Marici
Plume Study

HD-24045-Marici-Plume-1.3

August 14, 2025

Prepared for:

Marici Project LLC

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1 Executive Summary

A plume study was conducted for the Marici BESS (battery energy storage system) site to determine toxicity and flammability hazards posed to nearby areas during possible battery failure scenarios. The study considers toxic species that can be released by Li-ion batteries during thermal failures. Accumulation of flammable battery vent gas outside a failing BESS enclosure is also considered. Computational fluid dynamics (CFD) models were utilized to simulate plumes resulting from theoretical battery failure scenarios. The modeled scenarios considered (1) a non-fire scenario in which battery vent gas is released, (2) a small fire scenario, and (3) a large fire scenario. Low and high wind conditions were evaluated based on nearby meteorological data.

Based on the modeled scenarios, toxic gas species concentrations 2 m (6.6 ft) from ground level and flammable gas accumulation surrounding the BESS enclosure were estimated using Fire Dynamics Simulator (FDS), which is a CFD software developed by the National Institute of Standards and Technology (NIST) for fire modeling. This software has also been extensively validated for gas dispersion. A summary of the findings of the study is as follows:

- The large fire, high wind condition was found to result in the highest battery plume concentrations 2 m (6.6 ft) above ground level for much of the modeled distance downwind of the enclosures. The modeled average carbon monoxide concentrations may cause serious health effects (exceed the AEGL-2 level) up to approximately 5.8 m (19 ft) from the unit in a large fire scenario with high winds. The 99th percentile wind speed of 15 mph was used to model the high wind scenarios for the Marici site. For first responders who may be operating within this region, guidance for appropriate personal protective equipment (PPE) can be found in relevant Emergency Response Protocol (ERP) documents.
- Modeled carbon monoxide levels may exceed the AEGL-2 limit (150 ppm) at 2 m (6.6 ft) above ground level beyond the masonry wall in high wind conditions in areas where the wall is less than 5.8 m (19 ft) from the BESS enclosures. Concentrations at the AEGL-2 level may cause serious health effects.
- The high-wind gas release scenarios (with no fire) resulted in the greatest modeled distances for the OSHA PEL (8-hour average) and EPA NAAQ (1-hr) levels of carbon monoxide. The worst-case distances were 42 ft and 50 ft, respectively.
- Modeled unit gas release scenarios with an active NFPA 69 ventilation system did not result in flammable regions of battery vent gas outside the enclosure. The ventilation system diluted the gas such that it remained below the lower flammability limit (LFL).
- Over 600 houses are located within a half-mile of the Marici site. The nearest residential property is 111 ft away from the BESS enclosure at the edge of the site. At these distances, CO levels are expected to be below the EPA NAAQ (1-hr) level of 35 ppm.
- Hydrogen fluoride (HF) levels were not evaluated as HF was not measured during the UL 9540A testing for this system. HF has been measured in laboratory-scale battery thermal runaway tests; however, the range of reported measurements is wide. Thus, hydrogen fluoride may be a risk, but the exact magnitude of this risk is unknown. Hydrogen fluoride is highly reactive with a range of materials including metals and various organic compounds. It is unclear whether substantial HF concentrations persist at a distance away from larger module, rack, and ESS scales. HF can also be emitted from the combustion of plastic components in the ESS, such as wiring insulation and module or rack enclosure casings. Although these plastics are commonly fire-retarded, fire-retardant plastics can be overwhelmed if the severity of the fire is sufficiently large. Similar fire-retardant plastics are commonly found in non-battery applications and may pose similar emission hazards during fire conditions.

- Other toxic organic gases, such as volatile organic compounds (VOCs) make up only trace amounts of the battery vent gas. VOC release quantities are too small to exceed hazardous levels at any distance from the unit.

Note that this Executive Summary does not contain all of Hazard Dynamics' technical evaluations, analyses, conclusions, and recommendations. Hence, the main body of this report is at all times the controlling document.

2 Introduction

This report describes the results of a plume dispersion study conducted for the Marici battery energy storage system (BESS), which is being built in City of Industry, California. The Marici site uses the Sungrow PowerTitan 2.0 for lithium-ion battery energy storage. The purpose of a plume study is to identify and quantify potential risks associated with toxic and flammable gases produced by a battery energy storage system (BESS) under abnormal conditions.

Where appropriate data is unavailable, reasonable engineering assumptions will be made. These assumptions will be drawn from the available body of technical literature. This analysis was conducted using a set of probable worst-case scenarios based upon available test data such as UL 9540A reports and includes up to a fully-involved fire in a single unit.

This report will first provide background on the toxicity hazards of lithium-ion battery systems. Next, it will review the details of the Marici site as well as the energy storage system itself. Finally, the report will evaluate possible toxic and flammable gas scenarios and their consequences.

This analysis relies on the following information:

- Plans for the Marici site [1]
- Specifications for the PowerTitan 2.0 system [2]
- UL 9540A Cell test report for cell model L173F314, CSA Group – Kunshan Branch report number 80184345 dated 11/17/2023 [3]
- UL 9540A Module test report for module model P1044AL-AHA, TUVRheinland (Shanghai) Co., Ltd. report number CN23P68X 001 dated 12/16/2023 [4]
- UL 9540A Unit test report for unit model applies to various R0417BL and R0835BL unit configurations, TUVRheinland (Shanghai) Co., Ltd. report number CN23JPBV 001 dated 12/16/2023 [5]
- CFD Heat Flux Modeling Report and NFPA 69 CFD Analysis for the Sungrow PowerTitan 2.0 [6] [7]

3 Background on Lithium-Ion ESS Toxicity Hazards

3.1 Toxicity Hazards

Toxicity hazards may exist alone or in combination with fire and explosion hazards. A significant amount of the gas released during thermal runaway is carbon monoxide (CO), which is toxic. Depending on the conditions, the combustion of battery gases may burn off some carbon monoxide or create additional carbon monoxide from partially reacted hydrocarbons. Smaller amounts of other toxic gases may also be released depending on the cell, whether the gases burn, and if water or other suppression agents are added. Experiments show that lithium-ion cells in thermal runaway may release hydrogen fluoride (HF), hydrogen chloride (HCl), hydrogen cyanide (HCN), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and other gases [8]. When the gases burn, some of the toxic components may be consumed, although others may be generated. Smoke from many fires, including battery fires, is considered hazardous. Smoke typically includes asphyxiant gases, irritant toxic gases, and particulate matter. The introduction of water to a fire may change the composition of the smoke and can create water runoff, which may also contain hazardous substances. The use of other fire suppression agents may also alter the toxic release profile [9].

3.2 Toxic Gases of Interest

Abuse and failure of lithium-ion cells may result in gas production inside of the cells. When enough gas is produced, a safety vent may open, or the cell package may rupture. The gas mixture released is flammable and toxic and is primarily made up of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), and an assortment of hydrocarbons. If ignited, the combustion of these gases can lead to a fire or an explosion.

When a lithium-ion cell is exposed to high temperatures such as those due to fire exposure or propagating thermal runaway, it produces toxic compounds. Plastic contained in the battery system may contribute to these toxic combustion products. Such products may include carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), hydrogen chloride (HCl), and hydrogen fluoride (HF). The quantity of HF produced is related to the electrolyte solvent and the chemical reactions initiated. CO_2, H_2, and CH_4 are asphyxiant gases, or gases that can cause unconsciousness or death by suffocation because they displace oxygen in the air [8]. CO blocks the transport of oxygen by sticking to the hemoglobin in red blood cells. Poisoning by CO is often the major cause of death related to fire in which burns are not present [10]. Hydrogen cyanide (HCN) obstructs the function of mitochondria so that oxygen cannot be absorbed into the cells. Irritant gases include HF, HCl, SO_2, and NO_2. These gases have a toxic and irritating effect that can be significant even at very low concentrations. HCl is corrosive, highly irritating, and can cause severe injury to the respiratory tract if inhaled. SO_2 is extremely irritating and can form sulfurous acid when in contact with moisture. NO_2 and NO are especially irritating to the respiratory tract and lungs even at low concentrations. None of these irritants can be absorbed through the skin. HF, on the other hand, is not only severely irritating to the respiratory tract but can also penetrate skin and other tissues as the fluoride ion. When HF comes into contact with moisture, it can form hydrofluoric acid [11].

In evaluating harmful levels of toxic gases, it is helpful to reference levels known as IDLH (immediately dangerous to life or health) and AEGLs (acute exposure guideline levels). According to the Code of Federal Regulations, IDLH is defined as a concentration of any toxic, corrosive, or asphyxiant substance that poses an immediate threat to life, would cause irreversible or delayed adverse health effects, or would interfere with an individual's ability to escape from a dangerous atmosphere [11]. IDLH values were developed to address occupational exposures to chemicals and to help protect workers from acute or short-term exposures to high concentrations of some airborne chemicals that could result in undesirable health outcomes [12]. The AEGLs were developed by the EPA to define the health effects of a once-in-a-lifetime exposure to airborne chemicals. AEGLs are used by emergency responders when dealing with major chemical leaks, spills, or other exposures. AEGL concentrations are provided for different exposure times and health effect levels. Level 1 is discomfort or irritation, Level 2 is the onset of irreversible or serious health effects, and Level 3 describes life-threatening health effects [13]. Toxic gases related to battery energy storage systems along with their IDLH, AEGL-2, and AEGL-1 concentrations are shown in Table 1. The AEGL values presented in the table are based on an exposure time of 30 minutes, which is characteristic of how long someone evacuating might be exposed to a substance.

Table 1: Toxic chemicals that can be present during battery failure and concentrations of interest. The AEGL values shown are for a 30-minute exposure. (NR = Not recommended due to insufficient data)

Chemical	IDLH (ppm)	AEGL-3 (ppm)	AEGL-2 (ppm)	AEGL-1 (ppm)
Carbon Monoxide (CO)	1,200	600	150	NR
Carbon Dioxide (CO_2)	40,000	NR	NR	NR
Hydrogen Chloride (HCl)	50	210	43	1.8
Hydrogen Cyanide (HCN)	50	21	10	2.5
Hydrogen Fluoride (HF)	30	62	34	1
Nitrogen Dioxide (NO_2)	13	25	15	0.50
Nitric Oxide (NO)	100	NR	NR	NR
Sulfur Dioxide (SO_2)	100	30	0.75	0.20
Benzene (C_6H_6)	500	5,600	1,100	73
Toluene ($C_6H_5CH_3$)	500	5,200	760	67

4 Site and System Descriptions

4.1 Site Description

The Marici project is a lithium-ion BESS facility that will be located in City of Industry, California. The site will be about 17 miles east of downtown Los Angeles. The location of the site can be seen in Figure 1.

Figure 1: A map showing the location of the Marici site. This image was taken from Google Maps 2025.

The Marici project includes lithium-ion battery energy storage equipment made by Sungrow. Over 600 houses are located within a half-mile of the Marici site. The nearest residential property is 111 ft away from the BESS enclosure at the edge of the site. The site and its close surroundings are shown in Figure 2. Nearby exposures and their approximate distances from the BESS are also shown in Figure 2.

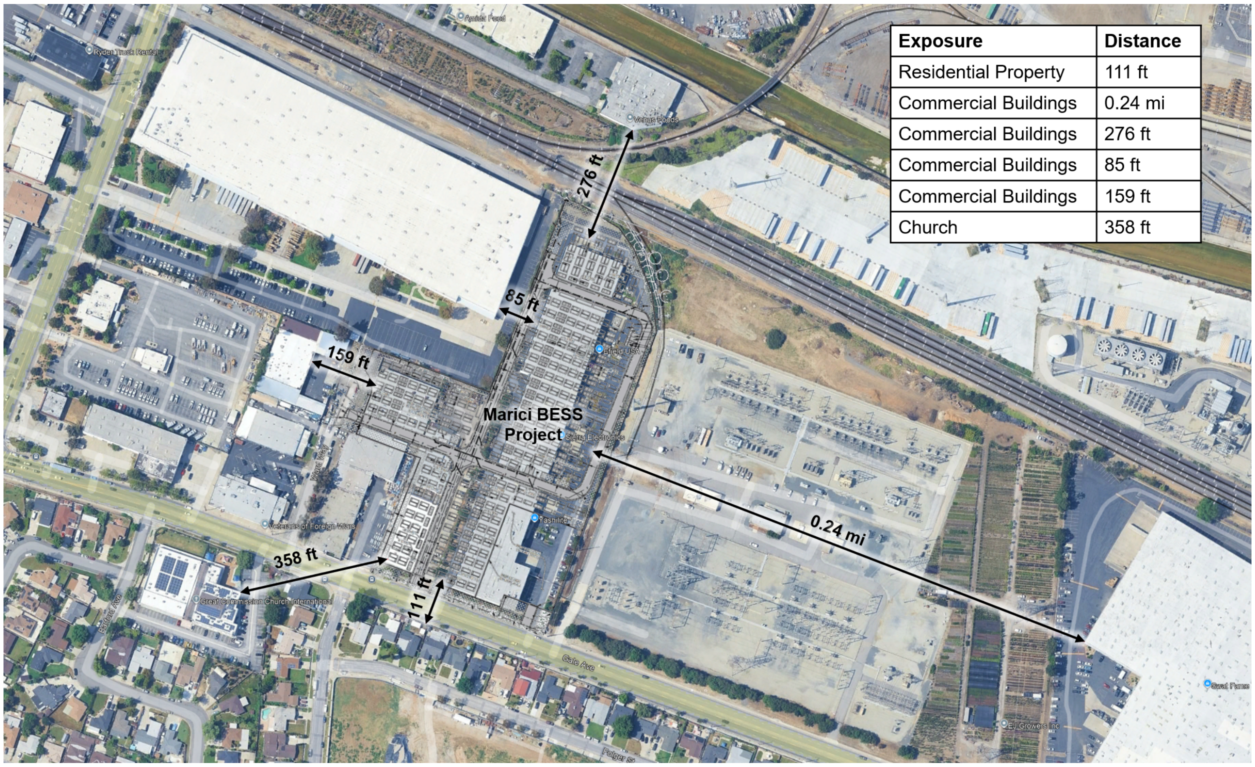

Figure 2: A satellite view of the Marici site location and its surroundings with the site drawing overlaid. The distances shown are measured from the nearest BESS enclosure. This image was taken from Google Earth 2025.

4.1.1 Typical Wind Conditions

In case of a toxic gas release, it is expected that the impacted area would be downwind of the site. The closest weather station for historical data is the San Gabriel Valley Airport site. According to historical wind information from 1985-2024, the prevailing winds generally come from the south-southwest (see Figure 3). The average wind speed is 6.9 mph or 3.08 m/s. Peak wind speeds may exceed 20 mph or 8.9 m/s approximately 0.284% of the time. Conditions are calm 20.1% of the time [14]. Because only a small percentage of winds exceed 20 mph, wind data was further analyzed to find the 99th percentile wind speed for use in the plume model. This wind speed was found to be 15 mph or 6.7 m/s.

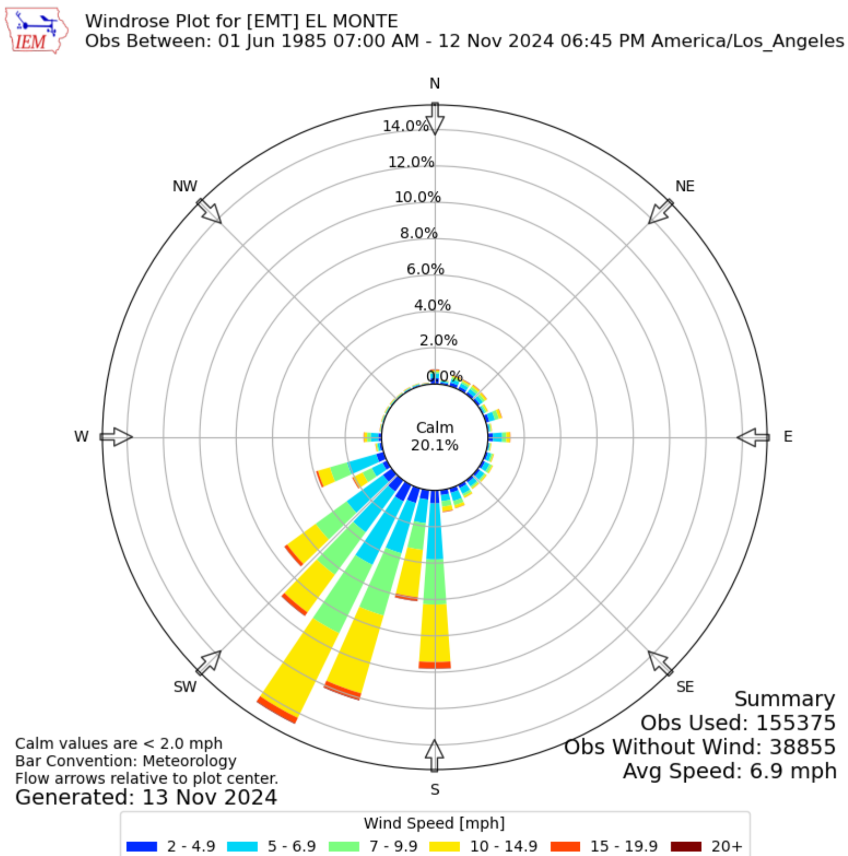

Figure 3: The wind rose for the San Gabriel Valley Airport weather station, which is the closest available station to the Marici site. This image was taken from the Iowa State University Iowa Environmental Mesonet website [14].

4.2 Energy Storage System Description

The Marici project uses modular outdoor-rated PowerTitan 2.0 battery units made by Sungrow. These units contain lithium-ion batteries installed in racks inside the enclosure. Each enclosure contains 6 racks with 8 modules each, for a total of 48 liquid-cooled battery modules. A PCS is underneath each rack [6]. The PowerTitan 2.0 includes a vent panel, heat and smoke detectors, a sound beacon, ventilation system, and flammable gas detector [2]. A PowerTitan 2.0 enclosure is shown in Figure 4.

Figure 4: An image of a Sungrow PowerTitan 2.0 battery storage system [2] [5].

The PowerTitan 2.0 enclosures include an NFPA 69 ventilation system to expel battery vent gas in case of cell failure. This system is designed to prevent an explosive atmosphere. An inlet louver is located on the left side of the enclosure near the bottom, and an exhaust fan is located on top of the enclosure near the right side (see Figure 5). The exhaust fan activates upon detection of hydrogen gas and expels air and vent gas at a rate of 750 m^3/h [7].

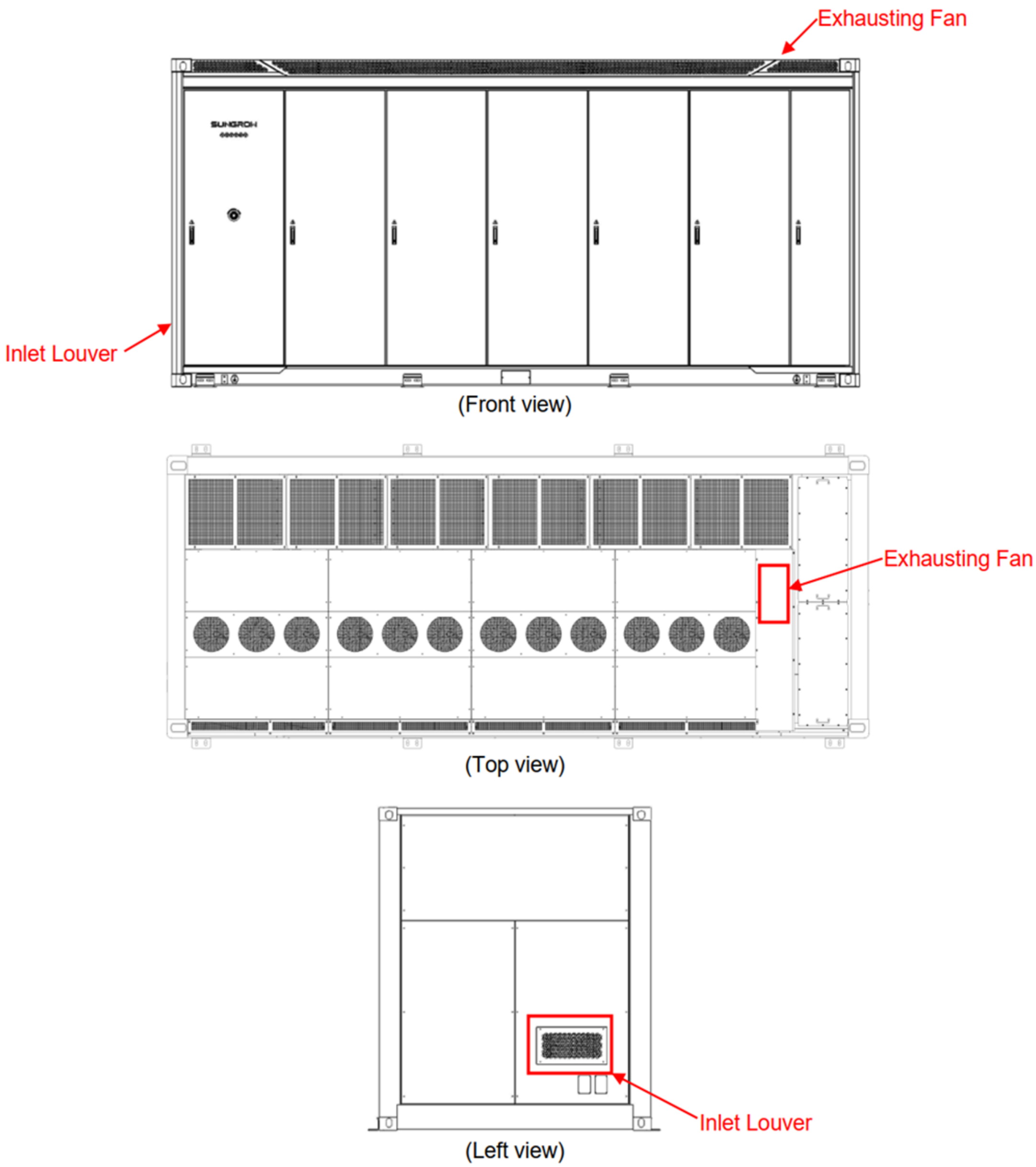

Figure 5: The configuration of the NFPA 69 ventilation system on the PowerTitan 2.0 enclosure [7].

The Marici site will consist of 480 enclosures [1]. The site also includes power conversion systems and other equipment. Figure 6 shows the planned layout of the site.

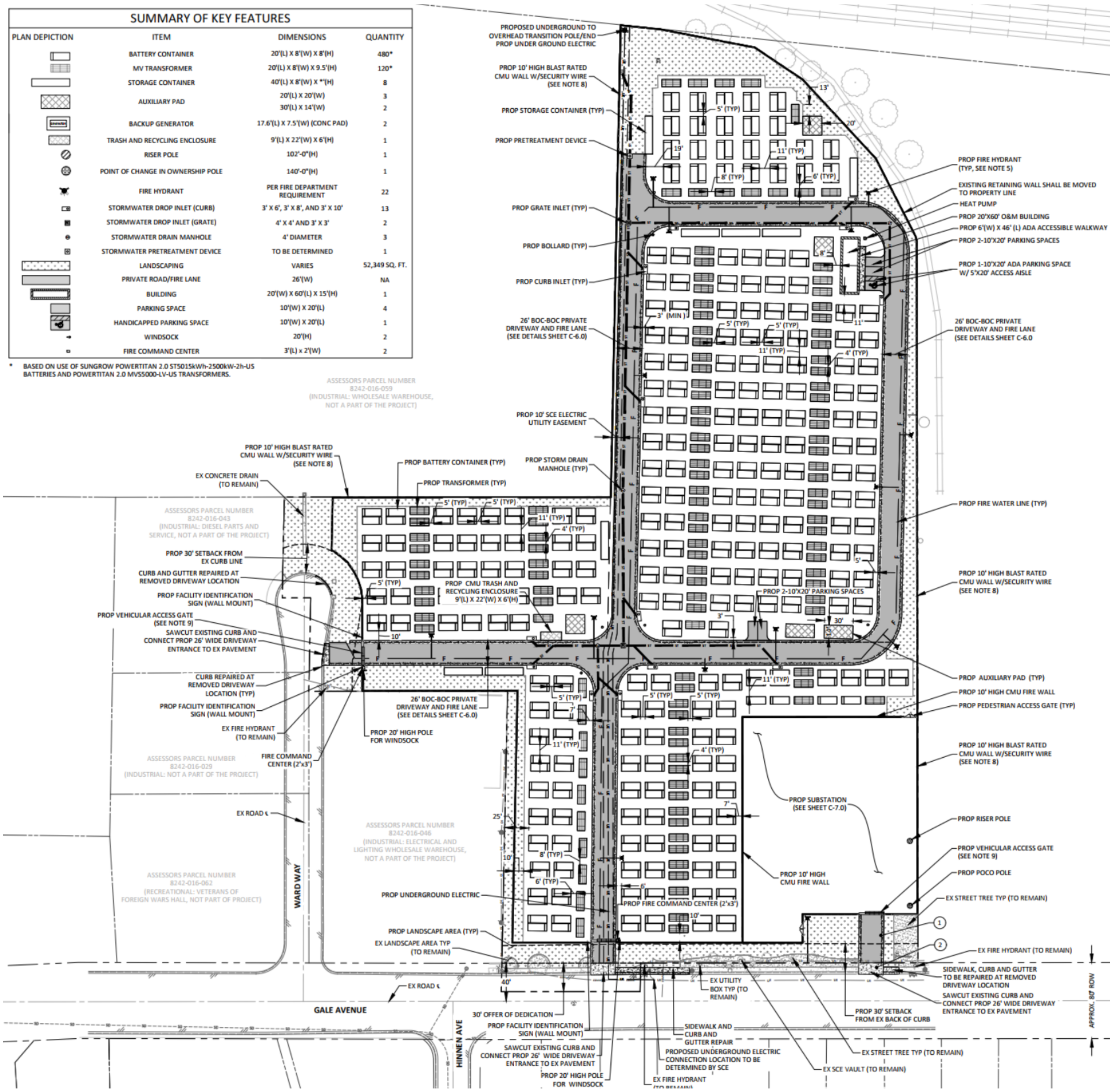

Figure 6: An engineering drawing indicating the planned layout of the Marici site, including the battery enclosures, power conversion systems, and other equipment [1].

5 UL 9540A Test Results

This analysis is based on test data from UL 9540A cell, module, and unit test results. During this testing, a cell is forced into thermal runaway while the outcome is observed. Gases released from the battery or batteries during thermal runaway are captured and analyzed for select chemical species. Depending on the outcome of cell-level testing, additional testing at the module level and full unit level may also be required. For this plume analysis, UL 9540A data from cell-level [3], module-level [4], and unit-level [5] testing was reviewed. The results of these tests are described in Sections 5.1-5.3.

Since UL 9540A is primarily concerned with fire and explosion hazards, typical UL 9540A gas measurements are focused on major combustible gases and combustion products, such as hydrogen, carbon monoxide, carbon dioxide, and various hydrocarbons. Typically, carbon monoxide is the most significant toxicity hazard among the measured gases due to a comparatively low IDLH value and relative abundance in most battery gas. The UL 9540A test report for the CALB Group Co., Ltd. cells indicates that 192 L of gas was captured from a single cell. Of the gas captured, 13.924% by volume was carbon monoxide. This information, along with the remaining composition information, is listed in Table 3.

Cell-level gas composition information is collected by failing an individual cell inside of a sealed pressure vessel that is filled with an inert gas to prevent combustion. This method allows for the capture of the entire volume of emitted gas. Gas compositions from cell experiments are usually measured using a gas chromatograph (GC), which is typically more accurate than measurements taken from exhaust hoods during module and unit testing.

5.1 Cell Test

The system under consideration is comprised of CALB Group Co., Ltd. L173F314 cells, which are 314 Ahr lithium-ion LFP cells [3]. This cell was tested using the UL 9540A method. The results are given in the CSA Group – Kunshan Branch report 80184345 dated 11/17/2023. Figure 7 shows a cell during testing.

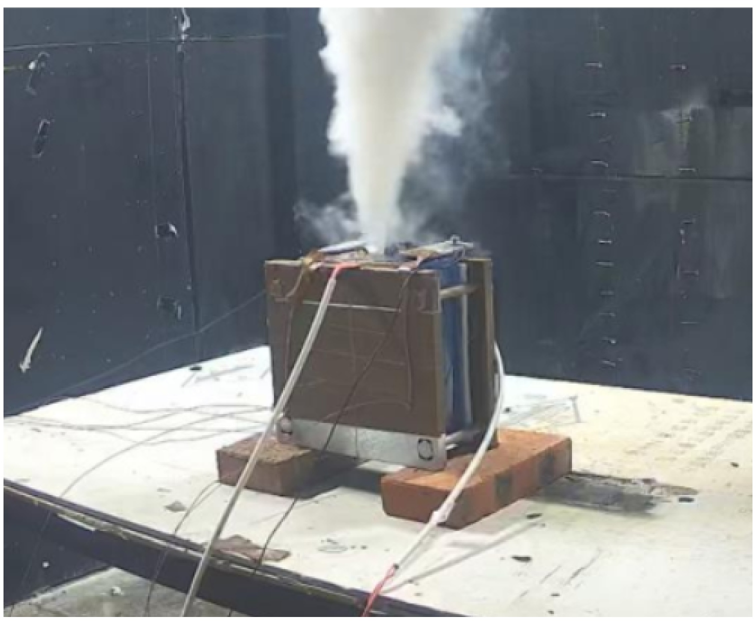

Figure 7: A CALB Group Co., Ltd. L173F314 cell during testing. This image was taken from the UL 9540A cell-level test report [3].

For UL 9540A testing, the L173F314 cells were heated until failure occurred. Cell details and results from UL 9540A testing are provided in Table 2.

The UL 9540A cell report showed that the cells go into thermal runaway and release a mixture of flammable gases when heated externally until failure. The vent gas composition from the UL 9540A cell report is listed in Table 3.

Table 2: Key cell properties from the UL 9540A cell test [3].

Parameter	Value
Cell Manufacturer	CALB Group Co., Ltd.
Cell Model	L173F314
Cell Chemistry	LFP
Cell Nominal Voltage	3.2 V
Cell Capacity	314 Ahr
Volume of Gas Released	192 L
Lower Flammability Limit (LFL) at ambient temperature	6.2%
Lower Flammability Limit (LFL) at venting temperature	5.6%
Burning Velocity (Su)	63.8 cm/s
Maximum Pressure (P_{max})	0.68 MPa

Table 3: The gas composition from the UL 9540A cell test [3]. Model Volume Percent will be addressed in Section 6 later in this document.

Name	Formula	Experimental Volume Percent	Model Volume Percent
Carbon Monoxide	CO	13.924	13.924
Carbon Dioxide	$CO2$	27.237	27.237
Hydrogen	$H2$	44.925	44.925
Methane	$CH4$	6.421	6.421
Acetylene	$C2H2$	0.339	0
Ethylene	$C2H4$	3.827	3.827
Ethane	$C2H6$	0.996	0.996
Propylene	$C3H6$	1.227	0
Propane	$C3H8$	0.322	2.670
C4 Total	$C4H10$	0.651	0
C5 Total	$C5H12$	0.131	0

5.2 Module Test

The CALB Group Co., Ltd. cells are located inside of module model P1044AL-AHA. A module was also tested using the UL 9540A method, and the results can be found in TUVRheinland (Shanghai) Co., Ltd. test report CN23P68X 001 dated 12/16/2023. Each module contains 104 cells in a 104S configuration [4]. Multiple thermocouples were attached for testing as seen in Figure 8.

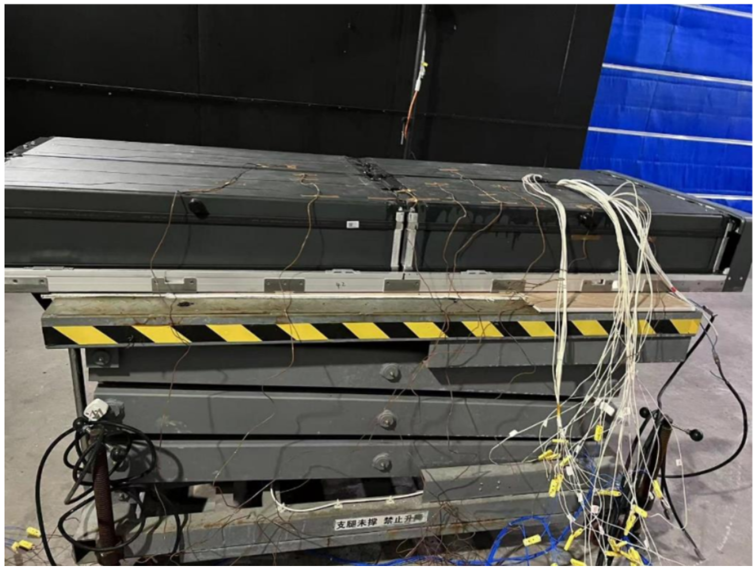

Figure 8: A module prepared for the UL 9540A test. This image was taken from the UL 9540A module-level test report [4].

Heaters were placed between cells 2, 3, and 4 in submodule 1, which was chosen due to its central location within the module. A diagram of the module construction is shown in Figure 9, and the locations of the thermocouples and initiating cells and can be seen in Figure 10. The temperature time history for the test is shown in Figure 11.

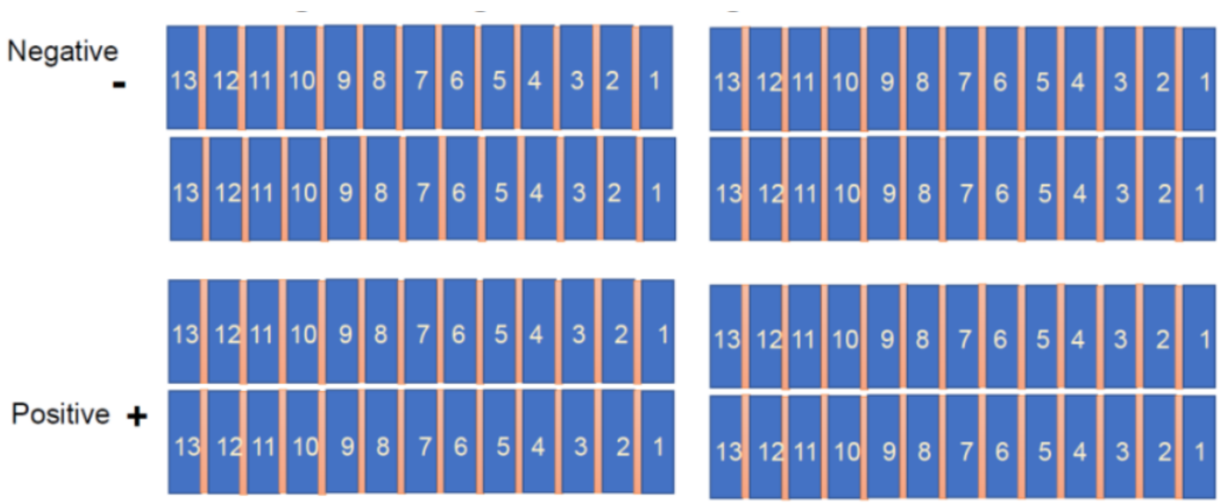

Figure 9: A diagram of the P1044AL-AHA module. This image was taken from the UL 9540A module-level test report [4].

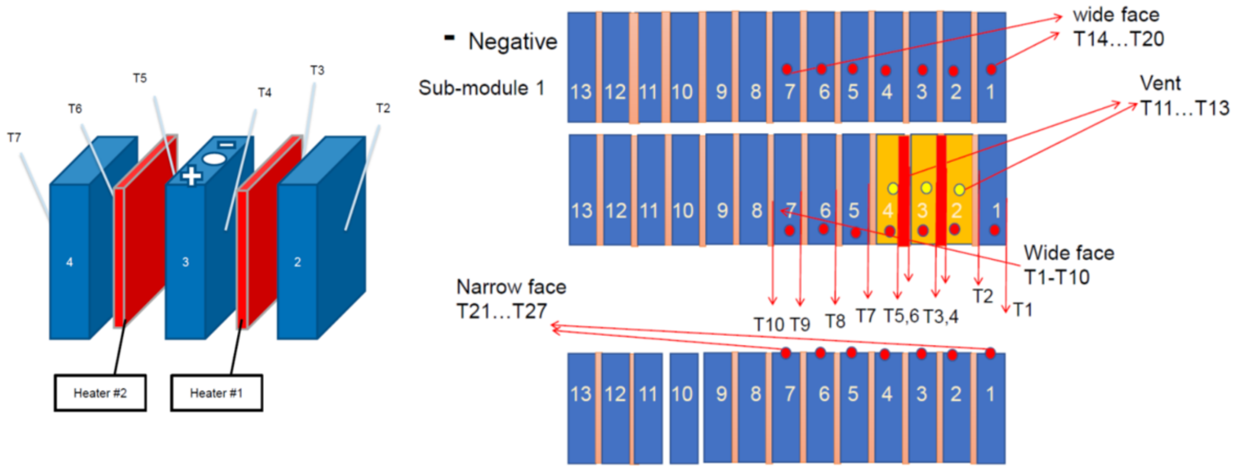

Figure 10: A diagram of the module setup for the UL 9540A test. This image was taken from the UL 9540A module-level test report [4].

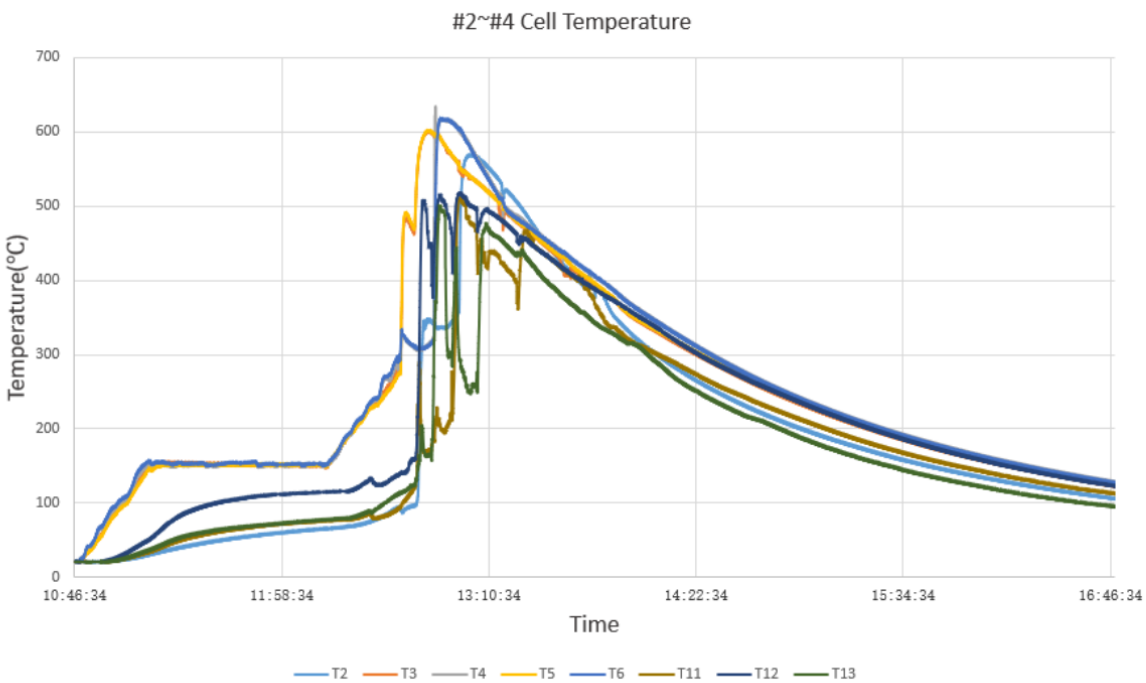

Figure 11: The temperature time history for the initiating cell from the UL 9540A module test. This image taken was from the UL 9540A module-level test report [4].

The initiating cells were heated until thermal runaway occurred. The three initiating cells went into thermal runaway and propagated to two other cells, making five cells in total that failed in thermal runaway [4]. Sparks, flying debris, and external flaming were not observed during the test. Figure 12 shows the module after the test.

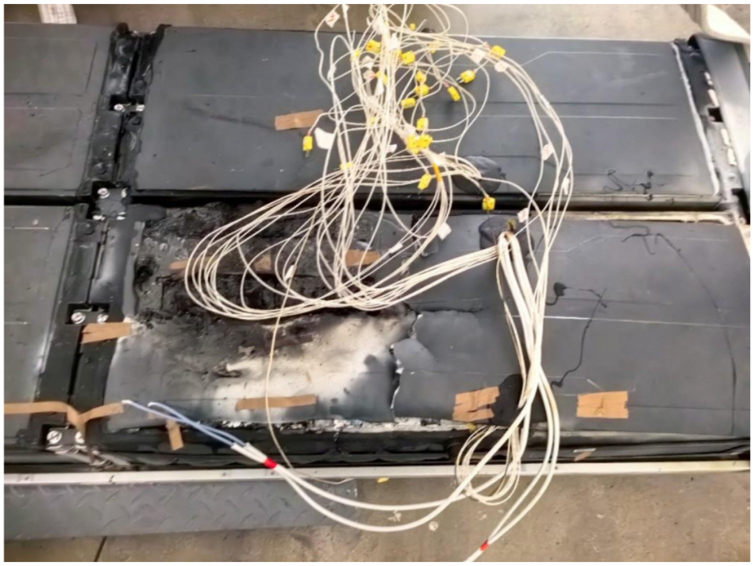

Figure 12: The module after the UL 9540A test. This image was taken from the UL 9540A module-level test report [4].

5.3 Unit Test

The UL 9540A unit test applies to various R0417BL and R0835BL unit configurations and is described in TUVRheinland (Shanghai) Co., Ltd. report CN23JPBV 001 dated 12/16/2023. In this test, a unit comprised of four modules was tested. The unit contained 416 individual cells [5]. The initiating module was configured identically to the module test. This module was then inserted into a full unit, which was placed in proximity to walls and target units. The configuration of the initiating unit is shown in Figure 13, a diagram of the test setup is shown in Figure 14, and a picture of the initiating unit is shown in Figure 15.

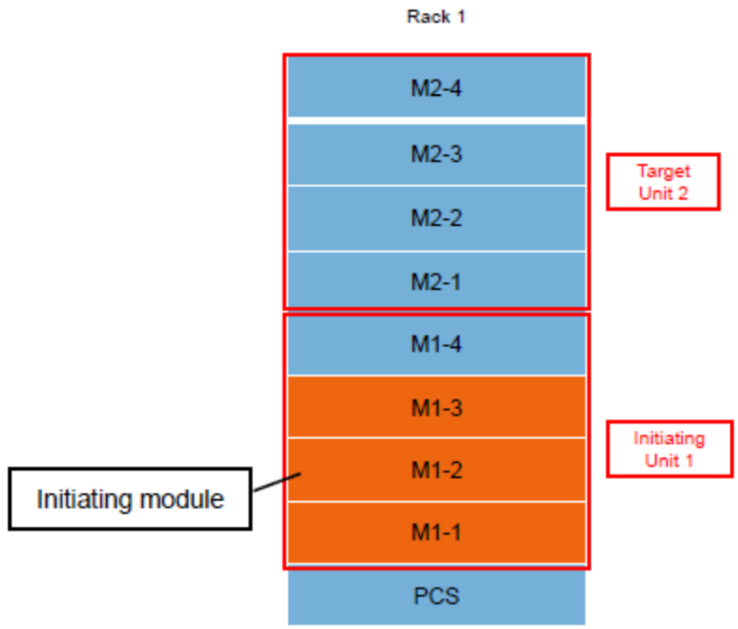

Figure 13: The initiating unit with the initiating module, target modules, and target unit labeled. This image was taken from the UL 9540A unit-level test report [5].

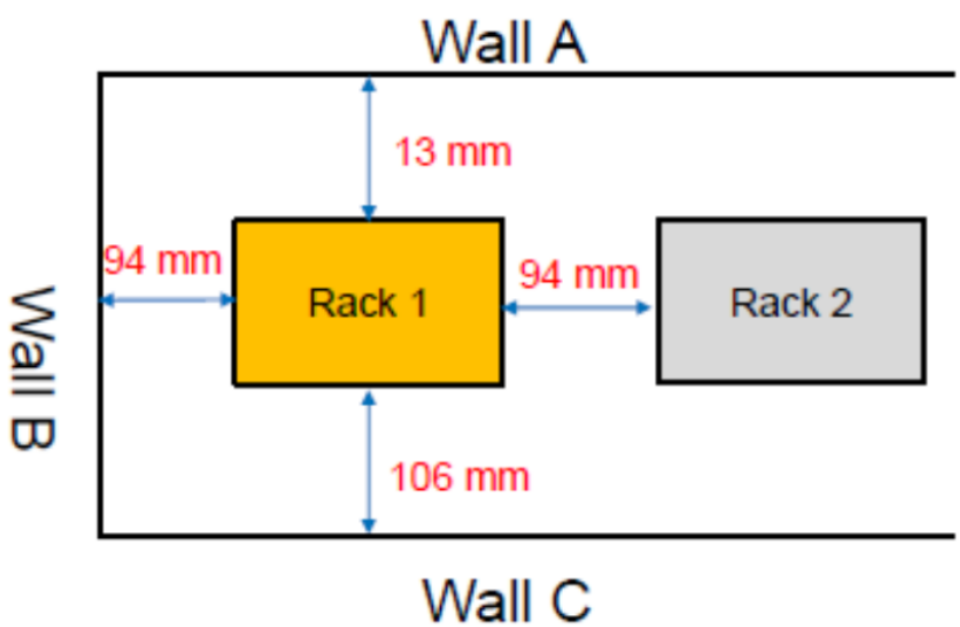

Figure 14: A diagram of the unit test setup. This image was taken from the UL 9540A unit-level test report [5].

Figure 15: A picture of the initiating unit. This image was taken from the UL 9540A unit-level test report [5].

Thermal runaway was initiated by activating the heaters on cells 2, 3, and 4 in submodule 1 in the initiating module. Once thermal runaway began, the power to the heaters was disconnected. The three initiating cells went into thermal runaway and propagated to two other cells, making a total of five failed cells inside the initiating module [5]. Thermal runaway did not propagate outside of the initiating module. Flaming, sparks, and flying debris were not observed.

6 Fire and Toxicity Modeling

Hazard Dynamics used data from the UL 9540A test reports to conduct plume modeling for a number of different failure scenarios. These models included cases of varying wind conditions, differing levels of failure severity, and with or without burning. Each scenario assumes a steady-state release and was modeled for 300 seconds.

Two different heat release rates (HRR) were used to represent two different sizes of fire. The large HRR of 34.8 MW represents a full enclosure burning. This value was calculated using cell and module information from the UL 9540A cell and module tests [4] [3]. In calculating the peak HRR used for the model, it was assumed that all cells and modules burned over the course of two hours (half an hour ramp up, steady burn for an hour, and half an hour ramp down). Flaming propagation between adjacent enclosures was not modeled as available UL 9540A test data did not demonstrate propagation between modules inside of a unit or between units. The small HRR of 2.2 MW was taken from the Heat Flux Analysis for the PowerTitan 2.0 system [6]. This HRR was used to evaluate the consequences of a smaller fire in which the entire enclosure does not burn. The modeled scenarios are shown in Table 4. The wind speeds used in the models will be discussed in Section 6.1.

Table 4: Marici fire plume model scenarios.

Name	Wind Speed (m/s)	Mass Release Rate (kg/s)	HRR (MW)
Small Fire, Low Wind	1.5	0.147	2.2
Small Fire, High Wind	6.7	0.147	2.2
Large Fire, Low Wind	1.5	2.32	34.8
Large Fire, High Wind	6.7	2.32	34.8

The non-fire scenarios model the release of lithium-ion battery vent gas in the absence of burning. Multiple battery vent gas release scenarios were used to model varying levels of thermal runaway propagation. These scenarios include the average module gas release based on the UL 9540A module test, the peak module gas release rate, the maximum gas release rate the NFPA 69 ventilation system can handle before the exhaust exceeds 25% LFL of the battery gases, a gas release rate representative of the failure of a string of batteries, and a gas release rate representative of a full unit failure. These scenarios are summarized in Table 5. Two scenarios consider the average module vent gas release with and without an active ventilation system. For these scenarios, a gas release rate of 0.000387 kg/s was calculated using the overall time cells entered into thermal runaway during the module-level test, the amount of gas released by a single cell during the cell-level test, and the number of cells failed during the module-level test [4] [3]. The calculation can be found in the appendix of this report. This gas release rate approximates the average release rate expected from five cells failing at different times as demonstrated in the module-level test. The peak module gas release rate for the module was taken from the gas release rate profile in the NFPA 69 report by TUV Rheinland [7]. This gas release rate profile shows that the cell failures in the UL 9540A module test did not overlap. Therefore, the highest instantaneous release from one cell was used to represent a worst-case module failure. This peak rate was also used to assess larger failures of a string and a unit. The string failure scenario assumes that two modules are failing at the same time, and the unit failure scenario assumes that four modules fail at the same time. While other modules in a string or unit may also fail, it is unlikely that they would all fail at the same time. Finally, the 25% LFL gas release scenarios were based on the NFPA 69 ventilation system flow rate of 750 m^3/h and an LFL of 6.2% [7] [3].

Table 5: Marici battery vent gas plume model scenarios.

Name	Wind Speed (m/s)	Mass Release Rate (kg/s)
Average module gas release, no ventilation	1.5	0.000387
Average module gas release, NFPA 69 ventilation	1.5	0.000387
Peak module gas release, NFPA 69 ventilation	1.5	.0015
Peak module gas release, NFPA 69 ventilation	6.7	.0015
25% LFL release, NFPA 69 ventilation	1.5	.00273
25% LFL release, NFPA 69 ventilation	6.7	.00273
String gas release, NFPA 69 ventilation	1.5	.0030
String gas release, NFPA 69 ventilation	6.7	.0030
Unit gas release, NFPA 69 ventilation	1.5	.0060
Unit gas release, NFPA 69 ventilation	6.7	.0060

For modeling purposes, the most significant components which account for more than 95% of the gas are modeled in the non-fire gas release mixture, while minor hydrocarbon elements are approximated as propane. The volume percents used in the model can be found in column four of Table 3.

6.1 Model Setup

Computational fluid dynamics (CFD) models of possible toxic and flammable plumes were created using Fire Dynamics Simulator (FDS) version 6.9.1. Fire Dynamics Simulator is a CFD software developed by the National Institute of Standards and Technology (NIST) for fire modeling. The code solves the Navier-Stokes equations using a large-eddy-simulation (LES) approach and is mainly intended for low-speed flows with an emphasis on smoke and heat transport from fires. The code has been extensively validated for a variety of scenarios involving fire, smoke, gas dispersion, and other transport phenomenon. For toxic plume modeling, the model uses grid sizes ranging from 0.25 m (9.8 in) to 2 m (6.6 ft) to capture both the flow near the source (starting 2 m from the enclosure) as well as the dispersion over a large flat downwind area up to 320 m (1050 ft) away from the source as shown in Figure 16. For flammable plume modeling, a smaller, more refined mesh was used, as the flammable region is expected to impact only the near-field region immediately around the BESS enclosure. The refined mesh for these models extends 5 m (16.4 ft) from the enclosure and uses a 0.1 m grid size.

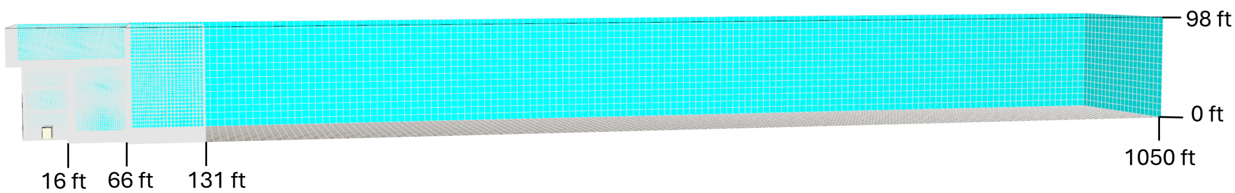

Figure 16: The toxic plume model with the grid displayed. The grid varies in size from 0.25 m near the unit to 2 m starting 40 m away from the unit. The model for flammable plume modeling only includes the portion of the model immediately around the enclosure with a mesh size of 0.1 m.

The EPA Risk Management Program recommends using a wind speed of 1.5 m/s (3.4 mph) and atmospheric stability class F conditions (stable atmosphere) for worst-case plume analysis for accidental chemical releases [15]. This wind speed was used in the model as well as the 99th percentile wind speed for the Marici site, which is roughly 6.7 m/s or 15 mph (see Figure 3). High wind speeds may act to partially overcome the upward tendency of a fire plume. The results presented here approximate worst-case results based on the wind speeds modeled and using stable atmospheric conditions with an Obukhov length of 350 meters. Because the Marici site is in a suburban area, a closed Davenport-Wieringa roughness length of 1.0 m was used.

The wind speeds used in the models are intended to be worst-case. Therefore, results from other wind speeds are expected to be bounded by the wind speeds used. Likewise, modeling a stable atmosphere, in which released gases would tend to stay near ground-level, is considered worst-case. Stable conditions may include fog, because the stability prevents vertical movement of the moist air near the ground. The moisture in fog conditions is not expected to make a plume resulting from battery vent gas release or a fire any worse. Rain during a BESS failure incident is expected to result in a less severe plume than modeled because the falling water could encourage mixing and dispersion over a wider area.

6.2 Plume Toxicity Results

Results were collected for battery vent gas concentrations (non-fire scenarios) and combustion product concentrations (fire scenarios). The gas concentration of interest was the concentration at 2 m (6.6 ft) above ground level. This corresponds to the concentration that people would experience when standing on level ground near an incident. Figure 17 shows the average vent gas concentrations, and Figure 18 shows the average combustion product gas concentrations at 2 m (6.6 ft) above ground level at different distances downwind of the unit. Figure 17 shows that vent gas concentrations remain relatively low even near the enclosure and diminish significantly away from the enclosure in scenarios without fire. For the scenarios with fire, overall combustion product concentrations at 2 m (6.6 ft) above ground level remain low with wind speeds of 1.5 m/s (3.4 mph). However, the fire scenarios with high winds speeds result in high combustion product concentrations near the enclosure. These concentrations drop quickly away from the burning enclosure. The modeled high wind speed was 6.7 m/s (15 mph), which is the 99th percentile wind speed at the Marici site. However, since toxic gases are only a fraction of the total battery vent gas or combustion products, toxic gas concentrations would be a fraction of these values.

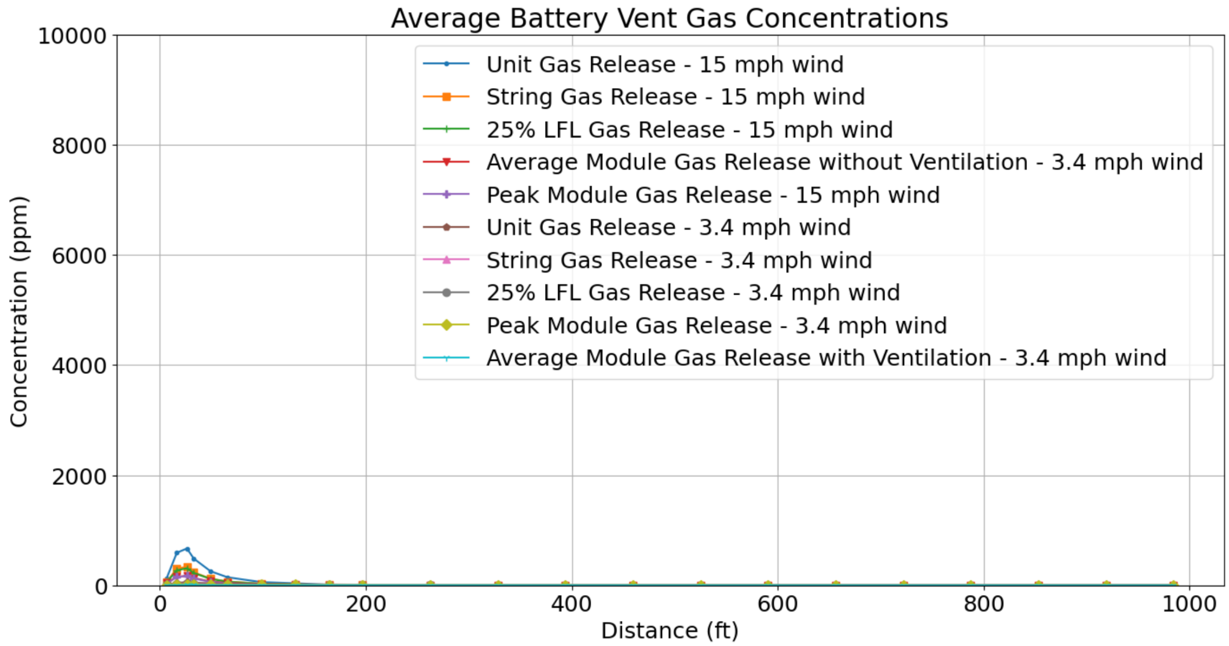

Figure 17: The average battery vent gas concentration versus the downwind distance for different gas release model scenarios.

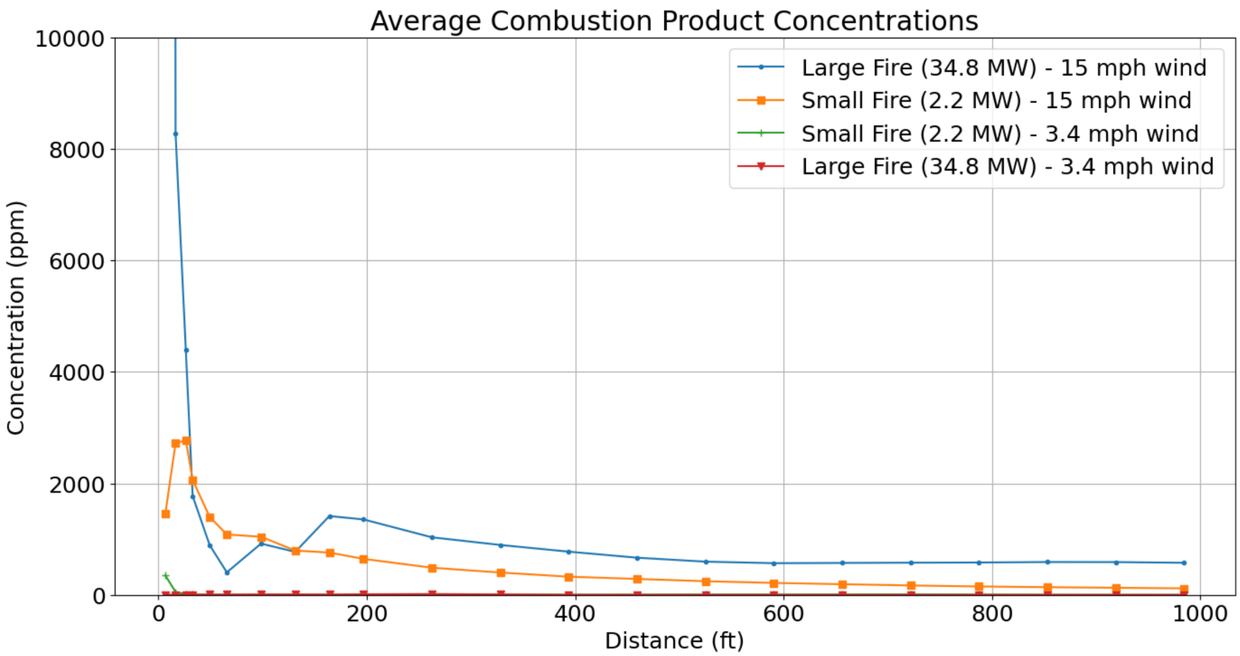

Figure 18: The average combustion products concentration versus the downwind distance for different fire model scenarios.

The trajectory of the battery vent gas coming out of the enclosure in scenarios without burning depends on the size of gas release, whether the ventilation system is active, and the wind speed. Figure 19 shows an average module gas release with no ventilation, while Figure 20 shows an average module gas release with ventilation. Because the exhaust fan is on top of the enclosure, it lofts the battery gas upward when activated. This results in much of the battery gas being above the 2 m (6.6 ft) level and more rapid mixing of the battery gas with the surrounding air.

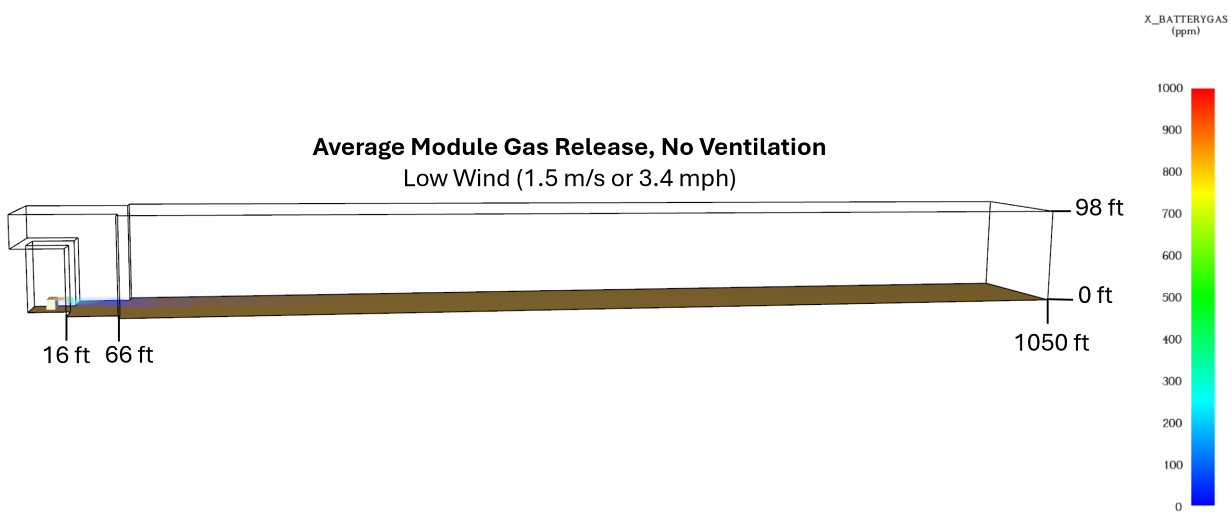

Figure 19: The model for an average module gas release scenario with no ventilation and low wind speeds. X_BATTERYGAS is the concentration of battery vent gas in ppm. The distances shown are measured from the front of the enclosure.

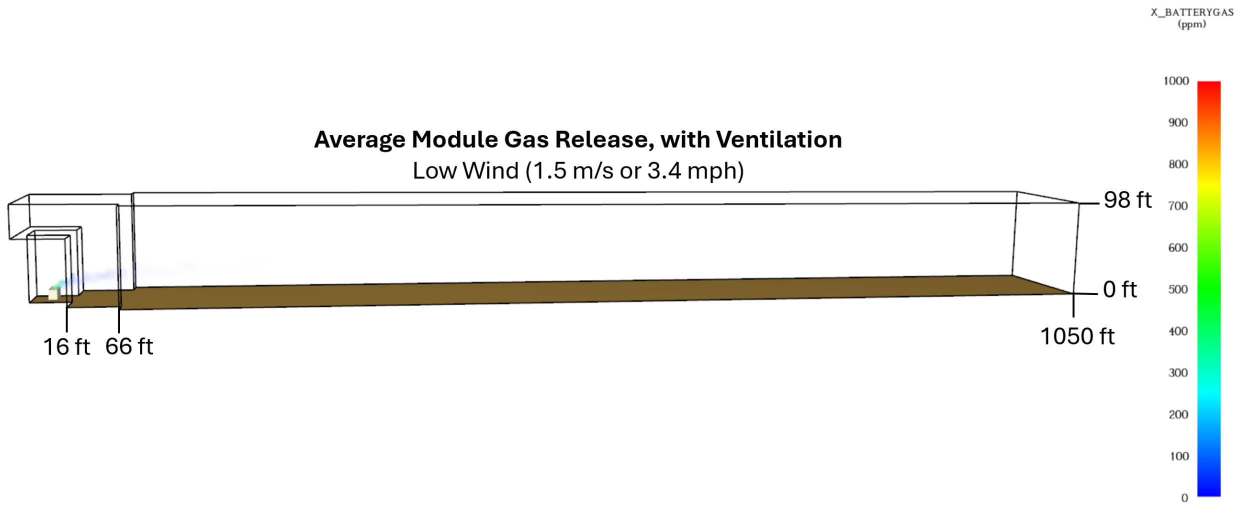

Figure 20: The model for an average module gas release scenario with ventilation and low wind speeds. X_BATTERYGAS is the concentration of battery vent gas in ppm. The distances shown are measured from the front of the enclosure.

The speed of the wind also affects the path and mixing of the battery vent gas expelled from the enclosure. Figure 21 shows a unit gas release under high wind conditions. In this scenario, the vent gas is lower to the ground and disperses more quickly than the low wind unit gas release scenario shown in Figure 22.

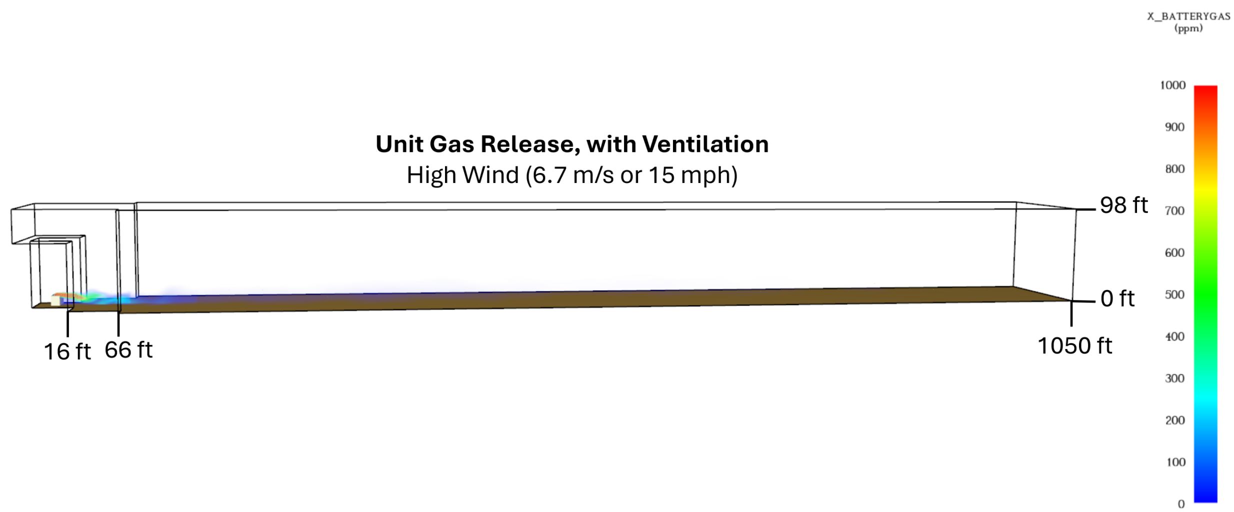

Figure 21: The model for a unit gas release scenario with ventilation and high wind speeds. X_BATTERYGAS is the concentration of battery vent gas in ppm. The distances shown are measured from the front of the enclosure.

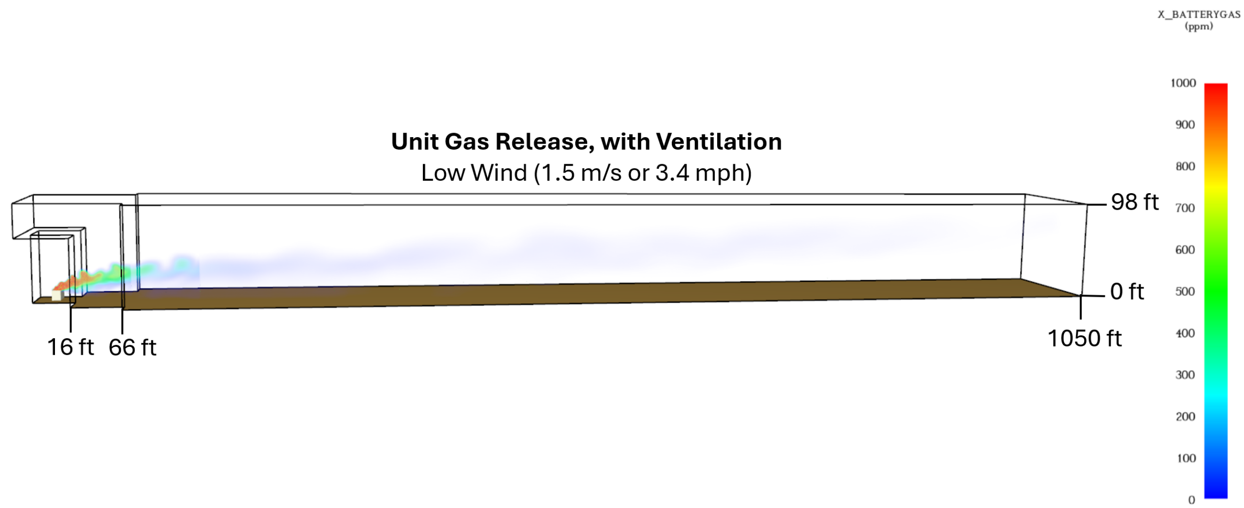

Figure 22: The model for a unit gas release scenario with ventilation and low wind speeds. X_BATTERYGAS is the concentration of battery vent gas in ppm. The distances shown are measured from the front of the enclosure.

The fire scenarios with greater wind speeds resulted in higher concentrations of combustion products 2 m (6.6 ft) above ground level. The heat from fire conditions makes gases more buoyant such that they rise away from the ground. In most common wind conditions, fire product concentrations are low at ground level. However, under conditions of high wind, this buoyant effect may be partially overcome. The scenarios with both fire and high winds yielded the highest gas concentrations at the greatest distances. Figure 23 shows the model with a full unit fire at high wind speeds. This figure shows that the hot combustion products do not rise immediately due to high wind conditions, but they do rise gradually. Additionally, mixing occurs as the combustion products move away from the enclosure. In contrast, Figure 24 shows that the combustion products rise immediately under low wind conditions.

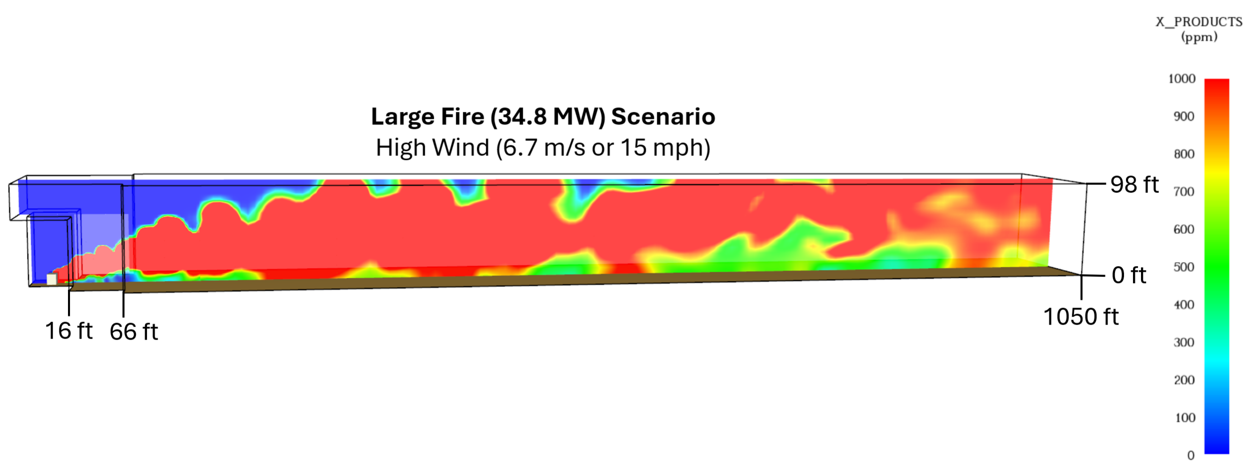

Figure 23: The model of a full unit fire with high wind conditions. In this scenario, the combustion products do not rise immediately due to high wind conditions, but they do rise over time while also mixing with air. X_PRODUCTS is the concentration of combustion products in ppm. The distances shown are measured from the front of the enclosure.

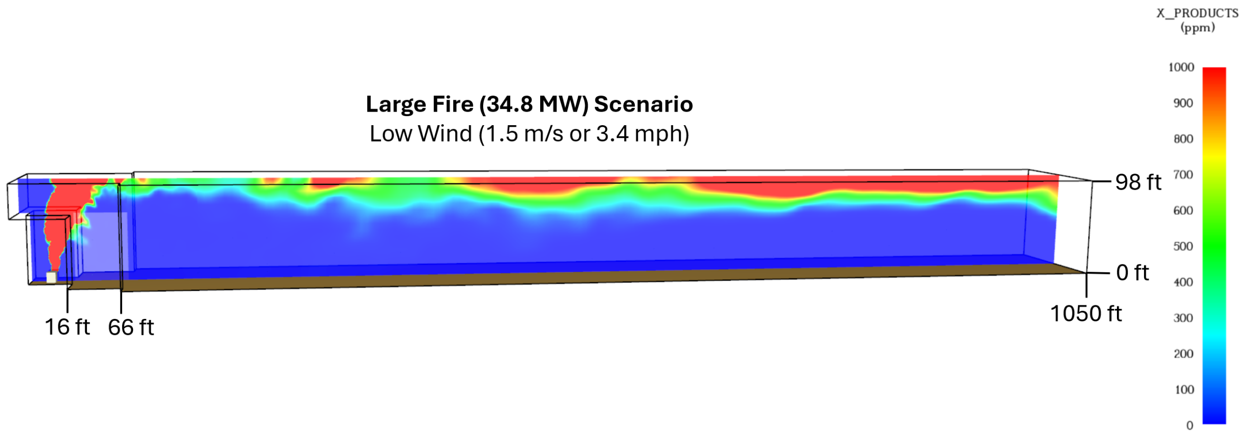

Figure 24: The model of a full unit fire with low wind conditions. In this scenario, the combustion products rise immediately and stay elevated for long distances. X_PRODUCTS is the concentration of combustion products in ppm. The distances shown are measured from the front of the enclosure.

Figure 25 shows that for a smaller fire with high winds, the combustion products stay near ground level for some distance before mixing occurs. In low wind conditions, combustion products for a small fire also rise but to a lesser degree than for a large fire scenario as shown in Figure 26.

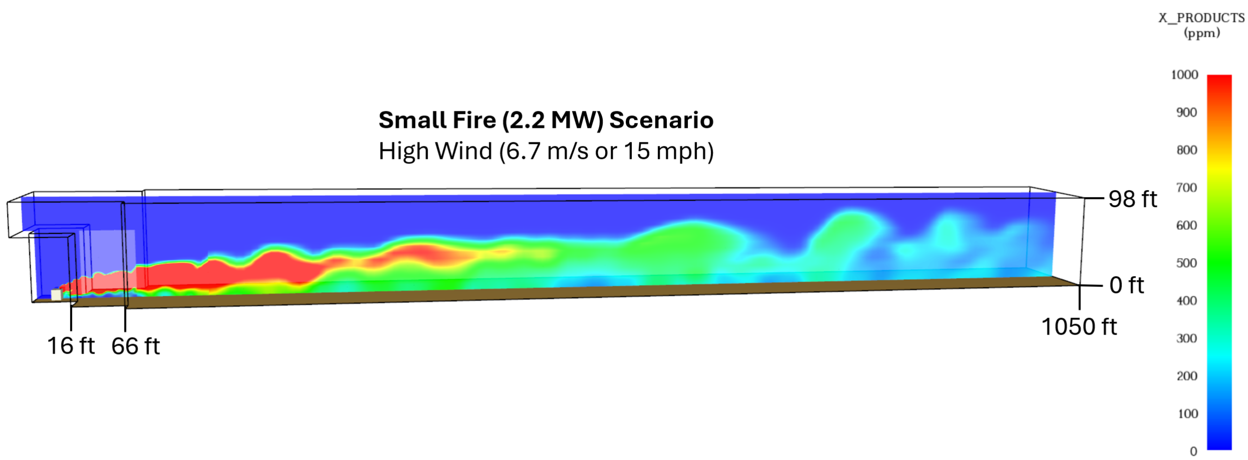

Figure 25: The model of a small fire with high wind conditions. In this scenario, the buoyant effects of the hot gas are partially overcome by the high wind such that the combustion products stay near ground level until mixing occurs. X_PRODUCTS is the concentration of combustion products in ppm. The distances shown are measured from the front of the enclosure.

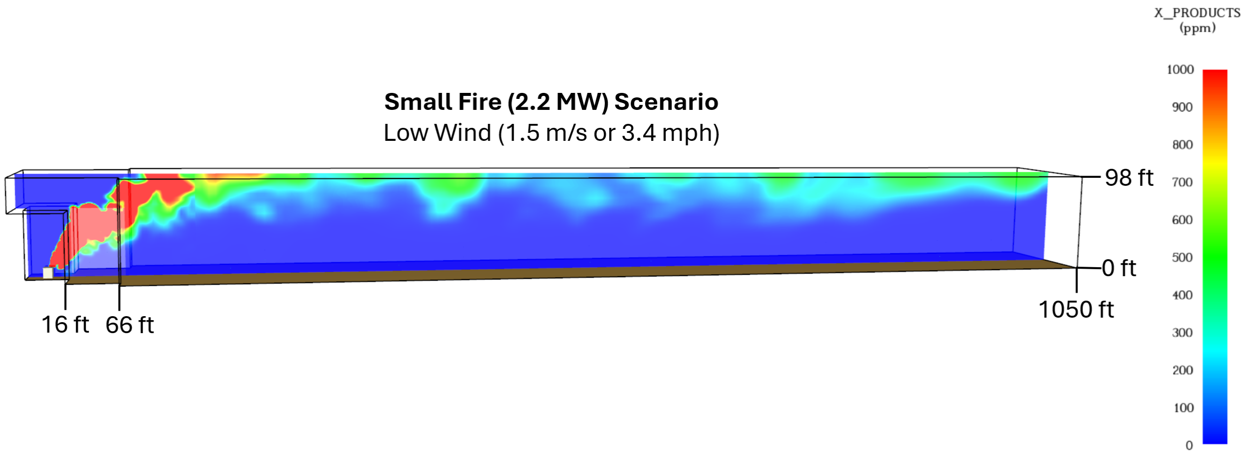

Figure 26: The model of a small fire with low wind conditions. In this scenario, combustion products rise to a lesser degree than in the large fire scenario. X_PRODUCTS is the concentration of combustion products in ppm. The distances shown are measured from the front of the enclosure.

Although multiple toxic gases may be components of battery vent gas, carbon monoxide (CO) is generally the most abundant toxic gas of concern that is regularly reported as part of UL 9540A testing. The UL 9540A cell test report for the PowerTitan 2.0 listed the carbon monoxide concentration as being 13.924%. This value was used to quantify the amount of carbon monoxide in the non-fire scenario. However, it is unclear what concentration of carbon monoxide may persist through a fire. Carbon monoxide concentration in burned gas is likely to be much lower than in the battery gas, as CO is flammable. Carbon monoxide due to incomplete combustion from the fire can also vary depending on the burning environment. Consequently, Hazard Dynamics estimated what amount of carbon monoxide might be present during a fire event using knowledge from work with many battery systems. The CO production was assumed to be 2% of the combustion products. This estimation was based on the measured combustion product concentration from the FDS models. The average carbon monoxide concentration over the 300 m (984 ft) model domain for the gas release scenarios and the fire scenarios are shown in Figure 27 and Figure 28, respectively.

Many different toxicity levels exist for carbon monoxide. The IDLH (Immediately Dangerous to Life and Health) level, the AEGL-3 (life-threatening health effects) level, and the AEGL-2 (serious health effects) level for a 30-minute exposure were discussed in Section 3.2. The EPA does not provide an AEGL-1 (temporary irritation) concentration for carbon monoxide. The IDLH and AEGL levels were created for short-term exposure to chemicals. Other toxicity levels were created to address long-term exposure. The OSHA Permissible Exposure Limits (PELs) were created to protect workers against health effects resulting from exposure to hazardous chemicals. Additionally, the EPA National Ambient Air Quality Standards (NAAQs) were created to protect public health from chemical exposure. Table 6 shows the concentration levels for various carbon monoxide toxicity levels as well as the worst-case distance modeled above the toxicity level. The large fire, high wind scenario was the only scenario with carbon monoxide concentrations that exceeded the IDLH and AEGL levels at 2 m (6.6 ft) above ground level. The unit gas release scenario with high winds resulted in the worst-case distances for the OSHA PEL and EPA NAAQ (1-hr) levels at 2 m (6.6 ft) above ground level. The fire scenarios with low wind remained below all reported toxicity levels at 2 m (6.6 ft) above ground level at all modeled distances.

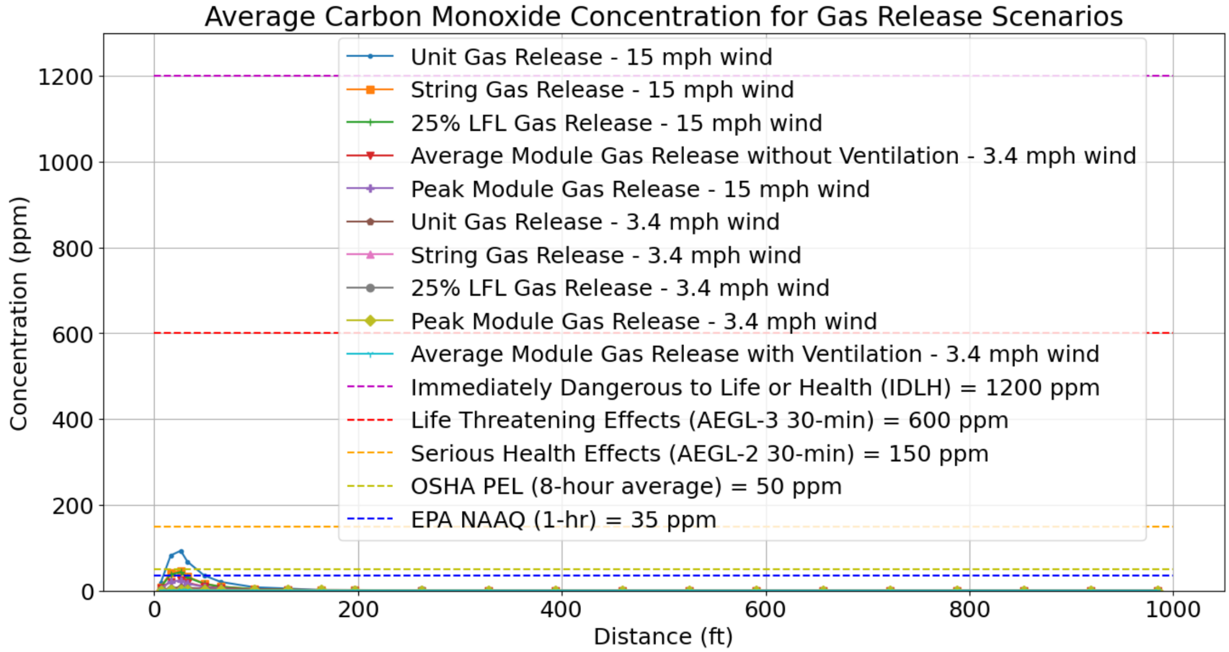

Figure 27: Average carbon monoxide concentrations as a function of distance for different battery vent gas release scenarios. The high wind speed modeled was 6.7 m/s (15 mph), which is the 99th percentile wind speed for the Marici site.

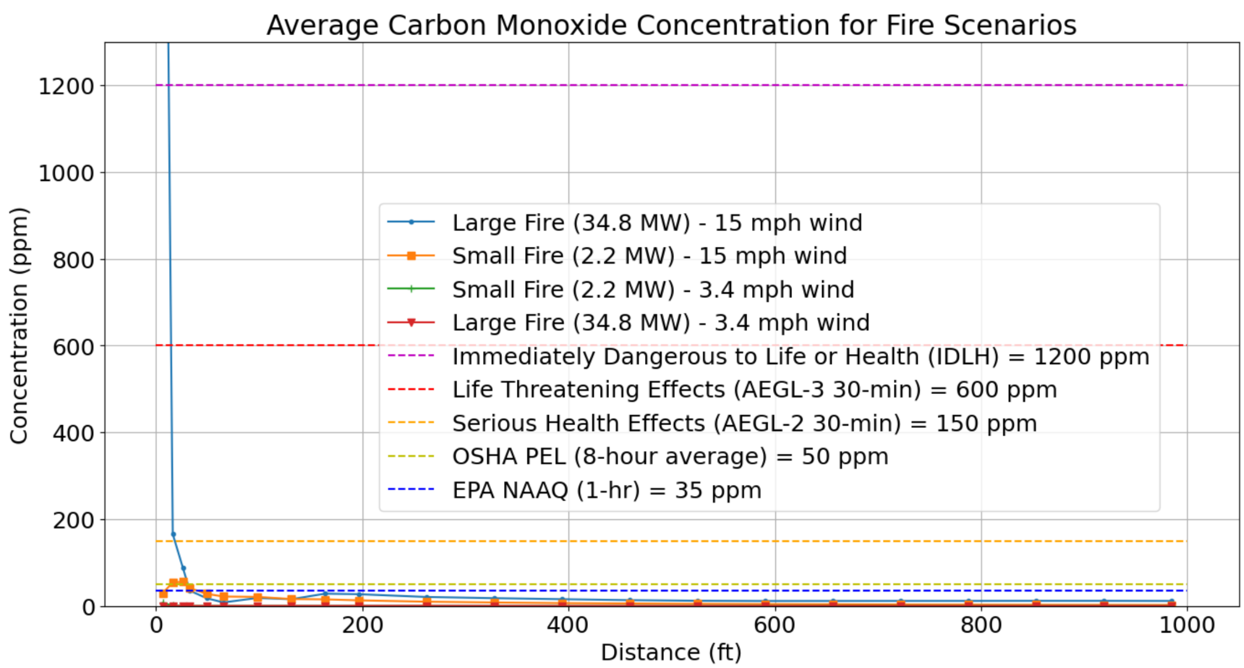

Figure 28: Average carbon monoxide concentrations as a function of distance for different combustion product release scenarios. The high wind speed modeled was 6.7 m/s (15 mph), which is the 99th percentile wind speed for the Marici site.

Table 6: Toxicity levels and worst-case modeled distances for carbon monoxide at 2 m (6.6 ft) above ground level.

Toxicity Level for CO	Concentration (ppm)	Worst-Case Modeled Distance
IDLH	1200	13 ft
AEGL-3 (30-minute)	600	15 ft
AEGL-2 (30-minute)	150	19 ft
OSHA PEL (8-hour average)	50	42 ft
EPA NAAQ (1-hour)	35	50 ft

Hydrogen fluoride (HF) is an acutely toxic gas species whose presence has been reported in some battery failure cases. Due to the high toxicity of hydrogen fluoride at quite low concentrations, it is of growing concern for safety analyses of lithium-ion battery systems. It is well accepted by researchers that a lithium-ion cell can generate HF during thermal runaway. However, HF measurements from large-scale fire tests of ESS are not publicly available. In large-scale ESS fires, hydrogen fluoride production is most likely dominated by the burning of fire-retardant plastics in battery systems rather than by the actual cells. HF generated from the cells can also react with other components such as the module casing or rack structure. In general, the publicly available data on hydrogen fluoride in battery failures remains limited, and the reported quantities vary widely. Amounts of hydrogen fluoride between 0 L/Wh and 0.24 L/Wh have been reported [8]. This indicates that HF could represent a significant percentage of the produced gas or not be present in significant amounts. The manner in which this value depends on cell chemistry, state of charge, or other factors is not well understood. Hydrogen fluoride is highly reactive with a range of materials including metals and various organic compounds. It is unclear whether substantial HF concentrations persist at a distance away from larger module, rack, and ESS scales. Hydrogen fluoride can be emitted from combustion of plastic components in the ESS, such as wiring insulation and module or rack enclosure casings. Although these plastics are commonly fire-retarded, fire-retardant plastics can be overwhelmed if the severity of the fire is sufficiently large. Such fire-retardant plastics are commonly found in non-battery applications and may pose similar emission hazards during fire conditions. While some testing laboratories will provide HF data, it is not currently required by UL 9540A or other standards currently in use in the United States. Hydrogen fluoride data was not provided for the PowerTitan 2.0 system. It is recommended that additional fire testing be performed in order to quantify what levels of hydrogen fluoride may exist for the PowerTitan 2.0.

Typically, hydrocarbons such as benzene and toluene are the only toxic gas concentrations other than carbon monoxide that are measured as part of the UL 9540A testing process. These do not present significant toxicity hazards compared to carbon monoxide and hydrogen fluoride, as their concentrations in battery gas are usually orders of magnitude less while having generally higher AEGL concentrations than CO and HF. For the CALB Group Co., Ltd. cells, the benzene and toluene concentrations were not reported.

6.3 Flammable Gas Plume

Several thermal runaway (TR) scenarios were considered for the flammable gas plume analysis: (1) Average TR of a single module, (2) Peak TR of a single module, (3) TR of a string of modules, and (4) TR of a BESS unit. The details of the scenarios can be found in Table 5. The average module thermal runaway scenario without ventilation resulted in a flammable region (battery vent gas concentration above LFL) that extended less than .1 m (4 in) vertically only directly over the exhaust fan (see Figure 29). The same gas release with ventilation did not result in a flammable region due to the dilution of battery gas resulting from air being mixed in by the exhaust fan. Next, the unit gas release cases were run as bounding scenarios. Neither the low wind nor the high wind unit gas release scenario resulted in the formation of a flammable cloud outside of the enclosure. Again, the battery gas was sufficiently diluted by the NFPA 69 ventilation system such that the concentration of battery vent gas did not exceed LFL outside of the enclosure. Because the unit gas release scenarios did not result in a flammable cloud outside of the enclosure due to the active ventilation system diluting the gas, the active ventilation system will also prevent formation of flammable gas clouds during module and string release scenarios. However, steady-state analyses, as considered here, are unable to quantify formation of smaller regions of flammable gas that can form due to intermittent or unsteady flow conditions. To qualitatively evaluate formation of these types of flammable gas clouds, battery gas concentrations at 1/2-LFL and 1/4-LFL were also evaluated. The worst-case regions for the unit gas release scenarios are shown in Figure 30. These results are also shown in Table 7. Since the flammable gas cloud is less far reaching than the toxic gas cloud, appropriate setbacks will be dictated by toxic gas plume results.

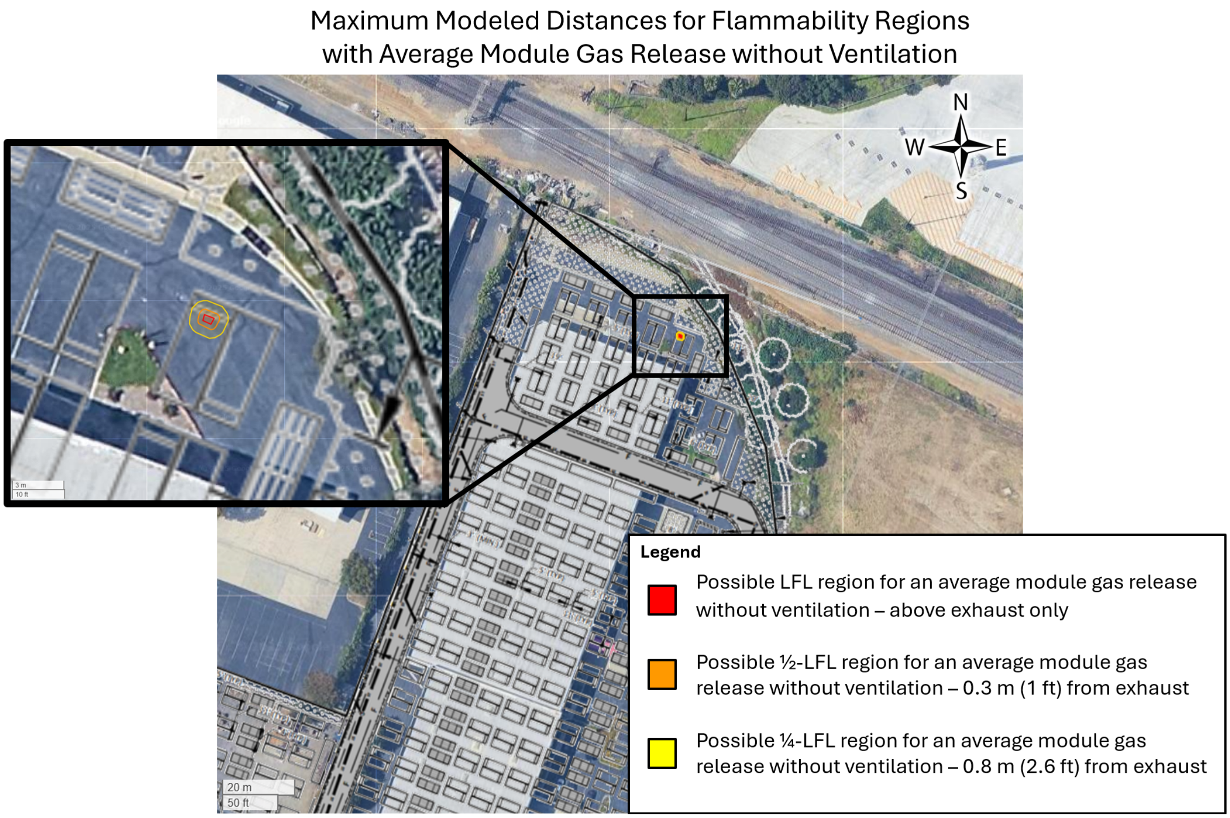

Figure 29: The worst-case battery vent gas regions for LFL, 1/2-LFL, and 1/4-LFL for an average module gas release without ventilation.

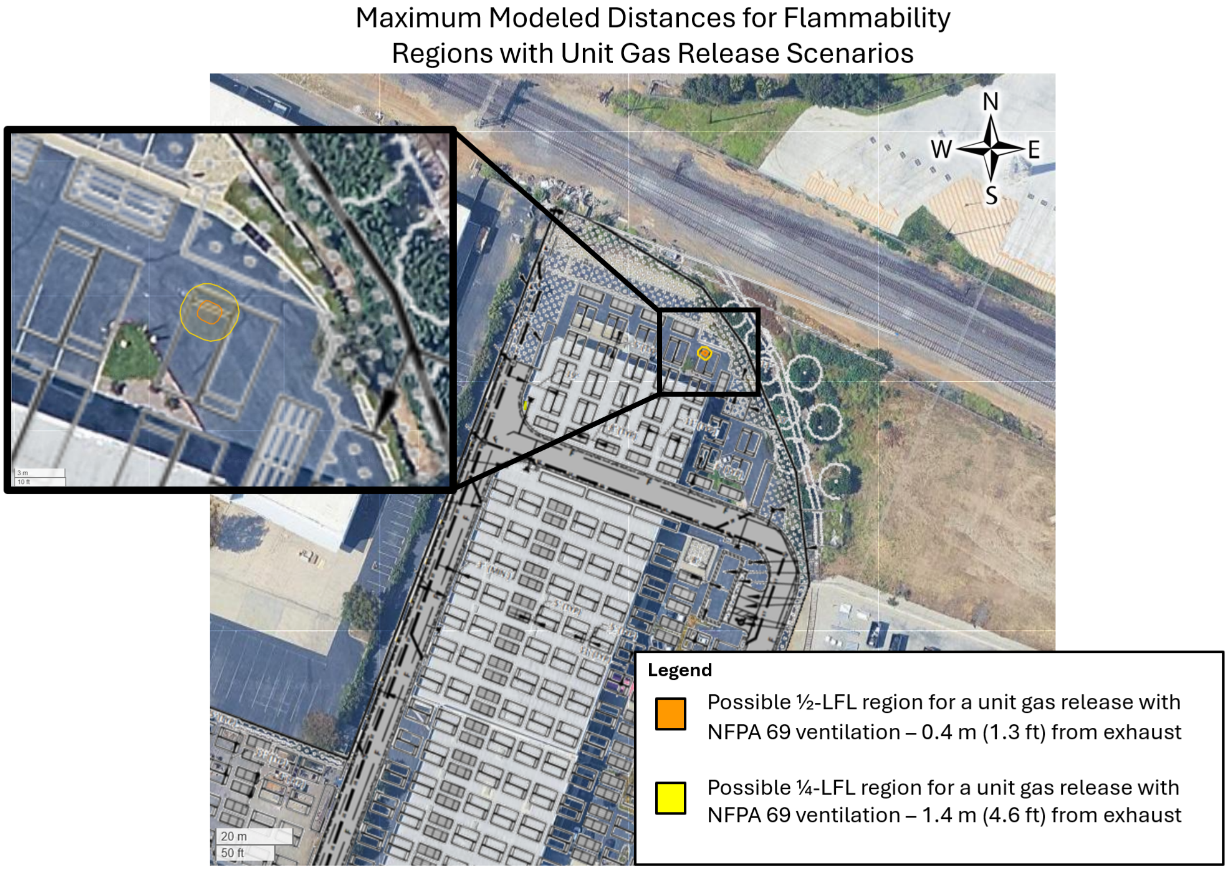

Figure 30: The worst-case battery vent gas regions for 1/2-LFL and 1/4-LFL for the unit gas release scenarios. Note that the battery vent gas concentrations did not reach LFL anywhere outside of the enclosure due to dilution resulting from the NFPA 69 ventilation system.

Table 7: The worst-case modeled distances for flammable regions outside of the enclosure

Scenario	LFL	1/2-LFL	1/4-LFL
Average Module Gas Release, No Ventilation, Low Wind	Above exhaust only	0.3 m (1 ft) from exhaust	0.8 m (2.6 ft) from exhaust
Average Module Gas Release, NFPA 69 Ventilation, Low Wind	NA	NA	NA
Unit Gas Release, NFPA 69 Ventilation, Low Wind	NA	0.4 m (1.3 ft) from exhaust	1.4 m (4.6 ft)t from exhaust
Unit Gas Release, NFPA 69 Ventilation, High Wind	NA	0.3 m (1 ft) from exhaust	1.1 m (3.6 ft) from exhaust

7 Emergency Response Considerations

This section provides emergency response considerations based on the plume modeling results. These considerations are based on CO toxicity hazards. A more complete discussion of emergency response considerations is typically included in separate Emergency Response Plan or Guideline (ERP/ERG) documents. As discussed above, UL 9540A does not require measurement of hydrogen fluoride (HF) during testing, and HF data was not provided for the PowerTitan 2.0 system. As such, HF concentrations were not evaluated. Responders should be aware that smoke plumes may contain HF and other common toxic combustion products and, at a minimum, should follow procedures for protection against toxic combustion products in smoke.

- For a single involved unit in worst-case modeled conditions, concentrations at 2 m (6.6 ft) above ground level are not expected to exceed AEGL-2 for CO (150 ppm) beyond 19 ft from the enclosure. Evacuation of personnel and people within the facility property lines is recommended. Personnel should be evacuated to locations upwind of the facility. Concentrations 2 m (6.6 ft) above ground level that exceed EPA NAAQ (1-hour) limits (35 ppm) are not expected to extend more than 50 ft from the enclosure. This concentration may extend into neighboring parking lots and public ways. During a failure event, evacuation of buildings immediately adjacent to the site and limiting use of public ways adjacent to the site should be considered.
- CO concentrations may exceed IDLH up to 13 ft from the involved container. All personnel engaged in fire suppression and rescue operations near the involved container should use appropriate PPE such as SCBA and bunker gear.
- CO concentrations may exceed 8-hr OSHA PEL limits up to 42 ft away from an involved unit. It is recommended that support personnel without breathing apparatus and the command post be located at least this distance from involved units.
- Flammable gas clouds are not expected to be present outside of the container if the NFPA 69 ventilation fan is active.
- Although flammable gas hazards do not extend beyond the property line and toxicity hazards over a 30-minute exposure period are likely near the site boundary only during high wind conditions, monitoring of toxic and flammable gas species downwind from the property line may be considered. If toxic and flammable gas species are measured to exceed permissible levels, evacuation or shelter-in-place of downwind areas may be required. Evacuation distances can be informed by Table 6.
- Although the scope of the plume modeling conducted in this study is to address airborne species, water run-off from fire fighting activities may also include metal contaminants and other toxic pollutants. Data on water pollutants was not provided for this specific system. If there is a concern about water pollution, water containment barriers or discontinuation of water use may be considered.
- An offensive attack to extinguish a BESS creates unnecessary risk and is unlikely to be successful. Emergency responders to a BESS failure often deploy a defensive strategy, when possible. When using this strategy, firefighters take up a defensive position to protect neighboring infrastructure rather than attacking the BESS fire itself. The plume modeling conducted in this study considers this scenario as a worst-case bounding condition and models the plume as a steady-state release. If a long duration scenario is expected, common interventions include shelter-in-place and evacuation orders for the surrounding area. The exposure distances discussed above may be used to establish shelter-in-place or evacuation distances. If abnormally high wind conditions beyond the 99% wind speed (15 mph) occur or more than one enclosure fails, toxic gas concentrations may extend beyond the estimated distances. In this case, it may be appropriate to increase evacuation distances beyond the exposure distances discussed above. Air quality monitoring may be helpful in determining evacuation distances.
- The expected duration of a BESS failure event will depend on a range of factors. If a defensive firefighting strategy is used and the fire is limited to a single container, an active fire may last between 2-8 hours based on previous incidents and BESS unit fire testing. If fire does propagate to adjacent containers, the duration of the event could last longer

depending on the number of containers that catch fire as each may burn for 2 to 8 hours. However, several mitigation strategies are commonly deployed to prevent fire propagation from container to container, including appropriate separation between BESS units, use of fire or thermal barriers between units, or hardening of BESS enclosures. Evaluation of fire spread is beyond the scope of this plume study and is more appropriately addressed by the Fire Modeling Analysis.

8 Conclusion

Of the measured toxic gas species for which test data is available, carbon monoxide is of primary concern due to its comparatively high concentrations and toxicity. Carbon monoxide has an IDLH level of 1200 ppm, an AEGL-3 (life-threatening health effects) level for a 30-minute exposure of 600 ppm, and an AEGL-2 (serious health effects) level for a 30-minute exposure of 150 ppm. No AEGL-1 level is provided for CO. Carbon monoxide may constitute up to 13.924% of the unburned battery vent gas based upon the provided UL 9540A cell-level report. Carbon monoxide concentrations 2 m (6.6 ft) from ground level were measured by FDS for the non-fire scenarios and calculated using modeled fire product concentrations and typical carbon monoxide levels present during lithium-ion battery fires for the fire scenarios. The modeled average carbon monoxide concentrations may be immediately dangerous to life and health up to 13 ft, cause life-threatening health effects (exceed the AEGL-3 level) up to 15 ft, and cause serious health effects (exceed the AEGL-2 level) up to approximately 19 ft from the unit in a large fire scenario with high winds. The modeled average carbon monoxide concentrations may exceed EPA NAAQ 1-hr levels and cause physical symptoms up to approximately 50 ft from the unit during a unit thermal runaway gas release scenario with high winds. The modeled high wind speed was 6.7 m/s (15 mph), which is the 99th percentile wind speed at the Marici site. No toxicity consequences were present for the modeled scenarios with low wind conditions. Hydrogen fluoride was not measured during the UL 9540A testing for this system. However, it is has been reported in some battery failure cases. Thus, hydrogen fluoride is a risk, but the exact magnitude of this risk is unknown. If quantification of HF levels are desired, it is recommended that additional fire testing beyond the scope of the UL 9540A testing be performed in order to quantify what levels of hydrogen fluoride may exist for the PowerTitan 2.0. Other measured toxic gases make up only trace amounts of the battery vent gas. Hydrocarbon release quantities are too small to exceed IDLH or AEGL levels at any distance from the unit.

Provided planning documents [1] and publicly available maps indicate that the Marici site is located in an area with residential neighborhoods and commercial buildings. Over 600 houses are located within a half-mile of the Marici site. The nearest residential property is 111 ft away from the BESS enclosure at the edge of the site (see Figure 2). Based on the model results and the prevailing wind direction at the site (from the south-southwest), it is unlikely that toxic levels of carbon monoxide that may result in irreversible or serious health effects would reach populated areas in the event of a single BESS unit experiencing a failure event. Based on worst-case modeled carbon monoxide concentrations that could reach AEGL-2 (irreversible or serious health effects), BESS enclosure setbacks from the property line should either exceed 19 ft or a sufficient and reliable means of notification should be provided for areas where the property line is less than 19 ft from the nearest BESS enclosure. Sufficient and reliable means of notification could include, but are not limited to, visual and audible alarms to alert people who may be in the vicinity of the site or providing procedures requiring site personnel to secure the area in the event of a BESS failure. A larger setback of 50 ft may be considered for sensitive receptors to reduce possible physical symptoms that could result from long-term exposure to low concentrations of carbon monoxide.

Given the uncertainties inherent in modeling and the diversity of possible outcomes, it is recommended that all non-essential personnel evacuate the immediate area and that emergency response personnel wear SCBA when operating in the vicinity of a unit that is in thermal runaway.

Given the potential risk of toxicity hazards during failure scenarios of the BESS, appropriate emergency response protocols should be considered and developed in collaboration with local emergency personnel. Due to the suburban location of the site, officials may want to consider protective action guidance, especially during high wind conditions. This may include shelter and evacuation actions. These protective actions could be informed by carbon monoxide measurements, HF measurements, or observation of irritating smoke particulates. Evacuation during an event can allow occupants to remove themselves from the incident but poses the risk of exposure during a brief period of evacuation. Evacuation is often a better option for a prolonged event. Based on the model results, evacuation for occupants during an evacuation in proximity to the involved battery system is not likely to cause exposure to IDLH, AEGL-3, or AEGL-2 levels of toxic gases which could cause permanent injury or impede evacuation. Shelter-in-place actions include staying inside and closing windows and doors such that toxic materials do not enter the building. Shelter-in-place may expose people to smaller concentrations of material for a longer period of time and can be a good option for short incidents but becomes unreasonable for long incidents. Figure 31 shows the areas that could have toxic gas concentrations exceeding IDLH (immediately dangerous to life or health), AEGL-3 (life-threatening health effects), and AEGL-2 (serious health effects) based on the worst-case modeled scenarios for high winds at the Marici project site. Areas that could have toxic gas concentrations that exceed OSHA PEL and EPA NAAQ (physical symptoms) are also shown. These distances were measured from the outermost BESS enclosures. Note that this figure does not consider possible hydrogen fluoride concentrations.

Maximum Distances for Toxicity Consequences with
99th Percentile 15 mph High Wind

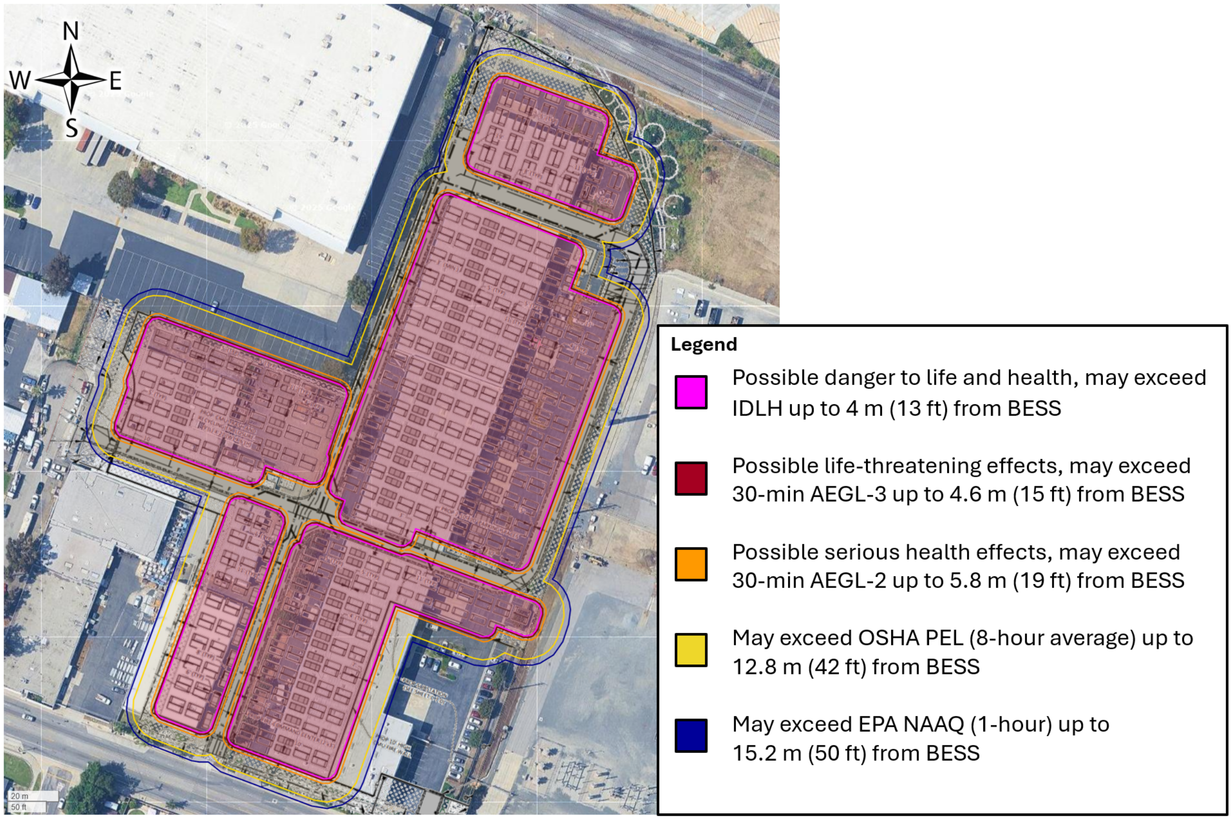

Figure 31: Satellite imagery of the immediate site surroundings with overlaid areas containing possible levels of toxic gases with steady 6.7 m/s (15 mph) wind, which is the 99th percentile wind speed at the Marici site. The buffer colors correspond with the toxicity levels shown in Figures 27 and 28. No toxicity consequences were present for the modeled scenarios with low wind conditions. Note that these buffers do not account for possible hydrogen fluoride concentrations. This image was produced using Open Street Map and Google Maps.

The buffers in Figure 31 show the maximum modeled distances for critical concentrations in all possible wind conditions. In reality, the wind will only come from one direction at a time, so a plume resulting from BESS failure will travel predominantly in one direction. Figure 32 shows a modeled plume for a high wind coming from the prevailing wind direction, which is south-southwest for the Marici site.

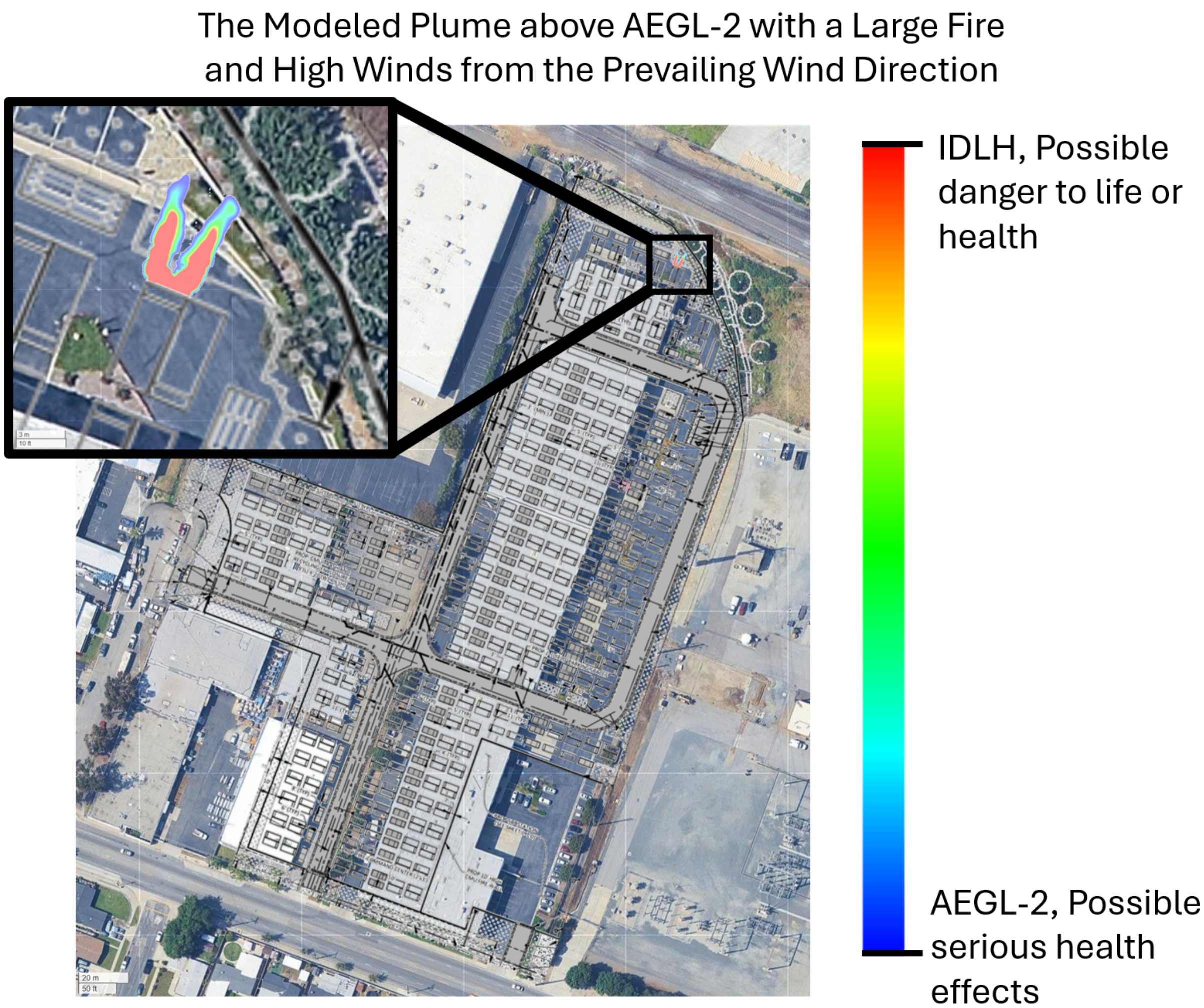

Figure 32: Satellite imagery of the immediate site surroundings with an overlaid plume that was modeled with 15 mph wind from the south-southwest. Note that this plume does not consider possible hydrogen fluoride levels. This image was produced using Open Street Map and Google Maps.

The analysis in this report assumes that only one battery unit fails or burns at a time and that gas release scenarios are consistent with UL 9540A testing. There are several conditions that may lead to worse consequences than those predicted by this model. These conditions include, but are not limited to, thermal runaway propagation exceeding the measured release rate and involvement of multiple units.

9 Limitations

- The study presented in this report is intended for use by client to assist with their decision making related to toxicity risks due to plume transport and evolution from Lithium-ion Battery Energy Storage Systems (BESS). This study specifically does not address other energy storage designs, feasibility of other toxic gas mitigation methods, or compliance to local codes and standards. The scope of the analysis was strictly limited to collection of data relevant to scope.

- The scope of services performed may not adequately address the needs of other users of this report, and any re-use of this report is at the sole risk of the user. This study is based on observations and information available at the time of the analysis. No guarantee or warranty as to future life or performance of any reviewed condition is expressed or implied.
- In the analysis, we have relied on documentation, including but not limited to facility design, BESS design, and other siting documents provided by the client. We cannot verify the correctness of this data and rely on the client for their accuracy. Although we have exercised usual and customary care in the conduct of this analysis, the responsibility for the design and manufacture of the product remains fully with the client.
- The methodology forming the basis of the results presented in this report is based on mathematical modeling of physical systems and data from third parties. Given the nature of these evaluations, significant uncertainties are associated with the various computations. These uncertainties are inherent in the methodology and subsequently in the generated results. Furthermore, the assumptions adopted do not constitute the exclusive set of reasonable assumptions, and use of a different set of assumptions or methodology could produce materially different results.

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A Appendix

1.1 Gas Release Rate

Module propagation time

$$t_{modulepropagation} = 2225.00000 \text{ second}$$

The amount of gas released by a cell in the cell-level test

$$V_{gascell} = 0.19200 \text{ meter}^3$$

Cells failed in module test

$$n_{cells} = 5$$

Average module release rate

$$r_{gasrelease} = V_{gascell} \cdot \frac{n_{cells}}{t_{modulepropagation}} = 0.19200 \text{ meter}^3 \cdot \frac{5}{2225.00000 \text{ second}} = 0.00043 \frac{\text{meter}^3}{\text{second}}$$

Density of the battery gas

$$\rho_{gas} = 0.89706 \frac{\text{kilogram}}{\text{meter}^3}$$

$$G = r_{gasrelease} \cdot \rho_{gas} = 0.00043 \frac{\text{meter}^3}{\text{second}} \cdot 0.89706 \frac{\text{kilogram}}{\text{meter}^3} = 0.00039 \frac{\text{kilogram}}{\text{second}}$$

$0.00038704758411451615 \frac{\text{kilogram}}{\text{second}}$

B Revisions

Table 8: Document revision history.

Revision	Date	Description
0.1	March 14 2025	Initial draft version submitted to client for review.
1.0	April 29 2025	Final draft with updates based on client comments.
1.1	May 9 2025	Final version updated based on client comments.
1.2	May 16 2025	Final version updated based on client comments.
1.3	August 14 2025	Distances measured from BESS enclosures.