FISHER ENGINEERING

PROJECT NAME

Tesla Megapack 2 and Megapack 2XL

Fire Protection Engineering Analysis

DATE SUBMITTED

January 23, 2023

PREPARED FOR

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EXECUTIVE SUMMARY

Fisher Engineering, Inc. (FEI) performed a fire protection engineering (FPE) analysis of Tesla's new suite of battery energy storage systems (BESS), known as the Megapack 2 (MP2) and Megapack 2XL (MP2XL). The MP2 and MP2XL (MP2/2XL) are lithium-ion BESS with a storage capacity between approximately one and four megawatt hours (MWh). Their design, construction, and operation are substantially similar, and they are meant for outdoor installations, mounted to the ground, in commercial and industrial applications. This FPE analysis included a review of the MP2/2XL, its construction, design, fire safety features, UL 9540A cell, module and unit level test data, additional internal unit level fire tests and fire propagation modeling. This executive summary is an abbreviated list of our analysis and conclusions. Refer to the main report for details of the analysis and a full list of conclusions.

Based on a review of the MP2/2XL, its fire safety features, UL 9540A test results, additional internal MP2/2XL unit level fire testing and fire propagation modeling, FEI offers the following summary of our findings:

1. The design and construction of the MP2 and MP2XL are almost identical other than the MP2XL is greater in length to accommodate additional battery modules. They use the exact same cells, battery modules, and power electronics (i.e., all the same internal components) and the fire safety features of both are nearly identical. Given the similarities between the MP2 and MP2XL, the fire test and fire modeling results that have been summarized in this report can be applied to both the MP2 and MP2XL.
2. The MP2/2XL is listed to all product design standards (such as UL and IEC) required of a BESS and has been tested to UL 9540A at the cell, module, and unit level.
3. Cell and module level UL 9540A testing demonstrated that flammable gases vent from the MP2/2XL cells during thermal runaway; however, they do not release toxic gases sometimes associated with the failure of lithium-ion batteries, such as HCN, HCL and HF.
4. Unit level UL 9540A testing demonstrated that the MP2/2XL meets or exceeds all the performance criteria of UL 9540A, Table 9.1 and UL 9540A installation level testing is not required for a MP2/2XL installation.
    a. The test was initiated through the simultaneous heating and subsequent failure of six cells within a single battery module of the initiating MP2 cabinet.
    b. This resulted in thermal runaway propagating to a seventh cell within the battery module; however, thermal runaway did not propagate any further than the seventh cell, nor did this failure lead to a fire within the MP2 cabinet.
    c. The failure did not result in any observations of explosion hazards, including but not limited to, observations of a deflagration, projectiles, flying debris, detonation, or other explosive discharge of gases.

5. Internal unit level products of combustion testing demonstrated that HF was only detected at trace levels (0.10 and 0.12 ppm) in two sampling locations (approximately 20 feet upwind and 5 feet downwind from the MP2/2XL) when six cells within MP2/2XL cabinet were forced into thermal runaway. This trace quantity of HF was detected over the entire 2½ hour test duration (i.e., it was the cumulative quantity detected) and is well below the Immediately Dangerous to Life or Health (IDLH) value of 30 ppm for HF. The testing also found no traces of twenty-seven different metals, including lithium and mercury.
6. Internal destructive unit level testing demonstrated that the MP2/2XL is capable of safely failing in the extreme case of a catastrophic failure of a battery module (the forced thermal runaway of 48 cells simultaneously). This destructive unit level test led to a slow progressing fire that burned for 6 hours and 40 minutes until flaming ceased, only consuming one-half of the battery modules in the cabinet.
7. Fire modeling demonstrated that, in the unlikely event of a fire, it would not propagate from one MP2/2XL cabinet to adjacent cabinets installed 6 inches behind, 6 inches to the side and 8 feet directly in front of the initiating MP2/2XL. This result was analyzed for both no wind and worst-case wind conditions where flames could tilt towards the adjacent MP2/2XL cabinets.
8. In summary, unit level UL 9540A testing, destructive unit level testing and a fire propagation model demonstrated that:
    a. The MP2/2XL explosion control system can mitigate the deflagration hazard even with an extreme failure scenario of a battery module (the forced thermal runaway of 48 cells simultaneously) resulting in the MP2/2XL safely failing.
    b. An integral fire suppression system or an external fire suppression system is not required to stop the spread of fire from a MP2/2XL cabinet to adjacent MP2/2XL cabinets when installed at clearances of 8 feet in front, 6 inches behind and 6 inches to the sides.
    c. Manual fire suppression (hose lines) is not required to stop the spread of fire from a MP2 cabinet to adjacent MP2/2XL cabinets when installed at clearances of 8 feet in front, 6 inches behind and 6 inches to the sides.
9. Based on a review of the MP2/2XL, its fire safety features, UL 9540A test results, additional internal MP2/2XL unit level fire testing and fire propagation modeling, the MP2/2XL can meet or exceed installation level codes and standards, such as the IFC and NFPA 855, required for outdoor, ground mounted BESS installations when installed in accordance with the MP2 and MP2XL Design and Installation Manual.

INTRODUCTION

Fisher Engineering, Inc. (FEI) performed a fire protection engineering (FPE) analysis of Tesla's new suite of battery energy storage systems (BESS), known as the Megapack 2 (MP2) and Megapack 2XL (MP2XL). The MP2 and MP2XL (MP2/2XL) are lithium-ion BESS with a storage capacity between approximately one and four megawatt hours (MWh). Their design, construction, and operation are substantially similar, and they are meant for outdoor installations, mounted to the ground, in commercial and industrial applications. This FPE analysis included a review of the MP2/2XL, its construction, design, fire safety features, UL 9540A cell, module and unit level test data, additional internal unit level fire tests and fire propagation modeling. This narrative has been prepared by FEI and summarizes our analysis. It is intended to be used as a tool for a project designer, installer, fire code official (FCO) or an authority having jurisdiction (AHJ) to assist in their design, installation, or review of a MP2/2XL installation.

Applicable Codes, Standards and Test Methods

The following codes and standards have been applied to this analysis:

- 2021 International Fire Code® (IFC).
- 2021 NFPA 1, *Fire Code* (NFPA 1).
- 2023 NFPA 855, *Standard for the Installation of Stationary Energy Storage Systems* (NFPA 855).
- 2018 NFPA 68, *Standard on Explosion Protection by Deflagration Venting* (NFPA 68).
- 2019 NFPA 69, *Standard on Explosion Prevention Systems* (NFPA 69).
- IEC 60529, *Degrees of Protection Provided by Enclosures*, 2.2 Edition, January 2019 (IP Code).
- IEC 62619, *Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for secondary lithium cells and batteries, for use in industrial applications*, Edition 1.0, 2017 (IEC 62619).
- IEC 62933-5-2, *Electrical energy storage (EES) systems - Part 5-2: Safety requirements for grid-integrated EES systems - Electrochemical-based systems*, April 15, 2020 (IEC 62933-5-2).
- UL 1642, *Lithium Batteries*, Edition 6, September 29, 2020 (UL 1642).
- UL 1973, *Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications*, Edition 2, February 7, 2018 (UL 1973).
- UL 9540, *Standard for Safety of Energy Storage Systems and Equipment*, Edition 2, February 27, 2020 (UL 9540).
- UL 9540A, *Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems*, Edition 4, November 12, 2019 (UL 9540A).

Reference Materials

In addition to the applicable fire codes, standards and test methods listed above, the following reference materials were reviewed as part of this analysis:

- MP2 Design and Installation Manual - Rev. 2.5, dated December 19, 2022 (MP2 DIM).
- MP2XL Design and Installation Manual – Rev. 1.8, dated December 20, 2022 (MP2XL DIM).
- MP2 Operation and Maintenance Manual - Rev. 1.2, dated December 6, 2022 (MP2 O&MM).
- Industrial Lithium-Ion Battery Emergency Response Guide – Rev. 2.6, dated November 11, 2022 (ERG).
- MP2/2XL UL 9540A Cell Level Fire Test Report, dated February 25, 2022.
- MP2/2XL UL 9540A Module Level Fire Test Report, dated July 15, 2022.
- MP2/2XL UL 9540A Unit Level Fire Test Report, dated August 5, 2022.
- Megapack 2 Compliance Packet – Rev. 2.6, dated September 7, 2022.
- Megapack 2XL Compliance Packet – Rev. 1.8, dated September 27, 2022.

MP2/2XL CONSTRUCTION AND DESIGN

The MP2 are a fully integrated BESS consisting of battery modules, power electronics, a thermal management system, and control systems all pre-assembled within a single cabinet. The MP2 is approximately 23.75 feet (ft) in length, 5.4 ft deep, 8.2 ft in height, and can weigh up to 67,250 pounds or 7.250 meters (m) by 1.637 m by 2.506 m and 30,500 kilograms (kg). It is a modular style BESS, where the number of battery modules can be adjusted to increase/decrease the storage capacity of an individual MP2 cabinet. Furthermore, additional MP2 cabinets can be added to the site to increase the overall storage capacity of the BESS. Below is a brief description of the MP2, its components, design listing, and fire safety features. For a more detailed discussion on the MP2 components, their location, functionality, and purpose, refer to the MP2 DIM.

Cabinet Layout

The MP2 is intended for outdoor installations, ground mounted to a foundation or base strong enough to support the weight of the equipment and anchor loads (includes concrete pads, grade beams, etc.). The thermal roof (part of the MP2's thermal management system) is enclosed within an IP20 enclosure that sits above the battery module bays, as shown in Figure 1. The lithium-ion batteries are housed inside an IP66 steel enclosure (battery module bay) that provides protection against particle and water ingress coming into contact with the battery modules and power electronics. The IP66 enclosure is one continuous unit, meaning each of the eight bays shown in Figure 1 are open to one another. However, when the MP2 cabinet is populated with battery modules, it cannot be entered. This modular, cabinet style approach allows for the system to be easily maintained and serviced from outside the cabinets (i.e., the battery modules, thermal management system and power electronics are serviced through doors located on the front of the cabinets or from the top through the thermal roof), thus eliminating the need for personnel to enter an enclosure, structure, building or container to perform those activities. Since the BESS cabinets do not permit walk-in access, they are not defined as occupied buildings or structures per the IFC, NFPA 1 or NFPA 855.

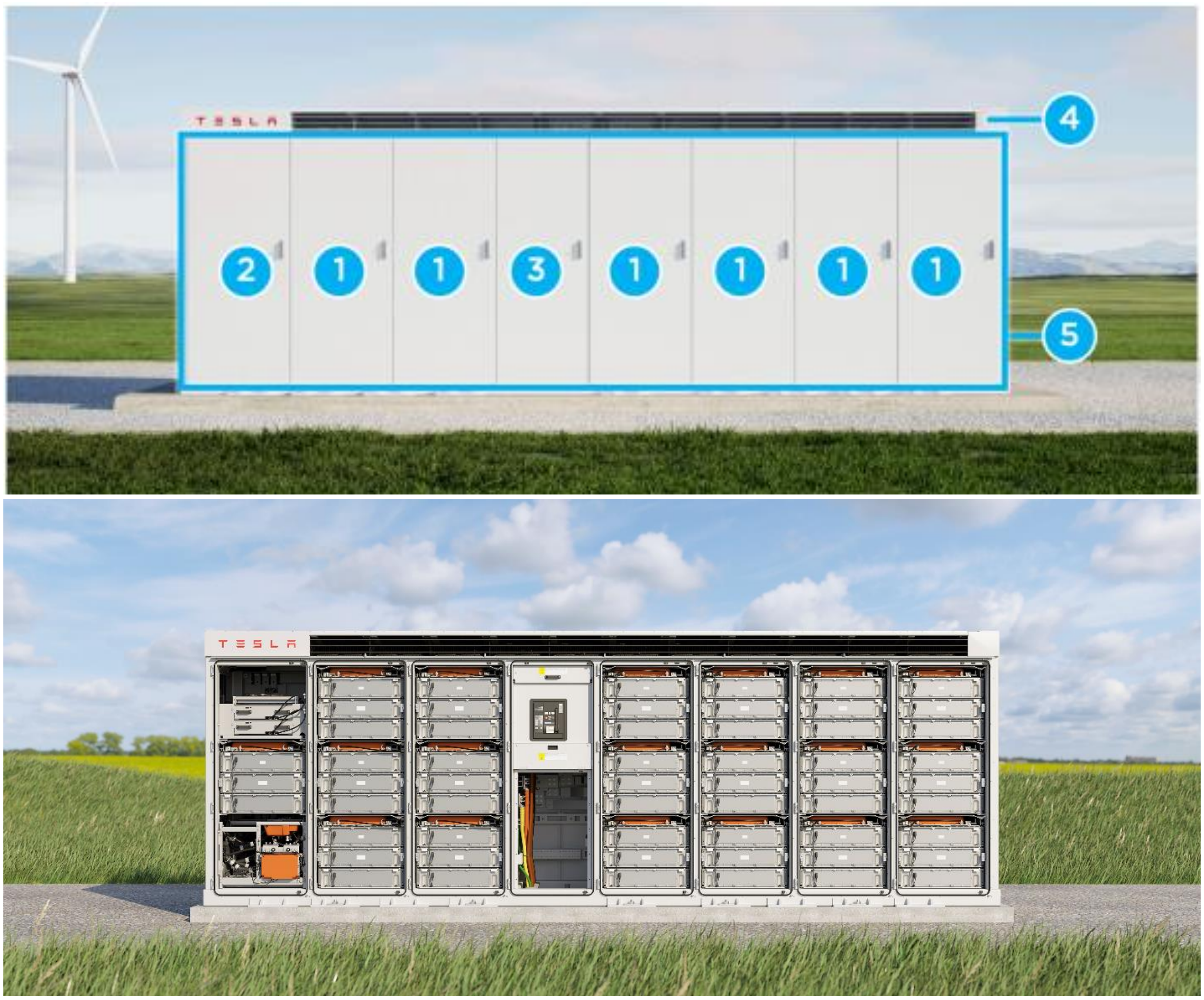

Figure 1 MP2 internal components: (1) Battery Module Bays, (2) Thermal Bay, (3) Customer Interface Bay, (4) IP20 Thermal Roof Enclosure, (5) IP66 Enclosure.

Cells and Battery Modules

The MP2 can be populated with between seven to nineteen battery modules with a maximum storage capacity of 2,890.8 kilowatt hours (kWh) for the 2-hour duration system, 2,564.8 kWh for the 3-hour duration system and 3,100.8 kWh for the 4-hour duration system. Each battery module contains three battery trays, as shown in Figure 2, which are arrays of prismatic, lithium phosphate (LFP) cells. The LFP cells (the cells) utilized in the MP2 are 157.2 Ah with a nominal voltage 3.22 Vdc and are individually hermetically sealed. They are approximately 50.75 millimeters (mm) by 166.0 mm by 169.3 mm and weigh 2,991 grams (g). Each battery tray contains 112 cells, as shown in Figure 2; meaning, each battery module has 336 cells and a fully populated MP2 (nineteen battery modules) can have up to 6,384 cells.

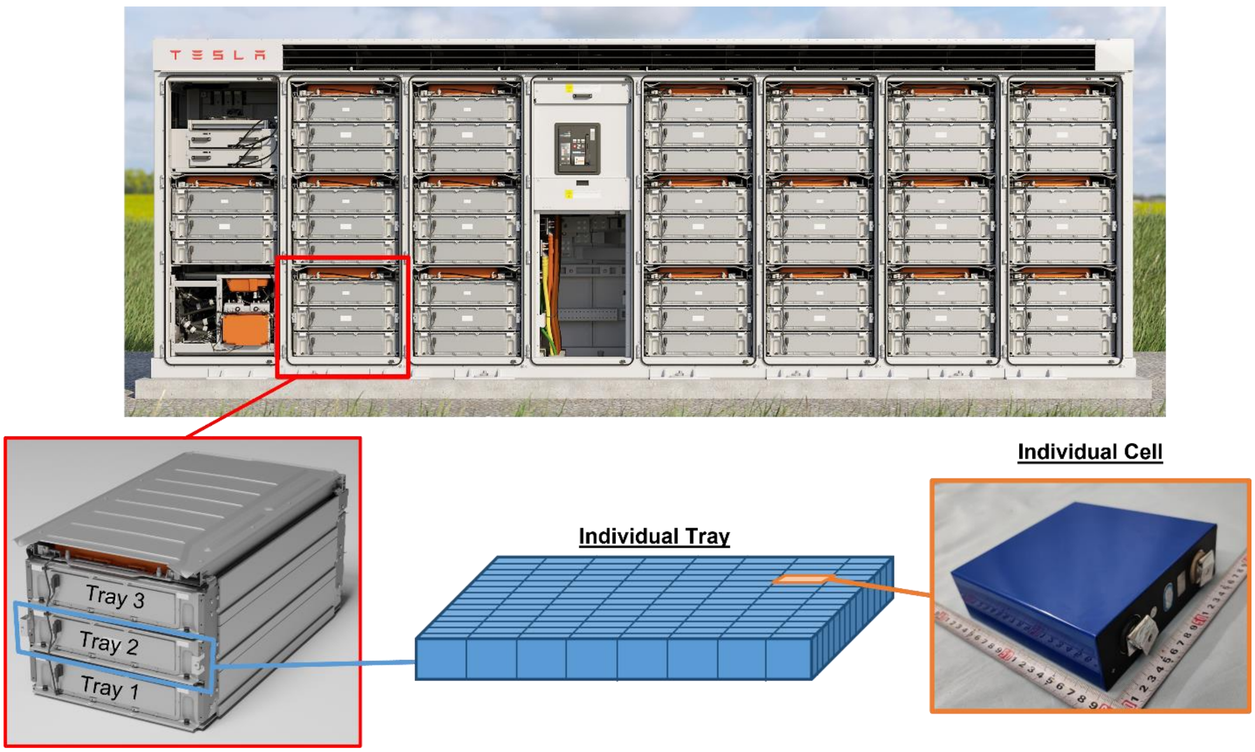

Figure 2 MP2 unit layout, module layout, generalized tray layout, and an individual cell.

Customer Interface Bay

The customer interface bay (CIB) is a user-accessible area designed for operation and servicing. The CIB, as shown in Figure 1, includes: the main AC breaker, a status panel and controller area network (CAN) interface for service personnel, customer input/output (I/O) terminals and the keylock switch (a "Lock Out/Tag Out" switch), which shuts down the AC bus to permit MP2 maintenance by service personnel.

Thermal Management System

The thermal management system (TMS) provides a suitable operating temperature for MP2 using liquid cooling via a 50/50 mixture of ethylene glycol and water and R-134a refrigerant. The thermal bay and thermal roof, as shown in Figure 1, houses the components of the TMS. The TMS contains a closed-loop liquid cooling system that circulates liquid coolant throughout the battery modules and power electronics to maintain an optimum operating temperature. The TMS works autonomously and does not require user feedback or controls to turn the system on when needed or to adjust temperature settings. The thermal roof, located above the battery bays within an IP20 enclosure, provides a ventilation airspace and contains fans and radiators that cool the ethylene glycol-water solution. The liquid cooling system utilizes approximately 360 liters (79 gallons) of the ethylene glycol-water solution, and the vapor compression portion of the cooling cycle utilizes 7.6 kilograms (16.8 pounds) of R-134a refrigerant.

MP2XL Construction and Design

The MP2XL is the larger version of the MP2. It is equipped with twenty-four battery modules to the nineteen found in the MP2. Its design, however, is almost identical to the MP2 other than being greater in length to accommodate the additional battery modules. Meaning, the MP2XL uses the exact same cells, battery modules, and power electronics (i.e., all the same internal components) that the MP2 utilizes in its design. Just like the MP2, the MP2XL is a standalone BESS consisting of battery modules, power electronics, a thermal management system, and control systems all pre-assembled within a single cabinet that is approximately 28.9 ft in length, 5.4 ft deep, 9.2 ft in height, and can weigh up to 84,000 pounds (8.800 m by 1.65 m by 2.785 m and 38,100 kg). Other small differences between the smaller MP2 and the MP2XL include:

- The MP2XL can be populated with up to twenty-four battery modules with a maximum storage capacity of 3,854.4 kWh for the 2-hour duration system, 3,847.2 kWh for the 3-hour duration system and 3,916.8 kWh for the 4-hour duration system. With up to twenty-four battery modules, the MP2XL can have up to 8,064 LFP cells.
- The thermal cabinet is located in the center of the cabinet next to the CIB, with four battery module bays flanking them on either side, as shown in Figure 3.
- The liquid cooling system utilizes approximately 400 liters (106 gallons) of the ethylene glycol-water solution, and the vapor compression portion of the cooling cycle utilizes 3.0 kilograms (6.6 pounds) of R-134a refrigerant.

For a more detailed discussion on the MP2XL components, their location, functionality, and purpose, refer to the MP2XL DIM. In addition, for a side-by-side direct comparison between the Megapack products, refer to Appendix 1, MP1 vs. MP2/2XL Comparison.

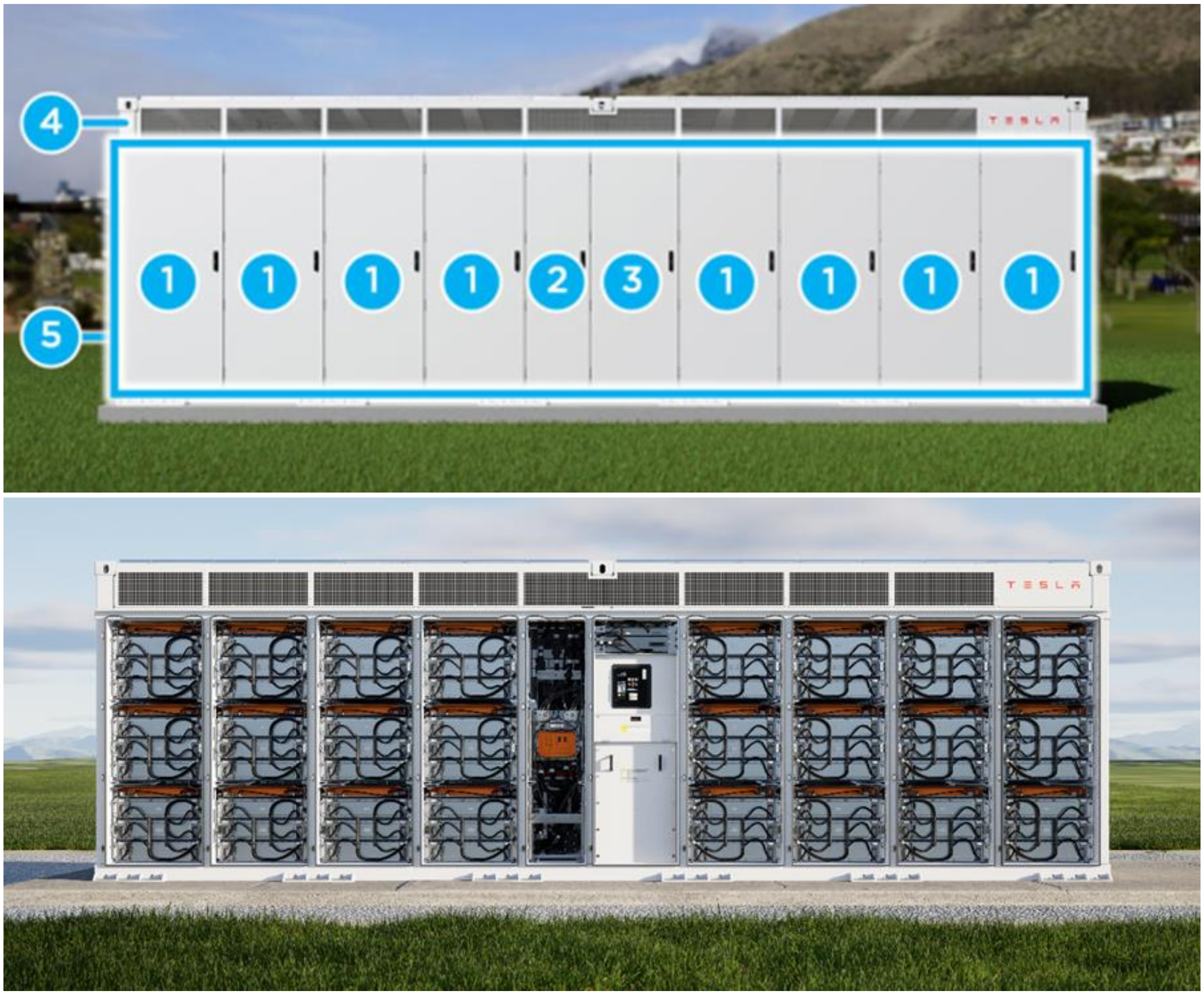

Figure 3 MP2XL internal components: (1) Battery Module Bays, (2) Thermal Cabinet, (3) Customer Interface Bay, (4) IP20 Thermal Roof Enclosure, (5) IP66 Enclosure.

MP2/2XL PRODUCT LISTINGS

The MP2/2XL and their subcomponents are certified or listed to multiple national and international product design standards. These certifications and listings apply to the cells, battery modules, inverters, power electronics, control systems, integration between the BESS and the grid, as well as the BESS as a whole. The standards highlighted below pertain to the lithium-ion cells, the battery modules and the MP2/2XL BESS at the unit level. For a full listing of all certifications and listings for all the MP2/2XL components, please refer to the MP2 and MP2XL Compliance Packets.

Cell and Module Level

The lithium-ion batteries utilized in MP2/2XL are certified and listed to national and international product safety standards from entities such as UL, LLC (UL) and the International Electrotechnical Commission (IEC). These certifications include, but are not limited to:

UL 1642: This certification standard is applicable to secondary (rechargeable) lithium-ion cells and batteries used as a power source (such as BESS). The standard's requirements are intended to reduce the risk of fire or explosion when the battery is used in a product. For example, the standard subjects lithium-ion batteries to severe abuse conditions, such as nail puncture and projectile tests, and evaluates if they can safely withstand them.

UL 1973: This certification standard is applicable to batteries and battery systems utilized for energy storage. The standard evaluates the battery system's ability to safely withstand simulated abuse conditions. For example, the standard subjects module-level stationary batteries to an internal fire exposure test to force a thermal runaway in one cell to ensure it does not explode, propagate fire to neighboring cells, or propagate to the rest of the modular battery system. UL 1973 applies to stationary BESS applications, such as photovoltaic installations and wind turbine energy storage systems, as well as other specialized energy storage systems, such as light electric rail (LER) operations.

IEC 62619: This safety standard specifies requirements and tests to ensure the safe operation of secondary (rechargeable) lithium-ion cells and batteries used in ESS and in other industrial applications. Electrical safety is covered under Clause 8 of the standard, which requires the completion of a risk analysis to determine specific electrical safety issues associated with the intended use of a given battery system or device.

Unit Level

The MP2/2XL, as entire units, are also certified, tested, and listed to national and international product safety standards and test methods, including, but not limited to:

IEC 62933-5-2: This safety standard addresses various aspects of BESS, including the requirements for grid-integrated BESS.

UL 9540: This standard covers energy storage systems (including lithium-ion BESS) for stationary indoor and outdoor installations and establishes the system-level certification for energy storage systems and its associated equipment.

UL 9540A: The test methodology evaluates the fire characteristics and thermal runaway fire propagation of a BESS (including lithium-ion BESS). The test method provides a means to evaluate thermal runaway and fire propagation at the cell level, module level, and unit level. The data generated from the test method can be used to determine the fire and explosion protection required for a BESS installation based on fire test data. This test is specifically referenced by the IFC, NFPA 1 and 855 to demonstrate the functionality of the BESS fire protection features during large-scale fire testing.

MP2/2XL FIRE SAFETY FEATURES

In addition to meeting all the design standards (UL, IEC, etc.), the MP2/2XL is also designed with the following fire and life safety features:

Battery Management System

The MP2/2XL has an integrated battery management system (BMS) that tracks the performance, voltage, current and state of charge of the cells (among many other datapoints). The BMS is a layered system, where each battery module has its own BMS and the MP2/2XL itself has a bus controller supervising the output of all the battery modules at the AC bus level. The BMS is engineered to react to fault conditions in an autonomous manner, with safeguards built into the firmware. These fault conditions include, but are not limited to, over-temperature, loss of communication, over-voltage, and isolation. For instance, to prevent a cell over-temperature the TMS is enabled by the BMS to cool the cells/module. This action by the BMS (which is just one example of many ways the BMS can respond to a fault condition) can either prevent thermal runaway from occurring in the cell or prohibit the propagation of thermal runaway to adjacent cells. Depending on the severity of the fault condition, the BMS can automatically isolate the affected battery module temporarily (less severe fault) or it can permanently disconnect the module.

Site Controller and Monitoring

Beyond the built-in safeguards of the BMS described above, MP2/2XL is supported by Tesla's Local Operations Center (LOC), which is designed to support the global fleet of energy storage products. The MP2/2XL has 24/7 remote monitoring, diagnostics, and troubleshooting capabilities, without the need of having a Tesla technician on site. Customers and first responders also benefit from immediate hotline support from trained technicians via these local operation centers. Additionally, the local energy provider or the facility monitor the MP2/2XL through a local Supervisory Control and Data Acquisition (SCADA) system. All faults are transmitted to a Tesla LOC, alerting them to off-normal conditions that may require corrective action, either through remote means or an in-person field service visit. This communication link is accomplished via the Tesla Site Controller (TSC). The TSC provides the single point of interface for the utility, network operator, and/or the customer's SCADA systems to control and monitor the entire energy storage site. It dictates the charge and discharge functions of the MP2/2XL cabinets, aggregating real-time information and using the information to optimize the commands sent to each individual MP2/2XL cabinet. As such, every MP2/2XL has a wired Ethernet connection to the TSC, which communicates with a Tesla LOC via a built-in cellular modem. If the cellular network in the installation area is not sufficient, a hardwired internet connection can be provided. Additionally, if the BESS owner or operator wants a network connection for a control interface, the TSC becomes that point of connection to the MP2/2XL cabinet at the site.

Electrical Fault Protection Devices

The MP2/2XL have several passive and active safety control mechanisms installed within the battery module circuit and distribution circuit that would be available to interrupt a fault current. At a high level, these electrical fault protection features include:

- Battery module overcurrent protection: The battery modules contain DC single-use fusible links mounted directly on the battery modules. These fuses are one time only use safety devices that can interrupt the flow of an overcurrent in the battery module during an off-normal electrical event.
- Inverter DC protection: The inverter modules, which are installed at each of the battery modules, are equipped with their own high-speed pyrotechnic fuse that can isolate the battery module passively or actively during an off-normal event.
- Inverter AC protection: In addition, each inverter module is equipped with its own AC contactor and AC fuses should an off-normal electrical event occur at the inverter module on the AC side of the circuit.
- Ground fault protection: Finally, the MP2/2XL are also provided with a DC ground fault detection system. It measures insulation resistance prior to operation and looks for excessive leakage current during operation. Additionally, the MP2/2XL also contains an AC circuit breaker, with ground-fault trip settings, which is installed within the CIB to provide distribution system protection.

Explosion Control System

The MP2/XL includes an explosion control system to mitigate the risk of an uncontrolled deflagration. The system includes twenty-two pressure-sensitive vents (overpressure vents) and twelve sparkers installed throughout the battery module bay designed to ignite flammable gases very early in a thermal runaway event before they accumulate within the enclosure and become an explosion hazard. The sparkers are installed at a variety of locations and heights throughout the battery module bay to ensure the flammable gases released during thermal runaway quickly meet an ignition source. The twenty-two overpressure vents are installed in the roof of the sealed battery module bay's IP66 enclosure and permit gases, products of combustion and flames to safely exhaust through the roof during a thermal event. By designing this natural ventilation flow path, flammable gases are not permitted to accumulate within the MP2 cabinet, reducing the risk of a deflagration or explosion that could compromise the cabinet's integrity, push open the front doors, or expel projectiles from the cabinet. In addition, the ventilation path creates a controlled fire condition, should one occur, out the top of the MP2 cabinet. By maintaining the MP2 cabinet's integrity, keeping all the doors shut during a fire event, reducing the risk of projectiles, and creating a controlled path for flames to exit the top of the MP2 cabinet, the likelihood of a thermal event having an impact on life safety, site personnel or first responders, is reduced. In addition, by maintaining these features, the likelihood of a fire propagating to adjacent MP2 cabinets, electrical equipment or other exposures is also reduced and can be designed for at the installation level (i.e., maintain clearances, emergency response plans, etc.).

The overpressure vents themselves are passive and are not actuated or controlled by another device. As such, they are not active deflagration vents listed to corresponding explosion and deflagration standards such as NFPA 68 or 69. Their rubber seals are designed to release during an overpressure event, such as the rapid ignition of flammable gases by a sparker or melt out during a fire event inside the battery module bay. The number and total area of overpressure vents is sized following the requirements of NFPA 68. They are designed to relieve with a safety factor of 2.5 times the enclosure's strength, including the front doors. Specifically, the overpressure vents are designed to open when subjected to an overpressure of 12 kPa or 250 pounds per square foot (psf), whereas the steel, IP66 battery module bay enclosure has an enclosure strength of 30 kPa (626 psf). Meaning, during an overpressure event inside the MP2 cabinet, the overpressure vents will open when subjected to an overpressure of approximately 12 kPa (250 psf), well before the integrity of the enclosure itself becomes compromised at 30 kPa (626 psf) with a 2.5 times safety factor.

Tesla developed the overpressure vents and sparker system because the application of NFPA 68 or NFPA 69 is not suitable for cabinets without large volumes of open space, as is typical of BESS cabinets. This engineered approach is permitted by NFPA 855[1] provided it is validated through large-scale, unit level fire testing, which Tesla has performed as described in the following sections.

MP2XL Fire Safety Features

Similar to the construction and design of the cabinet, the fire safety features of the MP2XL are almost identical to the MP2. The BMS, site controller, monitoring services, and electrical fault

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1 NFPA 855, Section 9.6.5.6.4.

protection devices are identical or are substantially similar. The explosion control system differs only in the number of overpressure vents. The larger MP2XL has twenty-six overpressure vents) compared to twenty-two incorporated into the MP2. All other features of the explosion control system, including the twelve sparkers, the 30 kPa cabinet strength, and the 2.5 times safety factor of the overpressure vents are identical to the MP2.

UL 9540A CELL AND MODULE LEVEL TESTING

The UL 9540A test method provides a method to evaluate thermal runaway and fire propagation of a lithium-ion BESS at the cell level, module level, and unit level. The data generated from the test method can be used to determine the fire and explosion protection systems/features required for a BESS installation. The data generated includes, but is not limited to, thermal runaway characteristics of the cell; cell thermal runaway gas composition; the fire propagation potential from cell to cell, module to module and unit to unit; products of combustion; and heat release rate. Although this report focuses on unit level fire tests that were performed on the MP2/2XL, it is worth noting the cells and modules utilized within the MP2/2XL were also tested to UL 9540A. A summary of their results is provided below as well as a more detailed description of the unit level fire test.

UL 9540A Cell Level Testing

Cell level testing was conducted at UL in December 2021. UL is an OSHA-approved Nationally Recognized Testing Laboratory (NRTL) and offers the UL mark for products. Testing was performed on five 3.22 V, 157.2 Ah, LFP cells manufactured by Contemporary Amperex Technology Co., Ltd. (CATL) for use in the MP2/2XL. Each cell was charged to 100% state of charge (SOC) prior to testing. Thermal runaway was initiated via film strip heaters installed on both of the wide side surfaces of each cell, as shown in Figure 4. Meaning two heaters were installed on each cell. The heaters were programmed to increase the temperature of the cell's surface by approximately 4.5 - 4.8°C per minute until the cell vented and went into thermal runaway. The cell was placed within an enclosed enclosure and the products released during testing were collected and analyzed.

Key takeaways from the tests include:

- The average cell vent temperature was determined to be 174°C (345°F).
- The average thermal runaway temperature was determined to be 239°C (462°F).
- Gases generated from the cell were identified as flammable, as listed in Table 1.
    - The vent gases were predominantly (approximately 95%) Carbon Monoxide (CO), Carbon Dioxide (CO_2), Hydrogen (H_2), and Methane (CH_4).
    - The remaining constituent gases were a variety of hydrocarbons.

- Toxic gases sometimes associated with lithium-ion batteries, such as Hydrogen Fluoride (HF), Hydrogen Chloride (HCL), and Hydrogen Cyanide (HCN) were not vented from the cell.

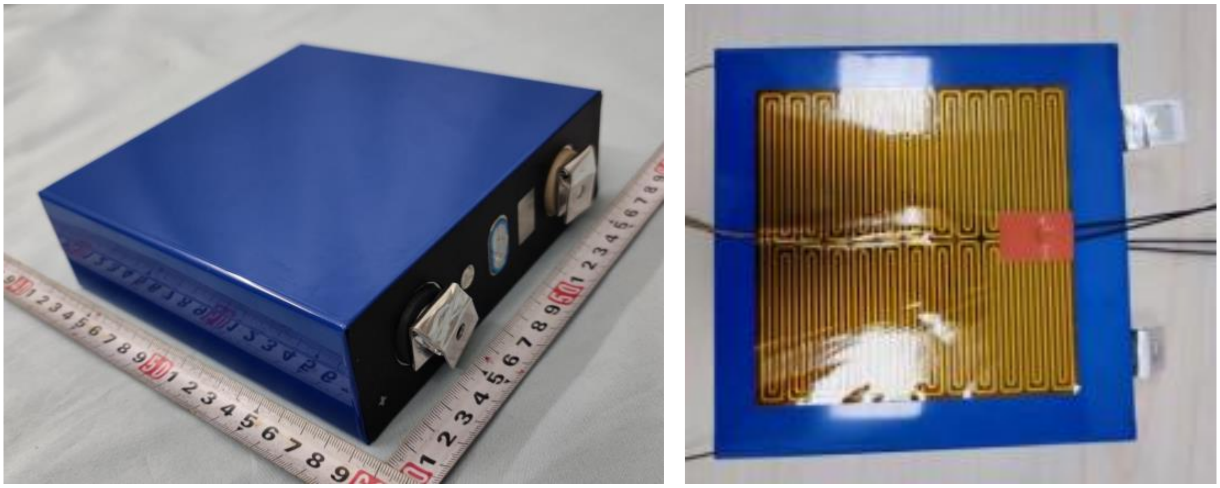

Figure 4 Individual cell tested to UL 9540A (left) and installed film strip heater (right).

<u>Performance Criteria</u>

UL 9540A, Section 7.7 outlines the performance criteria for the cell level test. If all these conditions are met, further testing (such as module, unit, or installation level tests) are not required. The acceptable performance criteria during the UL 9540A cell level test are as follows:

1. Thermal runaway cannot be induced in the cell.
2. The cell vent gas does not present a flammability hazard when mixed with any volume of air, at both ambient and vent temperatures.

Given the cell went into thermal runaway and vented flammable gases, UL 9540A module level testing was required.

Table 1 Cell Vent Gases: UL 9540A Cell Level Testing (Excluding O_2 and N_2)

Gas Name	Chemical Structure	% Measured	Component LFL
Carbon Monoxide	CO	10.881	10.9
Carbon Dioxide	CO_2	27.107	N/A
Hydrogen	H_2	50.148	4.0
Methane	CH_4	6.428	4.4
Acetylene	C_2H_2	0.264	2.3
Ethylene	C_2H_4	3.283	2.4
Ethane	C_2H_6	1.100	2.4
Propene	C_3H_6	0.379	1.8
Propane	C_3H_8	0.125	1.7
-	C4 (Total)	0.190	N/A
-	C5 (Total)	0.027	N/A
-	C6 (Total)	0.005	N/A
Benzene	C_6H_6	0.002	1.2
Toluene	C_7H_8	0.002	1.0
Dimethyl Carbonate	$C_3H_6O_3$	0.055	N/A
Ethyl Methyl Carbonate	$C_4H_8O_3$	0.004	N/A
Total	-	100	-

UL 9540A Module Level Testing

Module level testing was conducted at a TÜV SÜD (TÜV) laboratory in May 2022. TÜV is an OSHA-approved NRTL and offers the cTUVus mark, which is equivalent to other NRTL marks such as UL, ETL or CSA. Testing was performed on an entire MP2/2XL tray of LFP cells manufactured by CATL, as shown in Figure 5. The test results summarized below are from the May 2022 test.

Each cell within the tray was charged to 100% SOC prior to testing. During the test, the MP2/2XL tray is not connected to the BMS or TMS; meaning, they are not actively operating to prevent thermal runaway in a cell or to prohibit the propagation of thermal runaway from cell to cell. Thermal runaway was initiated via film strip heaters installed on both of the wide side surfaces of two cells, similar to the cell level test (see Figure 4). This resulted in the simultaneous heating of six cells forcing multiple cells into thermal runaway at the same time. The heaters were programmed to increase the temperature of the cell's surface by approximately 4.17 - 4.52°C per minute until the cells vented and went into thermal runaway. The tray was placed under an instrumented hood and the products released during combustion were collected and analyzed.

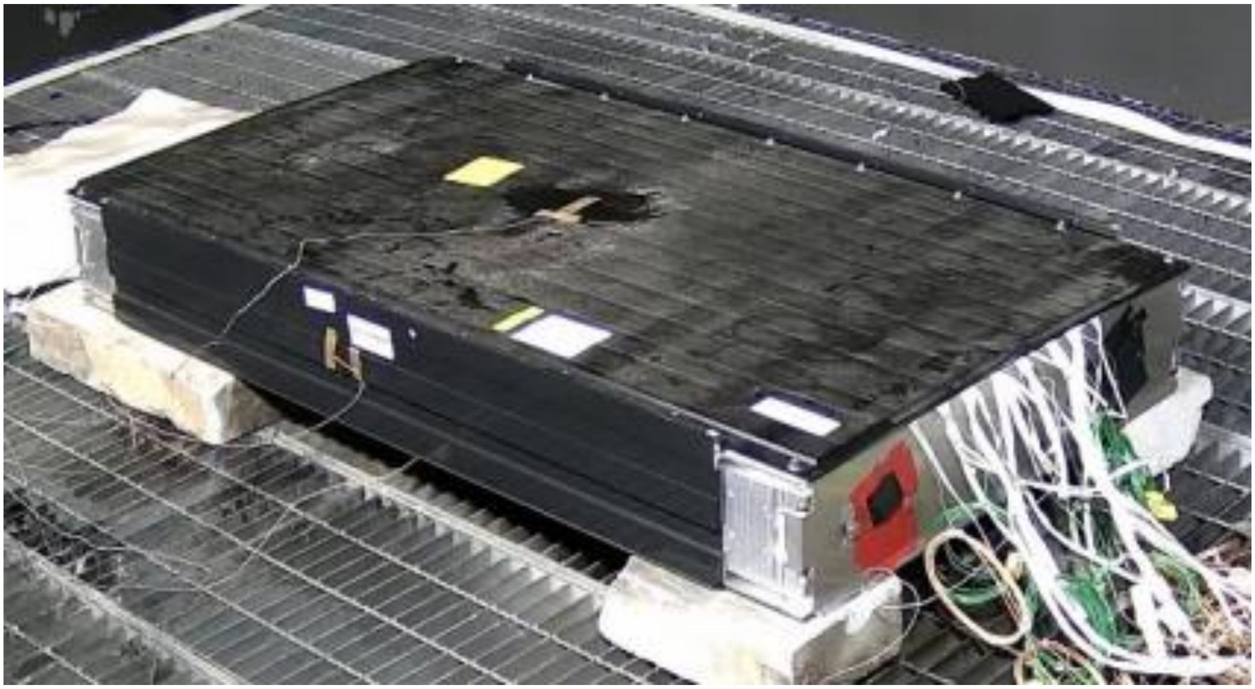

Figure 5 Tray tested to UL 9540A module level testing.

Key takeaways from the UL 9540A module level test include:

- Thermal runaway propagated from the initiating cells to all the cells in the MP2/2XL tray.
- Once ignited, the MP2/2XL tray took approximately 30-35 minutes to burn itself out.
- Based on the test observations and the HRR plot, a MP2/2XL tray fire appears to be a slow progressing thermal event (i.e., requiring over 30 minutes to burn itself out).
- Sparks and flying debris were observed, however, there were no explosive discharges of gases.
- Gases generated from the cell were identified as flammable, as listed in Table 2. However, toxic gases sometimes associated with lithium-ion batteries, such as HF, HCL, and HCN, were not detected during the combustion of the MP2/2XL tray.

<u>Performance Criteria</u>

UL 9540A, Section 8.4 outlines the performance criteria for the module level test. If all these conditions are met, further testing (such as unit or installation level tests) are not required. The acceptable performance criteria during the UL 9540A module level test are as follows:

1. Thermal runaway is contained by module design.

2. Cell vent gas is nonflammable as determined by the cell level test.

Given the cell vent gases are flammable (as summarized previously) and the module was consumed, UL 9540A unit level testing was required.

Table 2 Products of Combustion: UL 9540A Module Level Testing

Gas Name	Chemical Structure	Measurement Peak (ppm)	Detection Method
Carbon Monoxide	CO	204.84	FTIR
Carbon Dioxide	CO_2	6720.62	FTIR
Methane	CH_4	67.83	FTIR
Acetylene	C_2H_2	17.11	FTIR
Ethene	C_2H_4	Not Detected	FTIR
Ethane	C_2H_6	Not Detected	FTIR
Propane	C_3H_8	Not Detected	FTIR
Butane	C_3H_4	Not Detected	FTIR
Pentane	C_3H_6	Not Detected	FTIR
Benzene	C_6H_6	9.01	FTIR
Hexane	C_7H_{14}	Not Detected	FTIR
Hydrofluoric Acid	HF	Not Detected	FTIR
Hydrogen Chloride	HCL	Not Detected	FTIR
Hydrogen Cyanide	HCN	Not Detected	FTIR
Hydrogen	H_2	446	Hydrogen Sensor
Total Hydrocarbons	(Propane Equivalent)	246.53	FID

UL 9540A UNIT LEVEL FIRE TESTING

The unit level fire test was conducted at the Northern Nevada Research Center on March 9, 2022 and was certified by TÜV. TÜV is an OSHA-approved NRTL and offers the cTUVus mark, which is equivalent to other NRTL marks such as UL, ETL or CSA.

Test Unit

The test was performed on a fully populated MP2, consisting of nineteen battery modules, with a capacity of 3,100.8 kWh, tested at 100% SOC. Of all the MP2 variations, the unit tested during UL 9540A unit level testing is the largest capacity variation Tesla manufactures. In addition, during the test, the BMS and TMS are disabled; meaning, they are not actively operating to prevent thermal runaway in a cell or to prohibit the propagation of thermal runaway from cell to cell, or module to module. As such, the UL 9540A unit level fire test can be considered a worst-case fire scenario, where: (1) the unit tested was the largest variation in terms of energy capacity; (2) the unit tested was at the highest energy density possible (100% SOC); and (3) the BMS and TMS were disabled and, therefore, unable to actively respond to the thermal runaway condition. As such, any tests performed on a smaller capacity MP2, at a lower SOC, or on an operating MP2 (one with an active BMS and TMS) would be expected to perform similarly, if not better, than this worst-case scenario. Below is a summary of the UL 9540A unit level fire test results as well as a description of the performance of key fire safety features/systems during the test.

Test Setup

The test setup included all the required instrumentation and data collection as required by UL 9540A as well as some additional measurements that go beyond what is required. These additional measurements were collected to provide additional information to project designers, installers, a FCO or an AHJ to assist in their design, installation, or review of a MP2 installation.

Initiation

The initiating battery module was chosen to be the bottom battery module from Bay 7, in the middle battery tray, as shown in Figure 6. This location was deemed to be the worst-case, given there are battery trays directly above it and below it. In addition, by initiating in the bottom battery module, there are two additional battery modules installed directly above the initiation location. Within the battery tray itself, six interior cells were simultaneously heated via four film heaters, as shown in Figure 7. The heaters were programed to provide a heating rate of 5°C (9°F) per minute, as specified by UL 9540A. The number of cells and the location were selected to provide the greatest thermal exposure to adjacent cells to ensure cell to cell propagation during the test. The objective of this initiation method is to simulate a mass failure of multiple cells in a localized area within the same battery module.

Figure 6 Initiation location: Bay 7, bottom battery module within tray 2.

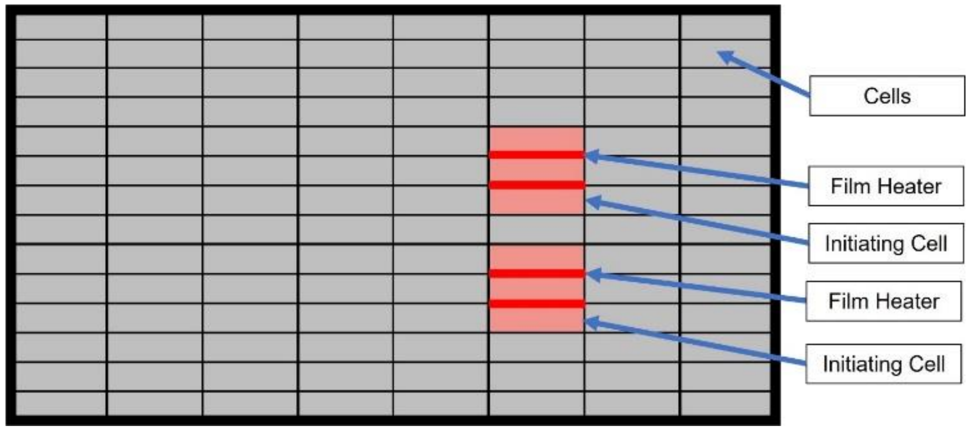

Figure 7 Film heater locations within the initiating tray.

Instrumentation

Outside the initiating battery module and MP2 cabinet, three additional target MP2 cabinets were installed: (1) 6 inches (in) or 150 mm behind the initiating MP2; (2) 6 in (150 mm) to the side of the initiating MP2; and (3) 8 ft (2.44 m) in front the initiating MP2, as shown in Figure 8.

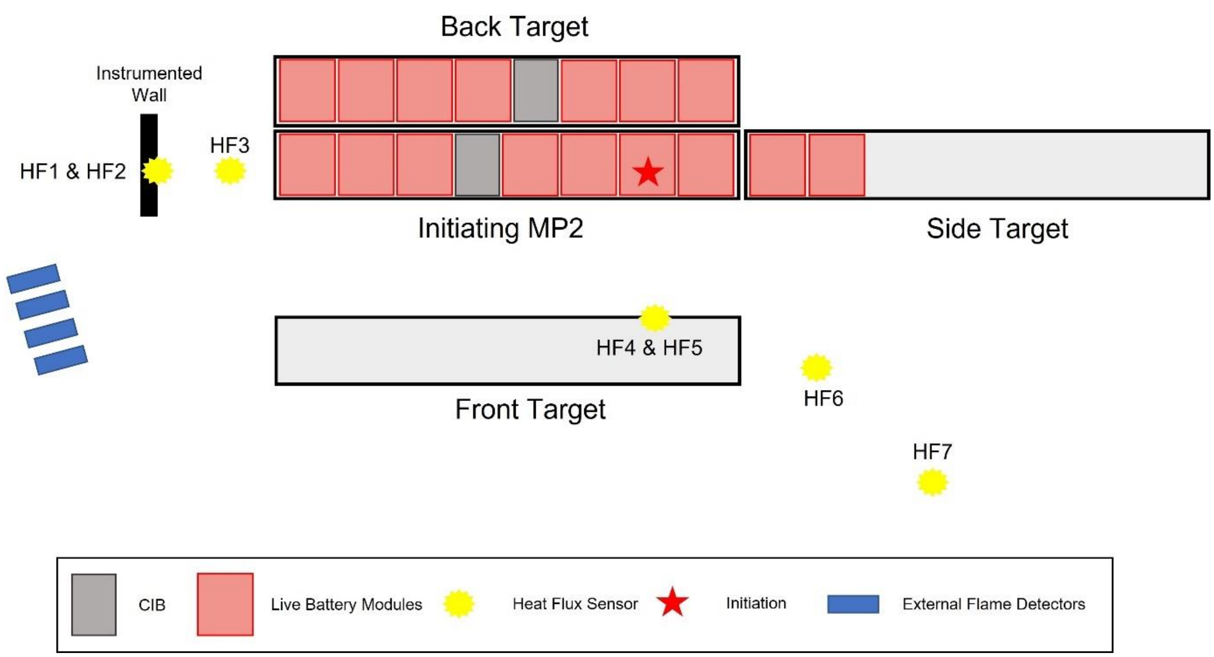

Figure 8 Instrumentation and target MP2 cabinet setup (top view).

The two target MP2 cabinets behind and to the side were populated with 100% SOC battery modules to simulate a multiple MP2 cabinet installation and to determine if thermal runaway and/or fire will propagate from one MP2 cabinet to adjacent cabinets at separation distances of 6 in (150 mm). Additionally, a combustible, instrumented wall (wood framing with plywood facing, painted black) was installed 5 ft (1.52 m) to the side of the initiating MP2 to demonstrate if fire could spread to a combustible surface (plywood wall) during the test.

Thermocouples were installed in the initiating battery module on the external surface of the initiating cells, inside the initiating MP2 cabinet, inside the target MP2 cabinets, on the instrumented wall and on the exterior surfaces of all the MP2 target cabinets. Heat flux sensors were installed at distances of 3, 5, 8, 20 and 30 ft (0.91, 1.52, 2.44, 6.10, and 9.14 m) from the initiating MP2, as shown in Figure 8. Two external flame detectors and two thermal imagers were installed facing the initiating MP2 to demonstrate their functionality should flames exit the initiating MP2 during the test.

Test Results

The test was performed starting around 11:30 am on March 9, 2022. The ambient temperature was between 50.5°F and 52.9°F. It was a sunny, clear day with no precipitation and a relative humidity between 14% and 19%. These outdoor environmental conditions meet the requirements of UL 9540A, Section 9.1.2. The cameras and instrumentation were turned ON at or around time 0:00:00 (hours: minutes: seconds) and the heaters within the initiating MP2 were turned ON at time 0:09:25. Six cells were heated simultaneously for over 1-hour and 18 minutes until the first initiation cell reached its thermal runway temperature[2] (as measured on the external surface of the cell via a thermocouple) of 239°C (462°F). Fifteen minutes later, the second group of initiating cells reached their thermal runaway temperature. Around 6 minutes later (approximately 1-hour 39 minutes into the test), light smoking/off-gassing was observed exiting the MP2 cabinet in the location where instrumentation was routed into the cabinet (i.e., where thermocouple wiring and power wiring for the film heaters were in contact with the gasket that forms a tight seal for Bay 7's front door). Cell to cell propagation (thermal runaway spreading beyond the initial six cells being forcibly heated) was confirmed at approximately 1 hour 45 minutes when a seventh cell reached a temperature of 239°C (462°F). The heaters continued to run for an additional 5 minutes after this observation and then were shut off (at approximately 1 hour and 51 minutes into the test). Thermocouple temperatures inside the initiating MP2 subsided and no additional off-gassing, smoking or thermal runaways were observed. By 2 hours and 30 minutes, the test ended. However, a period of observation and data collection continued for hours afterwards to ensure the MP2 does not demonstrate any signs of distress. Table 3 provides a summary of key events from the UL 9540A unit level fire test of the MP2.

2 As determined by UL 9540A cell level test (see previous discussion).

Table 3 UL 9540A Unit Level Fire Testing: Timeline of Key Events

Elapsed Time hr:min:sec	Event
00:00:00	**Start of Test. Cameras and Data acquisition system (DAQ) turned on.**
0:09:25	Heaters ON.
1:18:18	First group of initiating cells reach thermal runaway temperature of 239°C (462°F).
1:33:38	Second group of initiating cells reach thermal runaway temperature of 239°C (462°F).
1:39:28	Smoke observed exiting out the bottom of the initiating MP2 cabinet's bay door where instrumentation was routed into the cabinet.
1:45:48	Confirmation of cell propagation to a 7th cell via internal thermocouple measurements.
1:51:09	Heaters turned OFF.
2:00:00	No additional smoke was observed from the initiating MP2 cabinet. Internal temperatures subside.
2:30:00	**End of Test.**
Post Test Overhaul	The initiating MP2 cabinet was observed for several hours afterwards and allowed to cool. No additional off-gassing, smoking, elevated temperatures, fire, thermal runaways, or signs of off-normal conditions were observed.

After 24 hours, the initiating MP2 had not shown any signs of abnormal conditions or distress since the test had concluded (no additional off-gassing, smoking, smells, thermal runaway, or flare ups) and it was opened for inspection. Prior to opening the initiating MP2, handheld gas detection devices were utilized around the cabinets and did not detect the presence of flammable gases nor were flammable gases detected internally after the Bay 7 door was opened.

A visual inspection of the initiating MP2 yielded the following observations:

- Seven cells had gone into thermal runaway: the six that were forcibly heated and one additional cell, as illustrated in Figure 9. This demonstrated that cell to cell propagation had occurred during the test, as is required by UL 9540A.
- No other signs of distress were observed in the initiating battery module. Thermal runway had not propagated beyond the seven cells within Tray 2, nor had it spread to the tray above or below it within the battery module.

- Internal cell components were observed inside the initiating MP2 cabinet in the area of the initiating battery module and around Bay 7's front door; however, no free-flowing liquid or runoff was observed.
- The overpressure vents in Bay 7 had not opened, indicating that the internal pressure within Bay 7 did not see a significant rise during the failure of the seven cells.
- Visible clues of fire damage to surrounding components (plastics, electronics, etc.) were not observed. Based on this observation, it is likely that a sustained fire did not occur around the initiating battery module, even with the failure of seven cells occurring.
- The battery modules within the target MP2 cabinets installed 6 in (150 mm) behind and to the sides were also unaffected.

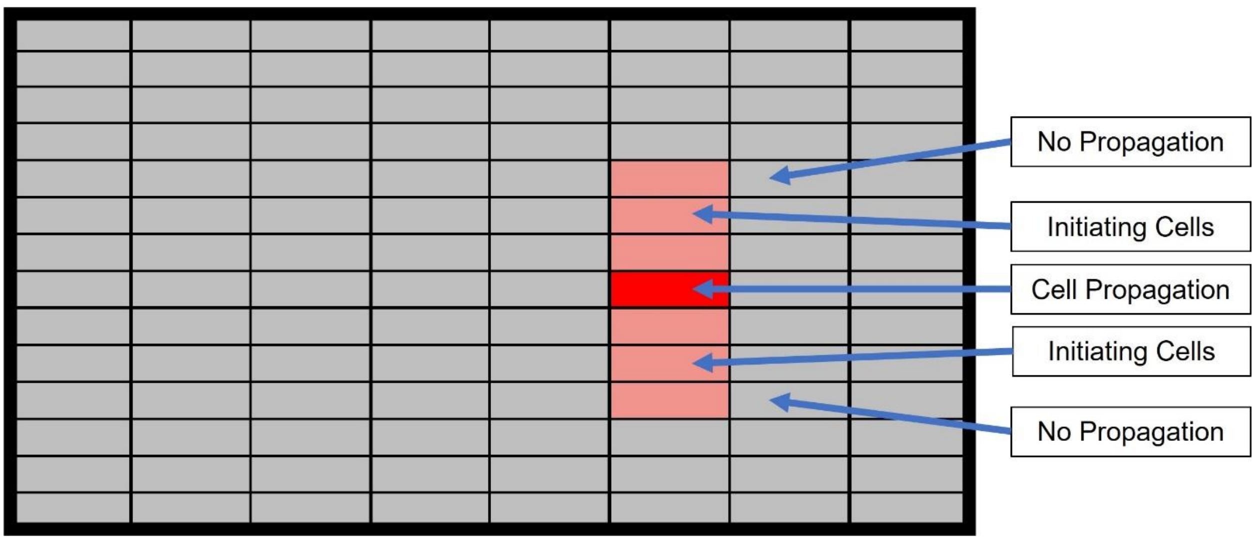

Figure 9 Cell propagation during UL 9540A unit level fire testing: six initiating cells (pink), one cell experiencing thermal runway propagation (red), and cells without thermal runway propagation (grey cells).

<u>Fire Propagation</u>

UL 9540A unit level fire testing of the MP2 demonstrated that an internal failure event causing thermal runaway of six cells nearly simultaneously will not propagate thermal runaway throughout the battery module. The nearly simultaneous failure resulted in thermal runaway propagating only to one additional cell and no further. The first group of initiating cells went into thermal runaway approximately 1-hour and 18 minutes into the test, as shown in Figure 10. This observation is based on internal thermocouple measurements installed on the surface of the cells within the initiating battery module. Fifteen minutes later the second group of initiating cells went into thermal runaway and cell to cell propagation was confirmed at approximately 1-hour 45 minutes when a seventh cell reached of 239°C (462°F). Note, this result was with a disabled

BMS and TMS (i.e., no safety protections were in place). Thermal runaway did not propagate beyond the seventh cell within Tray 2 of the initiator module, nor did it propagate to the battery modules installed above. In addition, thermal runaway did not propagate to the target MP2 cabinets installed 6 in (150 mm) behind and to the sides of the initiating MP2 cabinet. Lastly, no flaming was observed outside of the unit during the test.

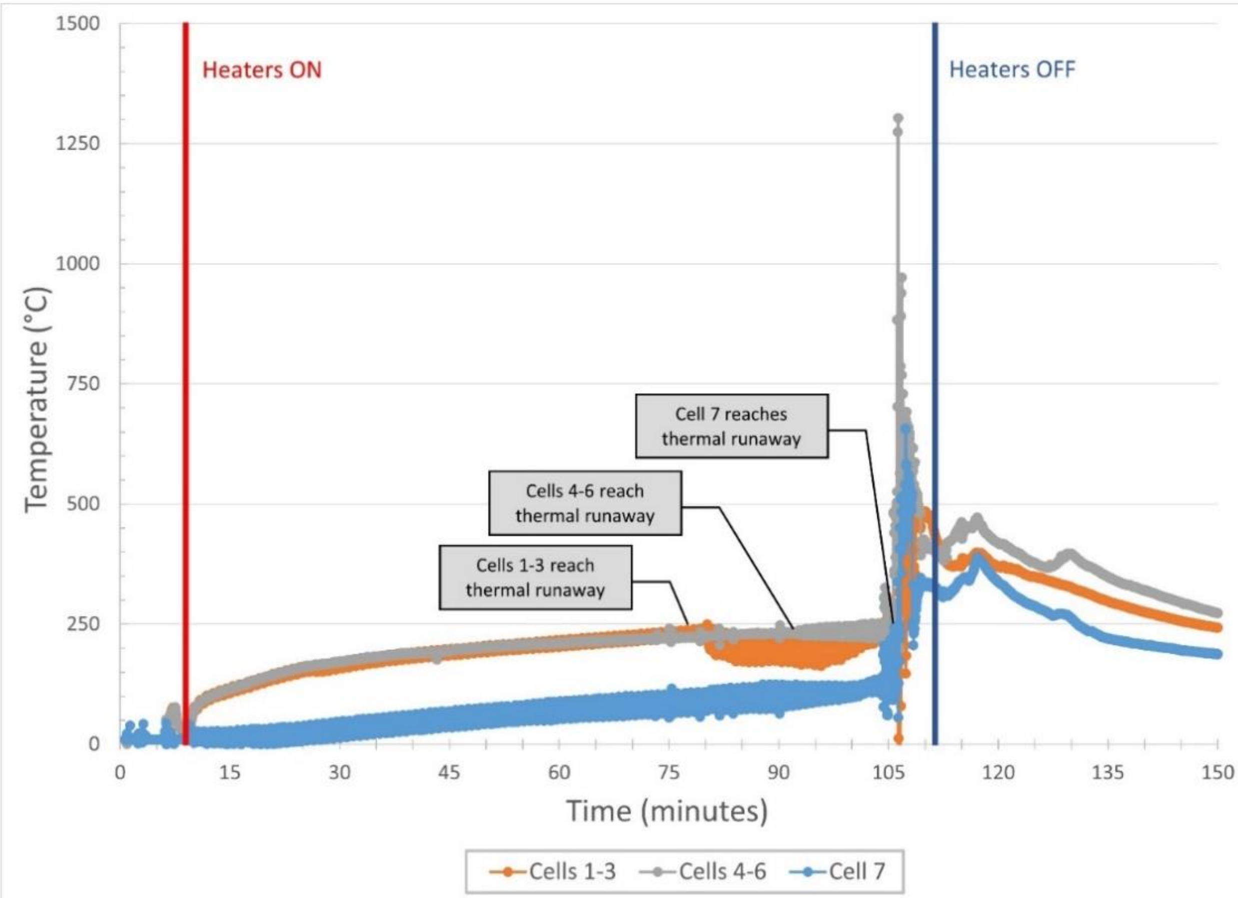

Figure 10 Cell surface temperatures recorded during UL 9540A unit level fire testing. Approximate Time to Thermal Runaway: Cells 1-3: 78 minutes; Cells 4-6: 93 minutes; and Cell 7: 105 minutes.

<u>Target Battery Module Surface Temperatures</u>

As shown in Table 4, surface temperatures of battery modules within the target MP2 cabinets did not exceed 174°C (345°F), the temperature at which thermally initiated cell venting occurs.[3]

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3 As determined by UL 9540A cell level testing (see previous discussion).

Table 4 Target Battery Module Surface Temperatures

Location	Maximum Battery Module Temperature Recorded	Ambient Temperature at the Start of Test	Cell Venting Temperature	Cell Thermal Runaway Temperature
Back Target Modules	13.8°C (56.4°F)	10.2°C (50.4°F)	174°C (345°F)	239°C (462°F)
Side Target Modules	13.2°C (55.8°F)	8.0°C (46.4°F)	174°C (345°F)	239°C (462°F)

These temperatures were recorded at the battery modules closest to the initiating battery module, as shown in Figure 11. As plotted in Figure 12, the internal temperature of the target battery modules gently rose throughout the 2½-hour test as the ambient, outdoor temperature also increased from 10.3°C to 11.6°C. These temperature measurements indicate the target battery modules were not affected by the thermal runaway of the seven cells within the initiating battery module.

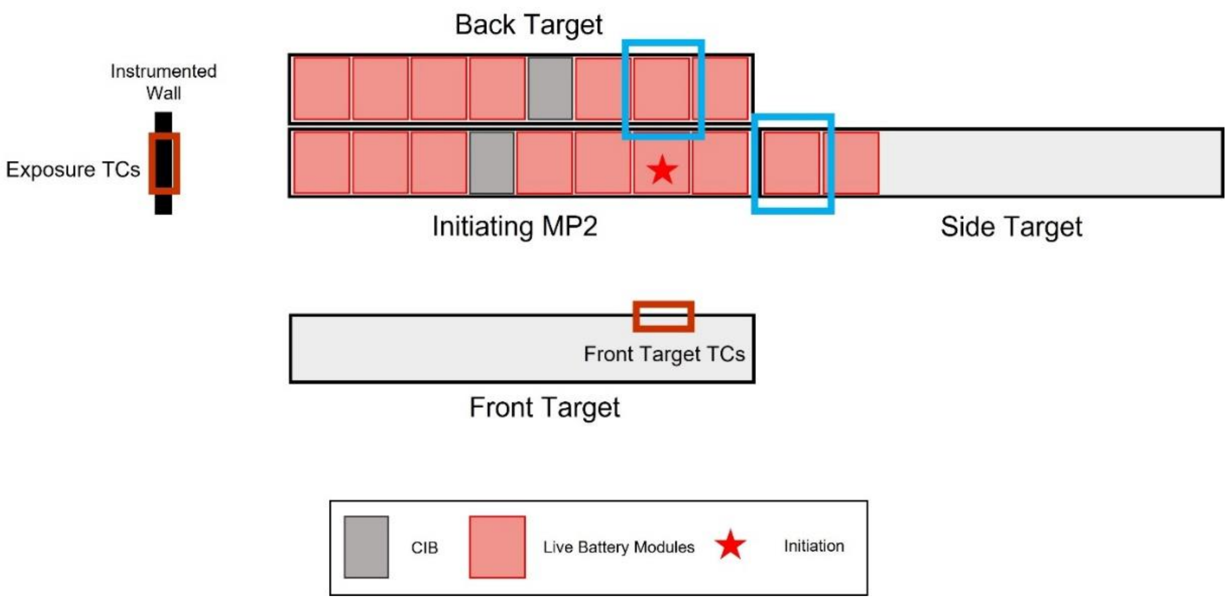

Figure 11 Location of temperature measurements at side and back target battery modules (blue boxes) and the front target and side exposure surface temperatures (brown boxes).

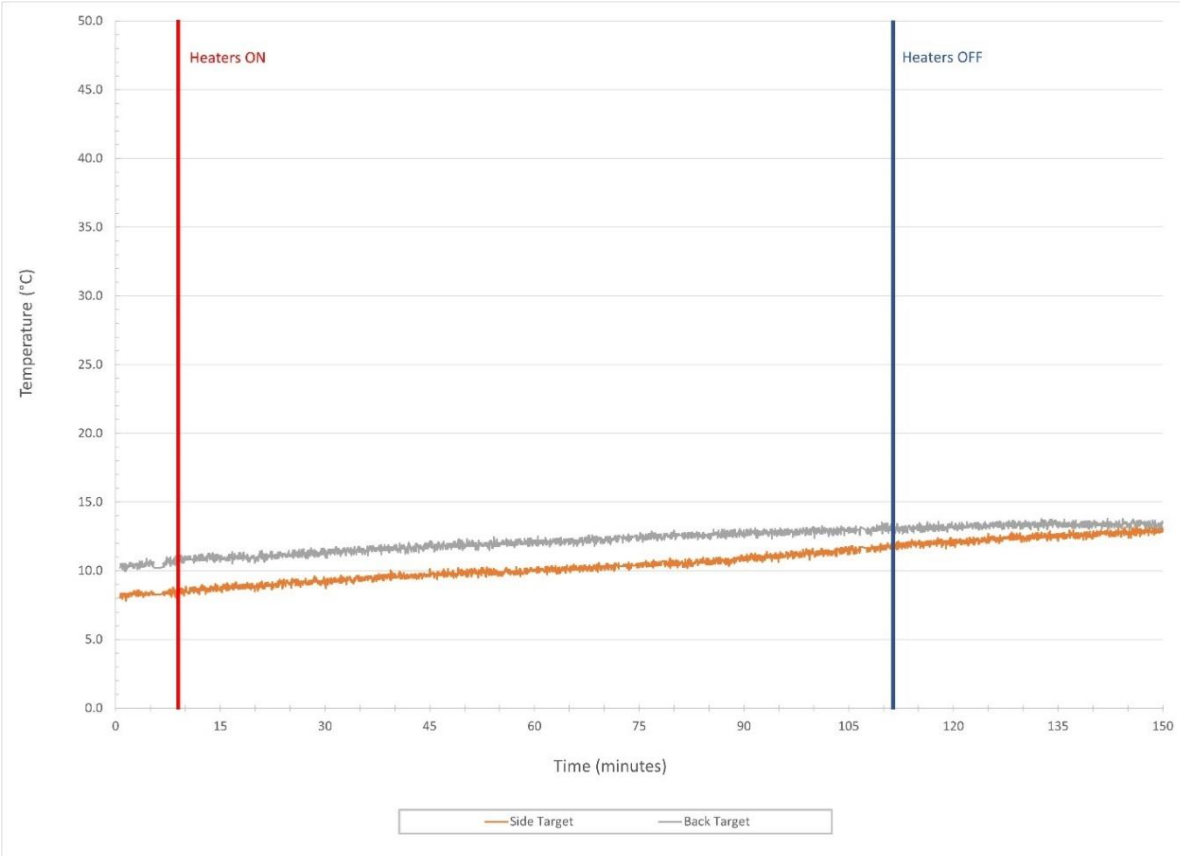

Figure 12 Side and back target battery module temperatures during UL 9540A unit level fire testing.

<u>Exposure Surface Temperatures</u>

As shown in Table 5, surface temperatures on exposures 5 ft (1.52 m) to the side (instrumented wall) and 8 ft (2.44 m) directly in front of the initiating MP2 cabinet (front target) did not exceed 97°C (175°F) above ambient.

Table 5 Exposure Surface Temperatures

Location	Maximum Temperature Recorded	Ambient Temperature Recorded by the TC at the Start of Test	Temperature Rise Above Ambient
Front Target Surface	16.8°C (62.2°F)	11.3°C (52.3°F)	5.5°C (9.9°F)
Instrumented Wall Surface	25.9°C (78.6°F)	20.4°C (68.7°F)	5.5°C (9.9°F)

These temperatures were recorded directly in front of the initiating battery module and at the instrumented wall, as shown in Figure 11. As plotted in Figure 13, the surface temperature of the front target gently rose throughout the 2½-hour test from a starting temperature of 11.3°C

(52.3°F) to a maximum surface temperature of 16.8°C (62.2°F). Similarly, as plotted in Figure 14, the 24 thermocouples installed on the instrumented wall also gentle rose throughout the test and fluctuated slightly with the outdoor environmental conditions (i.e., wind blowing, sun exposure, increasing ambient temperatures). The maximum temperature measured on the instrumented wall was 25.9°C (78.6°F), which was temperature rise of 5.5°C (9.9°F) above its ambient temperature at the start of the test. Note, the temperature rise above ambient reported in Table 5 can be attributed to the environmental conditions during the 2½-hour test and are not directly related to the thermal runaway of the seven cells within the initiating MP2. As these measurements are surface temperatures, the temperature rise within the front target surface and the instrumented wall surface is predominantly due to the sun heating up those surfaces during the test (the test was run between 11 am and 1:30 pm on a mostly sunny day). These temperature measurements indicate an exposure surface 5 ft (1.52 m) to the side and adjacent MP2 cabinets 8 ft (2.44 m) in front were not affected by the thermal runaway of the seven cells within initiating battery module.

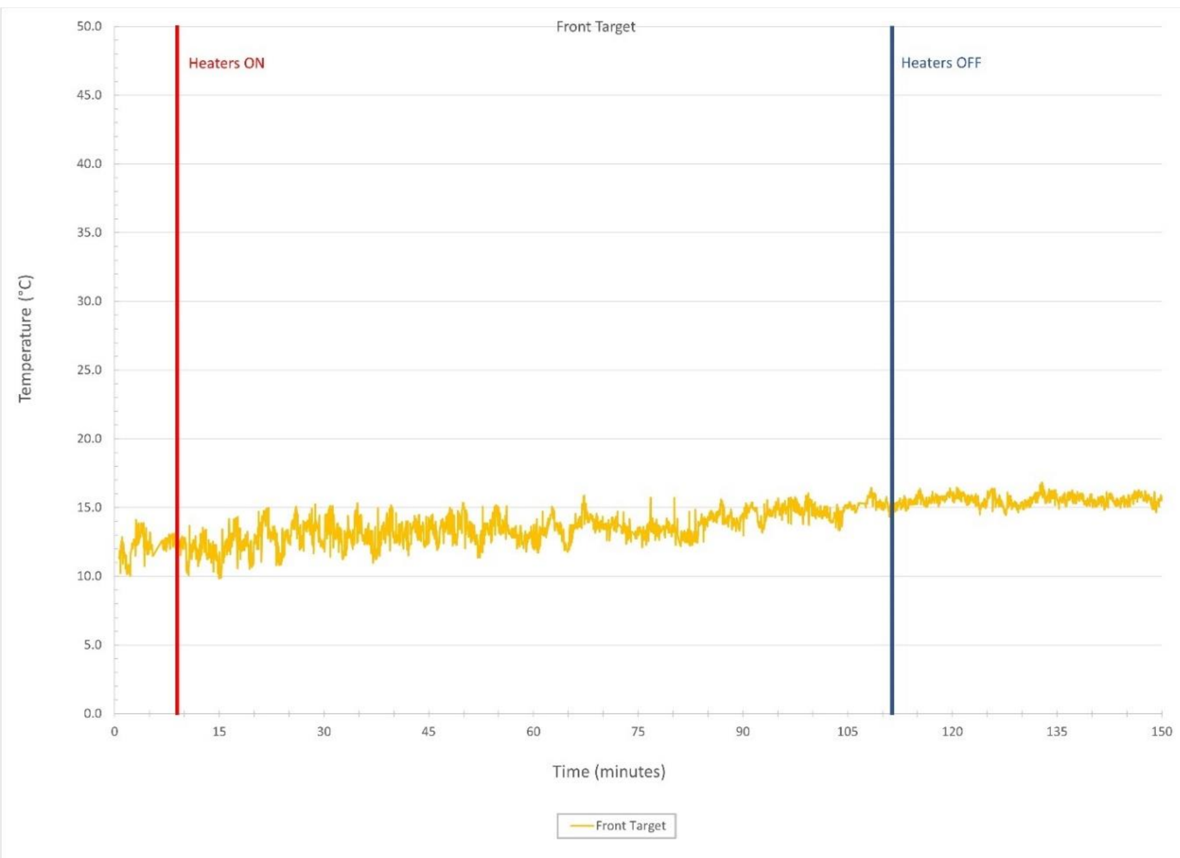

Figure 13 Front target external surface temperature 8 ft (2.44 m) directly in front of the initiating module.

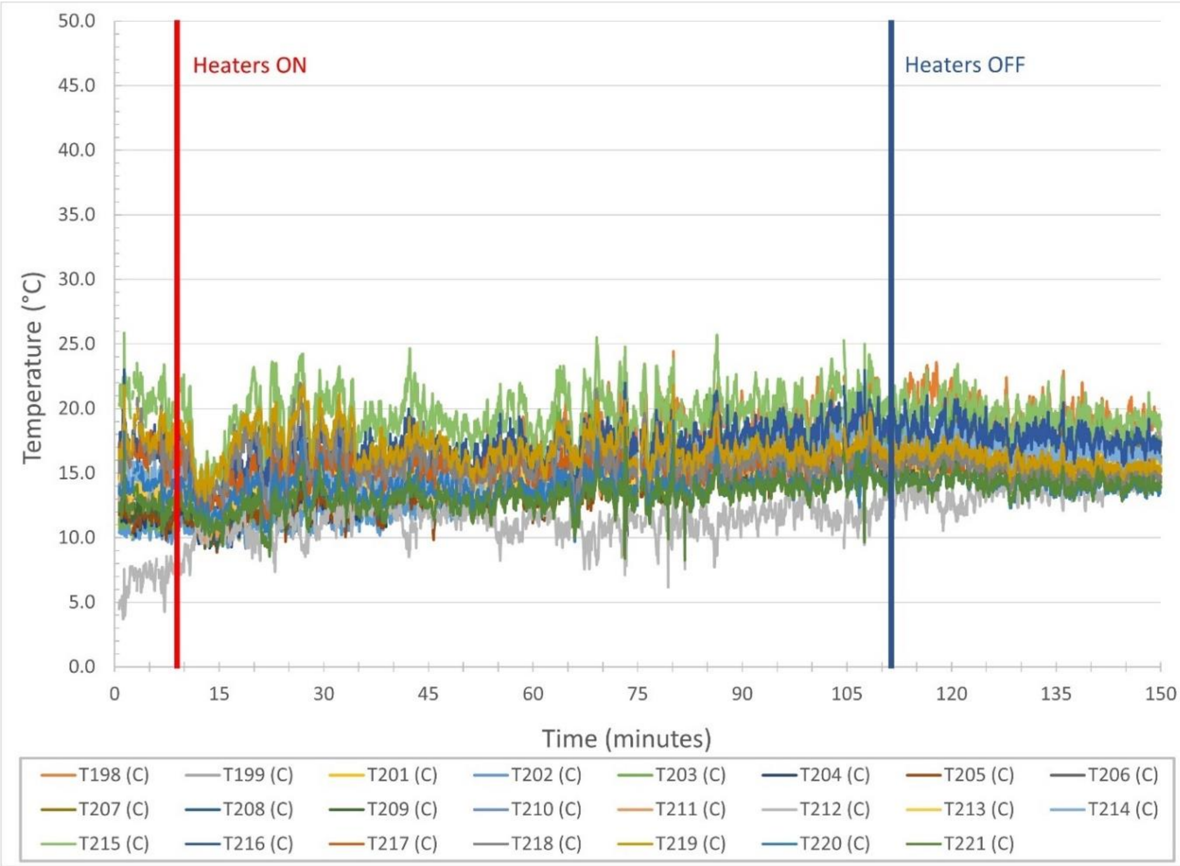

Figure 14 Instrumented wall surface temperatures during UL 9540A unit level fire testing. (Note: T200, the 24th thermocouple installed on the instrumented wall, did not work during testing, and was therefore removed from this plot as the measurements recorded were erroneous).

Heat Flux Measurements

Heat flux measurements were recorded throughout the UL 9540A unit level fire test at distances of 3, 5, 8, 20 and 30 ft (0.91, 1.52, 2.44, 6.10, and 9.14 m). Since flames did not occur outside the initiating MP2 cabinet, predictably, these measurements were essentially 0.00 kW/m^2 throughout the entire test, as summarized in Table 6 and plotted in Figure 15. The maximum heat flux recorded was 0.0000016 W/m^2, which was recorded at both the front target and at a distance of 20 ft from the initiating MP2. Note, these heat flux values, in W/m^2, are essentially reading no heat flux values at all, as would be expected given no flaming was observed outside the MP2 cabinet nor was the cabinet itself warmed enough to impose a heat flux on the sensors. These heat flux measurements indicate an exposure surface 3-5 ft (0.91-1.52 m) to the side, an adjacent MP2 cabinet 8 ft (2.44 m) in front, and other exposures further away at 20-30 ft (6.10-9.14 m), were not affected by the thermal runaway of the seven cells within initiating battery module. Furthermore, the heat flux measurements in front of and to the side of the initiating MP2 cabinet did not exceed 1.3 kW/m^2 at any time during the test, as required by UL 9540A. For individual plots of all seven heat flux sensors refer to Appendix 2, Heat Flux Plots.

Table 6 Maximum Recorded Heat Fluxes

Location	Maximum Heat Flux Recorded (W/m^2)
HF1	0.0000013
HF2	0.0000013
HF3	0.0000014
HF4	0.0000016
HF5	0.0000014
HF6	0.0000016
HF7	0.0000013

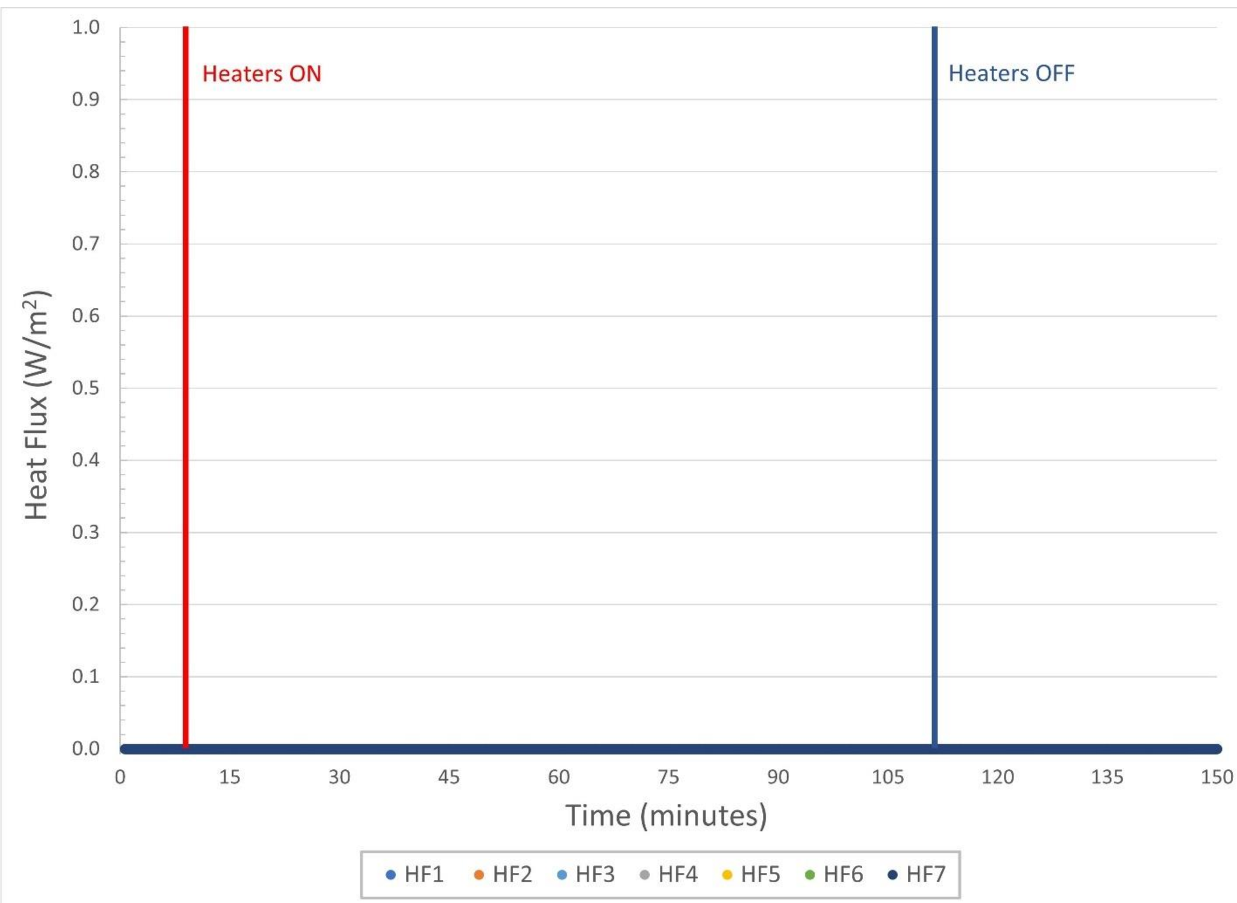

Figure 15 Heat flux measurements recorded during UL 9540A unit level fire testing.

External Fire Detection System

The MP2 does not have an internal fire detection system or one that is integral to its design/construction. During the UL 9540A unit level fire test, two multi-spectrum IR flame detectors and two thermal imagers from differing manufacturers were installed pointing directly at the front and top of the initiating MP2 cabinet. None of the detectors activated during the fire test. This result is expected, as no flames were observed out of the cabinet during the test.

Fire Suppression System

The MP2 does not have an internal fire suppression system or one that is integral to its design/construction. The UL 9540A unit level fire test results demonstrate that a suppression system is not required to stop the spread of fire from cell to cell, module to module or MP2 cabinet to cabinet when a near simultaneous failure of up to six cells occurs within the same battery module.

The UL 9540A unit level fire test also demonstrated that manual fire suppression (hose lines) is not required to stop the spread of fire from a MP2 cabinet to adjacent MP2 cabinets installed 6 in (150 mm) behind and to the sides when a near simultaneous failure of up to six cells occurs within the same battery module.

Explosion Control

UL 9540A unit level fire testing of the MP2 demonstrated that a failure event causing the near simultaneous thermal runaway of six cells will not cause a deflagration. During the test, pressure transducers were installed within the battery module bay to monitor overpressures within the MP2 cabinet. After the test, no pressure spikes were observed in the data, indicating no sudden increase in pressure occurred within the MP2 cabinet during the UL 9540A unit level test. In addition, the overpressure vents did not open, the MP2 cabinet doors were not forced open nor did the MP2 cabinet fail to hold containment. Meaning, no visual indications of an overpressure event occurring inside the MP2 cabinet were observed. Light smoking/off-gassing (i.e., not a pressurized discharge or deflagration) did escape the initiating MP2 during the test, likely through pathways created by the required instrumentation (thermocouples, film heaters, etc.) for the test; however, explosion hazards, including but not limited to, observations of a deflagration, projectiles, flying debris, detonation, hazardous pressure waves, shrapnel, or other explosive discharge of gases were not observed.

Runoff/Products of Combustion

UL 9540A large-scale fire testing does not require the collection of runoff or products of combustion as part of an outdoor installation test. However, during the large-scale test, and afterwards during cleanup, no liquid runoff (such as the water-glycol solution from the TMS) was observed. Internal cell components were observed after the test on the interior of the cabinet and around the Bay 7 door as would be expected after the failure of seven cells. However, no free-flowing liquid, or runoff was observed once the MP2 doors were opened. If necessary, should a failure event occur, internal cell components/electrolyte can be disposed of in an appropriate manner as specified by Tesla's ERG and Safety Data Sheets (SDS).

Performance Criteria

UL 9540A, Table 9.1 outlines the performance criteria for outdoor, ground mounted BESS. If all these conditions are met, further testing (such as installation level tests) is not required. The performance criteria during the UL 9540A unit level fire test is as follows:

1. No flaming observed outside of the unit.
2. Surface temperatures of battery modules within the targets adjacent to the initiating unit cannot exceed the temperature at which thermally initiated cell venting occurs.
3. Surface temperatures on exposures 5 ft (1.52 m) to the side and 8 ft (2.44 m) in front of the initiating unit cannot exceed 97°C (175°F) above ambient.
4. No explosion hazards, including but not limited to, observations of a deflagration, projectiles, flying debris, detonation, or other explosive discharge of gases observed.
5. Heat flux in the center of the accessible means of egress cannot exceed 1.3 kW/m^2.

As described above, no flaming was observed outside the MP2 cabinet during the unit level test. In addition, surface temperatures of the battery modules within the targets were below the temperature at which cell venting occurs (174°C or 345°F), and external surface temperatures on exposures 5 and 8 ft (1.52 and 2.44 m) away did not exceed 97°C (175°F) above ambient. Lastly, no explosion hazards were observed, and all heat fluxes remained below 1.3 kW/m^2. Based on the above UL 9540A unit level fire test results, the MP2 meets all five of the above performance criteria. By meeting the unit level performance criteria, UL 9540A installation level testing is not required for a MP2 installation.

MP2XL UL 9540A Unit Level Testing

The MP2XL design is almost identical to the MP2 other than being greater in length to accommodate the additional battery modules. It uses the exact same cells, battery modules, and power electronics (i.e., all the same internal components) that the MP2 utilizes in its design. In addition, the design of cabinet itself, enclosure strength, and fire safety features, such as the BMS, site controller, monitoring, electrical fault protections, and explosion control system are nearly identical for the two products. Given the limited module propagation observed during UL 9540A unit level testing of the MP2 (seven cells went into runaway) the test results are expected to be no different for the MP2XL. As shown in Figure 16, if the test were run on the MP2XL, the same internal components (cells and battery modules) would be tested in the same location within the cabinet (i.e., surrounded by twelve battery modules until reaching the CIB). Furthermore, given the MP2XL is larger in volume, the deflagration risk in the test would be less as the flammable gas concentrations within the battery module bay would mixing with more ambient air, and thus would be lower.

Similarly, after reviewing the MP2 unit level fire test results and comparing the MP2 and MP2XL products to one another, TÜV determined the MP2 UL 9540A unit level fire test results can be applied to the MP2XL and an additional UL 9540A unit level fire test for the MP2XL was not required for its listing. As such, given all these factors, a stand-alone MP2XL unit level fire test was not performed, nor required. The UL 9540A unit level fire test results, described above for the MP2, can be applied to the MP2XL.

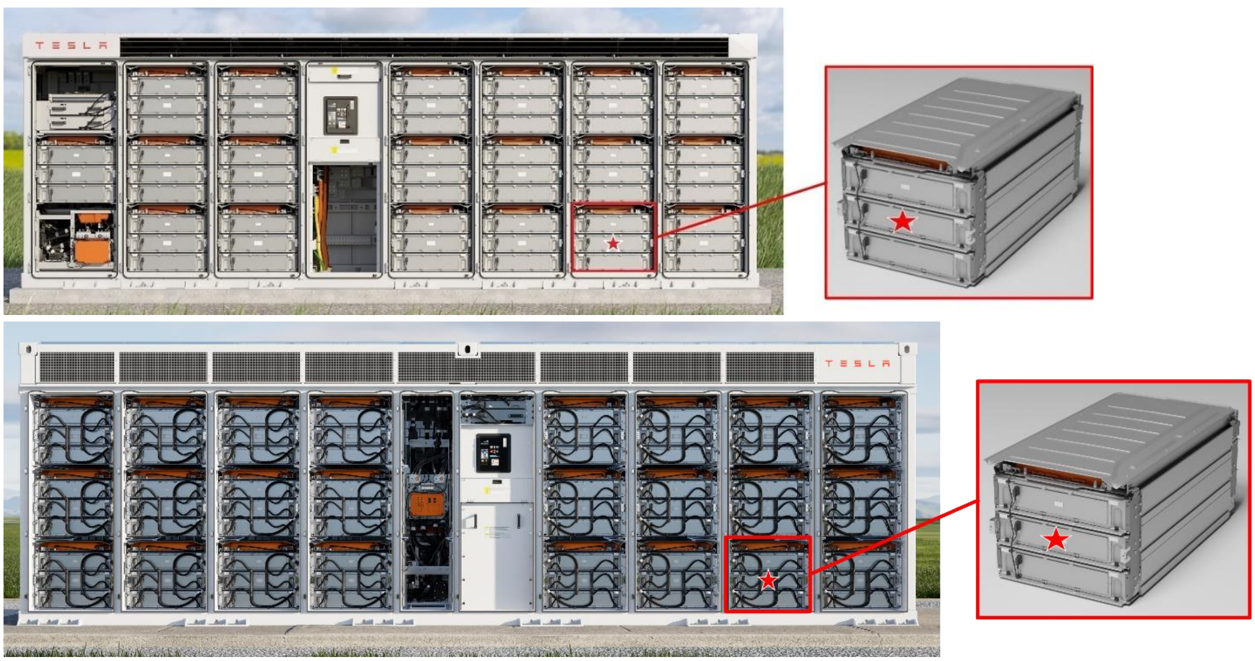

Figure 16 MP2 vs. MP2XL internal components comparison.

INTERNAL TESTING AND ANALYSIS

In addition to cell, module, and unit level UL 9540A testing required for its UL 9540 listing and required to meet installation level codes and standards, such as the IFC and NFPA 855, Tesla also performed extensive internal product testing and fire modeling for the MP2/2XL. This included destructive product testing that is beyond what is required for UL product listing and is also in excess of MP2/2XL failure scenarios contemplated by Tesla. Below is a summary of some of these fire tests and analyses, for information only. They include additional unit level products of combustion testing, destructive unit level testing and fire propagation modeling.

Unit Level Products of Combustion Testing

Products of combustion are not required to be collected during the outdoor UL 9540A unit level fire test; however, they were collected during cell and module level testing, as summarized previously. To provide additional products of combustion data during a unit level test, gas samples were collected during an internal, unit level fire test performed by Tesla on the MP2. This test was performed just as described above for the UL 9540A unit level test with gas samples being collected at two different locations: approximately 20 ft upwind and 5 ft downwind from the initiating MP2, as shown in Figure 17.

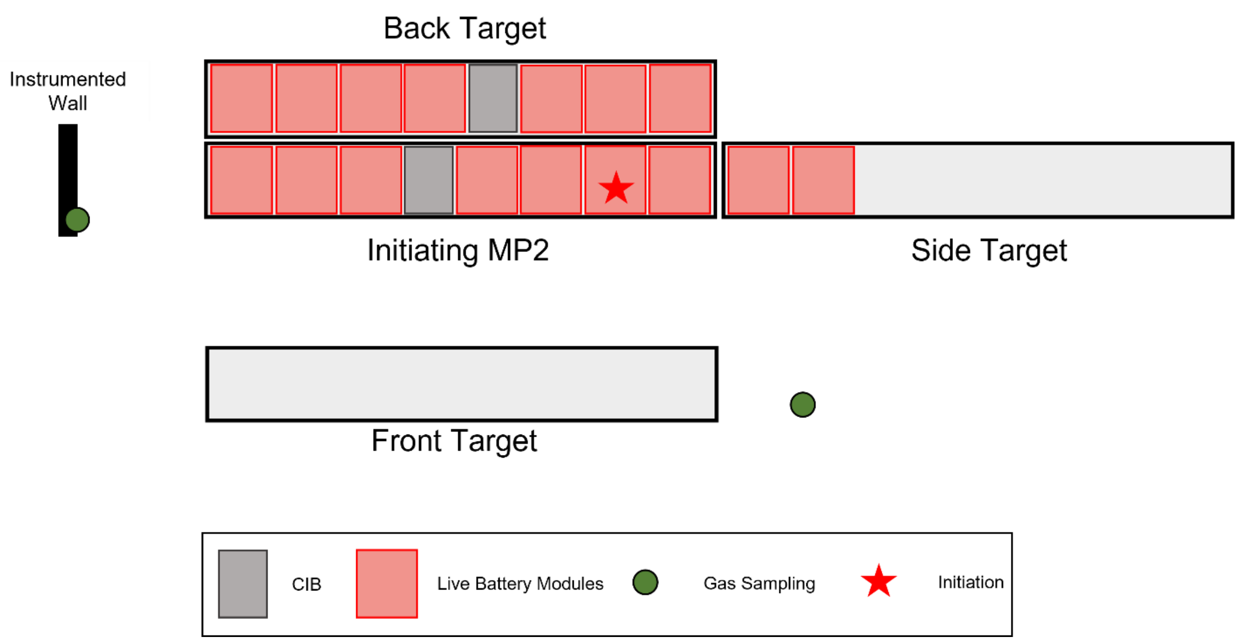

Figure 17 Unit level products of combustion test setup.

These gas samples were collected to provide additional data to first responders of possible airborne contaminants during an emergency event involving a MP2/2XL.[4] During that test, six cells were forced into thermal runaway with propagation occurring to a seventh. Similarly, the test did not create a fire nor did thermal runaway spread to adjacent battery modules or target MP2 cabinets, as was observed during the UL 9540A unit level test. After the test, these gas samples were sent to an independent, third-party laboratory for analysis after the test was

[4] Given the similarities between the MP2 and MP2XL, as described previously, the results from this unit level products of combustion test can be applied to both the MP2 and MP2XL.

completed. The gas samples were analyzed for traces of twenty-seven different metals, including: Aluminum, Arsenic, Barium, Beryllium, Cadmium, Calcium, Chromium, Cobalt, Copper, Iron, Lead, Lithium, Magnesium, Manganese, Molybdenum, Nickel, Phosphorus, Selenium, Silver, Sodium, Tellurium, Thallium, Titanium, Vanadium, Yttrium, Zinc, Zirconium. The test results found no traces of these metals in the gas samples collected. The gas samples were also analyzed for traces of Mercury and Hydrogen Fluoride (HF), two byproducts that are commonly of concern when discussing a lithium-ion battery fire or thermal runaway event. The gas samples found no traces of Mercury over the entire 2½ hour test duration. HF was detected at values of 0.10 and 0.12 parts per million (ppm) in the two sampling locations. This trace quantity was detected over the entire 2½ hour test duration, meaning it was the cumulative quantity that was measured over the entire duration of the test. For reference, according to National Institute for Occupational Safety & Health (NIOSH), HF's Immediately Dangerous to Life or Health (IDLH) value is 30 ppm, indicating the quantity of HF detected during the unit level products of combustion fire test is well below, two orders of magnitude lower, than the IDLH value for HF.[5]

Destructive Unit Level Test

Tesla performed a destructive unit level test to demonstrate how the MP2/2XL is capable of safely failing even in the extreme case of a catastrophic failure within one of its battery modules. This destructive test is well beyond what is required for UL product listing and is also in excess of any plausible MP2/2XL failure scenario contemplated by Tesla. In addition, the destructive unit level test also further validated the effectiveness of the explosion control system. It was conducted at the Northern Nevada Research Center on May 19, 2022.

<u>Test Unit</u>

The test was performed on a fully populated MP2XL, consisting of twenty-four battery modules, with a capacity of 3,916.8 kWh, tested at 100% SOC. Of all the MP2/2XL variations, the unit tested during the unit level destructive test is the largest capacity variation Tesla manufactures.[6] During the test, the BMS and TMS were disabled; meaning, they are not actively operating to prevent thermal runaway in a cell or to prohibit the propagation of thermal runaway from cell to cell, or module to module. As such, this test can be considered a worst-case scenario where: (1) the unit tested was the largest variation in terms of energy capacity; (2) the unit tested was at the highest energy density possible (100% SOC); and (3) the BMS and TMS were disabled and, therefore, unable to actively respond to the thermal runaway condition. As such, any tests performed on a

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5 https://www.cdc.gov/niosh/ershdb/emergencyresponsecard_29750030.html

6 Given the similarities between the MP2 and MP2XL, the results from this unit level destructive test can be applied to both the MP2 and MP2XL.

smaller capacity MP2/2XL unit, at a lower SOC, or on an operating MP2/2XL (i.e., one with an active BMS and TMS) would be expected to perform similarly, if not better, than this worst-case scenario. Below is a summary of the unit level destructive test results as well as a description of the performance of key fire safety features/systems during the test.

Test Setup and Initiation

The test was performed in the spirit of the UL 9540A unit level fire test method; however, it was not performed precisely to the test method given the objective of the test was to create a severe failure scenario, well beyond what is contemplated by the UL test methods. As such, one MP2XL cabinet was positioned on a concrete pad in the open air for testing. No additional target cabinets were installed around it. Identical to the UL 9540A unit level fire test described above, the initiating battery module was chosen to be the bottom battery module from Bay 9, in the middle battery tray (tray #2), as shown in Figure 18.

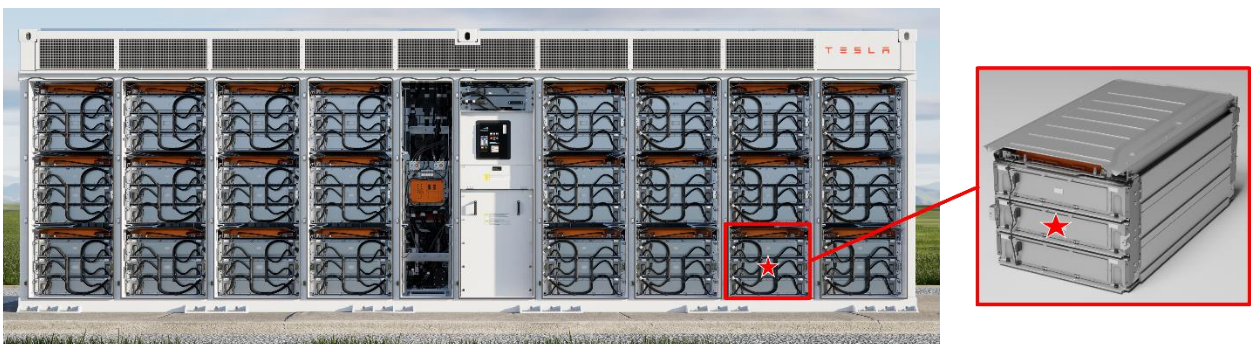

Figure 18 Initiation location: Bay 9, bottom battery module, tray #2.

Within the battery tray itself, forty-eight interior cells were simultaneously heated via thirty-two film heaters, as shown in Figure 19. The heaters were programed to provide a heating rate of 5°C (9°F) per minute, as specified by UL 9540A. The number of cells and the location were selected to provide the greatest thermal exposure to adjacent cells to ensure cell to cell propagation during the test. The objective of this initiation method is to simulate a mass failure of nearly half the tray in order to force a thermal event.

Instrumentation

The test was documented with multiple cameras on the outside and within the thermal roof to document the test. The purpose of the cameras installed in the thermal roof was to visually capture the activation and opening of the overpressure vents. In addition, pressure transducers were installed within the battery module bay to monitor the pressure profile within the enclosure. Lastly, a thermal imaging camera was utilized during testing to monitor the external surface temperatures of the cabinet, if necessary.

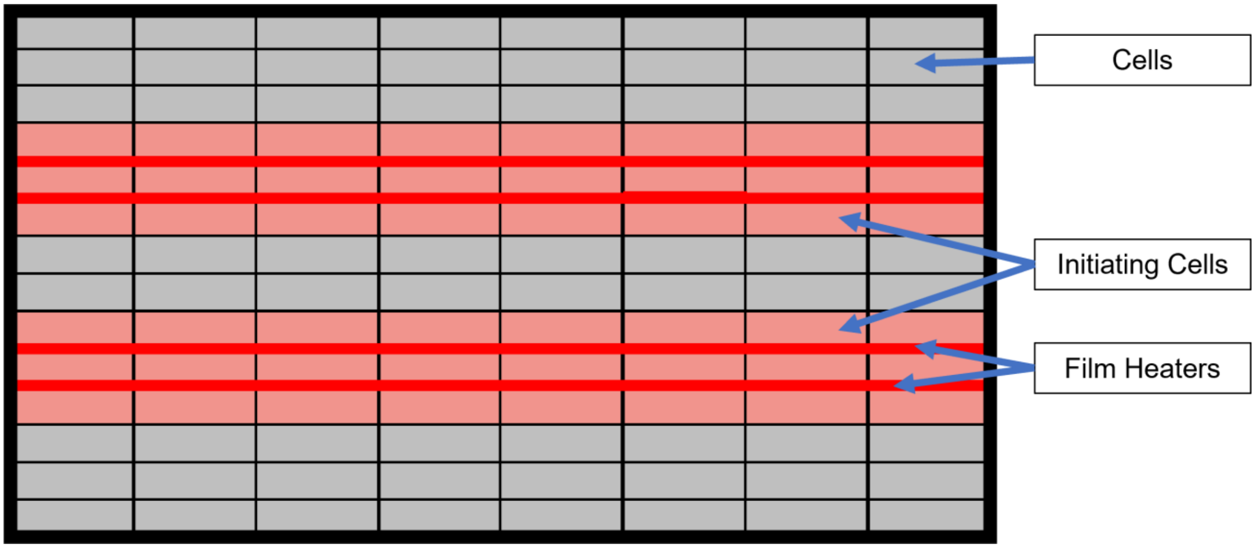

Figure 19 Film heater locations within the initiating tray.

Test Results

The test was performed starting around 2:15 pm on May 19, 2022. The ambient temperature was between 50°F and 75°F. It was a sunny, clear day with no precipitation and a relative humidity between 20% and 40%. Although not testing to UL 9540A, these outdoor environmental conditions met the requirements of UL 9540A, Section 9.1.2 for outdoor unit level fire testing. Table 7 provides a summary of key events from the destructive unit level fire test.

Table 7 Destructive Unit Level Testing: Timeline of Key Events

Approximate Elapsed Time hr:min:sec	**Event**
00:00:00	**Start of Test. Cameras, DAQ and heaters turned on.**
0:40:44	First thermal runaway confirmed.
1:14:08	An overpressure event occurred. An overpressure vent opened, and the cabinet doors remained closed. Smoking observed.
1:24:00	Flames observed predominantly coming out the front doors of the cabinet and out the front grill of the thermal roof (just above the doors).
2:30:00	Flames spread to the adjacent battery bays 8 and 10. Approximate peak flame intensity.
4:00:00	Flames spread to adjacent battery bay 7.
8:04:00	Flaming ceases. Flames did not spread to any other battery bays. **End of Test.**

Key takeaways from the unit level destructive test include:

- Thermal runaway propagated from the initiating cells to all the cells in the initiating tray.
- A thermal event occurred, likely initiated by the ignition of flammable gases by the sparker system. An overpressure vent installed above the initiating battery module opened and was visually confirmed through video. The cabinet doors immediately adjacent to the initiating battery module remained closed. No hazardous pressure waves, debris, shrapnel, or pieces of the cabinet were ejected.
- After approximately 10 minutes of smoking, a sustained fire began within the initiating battery module. The fire spread to the adjacent battery bays until reaching the CIB and stopped. The fire only burned half of the cabinet.
- Fire spread from battery bay to battery bay was a slow progressing event. In total, visible flames were observed for 6 hours and 40 minutes while the four battery bays (bays 7-10) burned, as shown in Figure 20.

Figure 20 Fire progression during unit level destructive testing (first three hours): images captured every 15 minutes moving left to right. Initial flaming (top left), peak flame intensity occurring 60-90 minutes after initial flaming (top right) before diminishing for the remainder of the test (bottom left to right).

- Maximum flame heights were observed to be 11.5 ft (3.5 m) from ground to the top of the flame, 2.5 ft (0.75 m) above the top of the cabinet and had a base (a width) of 3.3 ft (1 m) during peak flame intensity. This peak flame intensity occurred approximately 60-90 minutes after initial flaming was observed.
- An analysis of the pressure profile inside the cabinet during the test demonstrated the operation of the explosion control system, as shown in Figure 21. Pressure inside the cabinet increased to nearly 11 kPa (1.60 psi) until the deflagration vent opened and the

pressure diminished. The overpressure vents are designed to operate at approximately 12 kPa (1.74 psi), or 2.5 times below the cabinet's strength of 30 kPa (4.35 psi).

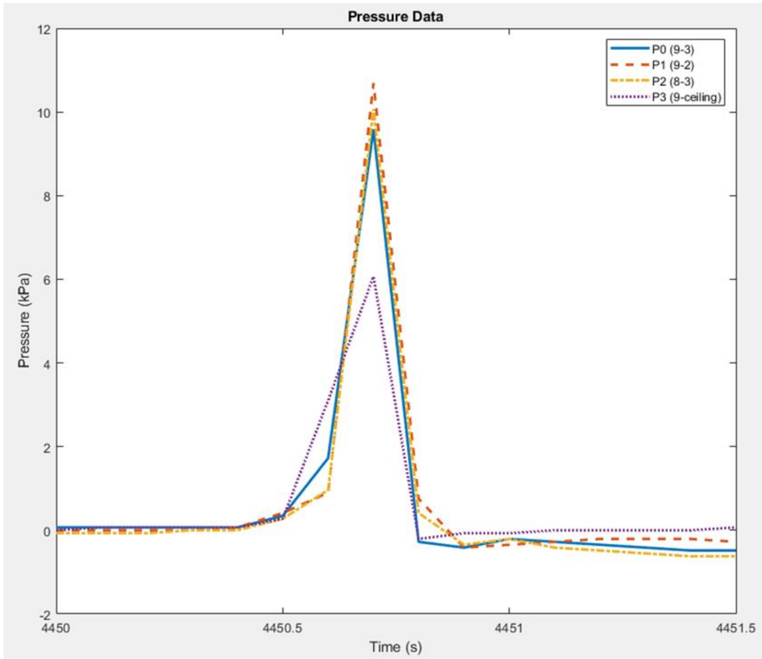

Figure 21 Pressure profile inside the MP2XL cabinet just before and after the thermal event.

- After the test, the initiating MP2XL cabinet was observed for several hours afterwards and allowed to cool. No additional fire, thermal runaways, or signs of off-normal conditions were observed. The battery modules on the left side of the MP2XL cabinet (battery bays 1-4) did not go into thermal runaway.

The destructive unit level test demonstrated that the MP2/2XL cabinets are capable of safely failing in the extreme case of a catastrophic failure with one of its battery modules. During the test, forty-eight cells were simultaneously heated to thermal runaway to demonstrate how severe a failure must be to initiate a thermal event and subsequent fire. During this extreme failure scenario, the flammable gases safely ignited, leading to the operation of the overpressure vent in the ceiling of the battery module bay. This thermal event did not blow open the cabinet's doors (they remained shut) and no hazardous pressure waves, debris, shrapnel, or pieces of the cabinet were ejected. In addition, pressures measured inside the cabinet during the test remained below the strength of the enclosure by a factor of over 2.5 times, as designed. The unit level destructive test results further validated the explosion control system for the MP2/2XL. As described previously, the explosion control system is not designed to prescriptive NFPA 68 or NFPA 69 requirements. NFPA 855 permits this engineered (performance based) approach only if unit level testing is performed validating the engineered explosion control system can mitigate the risks of explosions to ensure no hazardous pressure waves, debris, shrapnel, or pieces of the enclosure are ejected.[7] UL 9540A unit level fire testing demonstrated that the explosion control system can mitigate the deflagration hazard of the MP2/2XL and the destructive unit level test further demonstrated that the explosion control system can mitigate the deflagration hazard even with an extreme failure scenario (simultaneous failure of forty-eight cells). This destructive unit level test led to a slow progressing fire that burned for 6 hours and 40 minutes until flaming ceased. The fire failed to spread past the CIB and only half of the cabinet's battery modules became involved in the fire.

Fire Propagation Modeling

Since a sustained fire did not occur during UL 9540A unit level fire testing, Tesla generated a fire propagation model to determine the expected heat flux emitting from a MP2/2XL to target MP2/2XL cabinets installed 8 ft in front, 6 inches behind and 6 inches to the side of the initiating MP2/2XL cabinet.[8] The effect of that heat flux on the battery modules of the target MP2/2XL cabinets was then determined to identify the fire propagation risk, or lack therefore, from MP2/2XL cabinets. In addition, the fire propagation model provides anticipated heat fluxes to other exposures (i.e., other equipment, combustibles, buildings, etc.) at varying distances up to 100 ft away from the MP2/2XL. Below is a summary of the model, its basis/validation, and findings. It consists of two separate analyses that are coupled together to determine the fire propagation potential of the MP2/2XL: a heat flux model and a thermal runaway model. The heat flux model was created to determine the estimated heat flux that a MP2/2XL fire could have on surrounding exposures and the thermal runaway model was created to calculate the temperature rise at the battery modules based on an external heat flux acting upon the MP2/2XL. The fire propagation model was created to provide additional information regarding the fire propagation potential of a MP2/2XL cabinet to a project designer, installer, FCO or an AHJ to assist in their design, installation, or review of a MP2/2XL installation.

<u>Heat Flux Model Basis and Validation – No Wind</u>

The heat flux model was based on heat being transferred to the target MP2/2XL cabinets in two dominant modes: heat flux emitted from the flames out the front of the MP2/2XL and heat flux emitted from the hot surface of the MP2/2XL cabinet itself, as shown in Figure 22. These modes of heat transfer were observed in the destructive unit level test where the fire in a MP2XL cabinet principally exited the cabinet through the front door and front grill of the thermal roof.

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[7] NFPA 855, Section 9.6.5.6.4.

[8] Tesla's MP2 and MP2XL DIM states cabinets can be installed within 6 inches to the sides and behind each other and 8 ft in front. The 8-foot distance in front of the cabinet is required for installation and maintenance activities.

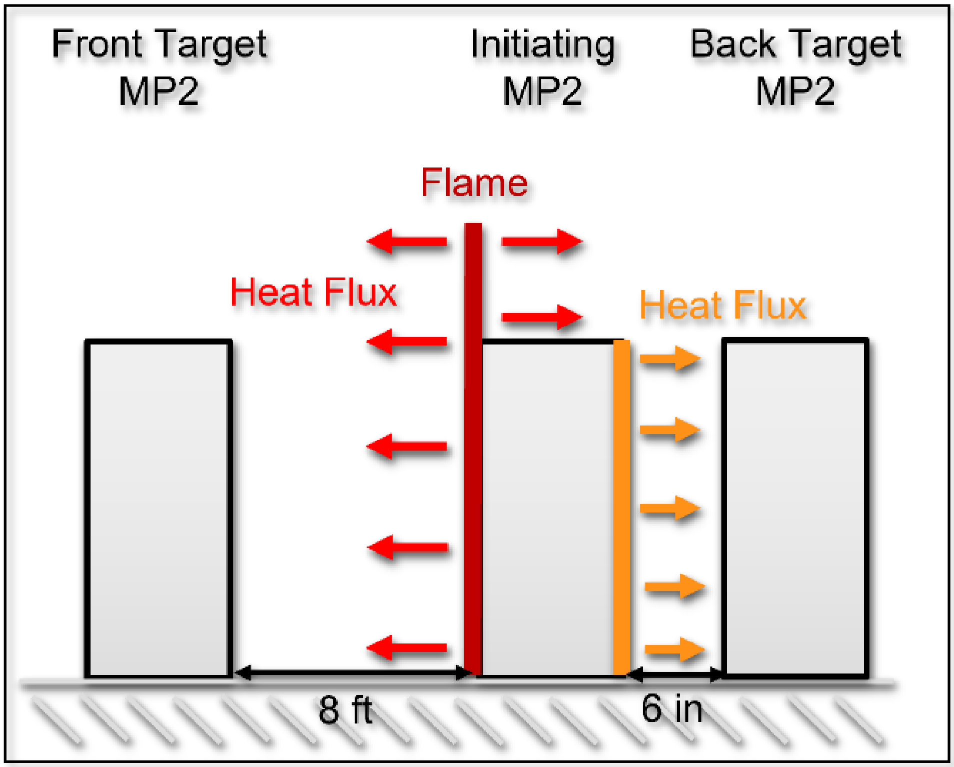

Figure 22 Heat flux model conditions: no wind condition.
Note: the illustration is for demonstrational purposes only. Not to scale.

In addition, the MP2XL cabinet radiated heat from its external surfaces to its surroundings as the fire inside the cabinet heated up the steel cabinet. These heat fluxes were calculated utilizing the solid flame radiation model formulas described by Hurley[9] and heat transfer formulas between parallel, rectangular plates (i.e., the exterior surfaces of adjacent MP2/2XL cabinets are two parallel, rectangular plates separated by 6 inches) outlined by Howell.[10]

For inputs, the flame radiation portion of the heat flux model required an estimated flame height, width, and temperature from a MP2/2XL fire. These values were obtained from the destructive unit level test described above, where flame heights and widths were determined throughout the test based on a review of the fire test videos, as shown in Figure 20. For the flame temperature, this input was assumed to be 1200 Kelvin (K) or 927°C, a typical flame temperature assumption for this type of fire. For the estimated flame heights and widths, the model was first analyzed with no wind (i.e., the flames emit directly vertical with little or no tilt in either direction). With these inputs the heat flux model can provide a conservative time v. heat flux plot

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9 Hurley, M.J., Gottuk, D.T., Hall Jr, J.R., Harada, K., Kuligowski, E.D., Puchovsky, M., & Wieczorek, C.J. (2015). SFPE handbook of fire protection engineering.

10 Howell, J.R. (2010). A catalog of radiation heat transfer configuration factors.

that tracks the expected heat flux over the course of a MP2/2XL fire event based upon the flame characteristics observed from unit level fire tests.

The high temperature surface radiation portion of the heat flux model required an estimated external surface temperature of the MP2/2XL cabinet. These values were also obtained from the destructive unit level test described above, where a thermal imager was utilized to determine the external surface temperature of cabinet throughout the test. During the destructive unit level test, localized hot spots were observed as the fire slowly spread from battery module to battery module, as shown in Figure 23. To address this complexity, the heat flux model instead chose to conservatively apply a single temperature to the entire back surface of the MP2/2XL cabinet as a function of time. Meaning, although the fire observed in the destructive unit level fire test created small, localized hot spots (related to which battery module was on fire at the time) on the exterior cabinet surface, the heat flux model applied a uniform temperature to the entire back surface of the MP2/2XL cabinet. With these inputs the heat flux model provided a conservative time v. heat flux plot that tracks the expected heat flux over the course of a MP2/2XL fire event based upon the exterior surface temperatures observed from the destructive unit level fire test.

To validate the heat flux model, it was first applied to a fire test performed on the original Megapack (MP1). During unit level fire testing of the MP1, a fire event consumed the entire cabinet and external heat fluxes were collected by heat flux sensors. The inputs for the model were determined by reviewing the fire test videos and thermal imager data.

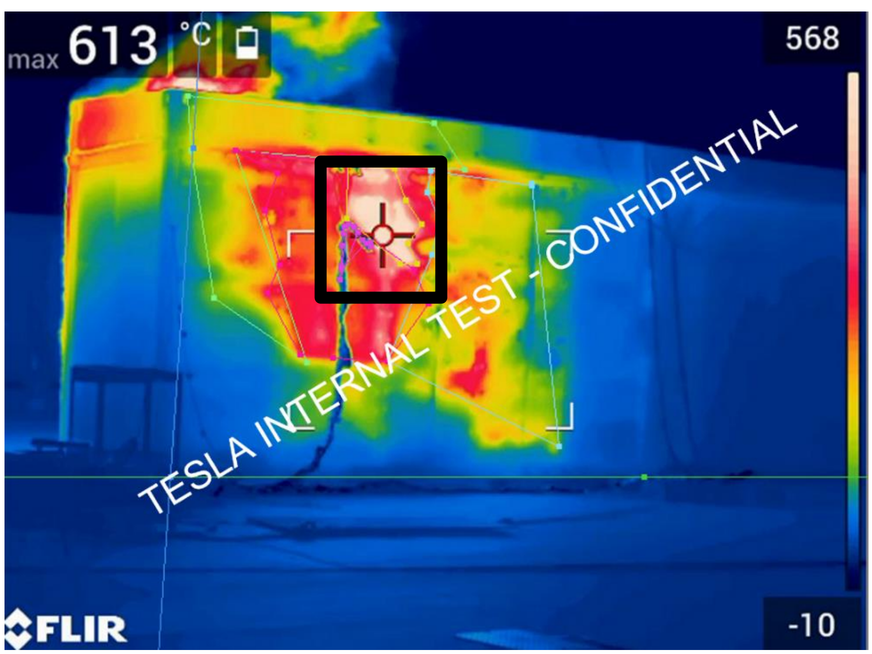

Figure 23 Typical "hot spot" (see black box) observed during the destructive unit level test.

The model generated the estimated heat fluxes emitting off the flames and when compared to the fire test data collected by the heat flux sensors, the model shows consistency in predicting the heat flux that was measured, typically within 20%. Given the heat flux model is being compared to an outdoor fire test, with its inherent unpredictability, this level of accuracy is more than acceptable. In addition, the model was also consistently conservative by overpredicting the heat flux compared to what was measured by the heat flux sensors. For instance, during one 30–40-minute window where there was limited wind interference (i.e., a no wind condition), the model predicted an average heat flux of 17.4 kW/m^2 at 8 ft in front of the MP1. The heat flux sensor installed 8 ft in front of the MP1 measured a heat flux, on average, of 15.0 kW/m^2 during this same 30–40-minute period.

In addition, the inputs for the external surface temperature utilized for the heat flux model were conservatively applied to the entire back surface of the MP2/2XL cabinet. Meaning, although the fire observed in the destructive unit level fire test created localized hot spots on the exterior cabinet surface, the heat flux model characterized the entire back of the MP2/2XL cabinet as a high temperature surface. This emits a heat flux from the external surface of the MP2/2XL cabinet over a much larger area than what was observed in the destructive unit level test (where the fire only created small localized hot spots, shown in Figure 23) as the fire slowly spread from battery module to battery module.

Heat Flux Model Basis and Validation – With Wind

With the model showing a good correlation between predicted heat fluxes and actual fire test data from the MP1 during no wind conditions, it was then adjusted to predict the heat flux imposed on target MP2/2XL cabinets with wind. By adjusting the tilt of the flames, worst-case wind conditions can be accounted for and added to the model. Based on the theoretical worst-case flame tilt, a sustained angle of 45 degrees,[11] as shown in Figure 24, would apply the largest heat flux onto the surfaces of neighboring MP2/2XL cabinets and would present the greatest risk of thermal runaway propagation. By accounting for the worst-case flame tilt (i.e., 45 degrees), the magnitude of the wind speed is not a concern. Meaning, if the wind speed is lower, then the flame tilt will be less than 45 degrees and the heat flux from that flame will be less than what the model is predicting. Similarly, if the wind speed creates a flame that has a tilt angle greater than 45 degrees, then the heat flux that flame will impose on the adjacent MP2/2XL cabinets will also be lower than the worst-case 45-degree scenario that the model is assuming.

11 Howell, J.R. (2010). A catalog of radiation heat transfer configuration factors.

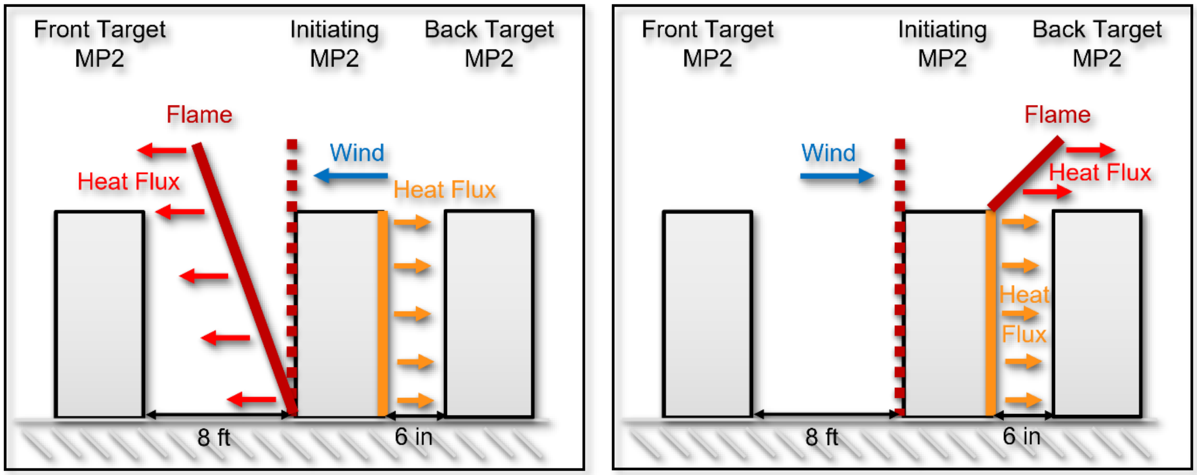

Figure 24 Heat flux model conditions: with wind blowing towards the front target (left) and with wind blowing towards the back target with flames exiting the top of the MP2 cabinet (right). Note: the illustrations are not to scale.

This sustained, 45-degree flame tilt is conservative in that it is applied consistently over the entire duration of the heat flux model. In addition, for the flame tilt towards the front target, the flame was assumed to tilt from ground level to the top of the flame, which is another conservative assumption to the heat flux model. This creates a tilted flame that would not be expected in a fire event as the MP2/2XL cabinet itself would obstruct the wind from tilting the flames that low to the ground. Lastly, the wind condition for towards the back target MP2/2XL analyzes the flames exiting the top right corner of the MP2/2XL cabinet and emitting a sustained heat flux at a 45-degree angle directly to the top of the back target. This conservative approach results in a much shorter distance between the flame and the back target and thus a larger heat flux being imposed on the back target.

<u>Heat Flux Model Results</u>

The heat flux model determined the anticipated heat flux emitted from a MP2/2XL fire as a function of time for each of the scenarios described above. Figure 25 provides the modeled heat fluxes emitting off the hot MP2/2XL cabinet surface only (i.e., excluding the flame heat flux) as a function of time, Figure 26 provides the modeled heat fluxes emitting off the flames for the three wind conditions described above, and Table 8 provides the peak heat fluxes determined by the models for each scenario.

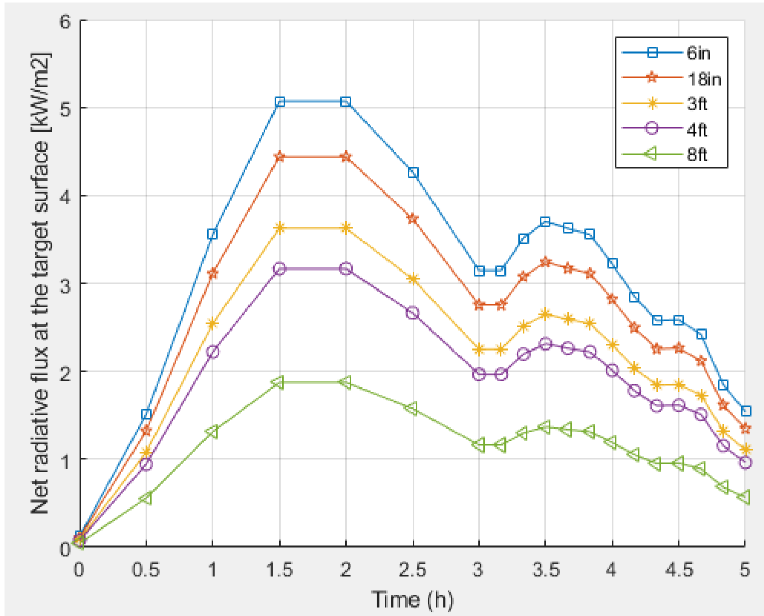

Figure 25 Heat flux emitting off the MP2 cabinet surface, as a function of time, at varying distances as determined by the heat flux model.

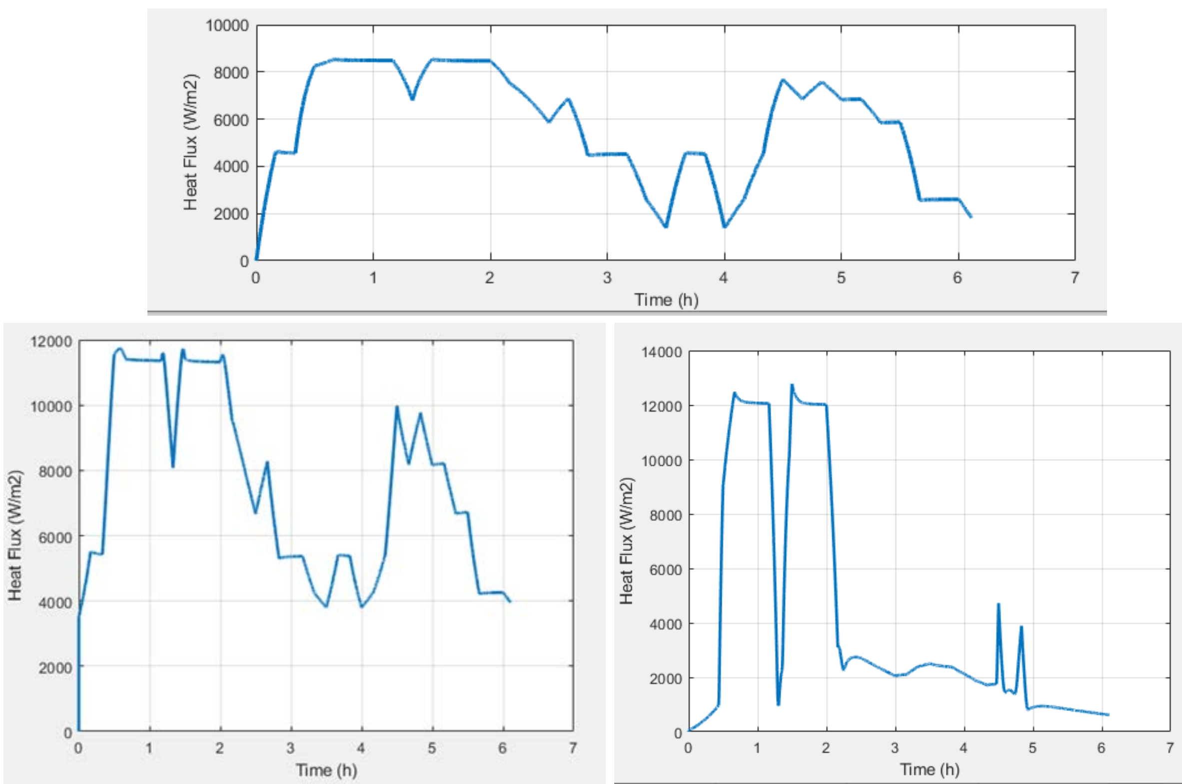

Figure 26 Heat flux emitting off the flames, as a function of time, as determined by the heat flux model: no wind condition (top); wind blowing towards the front target (bottom left); and wind blowing towards the back target (bottom right).

Table 8 Heat Flux Model Summary Results

Radiation Emitting From	Condition	Target Location and Distance		Maximum Predicted Heat Flux (W/m²)
MP2/2XL Cabinet (hot surface)	With or Without Wind	Back and Side Targets	6 in	5,125
			18 in	4,400
			3 ft	3,650
			4 ft	3,175
			8 ft	2,900
Flames: Front of the MP2/2XL Cabinet	No wind (vertical flames)	Front Target	8 ft	8,500
Flames: Front of the MP2/2XL Cabinet	Worst-case wind (45° tilted flames)		8 ft	11,765
Flames: Top of the MP2/2XL Cabinet	Worst-case wind (45° tilted flames)	Back and Side Targets	6 in	12,828

In addition to creating heat flux profiles for the purpose of analyzing the fire propagation risk to neighboring MP2/2XL cabinets, the heat flux model was also utilized to determine the estimated heat fluxes at distances further from the MP2/2XL cabinet, as shown in Figure 27. These values can be utilized, as necessary, to analyze the risk to other exposures in proximity to a MP2/2XL.

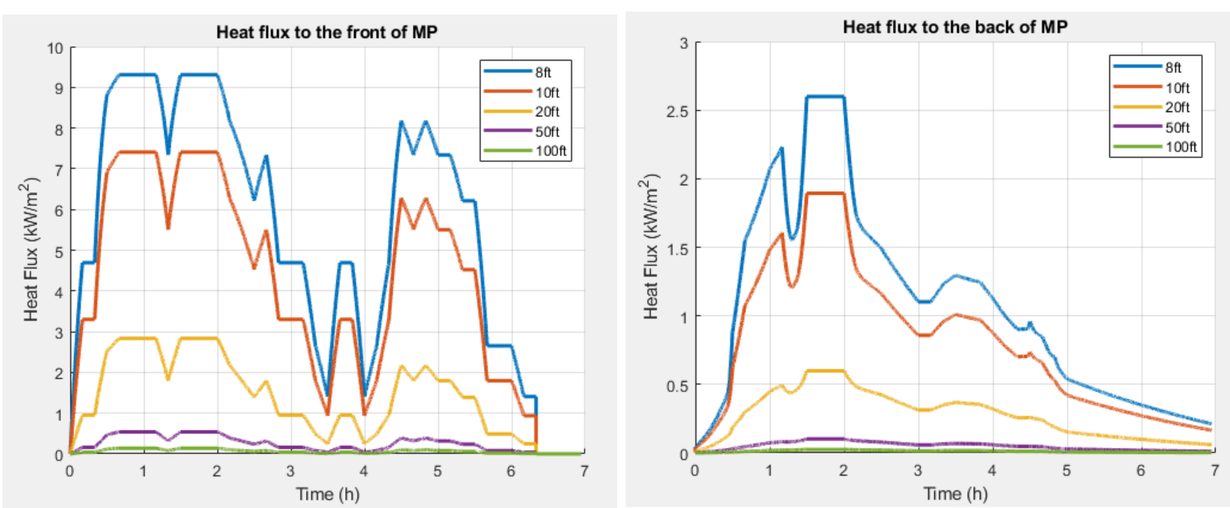

Figure 27 Heat flux versus time as determined by the heat flux model in front of the MP2 cabinet (left) and behind the MP2 cabinet (right).

Thermal Runway Model Basis

The second step of the fire propagation model was the thermal runaway model. This model analyzes the heat transfer from the heat flux emitting off a MP2/2XL fire to the battery modules of adjacent MP2/2XL cabinets. For this analysis, the adjacent MP2/2XL cabinets were 8 ft in front, 6 inches behind and 6 inches to the side of the initiating MP2/2XL cabinet, just as they would be in a typical installation. The temperature rise at the battery modules of these adjacent MP2/2XL cabinets was calculated by determining the heat transfer across the 6-inch and 8-foot gaps and through the exterior surface of the MP2/2XL cabinet before reaching the battery modules. The heat transfer across these gaps was calculated utilizing a 1D transient heat transfer model as described by Bergman.[12] For inputs, the model required a heat flux as a function of time, as determined in the heat flux model described above. With those heat fluxes, the thermal runaway model can provide a temperature curve as a function of time. This curve tracks the expected temperature at the battery modules over the course of a MP2/2XL fire event based upon the heat flux acting upon the target MP2/2XL cabinet.

Fire Propagation Model Results

Coupling the heat flux and thermal runaway models together creates the fire propagation model. Table 9 summarizes the results of the fire propagation model at target MP2/2XL cabinets 8 ft in front of the initiating MP2 as well as 6 inches behind and to the side.

Table 9 Summary Results for the Fire Propagation Model

Target Location	Condition	Maximum Predicted Battery Module Temperature	Cell Thermal Runaway Temperature
Back and Side Target Modules	No wind (vertical flames)	102°C (216°F)	239°C (462°F)
Back and Side Target Modules	Worst-case wind (45° tilted flames)	150°C (302°F)	239°C (462°F)
Front Target Modules	No wind (vertical flames)	129°C (264°F)	239°C (462°F)
Front Target Modules	Worst-case wind (45° tilted flames)	164°C (327°F)	239°C (462°F)

As shown, the fire propagation model predicts maximum temperatures at adjacent battery modules over the course of a 6 hour and 40-minute MP2/2XL fire (as was observed in the

12 Bergman, T.L., Bergman, T.L., Incropera, F.P., Dewitt, D.P., & Lavine, A.S. (2011). Fundamentals of heat and mass transfer.

destructive unit level fire test) below the threshold for cell thermal runaway (239°C or 462°F). As such, based on the fire propagation model, in the unlikely event of a MP2 fire, and accounting for worst-case wind conditions, thermal runaway would not propagate to a MP2/2XL installed 8 ft in front, 6 inches behind or 6 inches to the side of the initiating MP2/2XL cabinet.

MEGAPACK 1 VS. MEGAPACK 2 AND MEGAPACK 2XL

From the exterior the original Megapack (the MP1) and the second generation Megapack (MP2/2XL) appear substantially similar: a lithium-ion battery cabinet with the similar dimensions. In addition, many of the same safety features incorporated into the MP1, including the layered BMS, TMS, and deflagration control system, are also included in the design of the MP2. The most significant difference between the two products is the change in the cells utilized within the battery modules. The MP1 utilized cylindrical 2170 lithium-ion nickel manganese cobalt oxide (NMC) cells whereas the MP2/2XL is utilizing prismatic, LFP cells. The LFP cells were found to require more energy to go into thermal runaway[13] and were less likely to propagate to adjacent cells. For instance, UL 9540A unit level fire testing of the MP1 resulted in the combustion of the entire cabinet as thermal runaway propagated from the initiator module to adjacent cells and ultimately, adjacent battery modules. This resulted in a fire (ignited by the sparker system) within the cabinet and flames exiting the cabinet through the thermal roof. As described above, thermal runaway during the UL 9540A unit level fire test in the MP2/2XL only propagated to a single additional cell (a seventh cell) beyond the initial six that were forced into runaway and no external flaming was observed. This result indicates a reduced propensity for fire spread both within the MP2/2XL cabinet (from battery module to battery module for instance) and externally from MP2/2XL cabinet to adjacent cabinets, then was observed in the MP1. For a side-by-side direct comparison between the Megapack products, refer to Appendix 1, MP1 vs. MP2/2XL Comparison.

CONCLUSIONS

Based on our review of the available materials, our background, experience and training, and the analysis performed to date described above, the following conclusions are submitted within a reasonable degree of scientific and engineering certainty:

1. The MP2/2XL is listed to all product design standards (such as UL and IEC) required of a BESS and has been tested to UL 9540A at the cell, module, and unit level.

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13 UL 9540A cell level testing indicates thermal runaway initiates at 139°C (282°F) for NMC cells vs. 239°C (462°F) for LFP cells.

2. Cell and module level UL 9540A testing demonstrated that the venting and combustion of the MP2/2XL cells releases flammable gases that are commonly detected in a vented lithium-ion cell; however, they do not release toxic gases sometimes associated with the failure of lithium-ion batteries, such as HCN, HCL and HF.
3. The largest variant of the MP2, a 3,100.8-kWh unit, was tested at a worst-case scenario (i.e., 100% SOC with the BMS and TMS disabled) to the UL 9540A unit level fire test method.
    a. The UL 9540A unit level fire test was initiated through the simultaneous heating and subsequent failure of six cells within a single battery module of the initiating MP2 cabinet.
    b. This resulted in thermal runaway propagating to a seventh cell within the battery module; however, thermal runaway did not propagate any further than the seventh cell, nor did thermal runaway propagate to adjacent battery modules within the initiating MP2 cabinet, or to the target MP2 cabinets installed at separation distances of 6 in (150 mm) behind and to the sides of the initiating MP2 cabinet.
    c. The maximum surface temperature recorded at the target MP2 cabinets was 16.8°C (62.2°F) on the front target MP2 cabinet installed 8 ft (2.44 m) directly in front of the initiating MP2. Cell venting occurs at 174°C (345°F) and thermal runaway occurs at 239°C (462°F). These temperature measurements indicate propagation to the battery modules within a MP2 cabinet installed at clearances of 8 ft (2.44 m) is not possible.
4. Based on this failure scenario, a nearly simultaneous failure of six cells within the same battery module, the performance criteria outlined in UL 9540A, Table 9.1 for outdoor, ground mounted BESS were all met. Specifically, the performance criteria results were:
    a. No flaming was observed outside of the unit.
    b. Surface temperatures of battery modules within the target MP2 cabinets adjacent to the initiating MP2 cabinet did not exceed the temperature at which thermally initiated cell venting occurs. The maximum temperatures recorded at the battery modules of the adjacent MP2 cabinets were 13.8°C (56.4°F) and 13.2°C (55.8°F). These temperatures are significantly below the temperature at which cell venting occurs (174°C or 345°F).
    c. Surface temperatures on exposures 5 ft (1.52 m) to the side and 8 ft (2.44 m) in front of the initiating MP2 cabinet did not exceed 97°C (175°F) above ambient. The maximum external surface temperatures recorded at the instrumented wall 5 ft (1.52 m) to the side was 25.9°C (78.6°F) with a temperature rise above ambient of 5.5°C (9.9°F). The maximum external surface temperatures recorded at the front target 8 ft (2.44 m) directly in front of the initiating MP2 was 16.8°C (62.2°F) with a temperature rise above ambient of 5.5°C (9.9°F). These temperatures are significantly below the maximum permitted temperature rise above ambient of 97°C (175°F).
    d. Explosion hazards, including but not limited to, observations of a deflagration, projectiles, flying debris, detonation, or other explosive discharge of gases were not observed.

   e. Heat flux measurements did not exceed 1.3 kW/m^2. The maximum heat flux recorded was 0.0000016 W/m^2, which was the sensor installed on the front target MP2 cabinet and was the ambient heat flux the sensor was exposed to throughout the test.
5. Based on a review of the MP2, its fire safety features and the UL 9540A unit level fire test results, the MP2 meets or exceeds all the performance criteria of UL 9540A, Table 9.1 and UL 9540A installation level testing is not required for a MP2 installation.
6. The MP2XL design is almost identical to the MP2 other than being greater in length to accommodate the additional battery modules. Given the limited module propagation observed during UL 9540A unit level testing of the MP2 (seven cells went into runaway) the behavior is expected to be no different with the MP2XL. As such, a stand-alone UL9540A unit level fire test for the MP2XL was not performed. The UL 9540A unit level fire test results, described above for the MP2, can be applied to the MP2XL.
   a. Similarly, after reviewing the MP2 unit level fire test results and comparing the MP2 and MP2XL to one another, TÜV determined the MP2 UL 9540A unit level fire test results can be applied to the MP2XL and an additional UL 9540A unit level fire test for the MP2XL was not required for its listing.
7. Smaller capacity MP2/2XL cabinets, populated with less battery modules, would be expected to perform similarly given they are designed and constructed substantially similar (with the same cells, battery modules, fire safety features, etc.) than the larger capacity MP2/2XL cabinets that were tested as described in this report.
8. Additional findings based on the UL 9540A unit level fire test results, are as follows:
   a. None of the external fire detectors activated during the fire test (two multi-spectrum IR flame detectors and two thermal imagers). This result is expected, as no flaming was observed outside of the cabinet during the test; however, previous testing by Tesla on the MP1 has demonstrated that multi-spectrum IR flame detectors can detect a fire should flames exit the cabinet through the thermal roof.
   b. An integral fire suppression system or an external fire suppression system is not required to stop the spread of fire from cell to cell, module to module or MP2/2XL cabinet to cabinet when a near simultaneous failure of up to six cells occurs within the same battery module.
   c. Manual fire suppression (hose lines) is not required to stop the spread of fire from a MP2/2XL cabinet to adjacent MP2/2XL cabinets installed 6 in (150 mm) behind and to the sides when a near simultaneous failure of up to six cells occurs within the same battery module.
9. Additional findings based on internal testing and analysis performed by Tesla are as follows:
   a. Unit level products of combustion testing demonstrated that HF was only detected at trace levels (0.10 and 0.12 ppm) in two sampling locations approximately 20 ft upwind

and 5 ft downwind from the initiating MP2. This trace quantity was detected over the entire 2½ hour test duration (i.e., is the cumulative quantity measured) and is well below the HF IDLH value of 30 ppm. Note HF was not detected in the UL 9540A cell or module level vent gas constituents. In addition, unit level products of combustion testing found no traces of twenty-seven different metals, including lithium and mercury.

b. Destructive unit level testing demonstrated that the MP2/2XL is capable of safely failing in the extreme case of a catastrophic failure with one of its battery modules. The destructive unit level test results further validated the explosion control system and demonstrated that it can mitigate the deflagration hazard even with an extreme failure scenario (simultaneous failure of forty-eight cells). This destructive unit level test led to a slow progressing fire that burned for 6 hours and 40 minutes until flaming ceased. In addition, the fire failed to spread past the CIB and only half of the cabinet's battery modules became involved in the fire.

c. Fire modeling demonstrated that in the unlikely event of a fire, it would not propagate from one MP2/2XL cabinet to adjacent cabinets installed 6 inches behind, 6 inches to the side or 8 ft directly in front of the initiating MP2/2XL. This result was analyzed for both no wind and worst-case wind conditions where flames could tilt towards the MP2/2XL installed in front of the initiating MP2/2XL or could tilt towards the back MP2/2XL cabinet.

10. Based on a review of the MP2/2XL, its fire safety features, UL 9540A test results, additional internal MP2/2XL unit level fire testing and fire propagation modeling, the MP2/2XL can meet or exceed all the installation level codes and standards, such as the IFC and NFPA 855, required for outdoor, ground mounted BESS installations when installed in accordance with the MP2 and MP2XL DIM.

If you have any questions or comments, please do not hesitate to contact us.

Sincerely,
Fisher Engineering Inc.

Andrew Blum, PE, CFEI, CVFI
Senior Fire Protection Engineer

Reviewed by

Doug Fisher, PE, FSFPE
Principal Fire Protection Engineer

QUALIFICATIONS

Mr. Andrew Blum graduated from the University of Maryland with a Bachelor of Science and Master of Science degree in Fire Protection Engineering. His experience includes design, review, inspection, and analysis of fire protection system installations, fire hazard analysis, life safety/building code surveys, computer fire modeling, small and large-scale fire testing, interpretation and enforcement of fire/building codes, as well as fire/explosion investigations, and fire protection systems failure analysis/investigations.

Mr. Blum is a registered professional fire protection engineer and has extensive experience utilizing the National Fire Protection Association (NFPA) codes, standards, and recommended practices, model building and fire codes from the International Code Council (ICC) and product safety standards, such as UL standards and listings in his analyses. He has experience in performing and supervising small- to large-scale fire tests. These tests include firsthand fire testing experience with nationally and internationally accepted standards published by the NFPA, ASTM, ISO, UL, FM, and CFR. He also has specific expertise in fire-testing lithium-ion batteries used in consumer electronics/products, electric drive vehicles, in storage configurations and in BESS. This experience includes performing, analyzing, or reviewing (as a technical panelist) fire tests of lithium-ion batteries for the NFPA's Fire Protection Research Foundation.

Mr. Blum is a principal member on the technical committee on NFPA 855, *Standard for the Installation of Stationary Energy Storage Systems* and is an active member of the NFPA, ICC, ASTM, and Society of Fire Protection Engineers (SFPE). He has presented many times on the topic of lithium-ion batteries as it relates to fire safety and has published numerous papers/reports on the same subject, including lithium-ion BESS.

LIMITATIONS

At the request of Tesla, FEI performed an FPE analysis of their new BESS. The MP2/2XL is a ground mounted lithium-ion BESS with a storage capacity between approximately one and four MWh. It is meant for outdoor installations, mounted to the ground, for commercial and industrial applications. This FPE analysis included a review of the MP2/2XL, its construction, design, fire safety features, UL 9540A cell, module and unit level test data, additional internal unit level fire tests and fire propagation modeling. The scope of services performed during this analysis may not adequately address the needs of other users of this report, and any re-use of this report or its conclusions presented herein are at the sole risk of the user. The opinions and comments formulated during this assessment are based on observations and information available at the time of the analysis from the UL 9540A unit level fire test. No guarantee or warranty as to future life or performance of any reviewed condition is expressed or implied.

FISHER ENGINEERING

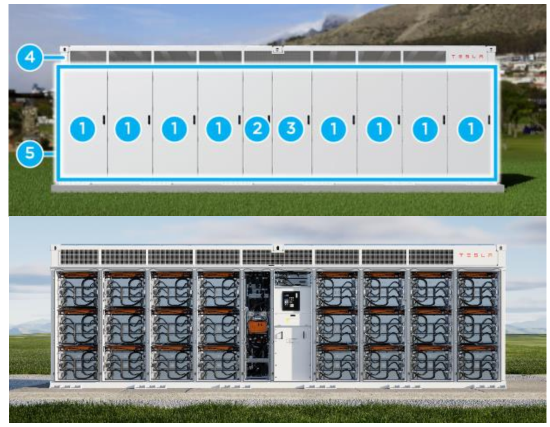
APPENDIX 1

Megapack 1 vs. Megapack 2/2XL Comparison

<table>
<tr><th>Megapack 1</th><th>Megapack 2</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">Cells and Battery Modules:</td></tr>
<tr><td>Cylindrical 2170 NMC</td><td>Prismatic LFP</td></tr>
<tr><td>1,000 Cells per Tray, 12 Cell Trays
12,000 Cells per Battery Module</td><td>112 Cells per Tray, 3 Cell Trays
336 Cells per Battery Module</td></tr>
<tr><td colspan="2">Each Module Equipped with an Integrated BMS</td></tr>
<tr><td colspan="2">Layout/Construction:</td></tr>
<tr><td colspan="2">Modular Cabinet Design, Not Occupiable</td></tr>
<tr><td colspan="2">Thermal Bay, Customer Interface Bay, IP66 Battery Module Bay, and Thermal Roof</td></tr>
<tr><td>23.5 x 5.4 x 8.3 ft</td><td>23.75 x 5.4 x 8.2 ft</td></tr>
<tr><td>Up to 17 Battery Modules</td><td>Up to 19 Battery Modules</td></tr>
<tr><td colspan="2">Safety Features:</td></tr>
<tr><td colspan="2">Thermal Management System:
Closed Loop Liquid Coolant System and R-134A Refrigerant</td></tr>
<tr><td colspan="2">Customer Interface Bay:
User-accessible Area Designed for Operation and Servicing</td></tr>
<tr><td colspan="2">Electrical Fault Protection:
Passive and Active Safety Control Mechanisms (Fuses, Circuit Interrupters, Pyrotechnic Fuse) Installed within the Battery Module Circuits and Distribution Circuit</td></tr>
<tr><td colspan="2">Autonomous BMS with 24/7 Remote Monitoring by Tesla Operation Facilities</td></tr>
<tr><td colspan="2">No Integral Fire Detection or Fire Suppression System</td></tr>
<tr><td>Thermal Insulation</td><td>No Thermal Insulation[1]</td></tr>
<tr><td colspan="2">Explosion Control System:</td></tr>
<tr><td>33 Overpressure Vents, 8 Sparkers</td><td>22 Overpressure Vents, 12 Sparkers[1]</td></tr>
</table>

[1] Modified explosion control system and thermal insulation to account for the different cells (NMC vs. LFP) utilized in the MP2.

Megapack 1	Megapack 2
 	 
Listings and Certifications	
Component and BESS Design Certifications/Listings (UL9540 and IEC 62933-5-2)	
Installation Level Codes and Standards (IFC and NFPA 855)	
UL 9540A Unit Level Test Results	
Internally Heated Cells: **Led to Cascading Thermal Runaway of All Cells**	**Internally Heated Cells:** **Led to Thermal Runaway of One Additional Cell**
Fire Propagation: **Consumed the Entire Cabinet**	**No Fire Propagation:** **No Evidence of Sustained Flaming**
Flames Observed Outside the Cabinet Exiting via the Thermal Roof	**No Flames Observed Outside the Cabinet**
Heat Fluxes Recorded at Distances of up to 20-30 ft From the Cabinet	**No Heat Fluxes Recorded at Distances of up to 20-30 ft From the Cabinet**
Explosion hazards, including but not limited to, observations of a deflagration, projectiles, flying debris, detonation, or other explosive discharge of gases were not observed.	
No Fire Propagation to Adjacent Cabinets at 6-inch (150 mm) Spacing to the Sides and Behind	
No Fire Propagation to Adjacent Cabinets at 8 ft (2.44 m) Spacing Directly in Front	
Integral Fire Suppression Not Required to Stop Cabinet to Cabinet Fire Spread	
Manual Fire Suppression (Hose Lines) Not Required to Stop Cabinet to Cabinet Fire Spread	
No Free-Flowing Liquid Runoff Observed After the Test	

Megapack 2	Megapack 2XL
	
Cells and Battery Modules:	
Same Cells, Battery Modules and Integrated BMS	
Layout/Construction:	
Same Modular Cabinet Design, Not Occupiable with the Same or Substantially Similar Thermal Bay, Customer Interface Bay, IP66 Battery Module Bay, and Thermal Roof	
23.8 x 5.4 x 8.2 ft	**28.9 x 5.4 x 9.2 ft**
Up to 19 Battery Modules (3,100.8 kWh)	**Up to 24 Battery Modules (3,916.8 kWh)**
Safety Features:	
Same or Substantially Similar Thermal Management System, Customer Interface, Electrical Fault Protections and Autonomous BMS with 24/7 Remote Monitoring by Tesla Operation Facilities	
No Integral Fire Detection or Fire Suppression System	
Explosion Control System:	
22 Overpressure Vents, 12 Sparkers	**26 Overpressure Vents, 12 Sparkers**
Listings and Certifications	
Has the Same Component and BESS Design Certifications/Listings (UL 9540 and IEC 62933-5-2)	
Meets the Same Installation Level Codes and Standards (IFC and NFPA 855)	
UL 9540A Unit Level Test Results	
Same UL 9540A Fire Test Results: No Fire Propagation or Evidence of Sustained Flaming, No Flames Observed Outside the Cabinet, No Fire Propagation to Adjacent Cabinets, Integral Fire Suppression or Manual Fire Suppression (Hose Lines) Not Required to Stop Cabinet to Cabinet Fire Spread, No Observations of Explosion Hazards, No Free-Flowing Liquid Runoff Observed After the Test	

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APPENDIX 2

Heat Flux Plots

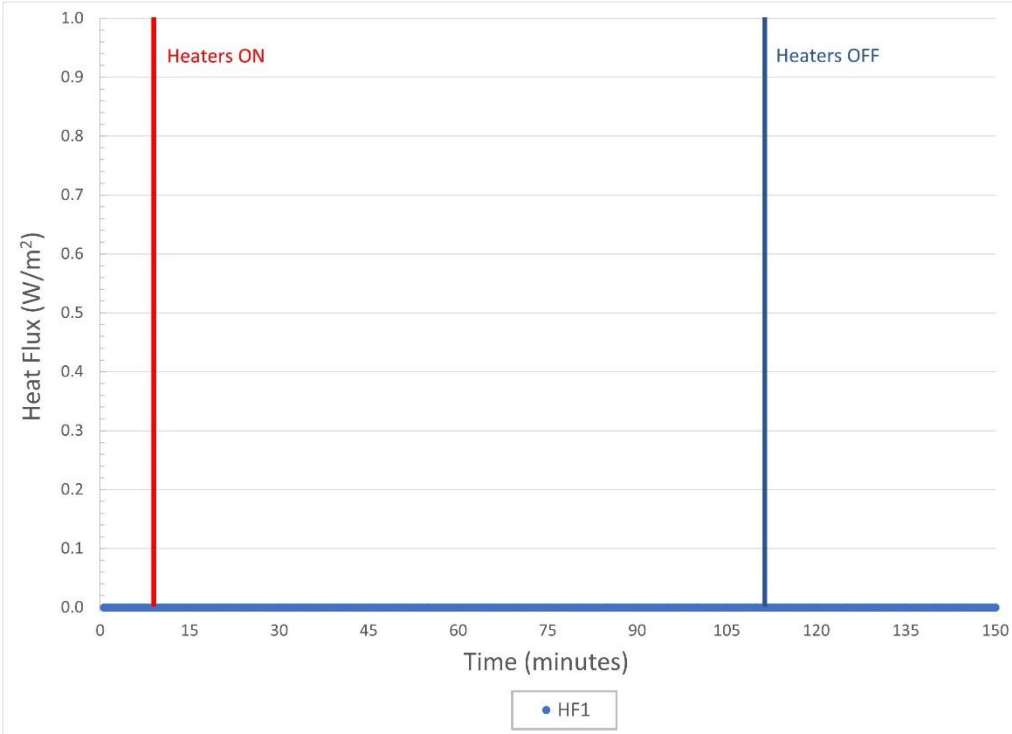

Figure 28 HF1 measurements recorded during UL 9540A unit level fire testing.

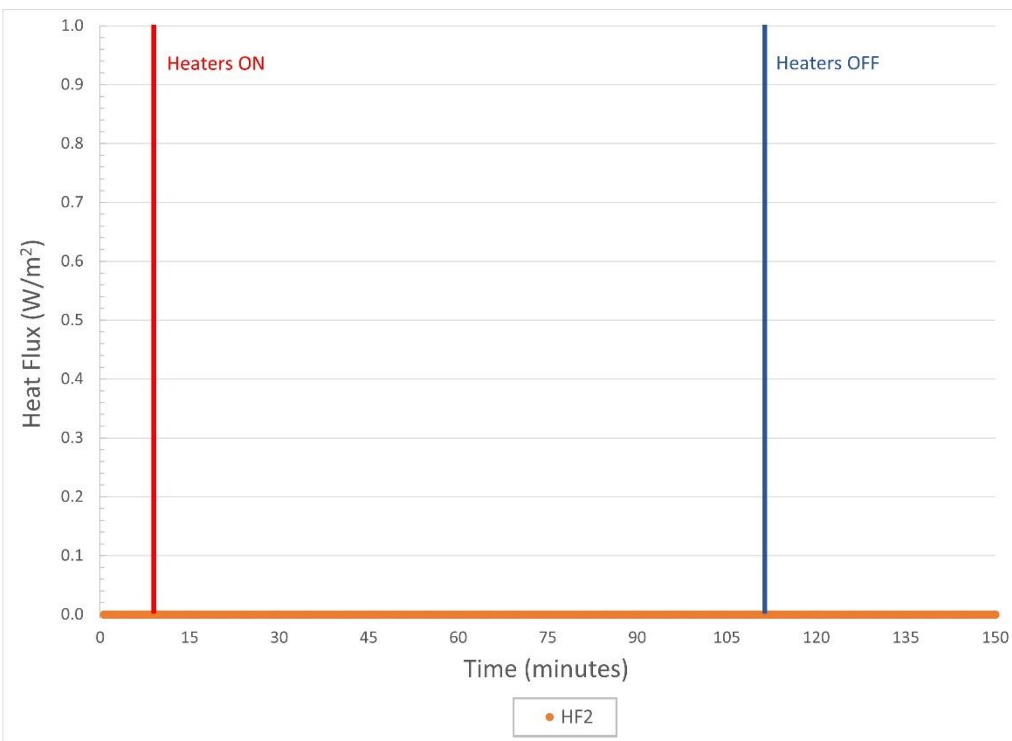

Figure 29 HF2 measurements recorded during UL 9540A unit level fire testing.

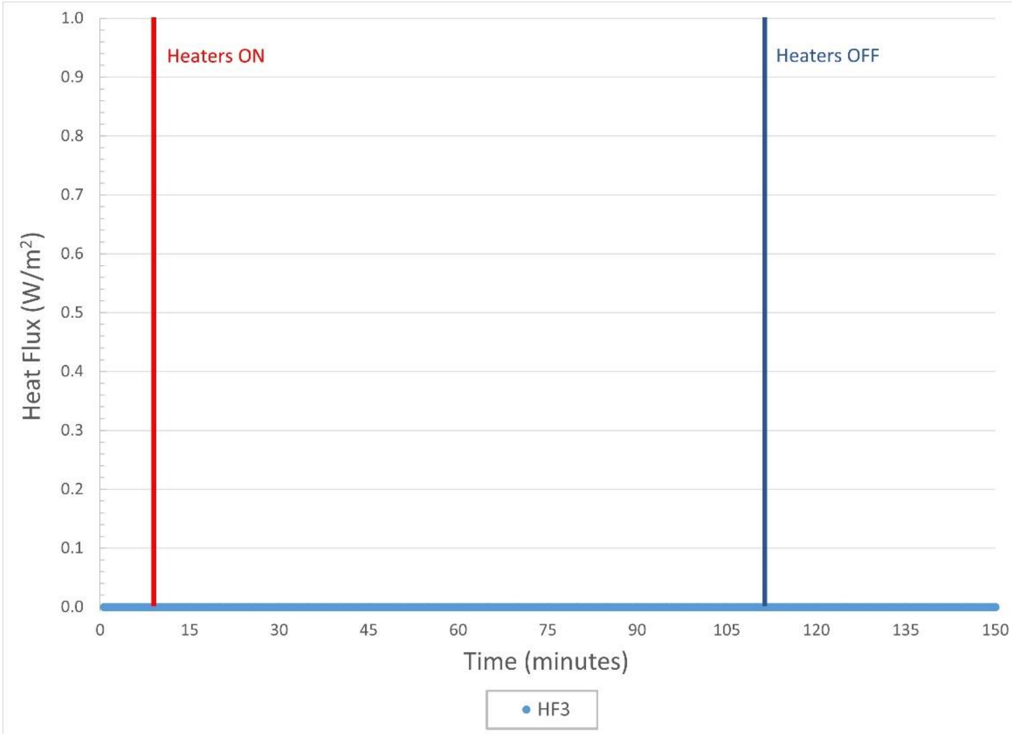

Figure 30 HF3 measurements recorded during UL 9540A unit level fire testing.

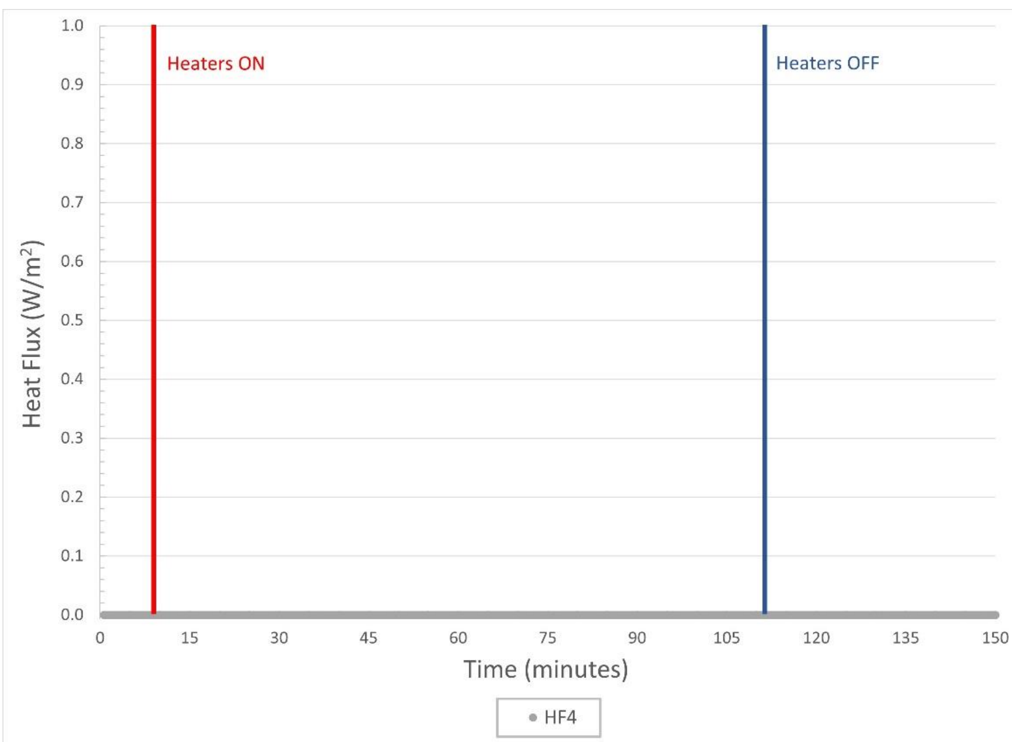

Figure 31 HF4 measurements recorded during UL 9540A unit level fire testing.

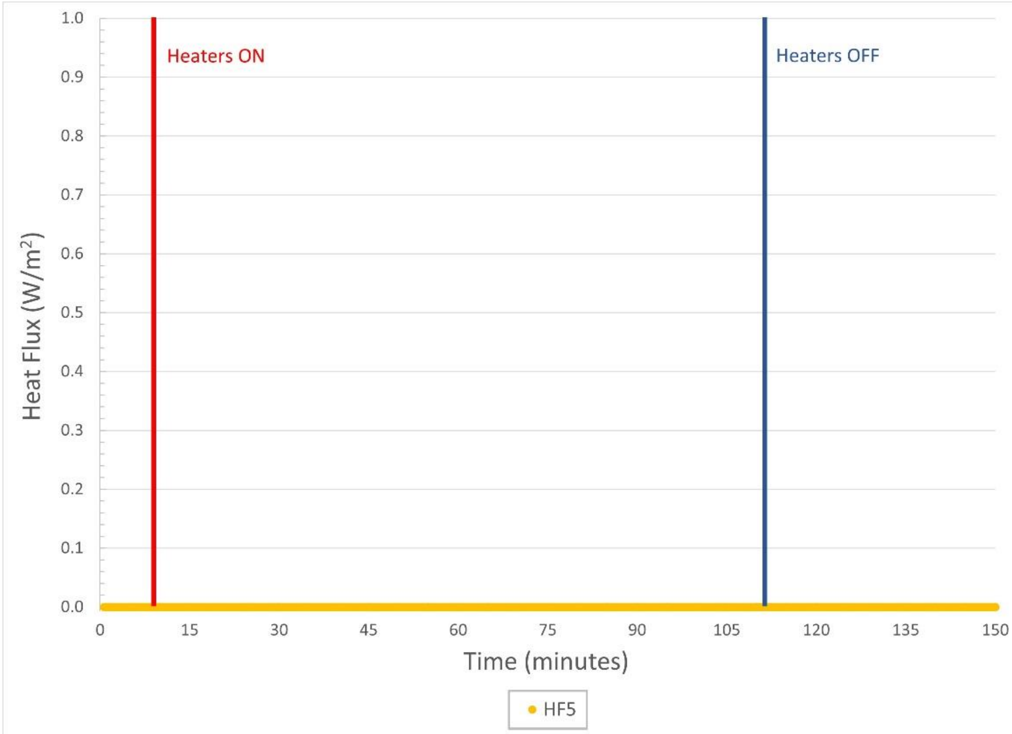

Figure 32 HF5 measurements recorded during UL 9540A unit level fire testing.

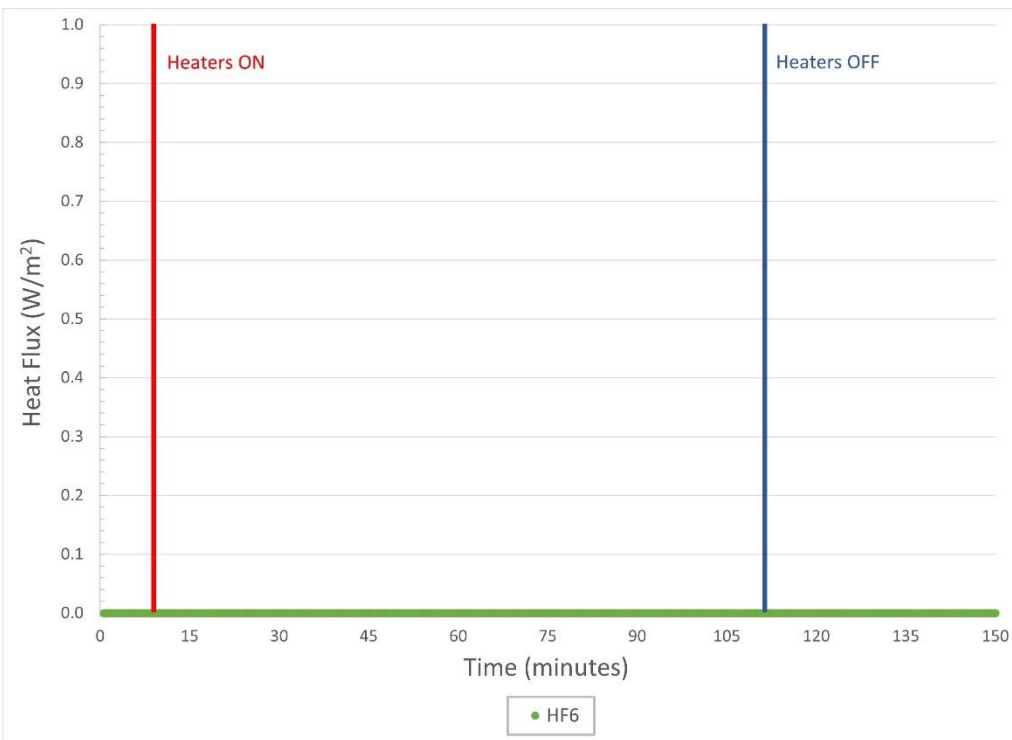

Figure 33 HF6 measurements recorded during UL 9540A unit level fire testing.

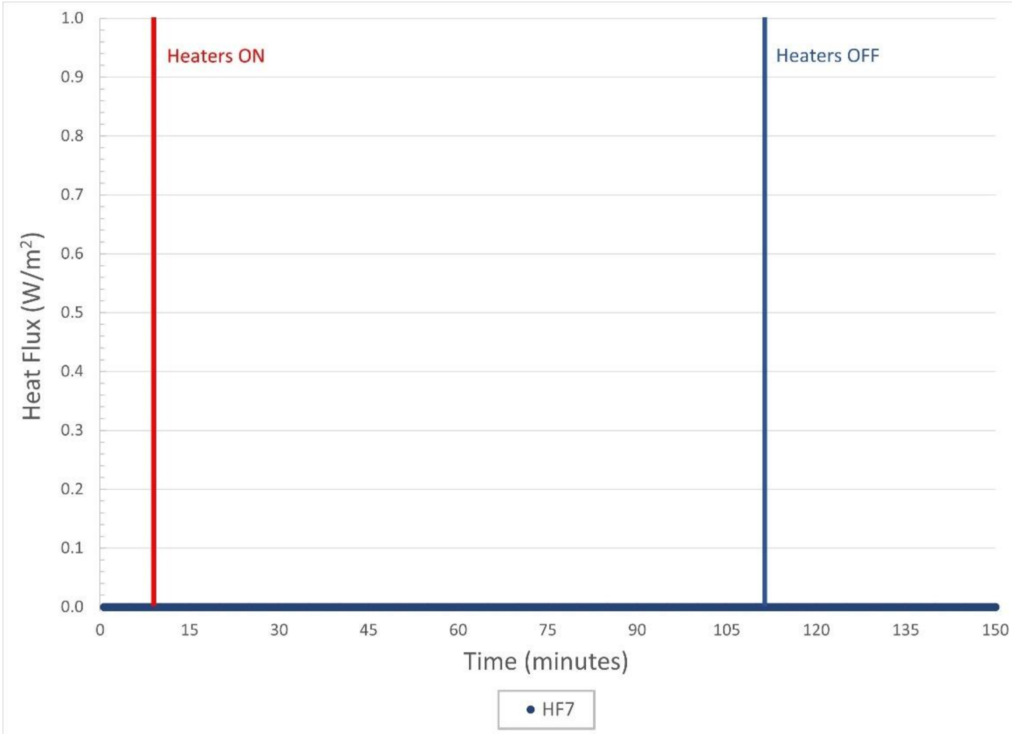

Figure 34 HF7 measurements recorded during UL 9540A unit level fire testing.