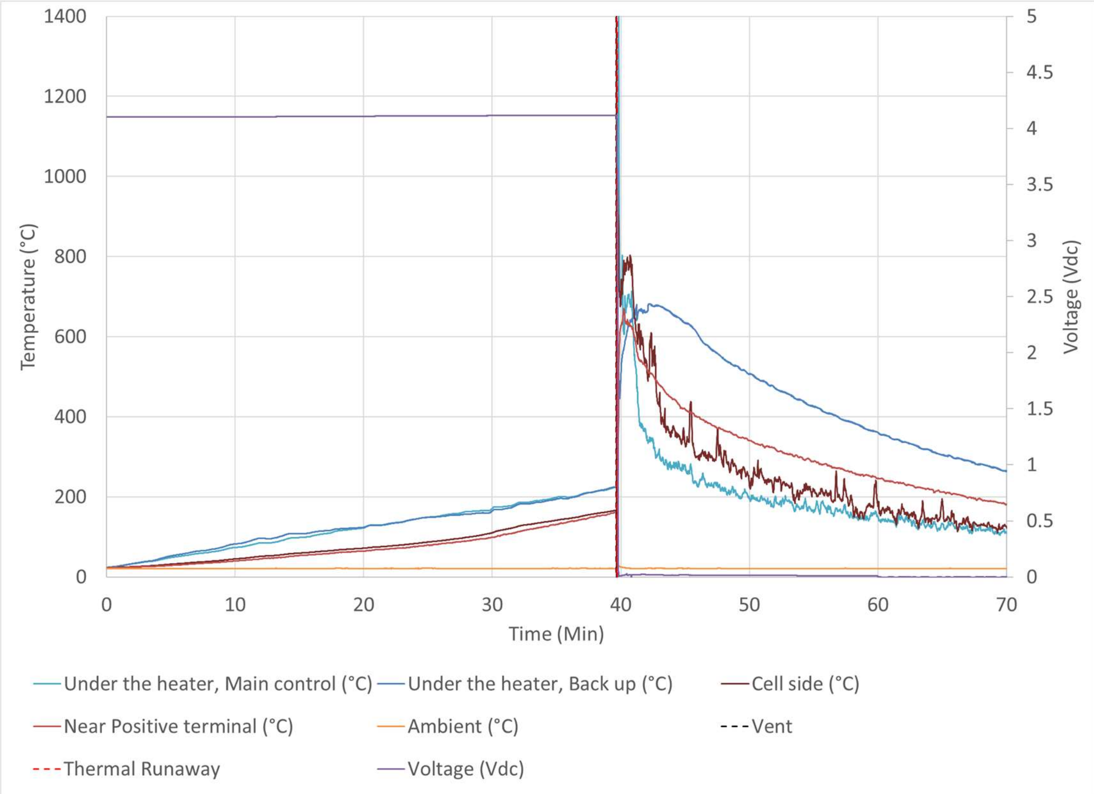


Figure C3: Sample 3 - Thermal Runaway & Vent Temperature

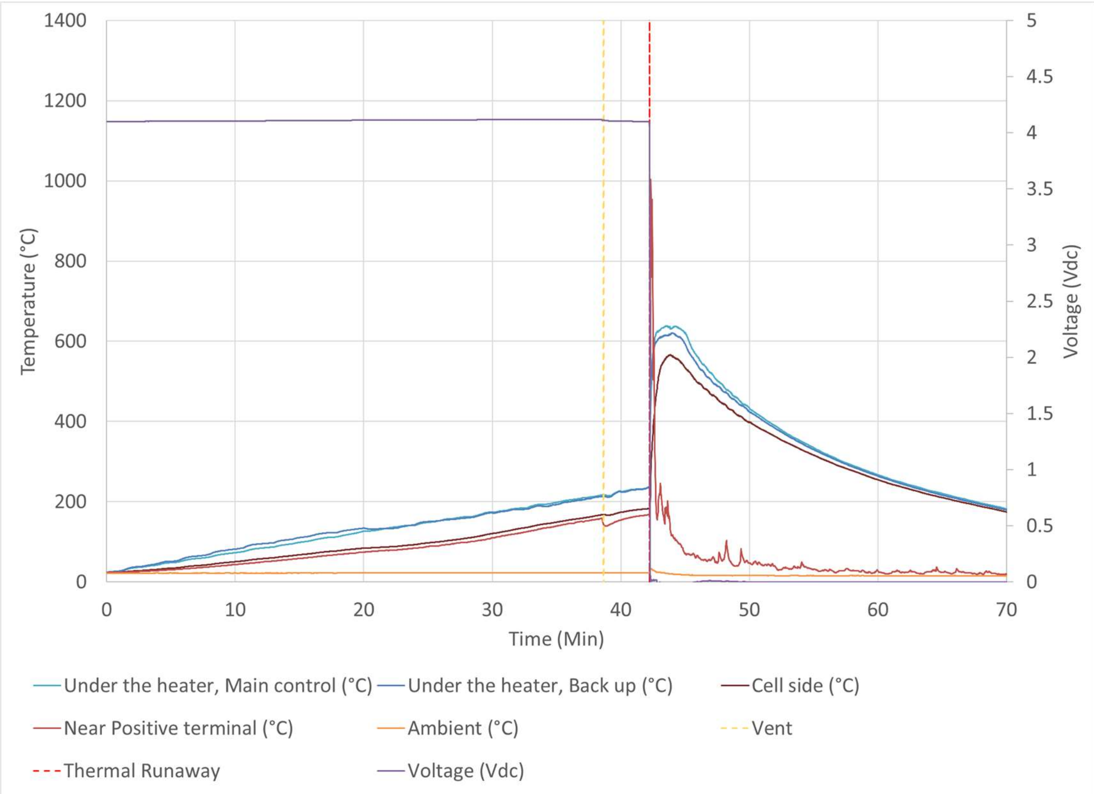


Figure C4: Sample 4 - Thermal Runaway & Vent Temperature

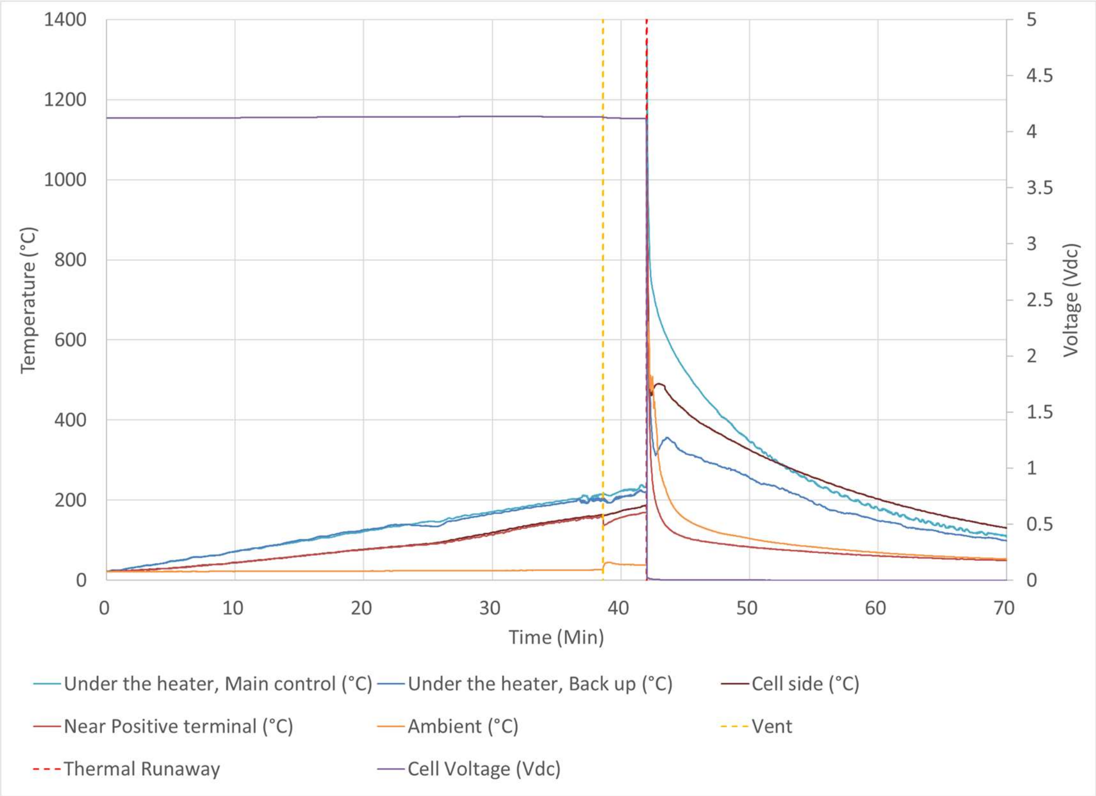
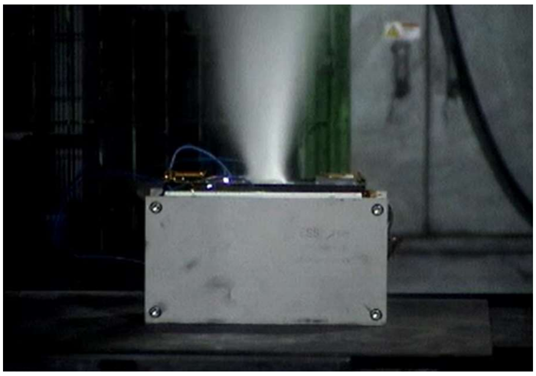
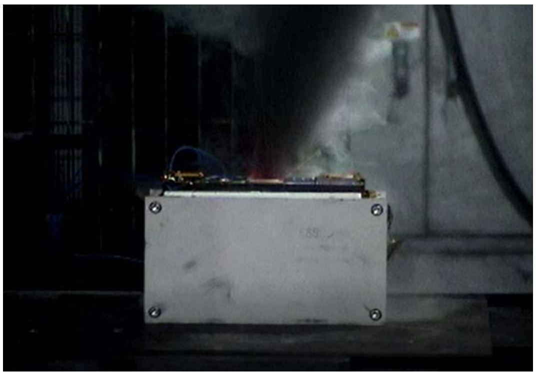
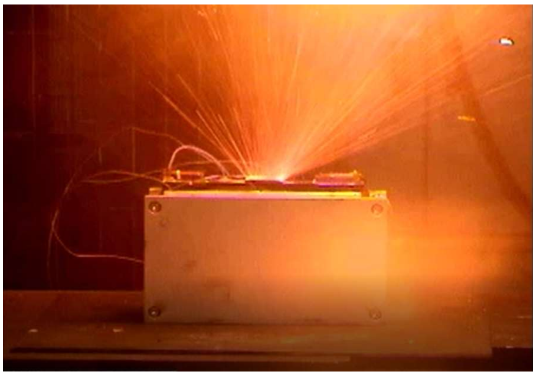


Figure C5: Sample 5 - Thermal Runaway & Vent Temperature

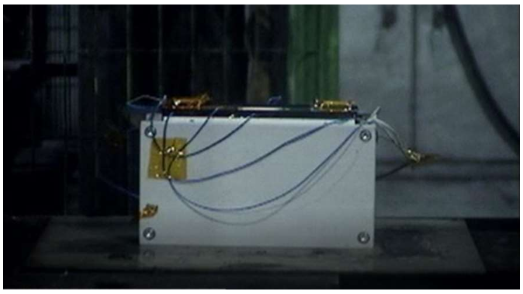
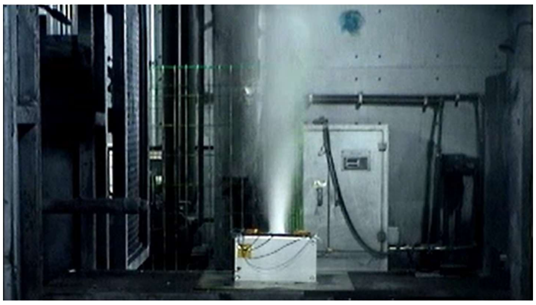
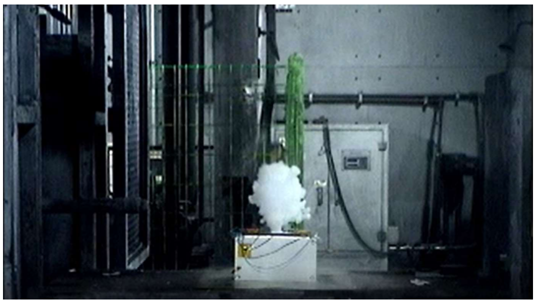
Attachment D: Cell Testing Photos - (*Pages **26** through **30***)

Cell Test 1

	
Cell 1 - Start of test (00:00:00)	Cell 1 - Venting (00:39:54)
	
Cell 1 - Immediately before thermal runaway* (00:43:54)	Cell 1 - Thermal runaway (00:43:55)
	
Cell 1 - After the end of test	

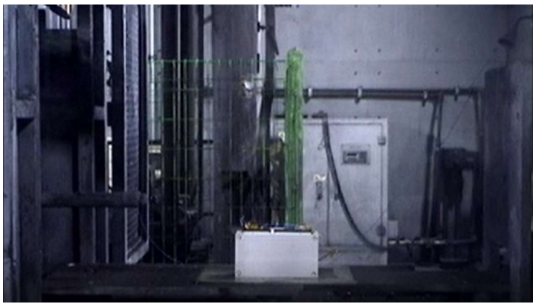
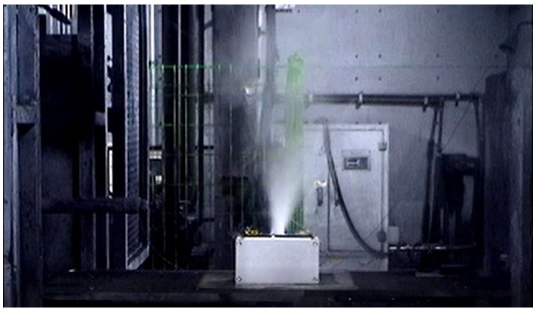
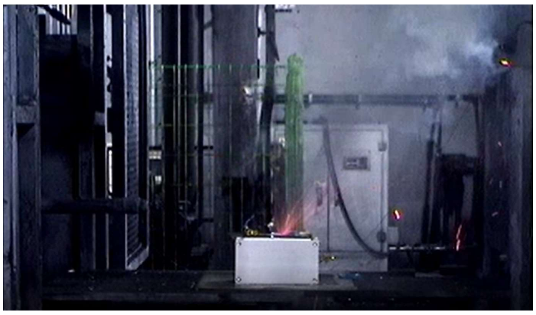
*Note: Thermal runaway was determined when the temperature of the cell surface increased in an uncontrollable manner.

Cell Test 2

	
Cell 2 - Start of test (00:00:00)	Cell 2 - Venting (00:39:13)
	
Cell 2 - Immediately before thermal runaway* (00:42:57)	Cell 2 - Thermal runaway (00:42:58)
	
Cell 2 - After the end of test	

*Note: Thermal runaway was determined when the temperature of the cell surface increased in an uncontrollable manner.

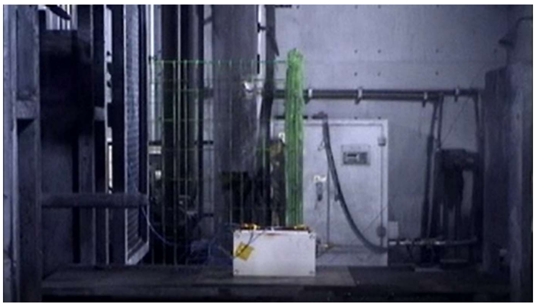
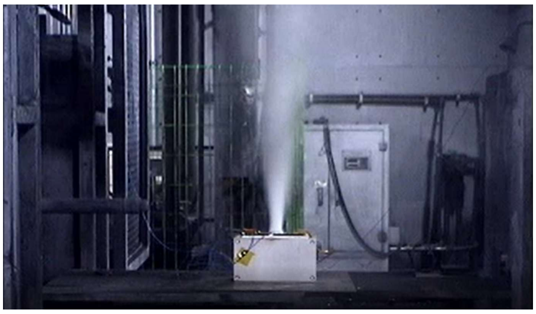
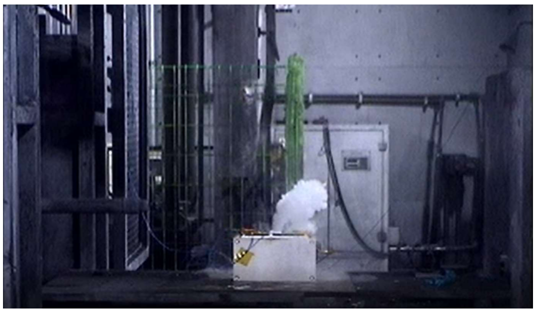
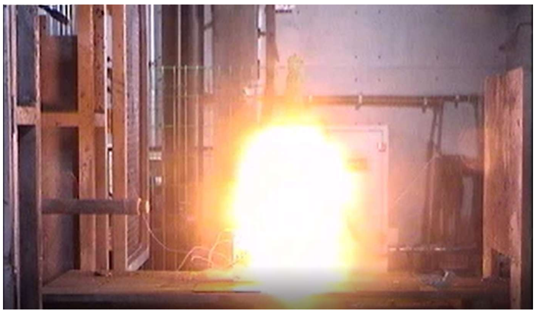
Cell Test 3

	
Cell 3 - Start of test (00:00:00)	Cell 3 - Venting (00:39:42)
	
Cell 3 - Immediately before thermal runaway* (00:39:42)	Cell 3 - Thermal runaway (00:39:43)

Cell 3 - After the end of test

*Note: Thermal runaway was determined when the temperature of the cell surface increased in an uncontrollable manner.

Cell Test 4

	
Cell 4 - Start of test (00:00:00)	Cell 4 - Venting (00:38:40)
	
Cell 4 - Immediately before thermal runaway* (00:42:16)	Cell 4 - Thermal runaway (00:42:17)

Cell 4 - After the end of test

*Note: Thermal runaway was determined when the temperature of the cell surface increased in an uncontrollable manner.

Cell Test 5

Video was not recorded because this cell was placed inside the gas collection vessel

Attachment E: Cell Test Datasheets - (*Pages **31** through **31***)

Cell Test Datasheet is stored in the UL database

Attachment F: Cell vent gas test chamber photo and profile of chamber gas analysis (O_2 and Pressure) - (*Pages **32** through **33***)

This Attachment depicts the equipment used to capture the vented gases.

<Vessel>

Figure F1: Gas Collection Chamber Test Set-up

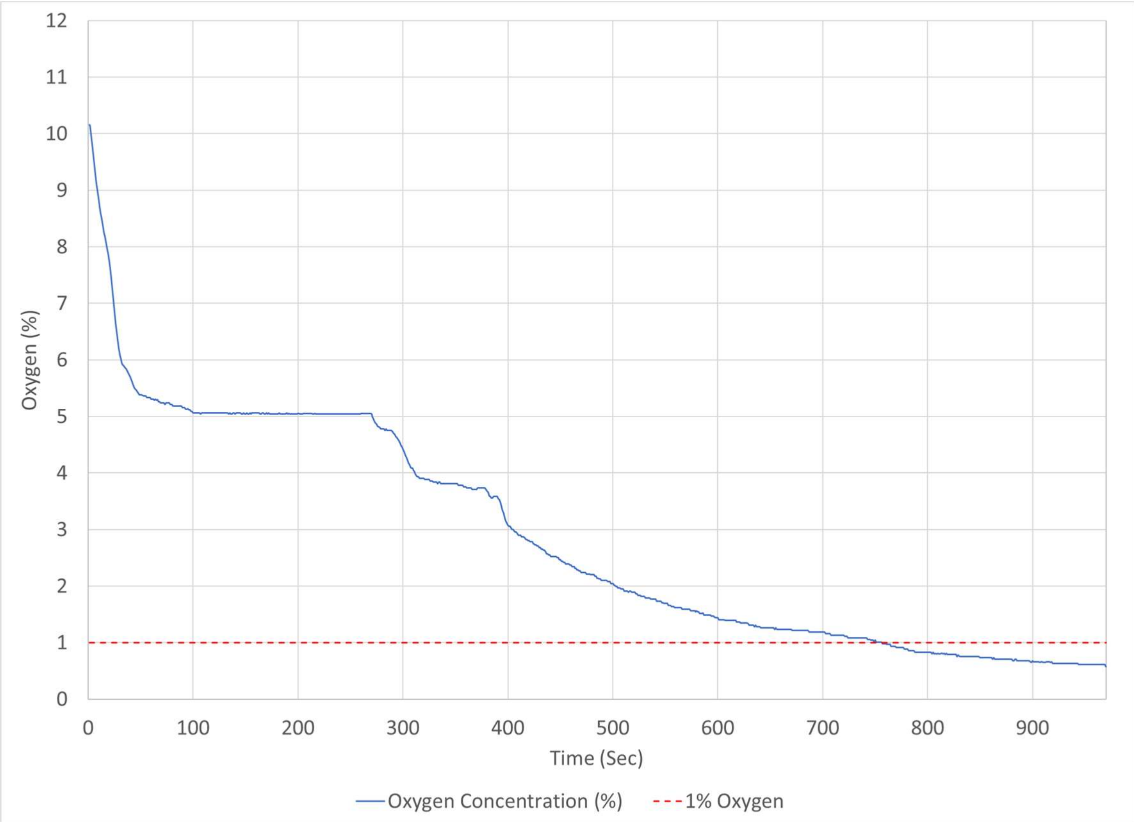


Figure F2: Gas Collection Chamber – Concentration Profile during Oxygen Purge

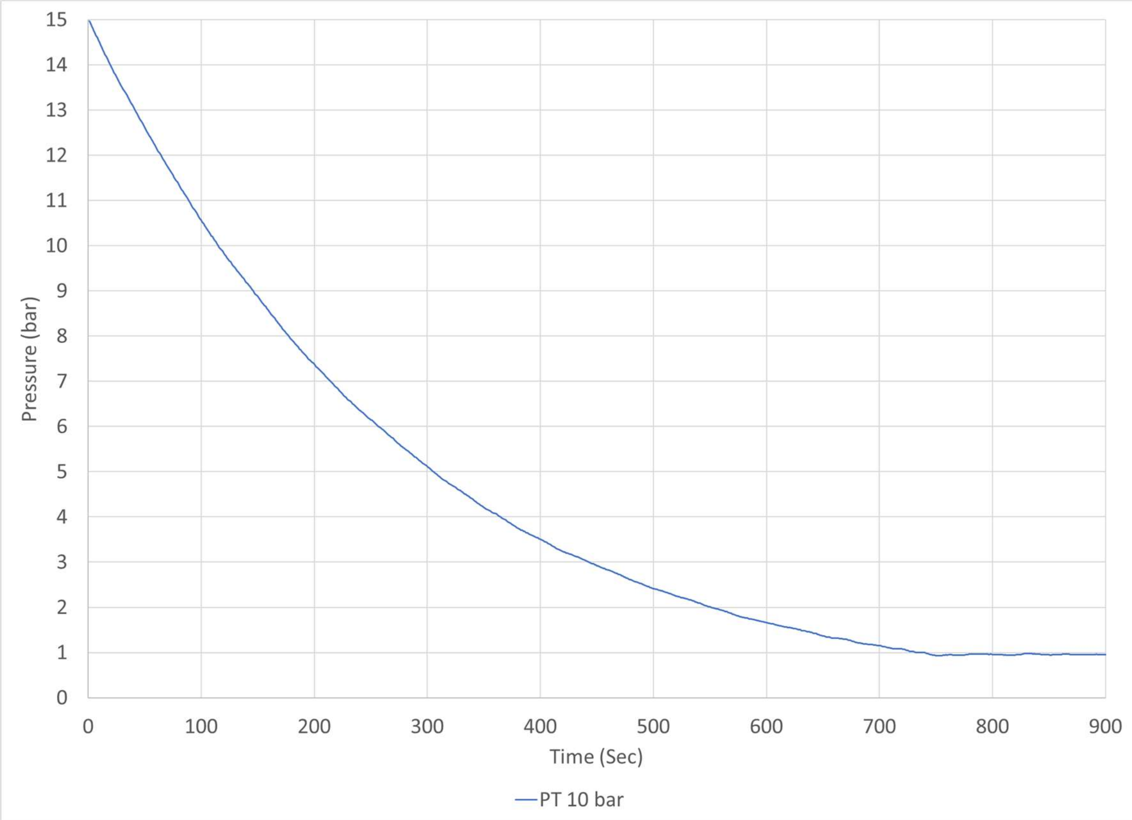


Figure F3: Gas Collection Chamber – Pressure Profile prior to Gas Collection Test

Attachment G: Certification Requirement decisions (*Pages* **34** *through* **34**)

UNDERWRITERS LABORATORIES INC. CERTIFICATION REQUIREMENT DECISION

This Certification Requirement Decision is prepared by UL LLC. It is normative for the applicable UL Product Certification Program(s); however, it is currently not part of the UL Standard(s) referenced below.

Product Category (CCN): AACD
Standard Number: UL 9540A
Standard Title: Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems
Edition Date: November 12, 2019
Edition Number: 4
Section / Paragraph Reference: 7.3.1.5
Subject: Option to do a continuous thermal ramp until thermal runaway

DECISION:

7.3.1.5 Before beginning the test, a surface temperature shall be determined to approximate the temperature at which internal short circuiting within the cell will occur that could lead to a thermal runaway condition. For Li-ion cells, the surface temperature hold point shall be between 5°C (9°F) and 15°C (27°F) greater than the melting temperature of the cell separator material as determined from differential scanning calorimetry (DSC) data of the separator in accordance with UL 2591 (UL 746A). Thermal runaway may occur before this hold point temperature range is reached. However, if thermal runaway is not achieved at this hold point temperature after a period of 4 h, the cell heating rate according to 7.3.1.2 shall be reestablished until thermal runaway occurs or it is demonstrated that thermal runaway is not achievable by heating.

Exception: If the separator information is not available or at the manufacturer's discretion, the thermal ramp can be conducted continuously without a hold point until thermal runaway.

RATIONALE FOR DECISION:

The cell failure method had always been a thermal ramp until thermal runaway occurred. The hold temperature was established because of concern that if the thermal ramp continued at too high of a temperature, it may melt the cell casing. However, the separator information may not always be available and it may be just easier to conduct the test with a continuous thermal ramp if the client is in agreement. In either case, the goal is to establish a thermal runaway condition.

<Certification Requirement Decision dated on 2020-05-20>

MODULE TEST REPORT
UL 9540A
Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems (AACD)

Project Number. ....:	**4790351859**
Date of issue.................................:	**2023-07-10**
Total number of pages ....:	**35**
UL Report Office ....:	**UL Solutions**
Applicant's name ....:	**Samsung SDI**
Address..:	**428-5 GONGSE-DONG GIHEUNG-GU YONGIN-SI, GYEONGGI-DO, 446-577 KR**
Test specification:	4th Edition, Section 8, November 12, 2019
Standard..:	UL 9540A, Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems
Test procedure ....:	8.1 – 8.4
Non-standard test method ....:	N/A

Cell level information	
Cells in Module:	
●Manufacturer Name	Samsung SDI
●Part Number	CP1495L101A
●Chemistry	Lithium Nickel Aluminium Cobalt Oxide (LiNiAlCoO2)
●Format	Prismatic
Ratings (Vdc, Ah) :	3.68 V , 145Ah
Was the cell certified? :	Yes
Standard the cell was certified to:	UL 1973 (File Number: MH64496)
Organization that certified the cell:	UL Solutions
Average cell surface temperature at gas venting, °C:	166
Average cell surface temperature at thermal runaway, °C:	178
Gas Volume:	423
Lower flammability limit (LFL), % volume in air at the ambient temperature:	8.04
Lower flammability limit (LFL), % volume in air at the venting temperature:	6.74
Burning velocity (S_u) cm/s:	88.40
Maximum pressure (P_{max}) psig:	105.3

Cell Gas Composition:

Gas		Measured %
Hydrogen	**H2**	**32.7**
Carbon monoxide	**CO**	**40.9**
Methane	**CH4**	15.43
Ethylene	**C2H4**	0.56
Ethane	**C2H6**	1.06
Carbon dioxide	**CO2**	**9.2**
Propene (Propylene)	**C3H6**	**0.04**
Propane	**C3H8**	**0.03**
C4 Total	**C4H?**	**0.05**
C5 Total	**C5H?**	**0.01**
Benzene	**C6H6**	**0.06**
Total	**-**	**100.00**

Module Level Information	
Model No:	E5S (MS3204L101A)
Ratings (Vdc, Ah) :	110.4, 290
Module cell configuration (xS/yP) ……:	30S/2P
Module dimensions (W x D x H (mm)) :	388.2 x 1751.8 x 155.0 (without mounting bracket)
Module weight (kgs) :	173
Module enclosure material:	Plastic Cover : PC(M3020PN), 2.5T Mica Sheet 0.3t(&Aerogel) Sheet
Was the module certified? :	Yes (MH49407)
Standard the module was certified to:	UL 1973
Organization that certified test item:	UL Solutions
Cell failure test method performed for the module level (summary of method and test clause): ☒ External heating using thin film with 4°C to 7°C thermal ramp. ☐ Nail Penetration ☐ Overcharge ☐ External short circuit (***X*** Ω *external resistance*) ☐ Others	
Description of method used to fail cells if other than external thin film heater with thermal ramp, : **N/A**	
Description of components employed within the module that serve to supress propagation (fire protection features).	
Number of initiating cells failed to achieve propagation.	1
Thermal Runaway Propagation:	Yes
Maximum Smoke Release Rate (m^2/s)	7.06
Total Smoke Released: (m^2)	3516
Total smoke released duration (hh:mm:ss)	04:44:13
Peak Chemical Heat Release Rate: (kW):	3935
External Flaming:	Yes
Location(s) of Flame Venting:	Flaming out of the top of the module
Flying Debris:	Yes

	Re-ignitions:	No re-ignition

Summary of Module level test Gas Analysis Data:

Gas Analysis:

☒ **Flame ionization detection**

☐ **Fourier-Transform infrared Spectrometer**

☒ **Hydrogen Sensor (palladium-nickel, thin-film solid state sensor)**

☒ **White light source with photo detector (smoke release rate)**

- **Gas Composition & Volume for Each Compound (Pre-flaming and After flame):**

Gas Compound	Gas Type	Pre-Flaming (L)	Flaming (L)	Minimum detectable flow rate(LPM)
Total Hydrocarbons (Propane Equivalent)	Hydrocarbons	6.61	677.14	0.04
Carbon Dioxide	Carbon Containing	Below detectable limit	39542.50	3.11
Carbon Monoxide	Carbon Containing	Below detectable limit	1421.12	0.44
Hydrogen	Hydrogen	*	*	*

*The hydrogen measurement system malfunctioned during the test, however, the same module design was tested with different charging specifications and the hydrogen quantity was below detectable limits – Please refer to the report under UL project 4790648531

Summary of Module testing:

Performance Criteria in accordance with Clause 8.4 and Figure 1.1:

[X] The effects of thermal runaway was not contained by the module design;

[X] Cell vent gas (based upon the cell level test) was flammable

Necessity of a unit level test

[X] The performance criteria of the module level test as indicated in 8.4 and as shown in Figure 1.1 of UL 9540A 4th edition has not been met, therefore unit level testing in accordance with UL 9540A will need to be conducted on a complete unit employing this module.

[ ] The performance criteria of the module level test as indicated in 8.4 and as shown in Figure 1.1 of UL 9540A 4th edition has been met, therefore unit level testing in accordance with UL 9540A need not be conducted.

Testing Laboratory information

Testing Laboratory and testing location(s):

Testing Laboratory:	UL Solutions
Testing location/ address ....:	333 Pfingsten Rd. Northbrook, IL 60062 USA
Tested by (name, signature) ....:	Miguel Berumen

Witnessed by (for 3rd Party Lab Test Location) (name, signature) ....:	N/A	N/A
Project Handler (name, signature):	Daniel Wade	
Reviewer (name, signature) ……………..:	Sean Yang	

List of Attachments (including a total number of pages in each attachment):
Attachment A: Module Conditioning (Charge/discharge) Profiles - (*Pages **19** through **20***)
Attachment B: Module Construction Photos - (Pages ***21*** through ***22***)
Attachment C: Module Instrumentation Photos - (*Pages **23** through **24***)
Attachment D: Module and Initiating Cell(s) Temperature Profiles During Testing - (*Pages **25** through **26***)
Attachment E: Module Testing Photos - (*Pages **27** through **29***)
Attachment F: Module Test Datasheets - (*Pages **30** through **30***)
Attachment G: Module Gas Flow Rate and Heat Release Profiles - (*Pages **31** through **32***)
Attachment H: Certification Requirement Decision - (*Pages **33** through **35***)

Photo(s) of module:

Test Item Charge/Discharge Specifications:	
• **Charge current, A:**	**58.0**
• **Standard Full charge Voltage, Vdc:**	**124.5**
• **Charge temperature range, °C:**	**23 ± 5**
• **End of charge current, A:**	**58.0**
• **Discharge current, A:**	**58.0**
• **End of discharge voltage, Vdc:**	**93.0**
• **Discharge temperature range, °C:**	**23 ± 5**

Test item particulars... :	
Possible test case verdicts:	
- test case does not apply to the test object...........:	N/A
- test object does meet the requirement..................:	P (Pass)
- test object does not meet the requirement...........:	F (Fail)
- test object was completed per the requirement...:	C(Complete)
- test object was completed with modification……:	M(Modification)
Testing..:	
Date of receipt of test item ....:	
Date (s) of performance of tests ....:	

General remarks:

"(See Enclosure #)" refers to additional information appended to the report.
"(See appended table)" refers to a table appended to the report.

Throughout this report a point is used as the decimal separator.

Manufacturer's Declaration of samples submitted for test:

The applicant for this report includes samples from more than one factory location and a declaration from the Manufacturer stating that the sample(s) submitted for evaluation is (are) representative of the products from each factory has been provided...........................:	☐ **Yes** ☐ **Not applicable**
Name and address of factory (ies) ....:	Samsung SDI 163, Bangudae-ro Samnam-eup, Ulju-gun Ulsan, Republic of Korea

General product information and other remarks:

The E5S (MS3204L101A) lithium ion module sis manufactured by Samsung SDI. The module is rated 110.4Vdc and 290Ah. The module contains sixty CP1495L101A Samsung SDI cells arranged in a 30S/2P configuration.

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

5.0	**CONSTRUCTION**		**Verdict**
5.2	**Module Construction**		—
5.2.1, 5.2.3	Construction information	See Test Item Description at the beginning of this report	—
	General layout of module contents	See Attachment B	—
5.2.2	Module certified to UL 1973	**Yes (MH49407)**	C
	Organization that certified module:	**UL Solutions**	—
6.0	**PERFORMANCE**		**Verdict**
6.1	**General**		
8.1	**Samples**		
8.1.1	Samples conditioned through charge discharge cycling a minimum of 2 cycles.	See Attachment A for profiles See Table 1 for specifications See also Table 2	C
8.1.2	100% SOC and stabilize from 1h to 8 h before testing		
8.1.3	Electronic controls such as BMS not relied upon during testing.		C
8.2	**Test Method**		
8.2.1	Ambient indoor laboratory conditions: 25 ±5°C (77 ±9°F) ≤50 ±25% RH at the initiation of the test.	See Table 3 See Attachment F	C
8.2.2	Test conducted under a smoke collection hood appropriately sized for the module		C
8.2.3	The weight of the module was recorded before and after testing, (kg)	See Attachment F and Table 11	C
8,2,4	A sufficient number of cells were forced into thermal runaway to create a condition of cell to cell propagation within the module.	See Attachment C and F See Tables 4 and 5	C
	The location of the cell(s) forced into thermal runaway were selected to present the greatest thermal exposure to adjacent cells	See Attachment C for figures showing location within the module of the cell(s) forced into thermal runaway	C
8.2.5	The method used to initiating thermal runaway in the cell(s) were in accordance with 7.2	See Summary of Cell Testing at the beginning of this report.	C
8.2.6	The occurrence of thermal runaway was verified	See Test Results from Cell Level Test from the beginning of this report See Attachments D and F	C

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict
8.2.7	The module was placed on top of a non-combustible horizontal surface with the module orientation representative of its intended final installation.	See Attachment E	C
8.2.8	The chemical heat release rate of the module was measured with oxygen consumption calorimetry	See Table 10 See Attachment F and G	C
8.2.9	The chemical heat relate rate was measured for the duration of the test	See Attachment F and G	C
8.2.10	The chemical heat release rate was measured using the following equipment: ● Paramagnetic oxygen analyser ● Non-dispersive infrared carbon dioxide and carbon monoxide analyser ● Velocity probe ● Type K thermocouple	See Attachment G	C
	The instrumentation was located in the exhaust duct of the heat release rate calorimeter at a location that minimizes the influences of bends or exhaust devices.		C
8.2.11	The chemical heat release rate at each of the flows was calculated in accordance with 8.2.11.	See Attachment G	C
8.2.12	The hydrocarbon content of the vent gas was measured using flame ionization detection.	See Table 8 and 9	C
	Hydrogen gas shall be measured with a palladium-nickel thin-film solid state sensor.	See Table 9. The hydrogen measurement system malfunctioned during the test, however, the same module design was tested with different charging specifications and the hydrogen was below detectable limits.	C

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict
8.2.13	The hydrocarbon content of the vent gas may also be measured using a Fourier-Transform Infrared Spectrometer with a minimum resolution of 1 cm-1 and a path length of at least 2 m (6.6 ft), or equivalent gas analyzer.	See Attachment G FTIR analysis was not used in accordance with the Certification Requirement Decision: Corrections to gas measurement methods to make FTIR as an option for measuring hydrocarbon contents of gas emissions and to include Hydrogen measurements during the Unit Level Test. FTIR was considered redundant to the other gas measurement methods used	C
	Vent gas velocity and temperature measurements respectively were obtained in the exhaust duct of the heat release rate calorimeter using equipment specified in 8.2.10.		C
8.2.14	The light transmission in the exhaust duct of the heat release rate calorimeter was measured using a white light source and photo detector for the duration of the test.		C
8.2.15	Smoke release rate was calculated as outlined in 8.2.15	See Table 10 See Attachment G	C
8.3	**Module level test report**		
	a. Module manufacturer and model number; b. Number of cells in module; c. Module configuration;	See Test Item Description in beginning of this report.	C
	d. Module construction features;	See Attachment C See Critical Components Table ☐ See Also “Description of components employed within the module that impact propagation (fire protection features)” at the beginning of this report.	C
	e. Module voltage corresponding to the tested SOC;	See Table 3 See Attachment F	C
	f. Thermal runaway initiation method used;	See Attachment C and F	C
	g. Heat release rate versus time data;	See Table 10 See Attachment G	C
	h. Flammable gas generation and composition data;	See Attachment F and G See Tables 8 and 9	C

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict
	i. Peak smoke release rate and total smoke release data.	See Table 10 See Attachment F	C
	j. Observation(s) of flying debris or explosive discharge of gases;	See Attachment F and Table 12	C
	k. Observation(s) of sparks, electrical arcs, or other electrical events;	See Attachment F and Table 12	C
	l. Identification/location of cells(s) that exhibited thermal runaway within the module;	See Tables 4 and 5	C
	m. Locations and visual estimations of flame extension and duration from the module;	See Attachments E and F See Table 7	C
	n. Module weight loss;	See Table 11	C
	o. Video of the test.	Videos were recorded and stored in UL database at the request of Samsung SDI. However, the snapshots of the test are provided in the report. See Attachments E	C
8.4	**Performance – Module level**		
8.4.1	The following performance conditions are met during the module level test: a) Thermal runaway is contained by module design;	External flaming was observed.	F
	b) Cell vent gas is nonflammable as determined by the cell level test	The vent gas is flammable.	F

Table 1 – Specified conditioning parameters			
Charging:		**Discharging:**	
Current (CC), A	58.0	Current (CC), A	58.0
Standard full Charge Voltage, Vdc	124.5	End of discharge voltage, Vdc	93.0
End of charge current, A	58.0	Discharging Test Ambient, °C	23 ± 5
Charging Test Ambient, °C	23 ± 5		
Refer to Attachment A for charge/discharge profiles for the module.			

Table 2 – Charge completion and module test initiation times	
Charge Completion Date and Time	**Module Test Date and Time**
2023/04/10 / 13:33:41	2023/04/12 / 15:20:17

Table 3 - Test Initiation Details	
	Module No.:
Test Date	2023/04/12
Test Start Time	15:20:17
Initial Lab Temperature	25.6 °C
Initial Relative Humidity	36.5%
Module OCV at Start of Test, Vdc	123.28

Table 4 – Approximate time of thermal runaway propagation through module		
Location	**Event**	**Time (HH:MM:SS)**
Initiating Cell	Thermal Runaway	0:46:14
Cell 35	First cell propagation	0:58:04
Cell 31	Second cell propagation	1:13:49
Propagation	Propagation of instrumented cells throughout the module	0:58:04 ~ 5:02:20

Table 5 – Test overview timeline		
Time (HH:MM:SS)	**Event**	**Description**
00:00:00	Test Start	Test started – The initiating cells temperature was increase at a rate of 5 °C/minute until thermal runaway occurred. The thermocouple on the side of the cell not covered by the heater was used to monitored to control the heating rate.
00:45:26	Vent	Gas vented from the module and the temperature of the initiating cell suddenly decreased.

00:46:14	Thermal Runaway	Gas vented from the top of the module above the initiating cell venting area in 48 seconds after the venting. The temperature of the cell increase in an uncontrollable manner at 00:46:14 into the test. At this time dark smoke and sparks exited the module above the initiating cell vent area.
00:46:15	Ignition	One second after thermal runaway the gas/smoke exiting the top of the module above the initiating cell vent area ignited.
0:58:04 ~ 05:25:28	Propagation	Cell to cell propagation occurred on instrumented cells.
02:39:45	Maximum Heat Release Rate	Maximum heat release rate was observed. 1,872 kW connective HRR and 3,935 kW chemical HRR.
05:25:28	Flaming End	No further flames were observed after 5:25:28.
05:29:15	Test Terminated	Video recording was stopped at 05:29:15 after test start. However, the sample remained in the testing room overnight and no further thermal runaway or re-ignition was observed.

Table 6 – Gases measured and measurement methods used in unit level testing			
Measurement Method	**Gases Measured**	**Chemical Formula**	**Gas Type**
Flame Ionization Detection (FID)	Total Hydrocarbons	-	Hydrocarbons
Solid-state Hydrogen Sensor	Hydrogen	H_2	
Non-dispersive infrared spectroscopy (NDIR)	Carbon Dioxide	CO_2	Carbon Containing
	Carbon Monoxide	CO	Carbon Containing
~~[ ] Fourier-Transform Infrared Spectrometer (FTIR)~~	~~Acetylene~~	~~C_2H_2~~	~~Hydrocarbons~~
	~~Ethylene~~	~~C_2H_4~~	~~Hydrocarbons~~
	~~Methane~~	~~CH_4~~	~~Hydrocarbons~~
	~~Methanol~~	~~CH_3OH~~	~~Hydrocarbons~~
	~~Propane~~	~~C_3H_8~~	~~Hydrocarbons~~
	~~Formaldehyde~~	~~CH_2O~~	~~Hydrocarbons (Aldehydes)~~
	~~Hydrogen Bromide~~	~~HBr~~	~~Hydrogen Halides~~
	~~Hydrogen Chloride~~	~~HCl~~	~~Hydrogen Halides~~
	~~Hydrogen Fluoride~~	~~HF~~	~~Hydrogen Halides~~
	~~Ammonia~~	~~NH_3~~	~~Nitrogen Containing~~
	~~Hydrogen Cyanide~~	~~HCN~~	~~Nitrogen Containing~~
# - This table was modified to reflect the gases measured during testing.			

Table 7 - Gas generation periods	
Time	**Condition**
0:45:26 – 0:46:15	Pre-Flaming
0:46:15 – 5:25:28	Flaming
External Flaming of Gas	
Condition	**Duration (hh:mm:ss)**
External Flaming of Vent Gases:	4:39:13

Table 8– Summary of battery gas volumes for deflagration hazard calculations				
Gas Component	Gas Type	During Pre-flaming (L)	During Flaming (L)	Minimum detectable flow rate(LPM)
Total Hydrocarbons (Propane Equivalent)	Hydrocarbons	6.61	677.14	0.04
Carbon Dioxide	Carbon Containing	Below detectable limit	39542.50	3.11
Carbon Monoxide	Carbon Containing	Below detectable limit	1421.12	0.44
Hydrogen	Hydrogen	*	*	*

*The hydrogen measurement system malfunctioned during the test, however, the same module design was tested with different charging specifications and the hydrogen quantity was below detectable limits Please refer to the report under UL project 4790648531.

Table 8A – Summary of battery gas volumes identified during thermal runaway in module test			
Gas Component	**Gas Type**	**During Pre-flaming (L)**	**During Flaming (L)**
Carbon Dioxide	Carbon Containing		
Carbon Monoxide	Carbon Containing		
Ethylene	Hydrocarbons		
Methane	Hydrocarbons		

Table 9 – Smoke and heat release rate			
Heat Release Rate (HRR)		**Smoke Release Rate (SRR)**	
Peak Chemical HRR (kW)	3935	Maximum SRR (m^2/s)	7.06
		Total Smoke Released (m^2)	2702

Table 10 – Module Weight During Test, kg	
Before Test:	171.5
After Test:	81.2
Weight Loss:	90.3

Table 11 – Other Observations during module test		
	Observed, Yes/No	Location
Flying debris	Yes	Out of top of module during thermal runaways
Explosive discharge of gas	Yes	Started with venting area of the initiating cells.
Sparks or electrical arcs	Yes	Sparks above each cell venting area

TABLE: Critical components information					
Object / Part No.	**Manufacturer/ trademark**	**Type / model**	**Technical data**	**Standard**	**Mark(s) of conformity**
Cells	SAMSUNG SDI	CP1495L101A	145 Ah, 3.68 V	UL1973	RU (MH49407)
Case	-	-	Material SGCD 1.0T SGCD1.2T SGCC 2.0T	-	-
Plastic cover	LOTTE CHEMICAL CORPORATION	UF-1002	PC, 5VA, 80℃, Min Thickness: 2.50 mm	UL 746 UL 94	RU (E115797)
Hybrid busbar (Resin)	LOTTE CHEMICAL CORPORATION	TH-1100	PC, V-0, RTI[Elec]		

~~**List of test equipment used:**~~

~~A completed list of used test equipment shall be provided in the Test Reports when a Customer's Testing Facility has been used.~~

~~**Clause**~~	~~**Measurement / testing**~~	~~**Testing / measuring equipment / material used, (Equipment ID)**~~	~~**Range used**~~	~~**Last Calibration date**~~	~~**Calibration due date**~~

Test equipment recorded in internal UL Solutions database.

Attachment A: Module Conditioning (Charge/discharge) Profiles - (*Pages **19** through **20***)

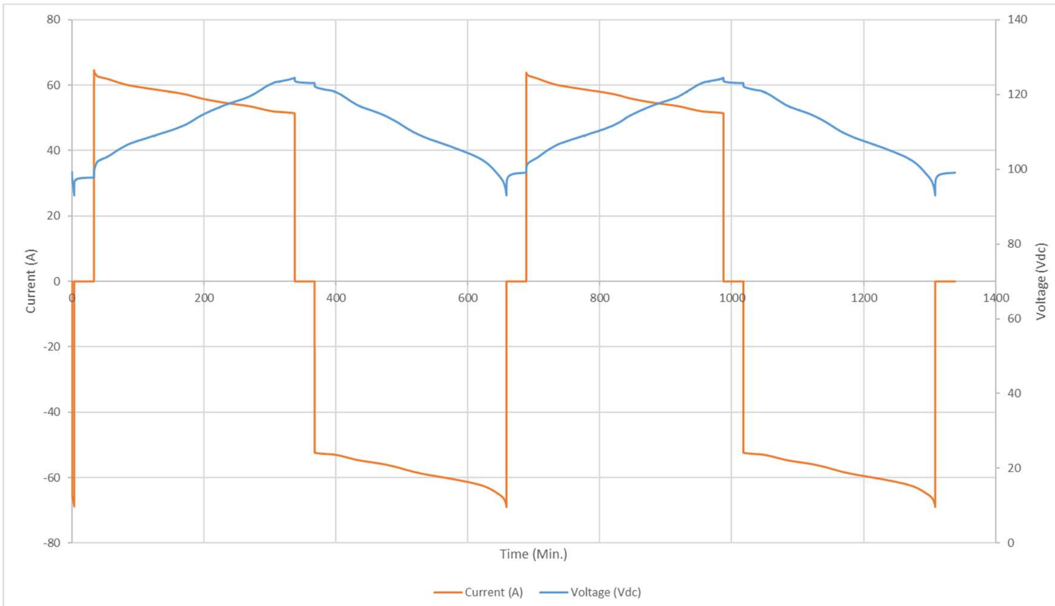


Figure A1 – Module Cycling

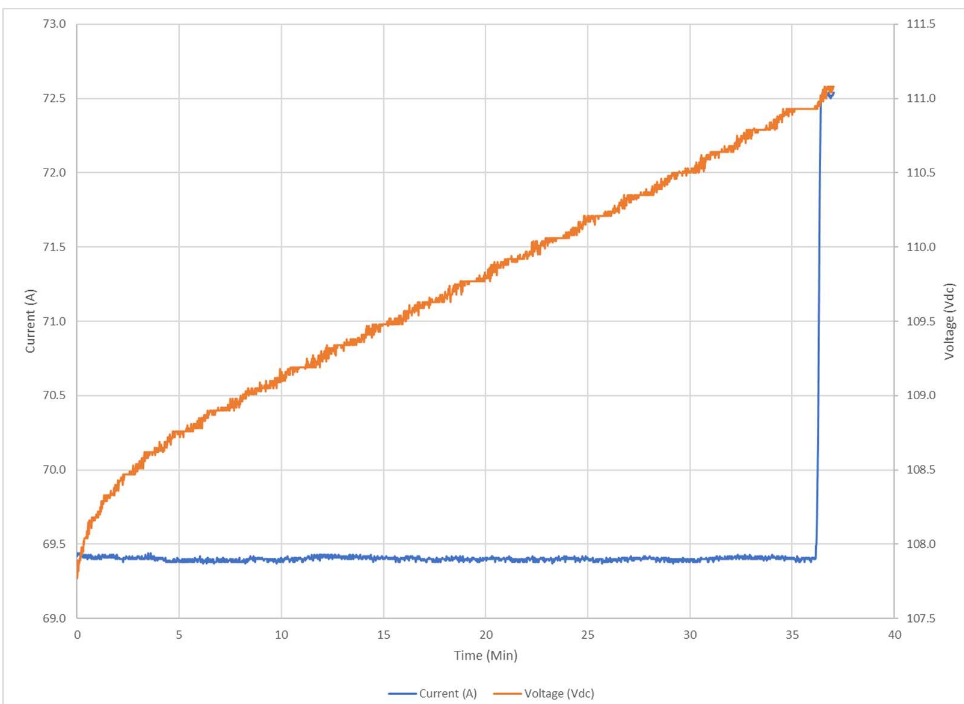


Figure A2: Module Charge Part 1

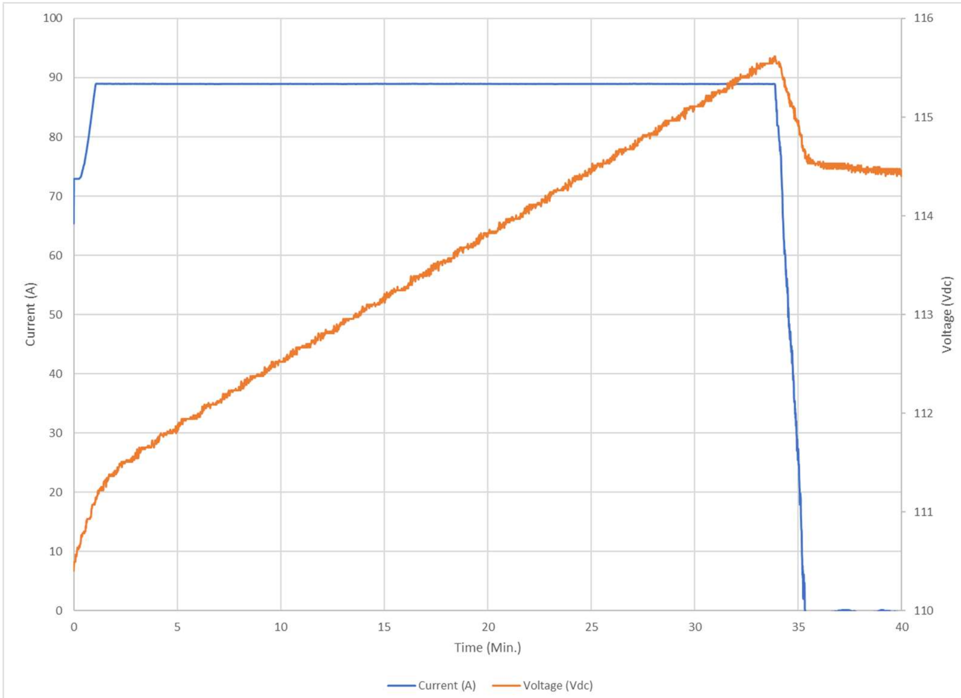


Figure A3: Module Charge Part 2 (At 34 minutes the charge ended and was restarted at a later time)

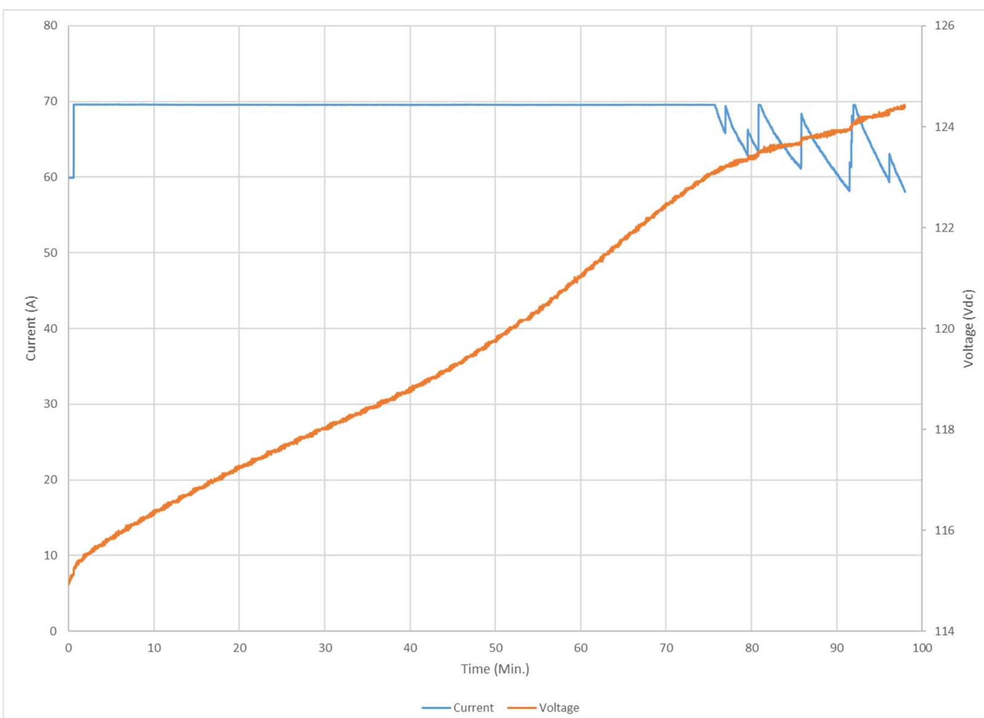


Figure A4: Module Charge Part 3

Attachment B: Module Construction Photos - (Pages ***21*** through ***22***)

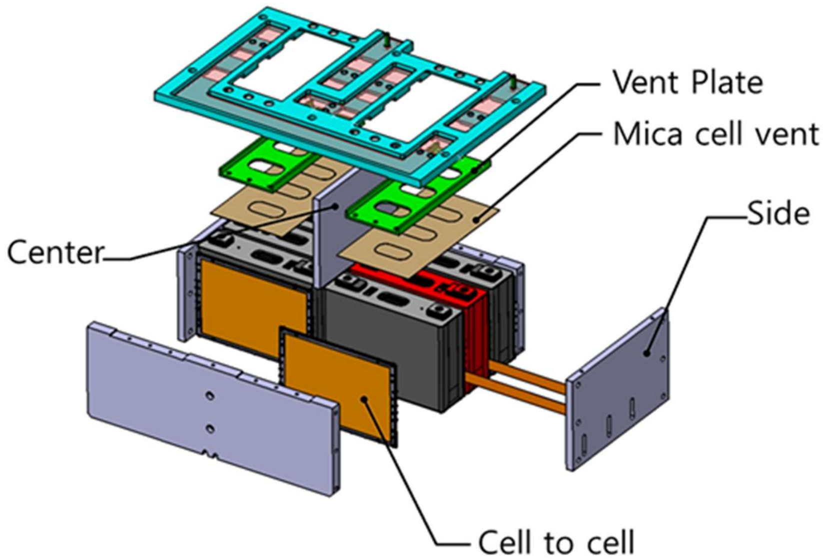


Figure B1: Component diagram

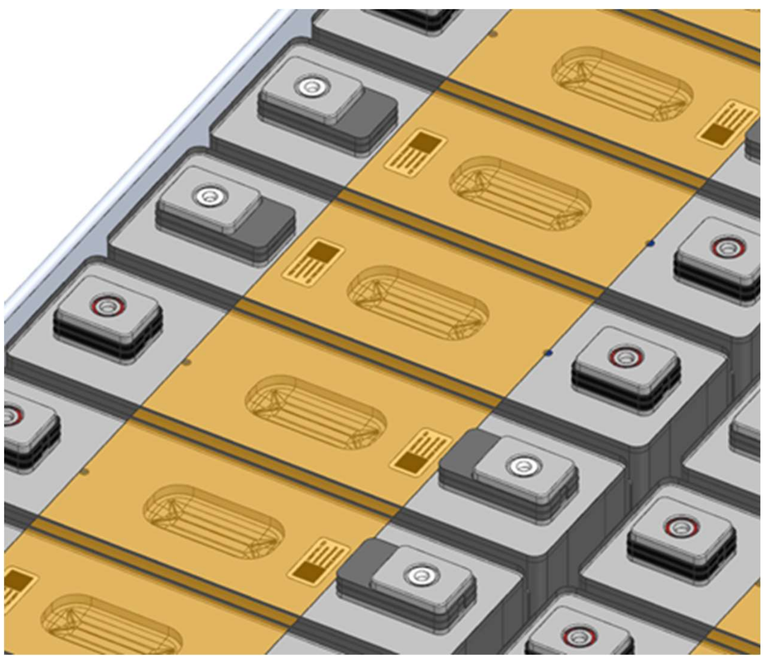


Figure B2: Cell layout

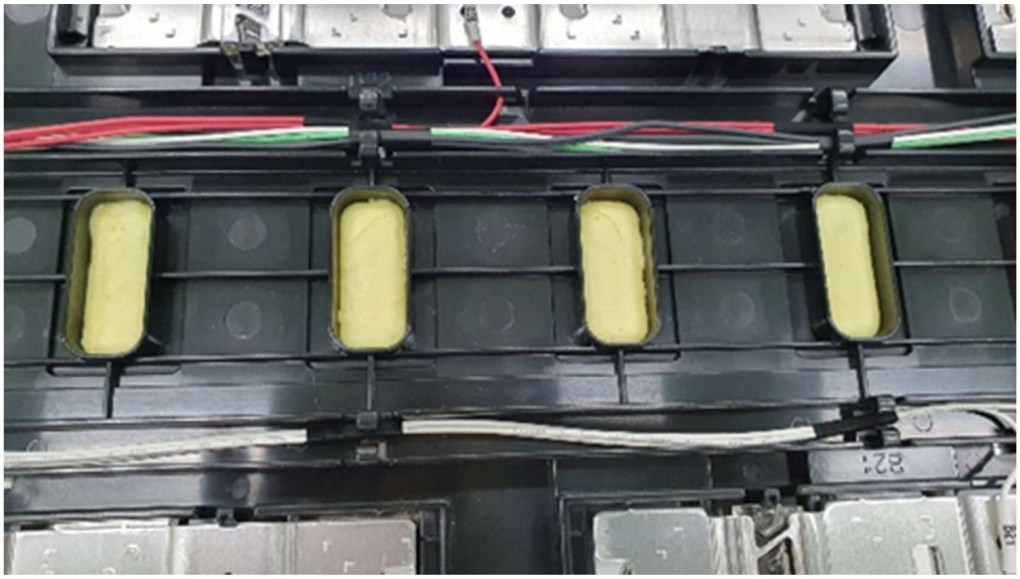


Figure B3: Cell vent

Figure B4: Overview of module

Attachment C: Module Instrumentation Photos - (*Pages **23** through **24***)

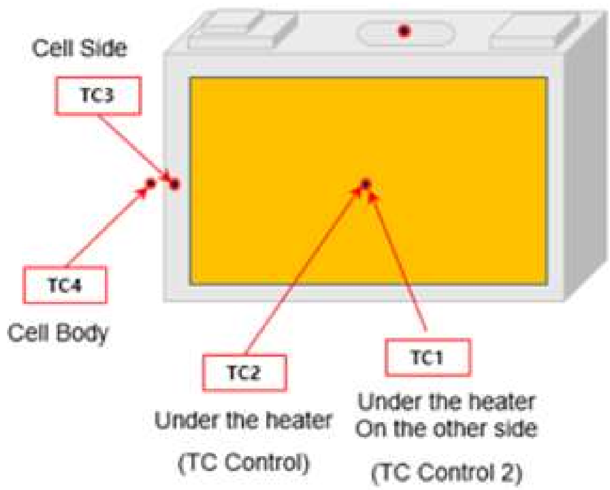


Figure C1: Cell Instrumentation

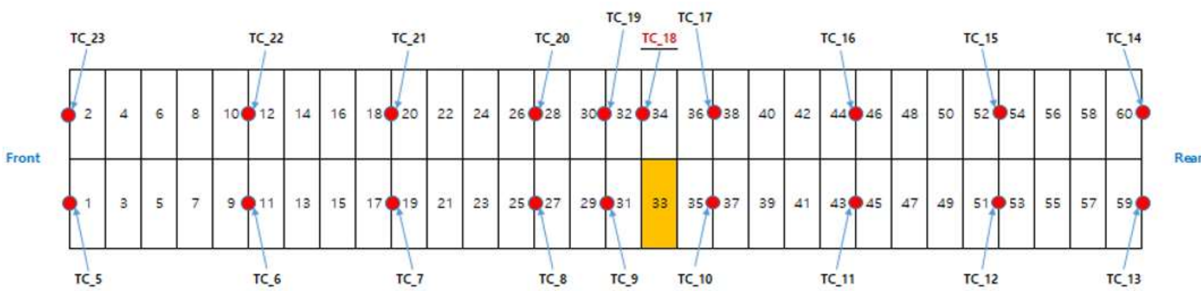


Figure C2: Module Cell Instrumentation

Figure C3: Left side module instrumentation

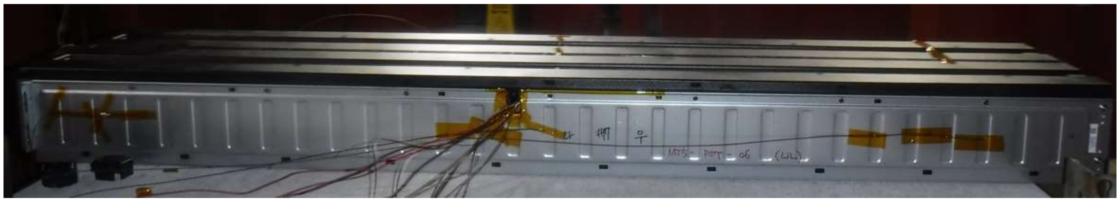


Figure C4: Right side module instrumentation

Figure C5: Rear module instrumentation

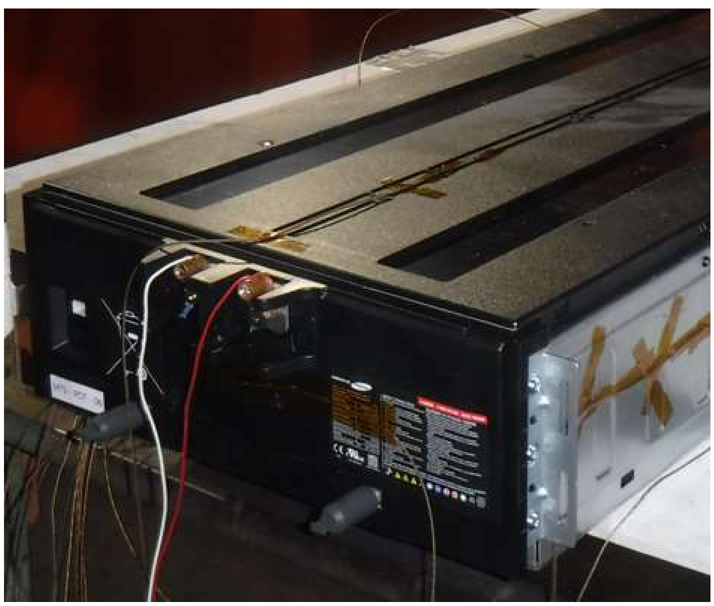


Figure C6: Front module instrumentation

Attachment D: Module and Initiating Cell(s) Temperature Profiles During Testing - (*Pages **25** through **26***)

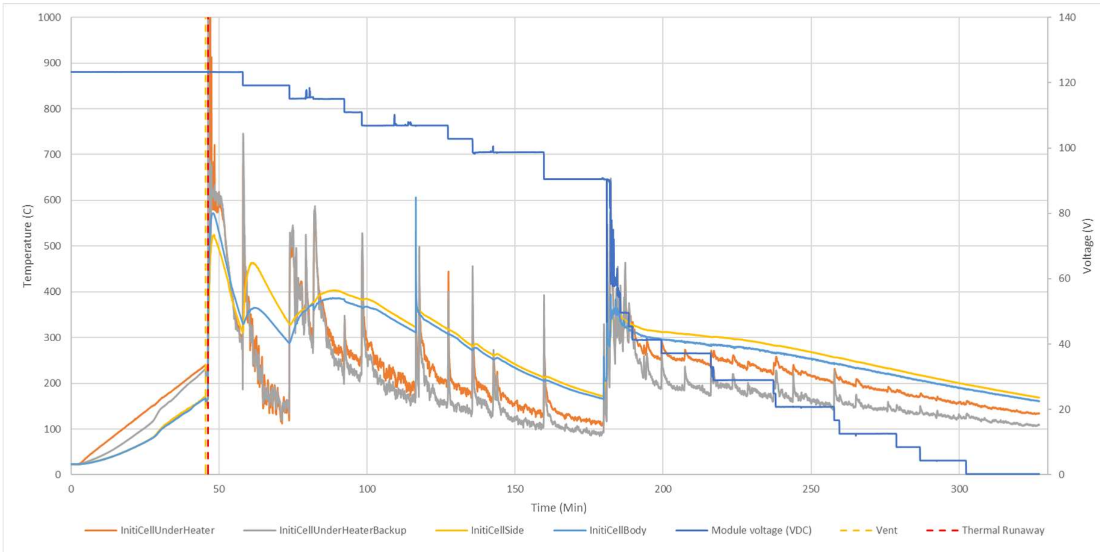


Figure D1: Initiating cell

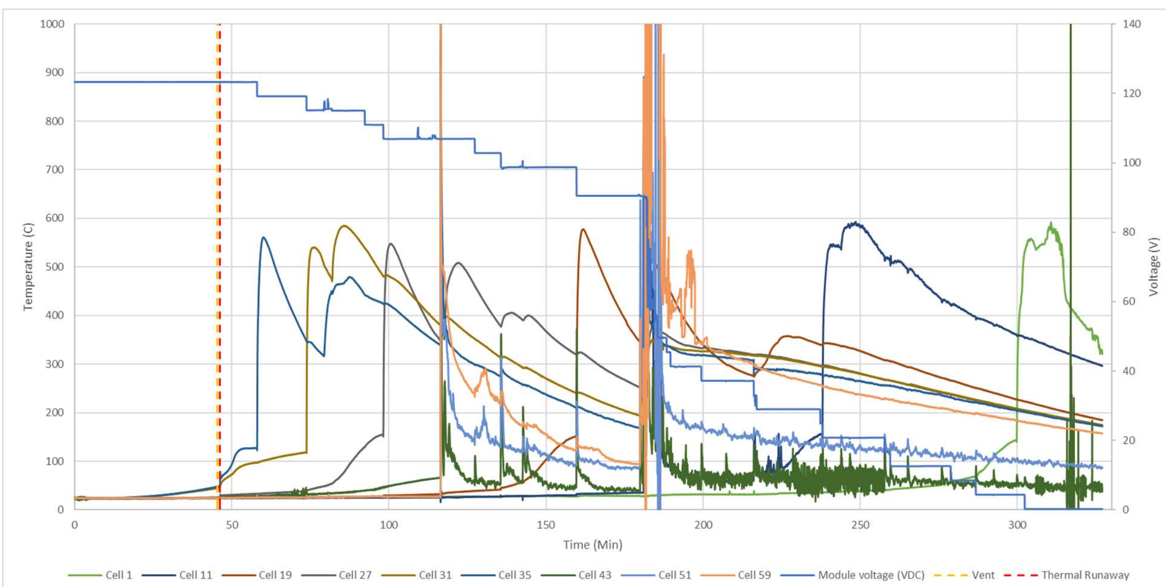


Figure D2: Cells in the initiating cell row

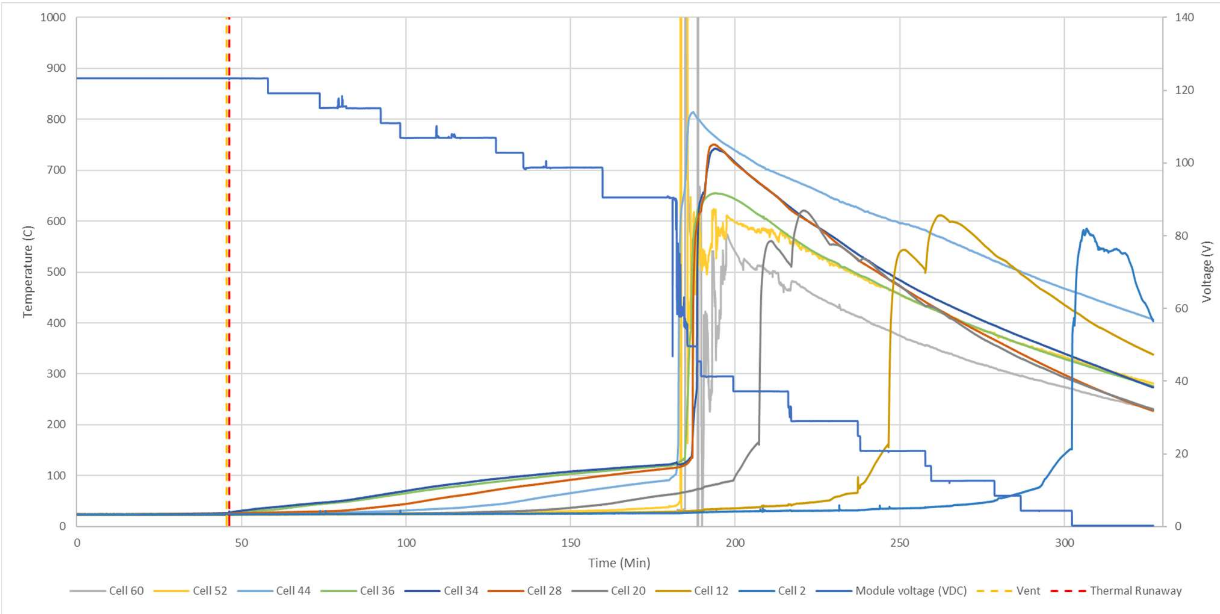


Figure D3: Cells in row without initiating cell

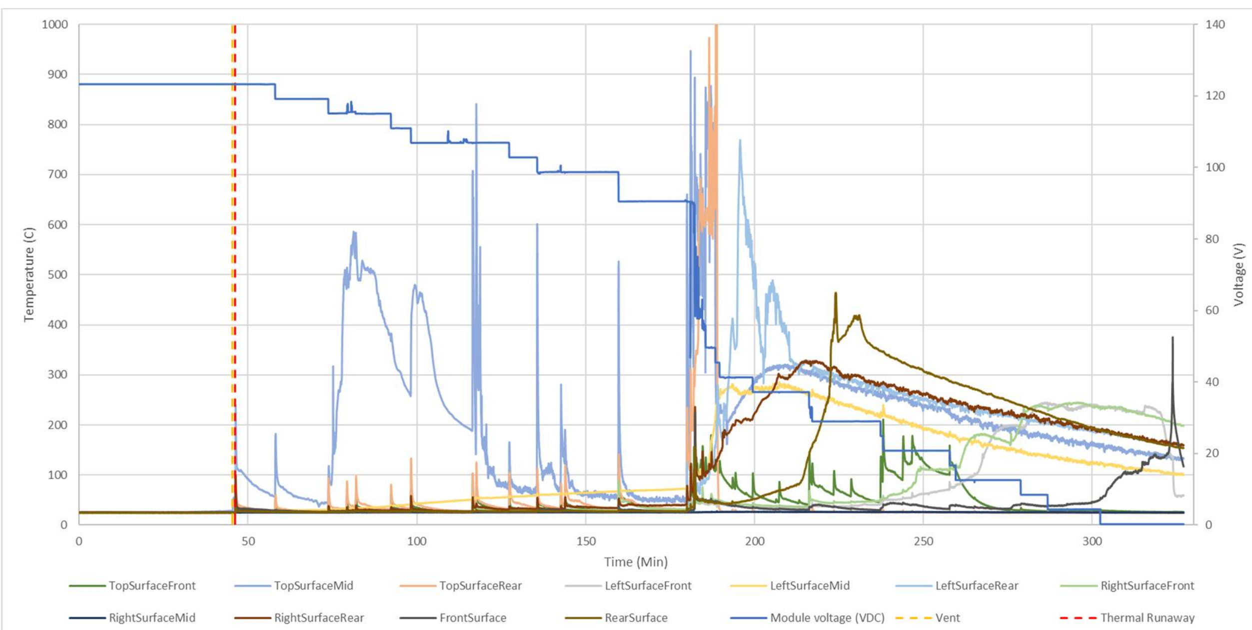


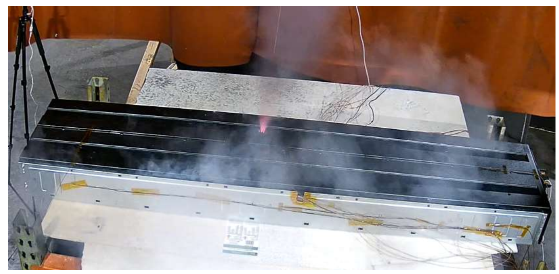
Figure D4: Exterior temperatures

Attachment E: Module Testing Photos - (*Pages **27** through **29***)

(a) Test Start
00:00:00

(b) Vent
00:45:26

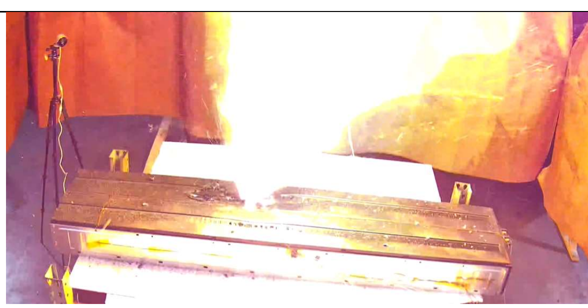
(c) Thermal Runaway (Initiating Cell)
00:46:14



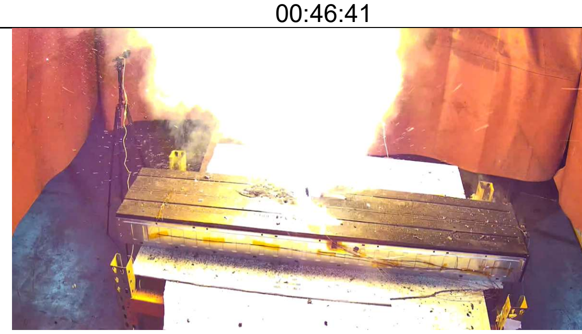
(d) First Flame
00:46:15

(e) Continuation of Initiating Cell Thermal Runaway
00:46:18

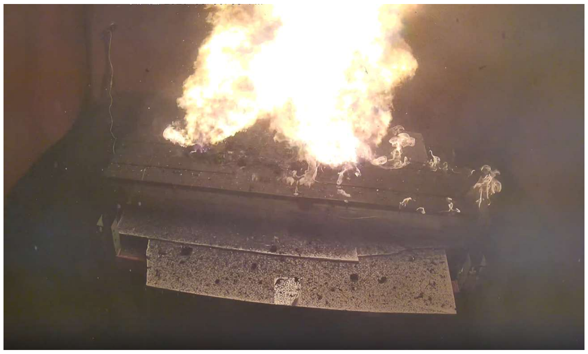
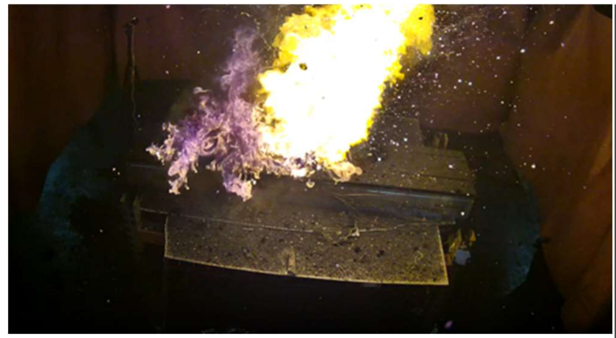
(f) Continued Flaming (post initiating cell thermal runaway)
00:46:41



(g) First propagation after Initiating Cell (Cell 35)
00:58:04



(h) Second propagation After Initiating Cell (Cell 31)
1:13:49

 (i) Maximum Chemical and Convective Heat Release Rate 02:39:45	 (j) Maximum Smoke Release Rate 03:07:07
 (k) Continued Thermal Runaway 04:35:51	 (l) Last Flame 05:25:28

Attachment F: Module Test Datasheets - (*Pages **30** through **30***)
Datasheet is stored internally in UL Solution’s database.

Attachment G: Module Gas Flow Rate and Heat Release Profiles - (*Pages **31** through **32***)

*The hydrogen measurement system malfunctioned during the test, however, the same module design was tested with different charging specifications and the hydrogen quantity was below detectable limits – Please refer to the report under UL project 4790648531

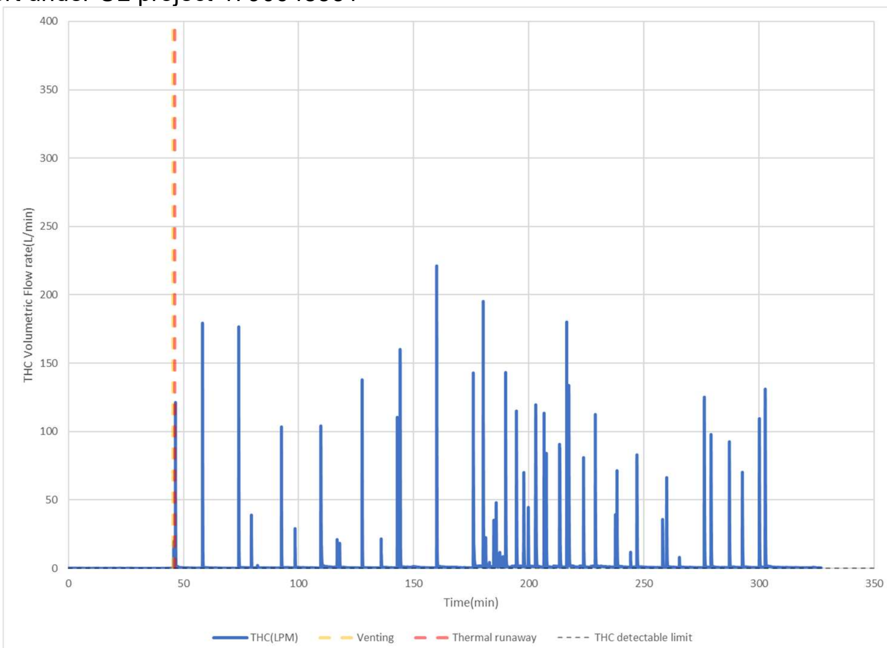


Figure G1 – Volumetric flow rates of gases (Total Hydrocarbon)

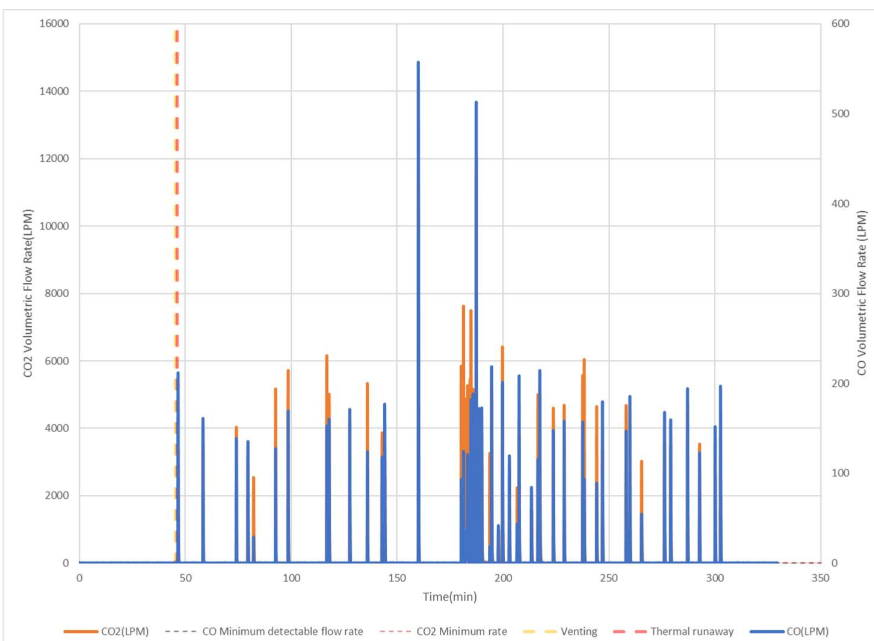


Figure G1 – Volumetric flow rates of gases (carbon monoxide and carbon dioxide)

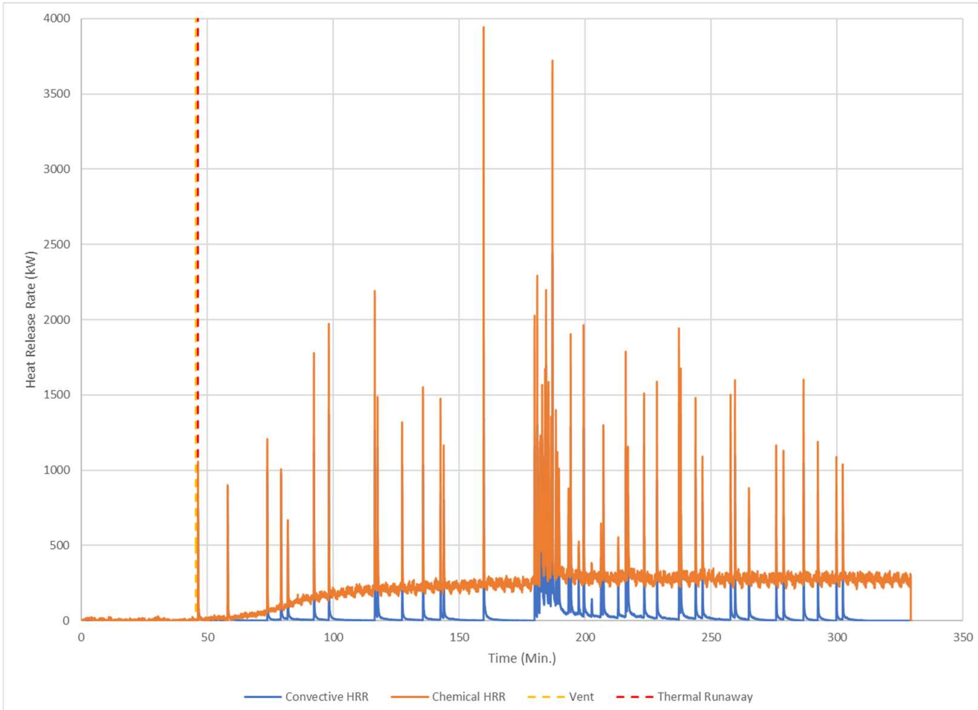


Figure G2 – Heat Release Rate

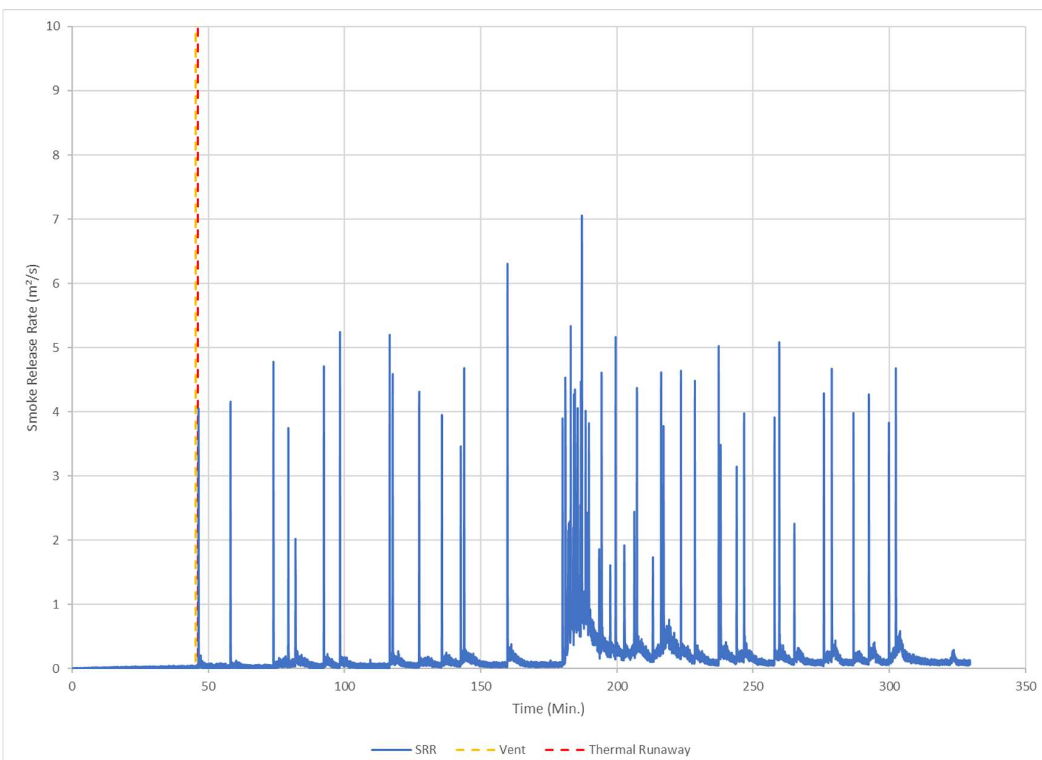


Figure G3 – Smoke Release Rate

Attachment H: Certification Requirement Decision - (*Pages **33** through **35***)

UNDERWRITERS LABORATORIES INC. CERTIFICATION REQUIREMENT DECISION

This Certification Requirement Decision is prepared by UL LLC. It is normative for the applicable UL Product Certification Program(s); however, it is currently not part of the UL Standard(s) referenced below.

Product Category (CCN): AACD
Standard Number: UL 9540A
Standard Title: Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems
Edition Date: November 12, 2019
Edition Number: 4
Section / Paragraph Reference: 7.3.1.5
Subject: Option to do a continuous thermal ramp until thermal runaway

DECISION:

7.3.1.5 Before beginning the test, a surface temperature shall be determined to approximate the temperature at which internal short circuiting within the cell will occur that could lead to a thermal runaway condition. For Li-ion cells, the surface temperature hold point shall be between 5°C (9°F) and 15°C (27°F) greater than the melting temperature of the cell separator material as determined from differential scanning calorimetry (DSC) data of the separator in accordance with UL 2591 (UL 746A). Thermal runaway may occur before this hold point temperature range is reached. However, if thermal runaway is not achieved at this hold point temperature after a period of 4 h, the cell heating rate according to 7.3.1.2 shall be reestablished until thermal runaway occurs or it is demonstrated that thermal runaway is not achievable by heating.

Exception: If the separator information is not available or at the manufacturer's discretion, the thermal ramp can be conducted continuously without a hold point until thermal runaway.

RATIONALE FOR DECISION:

The cell failure method had always been a thermal ramp until thermal runaway occurred. The hold temperature was established because of concern that if the thermal ramp continued at too high of a temperature, it may melt the cell casing. However, the separator information may not always be available and it may be just easier to conduct the test with a continuous thermal ramp if the client is in agreement. In either case, the goal is to establish a thermal runaway condition.

UNDERWRITERS LABORATORIES INC. CERTIFICATION REQUIREMENT DECISION

This Certification Requirement Decision is prepared by UL LLC. It is normative for the applicable UL Product Certification Program(s); however, it is currently not part of the UL Standard(s) referenced below.

Product Category (CCN): AACD
Standard Number: UL 9540A
Standard Title: Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems
Edition Date: November 12, 2019
Edition Number: 4
Section / Paragraph Reference: 8.12, 8.13, 9.24, 9.25, 10.3.13
Subject: Corrections to gas measurement methods to make FTIR as an option for measuring hydrocarbon contents of gas emissions and to include Hydrogen measurements during the Unit Level Test.

DECISION:

8.2.132 The hydrocarbon content of the vent gas shall be measured using flame ionization detection. Hydrogen gas shall be measured with a palladium-nickel thin-film solid state sensor.

8.2.123 The hydrocarbon components of the Vvent gas composition may additionally shall be measured using a Fourier-Transform Infrared Spectrometer with a minimum resolution of 1 cm-1 and a path length of at least 2 m (6.6 ft), or an equivalent gas analyzer,. and vVelocity and temperature measurements respectively shall be obtained in the exhaust duct of the heat release rate calorimeter using equipment specified in 8.2.10.

9.2.24 The composition, velocity and temperature of the initiating BESS unit vent gases shall be measured within the calorimeter's exhaust duct as outlined in 8.2.10. The hydrocarbon content of the vent gas shall be measured using flame ionization detection. Hydrogen gas shall be measured with a palladium-nickel thin-film solid state sensor. Gas composition shall be measured using a Fourier-Transform Infrared Spectrometer with a minimum resolution of 1 cm-1 and a path length of at least 2.0 m (6.6 ft), or equivalent gas analyzer. Composition, velocity and temperature instrumentation shall be collocated with heat release rate calorimetry instrumentation.

9.2.25 The hydrocarbon content of the vent gas shall may additionally also be measured using flame ionization detection. a Fourier-Transform Infrared Spectrometer with a minimum resolution of 1 cm-1 and a path length of at least 2.0 m (6.6 ft), or equivalent gas analyzer

10.3.13 The composition of BESS unit vent gases shall be measured as outlined in Section 9.2.24. The hydrocarbon content may additionally be measured as outlined in accordance with 9.2.25 using a Fourier-Transform Infrared Spectrometer with a minimum resolution of 1 cm-1 and a path length of at least 2.0 m (6.6 ft), total hydrocarbon analyzer, and hydrogen analyzer. The gas composition sampling port shall be located in the ceiling jet, 25-mm (1-in) below the ceiling

RATIONALE FOR DECISION:

In the 4th edition of UL 9540A, there is redundancy in the two measurement methodologies used to characterize the volume of flammable gas released during module and unit level testing (Flame Ionization Detection (FID) and Fourier Transform Infrared Spectroscopy (FTIR)). Both FTIR and FID were developed as required measurements for module and unit level testing in the first three editions of UL 9540A before data existed that enabled an understanding of the typical compositions of battery gas. Both FID and FTIR were specified as requirements because it was not clear that FID alone would provide an adequate characterization of all flammable gases released by batteries in thermal runaway. Therefore, FTIR was first intended to provide a means to quantify non-hydrocarbon flammable gases as well as to serve as a backup for FID measurement. FTIR, to a lesser degree, was also identified as a potential backup or improvement for CO and CO_2. Experience has demonstrated that an improvement to CO and CO_2 measurement is not necessary and a backup to non-dispersive infrared spectroscopy (NDIR) measurement has not been needed. Therefore, the FTIR will remain in the standard but as an optional additional measurement method.

In addition, hydrogen is measured with a hydrogen specific sensor, because neither FID or FTIR are capable of measuring hydrogen.

The list of equipment in Table 1 demonstrates overlap in the methodologies used for gas measurement.

Table 1 – Gas measurement equipment for fire and explosion hazards

Gas Hazard	Measurement Equipment
Hydrocarbons	1. Total unburned hydrocarbons by flame ionization detector (FID) 2. Individual components by Fourier Transform infrared spectrometry (FTIR)
Carbon monoxide (CO), Carbon dioxide (CO_2)	1. Individual components by non-dispersive infrared spectrometry (NDIR) 2. Individual components by FTIR
Hydrogen	1. Hydrogen sensor

UNIT TEST REPORT
UL 9540A
Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems (AACD)

Project Number..............................:	**4790648531**
Date of issue ....:	**2023-06-28**
Total number of pages...................:	**56**
UL Report Office ....:	**UL Solutions** **333 Pfingsten Road** **Northbrook, IL 60062** **United States**
Applicant's name...........................:	**Samsung SDI Co Ltd**
Address ....:	**428-5 GONGSE-DONG GIHEUNG-GU** **YONGIN-SI, GYEONGGI-DO, 446-577** **KR**
Test specification:	4th Edition, Section 9, November 12, 2019
Standard...:	UL 9540A, Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems
Test procedure ....:	9.1 – 9.8
Non-standard test method ....:	

General disclaimer:

The test results presented in this report relate only to the sample tested in the test configuration noted on the list of the attachments.

UL LLC did not select the sample(s), determine whether the sample(s) was representative of production samples, witness the production of the test sample(s), nor were we provided with information relative to the formulation or identification of component materials used in the test sample(s).

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Cell level information	
Cells in Module:	
●Manufacturer Name	Samsung SDI
●Part Number	CP1495L101+
●Chemistry	Lithium-ion
●Format	Prismatic
Ratings (Vdc, Ah) :	3.68V, 145Ah
Cell certified? :	Yes
Standard the cell was certified to:	UL 1973
Organization that certified the cell:	UL Solutions (MH64496)
Average cell surface temperature at gas venting, °C:	166
Average cell surface temperature at thermal runaway, °C:	176
Gas Volume:	430.6
Lower flammability limit (LFL), % volume in air at the ambient temperature:	8.04
Lower flammability limits (LFL), % volume in air at the venting temperature:	6.74
Burning velocity (S_u) cm/s:	86.40
Maximum pressure (P_{max}) psig:	105.3

Cell level Gas Composition:

Gas	Measured %
Hydrogen	32.7
Carbon monoxide	40.9
Methane	15.43
Ethylene	0.56
Ethane	1.06
Carbon dioxide	9.2
Propene (Propylene)	0.04
Propane	0.03
C4 Total	0.05
C5 Total	0.01
Benzene	0.06
Total	**100**

Module level Information	
Model No.. :	MS3204L101A
Ratings (Vdc, Ah)............................ :	110.4VDC, 290Ah
Module dimensions (X x **Y** x **Z** (mm))……………….:	388.2 x 1751.8 x 155.0 mm
Module cell configuration (xS/**y**P) …...:	30S/2P
Module weight (kgs)………………………. :	173
Module enclosure material……………….. :	Plastic Cover : PC(M3020PN), 2.5T Mica Sheet 0.3t(&Aerogel) Sheet
Was the module certified? ………………………….:	Yes
Standard the module was certified to …………..:	UL 1973
Organization that certified test item …….:	UL Solutions (MH64496)
Number of initiating cells failed to achieve propagation.	1
Thermal Runaway Propagation:	Yes
External Flaming:	Yes
Location(s) of Flame Venting:	Flaming out of the top of the module
Flying Debris:	Yes
Re-ignitions:	No reignitions
Test Maximum Smoke Release Rate (m^2/s)	7.06
Test Total Smoke Released: (m^2)	3516.04
Test Peak Chemical Heat Release Rate: (kW):	3935

Module level test Gas Composition & Volume for Each Compound (Pre-flaming and After flame) :

Gas Compound	Gas Type	Pre-Flaming (L)	Flaming (L)	Minimum detectable flow rate(LPM)
Total Hydrocarbons (Propane Equivalent)	Hydrocarbons	6.61	677.14	0.04
Carbon Monoxide	Carbon Containing	Below detectable limit	39542.50	3.11
Carbon Dioxide	Carbon Containing	Below detectable limit	1421.12	0.44
Hydrogen[1]	Hydrogen	Below detectable limit	Below detectable limit	0.00

[1] *The hydrogen measurement system malfunctioned during the test; however, the same module design was tested with different charging specifications and the hydrogen quantity was below detectable limits – Please refer to the report under UL project 4790648531

Unit level Information	
Model No. :	PHR3843-001A
Ratings (Vdc, Ah)............................ :	1324.8V, 290 Ah
BESS dimensions (W x **D** x **H** (mm)**)……………….:**	960.5 * 1752 * 2352 mm
BESS module configuration	12S/1P
Number of modules in BESS	24
Module cell configuration (xS/**y**P**) …...:**	30S/2P
Number of cells in module.:	60
BESS weight (kgs)………………………. :	2524 kg
BESS enclosure material……………….. :	Metal case, Plastic Cover, Mica(&Aerogel) sheet
BESS Intended Installation: **Non Residential:** outdoor ground mounted, indoor floor mounted, outdoor wall mounted, indoor wall mounted, roof top, open garage **Residential:** Outdoor ground mounted, indoor floor mounted, outdoor wall mounted, indoor wall mounted	Non-Residential indoor floor mounted.
Residential Indoor Use: Smallest volume room installations specified.	N/A
Original Equipment Manufacturer (OEM):	Samsung SDI Co LTD
Branding Manufacturer (if not OEM):	N/A
Was the unit certified? ………………………….:	Yes
Standard the unit was certified to …………..:	UL 1973
Organization that certified the unit …….:	UL Solutions (MH49407)
Cell failure test method performed (summary of method and test clause): ☒ External heating using thin film with 4°C to 7°C thermal ramp. ☐ Nail Penetration ☐ Overcharge ☐ External short circuit (***X*** Ω *external resistance*) ☐ Others	
Description of method used to fail cells if other than external thin film heater with thermal ramp, : N/A	
Description of components employed within the BESS unit that serve to suppress propagation (fire protection features) The BESS Unit includes a smoke detection and NOVEC system as a fire suppression system. Once smoke is detected, a signal (signals from two smoke detectors) is sent to the fire control panel , which will open the solenoid valve on the NOVEC cylinder for NOVEC to be released into the integral suppression system pipes.	
Deviation from the module level test N/A	
Number of initiating cell(s)	1
Thermal Runaway Propagation:	No

External Flaming from BESS:	Yes
Location(s) of Flame Venting:	Front and Rear Top Surface
Maximum Target BESS Temperature, °C	20
Maximum Wall Surface Temperature[2], °C	172
Peak Chemical Heat Release Rate, kW	426
Peak Convective Heat Release Rate, kW	191
Maximum Smoke Heat Release Rate, m^2/s	1.1
Maximum Heat Flux on Target Modules, kW/m^2	0.70
Maximum Heat Flux of Egress Path, kW/m^2	6.74
Flying Debris:	No flying debris
Re-ignitions:	No reignitions

Gas Analysis:

☒ Flame ionization detection (FID)

☒ Non-Dispersive Infrared Spectrometer (NDIR)

☐ Fourier-Transform infrared Spectrometer

☒ Hydrogen Sensor (palladium-nickel, thin-film solid state sensor)

☒ White light source with photo detector (smoke release rate)

Summary of Unit level test Gas Analysis Data:

Unit level Gas Composition & Volume for Each Compound (Pre-flaming and After flame):

Gas Compound	Gas Type	Pre-Flaming (L)	Flaming (L)	Minimum detectable flow rate(LPM)
Total Hydrocarbons (Propane Equivalent)	Hydrocarbons[3]	Inconclusive	Inconclusive	2.21
Carbon Dioxide	Carbon Containing	Below detectable limit	343.97	11.24
Carbon Monoxide	Carbon Containing	Below detectable limit	789	8.91
Hydrogen	Hydrogen	Below detectable limit	Below detectable limit	20.67

[2] Maximum wall surface temperature averaged on 60 seconds.
[3] The increase of THC is due to NOVEC released from the system as the THC was analysed with FID.

Summary of BESS Unit Test Results
Performance Criteria in accordance with Table 9.1 for Indoor Floor Mounted non-residential unit
[ ] Flaming outside the initiating BESS unit was not observed; **[X]** Surface temperatures of modules within the target BESS units adjacent to the initiating BESS unit did not exceed the temperature at which thermally initiated cell venting occurs, as determined in 7.3.1.8; **[ ]** For BESS units intended for installation in locations with combustible constructions, surface temperature measurements on wall surfaces did not exceed 97°C (175°F) of temperature rise above ambient per 9.2.15; **[X]** Explosion hazards were not observed, including deflagration, detonation or accumulation (to within the flammability limits in an amount that can cause a deflagration) of battery vent gases; and **[ ]** Heat flux in the center of the accessible means of egress did not exceed 1.3 kW/m^2.

Necessity for an Installation level test
[X] The performance criteria of the unit level test as indicated in Table 9.1 of UL 9540A 4th edition has not been met, therefore an installation level testing in accordance with UL 9540A will need to be conducted on the representative the installation with this unit installed. **[ ]** The performance criteria of the unit level tests as indicated in Table 9.1 of UL 9540A 4th edition has been met, therefore an installation level testing in accordance with UL 9540A need not be conducted.

Testing Laboratory Information		
Testing Laboratory and testing location(s):		
Testing Laboratory:	UL Solutions	
Testing location/ address............................:	333 Pfingsten Road Northbrook, IL 60062 United States	
Tested by (name, signature) ....:	Jonathon Depasque	
Project Handler (name, signature)...............:	Bryan Chang	[signature]
Reviewer (name, signature) …………….:	Sean Yang	[signature]

List of Attachments (including a total number of pages in each attachment):
Attachment A: Sample Charging, OCV and SOC Measurement Profiles - (*Pages **25** through **28***)
Attachment B: BESS (including module and any integral fire detection and suppression systems) Construction Photos/Diagrams - (*Pages **29** through **32***)
Attachment C: BESS and Equipment Instrumentation and Test Installation Layout Photos/Diagrams - (*Pages **33** through **41***)
Attachment D: Temperature Profiles and Heat Flux Measurements During Testing (Initiating Cell and Module, Target Modules, Wall Surfaces, etc. - (*Pages **42** through **46***)
Attachment E: BESS Unit Testing and Post Testing Photos - (*Pages **47** through **50***)
Attachment F: BESS Unit Gas Flow Rate and Heat Release and Smoke Release Profiles - (*Pages **51** through **54***)
Attachment G: Certification Requirement Decision - (*Pages **55** through **56***)

Photo(s) of BESS unit:

Test Item Charge/Discharge Specifications:	
• **Charge current, A:**	90.0
• **Standard Full charge voltage, Vdc:**	124.5
• **Charge temperature range, °C:**	23 ± 5°C
• **End of charge current, A:**	58.0
• **Discharge current, A:**	58.0
• **End of discharge voltage, Vdc:**	93.0
• **Discharge temperature range, °C:**	23 ± 5°C

Test item particulars ....:	
Possible test case verdicts:	
- test case does not apply to the test object...........:	N/A
- test object does meet the requirement ....:	P (Pass)
- test object does not meet the requirement...........:	F (Fail)
- test object was completed per the requirement...:	C(Complete)
- test object was completed with modification……:	M(Modification)
Testing..:	
Date of receipt of test item ....:	2023-03-27
Date (s) of performance of tests...............................:	2023-04-06

General remarks:

"(See Enclosure #)" refers to additional information appended to the report.
"(See appended table)" refers to a table appended to the report.

Throughout this report a point is used as the decimal separator.

Manufacturer's Declaration of samples submitted for test:

The applicant for this report includes samples from more than one factory location and a declaration from the Manufacturer stating that the sample(s) submitted for evaluation is (are) representative of the products from each factory has been provided ....:	☐ **Yes** ☒ **Not applicable**
Name and address of factory (ies)..........................:	163, Bangudae-ro, Samnam-myeon, Ulju-gun, Ulsan, 689-710, Republic of Korea

General product information and other remarks:

The BESS Unit, Model PHR3843-001A, is composed of 12 MS3204L101A modules, rated 110.4V, 290Ah, in series Each module is composed of 60 cells in a 2P/30S configuration. Each cell, Model CP1495L101A, is rated 3.68V, 145Ah. The BESS Unit also includes a smoke detection and NOVEC system as a fire suppression system. Once smoke is detected, a signal is sent to the NOVEC system for NOVEC to be released into the BESS unit. The released NOVEC is intended to prevent thermal runaway propagation.

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

5.0	**CONSTRUCTION**		**Verdict**
5.3	**Battery energy storage system unit Construction**		—
5.3.1, 5.3.2	Construction information	See Test Item Description at the beginning of this report	—
5.3.2	General layout of BESS unit contents	See Attachment B	—
5.3.3	Details of integral fire suppression system	BESS Unit is installed with smoke detectors and a NOVEC System. Once smoke is detected, NOVEC is released to the system to cool down the modules.	
5.3.1	BESS certified to UL 9540	No	
	Organization that certified BESS:	N/A	—
6.0	**PERFORMANCE**		**Verdict**
6.1	**General**		
9.1	**Sample and test configuration**		
9.1.1	The unit level test conducted with BESS units installed as described in the manufacturer's instructions.	See Attachment C for test installations Installation type: Non-residential, indoor floor mounted.	C
9.1.2	The unit level test required one initiating BESS unit in which an internal fire condition in accordance with the module level test is initiated and target adjacent BESS units representative of an installation.	See Attachment C for test installations	C
	Tests conducted for indoor floor mounted installations are representative of both indoor floor mounted and outdoor ground mounted installations.	BESS Units are not intended for outdoor use.	N/A
	Tests conducted indoors with fire propagation hazards and separation distances between initiating and target units representative of the installation.	The distance between the initiating and target units is 0[mm].	C

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Clause	Requirement + Test	Result - Remark	Verdict

	Testing conducted outdoors for outdoor only installations with following in place: a) Wind screens with wind speed of ≤ 12 mph; b) Temperature range is 10°C to 40°C (50°F to 104°F); c) Humidity is < 90% RH; d) Sufficient light to observe the testing; e) There is no precipitation; f) There is control of vegetation and combustibles in the test area; and g) There are protection mechanisms in place to prevent inadvertent access by unauthorized persons in the test area.		C
9.1.3	Testing to determine fire characterization was done at the battery system level rather than a complete BESS		C
9.1.4	The initiating BESS contained components representative of a BESS unit in a complete installation.		C
	Combustible components that interconnect the initiating and target BESS units was included.		C
9.1.5	Target BESS units include the outer cabinet (if part of the design), racking, module enclosures, and components that retain cells components.		C
9.1.6	The initiating BESS was at the maximum operating state of charge (MOSOC),	See Table 2 and Attachment A	C
	After charging and prior to testing, the initiating BESS was at rest for a maximum period of 8 hours at room ambient.	See Table 2. The voltage of the initiating module was checked within 8 hours after charging and right before the test and no voltage drop was found. Based on this fact and at the request of Samsung, re-charging was not performed	M
9.1.7	The BESS unit included an integral fire suppression system.	The BESS units are installed with smoke detectors and a NOVEC System.	C
9.1.8	Electronics and software controls such as the battery management system (BMS) are not relied upon for this testing.		C
	Included a fire suppression control in accordance with UL 864 that is external to the BESS.	Fire suppression system is designed with the BESS.	N/A
9.2	**Test method – Indoor floor mounted BESS units**		

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict
9.2.1	Test room ambient temperature within 10°C (50°F) to 32°C (90°F).	See Table 2.	C
9.2.2	Access door(s) or panels on the initiating BESS unit and adjacent target BESS units were closed, latched and locked duration of the test.	The BESS units do not utilize doors or latches.	N/A
9.2.3	The initiating BESS unit was positioned adjacent to two instrumented wall sections.	See Attachment C.	C
9.2.4	Instrumented wall sections extend not less than 0.49 m (1.6 ft) horizontally beyond the exterior of target BESS units.		C
9.2.5	Instrumented wall sections were at least 0.61-m (2-ft) taller than the BESS unit height, but not less than 3.66 m (12 ft) in height above the bottom surface of the unit.		C
9.2.6	The surface of the instrumented wall sections was covered with 16-mm (5/8-in) gypsum wall board and painted flat black.	See Attachment C.	C
9.2.7	The initiating BESS unit was centred underneath an appropriately sized smoke collection hood of an oxygen consumption calorimeter.		C
9.2.8	The light transmission in the calorimeter's exhaust duct was measured using a white light source and photo detector. The smoke release rate was calculated.	See Table 12. See Attachment F.	C
9.2.9	The chemical and convective heat release rates were measured for the duration of the test.	See Table 12. See Attachment F.	C
9.2.10	The heat release rate measurement system was calibrated using an atomized heptane diffusion burner. The calibration was performed using flows of 3.8, 7.6, 11.4 and 15.2 L/min (1, 2, 3 and 4 gpm) of heptane.		C
9.2.11	The chemical heat release rate was measured using the following equipment: ● Paramagnetic oxygen analyser ● Non-dispersive infrared carbon dioxide and carbon monoxide analyser ● Velocity probe ● Type K thermocouple		C
9.2.12	The chemical heat release rate at each of the flows was calculated.		C
9.2.13	The physical spacing between BESS units (both initiating and target) and adjacent walls was representative of the intended installation.	See Attachment C.	C

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict
9.2.14	Separation distances were specified by the manufacturer for distance between: a) The BESS units and the instrumented wall sections; and b) Adjacent BESS units.	See Attachment C.	C
9.2.15	Wall surface temperature measurements were collected	See Table 6. See Attachment D.	C
	The intended installation is composed completely of non-combustible construction		C
9.2.16	Wall surface temperatures were measured in vertical array(s) at 152-mm (6-in) intervals for the full height of the instrumented wall sections using No. 24-gauge or smaller, Type-K exposed junction thermocouples.		C
	The thermocouples for measuring the temperature on wall surfaces were horizontally positioned in the wall locations to receive greatest thermal exposure from the initiating BESS unit.		C
9.2.17	Thermocouples were secured to gypsum surfaces and the thermocouple tip was depressed into the gypsum so as to be flush with the gypsum surface at the point of measurement .		C
9.2.18	Heat flux was measured with at least two water-cooled Schmidt-Boelter gauges at the surface of each instrumented wall: a) Both are collinear with the vertical thermocouple array; b) One is positioned to receive the greatest heat from the initiating module; and c) One is positioned to receive the greatest heat flux during potential propagation within the initiating BESS unit.		C
9.2.19	Heat flux was measured with 2 water-cooled Schmidt-Boelter gauges at the surface of each adjacent target BESS units facing initiating BESS unit: a) One is positioned at the elevation estimated to receive the greatest heat flux from the initiating module; and b) One is positioned at the elevation estimated to receive the greatest surface heat flux due to initiating BESS.		C

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Clause	Requirement + Test	Result - Remark	Verdict

9.2.20	Heat flux was measured with the sensing element of at least one water-cooled Schmidt-Boelter gauge positioned in the center of the accessible means of egress.		C
9.2.21	No. 24-gauge or smaller, Type-K exposed junction thermocouples were installed to measure the temperature of the surface proximate to the cells and between the cells and exposed face of the initiating module.	See Attachment C	C
	Each non-initiating module enclosure within the initiating BESS unit was instrumented with at least one No. 24-gauge or smaller Type-K thermocouple(s) within non-initiating modules.	See Attachment C	C
	Additional thermocouples were placed to account for convoluted geometries.		C
9.2.22	For residential use, the DUT was covered with a single layer of cheese cloth ignition indicator. The cheesecloth was untreated cotton cloth running 26 – 28 m2/kg with a count of 28 – 32 threads in either direction within a 6.45 cm^2 (1 in^2) area.		N/A
9.2.23	An internal fire condition in accordance with the module level test was created within a single module in the initiating BESS unit: a) The position selected to present the greatest thermal exposure to adjacent modules; and b) The setup was the same as that used to initiate and propagate thermal runaway within the module level test.	See Attachment C	C
9.2.24	The composition, velocity and temperature of the initiating BESS unit vent gases was measured within the calorimeter's exhaust duct. Composition, velocity and temperature instrumentation shall be collocated with heat release rate calorimetry instrumentation.		C
	Hydrogen gas shall be measured with a palladium-nickel thin-film solid state sensor.		C
	The hydrocarbon content of the vent gas may also be measured using a Fourier-Transform Infrared Spectrometer with a minimum resolution of 1 cm-1 and a path length of at least 2 m (6.6 ft), or equivalent gas analyzer.	See Attachment F.	N/A
9.2.25	The hydrocarbon content of the vent gas was measured using flame ionization detection.	See Tables 8, 9, 10 and 11.	C

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

9.7	**Unit level test report**		
9.7.1	Installation type tested:		C
9.7.2	Testing is intended to represent more than one installation type.	See Test Item Description in beginning of this report.	C
9.7.3	a. Unit manufacturer name and model number (and whether UL 9540 compliant);		C
	b. Number of modules in the initiating BESS unit		C
	c. BESS construction features;	See Attachment C. See Critical Components Table. ð See Also “Description of components employed within the module that impact propagation (fire protection features)” at the beginning of this report.	C
	d. Fire protection features/ detection/ suppression systems within unit		C
	e. Module voltages corresponding to the tested SOC;	See Table 13. See Attachment A.	C
	f. Thermal runaway initiation method used;	See Attachment C.	C
	g. Location of the initiating module within the BESS unit;	See Attachment C.	C
	h. Diagram and dimensions of the test setup including mounting location of the initiating and target BESS units, and the locations of walls, ceilings, and soffits;	See Attachment C.	C
	i. Observation of any flaming outside the initiating BESS enclosure and the maximum flame extension;	See Table 14.	C
	j. Chemical and convective heat release rate versus time data;	See Table 11. See Attachment F.	C
	k. Separation distances from the initiating BESS unit to target walls	See Attachment C	C
	l. Separation distances from the initiating BESS unit to target BESS units	See Attachment C	C
	m. The maximum wall surface and target BESS temperatures achieved during the test and the location of the measuring thermocouple;	Tables 5 and 6.	C
	n. The maximum ceiling or soffit surface temperatures achieved during the indoor or outdoor wall mounted test and the location of the measuring thermocouple;	Table 6.	C
	o) The maximum incident heat flux on target wall surfaces and target BESS units;	Table 7.	C

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict
	p) The maximum incident heat flux on target ceiling or soffit surfaces achieved during the indoor or outdoor wall mounted test;	Table 7.	C
	q. Flammable gas generation and composition data;	See Attachment F. See Tables 7, 8, 9, and 10.	C
	r. Peak smoke release rate and total smoke release data.	See Table 12. See Attachments F.	C
	s. Indication of the activation of integral fire protection systems and if activated the time into the test at which activation occurred;	Table 13 See Attachment D.	C
	t. Observation(s) of flying debris or explosive discharge of gases;	See Attachment E and Table 15 .	C
	u. Observation of re-ignition(s) from thermal runaway events	See Attachment E and Table 16.	C
	v. Observation(s) of sparks, electrical arcs, or other electrical events;	See Attachment E and Table 15.	C
	w. Observations of the damage to: 1) The initiating BESS unit; 2) Target BESS units; 3) Adjacent walls, ceilings, or soffits;	See Attachment E and Table 16.	C
	x. Video of the test.	The videos were provided to Samsung on the testing date.	C
9.8	**Performance at Unit level testing**		
9.8.1	Installation level testing in Section 10 was not required if the following performance conditions outlined in Table 9.1 are met during the unit level test.		F

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

Non-Residential Installations – Indoor floor mounted:			
	a) Flaming outside the initiating BESS unit is not observed;	Flaming was observed outside the initiating unit.	F
	b) Surface temperatures of modules within target BESS units do not exceed the cell venting temperature;	The maximum surface temperature of the modules in the Target Units was 31°C.	P
	c) For BESS units intended for installation in locations with combustible constructions, surface temperature measurements on wall surfaces do not exceed 97°C (175°F) rise above ambient;	The maximum surface temperature on the walls was 169°C.	F
	d) Explosion hazards are not observed, including deflagration, detonation or accumulation (to within the flammability limits in an amount that can cause a deflagration) of battery vent gases;	An explosion was observed during the test.	P
	e) Heat flux in the center of the accessible means of egress did not exceed 1.3 kW/m^2.	The heat flux gauge in line with the initiating module in the front wall measured 6.74kW/m^2.	F

Table 1 – Specified Unit charging and discharging parameters			
Charging:		**Discharging:**	
Current (CC), A	90.0	Current (CC), A	58.0
Standard Full Charge Voltage, Vdc	124.5	End of discharge voltage, Vdc	93.0
End of charge current, A	58.0	Discharging Test Ambient, °C	23 ± 5
Refer to Attachment A for charge/discharge profiles.			

Table 2 - Test Initiation Details	
Test Date	2023-04-06
Test Start Time (HH:MM:SS)	13:26:04
Initial Lab Temperature, °C	30
Initial Relative Humidity % RH	19
Module OCV at Start of Test, Vdc	124

Table 3 – Approximate time of thermal runaway propagation through module			
Locations (Cell #)	**Event**	**Time**	**Temperature of the cell**
Cell 33	Vent	00:42:17	164
Cell 33	Thermal Runaway	00:42:25	179

Table 4 – Test overview timeline		
Time (HH:MM:SS)	**Event**	**Description**
00:00:00	Test Start	Start of the Test, the thermocouple located on the side of the cell was used to monitor the temperature ramp to be within 4 to 7 °C/minute.
00:42:17	Initiating Cell Vent	Venting of Initiating Cell; Based on the temperature data, a sudden temperature dip was observed which was the indication of venting from the cell level test. Venting gas begins to release from the battery.
00:42:25	Initiating Cell Thermal Runaway	The initiating cell goes into thermal runaway; this was determined by the temperature rise in an uncontrollable manner indicating self-heating along with the gas released from the initiating module. . At this event, the power supply to the heaters was disconnected.
00:42:30	Ignition	External flaming was observed following thermal runaway of the initiating cell.
00:42:32	Two Seconds after Ignition	Following ignition, flaming was only observed above the initiating module.
00:42:30 – 00:47:39	External Flaming on the Camera	External flaming was observed following thermal runaway of the initiating cell on the camera installed in the rear wall. The external flaming on the camera lasts approximately for five minutes.

00:42:29	Smoke Detection – Alarm LED Turns On	Following the release of venting gas, the smoke detectors located at the top of the BESS unit activate and sends a sign to the NOVEC System. The system would release NOVEC based on signals from two different smoke detectors, however, based on the video analysis, which was the only analysis available to identify the time of smoke detection, it was not inconclusive to pinpoint the second smoke detector sending the signal.
00:42:30	NOVEC Release	Once the system detects smoke, a signal is sent to the NOVEC system to release the NOVEC to the battery modules.
00:54:42 – 01:08:23	NOVEC Flowing Over	NOVEC was observed overflowing and evaporating from the initiating module.
03:00:51	Test End	The data recording was stopped; however, the units remained in the testing room overnight until all the temperatures went down to the ambient temperature before the disposal.

Table 5 - Maximum Temperatures in Target Units			
Cell vent temperature from cell test data, °C			166
Target Unit 1		**Target Unit 2**	
Module Location No.	Temperature (°C)	Module Location No.	Temperature (°C)
Module 1	19	Module 1	15
Module 2	17	Module 2	15
Module 3	18	Module 3	15
Module 4	17	Module 4	15
Module 5	17	Module 5	15
Module 6	16	Module 6	15
Module 7	16	Module 7	15
Module 8	18	Module 8	15
Module 9	19	Module 9	15
Module 10	17	Module 10	15
Module 11	17	Module 11	15
Module 12	20	Module 12	16

Table 6 - Maximum Temperatures on Instrumented Wall					
Side Wall Temperatures					
Ambient Temperature: 39°C					
UL 9540A performance criteria, Ambient + 97°C: 127°C					
Height, mm (in)	Maximum Temperature (°C)	Height, mm (in)	Maximum Temperature (°C)	Height, mm (in)	Maximum Temperature (°C)
152.4 (6)	13	1371.6 (54)	13	2590.8 (102)	21
304.8 (12)	13	1524 (60)	13	2743.2 (108)	21
457.2 (18)	13	1676.4 (66)	13	2985.6 (114)	21
609.6 (24)	13	1828.8 (72)	13	3048 (120)	22
762 (30)	13	1981.2 (78)	13	3200.4 (126)	21
914.4 (36)	13	2133.6 (84)	14	3352.8 (132)	20
1066.8 (42)	13	2286 (90)	16	3505.2 (138)	21
1219.2 (48)	13	2438.4 (96)	21		
Front Wall Temperatures					
Height, mm (in)	Maximum Temperature (°C)	Height, mm (in)	Maximum Temperature (°C)	Height, mm (in)	Maximum Temperature (°C)
152.4 (6)	35	1371.6 (54)	101	2590.8 (102)	37
304.8 (12)	56	1524 (60)	78	2743.2 (108)	35
457.2 (18)	74	1676.4 (66)	71	2985.6 (114)	30
609.6 (24)	172	1828.8 (72)	63	3048 (120)	23
762 (30)	165	1981.2 (78)	61	3200.4 (126)	20
914.4 (36)	155	2133.6 (84)	53	3352.8 (132)	22
1066.8 (42)	119	2286 (90)	47	3505.2 (138)	19
1219.2 (48)	89	2438.4 (96)	44		
Note: Temperatures are measured constantly and then averaged every 60-seconds					

Table 7 – Heat Flux Measurements			
Summary of maximum heat flux in target units		Summary of maximum heat flux measured on instrumented walls	
Maximum Heat Flux, kW/m²			
Target Module No. 1:	0.01	Heat Flux Gauge No.	kW/m²
Target Module No. 2:	0.70	Side Wall (Mid-Height)	0.01
		Side Wall (Initiating Module)	0.04
		Front Wall (Mid-Height)	6.74
		Front Wall (Initiating Module)	4.20

Table 8 – Gases measured and measurement methods used in unit level testing			
Measurement Method	**Gases Measured**	**Chemical Formula**	**Gas Type**
Flame Ionization Detection (FID)	Total Hydrocarbons	-	Hydrocarbons
Solid-state Hydrogen Sensor	Hydrogen	H_2	
Non-dispersive infrared spectroscopy (NDIR)	Carbon Dioxide	CO_2	Carbon Containing
	Carbon Monoxide	CO	Carbon Containing
~~[ ] Fourier-Transform Infrared Spectrometer (FTIR)~~	~~Acetylene~~	~~C_2H_2~~	~~Hydrocarbons~~
	~~Ethylene~~	~~C_2H_4~~	~~Hydrocarbons~~
	~~Methane~~	~~CH_4~~	~~Hydrocarbons~~
	~~Methanol~~	~~CH_3OH~~	~~Hydrocarbons~~
	~~Propane~~	~~C_3H_8~~	~~Hydrocarbons~~
	~~Formaldehyde~~	~~CH_2O~~	~~Hydrocarbons (Aldehydes)~~
	~~Hydrogen Bromide~~	~~HBr~~	~~Hydrogen Halides~~
	~~Hydrogen Chloride~~	~~HCl~~	~~Hydrogen Halides~~
	~~Hydrogen Fluoride~~	~~HF~~	~~Hydrogen Halides~~
	~~Ammonia~~	~~NH_3~~	~~Nitrogen Containing~~
	~~Hydrogen Cyanide~~	~~HCN~~	~~Nitrogen Containing~~
# - This table was modified to reflect the gases measured during testing.			

Table 9 - Gas generation periods	
Time	**Condition**
00:42:17 – 00:42:25	Pre-Flaming
00:42:25 – 03:00:51	Flaming
External Flaming of Gas	
Condition	**Duration (hh:mm:ss)**
External Flaming of Vent Gases:	00:05:09

Table 10 – Summary of battery gas volumes for deflagration hazard calculations				
Gas Component	Gas Type	During Pre-flaming (L)	During Flaming (L)	Minimum detectable flow rate(LPM)
Total Hydrocarbons (Propane Equivalent)	Hydrocarbons[4]	Inconclusive	Inconclusive	2.21
Carbon Dioxide	Carbon Containing	Below detectable limit	343.97	11.24
Carbon Monoxide	Carbon Containing	Below detectable limit	789	8.91
Hydrogen	Hydrogen	Below detectable limit	Below detectable limit	20.67

Table 11 – Smoke and heat release rate			
Heat Release Rate (HRR)		**Smoke Release Rate (SRR)**	
Peak Chemical HRR (kW)	426	Maximum SRR (m^2/s)	1.1
Peak Convective HRR, (kW)	191	Total Smoke Released (m^2)	269.37

Table 12 – Integral Fire suppression system Details of Operation		
Time of operation of Sprinklers/Suppression System:	Time of Operation Start (HH:MM:SS)	Length of Operation (HH:MM:SS)
Smoke Detection[5]	00:42:29	00:00:01
NOVEC Release	00:42:30	00:12:53

4 The increase of THC is due to NOVEC released from the system as the THC was analysed with FID.
5 The system would release NOVEC based on signals from two different smoke detectors, however, based on the video analysis, which was the only analysis available to identify the time of smoke detection, it was not inconclusive to pinpoint the second smoke detector sending the signal.

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

Table 13 - Module OCV voltage measurement comparison before and after testing			
Module Location In Rack	OCV Prior to Test (V)	OCV Post Test (V)	Difference (V)
1	122.50	122.49	0.01
2	122.40	122.40	0.00
3	122.40	122.40	0.00
4	122.70	122.67	0.03
5	122.70	122.67	0.03
6	122.60	122.56	0.04
7	122.48	122.48	0.00
8	122.31	122.30	0.01
9	122.60	122.30	0.30
10 (Initiating)	123.10	122.78	0.32
11	122.55	122.55	0.00
12	122.40	122.40	0.00

Table 14 – Other Observations during Unit test		
	Observed, Yes/No	Comments/Location
Flaming outside of Unit	Yes	Flaming was observed at the front and rear of the initiating module.
Flying debris	No	
Explosive discharge of gas	Yes	
Sparks or electrical arcs	No	

Table 15 - Post Test Observations	
Thermal runaway behaviour	Yes
Re-ignitions	No reignitions
Explosions	No explosions
Other Observations	Batteries exhibited thermal runaway behaviour during disposal

TABLE: Critical components information					
Object / Part No.	**Manufacturer/ trademark**	**Type / model**	**Technical data**	**Standard**	**Mark(s) of conformity**
Cell	SAMSUNG SDI	CP1495L101A	145 Ah, 3.68 V	UL1973	UL Approved (MH64496)
Module	SAMSUNG SDI	MS3204L101A	2P30S, 32.016kWh	UL 1973	RU (MH49407)
Unit Enclosure	SAMSUNG SDI	PHR3843-001A	2P360S 384.192kWh	UL 1973	RU (MH49407)
Rack Assembly (for module, BCU both)	TEXON CO., LTD	SGHC / SGCC	t3.2, W960.5, L1752.0, H2352.0	-	-
Internal Wiring	JHOSIN HONGLIN TECHTRON	Type3817	AWG1, 125℃	UL 758	UL Approved (E115797)
Thermal Insulating Materials	Hanjung NCS	Mica, Aerogel	-	-	-
Smoke Detectors	POTTER	PAD300-PD	Addressable Smoke Detector	UL 268	Listed (S24776)
Fire Control Panel	POTTER	IPA-100	Addressable FACP	UL 864	Listed (S735)
Suppressant	3M	FK-5-1-12, 3MTMNovecTM1230 Fire Protection Fluid	>50kg of Novec Fluid, 360psi with nitrogen	-	-
NOVEC cylinder	GFI	F1230-CYL-58	-	-	-
Swaged Nipple Assy	GFI	SQF2S-1-7/ 8-12UN-OF1.5-SDI-S6	Orifice 1.50	-	-
Solenoid Valve	Fiwarec	F1120045	- 20 to 50 ℃	UL 864	UL Approved (S35768)
Plastic plug	LOTTE Chem	PP J-320	-	-	-
Pipes	Hanjung NCS	Brass	3/8”	-	-

Attachment A: Sample Charging, OCV and SOC Measurement Profiles - (*Pages **25** through **28***)

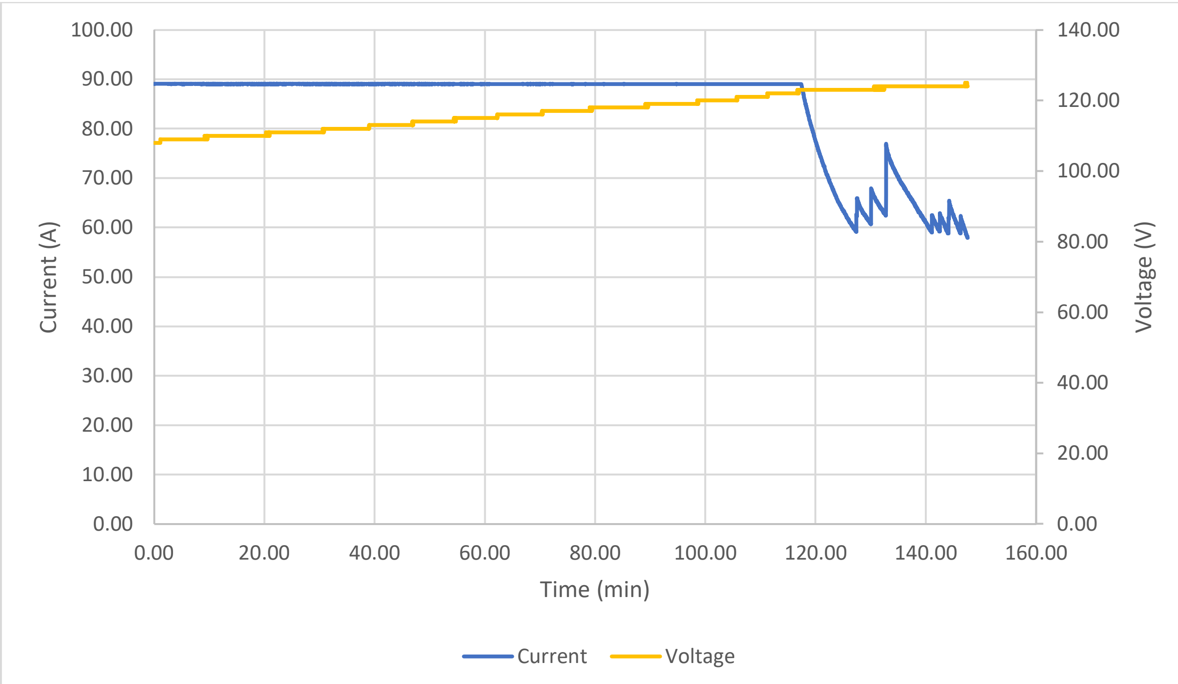


Figure A1 – Charge Profile for Initiating Module

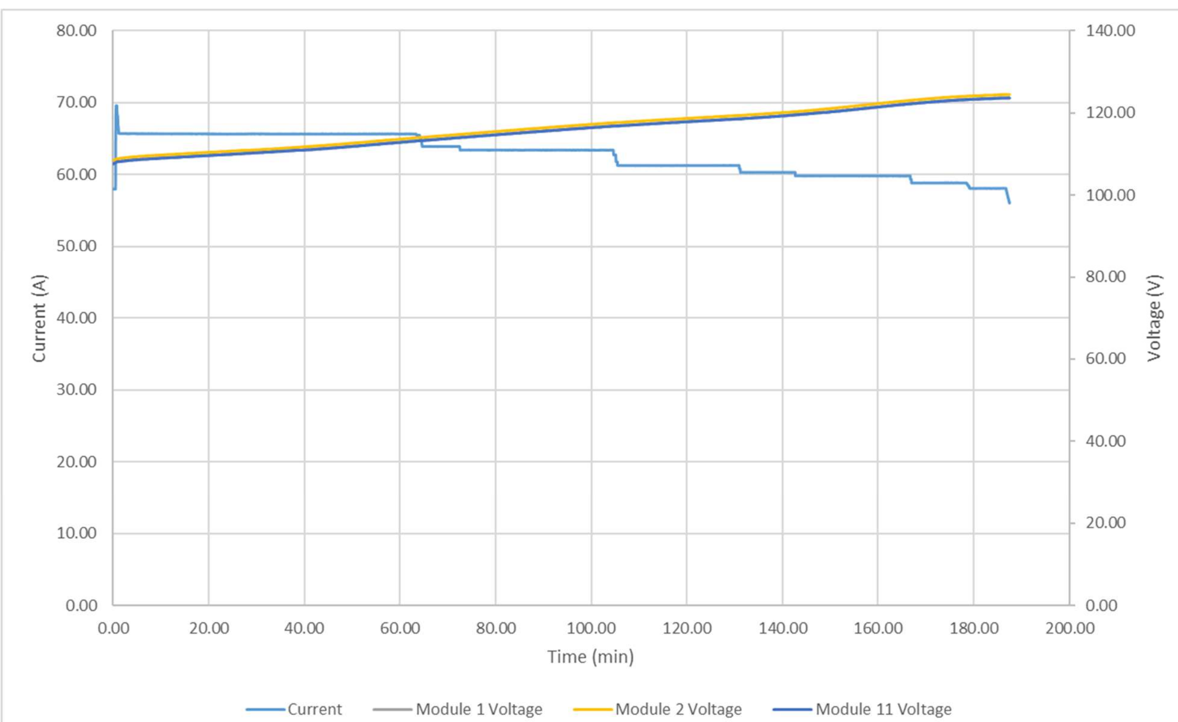


Figure A2 – Charge Profile for Modules 1, 2 and 11

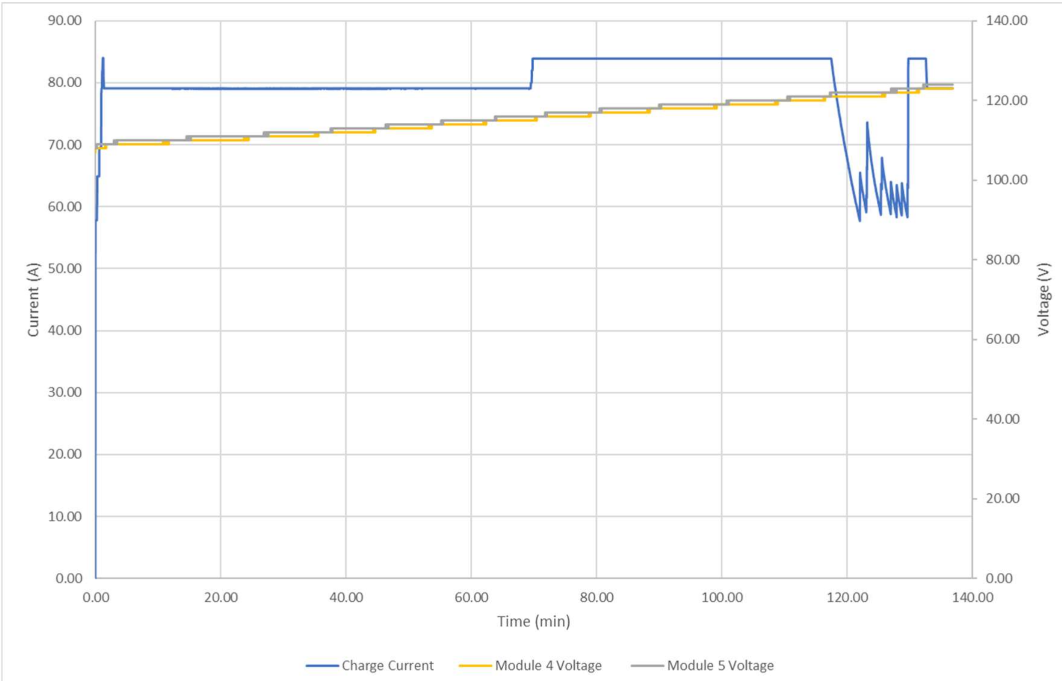


Figure A3 – First Charge Profile for Modules 4 and 5

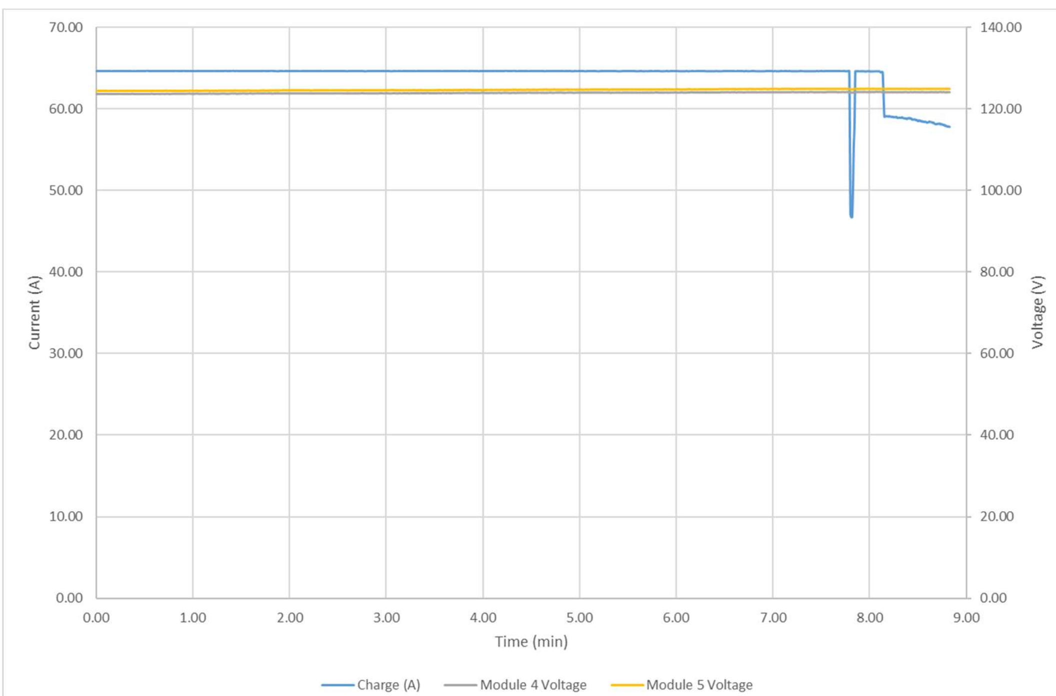


Figure A4 – Second Charge Profile for Modules 4 and 5

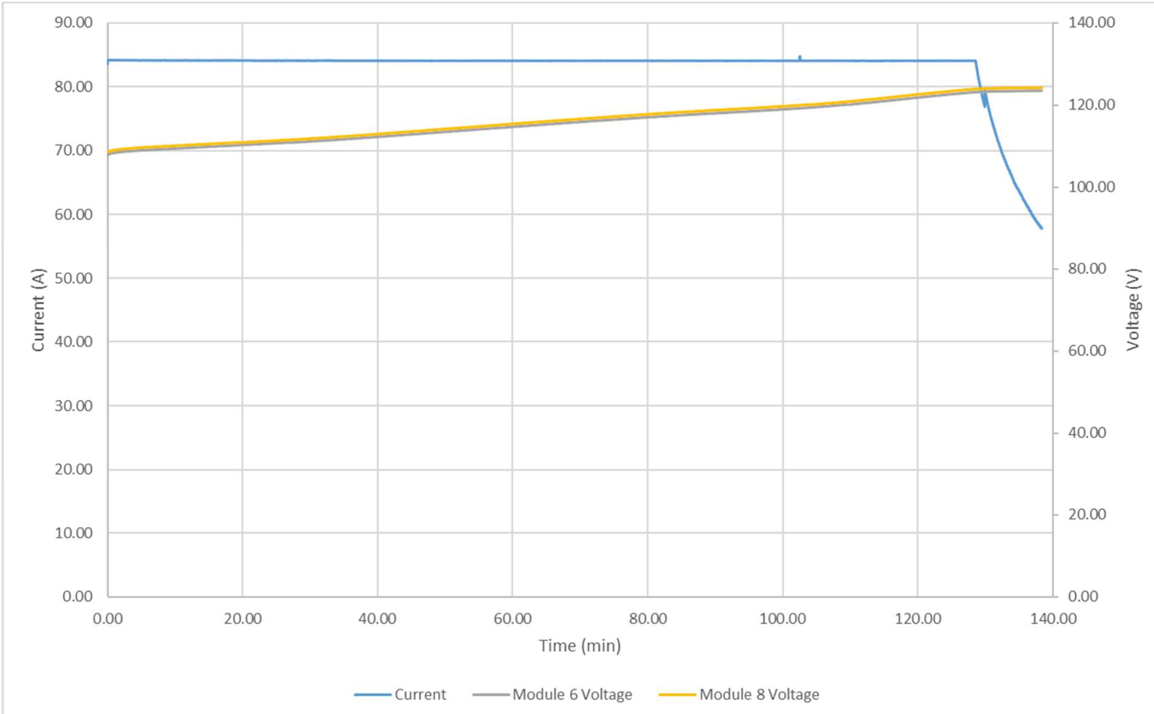


Figure A5 – Charge Profile for Modules 6 and 8

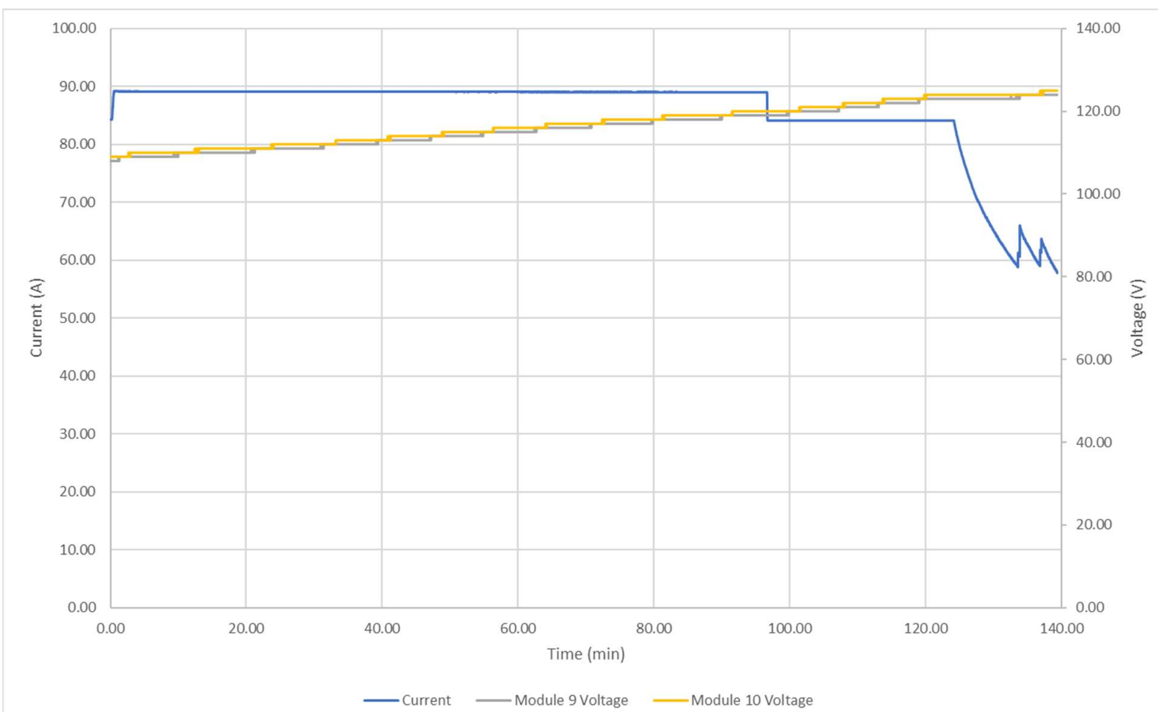


Figure A6 – Charge Profile for Modules 9 and 10

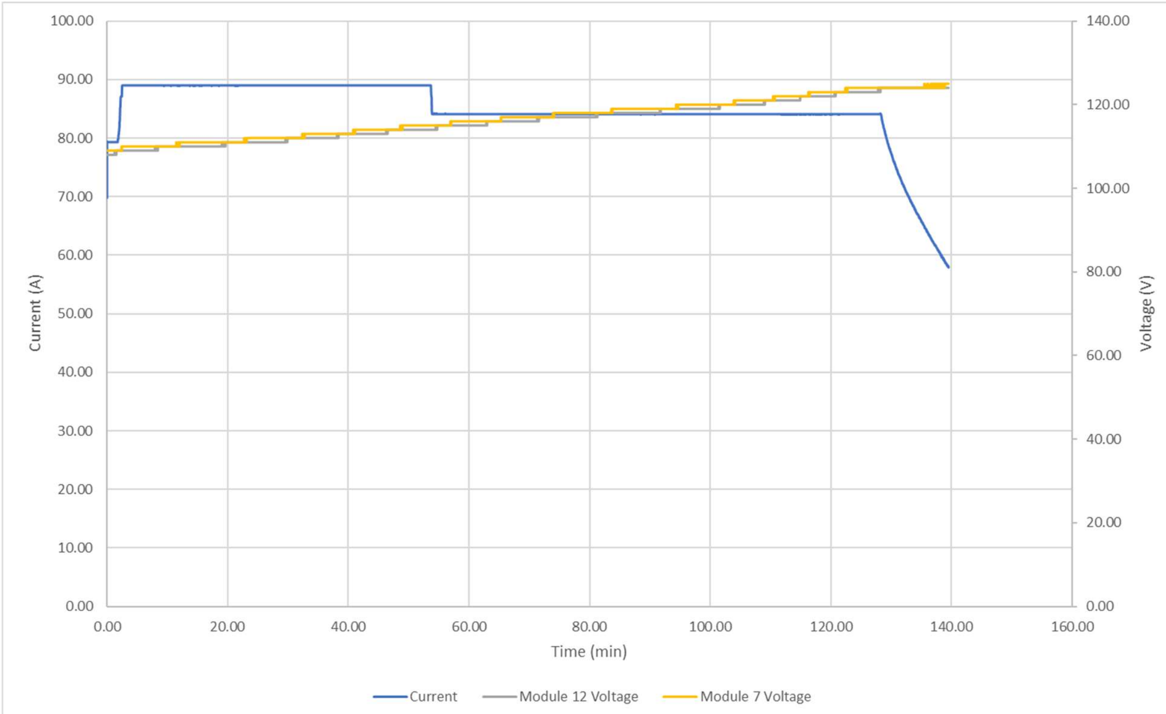


Figure A7 – Charge Profile for Modules 7 and 12

Attachment B: BESS (including module and any integral fire detection and suppression systems) Construction Photos/Diagrams - (*Pages **29** through **32***)

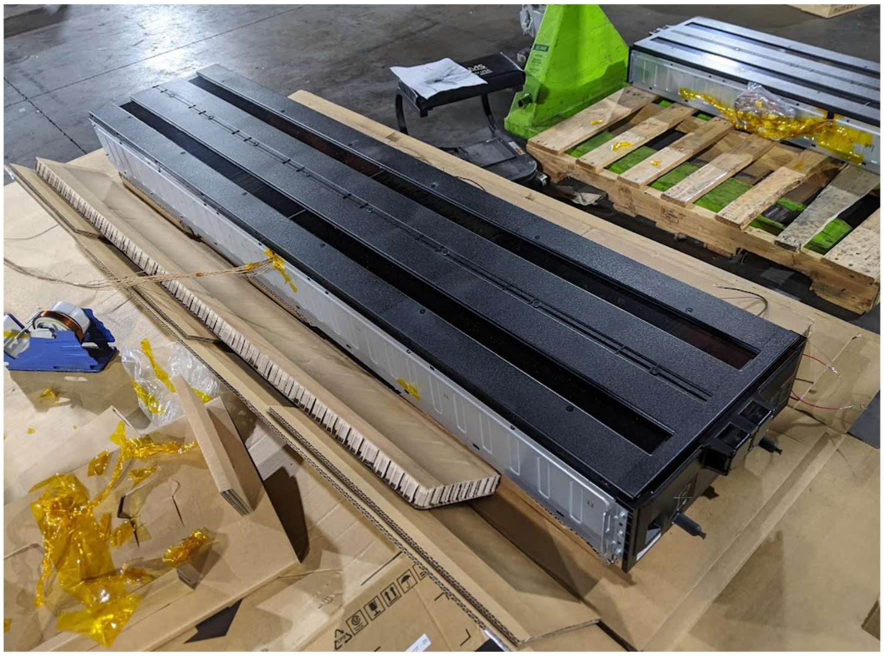


Figure B1 – Overall view of the Initiating Module

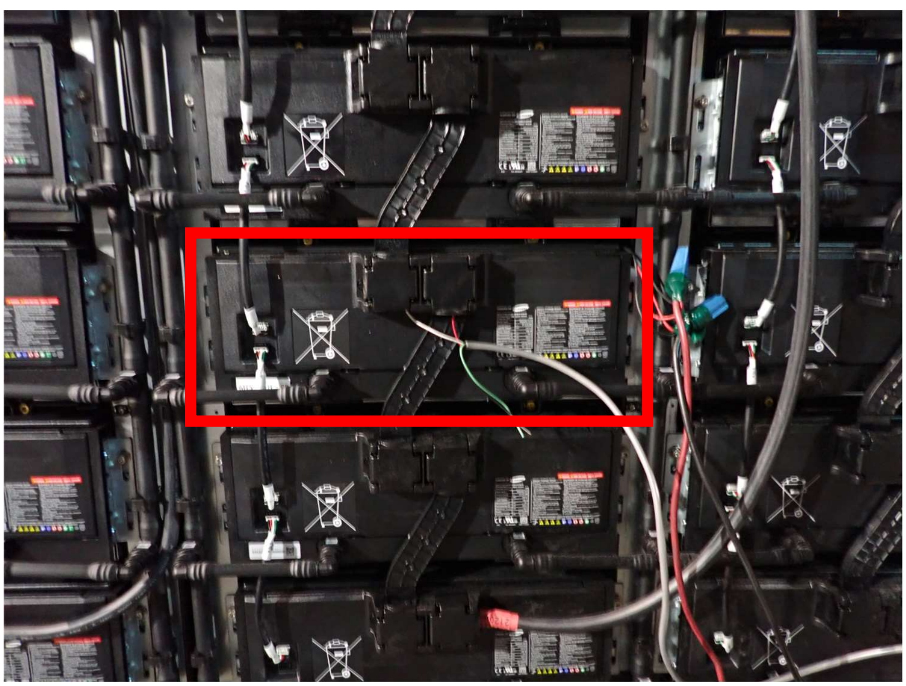


Figure B2 – Front view of the Initiating Module in the Initiating Unit (The third module from the bottom)

Figure B3 – Overall View of the Initiating and Target Units

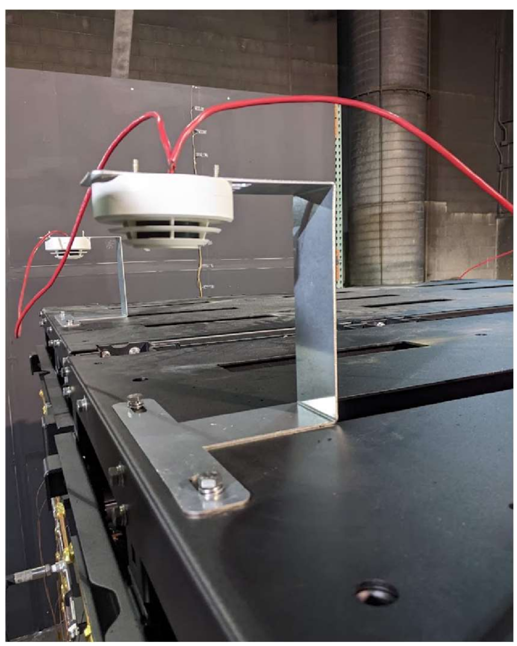


Figure B4 – Smoke Detectors Located on Top of Units

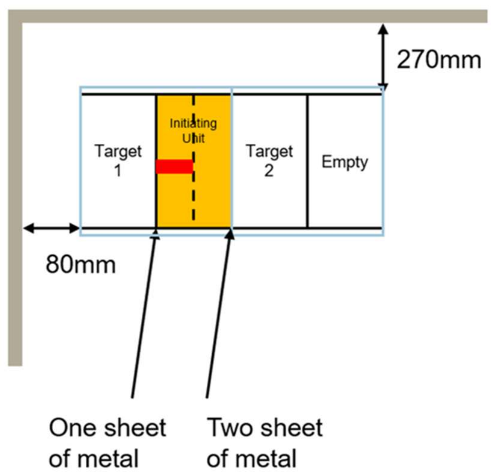
Figure B5 – Fire Panel System – Connected to the NOVEC Release System

Figure B6 –NOVEC cylinder with Connected pressure transducer and flow meter– only one cylinder was used and the other cylinder near the wall was a spare cylinder.

Figure B7 – Dummy Racks with NOVEC Piping[6]

[6] The dummy racks were used to simulate a potential pressure drop expected in the field. As more racks can be installed in the field, which could cause a pressure drop. The dummy rack was designed and provided by Samsung SDI.

Attachment C: : BESS and Equipment Instrumentation and Test Installation Layout Photos/Diagrams - (*Pages **33** through **41***)



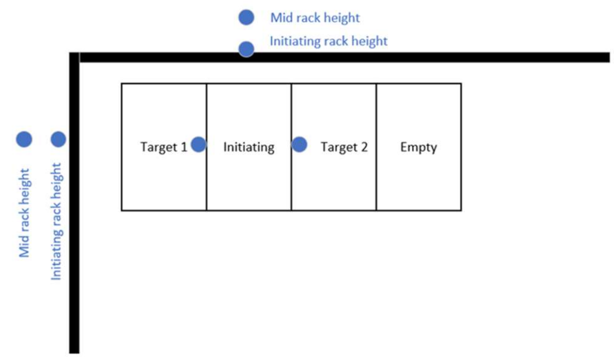
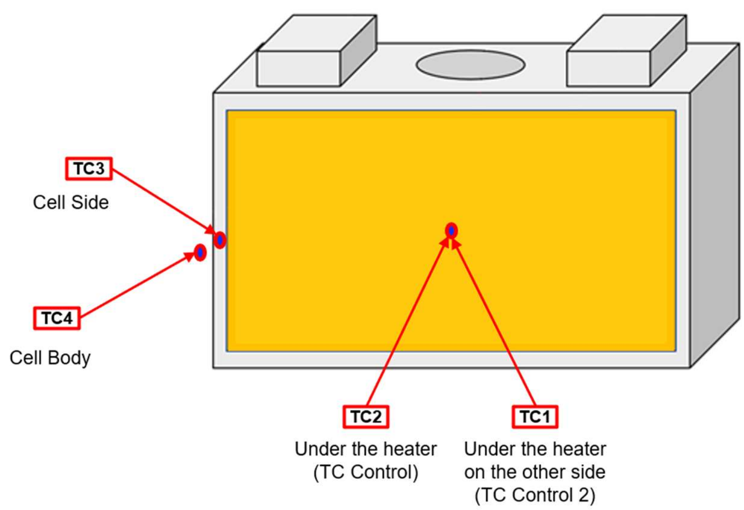
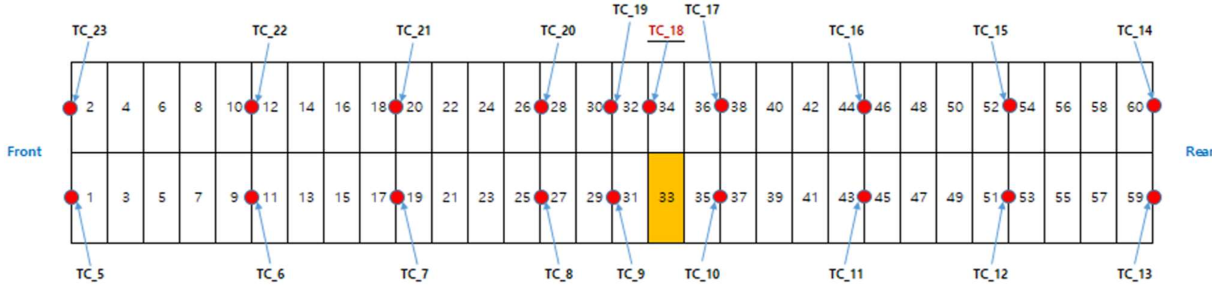


Figure C1 – Unit Configuration and Heat Flux Gauge Plan – Blue dots represent heat flux gauges installed in the instrumented walls and target units.



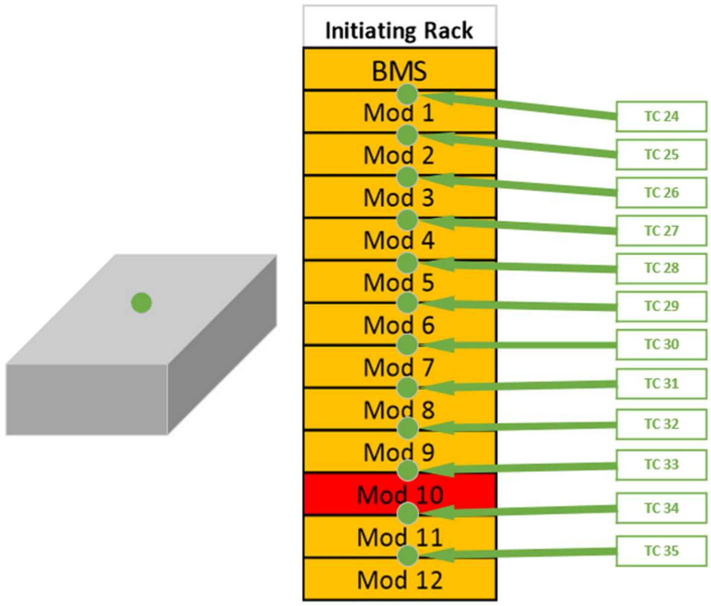
Thermocouple #	Description of Thermocouple Location
1	Heater Control – Located under the heater
2	Backup to Heater Control
3	Cell Side – Adjacent to the heater
4	Cell Body – On the surface perpendicular to the heated surface

Figure C2 – Thermocouple Locations and Descriptions for the Initiating Cell



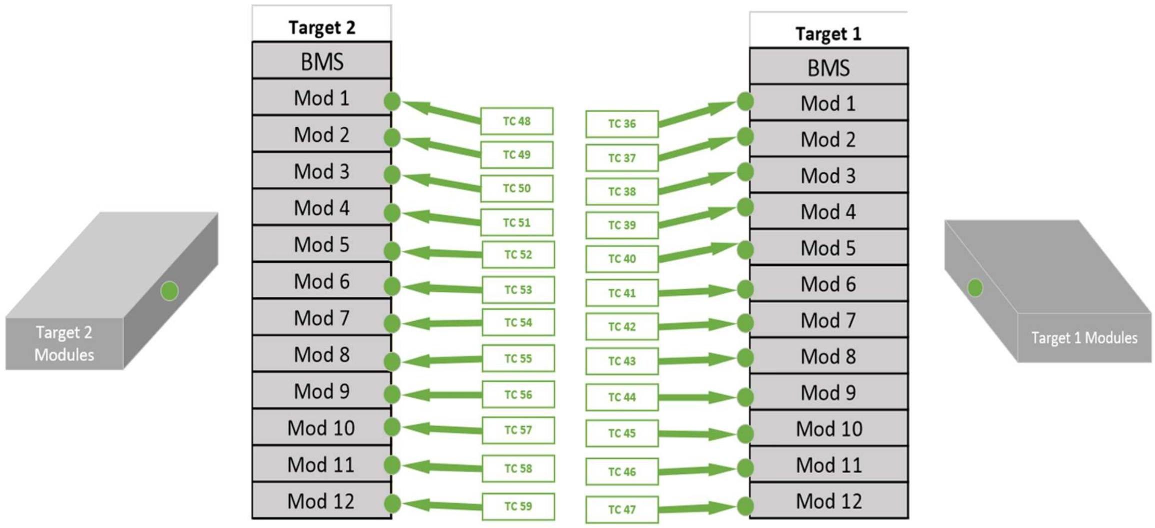
Thermocouple #	Description of Thermocouple Location
5	Cell 1
6	Cell 11
7	Cell 19
8	Cell 27
9	Cell 31
10	Cell 35
11	Cell 43
12	Cell 51
13	Cell 59
14	Cell 60
15	Cell 52
16	Cell 44
17	Cell 36
18	Cell 34
19	Cell 32
20	Cell 28
21	Cell 20
22	Cell 12
23	Cell 2

Figure C3 – Thermocouple Locations and Descriptions for the Initiating Module



Thermocouple #	Description of Thermocouple Location
24	Initiating Unit - Module 1
25	Initiating Unit - Module 2
26	Initiating Unit - Module 3
27	Initiating Unit - Module 4
28	Initiating Unit - Module 5
29	Initiating Unit - Module 6
30	Initiating Unit - Module 7
31	Initiating Unit - Module 8
32	Initiating Unit - Module 9
33	Initiating Unit - Module 10
34	Initiating Unit - Module 11
35	Initiating Unit - Module 12

Figure C4 – Thermocouple Locations and Descriptions for the Initiating Rack



Thermocouple #	Description of Thermocouple Location	Thermocouple #	Description of Thermocouple Location
36	Target 1 - Module 1	48	Target 2 - Module 1
37	Target 1 - Module 2	49	Target 2 - Module 2
38	Target 1 - Module 3	50	Target 2 - Module 3
39	Target 1 - Module 4	51	Target 2 - Module 4
40	Target 1 - Module 5	52	Target 2 - Module 5
41	Target 1 - Module 6	53	Target 2 - Module 6
42	Target 1 - Module 7	54	Target 2 - Module 7
43	Target 1 - Module 8	55	Target 2 - Module 8
44	Target 1 - Module 9	56	Target 2 - Module 9
45	Target 1 - Module 10	57	Target 2 - Module 10
46	Target 1 - Module 11	58	Target 2 - Module 11
47	Target 1 - Module 12	59	Target 2 - Module 12

Figure C5 – Thermocouple Locations and Descriptions for Target Units

Table C1 – Thermocouple Locations on Instrumented Walls

Thermocouple #	Description of Thermocouple Location	Thermocouple #	Description of Thermocouple Location
60	Front Wall - 6 inches	83	Side Wall - 6 inches
61	Front Wall - 12 inches	84	Side Wall - 12 inches
62	Front Wall - 18 inches	85	Side Wall - 18 inches
63	Front Wall - 24 inches	86	Side Wall - 24 inches
64	Front Wall - 30 inches	87	Side Wall - 30 inches
65	Front Wall - 36 inches	88	Side Wall - 36 inches
66	Front Wall - 42 inches	89	Side Wall - 42 inches
67	Front Wall - 48 inches	90	Side Wall - 48 inches
68	Front Wall - 54 inches	91	Side Wall - 54 inches
69	Front Wall - 60 inches	92	Side Wall - 60 inches
70	Front Wall - 66 inches	93	Side Wall - 66 inches
71	Front Wall - 72 inches	94	Side Wall - 72 inches
72	Front Wall - 78 inches	95	Side Wall - 78 inches
73	Front Wall - 84 inches	96	Side Wall - 84 inches
74	Front Wall - 90 inches	97	Side Wall - 90 inches
75	Front Wall - 96 inches	98	Side Wall - 96 inches
76	Front Wall - 102 inches	99	Side Wall - 102 inches
77	Front Wall - 108 inches	100	Side Wall - 108 inches
78	Front Wall - 114 inches	101	Side Wall - 114 inches
79	Front Wall - 120 inches	102	Side Wall - 120 inches
80	Front Wall - 126 inches	103	Side Wall - 126 inches
81	Front Wall - 132 inches	104	Side Wall - 132 inches
82	Front Wall - 138 inches	105	Side Wall - 138 inches

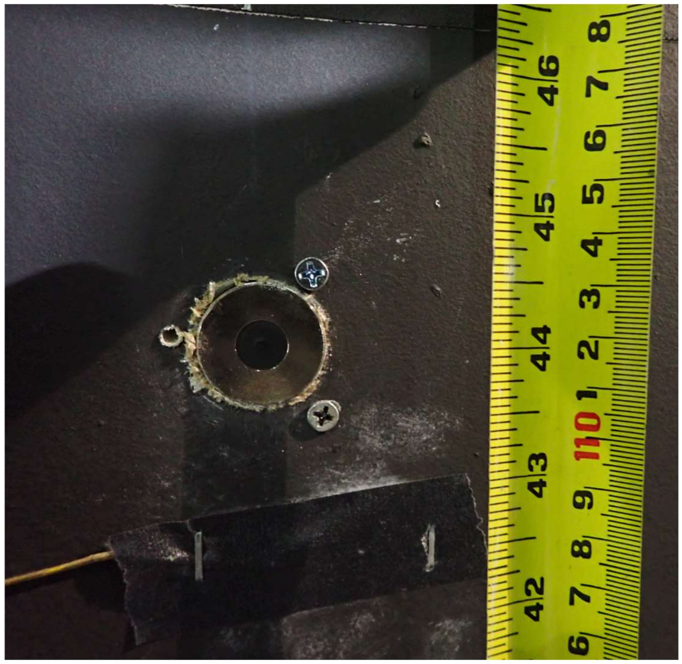


Figure C6 – Heat Flux Installed in the Front Wall at Mid-Unit Height

Figure C7 – Heat Flux Installed in the Front Wall at Initiating Module Height

Figure C8 – Heat Flux in Front Wall Centered with Initiating Unit

Figure C9 – Heat Flux Heat Flux Installed in the Side Wall at Mid-Unit Height

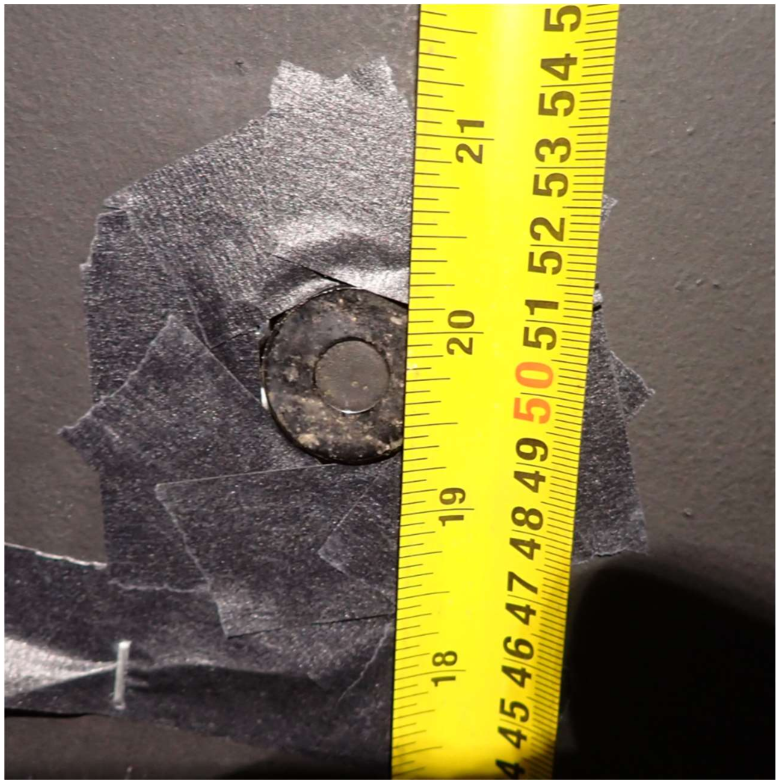


Figure C10 - Heat Flux Installed in the Side Wall at Initiating Module Height

Figure C11 – Heat Flux Installed in the Target Units

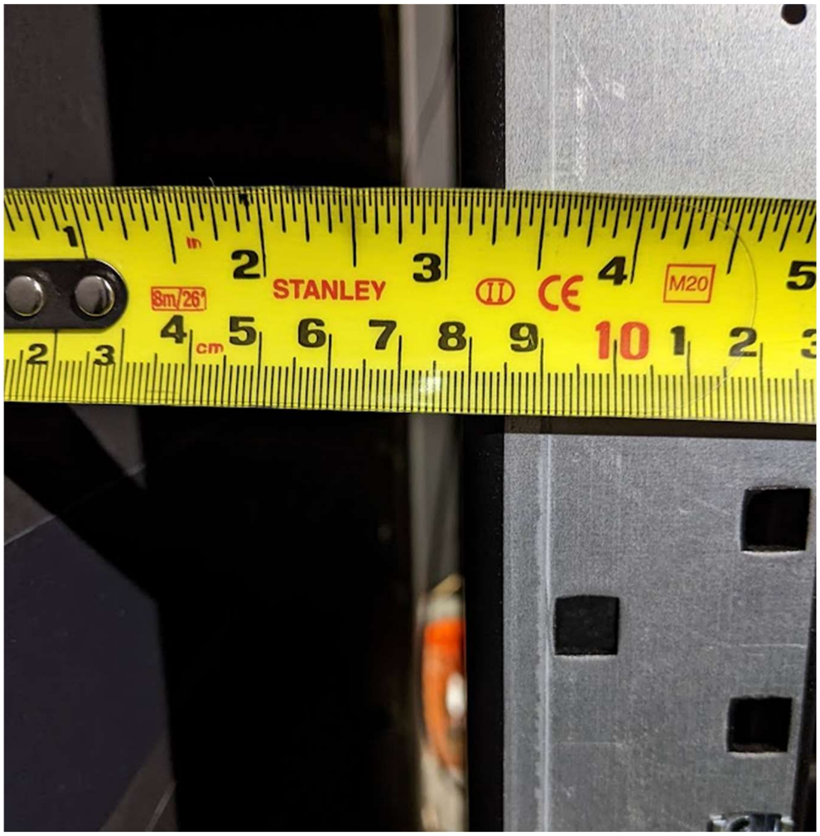


Figure C12 – Distance from Side Wall to Target Unit 2

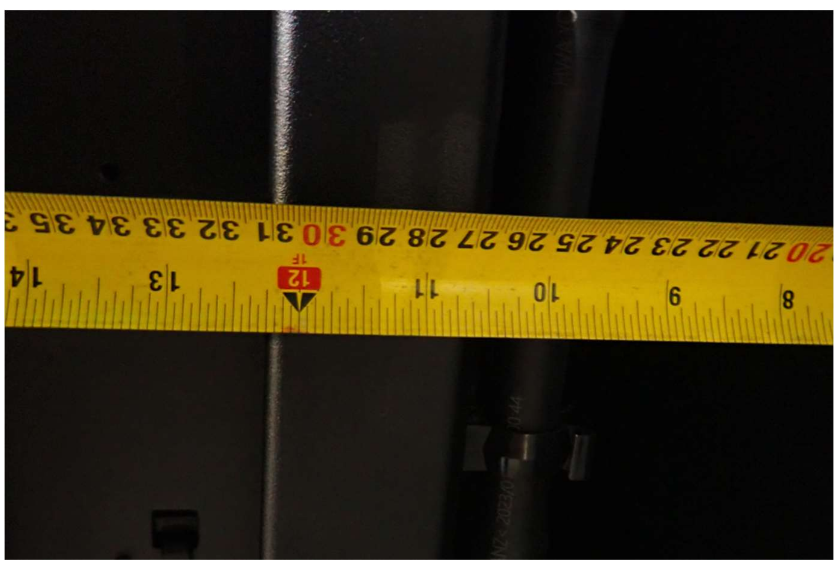


Figure C13 – Distance from Front Wall to Rear of Units

Attachment D: Temperature Profiles and Heat Flux Measurements During Testing (Initiating Cell and Module, Target Modules, Wall Surfaces, etc. - (*Pages **42** through **46***)

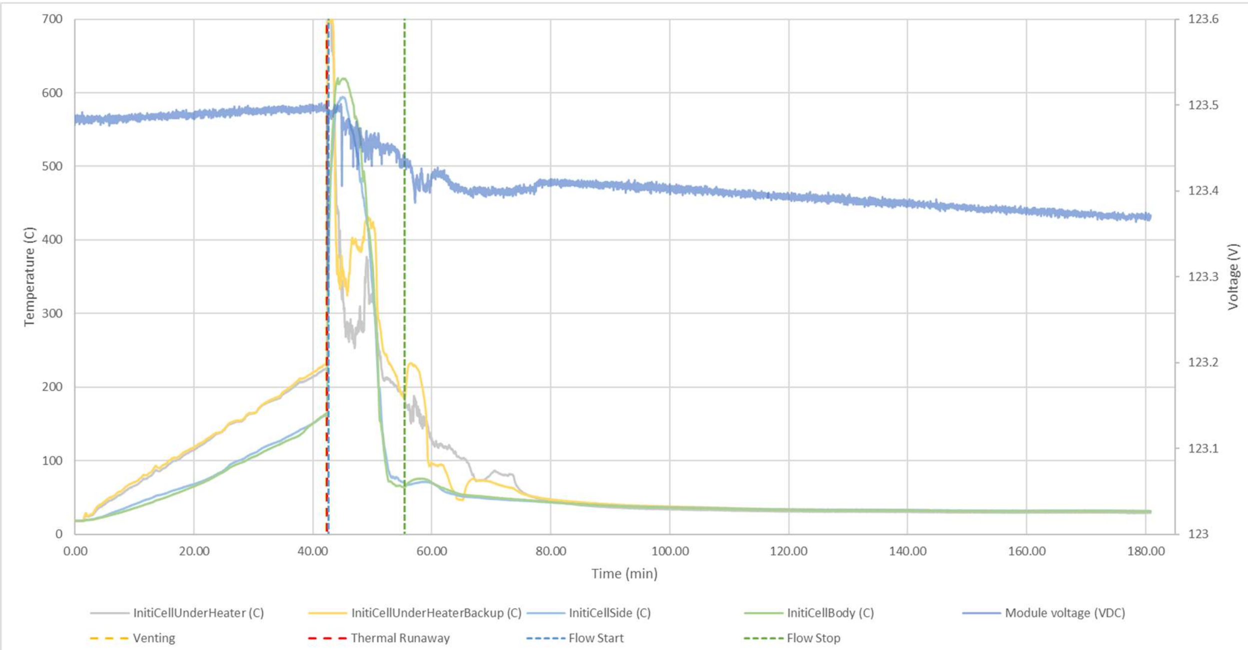


Figure D1 – Temperature Profiles for Initiating Cell (Cell 33)

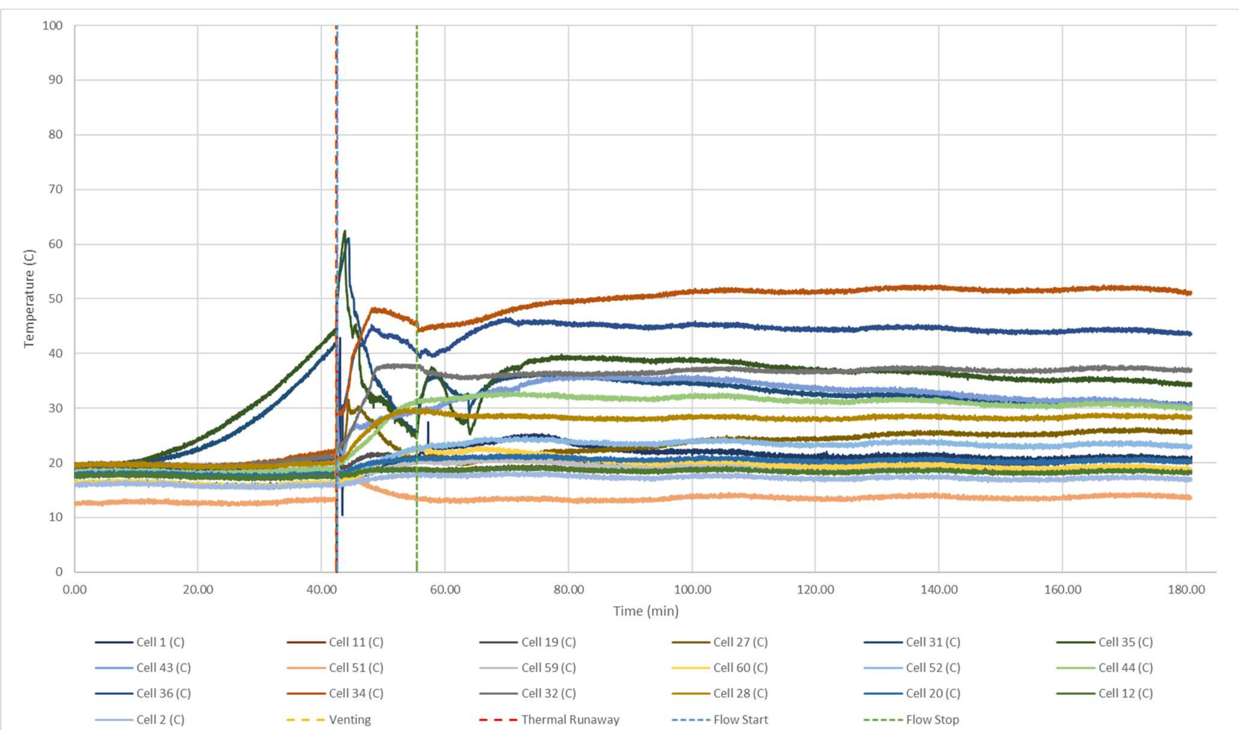


Figure D2 – Temperature Profiles for Non-Initiating Cells

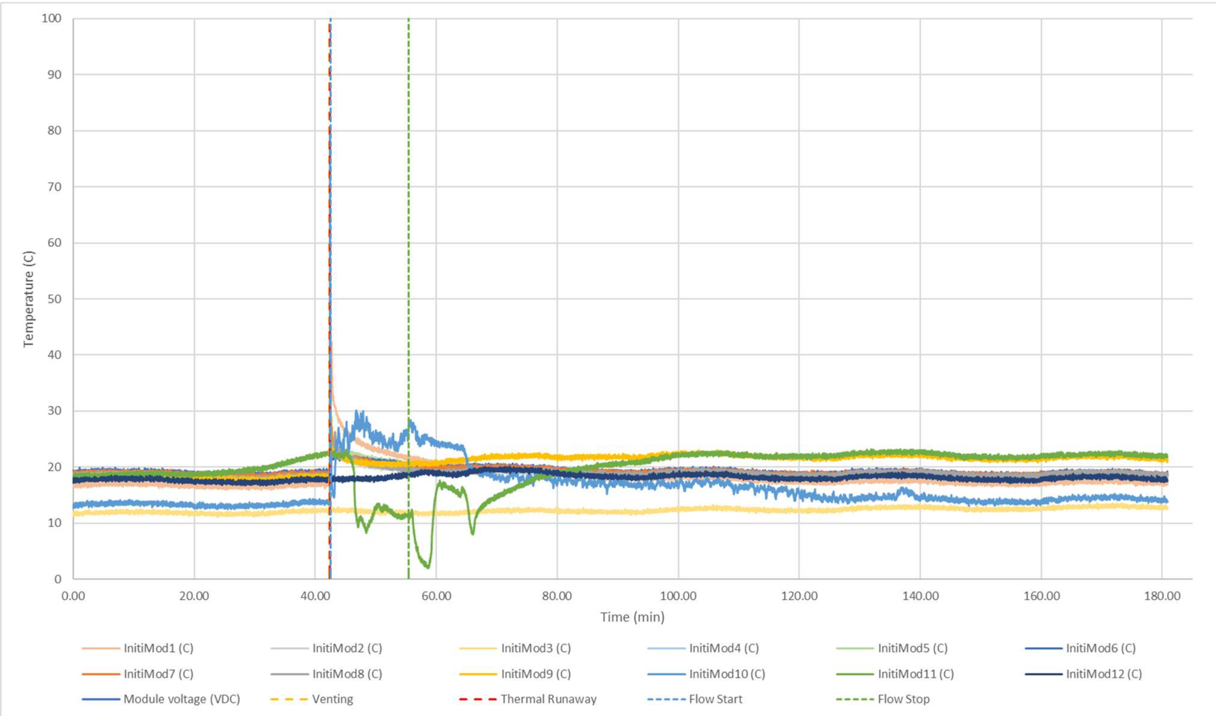


Figure D3 – Temperature Profiles for Modules in the Initiating Module

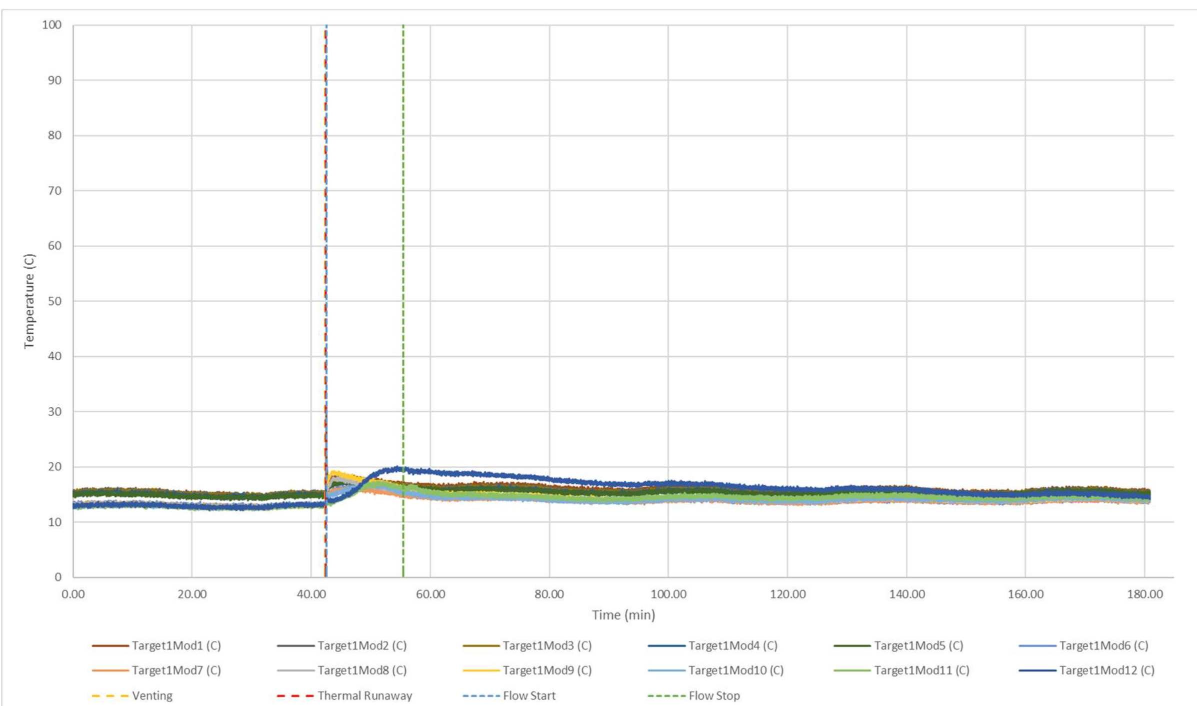


Figure D4 – Temperature Profiles for Modules in Target Unit 1

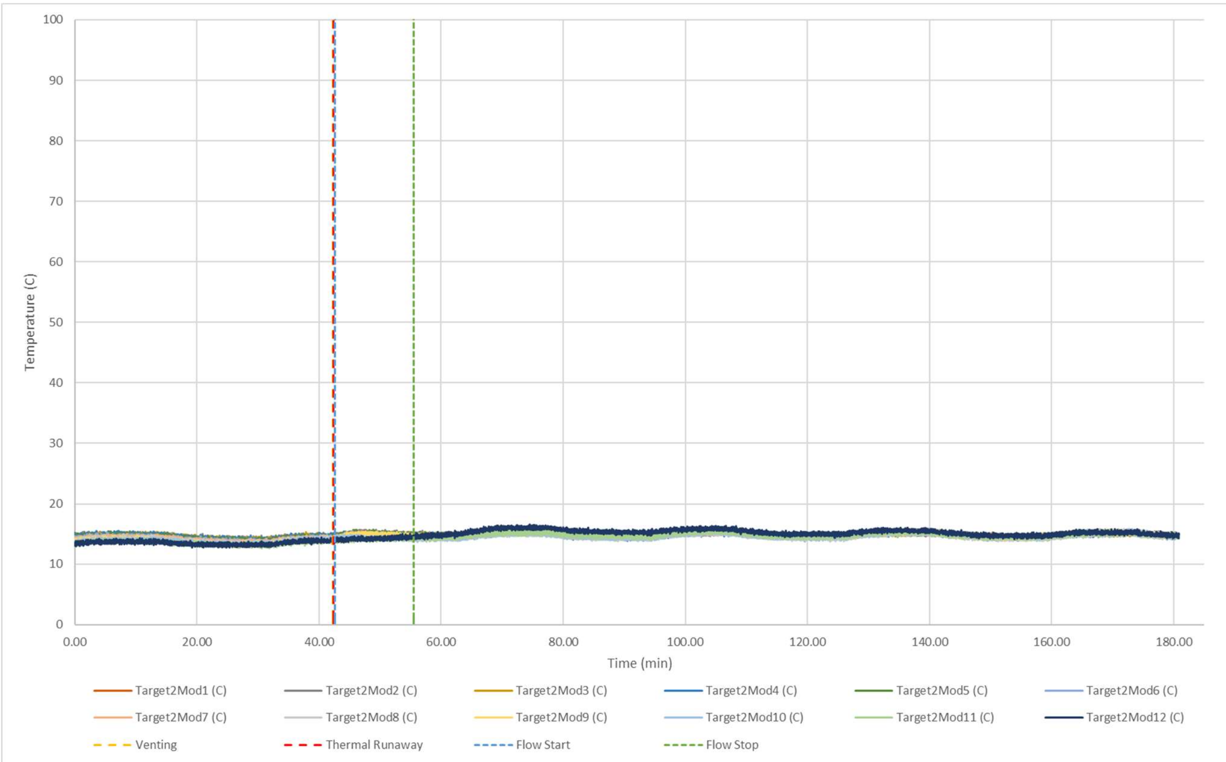


Figure D5 – Temperature Profiles for Modules in Target Unit 2

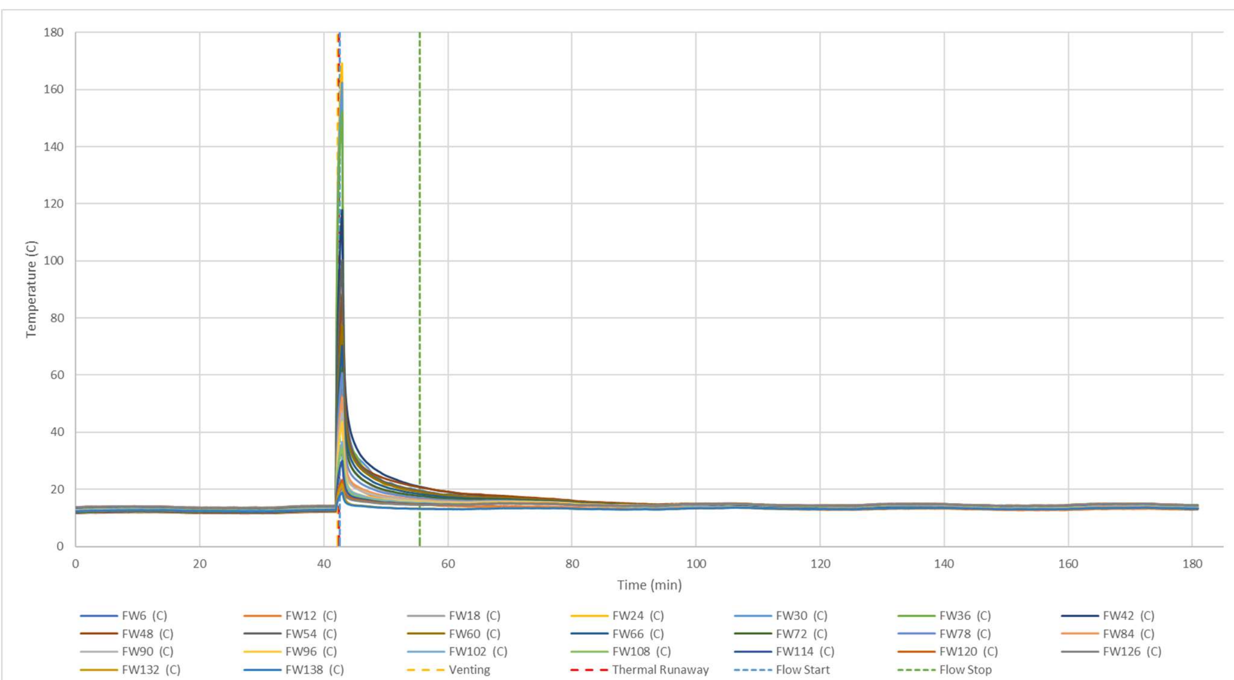


Figure D6 – Temperature Profiles for the Front Wall

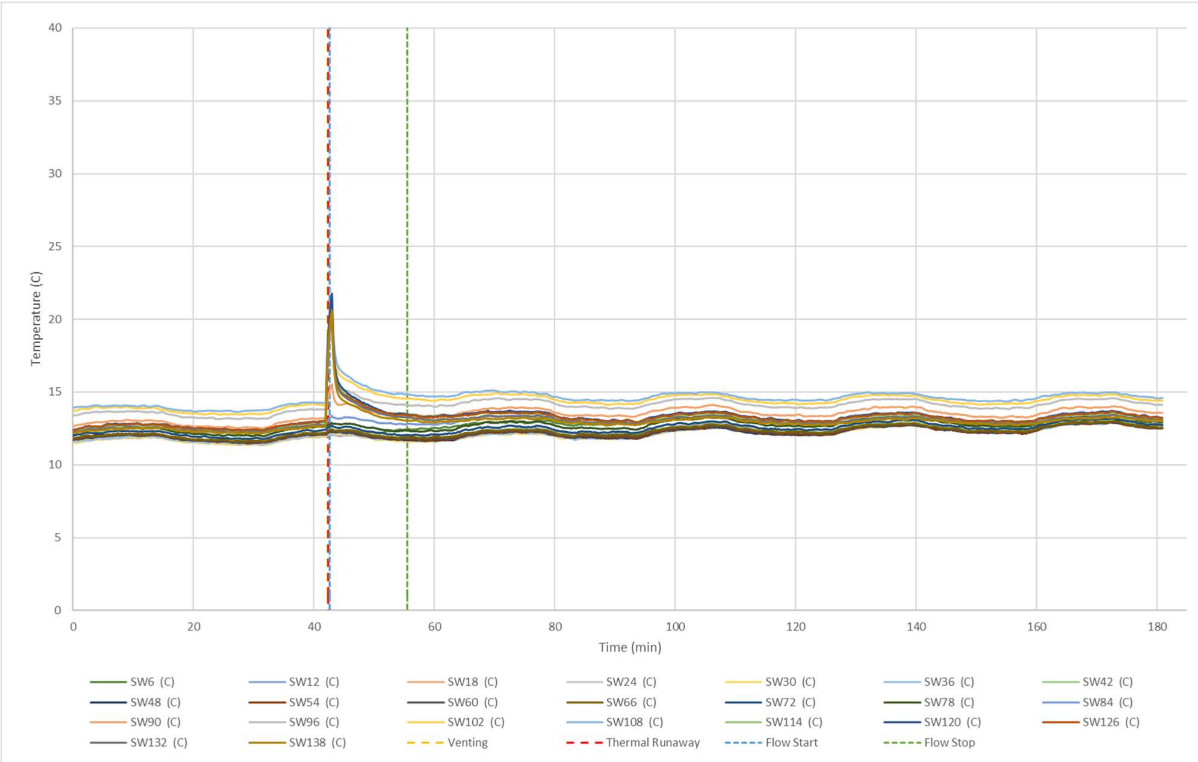


Figure D7 – Temperature Profiles for the Side Wall

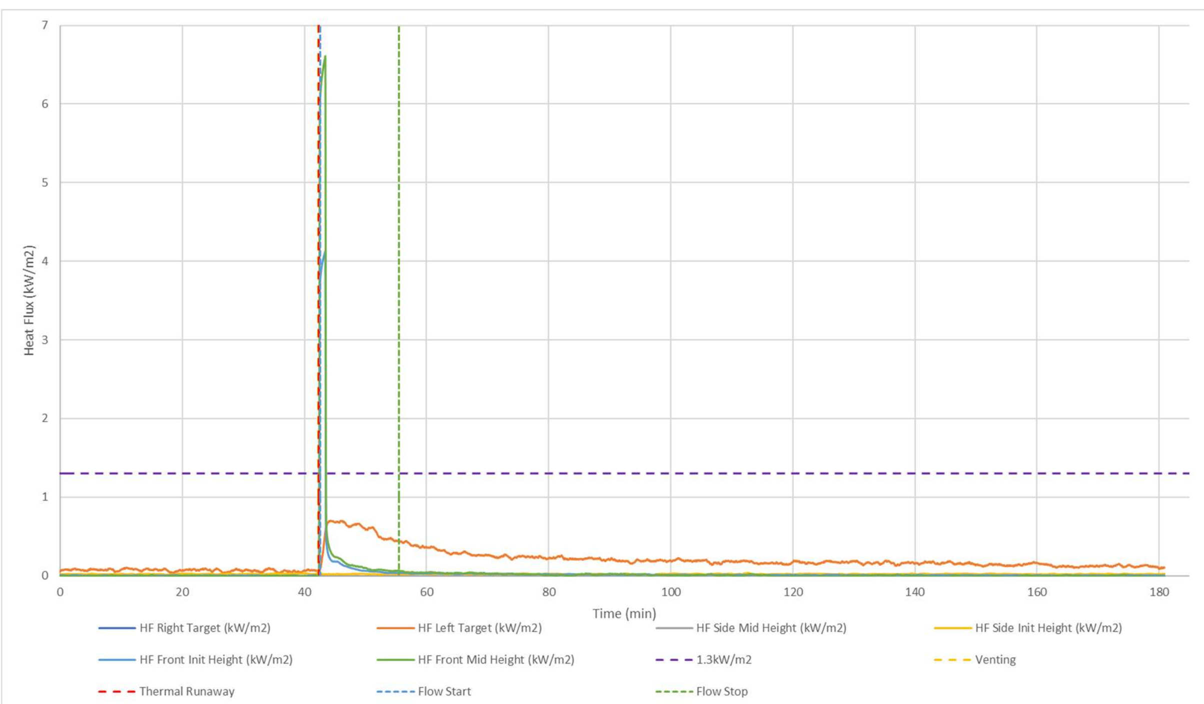


Figure D8 – Heat Flux Measurements during the Unit Test

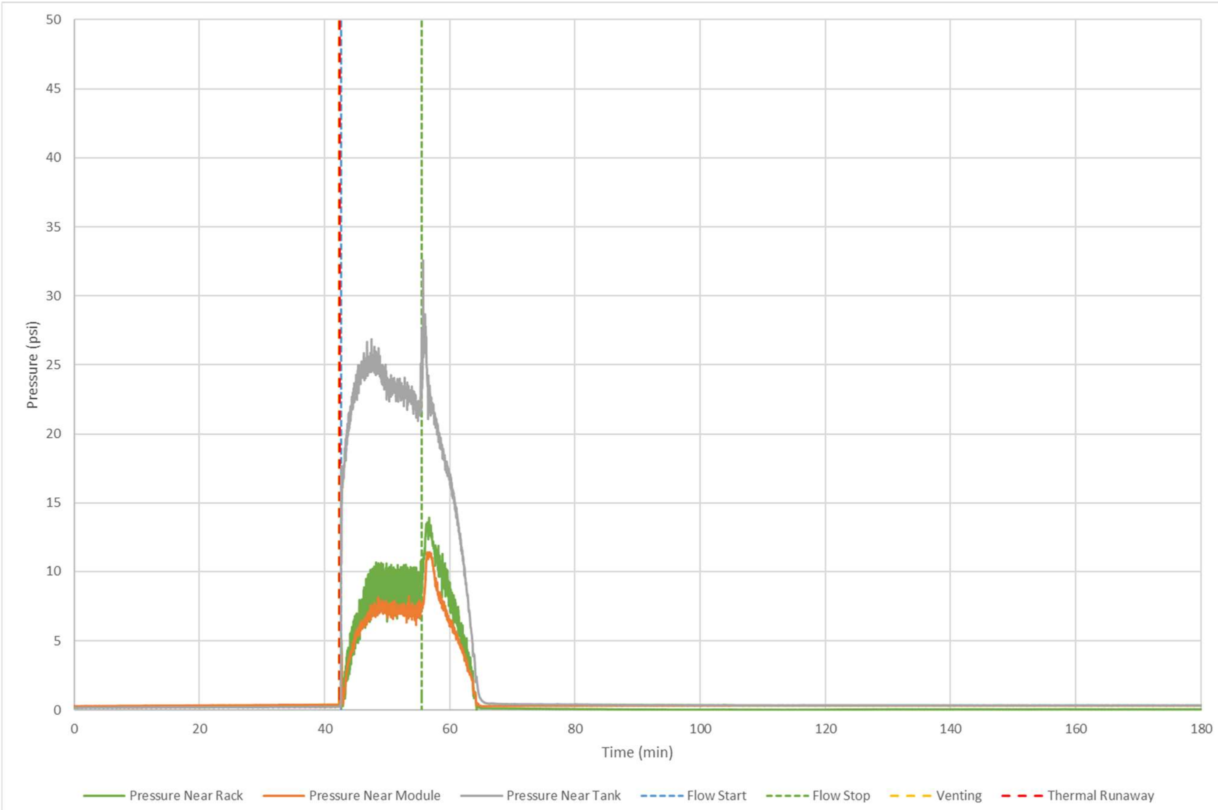
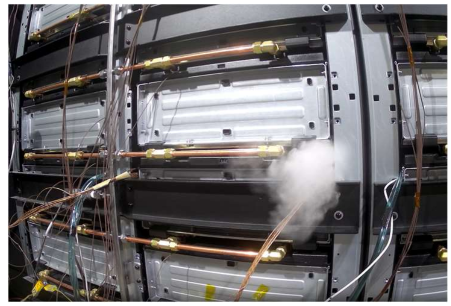
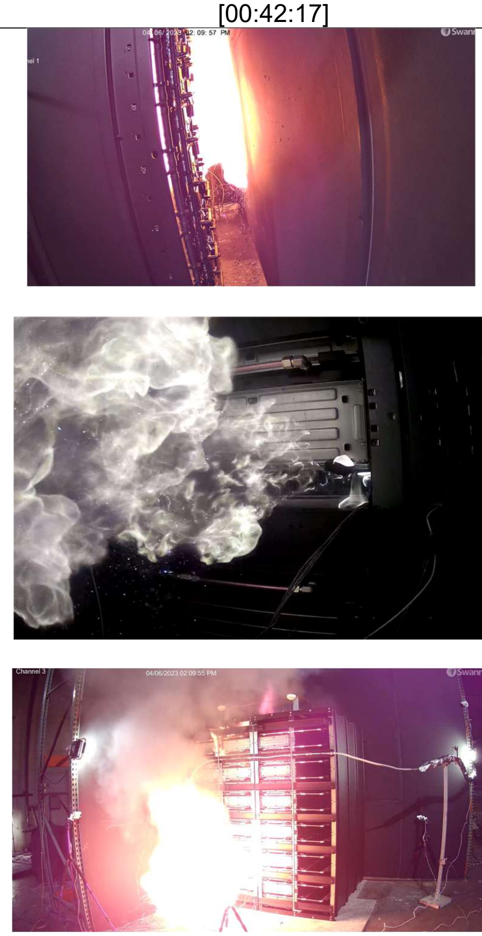
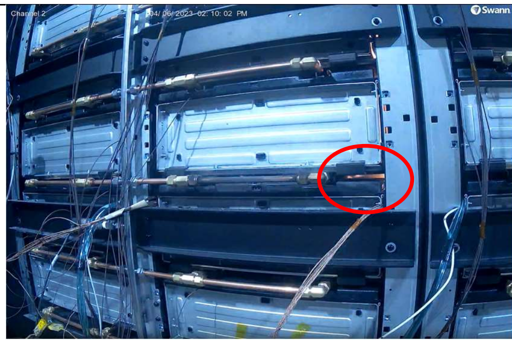
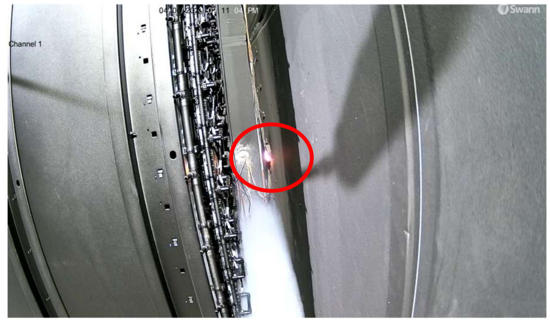
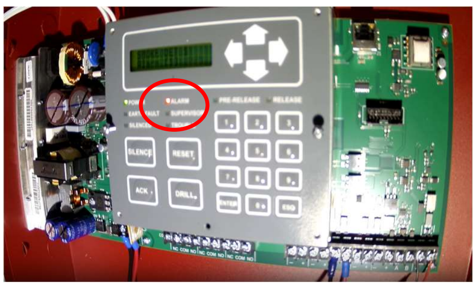
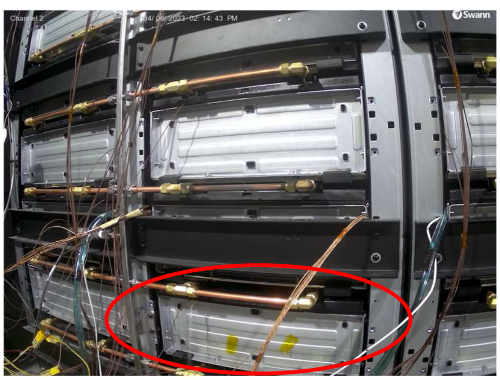


Figure D9 – Pressure Profiles for the NOVEC Tank, Initiating Module, and Rack

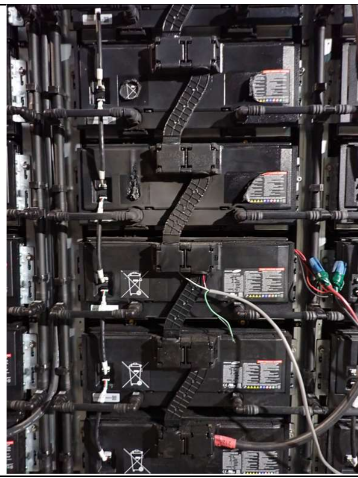
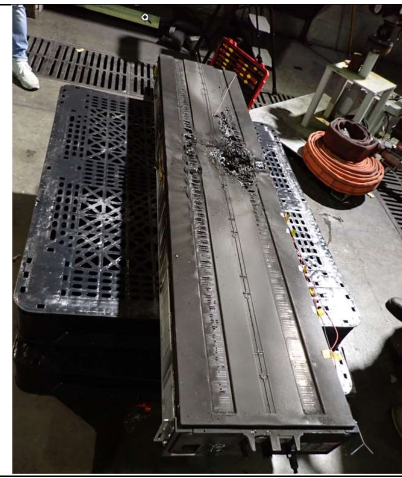
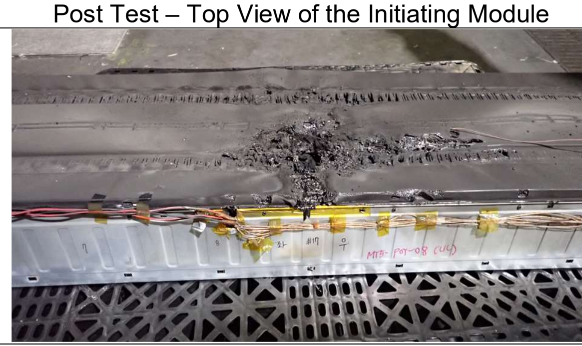
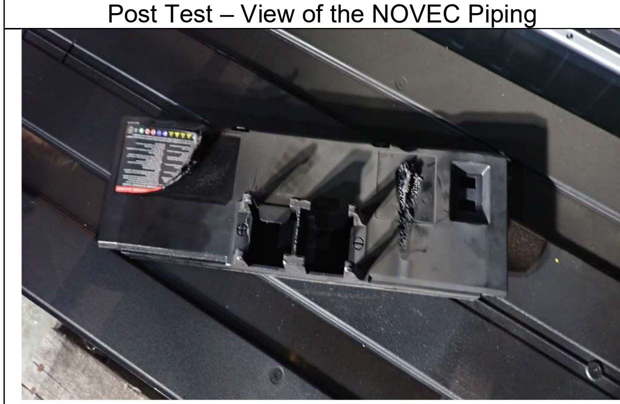
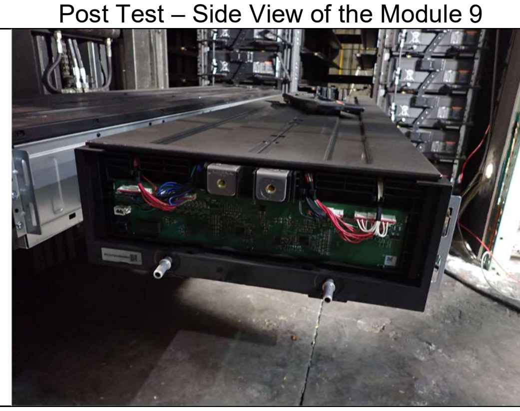
Attachment E: BESS Unit Testing and Post Testing Photos - (*Pages **47** through **50***)

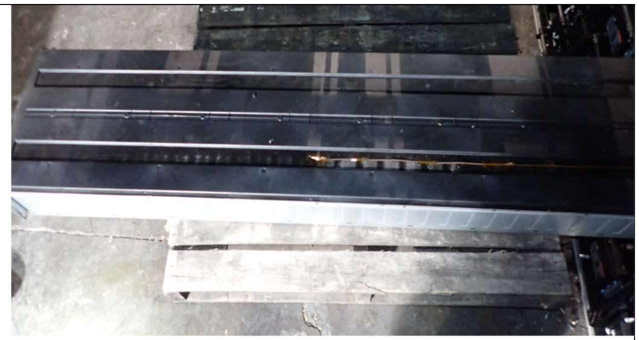
 (a) Test Start [00:00:00]	 (b) Initiating Unit Vent [00:42:17]
 (c) Initiating Unit Thermal Runaway [00:42:25]	 (d) Ignition [00:42:30]

 (e) Two Seconds after Ignition – Flaming was only observed above the Initiating Module [00:42:32 – 00:42:41[7]]	 (f) External Flaming on the Camera [00:42:30 – 00:47:39]
 (g) Smoke Detection – Alarm LED Turns On[8] [00:42:29]	 (h) NOVEC Release [00:42:30]
 (i) NOVEC Flowing Over on the top of the module below the initiating module [00:54:42 – 01:08:23]	 (j) Test End [03:00:51]

[7] The end of the flame was visually analysed based on the video taken at the back of the module

[8] The system would release NOVEC based on signals from two different smoke detectors, however, based on the video analysis, which was the only analysis available to identify the time of smoke detection, it was not inconclusive to pinpoint the second smoke detector sending the signal.

	
Post Test – Front View of the Initiating Unit	Post Test – Top View of the Initiating Module
	
Post Test – Rear View of the Initiating Module	Post Test – Side View of the Initiating Module
	
Post Test – View of the NOVEC Piping	Post Test – Side View of the Module 9
	
Post Test – Front Cover of Module 9	Post Test – Front View of Module 9

	
Post Test – Front View of Module 11	Post Test – Top View of Module 11

Attachment F: BESS Unit Gas Flow Rate and Heat Release and Smoke Release Profiles - (*Pages* ***51*** *through* ***54***)

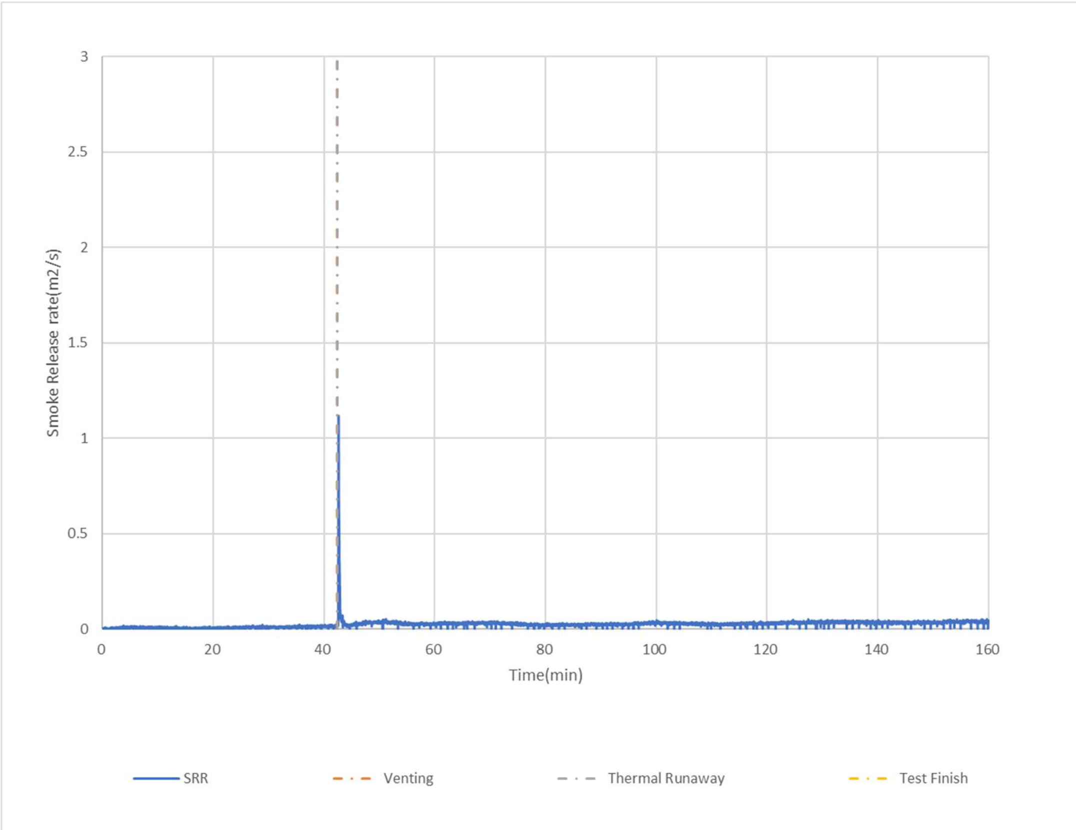


Figure G1 – Smoke Release Rate during the Unit Level Test

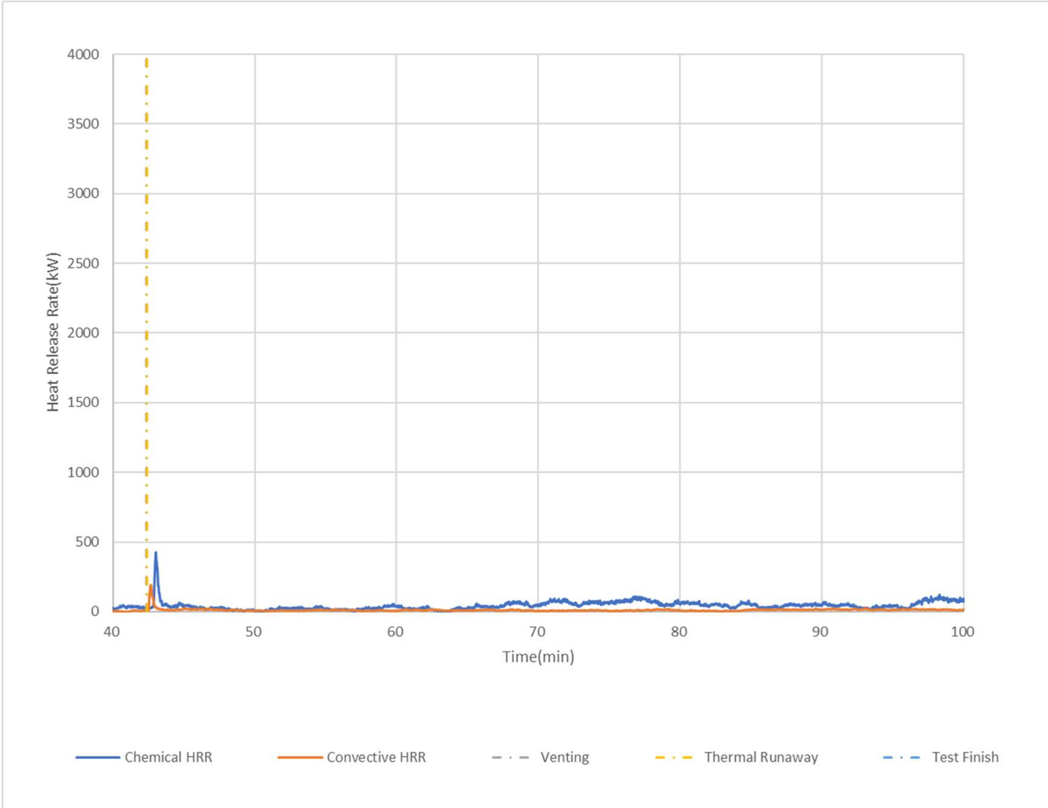


Figure G2 – Heat Release Rate during the Unit Level Test[9]

[9] No fire was observed after flame from the thermal runaway was extinguished. The increase of heat release rate around 70 minutes into the test is assumed to be due to the moisture and the depletion of oxygen coming from NOVEC released

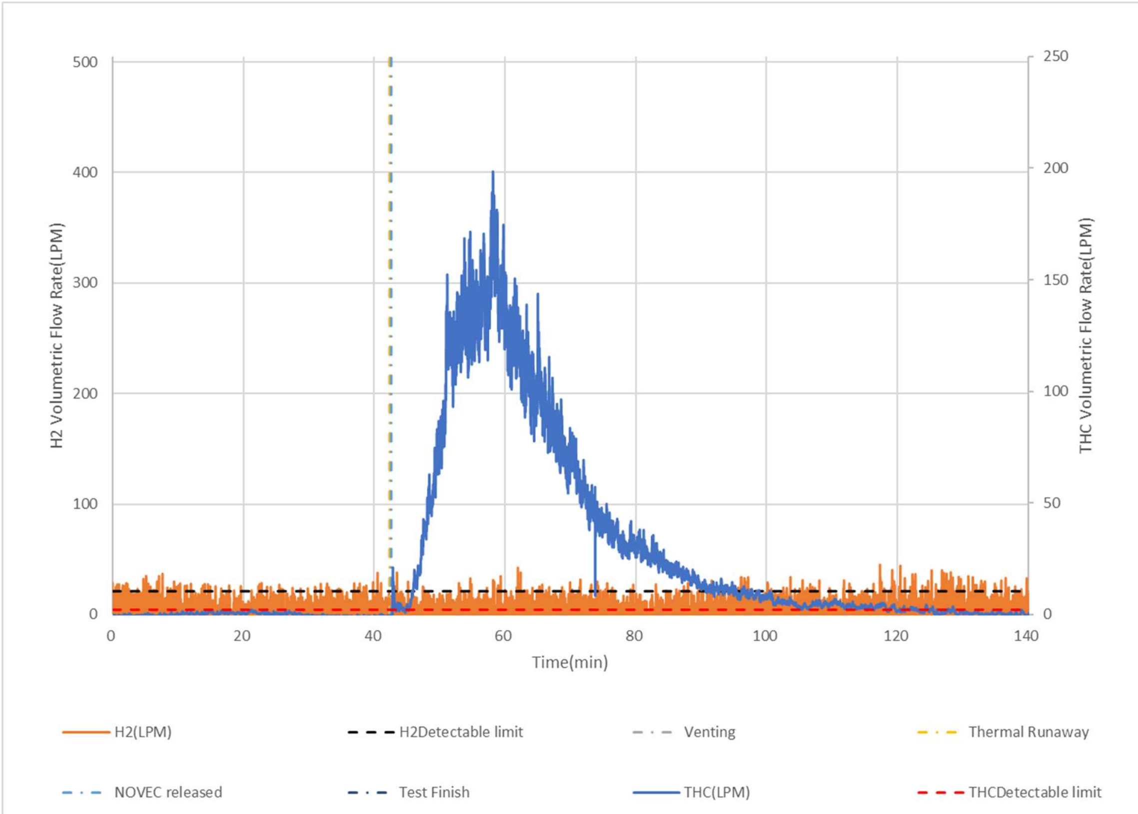


Figure G3 – H2[10] and THC[11] Volumetric Flow Rate during Unit Level Test

[10] The noise exceeded the minimum detectable limit intermittently, however, the concentration of H2 measured during the test confirmed that no hydrogen was measured during the test.
[11] The increase of THC is due to NOVEC released from the system as the THC was analyzed with FID.

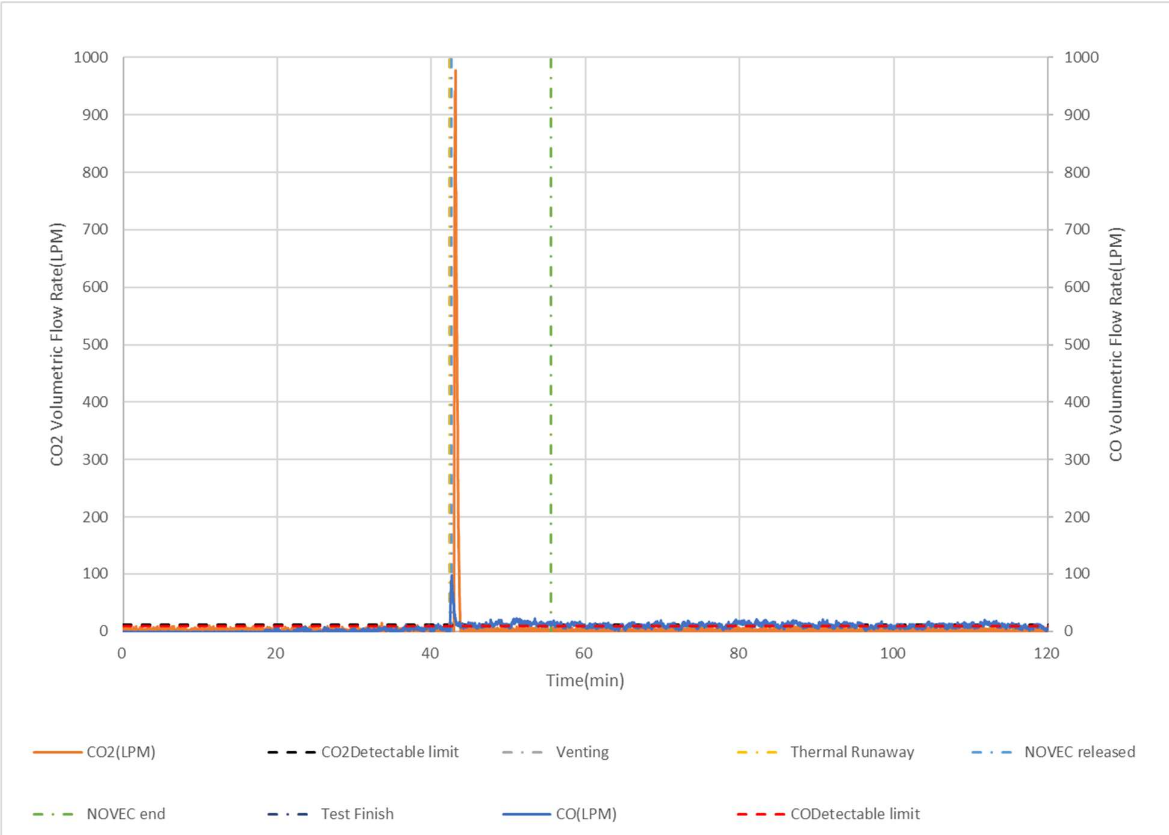


Figure G4 – CO and CO2 Volumetric Flow Rate during Unit Level Test

Attachment G: Certification Requirement Decision - (*Pages **55** through **56***)

CRD dated 2020-01-10 regarding the omission of FTIR provided below of for reference.

UNDERWRITERS LABORATORIES INC. CERTIFICATION REQUIREMENT DECISION

This Certification Requirement Decision is prepared by UL LLC. It is normative for the applicable UL Product Certification Program(s); however, it is currently not part of the UL Standard(s) referenced below.

Product Category (CCN): AACD
Standard Number: UL 9540A
Standard Title: Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems
Edition Date: November 12, 2019
Edition Number: 4
Section / Paragraph Reference: 8.12, 8.13, 9.24, 9.25, 10.3.13
Subject: Corrections to gas measurement methods to make FTIR as an option for measuring hydrocarbon contents of gas emissions and to include Hydrogen measurements during the Unit Level Test.

DECISION:

8.2.1~~3~~2 The hydrocarbon content of the vent gas shall be measured using flame ionization detection. Hydrogen gas shall be measured with a palladium-nickel thin-film solid state sensor.

8.2.1~~2~~3 The hydrocarbon components of the ~~V~~vent gas composition may additionally ~~shall~~ be measured using a Fourier-Transform Infrared Spectrometer with a minimum resolution of 1 cm-1 and a path length of at least 2 m (6.6 ft), or an equivalent gas analyzer~~,~~. ~~and v~~Velocity and temperature measurements respectively shall be obtained in the exhaust duct of the heat release rate calorimeter using equipment specified in 8.2.10.

9.2.24 The composition, velocity and temperature of the initiating BESS unit vent gases shall be measured within the calorimeter's exhaust duct as outlined in 8.2.10. The hydrocarbon content of the vent gas shall be measured using flame ionization detection. Hydrogen gas shall be measured with a palladium-nickel thin-film solid state sensor. ~~Gas composition shall be measured using a Fourier-Transform Infrared Spectrometer with a minimum resolution of 1 cm-1 and a path length of at least 2.0 m (6.6 ft), or equivalent gas analyzer.~~ Composition, velocity and temperature instrumentation shall be collocated with heat release rate calorimetry instrumentation.

9.2.25 The hydrocarbon content of the vent gas ~~shall~~ may additionally ~~also~~ be measured using ~~flame ionization detection.~~ a Fourier-Transform Infrared Spectrometer with a minimum resolution of 1 cm-1 and a path length of at least 2.0 m (6.6 ft), or equivalent gas analyzer

10.3.13 The composition of BESS unit vent gases shall be measured as outlined in Section 9.2.24. The hydrocarbon content may additionally be measured as outlined in accordance with 9.2.25 ~~using a Fourier-Transform Infrared Spectrometer with a minimum resolution of 1 cm-1 and a path length of at least 2.0 m (6.6 ft), total hydrocarbon analyzer, and hydrogen analyzer~~. The gas composition sampling port shall be located in the ceiling jet, 25-mm (1-in) below the ceiling

RATIONALE FOR DECISION:

In the 4th edition of UL 9540A, there is redundancy in the two measurement methodologies used to characterize the volume of flammable gas released during module and unit level testing (Flame Ionization Detection (FID) and Fourier Transform Infrared Spectroscopy (FTIR)). Both FTIR and FID were developed as required measurements for module and unit level testing in the first three editions of UL 9540A before data existed that enabled an understanding of the typical compositions of battery gas. Both FID and FTIR were specified as requirements because it was not clear that FID alone would provide an adequate characterization of all flammable gases released by batteries in thermal runaway. Therefore, FTIR was first intended to provide a means to quantify non-hydrocarbon flammable gases as well as to serve as a backup for FID measurement. FTIR, to a lesser degree, was also identified as a potential backup or improvement for CO and CO_2. Experience has demonstrated that an improvement to CO and CO_2 measurement is not necessary and a backup to non-dispersive infrared spectroscopy (NDIR) measurement has not been needed. Therefore, the FTIR will remain in the standard but as an optional additional measurement method.

In addition, hydrogen is measured with a hydrogen specific sensor, because neither FID or FTIR are capable of measuring hydrogen.

The list of equipment in Table 1 demonstrates overlap in the methodologies used for gas measurement.

Table 1 – Gas measurement equipment for fire and explosion hazards

Gas Hazard	Measurement Equipment
Hydrocarbons	1. Total unburned hydrocarbons by flame ionization detector (FID) 2. Individual components by Fourier Transform infrared spectrometry (FTIR)
Carbon monoxide (CO), Carbon dioxide (CO_2)	1. Individual components by non-dispersive infrared spectrometry (NDIR) 2. Individual components by FTIR
Hydrogen	1. Hydrogen sensor

INSTALLATION TEST REPORT
UL 9540A
Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems (AACD)

Project Number...............................:	**4790648557**
Date of issue ....:	**2023-07-07**
Total number of pages...................:	**61**
UL Report Office ....:	**UL LLC**
Applicant's name............................:	**SAMSUNG SDI CO LTD**
Address ....:	**428-5 GONGSE-DONG GIHEUNG-GU YONGIN-SI, GYEONGGI-DO 446-577 REPUBLIC OF KOREA**
Test specification:	4th Edition, Section 10, November 12, 2019
Standard ....:	UL 9540A, Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems
Test procedure ....:	10.1 – 10.8
Non-standard test method ....:	Requirements for the container test are not established in UL 9540A 4th edition, however, the requirements for the container system BESS in 10.6.2 in this report were in Certification Requirement Decision of UL9540A which is normative for the applicable UL Product Certification Program. No gas was measured by Fourier-Transform Infrared Spectrometer.

General disclaimer:

The test results presented in this report relate only to the sample tested in the test configuration noted on the list of the attachments.

UL did not select the sample(s), determine whether the sample(s) was representative of production samples, witness the production of the test sample(s), nor were we provided with information relative to the formulation or identification of component materials used in the test sample(s).

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Cell level information	
Cells in Module:	
● **Manufacturer Name**	Samsung SDI CO LTD
● **Part Number**	CP1495L101+
● **Chemistry**	LiNiCoAlO2
● **Format**	Prismatic
Ratings (Vdc, Ah) :	3.68 Vdc, 145 Ah
Cell certified? :	Yes
Standard the cell was certified to:	UL 1973
Organization that certified the cell:	UL Solutions (File Number: MH64496)
Average cell surface temperature at gas venting, °C:	166
Average cell surface temperature at thermal runaway, °C:	178
Gas Volume:	423
Lower flammability limit (LFL), % volume in air at the ambient temperature:	8.04
Lower flammability limits (LFL), % volume in air at the venting temperature:	6.74
Burning velocity (S_u) cm/s:	86.40
Maximum pressure (P_{max}) psig:	105.3

Cell level Gas Composition:

Gas	Measured %
Hydrogen	32.7 %
Carbon monoxide	40.9 %
Methane	15.43 %
Ethylene	0.56 %
Ethane	1.06 %
Carbon dioxide	9.2 %
Propene (Propylene)	0.04 %
Propane	0.03 %
C4 Total	0.05 %
C5 Total	0.01 %
Benzene	0.06 %
Total	**100 %**

Module level Information	
Module Manufacturer	
Model No... :	E5S (MS3204L101A)
Ratings (Vdc, Ah)............................ :	110.4 Vdc, 290 Ah
Module dimensions (X x **Y** x **Z** (mm)**)……………….:**	388.2 x 1751.8 x 155.0 (without mounting bracket)
Module cell configuration (xS/yP**) …...:**	30S/2P
Module weight (kgs)………………………. :	173
Module enclosure material……………….. :	Plastic Cover : PC(M3020PN), 2.5T Mica Sheet 0.3t(&Aerogel) Sheet
Was the module certified? ………………………….:	Yes
Standard the module was certified to …………..:	UL1973
Organization that certified test item …….:	UL Solutions (File Number: MH49407)
Number of initiating cells failed to achieve propagation.	1
Thermal Runaway Propagation:	Yes
External Flaming:	Yes
Location(s) of Flame Venting:	Flaming out of the top of the module
Flying Debris:	Yes
Re-ignitions:	No re-ignition
Test Maximum Smoke Release Rate (m^2/s)	7.06
Test Total Smoke Released: (m^2)	3516.04
Test Peak Chemical Heat Release Rate: (kW):	3935.15

Module level test Gas Composition & Volume for Each Compound (Pre-flaming and After flame) :

Gas Compound	Gas Type	Pre-Flaming (L)	Flaming (L)
Total Hydrocarbons (Propane Equivalent)	Hydrocarbons	6.61	677.14
Carbon Monoxide	Carbon Containing	Below detectable limit	39542.50
Carbon Dioxide	Carbon Containing	Below detectable limit	1421.12
Hydrogen	Hydrogen	*	*

*The hydrogen measurement system malfunctioned during the test, however, the same module design was tested with different charging specifications and the hydrogen quantity was below detectable limits. – Please refer to the report under UL project 4790648531

Unit level Information	
Unit Manufacturer	
Model No. :	PHR3843-001A (E5S)
Ratings (Vdc, Ah)............................ :	1324.8V, 290 Ah
BESS dimensions (W x **D** x **H** (mm)**)……………….:**	960.5 * 1752 * 2352 mm
BESS module configuration	12S/1P
Number of modules in BESS	24
Module cell configuration (xS/**y**P**) …...:**	30S/2P
Number of cells in module.:	60
BESS weight (kgs)………………………. :	2524 kg
BESS enclosure material……………….. :	Metal case, Plastic Cover, Mica(&Aerogel) sheet
BESS Intended Installation: **Non Residential:** outdoor ground mounted, indoor floor mounted, outdoor wall mounted, indoor wall mounted, roof top, open garage **Residential:** Outdoor ground mounted, indoor floor mounted, outdoor wall mounted, indoor wall mounted	Non-Residential indoor floor mounted.
Residential Indoor Use: Smallest volume room installations specified.	N/A
Original Equipment Manufacturer (OEM):	Samsung SDI Co LTD
Branding Manufacturer (if not OEM):	N/A
Was the unit certified? ………………………….:	Yes
Standard the unit was certified to …………..:	UL 1973
Organization that certified the unit …….:	UL Solutions (File Number: MH49407)
Description of components employed within the unit that serve to suppress propagation (fire protection features) The BESS Unit includes the direct injection system consisting of smoke detection, fire control panel, pipes and a NOVEC cylinder as a fire suppression system. Once smoke is detected, a signal (signals from two smoke detectors) is sent to the fire control panel , which will open the solenoid valve on the NOVEC cylinder for NOVEC to be released into the integral suppression system pipes.	
Deviation from the module level test N/A	
Number of initiating cell(s)	1
Thermal Runaway Propagation:	No
External Flaming from BESS:	Yes
Location(s) of Flame Venting:	Front and Rear Top Surface
Maximum Target BESS Temperature, °C	31

Maximum Wall Surface Temperature[1], °C	169
Peak Chemical Heat Release Rate, kW	426.1
Peak Convective Heat Release Rate, kW	191.4
Maximum Smoke Heat Release Rate, m^2/s	1.1
Maximum Heat Flux on Target Modules, kW/m^2	0.70
Maximum Heat Flux of Egress Path, kW/m^2	6.60
Flying Debris:	No flying debris
Re-ignitions:	No reignitions

Gas Analysis:

☒ Flame ionization detection (FID)

☒ Non-Dispersive Infrared Spectrometer (NDIR)

☐ Fourier-Transform infrared Spectrometer

☒ Hydrogen Sensor (palladium-nickel, thin-film solid state sensor)

☒ White light source with photo detector (smoke release rate)

Summary of Unit level test Gas Analysis Data:

Unit level Gas Composition & Volume for Each Compound (Pre-flaming and After flame):

Gas Compound	Gas Type	Pre-Flaming (L)	Flaming (L)
Total Hydrocarbons (Propane Equivalent)	Hydrocarbons	Below detectable limit	3340.26
Carbon Monoxide	Carbon Containing	Below detectable limit	343.97
Carbon Dioxide	Carbon Containing	Below detectable limit	789
Hydrogen	Hydrogen	Below detectable limit	Below detectable limit

[1] Maximum wall surface temperature averaged on 60 seconds.

Installation level Information	
Integrator	
Model No. ……………….:	E5S container[2]
Installation type : (Room/Container) ……………….:	Container
Installation dimensions (W x **D** x **H** (mm)**)……………….:**	2455 x 3688 x 3049
Number of the units in the container in the test….:	5[3]
Unit configuration(xS/**y**P**) …...:**	5S1P
Standard the ESS system was certified	N/A The container assembly was not certified to UL 9540
Organization that certified the ESS system …….:	N/A
Power Conditioning System included (Yes/No**)…….:**	No
Power Conditioning system manufacturer	N/A
Power Conditioning system Model No.	N/A
Standard the power conditioning system was certified	N/A
Organization that certified the power conditioning system …….:	N/A
Test method used in the test (Method 1, Method 2, Container)	Container
Description of explosion prevention means within the ESS system [4] N/A	
Description of components employed within the ESS system that serve to suppress propagation (fire protection features) The racks were equipped with copper pipes with a set of fusible plastic plugs sleeved in and positioned above the cell vent area and the copper pipes were connected to a NOVEC 1230 cylinder (50kg) through a swaged nipple assembly to control the pressure. The Direct injection clean agent cooling system was designed to discharge the NOVEC 1230 until the cylinder was empty; there was no mechanism that could stop the direct injection clean agent cooling system in the middle of discharge. However, a series of dummy racks was installed as well in order to simulate the pressure drop generated from the pipes in the racks in the field other than the real racks involved in the test. The direct injection system was not certified as a component for an ESS or evaluated as part of an ESS certification.	
Deviation from the unit level test N/A	
Number of initiating cell(s)	1
Thermal Runaway Propagation:	No propagation observed during the test
External Flaming from BESS:	No external flaming observed
Flame length (m)	No external flaming observed

[2] Please note that there is no specific model number of the container used for the Installation level was provided.
3 Four units were populated with dummy modules that had no cells, and only one unit was populated with fully charged cells.
[4] Please note that the final design will not employ the deflagration panel(s) described above, however, these panels were used for the safety of testing. The panel was designed by Samsung SDI.

	Maximum Target BESS Temperature, °C	75
	Maximum Wall Surface Temperature[5], °C	670
	Maximum heat flux measured in the egress path(kW/m2)	0.001
	Flying Debris:	No flying debris
	Re-ignitions:	No re-ignition

Summary of Installation level Test Results

Performance Criteria

~~[]For BESS units intended for installation in locations with combustible construction, surface temperature measurements along instrumented wall surfaces **[did] [did not]** exceed a temperature rise of 97C (175° F) above ambient.~~ [6]

[X]The surface temperature of modules within the BESS units adjacent to the initiating BESS unit ~~**[did]**~~ **[did not]** exceed the temperature at which thermally initiated cell venting occurs, as determined in 7.3.1.8.

[X]The fire spread on the cables in the flame indicator ~~**[did]**~~ **[did not]** extend horizontally beyond the initiating BESS enclosure dimensions.

[X]There ~~**[was]**~~ **[was no]** flaming outside the test room.

[X]There ~~**[was]**~~ **[was no]** observation of detonation.

[X]There ~~**[was]**~~ **[was no]** observation of deflagration, ~~[ ] which **[was] [was not]** mitigated by an engineered deflagration protection system~~.

[X]Heat flux in the center of the accessible means of egress ~~**[did]**~~ **[did not]** exceed 1.3 kW/m^2.

[X]There ~~**[was]**~~ **[was no]** observation of re-ignition within the initiating unit after the installation test had been concluded and the fire suppression system was discontinued

Necessity of a re-test

[X] An installation level test did meet the applicable performance criteria noted above, therefore the ESS system under test would not need to be revised and retested

[ ] An installation level test did not meet the applicable performance criteria noted above, therefore the ESS system under test would need to be revised and retested

Testing Laboratory Information

Testing Laboratory and testing location(s):

Testing Laboratory:	Samsung SDI CO LTD	
Testing location/ address ....:	163, Bangudae-ro, Samnam-eup Ulsan, Ulju-gun,44953, Republic of Korea	
Tested by (name, signature) ....:	KwangDeuk Lee	
Witnessed by (for 3rd Party Lab Test Location)	Leon Lee	Leon Lee

5 Maximum wall surface temperature averaged on 60 seconds.

6 Surface temperature rise is not applicable if the intended installation is composed completely of noncombustible materials in which wall assemblies, cables, wiring and any other combustible materials are not intended to be present in the BESS installation. In this case, the report shall note that the installation shall contain no combustible materials.

(name, signature) ....:		
Project Handler (name, signature)...............:	Leon Lee	Leon Lee
Reviewer (name, signature) …………….:	Sean Yang	

List of Attachments (including a total number of pages in each attachment):
Attachment A: Sample Charging, OCV and SOC Measurement Profiles - (*Pages **31** through **32***)
Attachment B: BESS (including module and any integral fire detection and suppression systems) Construction Photos/Diagrams - (*Pages **33** through **34***)
Attachment C: BESS and Equipment Instrumentation and Test Installation Layout Photos/Diagrams - (*Pages **35** through **40***)
Attachment D: Temperature Profiles and Heat Flux Measurements During Testing (Initiating Cell and Module, Target Modules, Wall Surfaces, etc. - (*Pages **41** through **44***)
Attachment E: BESS Unit Testing and Post Testing Photos - (*Pages **45** through **49***)
Attachment F: Fire suppression system and deflagration mitigation system – (*Pages **50** through **55***)
Attachment G: Certification Requirement Documents **(***Pages **56** through **61***)

Photo(s) of ESS System:

Figure 1 – Picture of the units in the container

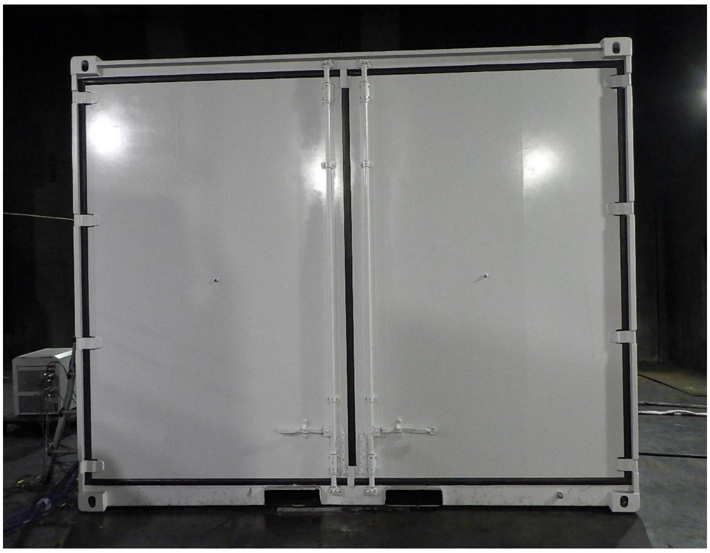


Figure 2 – Picture of the container

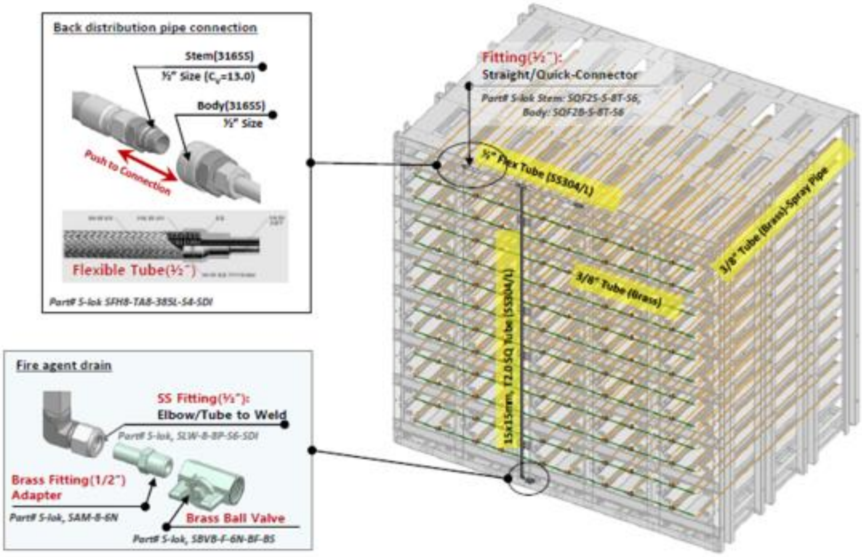
Test Item Charge/Discharge Specifications:	Per module
• **Charge current, A:**	90.0
• **Standard Full charge voltage, Vdc:**	124.5
• **Charge temperature range, °C:**	23 ± 5 °C
• **End of charge current, A:**	58.0
• **Discharge current, A:**	58.0
• **End of discharge voltage, Vdc:**	93.0

• **Discharge temperature range, °C:**	23 ± 5 °C

Photo(s) of Fire protection system:

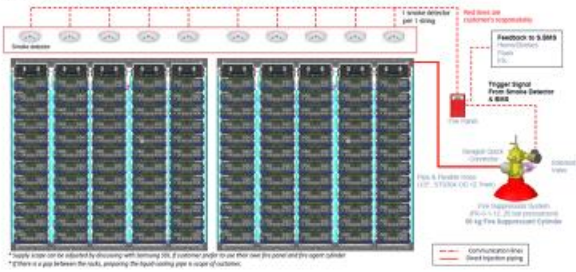
Frame design of Direct Injection

- 360S Configuration, consists of liquid cooling piping at the front and Direct Injection piping at the back



Method of Direct Injection

- Basic Supply Scope*:
  - Samsung: Pipes embedded in rack frames, fire panel, fire agent cylinder
  - Customer: Detectors, wires between smoke detectors and fire panel, pipe from the first rack frame to the fire agent cylinder, piping from one rack to another if racks are not directly adjacent to each other
- Maximum number of racks: up to 2P360S 22P racks (8.45 MWh) per one 50 kg fire agent cylinder



- Major Components for the fire suppressant direct injection

  Fire suppressant cylinder, solenoid valve, swaged quick connector, pipe/hose for rack connection, etc.

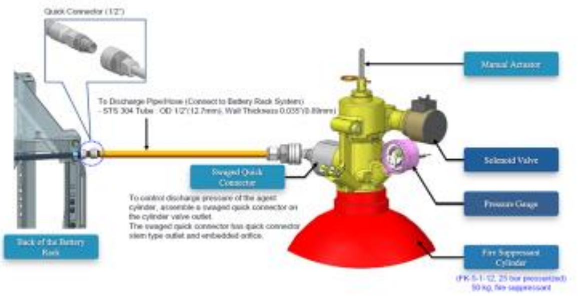


Figure 3 – Principle of the direct injection system, as per Samsung SDI

Specifications:	
• **Manufacturer:**	Samsung SDI CO. LTD
• **Model No.:**	Direct injection system
• **Suppressant Name:**	NOVEC 1230
• **Pipes diameter**	5/16"(Brass)
• **Suppressant storage type**	NOVEC 1230 cylinder
• **Initial pressure of the suppressant storage:**	362psig
• **Nozzle type**	Fusible plug
• **Number of the nozzles**	60 per module (one per cell)
• **Control panel Model No.**	V802-00121A(Fire Alarm Control Panel) V802-00122A(Module Box)
• **Smoke Detector type**	Photoelectric
• **Smoke Detector Model No.**	CPS-24

Photo(s) of (Deflagration mitigation) means:[7]

Specifications:	
• **manufacturer**	FDC CO., LTD
• **Model No.**	Explosion panel (2D0949-001)
• **Rating**	0.2 bar at Ambient temperature
• **Dimensions (W X D X H)**	1 m X 1 m
• **Location in the system/container**	On the ceiling

7 Please note that the final design will not employ the deflagration panel(s) described above, however, these panels were used for the safety of testing. The panel was designed by Samsung SDI.

Test item particulars ....:	
Possible test case verdicts:	
- test case does not apply to the test object...........:	N/A
- test object does meet the requirement ....:	P (Pass)
- test object does not meet the requirement...........:	F (Fail)
- test object was completed per the requirement...:	C(Complete)
- test object was completed with modification……:	M(Modification)
Testing...:	
Date of receipt of test item ....:	2023-03-20
Date (s) of performance of tests...............................:	2023-03-22
General remarks:	
"(See Enclosure #)" refers to additional information appended to the report. "(See appended table)" refers to a table appended to the report. **Throughout this report a point is used as the decimal separator.**	
Manufacturer's Declaration of samples submitted for test:	
The applicant for this report includes samples from more than one factory location and a declaration from the Manufacturer stating that the sample(s) submitted for evaluation is (are) representative of the products from each factory has been provided ....:	☐ **Yes** ☒ **Not applicable**
Name and address of factory (ies).......................... :	163, Bangudae-ro, Samnam-myeon, Ulju-gun, Ulsan, Republic of Korea
General product information and other remarks: Direct injection system container is a customized container (2455mm x 3688mm x 3049mm) equipped with two 1m by 1m deflagration panels on the top. The container did not have any suppression system other than the integral cooling system Samsung SDI designed. The racks used in the test was PHR3843-001A, which consists of modules (MS3204L101A) that has 60 of CP1495L101+ cells manufactured by Samsung SDI.	

	CONSTRUCTION		Verdict
5.3	**Battery energy storage system unit Construction**		—
5.3.1, 5.3.2	Construction information	See Test Item Description at the beginning of this report	—
5.3.2	General layout of BESS unit contents	See Attachment B	—
5.3.3	Details of integral fire suppression system	See Attachment C	
5.3.1	BESS certified to UL 9540	Not certified to UL9540	C
	Organization that certified BESS:		—
	PERFORMANCE		**Verdict**
6	**General**		
10	**Installation Level**		
10.1	**General**		
10.1.1	The installation level test method assesses the effectiveness of the fire and explosion mitigation methods for the BESS in its intended installation. a) Test Method 1 – "Effectiveness of sprinklers" is used to evaluate the effectiveness of sprinkler fire protection and explosion mitigation methods installed in accordance with code requirements. b) Test Method 2 – "Effectiveness of fire protection plan" is used to evaluate the effectiveness of other fire and explosion mitigation methods (e. g., gaseous agents, water mist systems, combination systems). c) Test Method 3 – Container System BESS installation level test	Requirements for the container test are not established in UL 9540A 4th edition, however, the requirements for the container system BESS in 10.6.2 in this report were in Certification Requirement Decision of UL9540A which is normative for the applicable UL Product Certification Program.	C
10.1.2	Installation level testing is not appropriate for units only intended for outdoor use or residential use.	Container (Installation) level test	N/A
	Container system BESSs as defined in this standard, although typically for outdoor use installations, are included in the installation level test as the container represents a type of installation that may be provided with integral fire detection and suppression and integral explosion or deflagration protection.	The integral fire suppression system (the direct injection system) was installed in the test. Please note that the final design will not employ the deflagration panel(s) described above, however, these panels were used for the safety of testing. The panel was designed by Samsung SDI.	C
10.2	**Sample and test configuration**		

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict
10.2.1	The samples (initiating BESS and target BESS) and their preparation for testing, including separation distances from walls, shall be identical to that used for the unit level test in Section 9	See Table 2 and Attachment C for test installations	C
10.2.2	A flame indicator consisting of a cable tray with fire rated cables that complies with UL 1685 and representative of the installation per the manufacturer's specifications was deployed above the BESS at a distance specified by end-use installation.	See Attachment C for test installations	N/A
	If the installation requires that cabling be installed below the BESS, then the flame indicator is not needed.		N/A
10.2.3	For container system BESS, the units utilized for initiating and target units are the battery system racks that are installed within the container. The container system BESS was populated with one initiating unit chosen as the location within the container that may result in worse case results and target units installed around and across the initiating BESS representative of the intended container layout.		C
	The Integral fire detection and suppression systems were installed in the system for the test.	The integral fire suppression system (the direct injection system) was installed in the test. Please note that the final design will not employ the deflagration panel(s) described above, however, these panels were used for the safety of testing. The panel was designed by Samsung SDI.	C
	Any wiring within the container either intended to be installed above the units or along them horizontally, that can be a source of fire spread, should be included in the container for the test.	No wiring either intended to be installed above the units or along them horizontally, that can be a source of fire spread in the container.	N/A
	Equipment mounted to openings in the container that may impact air flow and therefore test results, was included in the installation for the test.	No equipment mounted that may impact air flow in the container.	N/A
	Internal equipment such as a power conditioning/conversion system or switchgear, can be represented by their enclosures or other simulation means for temperature measurement purposes	No power conditioning/conversion system was included in the container.	N/A
10.3	**Test method 1 – Effectiveness of sprinklers**		

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

10.3.1	For BESS units with a height of 2.44 m (8 ft) or less,, The test was conducted in a 6.10 × 6.10 × 3.05-m (20 × 20 × 10-ft) high test room with one open 1.22 × 2.13-m (4 × 7-ft) high doorway or a room representative of the installation configuration as specified by the manufacturer.	See Attachment C for test installations	N/A
	The smallest test room anticipated by the manufacturer for BESS deployments, including footprint and ceiling height, was tested.		N/A
	For BESS units taller than 2.44 m (8 ft), the ceiling height was increased to be at least 0.61-m (2-ft) higher than the BESS units under test.	See Attachment C for test installations	N/A
	The explosion mitigation methods was installed in the test installation in accordance with the manufacturer's specifications.	See Attachment C for test installations	N/A
	Pressure sensors was installed at deflagration vents to determine the maximum pressure developed during the test.	Pressure sensors were installed at the top and sides of the container to measure the maximum pressure developed during the test. Please refer to Figure F8.	C
10.3.2	The test room was fitted with four sprinklers at 3.05-m (10-ft) spacing in the center of the test room.		N/A
	The sprinkler was standard spray, standard response with a temperature rating of 93° C (200° F), a nominal K-factor of 5.6, and sprinkler water density of 12.22 L/m2/min (0.3 gpm/ft2).		N/A
	If different specifications for the sprinklers with other densities, ratings and K-factors are indicated in the installation specifications, those were used for the installation test instead.		N/A
10.3.3	Walls were constructed with 16-mm (5/8-in) gypsum wall board. Instrumented wall sections were painted flat black.		N/A
10.3.4	The initiating BESS unit was positioned at manufacturer specified distances from test room instrumented walls and target BESS units	See Attachment C for test installations	N/A
10.3.5	Temperature measurements at the ceiling locations directly above the initiating and target BESS unit were collected by an array of thermocouples located 25-mm (1-in) below the ceiling and at 152-mm (6-in) intervals using No. 24-gauge Type-K exposed junction thermocouples		C

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

10.3.6	Instrumented wall surface temperature measurements were collected in a vertical array at 152- mm (6-in) intervals for the full height of the instrumented wall sections using No. 24-gauge Type-K exposed junction thermocouples to measure wall surface temperatures. Thermocouples were positioned in the wall locations anticipated to receive the greatest thermal exposure from the initiating BESS unit.		C
10.3.7	Thermocouples for wall surface temperature measurements were secured to gypsum surfaces by the use of staples placed over the insulated portion of the wires. The thermocouple tip was depressed into the gypsum so as to be flush with the gypsum surface at the point of measurement and held in thermal contact with the surface at that point by the use of pressure-sensitive paper tape.		N/A
10.3.8	Heat flux was measured with at least two water-cooled Schmidt-Boelter gauges at the surface of each instrumented wall: a) Both are collinear with the vertical thermocouple array; b) One is positioned to receive the greatest heat from the initiating module; and c) One is positioned to receive the greatest heat flux during potential propagation within the initiating BESS unit.	No wall was used for the test.	N/A
10.3.9	Heat flux was measured with 2 water-cooled Schmidt-Boelter gauges at the surface of each adjacent target BESS units facing initiating BESS unit: a) One is positioned at the elevation estimated to receive the greatest heat flux from the initiating module; and b) One is positioned at the elevation estimated to receive the greatest surface heat flux due to initiating BESS.	Only one heat flux gauge was installed in each target unit at the elevation estimated to receive the greatest heat flux due to the thermal runaway of the initiating module. No secondary heat flux was installed because: • the distance between each target unit and the initiating unit is 0 mm; and based upon engineering discretion, flaming was expected near the initiating module, and it was assumed that the area that would experience the greatest surface heat flux during thermal runaway in the initiating BESS was right next to the initiating module.	C

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

10.3.10	Heat flux was measured with the sensing element of at least one water-cooled Schmidt-Boelter gauge positioned in the center of the accessible means of egress.	Heat flux gauge was installed outside the container vertically and horizontally in line with the initiating cell. The distance between the gauge and the container was 0mm	C
10.3.11	No. 24-gauge or smaller Type-K exposed junction thermocouples were installed to measure the surface temperature of module enclosures within target BESS units. Three thermocouples were located at positions on the exterior of each module enclosure, nearest to the initiating BESS unit.		C
	A minimum of two, No. 24-gauge or smaller Type-K thermocouples were placed within each module to provide data to monitor the thermal conditions within non-initiating modules.		C
	Additional thermocouples may be placed to account for convoluted enclosure interior geometries.		N/A
10.3.12	An internal fire condition in accordance with the module level test was created within a single module in the initiating BESS unit: a) The position of the module was selected to present the greatest thermal exposure to adjacent modules (e. g. above, below, laterally), based on the results from the module level test; and b) The setup (i.e. type, quantity and positioning) of equipment for initiating thermal runaway in the module was the same as that used to initiate and propagate thermal runaway within the module level test (Section 8).		C
10.3.13	The composition of BESS unit vent gases was measured using a Fourier-Transform Infrared Spectrometer with a minimum resolution of 1 cm-1 and a path length of at least 2.0 m (6.6 ft), total hydrocarbon analyzer, and hydrogen analyzer. The gas composition sampling port was located in the ceiling jet, 25-mm (1-in) below the ceiling.	FTIR was not used in the test as the gas measurements were performed from the cell level to the unit level test. Please refer to Attachment G.	M
10.3.14	The test was terminated because: a) Temperatures measured inside each module of the initiating BESS return to below the cell vent temperature; b) The fire propagates to adjacent units or to adjacent walls; or c) A condition hazardous to test staff or the test facility requires mitigation.		C

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict
10.3.15	The initiating unit was under observation for 24 h after conclusion of the installation test to determine that re-ignition did not occur		C
10.3.16	**Container System BESS**		
10.3.16.1	A container system BESS that utilized sprinkler system fire suppression was tested in accordance with 10.3 except instead of the test room, the actual container was used as the test room		C
10.3.16.2	The installation included any targets representing major components (e.g. power conditioning system) installed within the container system, and temperatures were measured on these targets similar to the approach used for measuring temperatures on walls.		C
	The target can be represented by the equipment enclosure or a wall or other means placed in a similar manner to represent the location and layout of the components.		C
10.6	**Test method 2 – Effectiveness of fire protection plan**		
10.6.1	The test method 2 test set-up and test procedures are identical to that in 10.3, except instead of the sprinkler system set up of 10.3.2, the room shall be fitted with the specified fire protection and explosion mitigation equipment representative of a planned installation for the tested BESS system		N/A
10.6.2	**Container System BESS – Test Method 2**		
10.6.2.1	A container system BESS that utilizes an alternative fire suppression system shall be tested in accordance with 10.6 except instead of the test room, the actual container shall be used as the test room.	See Attachment C for test installations	C
10.6.2.2	The installation shall include any targets representing any major components (e.g. power conditioning system) installed within the container system and temperatures shall be measured on these targets similar to the approach used for measuring temperatures on walls.	Temperatures were measured on the cover of chiller (No chiller was filled in but just enclosure was used). See Attachment C for test installations	C
	The target can be represented by the equipment enclosure or a wall or other means placed in a similar manner to represent the location and layout of the components.		C
10.4	**Installation level test report**		
10.4.1	The report on installation level testing shall include the following:		

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

	a. Unit manufacturer name and model number (and whether compliant with UL 9540 or UL 1973); and the container system BESS manufacturer name and model number (and whether compliant with UL 9540) if container system;	The unit was certified to UL1973, however, the system including the direction injection system and the container, was not certified to the respective applicable standard.	C
	b. Number of modules in the initiating BESS unit	12 Modules	C
	c. The construction of the initiating BESS unit per 5.3 and the number of battery system racks and overall construction within the container for a container system BESS;	See Attachment C See Critical Components Table ☐ See Also “Description of components employed within the module that impact propagation (fire protection features)” at the beginning of this report.	C
	d. Module voltage(s) of initiating BESS corresponding to the tested SOC	Initiating voltage was measured during charging and the test.	C
	e. The thermal runaway initiation method used	External heating method, used for cell, module, and unit level test, was used for the container level test.	C
	f. Diagram and dimensions of the test setup including location of the initiating and target BESS units, and the locations of walls and ceilings, and location of included internal target components in the container system BESS (e.g. target integral power conditioning system or integral switch gear enclosure, etc.)	See Attachment C	C
	g. Location of initiating module within the BESS unit;	See Attachment C	C
	h. Separation distances from the initiating BESS unit	See Attachment C	C
	i. Separation distances from the initiating BESS unit to target BESS units	See Attachment C	C
	j. Distances of the flame indicator (if used) with respect to the BESS	See Attachment C	N/A
	k. Maximum temperature at the ceiling;	See Table 7	C
	l. Distance of fire spread within the flame indicator or indication of fire spread through wiring in a container system BESS;	No fire indicator was installed as specified by applicant. However, the thermocouple array was installed to measure the ceiling temperatures.	N/A
	m. The maximum wall surface and target BESS unit temperatures achieved during the test and the location of the measuring thermocouple;	Tables 5 and 6	C

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

	n. The maximum incident heat flux on target wall surfaces and target BESS units;	Target wall heat flux was not measured because the heat flux can be occluded by the target units on both sides of the initiating unit	M
	o) Voltages of initiating BESS		C
	p) Total number of sprinklers that operated and length of time the sprinklers operated during the test;	No sprinklers was installed during the test, however, the number of the Novec 1230 nozzles in the unit per module (60 per module) was provided in the report	N/A
	q. Gas generation and composition data, if measured		N/A
	r. Observation of flaming outside of the test room;	No flaming observed during the test	C
	s. Observation of installed explosion protection operation;	No explosion observed during the test	C
	t. Observation of flying debris or explosive discharge of gases;	No flying debris observed during the test	C
	u. Observation of re-ignition(s) from thermal runaway events;	No re-ignition observed during and after the test	C
	v. Observations of the damage to: 1) The initiating BESS unit; 2) Target BESS units; and 3) Adjacent walls;	See Figure E1 through Figure E5	C
	w. Photos and video of the test	Videos were recorded by Samsung SDI; this report provides the snapshots of the videos to indicate the major events.	C
	x. Fire protection features/detection/suppression systems within unit; and	Pressure and flow rate of NOVEC 1230 was measured during the test.	C
	y. Explosion and deflagration protection		C
	z. Sprinkler K-factor, RTI, manufacturer and model, number of sprinklers and layout, and length of time of operation of the sprinklers.	No sprinklers were installed for the test.	N/A
	Installation level test report – Test method 2 – Effectiveness of fire protection plan		

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

	The report on installation level testing shall include the following: a) The report information in 10.4.1 items (a) – (u), and (v) if applicable;		C
	b) Fire protection features/detection/suppression systems within installation; and		C
	c) Length of time of operation of the clean agent, or other suppression system in addition to any sprinklers used.		N/A
10.8	**Performance – Test method 2 – Effectiveness of fire protection plan**		
	See 10.5 for performance criteria.		C
10.5	**Performance at Installation level testing**		
10.5.1[8]	For BESS units intended for installation in locations with combustible construction, surface temperature measurements along instrumented wall surfaces shall not exceed a temperature rise of 97°C (175°F) above ambient.	The container door material was metal, therefore, it is non-combustible.	N/A
10.5.2	The surface temperature of modules within the BESS units adjacent to the initiating BESS unit shall not exceed the temperature at which thermally initiated cell venting occurs, as determined in 7.3.1.8.	The maximum temperature measured on the target units was 74°C and the vent temperature obtained from the cell level test was 166°C	P
10.5.3	The fire spread on the cables in the flame indicator shall not extend horizontally beyond the initiating BESS enclosure dimensions	No flame indicator was needed.	N/A
10.5.4	There shall be no flaming outside the test room.	No flaming observed outside the container	P
10.5.5	There is no observation of detonation. There is no observation of deflagration unless mitigated by an engineered deflagration protection system	No observation of explosion during the test	P
10.5.6	Heat flux in the center of the accessible means of egress shall not exceed 1.3 kW/m2.	Heat flux measured right in contact with the back side of the container was measured 0.001 W/m2	P

[8] Surface temperature rise is not applicable if the intended installation is composed completely of noncombustible materials in which wall assemblies, cables, wiring and any other combustible materials are not to be present in the BESS installation.

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

10.5.7	There shall be no observation of re-ignition within the initiating unit after the installation test had been concluded and the sprinkler operation was discontinued	No observation of re-ignition after the test was completed.	P
10.5.9.1	For container system, temperatures on any combustible construction within the container including target components shall not exceed a temperature rise of 97°C (175°F) above ambient	There is not any combustible construction within the container except for Unit. The maximum temperature measured on the target units was 74°C.	P
	There shall be no flaming outside of the container	No flaming observed outside the container	P

Table 1 – Specified Unit charging and discharging parameters			
Charging:		**Discharging:**	
Current (CC), A	90.0	Current (CC), A	58.0
Standard Full Charge Voltage ,Vdc	124.5	End of discharge voltage ,Vdc	93.0
End of charge current, A	58.0	Discharging Test Ambient, °C	23 ± 5
Refer to Attachment A for charge/discharge profiles.			

Table 2 - Test Initiation Details	
Test Date	2023-03-22
Test Start Time (HH:MM:SS)	02:09:34
Initial Lab Temperature, °C	22.0
Initial Relative Humidity % RH	53
Module OCV at Start of Test, Vdc	123.2

Table 1 – Approximate time of thermal runaway propagation through module			
Locations (Cell #)	**Event**	**Time**	**Temperature of the cell**
Initiating cell (Cell 33)	Venting	00:39:06	152
Initiating cell (Cell 33)	Thermal Runaway	00:40:13	165

Table 4 – Test overview timeline		
Time (HH:MM:SS)	**Event**	**Description**
00:00:00	Test Start	Test started and the initiating cell(cell 33) was heated by monitoring the temperature from the thermocouple instrumented on the cell side not covered by the heater.
00:39:06	Vent	Off gas generated from the initiating module and the temperature on the cell experienced a sudden drop. The temperature was controlled back to the range of 4 to 7 °C/min.
00:40:13	Thermal runaway	Gas was released from the module from 00:39:06, however, the data collected showed the temperature rise on the initiating cell in an uncontrollable manner from 00:40:13.
00:40:15	Ignition flaming	Ignition flaming was observed. (2 seconds after Thermal runaway)

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

00:40:24	First Smoke Detection	Following the release of venting gas, the first smoke detectors located at the top of the BESS unit activate and sends a sign to the NOVEC System.
00:40:26	Second Smoke Detection	The second smoke detection was turned on
00:40:26 - 00:52:38	Suppressant released	The flow rate measured through the flow meter confirmed that suppressant started flowing into the system at 00:40:26 and it ended at 00:52:38 After 00:52:38, nitrogen that pressurized the NOVEC in the cylinder was released, which was confirmed by the pressure increase.
02:19:57	Test Terminated	Data Acquisition was stopped however, the container was left in the testing room overnight.

Table 5 - Maximum Temperatures in Target Units					
Cell vent temperature from cell test data, °C			166		
Target Unit 1					
Module Location No.	Temper-ature (°C)	Module Location No.	Temper-ature (°C)	Module Location No.	Temper-ature (°C)
Target1Mod10Front	23	Target1Mod4Front	31	Target1Mod8Rear	24
Target1Mod10Center	37	Target1Mod4Rear	24	Target1Mod9Front	37
Target1Mod10Rear	25	Target1Mod5Front	29	Target1Mod9Rear	26
Target1Mod1Front	29	Target1Mod5Rear	24	Target1Mod11Front	51
Target1Mod1Rear	25	Target1Mod6Front	29	Target1Mod11Rear	24
Target1Mod2Front	30	Target1Mod6Rear	24	Target1Mod12Front	74
Target1Mod2Rear	24	Target1Mod7Front	31	Target1Mod12Rear	27
Target1Mod3Front	28	Target1Mod7Rear	24		
Target1Mod3Rear	24	Target1Mod8Front	38		
Target Unit 2					
Module Location No.	Temper-ature (°C)	Module Location No.	Temper-ature (°C)	Module Location No.	Temper-ature (°C)
Target2Mod10Front	23	Target2Mod4Front	32	Target2Mod8Rear	23
Target2Mod10Center	34	Target2Mod4Rear	24	Target2Mod9Front	26
Target2Mod10Rear	24	Target2Mod5Front	34	Target2Mod9Rear	24
Target2Mod1Front	39	Target2Mod5Rear	23	Target2Mod11Front	26
Target2Mod1Rear	40	Target2Mod6Front	26	Target2Mod11Rear	24
Target2Mod2Front	33	Target2Mod6Rear	23	Target2Mod12Front	43
Target2Mod2Rear	33	Target2Mod7Front	25	Target2Mod12Rear	24
Target2Mod3Front	32	Target2Mod7Rear	23		
Target2Mod3Rear	25	Target2Mod8Front	24		

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

Table 6 - Maximum Temperatures on the door[9] in front of the initiating unit					
Ambient Temperature:22°C					
UL 9540A performance criteria, Ambient + 97°C:119°C.[10]					
Height, mm	Maximum Temperature (°C)	Height, mm	Maximum Temperature (°C)	Height	Maximum Temperature (°C)
6in.	424	42in.	562	78in.	312
12in.	472	48in.	488	84in.	220
18in.	557	54in.	327	90in.	240
24in.	559	60in.	416	96in.	152
30in.	670	66in.	351	102in.	171
36in.	665	72in.	352		
Note: Temperatures are measured constantly and then averaged every 60-seconds					

Table 7 - Maximum Temperatures on the ceiling of the container					
Ambient Temperature:22°C					
UL 9540A performance criteria, Ambient + 97°C:119°C[11]					
Height, mm	Maximum Temperature (°C)	Height, mm	Maximum Temperature (°C)	Height	Maximum Temperature (°C)
6in.	266	54in.	423	102in.	139
12in.	154	60in.	107	108in.	209
18in.	145	66in.	237	114in.	197
24in.	187	72in.	214	120in.	218
30in.	271	78in.	241	126in.	280
36in.	198	84in.	270	132in.	319
42in.	245	90in.	483	138in.	387
48in.	326	96in.	246	102in.	139
Note: Temperatures are measured constantly and then averaged every 60-seconds					

Table 8 – Heat Flux Measurements	
Summary of maximum heat flux in target units	
Maximum Heat Flux, kW/m²	
Target 1 Module No.10:	0.015
Target 2 Module No.10:	0.015
Egress path measurement:	0.001

[9] Per the container layout, temperatures were measured on the chiller box.
[10] The criteria is not applicable, the door is not combustible.
[11] The criteria is not applicable, the ceiling is not combustible.

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

Table 9 – Integral Fire suppression system Details of Operation		
Time of operation of Sprinklers/Suppression System:	Time of Operation Start (HH:MM:SS)	Time after thermal runaway (HH:MM:SS)
First Smoke detection	00:40:24	00:00:11
Second Smoke detection	00:40:26	00:00:13
NOVEC released	00:40:26	00:00:13

Table 10 – Other Observations during Installation level test			
	Observed, Yes/No	Comments/Location	
Flaming outside of Unit	No	Length of flame:	No flaming observed
Flying debris	No	-	
Explosive discharge of gas	No	-	
Sparks or electrical arcs	No	-	

Table 11 - Post Test Observations	
Thermal runaway behaviour	No
Re-ignitions	No
Explosions	No
Other Observations	No

	TABLE: Critical components information				
Object / Part No.	**Manufacturer/ trademark**	**Type / model**	**Technical data**	**Standard**	**Mark(s) of conformity[1)]**
Cell	SAMSUNG SDI CO LTD	CP1495L101+	3.68 Vdc, 145 Ah	UL1973	UL Recognized
Module	SAMSUNG SDI CO LTD	MS3204L101A	2P30S/, 110.4Vdc, 290 Ah	UL1973	UL Recognized
Unit Enclosure	SAMSUNG SDI CO LTD	PHR3843-001A	2P360S 1324.8Vdc, 280Ah	UL1973	UL Recognized
Rack Assembly for module	Samsung SDI	SGHC/SGCC	Thickness: 3.2 mm Dimension: 960.5 mm x 1752 mm x 2352 mm	-	-
Rack Assembly for BCU	Interchangeable	SGHC/SGCC	Thickness: 3.2 mm Dimension: 960.5 mm x 1752 mm x 2352 mm	-	-
Liquid cooling system (*normal operations*)	SAMSUNG SDI CO LTD	Liquid Cooling system	-	-	-
Wiring	JHOSIN HONGLIN TECHTRON	Type3817	AWG1, 125℃	UL758	UL Approved
Thermal Insulating Materials	HANJUNG NCS CO., LTD	Mica, Aerogel			
Smoke Detectors	POTTER	PAD300-PD	Addressable Smoke Detector	UL268	Listed (S24776)
Fire Control Panel	POTTER	IPA-100	Addressable FACP	UL864	Listed (S735)
Suppressant	3M	FK-5-1-12, 3MTMNovecTM1230 Fire Protection Fluid	>50kg of Novec Fluid, 360psi with nitrogen	-	-
NOVEC cylinder	GFI	F1230-CYL-58	-	-	-
Swaged Nipple Assy	GFI	SQF2S-1-7/ 8-12UN-OF1.5- SDI-S6	Orifice 1.50	-	-

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

Solenoid Valve	Fiwarec	F1120045	- 20 to 50 ℃	UL 864	UL Approved (S35768)
Plastic plug	LOTTE Chem	PP J-320	-	-	-
Pipes	Hanjung NCS	Brass	3/8”	-	-

List of test equipment used:

A completed list of used test equipment shall be provided in the Test Reports when a Customer's/Third Party Testing Facility has been used.

Testing / measuring equipment / material used, (Equipment ID)	Range used	Last Calibration date	Calibration due date
Battery cycler	EVT 150-1200-1 Thy/ 1200V, 150A	2022-05-12	2023-05-12
Data Acquisition System (DL850E)	500°C/200V	2022-06-24/ 2022-06-15	2023-06-24/ 2023-06-15
Data Acquisition System (Fluke)	500°C/150V	2022-04-25/ 2022-04-11	2023-04-25/ 2023-04-11
Digital Multimeter	FLUKE 1000V	2022-05-31	2023-05-31
Electronic scales	CKE162 200kg	2022-05-13	2023-05-13
Stop watch	CASIO 86400 s (24hr)	2021-08-26	2023-08-26
Measuring tape	TAJIMA 7m	2022-11-08	2023-1108
Temperature and humidity recorder	608-H1 30.0% to 70.0%, 10.0°C to 30.0°C	2022-10-31	2023-10-31

Attachment A: Sample Charging, OCV and SOC Measurement Profiles - (*Pages **31** through **32***)

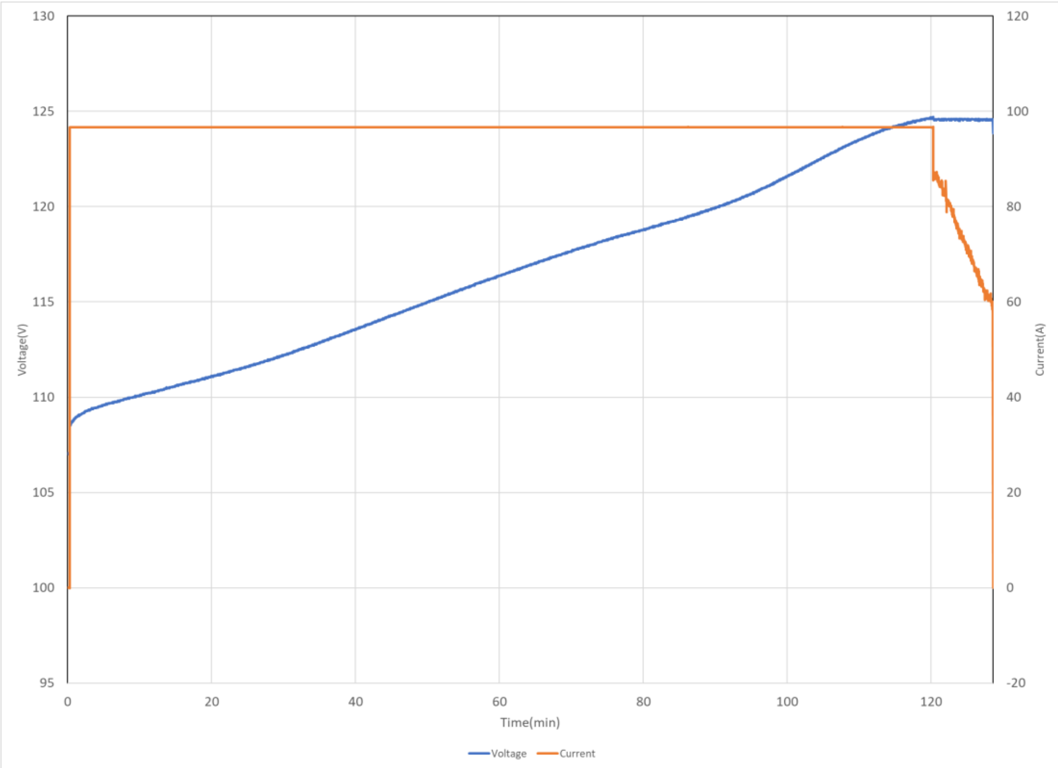


Figure A1 – Initiating module (module 10) charge profile

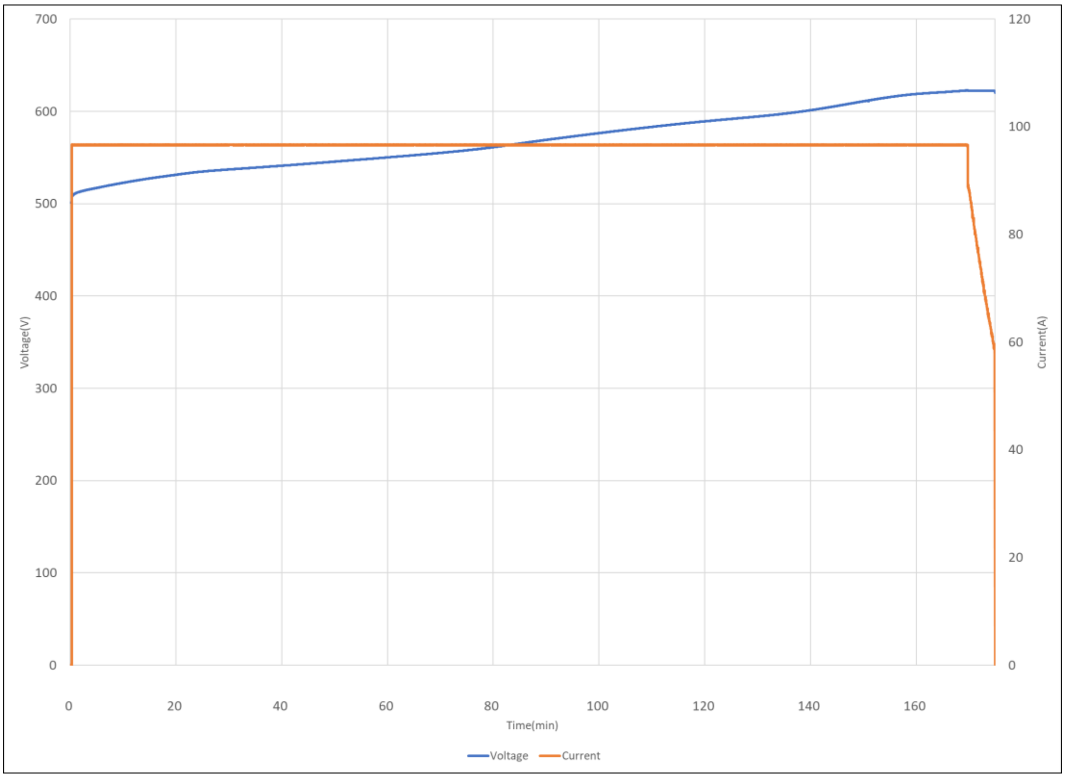


Figure A2 – Module 1 to 5 charge profile, connected in series

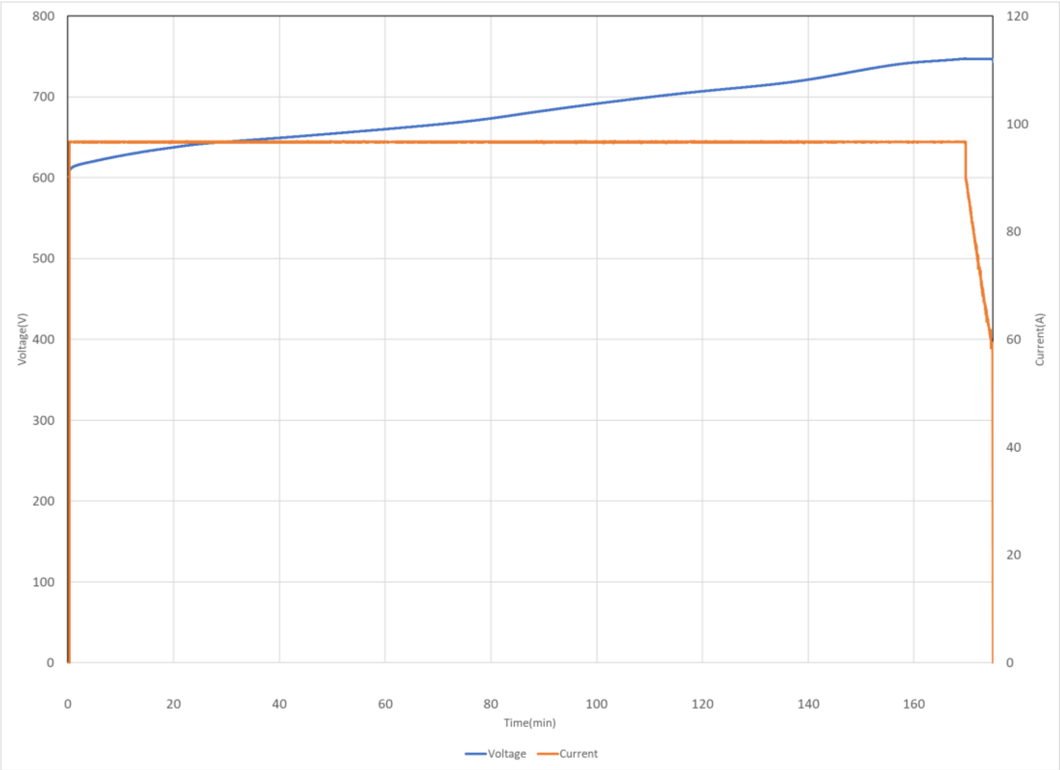


Figure A3 – Module 6 to 9 and Module 11, 12 charge profile, connected in series

Attachment B: BESS (including module and any integral fire detection and suppression systems) Construction Photos/Diagrams - (*Pages **33** through **34***)

Figure B1 – Photo of the initiating module

Figure B2 – Photo of Unit and BCP Box

Figure B3 – Dummy units populated on the other side of the container
(Initiating unit in red box and Target 1, 2 in blue box)

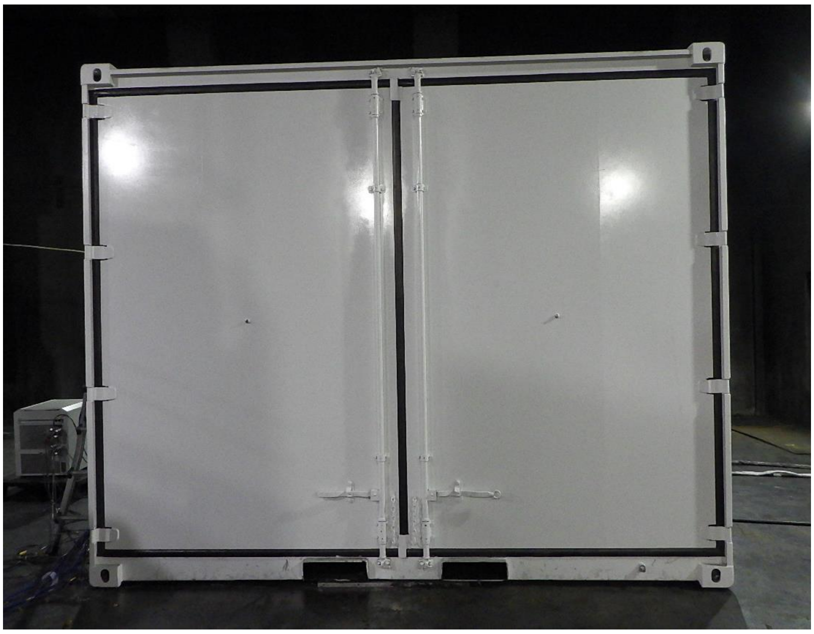


Figure B4 – Photo of the container

Attachment C: : BESS and Equipment Instrumentation and Test Installation Layout Photos/Diagrams - (*Pages **35** through **40***)

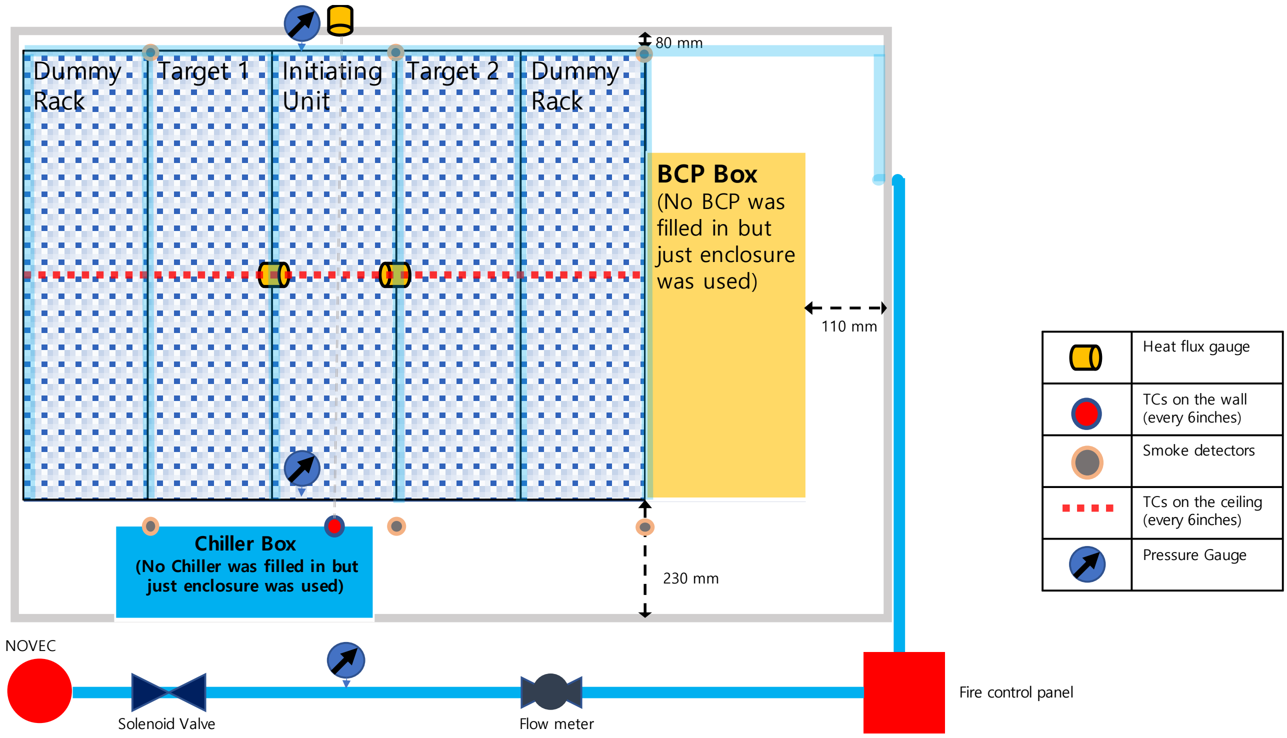


Figure C1 - Overall Layout Diagram

Table C1 – Test configuration

Test Configuration	
Clearance between Initiating Unit and Target Unit 1	0 mm
Clearance between Initiating Unit and Target Unit 2	0 mm
Clearance between Initiating Unit and the Door, front side of Unit	233 mm
Clearance between Initiating Unit and the back container enclosure, rear side of Unit	80 mm
Clearance between Initiating Unit and the side wall	110 mm (side of BCP) 0 mm (opposite side of BCP)

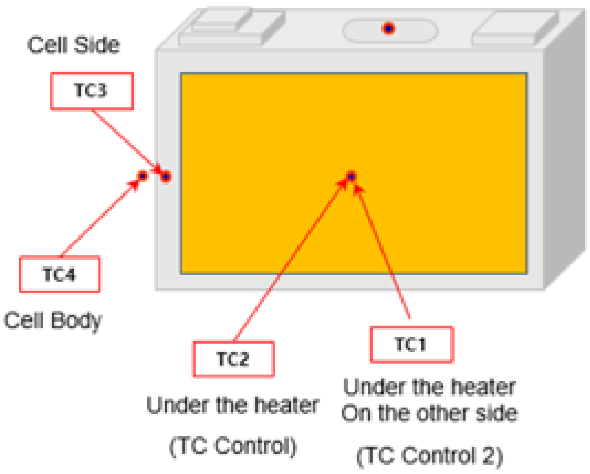


Figure C2 – Initiating cell thermocouples locations

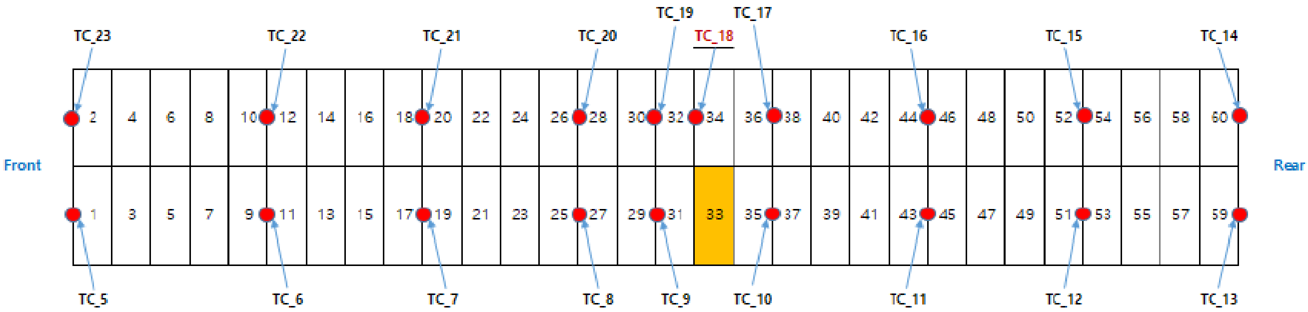


Figure C3 – Location of initiating cell and additional thermocouples within module

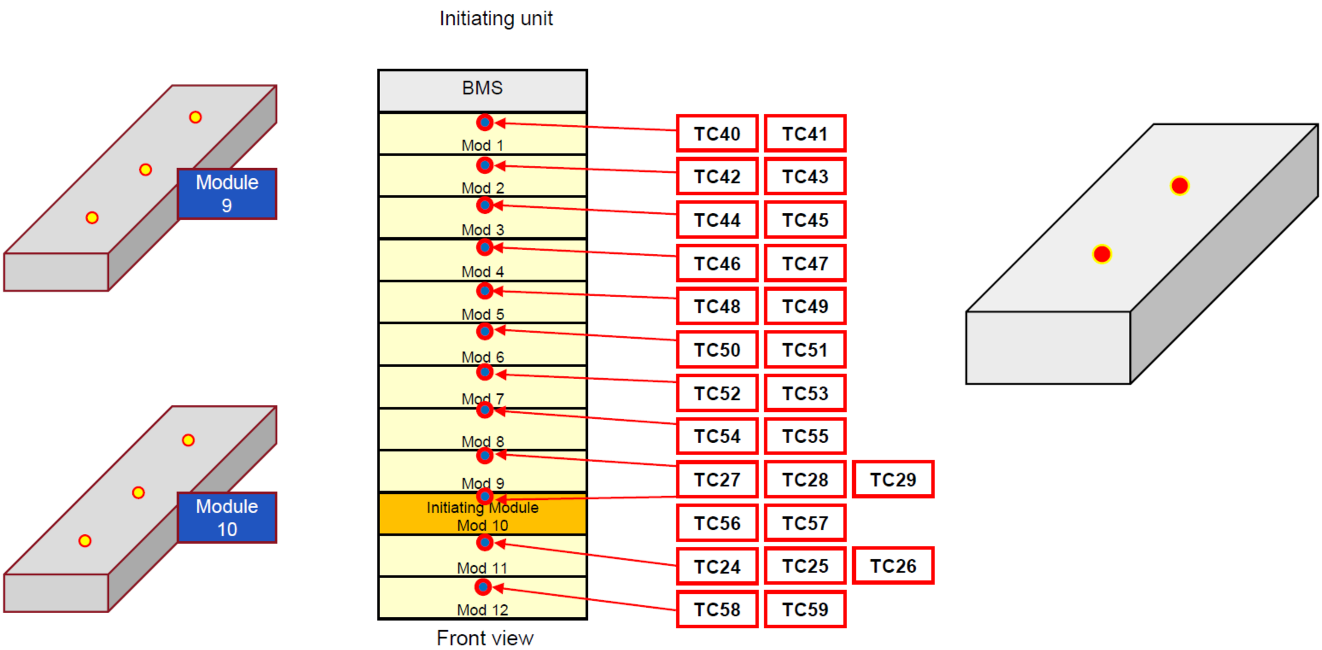


Figure C4 – Thermocouple locations for non-initiating modules in the initiating Unit

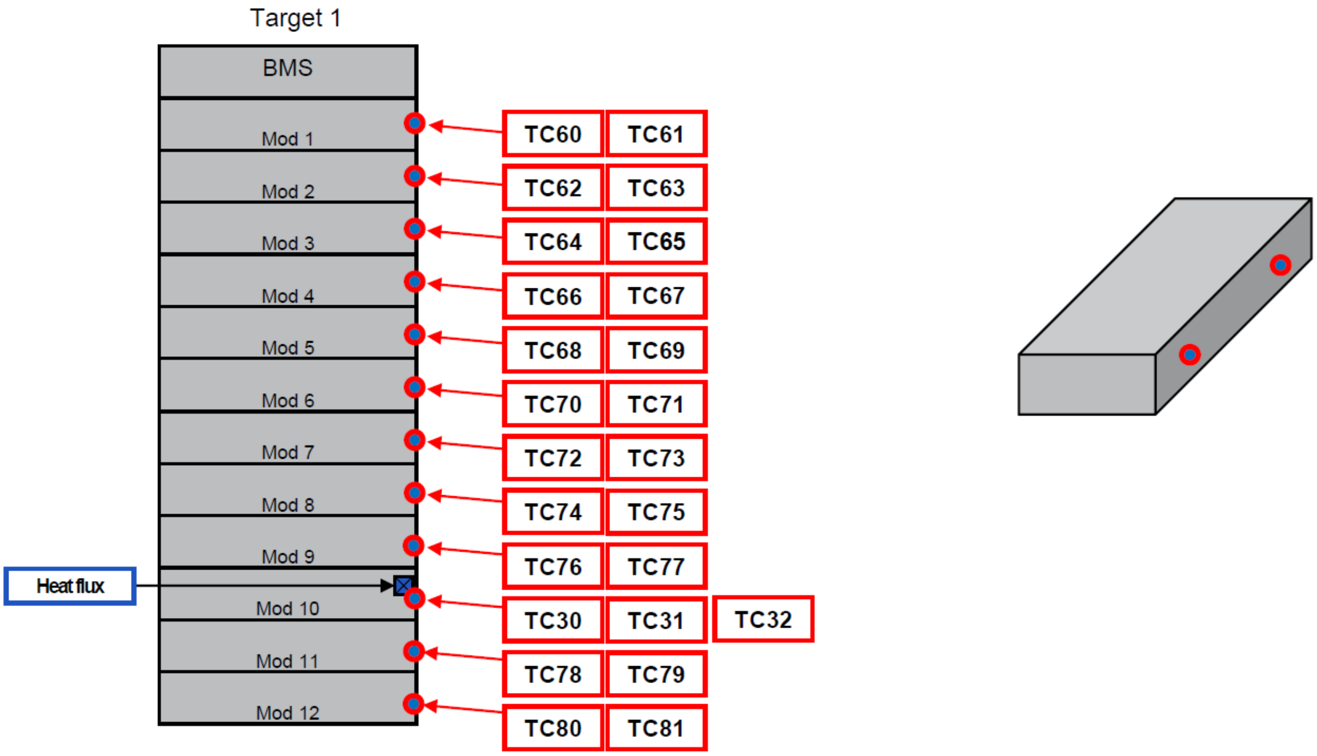


Figure C5 – Thermocouple and Heat flux locations in Target Unit 1

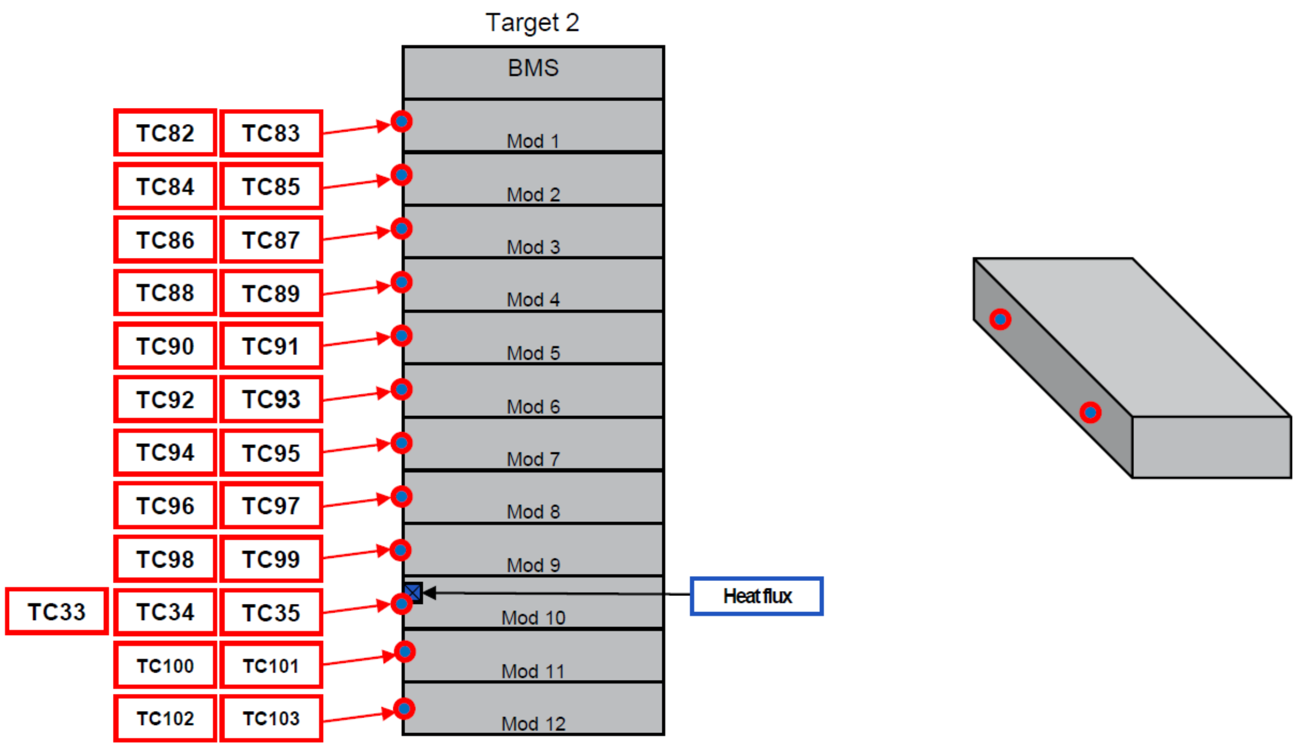


Figure C6 – Thermocouple and Heat flux locations in Target Unit 2

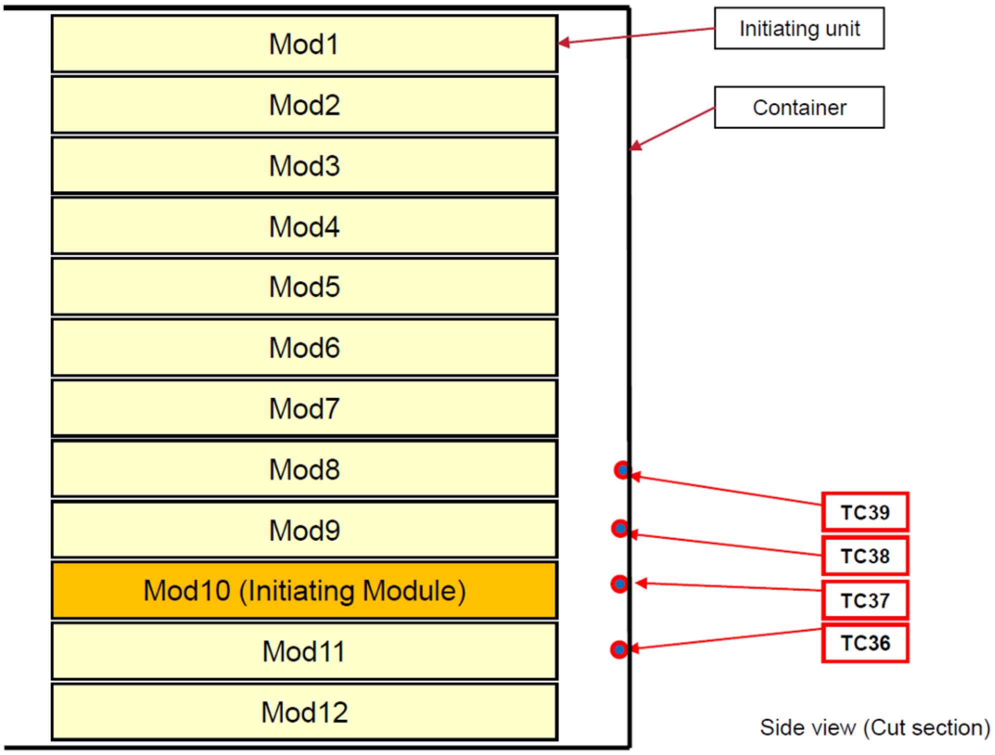


Figure C7 – Thermocouple locations at the back of the initiating unit

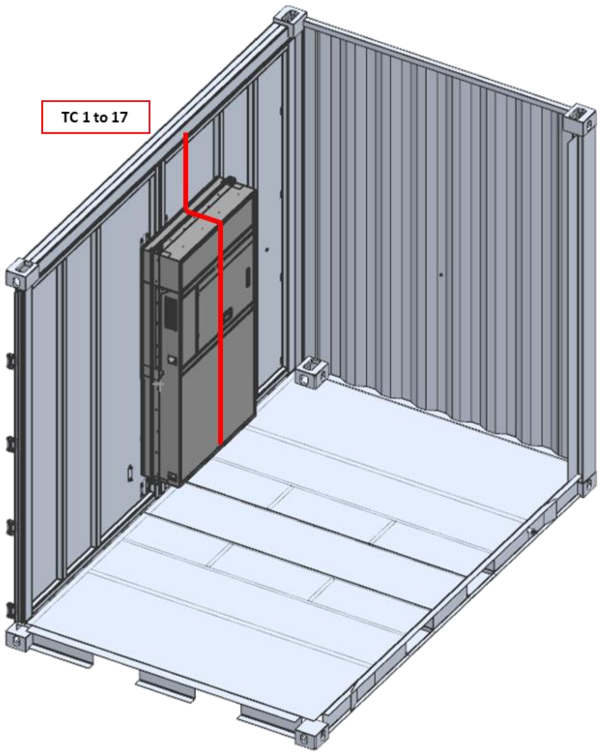


Figure C8 – Thermocouple locations on the front door of the container, aligned with the initiating cell location

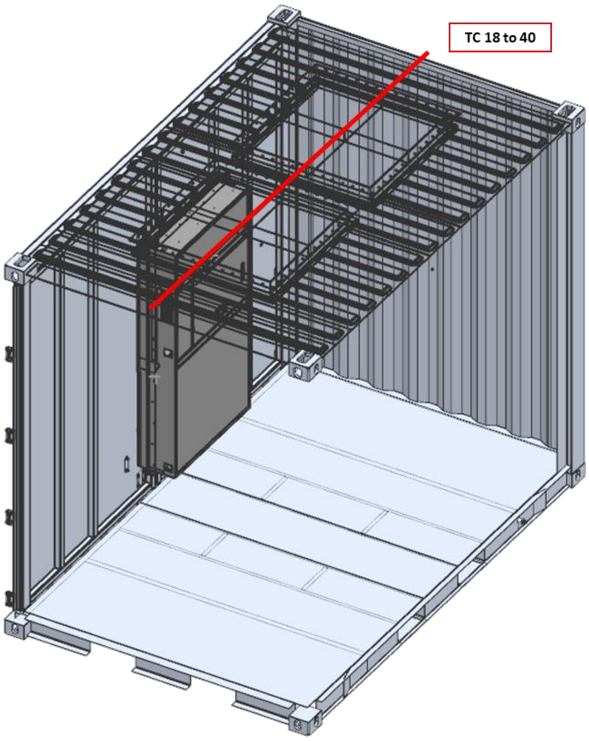


Figure C9 – Thermocouple locations on the ceiling of the container[12]

12 Thermocouples (K-type) were instrumented every six inches in accordance with 10.3.5

Figure C10 – Photo of the heat flux gauge (in the yellow circle) to account for the egress path and the pressure gauge to measure a potential explosion pressure (in the blue circle)

Attachment D: Temperature Profiles and Heat Flux Measurements During Testing (Initiating Cell and Module, Target Modules, Wall Surfaces, etc. - (*Pages **41** through **44***)

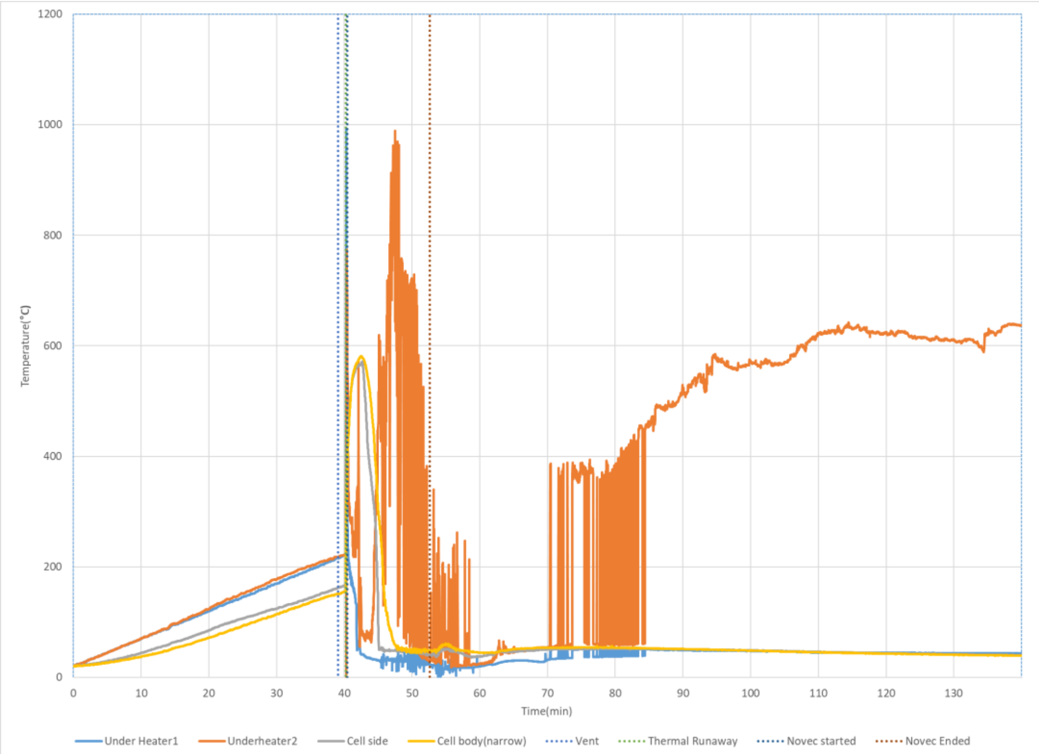


Figure D1 – Surface temperatures measured on the initiating cell during the test

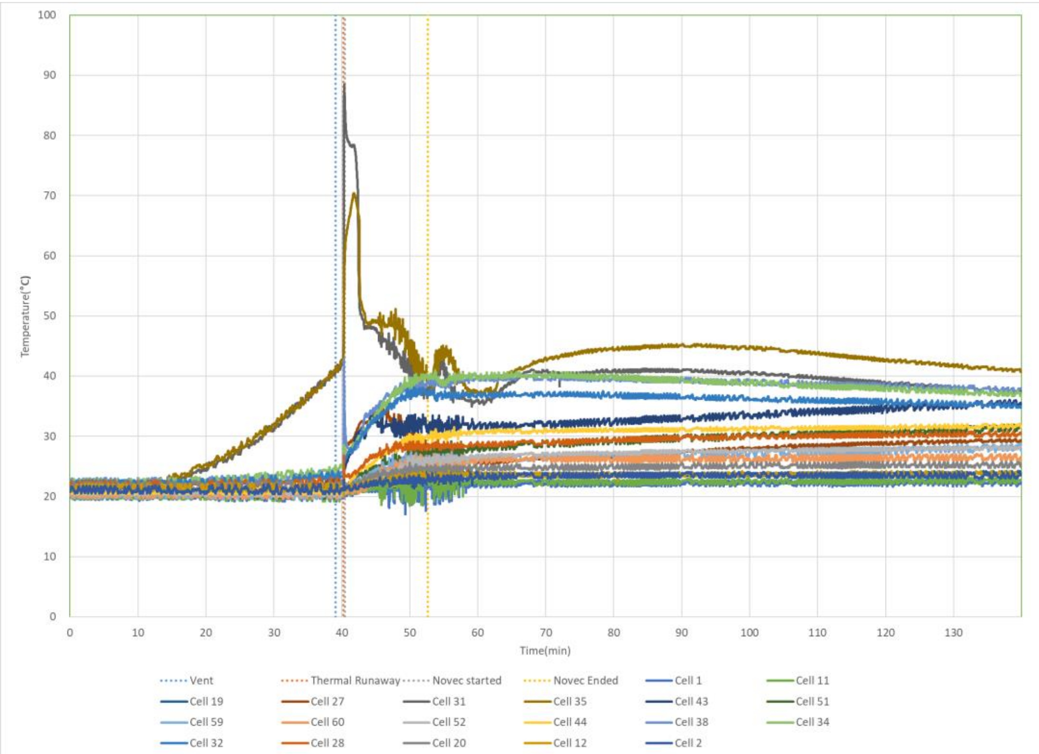


Figure D2 – Temperature measurements on the instrumented non-initiating cells in the initiating module

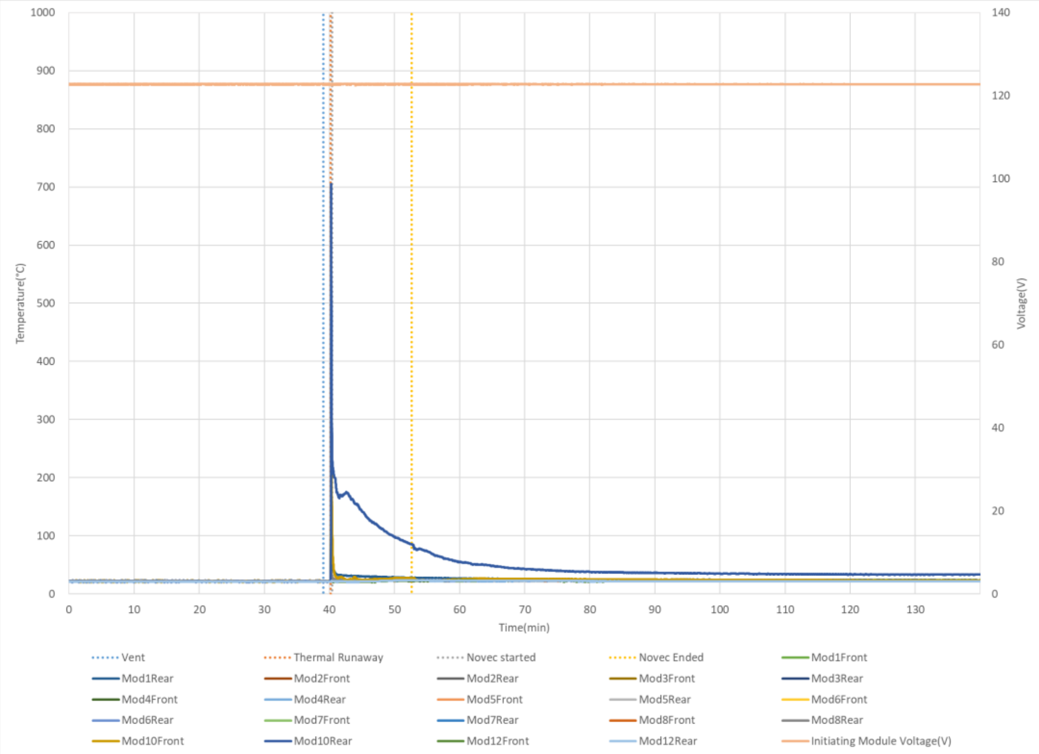


Figure D3 – Temperature and voltage measurement on the modules in the initiating unit

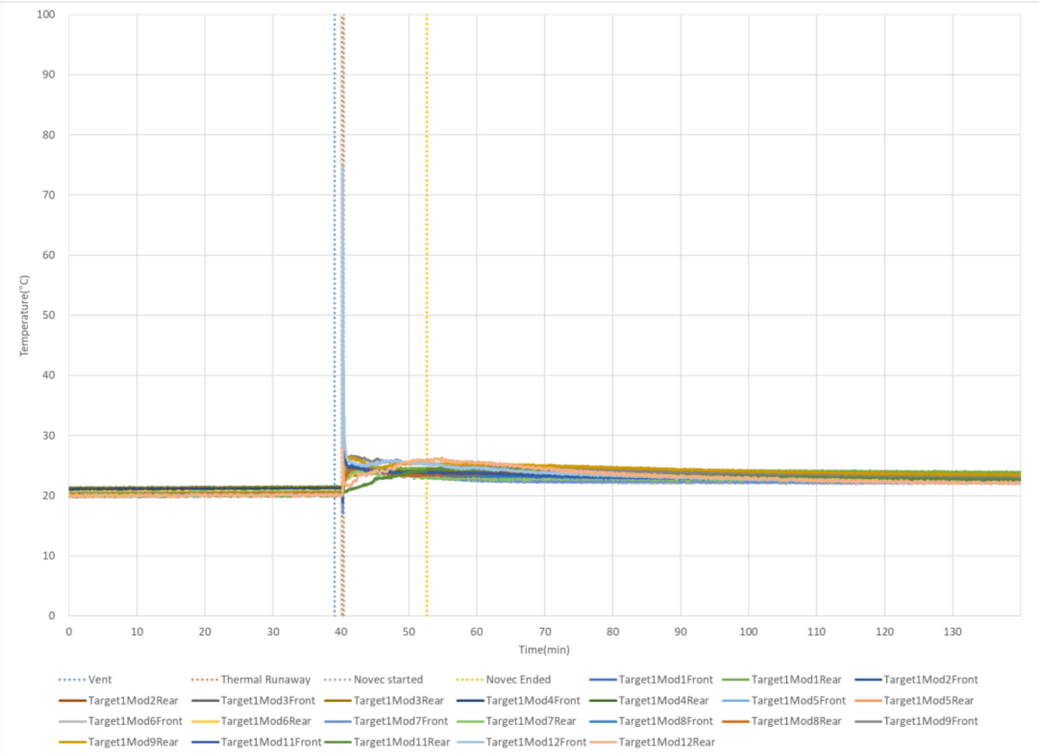


Figure D4 – Temperature measurement on the modules in the target unit 1

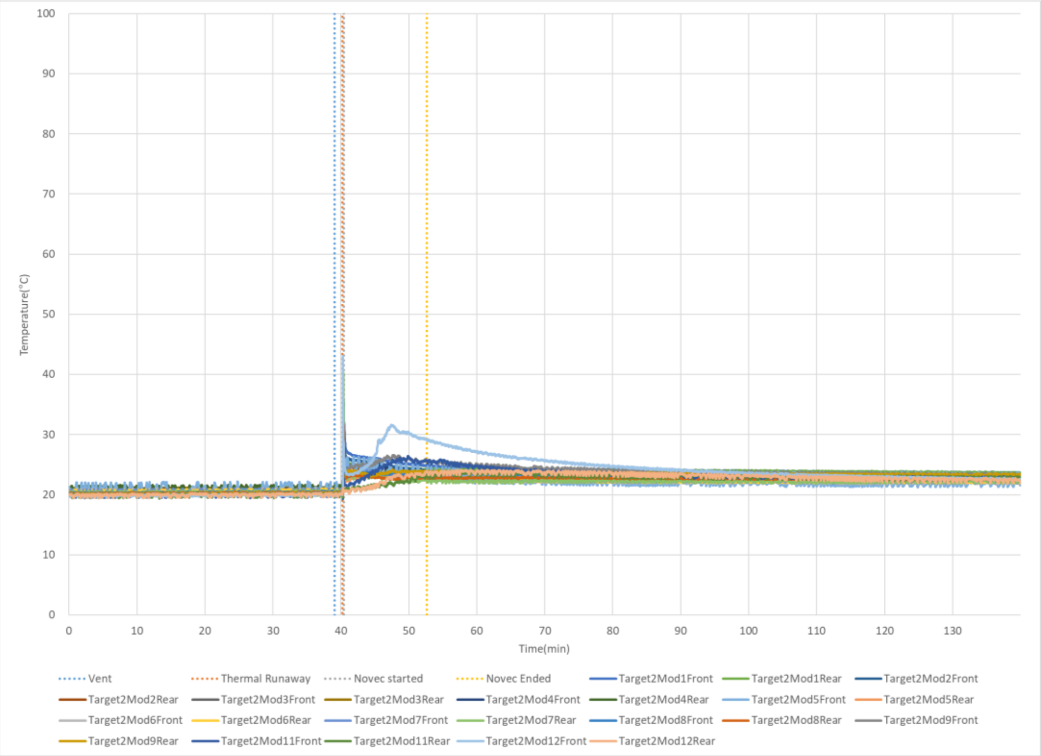


Figure D5 – Temperature measurement on the modules in the target unit 2

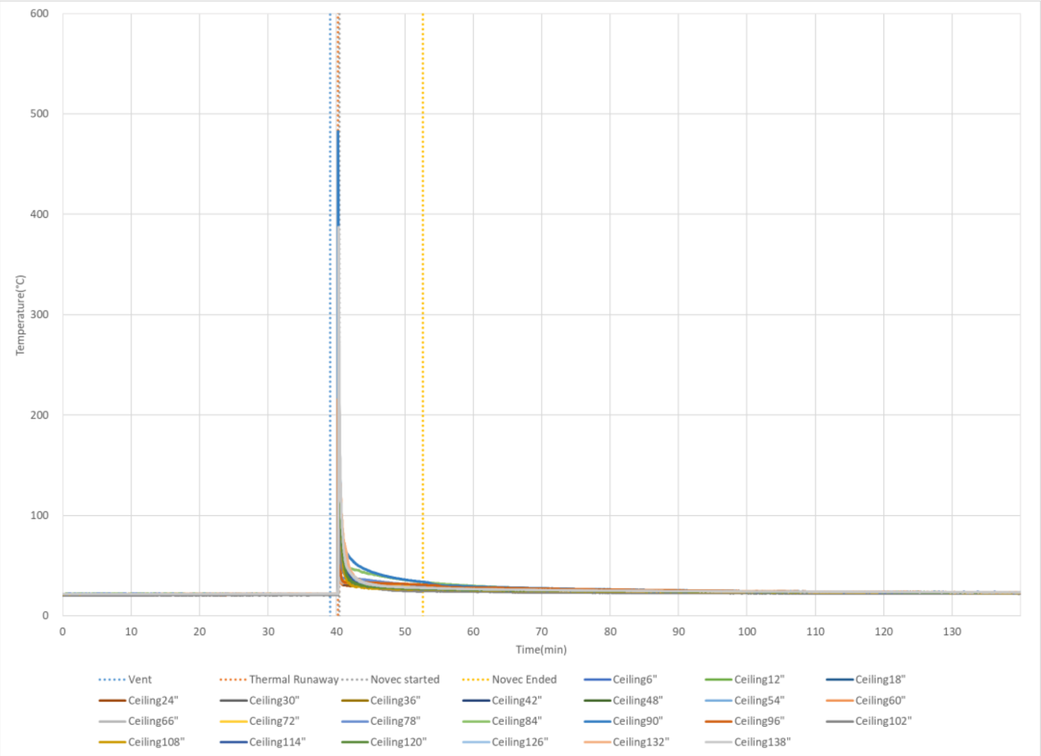


Figure D6 – Temperature measurement on the ceiling of the container

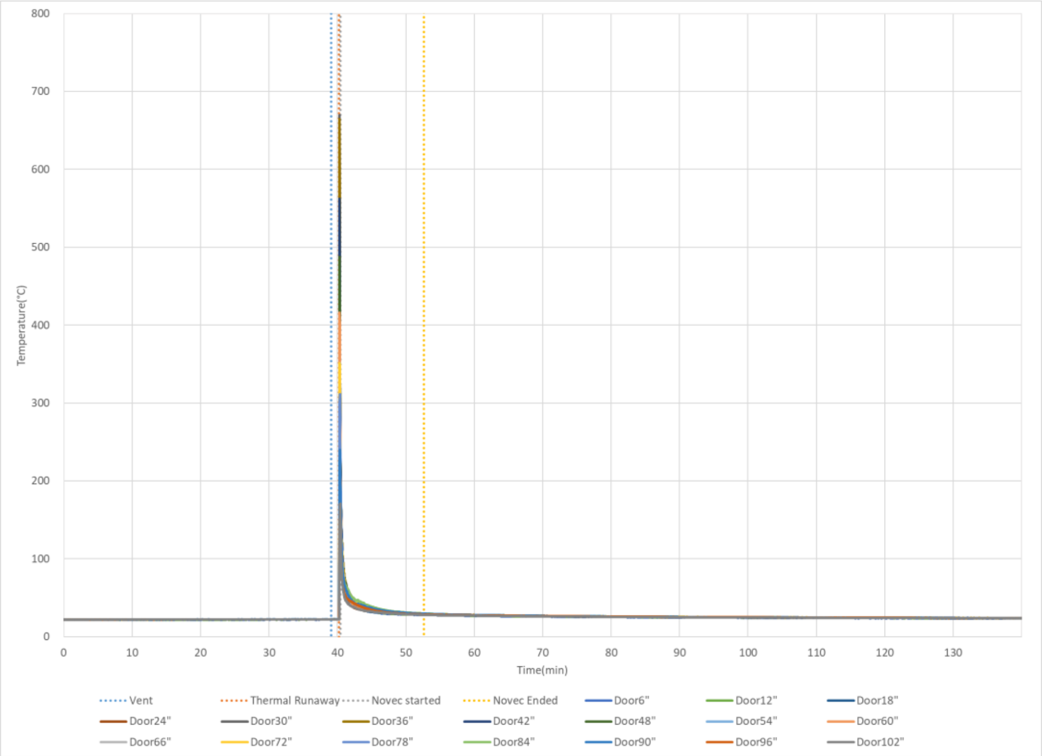


Figure D7 – Temperature measurement on the inside of the door of the container, located in front of the initiating unit

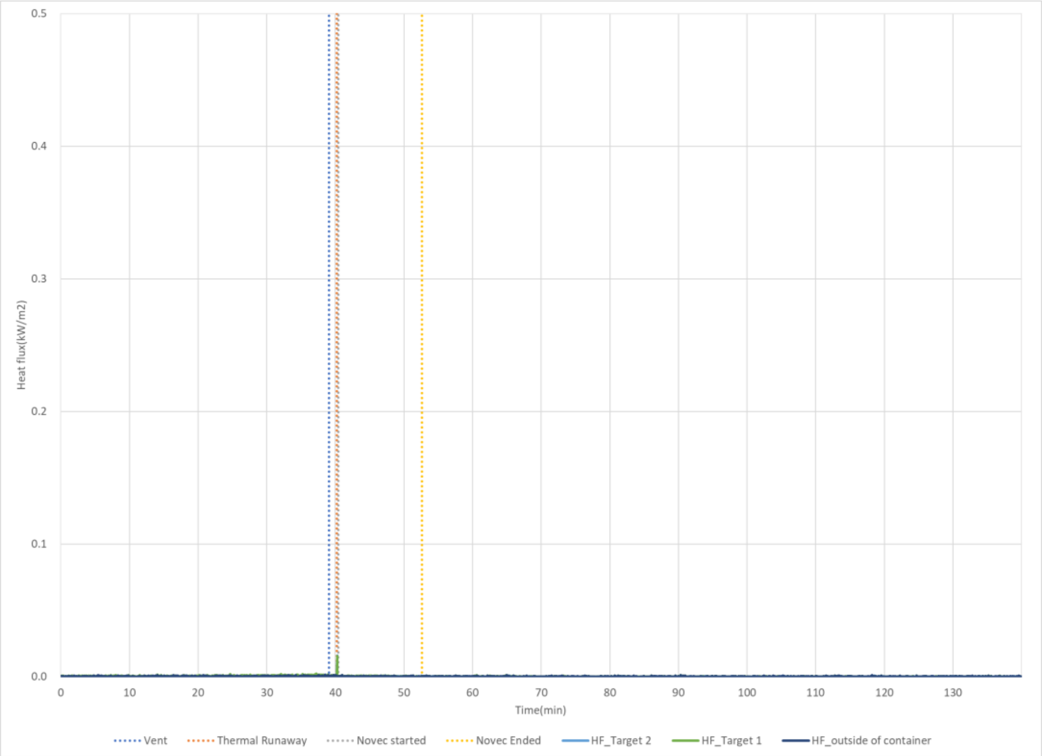


Figure D8 – Heat flux measurement for target units and outside the container

Attachment E: BESS Unit Testing and Post Testing Photos - (*Pages **45** through **49***)

 (a) Test Start [00:00:00]	 (b) Thermal runaway inside of the container [00:40:13]
 (c) Ignition flame observed [00:40:15]	 (d) Lost camera visibility [00:40:23]

 (e) The First Smoke detection [00:40:24]	 (f) The second Smoke detection and Novec release [00:40:26]
 (g) Recorded last snapshot [00:55:00]	 There was an error in recording located inside of container, some of snapshot of video were not available. (h) Test end [02:19:57]

Figure E1 – Photo of the units after the test

Figure E2 – Photo of the door with Chiller box enclosure and thermocouple arrays after the test

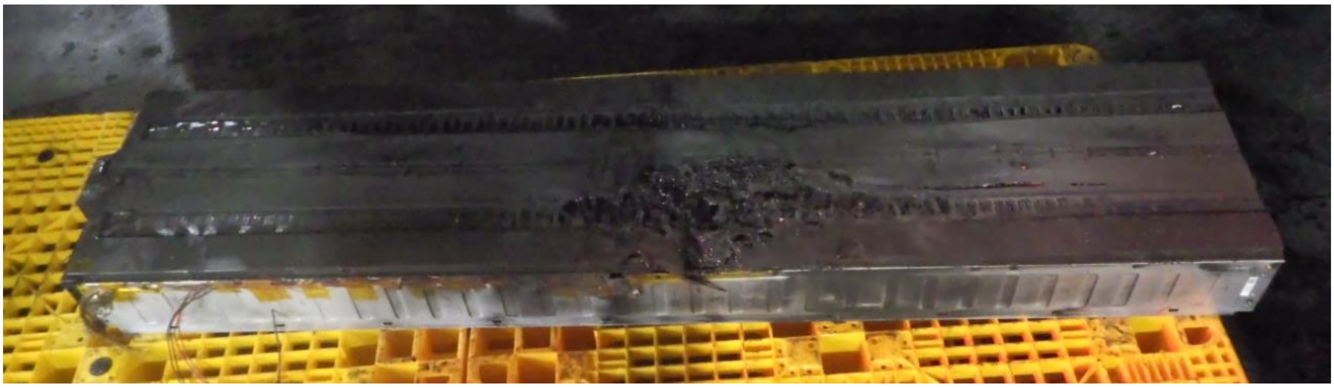


Figure E3 – Photo of the top of the initiating module after the test

Figure E4 - Photo of the side of the initiating module after the test

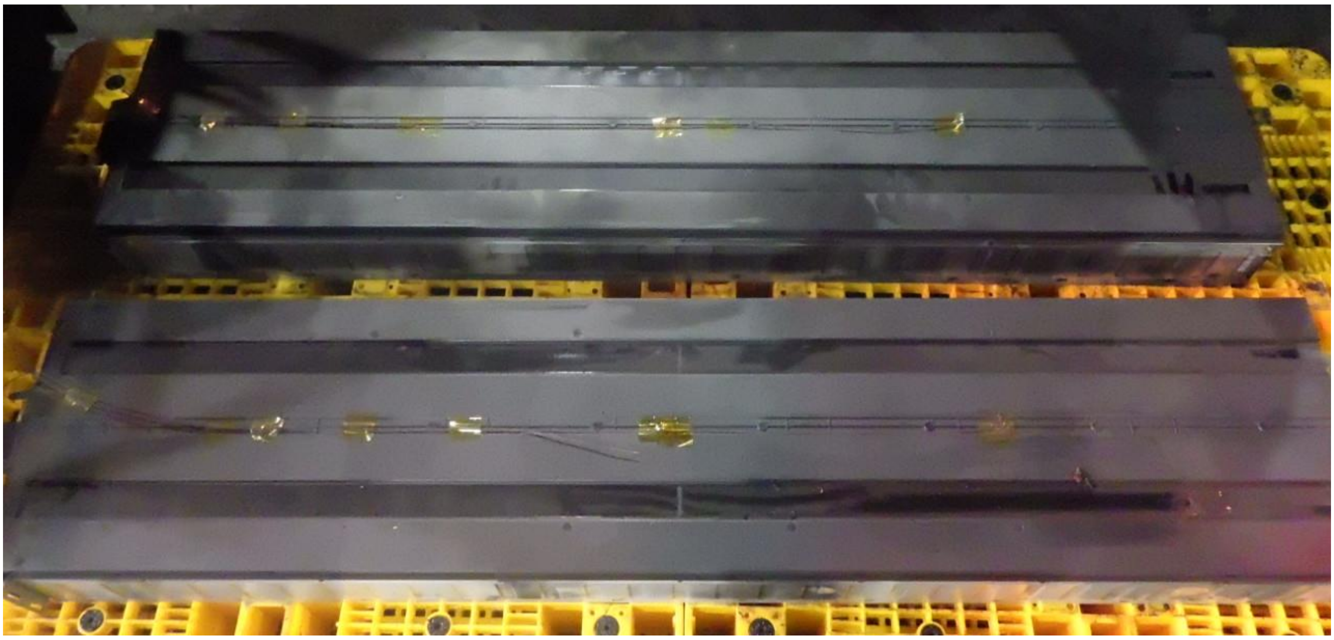
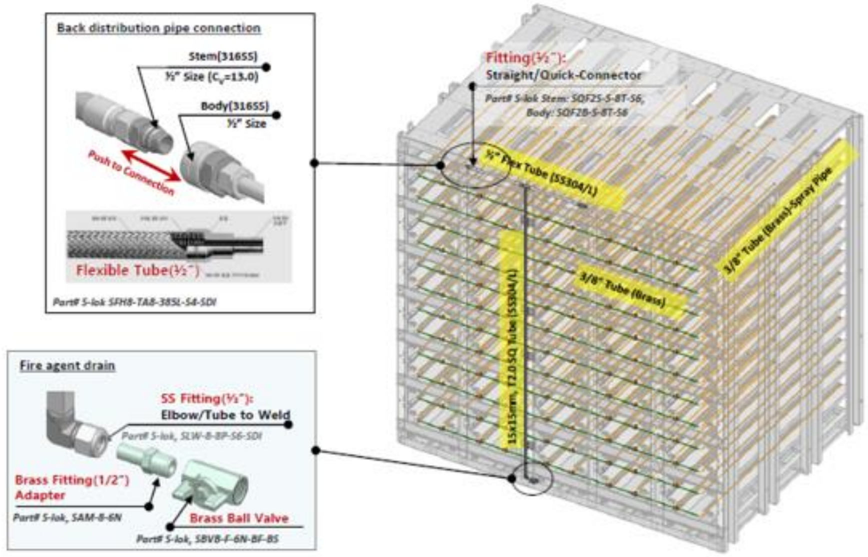


Figure E5 - Photo of the top and the bottom of the initiating module after the test

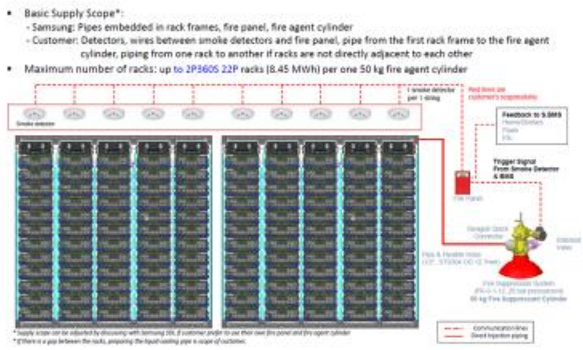
Attachment F: Fire suppression system and deflagration mitigation system - (*Pages **50** through **55***)

Frame design of Direct Injection

- 360S Configuration, consists of liquid cooling piping at the front and Direct Injection piping at the back



Method of Direct Injection



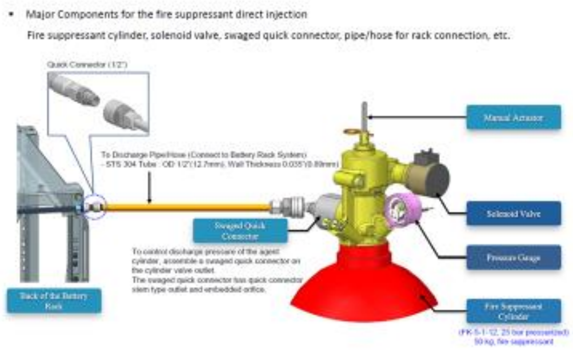


Figure F1 – Principle of the direct injection system, as per Samsung SDI

Figure F2 – Photo of Novec 1230 Cylinder

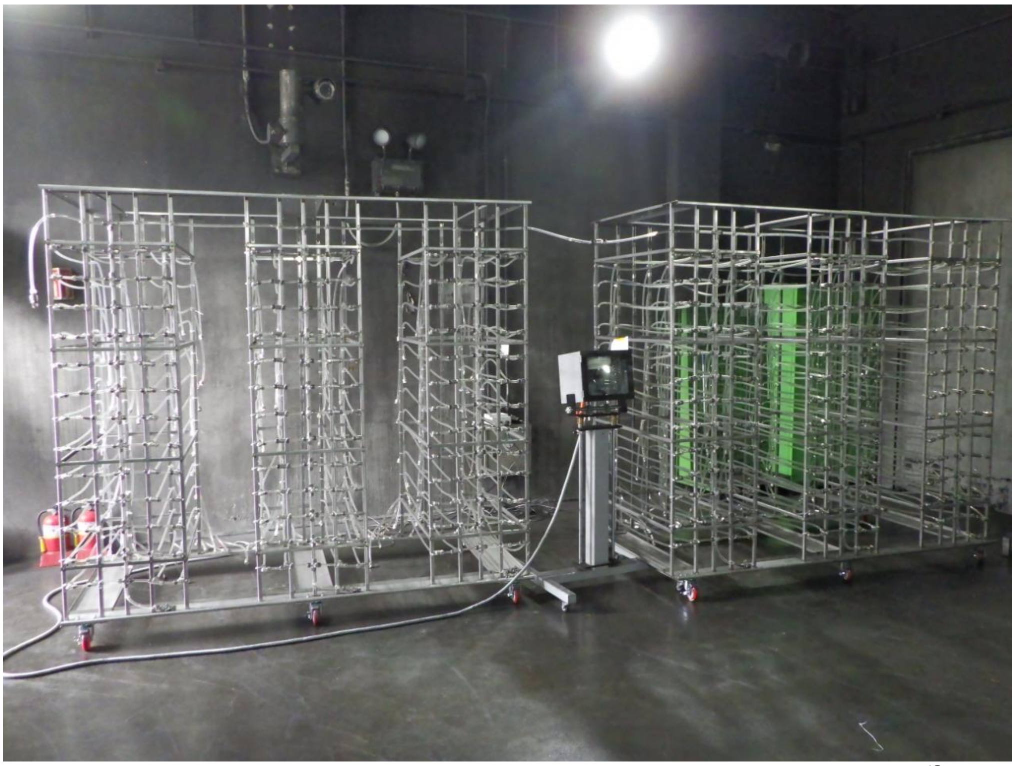


Figure F3 – Photo of dummy pipe racks to account for the pressure drop[13]

Figure F4 – Photo of the hoses going through the container wall and the urethane seal

[13] The dummy pipe racks were designed by Samsung to simulate the pressure drop of the suppressant to account for the case where more racks could be installed. The dummy racks were installed between the downstream of the cylinder and the container.

Figure F5 – Photo of the smoke detector installed above the rack

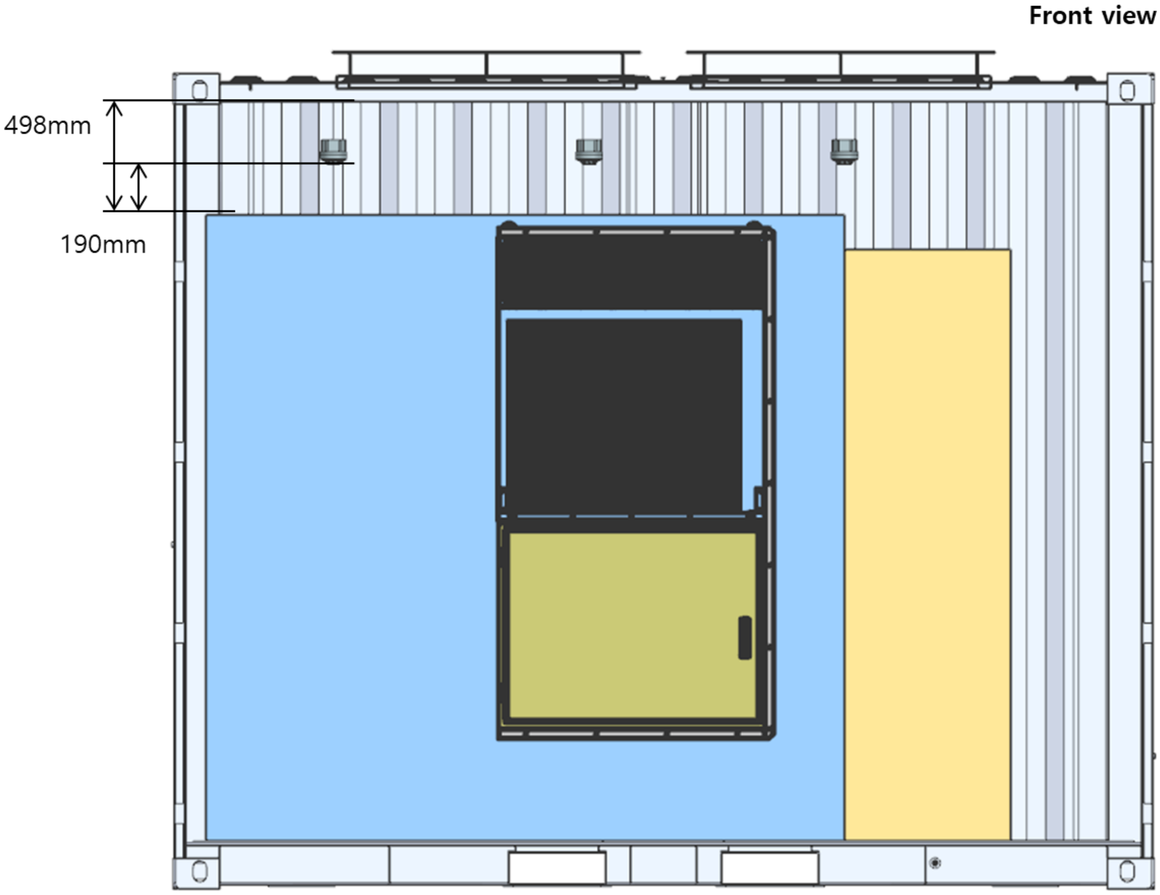


Figure F6 – Layout of the smoke detector

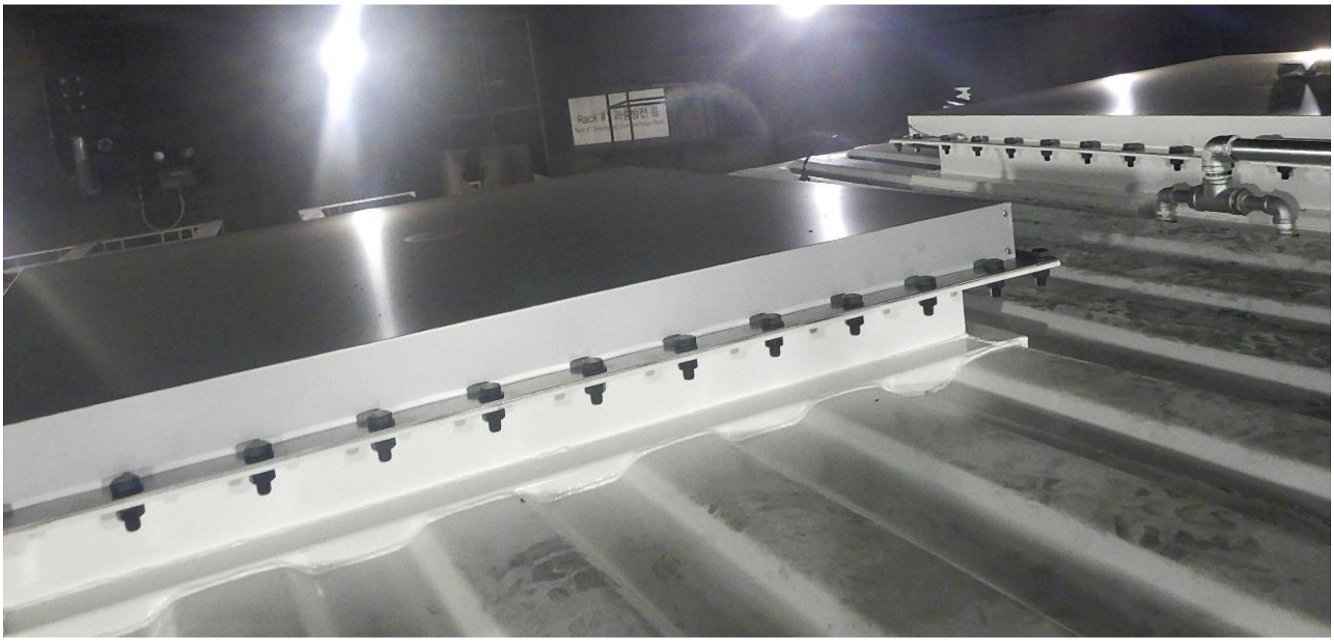


Figure F7 – Photo of the deflagration panel on the ceiling (taken from out side of the container)

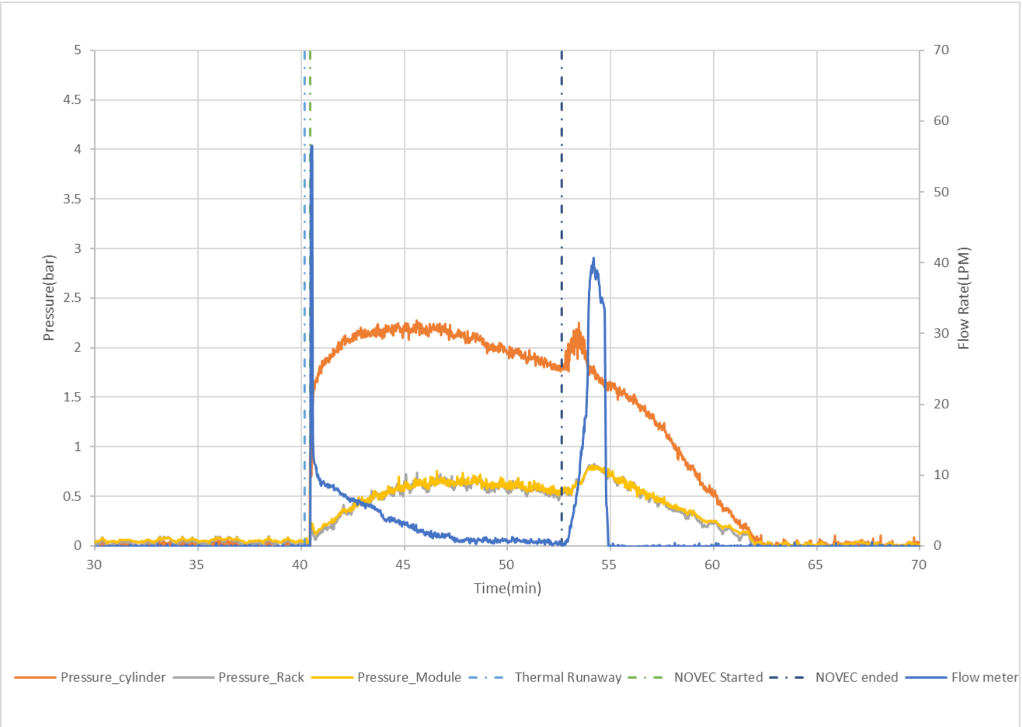


Figure F8 – Pressure and flow rate measurements on the cooling system

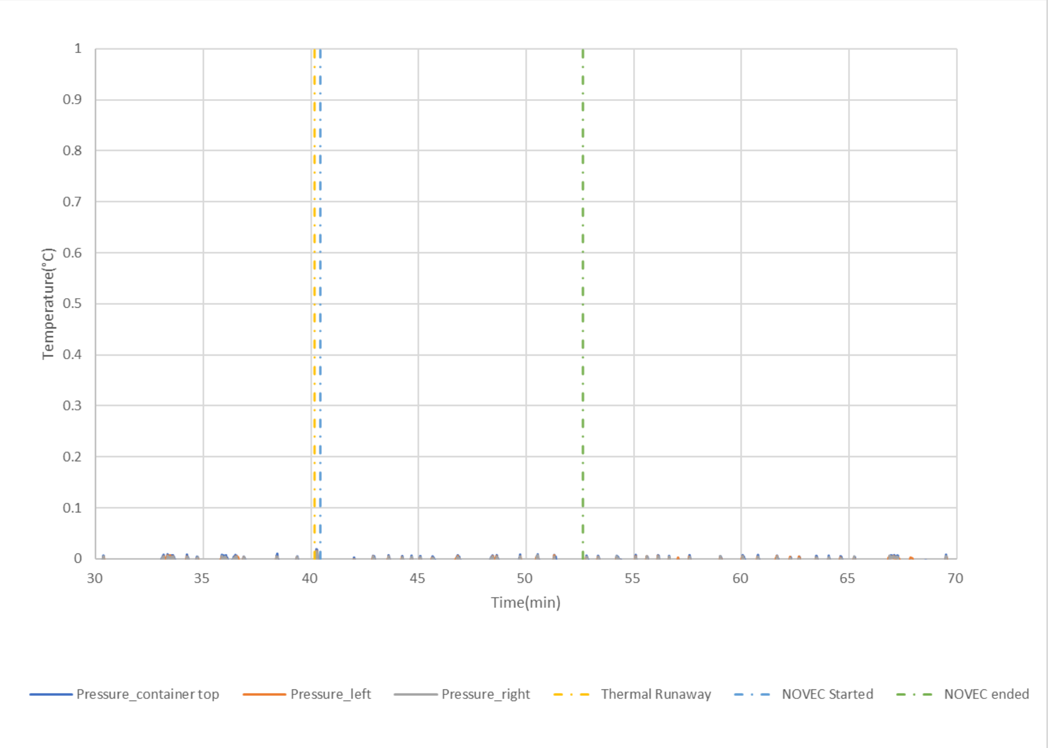


Figure F9 – Pressure measurements on the container

Attachment G: Certification requirement decision of container system BESS in UL9540A - (*Pages **56** through **61***)

UNDERWRITERS LABORATORIES INC. CERTIFICATION REQUIREMENT DECISION

This Certification Requirement Decision is prepared by UL LLC. It is normative for the applicable UL Product Certification Program(s); however, it is currently not part of the UL Standard(s) referenced below.

Product Category (CCN): AACD
Standard Number: UL 9540A
Standard Title: Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems
Edition Date: November 12, 2019
Edition Number: 4
Section / Paragraph Reference: Revised: 9.9.1, 10.1.2, 10.3.1, 10.4.1, 10.7.1
New: 4.4.1, 9.1.2.1, 10.1.1, 10.2.3, 10.3.16, 10.5.9, 10.6.2, 10.8.2
Subject: Test Approach for Multi-Battery Rack Container BESS

DECISION:

4.4.1 CONTAINER SYSTEM (BESS) – For the purposes of this standard, a large, enclosed BESS with multiple battery system racks that may or may not be a walk-in system and that may contain integral fire detection and suppression systems and may include integral deflagration or explosion protection.

9.1.1 The unit level test shall be conducted with BESS units installed as described in the manufacturer's instructions and this section. Test configurations include the following:

a) Indoor floor mounted non-residential use BESS;

b) Indoor floor mounted residential use BESS;

c) Outdoor ground mounted non-residential use BESS;

d) Outdoor ground mounted residential use BESS;

e) Indoor wall mounted non-residential use BESS;

f) Indoor wall mounted residential use BESS;

g) Outdoor wall mounted non-residential use BESS;

h) Outdoor wall mounted residential use BESS; ~~and~~

i) Rooftop and open garage non-residential use BESS installations~~.~~; and

j) Container system BESS.

9.1.2.1 For a container system BESS including those intended for outdoor installation only, the unit level test shall be in accordance with the indoor floor mounted unit level test using the battery system racks as the test units and with the test installation set up in accordance with the installation layout within the container.

STANDARD NUMBER: UL 9540A -2-

10.1.1 General

10.1.1 The installation level test method assesses the effectiveness of the fire and explosion mitigation methods for the BESS in its intended installation. The installation level testing does not apply to residential use BESS.

a) Test Method 1 – "Effectiveness of sprinklers" is used to evaluate the effectiveness of sprinkler fire protection and explosion mitigation methods installed in accordance with code requirements.

b) Test Method 2 – "Effectiveness of fire protection plan" is used to evaluate the effectiveness of other fire and explosion mitigation methods (e.g., gaseous agents, water mist systems, combination systems).

c) Test Method – Container System BESS installation level test

10.1.2 Installation level testing is not appropriate for units only intended for outdoor use or residential use. Container system BESSs as defined in this standard, although typically for outdoor use installations, are included in the installation level test as the container, which may include integral fire detection and suppression and integral explosion or deflagration protection represents a type of installation.

10.2.3 For container system BESS, the units utilized for initiating and target units are the battery system racks that are installed within the container. The container system BESS shall be populated with one initiating unit chosen as the location within the container that may result in worse case results and target units installed around and across the initiating BESS representative of the intended container layout. The fire detection and suppression systems and deflagration/explosion protection systems if provided for the container installation, shall be installed in the system for the test. Any wiring within the container either intended to be installed above the units or along them horizontally, that can be a source of fire spread, should be included in the container for the test. Equipment mounted to openings in the container that may impact air flow and therefore test results, should be included in the installation for the test. Internal equipment such as a power conditioning/conversion system or switchgear, can be represented by their enclosures or other simulation means for temperature measurement purposes.

10.3.1 For BESS units with a height of 2.44 m (8 ft) or less, the test shall be conducted in a 6.10 × 6.10 × 3.05-m (20 × 20 × 10-ft) high test room with one open 1.22 × 2.13-m (4 × 7-ft) high doorway or a room representative of the installation configuration as specified by the manufacturer. The smallest~~largest~~ test room anticipated by the manufacturer for BESS deployments, including footprint and ceiling height, shall be tested. For BESS units taller than 2.44 m (8 ft), the ceiling height shall be increased to be at least 0.61-m (2-ft) higher than the BESS units under test. The explosion mitigation methods shall be installed in the test installation in accordance with the manufacturer's specifications. Pressure sensors shall be installed as close to the deflagration vents as possible to determine the maximum pressure developed during the test. The pressure shall be measured with frequency of at least 5000 samples per second.

10.3.16 Test Method - Container System BESS Installation Level (Test Method 1)

10.3.16.1 A container system BESS that utilized sprinkler system fire suppression shall be tested in accordance with 10.3 except instead of the test room, the actual container shall be used as the test room.

10.3.16.2 Temperatures on walls, ceiling and target modules shall be measured in accordance with 10.3.5, 10.3.6 and 10.3.11.

10.3.16.3 The installation shall include any exposures representing major components (e.g. battery system racks, power conditioning system, HVAC, etc.) installed within the container system. Temperatures shall be measured on those exposures with combustible construction besides walls, ceiling and target modules. Temperatures on exposures with large surfaces (height > 12 inches) shall be measured similar to the approach used for measuring temperatures on walls. Temperatures on exposures with small surfaces (height ≤ 12 inches) shall be measured on at least one location where the greatest temperature is expected to be achieved. The exposure can be represented by the equipment enclosure or a wall or other means placed in a similar manner to represent the location and layout of the major component exposures.

10.4.1 The report on installation level testing shall include the following:

a) Unit manufacturer name and model number (and whether compliant with UL 9540 or UL 1973) and the container system BESS manufacturer name and model number (and whether compliant with UL 9540);

b) Number of modules in the initiating BESS unit;

c) The construction of the initiating BESS unit per 5.3, and the number of battery system racks and overall construction within the container for a container system BESS;

d) Module voltage(s) of initiating BESS corresponding to the tested SOC;

e) The thermal runaway initiation method used;

f) Diagram and dimensions of the test setup including location of the initiating and target BESS units, and the locations of walls and ceilings, and location of included internal target components in the container system BESS (e.g. target integral power conditioning system or integral switch gear enclosure, etc.);

g) Location of initiating module within the BESS unit;

h) Separation distances from the initiating BESS unit to (e.g. distances A and C in Figure 10.1);

i) Separation distances from the initiating BESS unit to target BESS units (e.g. distances D and E in Figure 10.1);

j) Distances of the flame indicator (if used) with respect to the BESS (e.g. distances A and B in Figure 10.2);

k) Maximum temperature at the ceiling or, for a container BESS, maximum temperature of the container ceiling;

l) Distance of fire spread within the flame indicator or indication of fire spread through wiring in a container system BESS;

m) The maximum wall surface and target BESS unit temperatures achieved during the test and the location of the measuring thermocouple;

n) The maximum incident heat flux on target wall surfaces and target BESS units;

o) Voltages of initiating BESS;

p) Total number of sprinklers that operated and length of time the sprinklers operated during the test;

q) Gas generation and composition data, if measured;

r) Observation of flaming outside of the test room or container and the length and location of the external flaming;

s) Observation of installed explosion/deflagration protection operation and maximum pressures measured at deflagration vents;

t~~s~~) Observation of flying debris or discharge of gases;

u~~t~~) Observation of re-ignition(s) from thermal runaway events;

v~~u~~) Observations of the damage to:

1) The initiating BESS unit;

2) Target BESS units; and

3) Adjacent walls;

w~~v~~) Photos and video of the test;

x~~w~~) Fire protection features/detection/suppression systems within unit; ~~and~~

y) Explosion and deflagration protection; and

z~~x~~) Sprinkler K-factor, RTI, manufacturer and model, number of sprinklers and layout and length of time of operation of the sprinklers.

10.5.9 Test Method - Container System BESS Installation Level (Test Method 1) - Performance

10.5.9.1 The performance of container system BESS subjected to installation test method 1, is the same as 10.5.2 through 10.5.8 except as follows:

a. Temperatures on any combustible construction within the container including target components shall not exceed a temperature rise of 97°C (175°F) above ambient.

b. There shall be no flaming outside of the container if intended for indoor installation.

10.6.2 Test Method - Container System BESS Installation Level (Test Method 2)

10.6.2.1 A container system BESS that utilizes an alternative fire suppression system shall be tested in accordance with 10.6 except as noted 10.6.2.2 through 10.6.2.5

10.6.2.2. The actual container shall be used as the test room instead of the test room described in 10.3.1,.

10.6.2.3 The installation shall include any targets representing any major components (e.g. power conditioning system) installed within the container system and temperatures shall be measured on these targets similar to the approach used for measuring temperatures on walls. The target can be represented by the equipment enclosure or a wall or other means placed in a similar manner to represent the location and layout of the components.

10.6.2.4 The walls outside of the container are not required to be instrumented, however, container wall surface temperatures shall be measured in vertical array(s) at 304-mm (12-in) intervals for the full height of the instrumented wall sections using No. 24-gauge or smaller, Type-K exposed junction thermocouples. The thermocouples for measuring the temperature on wall surfaces shall be horizontally positioned in the wall locations anticipated to receive the greatest thermal exposure from the initiating BESS unit.

10.6.2.5 Heat flux at the walls may be measured with the sensing element of at least two water-cooled Schmidt-Boelter or Gordon gauges at the surface of the container wall:

a) Both are collinear with the vertical thermocouple array;
b) One is positioned at the elevation estimated to receive the greatest heat flux due to the thermal runaway of the initiating module; and
c) One is positioned at the elevation estimated to receive the greatest heat flux during potential propagation of thermal runaway within the initiating BESS unit.

10.7.1 The report on installation level testing shall include the following:

a) The report information in 10.4.1 items (a) – (x~~u~~), and (y and z~~v~~) if applicable;

b) Fire protection features/detection/suppression systems within installation; and

c) Length of time of operation of the clean agent, or other suppression system in addition to any sprinklers used.

10.8.2 Test Method - Container System BESS Installation Level (Test Method 2) - Performance

10.8.2.1 See 10.5.9 for performance criteria for a container system.

RATIONALE FOR DECISION:

UL 9540A does not currently provide sufficient detail for testing large multi-battery rack container BESS. These systems should first conduct the unit level test of the battery rack layout representative of how they are installed in the container indoors under the calorimeter to obtain the off gassing data including the battery fire behavior during testing. Depending upon the results of this unit level test, an installation level test can be conducted with the racks installed within the container representative of the installation and how they were tested in the unit level with the supplied fire suppression and deflagration protection provided.

In this way the container becomes the "test room" similar to how we would conduct the installation test in a built test room representative of an indoor installation. It also provides sufficient data to understand the hazards that may be associated with the container BESS design without resulting in the testing hazards associated with trying to run the test on a completely populated container BESS.