Hazard Dynamics

Hidden Lakes BESS Plume Study

HD-24025-Stella-Plume-1.2

December 3, 2024

Prepared for:

League City

By:

Anna Jensen
Erik Archibald, Ph.D. P.E.
Kevin Marr, Ph.D. P.E.

Hazard Dynamics LLC
PO Box 1967
Pflugerville, TX 78691 USA

Contents

1 Introduction

This report describes the results of a plume dispersion study conducted for the Hidden Lakes BESS (battery energy storage system), which is being constructed by Stella Energy Solutions, LLC. in League City, Texas. The Hidden Lakes BESS site uses the Sungrow PowerTitan for lithium-ion battery energy storage. The purpose of a plume study is to identify and quantify potential risks associated with toxic gases produced by a battery energy storage system under abnormal conditions.

Where appropriate toxicity 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 Hidden Lakes BESS site as well as the energy storage system itself. Finally, the report will evaluate possible toxic gas scenarios and their consequences.

This analysis relies on the following information:

- Plans and location for the Hidden Lakes BESS site [1] [2] [3]
- Specifications for the Sungrow PowerTitan system [4] [5]
- UL 9540A Cell test report for cell model CB71173204EB, TUV Rheinland (Shanghai) Co., Ltd. report number CN225QAV 001 dated 1/28/2022 [6]
- UL 9540A Module test report for module model P573AL-121, P573BL-121, TUV Rheinland (Shanghai) Co., Ltd. report number CN22Q8G8 001 dated 3/11/2022 [7]
- UL 9540A Unit test report for unit model , TUV Rheinland (Shanghai) Co., Ltd. report number CN22216G 001 dated 3/19/2022 [8]

2 Background on Lithium-Ion ESS Toxicity Hazards

2.1 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 [9]. 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. For example, the clean agent Novec-1230, which is often used on ESS systems, can cause the generation of HF during fire conditions [10].

2.2 Review of Energy Storage Incidents with Toxicity Consequences

Battery energy storage systems are being built rapidly. According to the Electric Power Research Institute (EPRI) BESS Failure Event Database, there have been 79 incidents involving battery-based energy storage from October 2016 to the present [11]. Given this limited amount of data and a variety of evolving technologies, it is difficult to precisely determine the probability of system failure. However, these databases indicate that failure incidents do occur, although they are rare events.

The primary hazards associated with BESS failures are fire, explosion, and toxic gas or smoke plumes. Outcomes for incidents include interruption of service, equipment damage, loss of the entire structure, an offsite toxic plume, and explosions with possible casualties. Toxic smoke considerations have prompted offsite air quality monitoring in the U.S. and shelter-in-place warnings at incidents in Belgium, Australia, and the U.S. [12] [13] [14] [15] [16] [17] [18]. During thermal runaway of lithium-ion cells, flammable gases are released, which may accumulate and result in an explosion. Experiments have measured toxic gases including hydrogen fluoride (HF), hydrogen chloride (HCl), hydrogen cyanide (HCN), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and others [9]. However, there is little publicly available data for toxic components released during real-world incidents and which of these components pose the greatest hazard.

A few battery energy storage incidents involving toxicity consequences are described in this section. These descriptions are included to demonstrate what may occur in a real event, although past events may not necessarily be indicative of future events. All incidents described involve lithium-ion batteries.

Not only do the incidents described in this section demonstrate what has happened during past failure events, they may also indicate what is unlikely to happen. Although toxic gases may be released during a lithium-ion battery system failure event, to our knowledge none of the known incidents have involved deaths or serious injury due to the toxic gases. Although in some incidents those in proximity have experienced irritating odors, none seem to have experienced serious health effects due to toxicity. Like conventional fires, battery thermal runaway and fire incidents pose the greatest toxicity risk when very close to involved systems and populations farther away are likely to experience at most irritation, discomfort, or odors.

2.2.1 Victoria, Australia Incident

In Victoria, Australia a fire occurred at a newly constructed 450 MWh facility which was undergoing testing. The system consisted of 210 Tesla Megapack units. Two Megapack units burned completely. Figure 1 shows the two units during the fire. For two days the government issued an air quality warning due to the smoke plume. The fire was declared under control after three days. Firefighters deployed hose lines to cool off exposed units. Firefighters were on the scene for at least four days [13] [14].

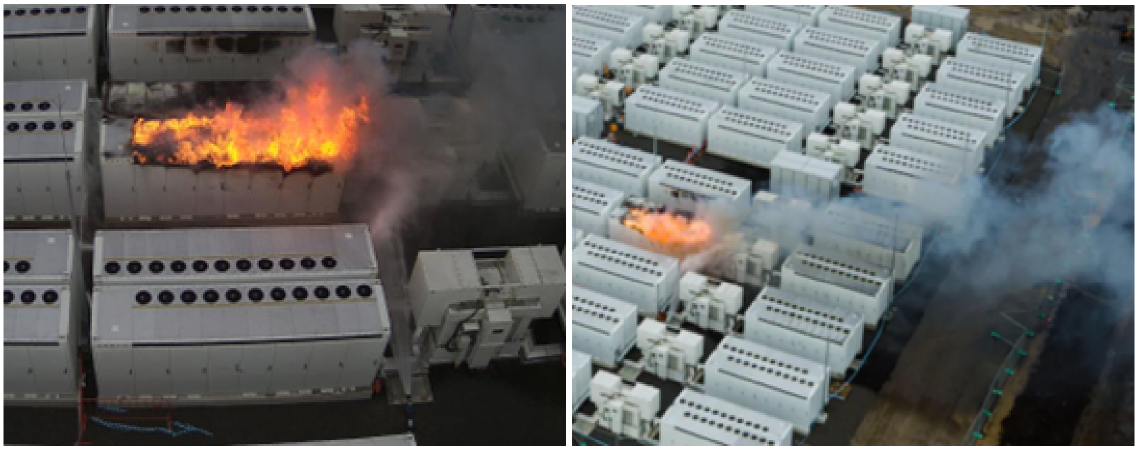


Figure 1: A Tesla Megapack fire at a large ESS project in Victoria, Australia.

2.2.2 Standish, MI Incident

On April 19th, 2021, a fire occurred inside a battery container at a facility in Standish, Michigan. Figure 2 shows smoke and gases coming from the container. The incident occurred in a new system that was not yet in service. A worker around the container noticed sparks and flashes and tried to extinguish the flames before safely escaping. The involved container was a complete loss, but the fire did not spread to the other seven ESS containers in the system. Fire department, hazardous materials, and emergency management personnel responded, and a shelter-in-place order was issued for a 1/2 mile radius downwind due to the gas and smoke produced. The shelter-in-place order was lifted less than four hours after the beginning of the incident [17].

Figure 2: An ESS Fire in Standish, MI USA.

2.2.3 Chandler, Arizona Incident

On Monday, April 18th, 2022, a battery fire broke out at the Dorman BESS Project in Chandler, Arizona. The 10-MW storage facility, housing 3,248 LG Chem lithium-ion batteries, is typically unmanned with periodic maintenance. The cause of the fire is unknown, but a sprinkler system was able to control it. Robots were sent inside the building the following Thursday to open doors and ventilate the structure. Firefighters maintained a defensive position against the fire given the hazardous materials inside the building. Businesses within roughly a quarter-mile area were asked to evacuate, and the nearest freeway was closed. The next day, the robots were sent back inside to measure gases before firefighters could enter [19].

2.2.4 Surprise, Arizona Explosion

The APS McMicken site was a 2 MWh NMC lithium-ion ESS in Surprise, Arizona. On April 19, 2019, one of the 27 racks in the building went into thermal runaway which led to an explosion that injured four firefighters. Figure 3 shows smoke and gas outside the building during the event. Thermal runaway began in a single cell. Within a few minutes, alarms were activated, circuit breakers were opened, and the clean agent suppression system discharged Novec 1230 extinguishing agent. The thermal runaway of that single cell propagated to other cells, eventually leading to thermal runaway of every cell in one rack. As each cell experienced thermal runaway, additional flammable and toxic gas was released into the building. On arrival, firefighters observed a low, white smoke with a strange smell. Firefighters used gas monitors to measure carbon monoxide at greater than 500 ppm and hydrogen cyanide at greater than 50 ppm around the perimeter of the site.

Figure 3: Smoke and gas at the APS McMicken site in Surprise, Arizona.

About three hours after the first runaway, firefighters opened the ESS door. Within a few minutes, a deflagration or explosion occurred. Firefighters described the deflagration as a loud noise and a jet of flame extending 75 ft outward and 20 ft vertically from the open door. During this event, the two firefighters by the door were thrown from their positions. One firefighter went through a chain-link fence and ended up in a bush about 70 ft from the door. The flame extended such that the bush the firefighter landed in was burning after the deflagration. The other firefighter near the door was thrown 30 ft. All four firefighters who had been near the deflagration lost consciousness and were taken to the hospital. The firefighters survived while suffering chemical and thermal burns, traumatic brain injury, broken ribs, broken legs, internal bleeding, spine damage, lacerations, and other injuries [20] [21].

2.2.5 Warwick, New York Incident

A lithium-ion battery fire started during a storm in Warwick, New York on the night of June 26, 2023 and continued to burn for at least two days (see Figure 4). Suppression units within the affected battery containers were activated. The batteries, which were manufactured by Powin, were reported to emit a strong odor that some compared to the smell of glue. Despite the strong smell, air quality measurements were reported to be within normal parameters. Air quality was monitored by hazmat crews and the Health Department. The Orange County Fire Coordinator stated, “In this case, the safest thing to do for everyone involved is to allow it to burn itself out.” County officials advised people within a quarter-mile of the site to stay indoors and keep windows closed as a precaution [22].

Figure 4: A fire in a Powin battery storage unit in Warwick, New York [22].

2.2.6 Lessons Learned from Toxicity Incidents

These incidents show that toxic gases can be released from failed battery systems, but in general the impact has been localized to areas in close proximity. Precautions such as sheltering-in-place or evacuation may be recommended near a lithium-ion battery energy storage system during a thermal runaway event. Toxic gases have been measured during testing and during actual failure events. However, Hazard Dynamics is unaware of serious health effects or death resulting from the toxicity of battery vent gas or combustion products during lithium-ion BESS failure.

2.3 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 [9]. 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 [23]. 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 [24].

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 [24]. 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 [25]. 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 [26]. 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

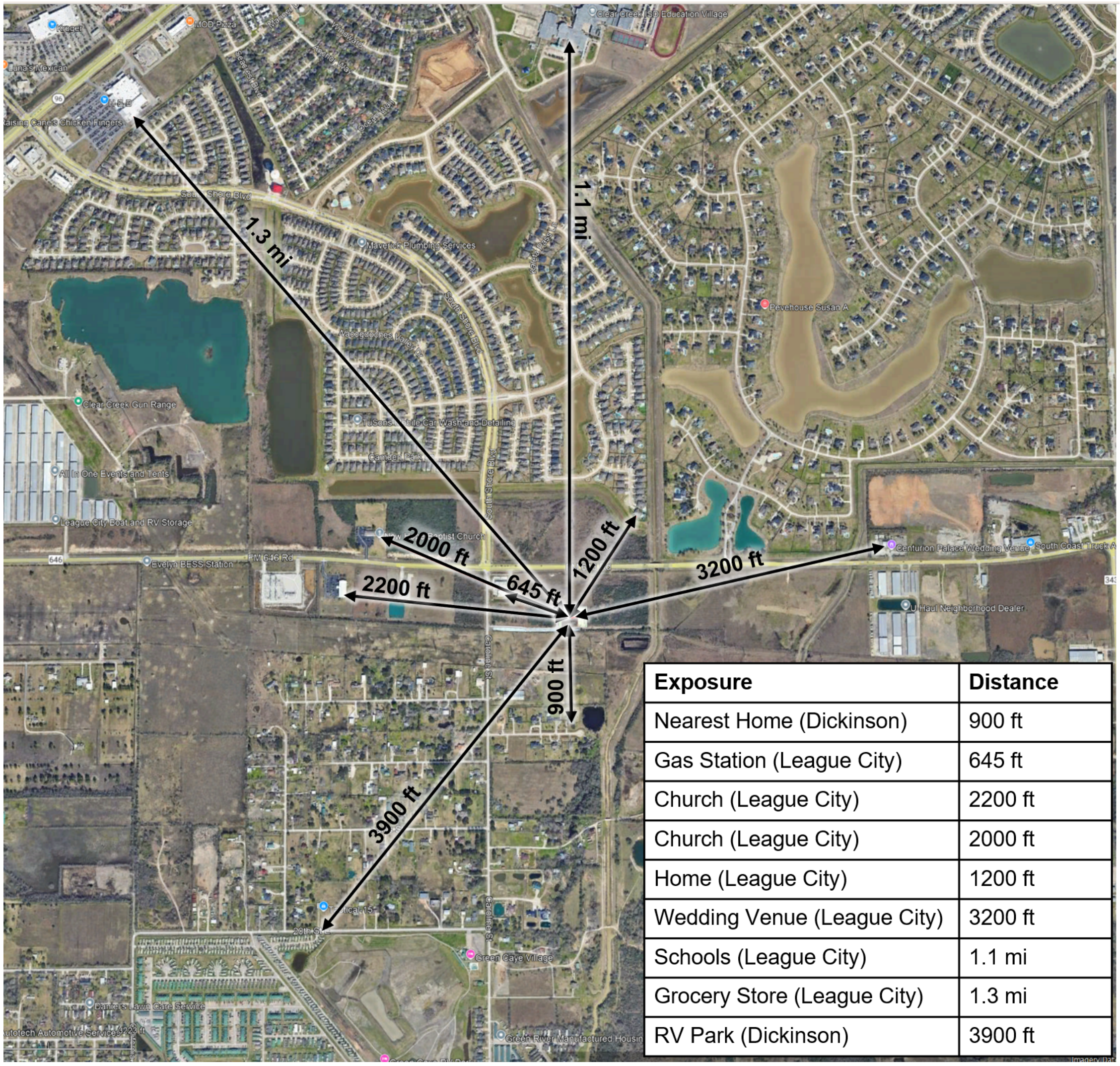
3 Site and System Descriptions

3.1 Site Description

The Hidden Lakes BESS project is a lithium-ion BESS facility that will be located in League City, Texas. It will be approximately 27 miles southeast of downtown Houston. The location of the site can be seen in Figure 5.

Figure 5: A map showing the location of the Hidden Lakes BESS site This image was taken from Google Maps 2024.

The project will be located on 1.7 acres of land and includes lithium-ion battery energy storage equipment [1]. The area immediately surrounding the Hidden Lakes BESS site is mostly open fields with some trees, but large neighborhoods and an RV park are in relatively close proximity. The nearest home is about 900 ft to the south of the site, and a gas station is 645 ft to the northwest. Notably, a group of schools is about 1.1 miles to the north of the site. The nearest home in League City is about 1200 ft north of the site. The site and its close surroundings are shown in Figure 6. Nearby exposures and their approximate distances from the BESS are also shown in Figure 6.



Exposure	Distance
Nearest Home (Dickinson)	900 ft
Gas Station (League City)	645 ft
Church (League City)	2200 ft
Church (League City)	2000 ft
Home (League City)	1200 ft
Wedding Venue (League City)	3200 ft
Schools (League City)	1.1 mi
Grocery Store (League City)	1.3 mi
RV Park (Dickinson)	3900 ft

Figure 6: A satellite view of the Hidden Lakes BESS site location and its surroundings. This image was taken from Google Earth 2024

3.1.1 Typical Wind Conditions

In case of a toxic gas release, it is expected that the impacted area would be downwind of the site. The two weather stations nearest the Hidden Lakes BESS site that provide historical data are the Pearland Regional Airport and Ellington Airport sites. According to historical wind information from 1998 to 2024 and 1970 to 2024, respectively, the prevailing winds generally come from the south-southeast (see Figure 7). The average wind speed ranges from 6.6 mph at Pearland Regional Airport to 7.1 mph at Ellington Airport. Peak wind speeds may exceed 20 mph. These peak wind speeds occur approximately 0.5% of the time at the Pearland Regional Airport site and 1.2% of the time at the Ellington Airport site. Based on historical conditions at both sites, winds are expected to be calm 17.9% to 23.5% of the time [27] [28].

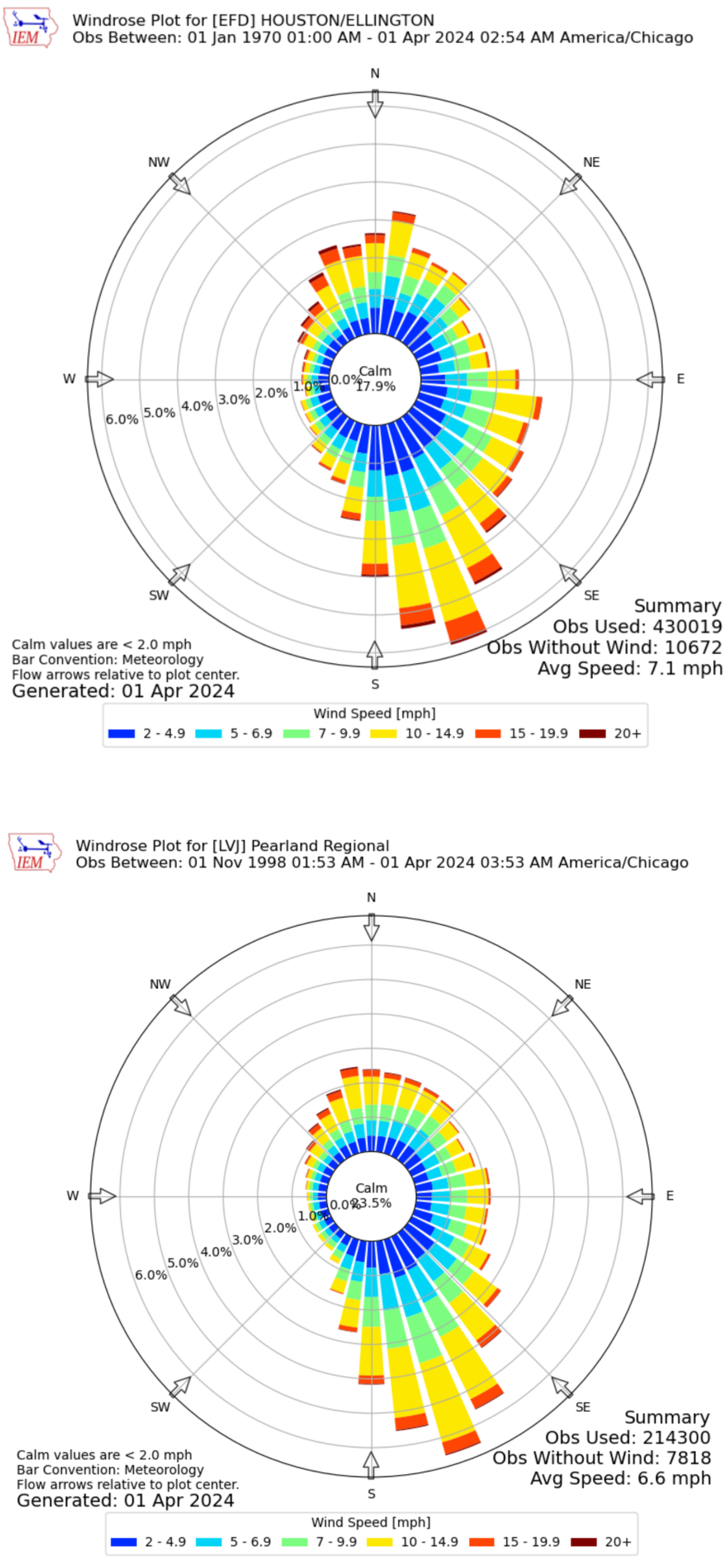


Figure 7: The wind roses for the Pearland Regional Airport and Ellington Airport weather stations, which are the two available weather stations near the Hidden Lakes BESS site. These images were taken from the Iowa State University Iowa Environmental Mesonet website [27] [28].

3.2 Energy Storage System Description

The Hidden Lakes BESS uses modular PowerTitan battery units made by Sungrow. These units contain two separate battery cabinets that each contain 24 modules of Ruipu Energy Co., Ltd lithium-ion cells for a total of 48 modules per enclosure. Each battery cabinet contains a smoke detector, a combustible gas detector, and a temperature detector. The PowerTitan enclosure also contains a liquid cooling unit, DCDC converters, a battery control panel (BCP), and an auxiliary power supply unit. The interior configuration of the PowerTitan can be seen in Figure 8, and the exterior of the enclosure can be seen in Figure 9 [4] [5].

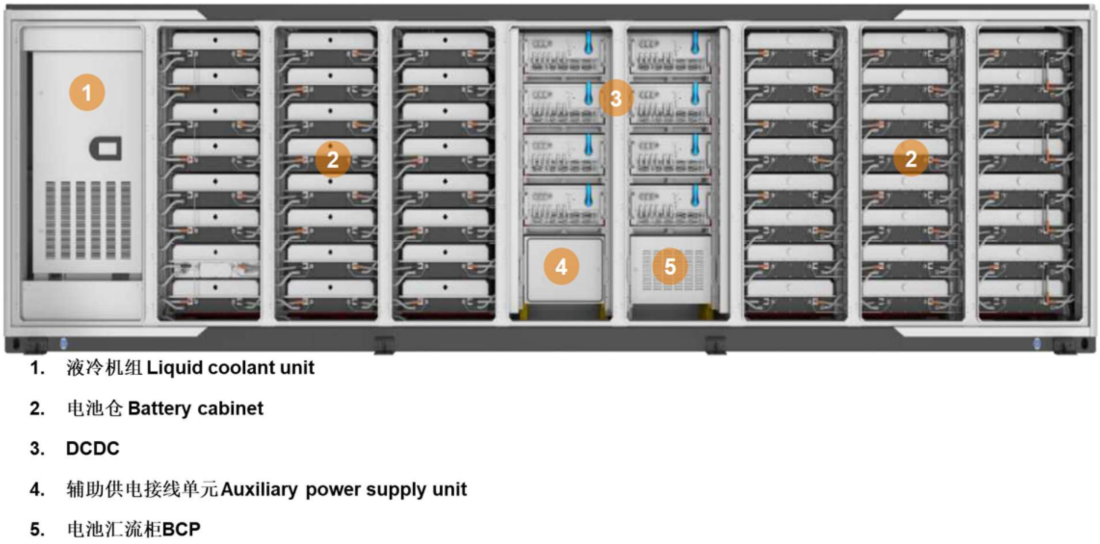


Figure 8: An image of the interior of the Sungrow PowerTitan battery storage system. [5].

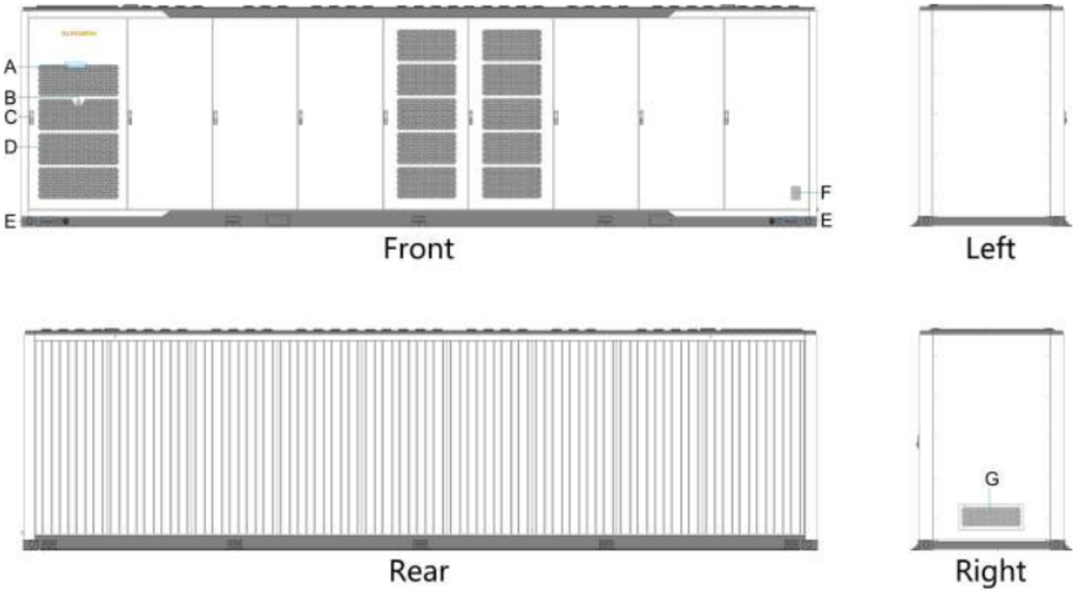


Figure 9: An image of exterior of the Sungrow PowerTitan battery storage system. [4].

The Hidden Lakes BESS will consist of 9 PowerTitan enclosures and will provide a total of 22410 kWh of energy storage [3]. The site also includes power conversion systems and other equipment. Figure 10 shows the planned layout of the site.

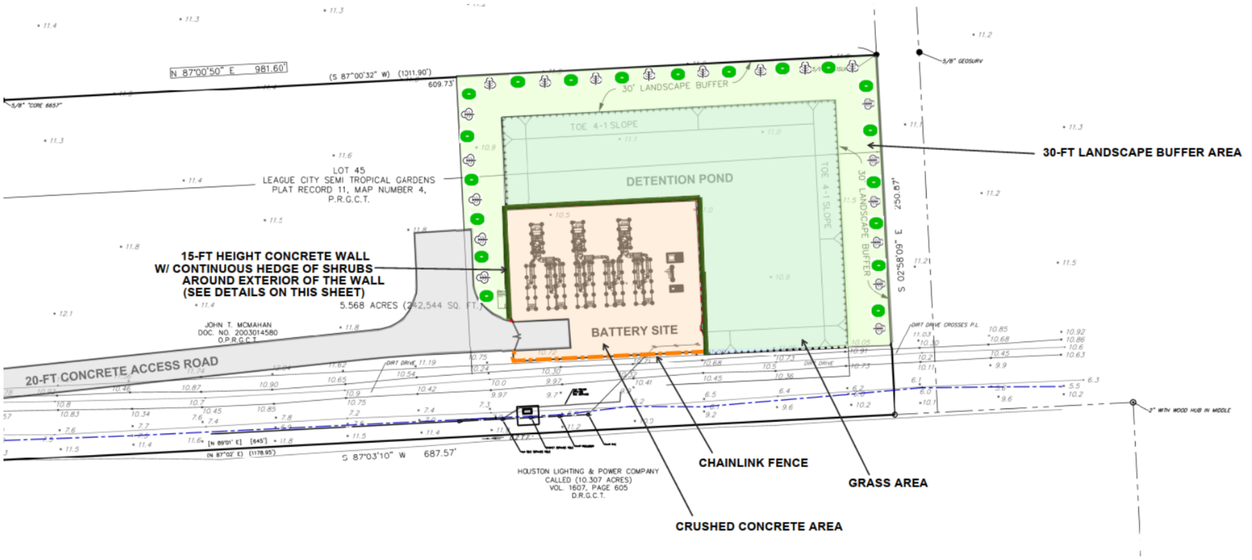


Figure 10: An engineering drawing indicating the planned layout of the Hidden Lakes BESS site, including the battery enclosures, power conversion systems, and other equipment [2].

4 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 [6], module-level [7], and unit-level [8] testing was reviewed. The results of these tests are described in Sections 4.1-4.3.

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 Ruipu Energy Co., Ltd cells indicates that 220 L of gas was captured from a single cell. Of the gas captured, 7.53% 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.

4.1 Cell Test

The system under consideration is comprised of Ruipu Energy Co., Ltd CB71173204EB cells, which are 280 Ahr lithium-ion LFP cells [6]. This cell was tested using the UL 9540A method. The results are given in the TUV Rheinland (Shanghai) Co., Ltd. report CN225QAV 001 dated 1/28/2022. Figure 11 shows a cell that was used for testing.

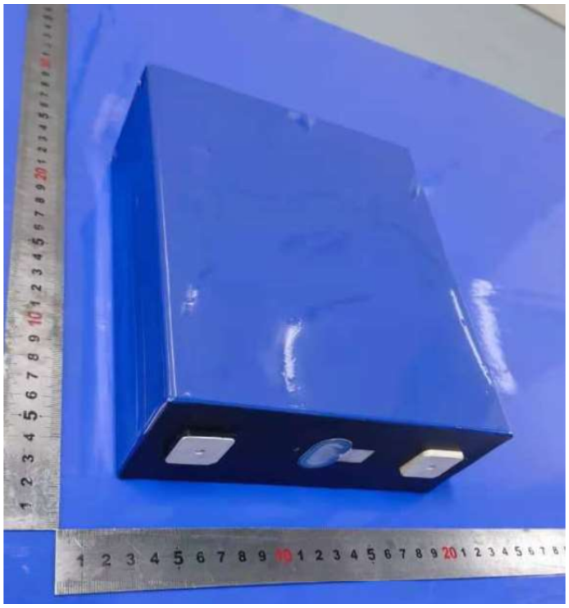


Figure 11: A Ruipu Energy Co., Ltd CB71173204EB cell that was used testing. This image was taken from the UL 9540A cell-level test report [6].

For UL 9540A testing, the CB71173204EB cells were heated until failure occurred. Cell details and results from UL 9540A testing are provided in Table 2.

Table 2: Key cell properties from the UL 9540A cell test [6].

Parameter	Value
Cell Manufacturer	Ruipu Energy Co., Ltd
Cell Model	CB71173204EB
Cell Chemistry	LFP
Cell Nominal Voltage	3.2 V
Cell Capacity	280 Ahr
Volume of Gas Released	220 L
Lower Flammability Limit (LFL) at ambient temperature	6.1%
Lower Flammability Limit (LFL) at venting temperature	5%
Burning Velocity (Su)	0.85 $\mathrm{m/s}$
Maximum Pressure (P_{max})	0.998 MPa

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 3: The gas composition from the UL 9540A cell test [6]. Model Volume Percent will be addressed in Section 5 later in this document.

Name	Formula	Experimental Volume Percent	Model Volume Percent
Carbon Monoxide	CO	7.530	7.534
Carbon Dioxide	$CO2$	25.660	25.673
Hydrogen	$H2$	49.350	49.375
Methane	$CH4$	6.370	6.373
Acetylene	$C2H2$	0.280	0
Ethylene	$C2H4$	7.140	7.144
Ethane	$C2H6$	1.840	1.841
Propene	$C3H6$	1.090	0
Propane	$C3H8$	0.390	2.061
C4 Total	$C4H10$	0.190	0
C5 Total	$C5H12$	0.090	0
C6 Total	$C6H14$	0.020	0
C7 Total	$C7H16$	0	0
Benzene	$C6H6$	0	0
Toluene	$C7H8$	0	0
Dimethyl Carbonate	$C3H6O3$	0	0
Ethyl Methyl Carbonate	$C4H8O3$	0	0

4.2 Module Test

The Ruipu Energy Co., Ltd cells are located inside of modules with model numbers P573AL-121, P573BL-121. A module was also tested using the UL 9540A method, and the results can be found in TUV Rheinland (Shanghai) Co., Ltd. test report CN22Q8G8 001 dated 3/11/2022. Each module contains 64 cells in a 1P64S configuration [7]. Multiple thermocouples were attached as seen in Figure 12.

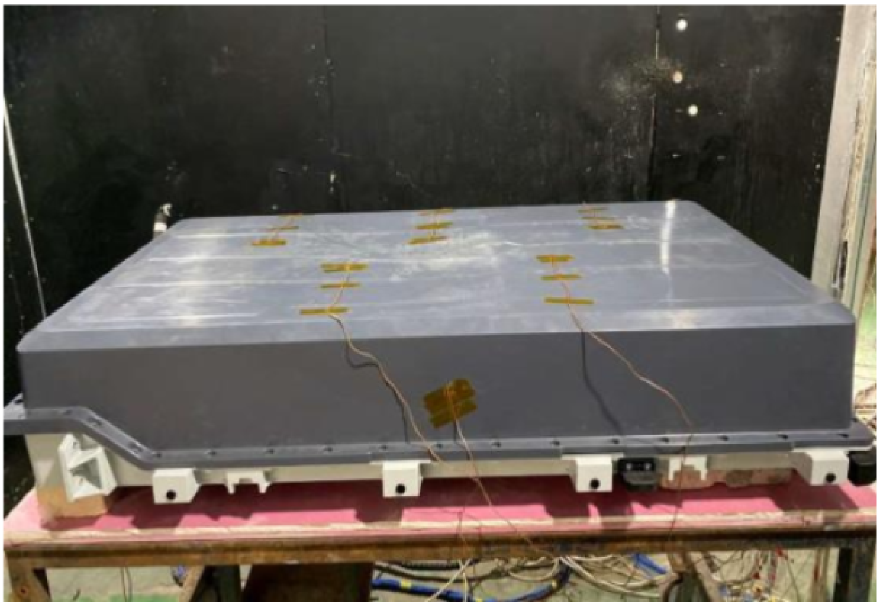


Figure 12: A module prepared for the UL 9540A test. This image was taken from the UL 9540A module-level test report [7].

Heaters were placed on cells 11, 12, and 13 in sub-module 2, which were chosen as the initiating cells due to their central location within the module. A diagram of the module construction, the location of the initiating cells, and thermocouple locations can be seen in Figure 13. The temperature time history for the test is shown in Figure 14.

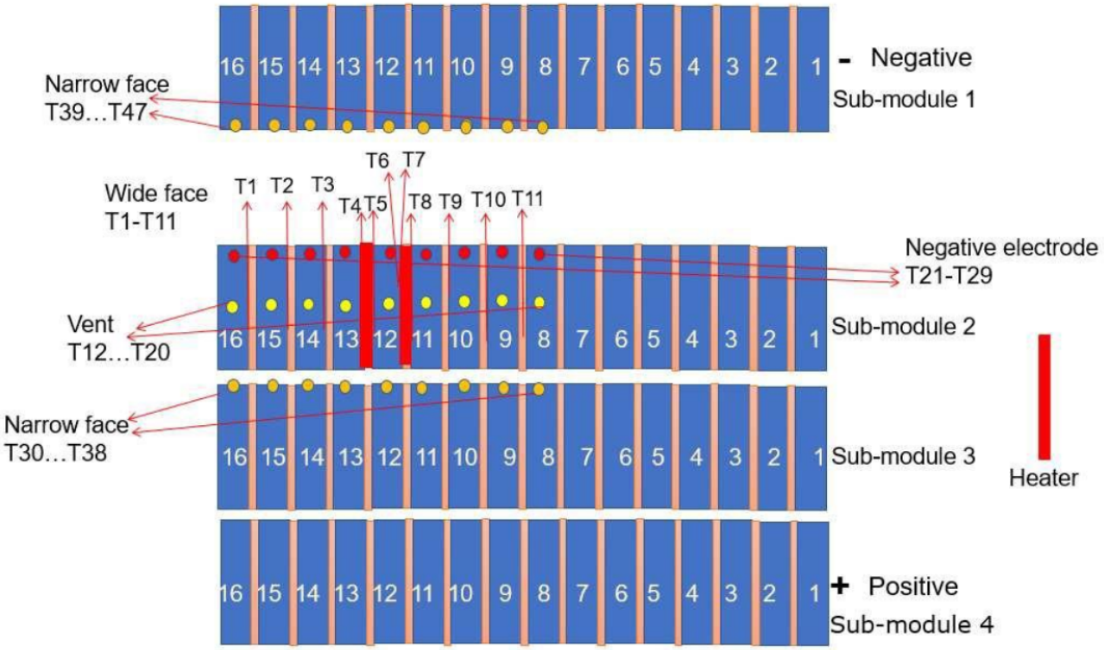


Figure 13: A diagram of the module setup for the UL 9540A test. This image was taken from the UL 9540A module-level test report [7].

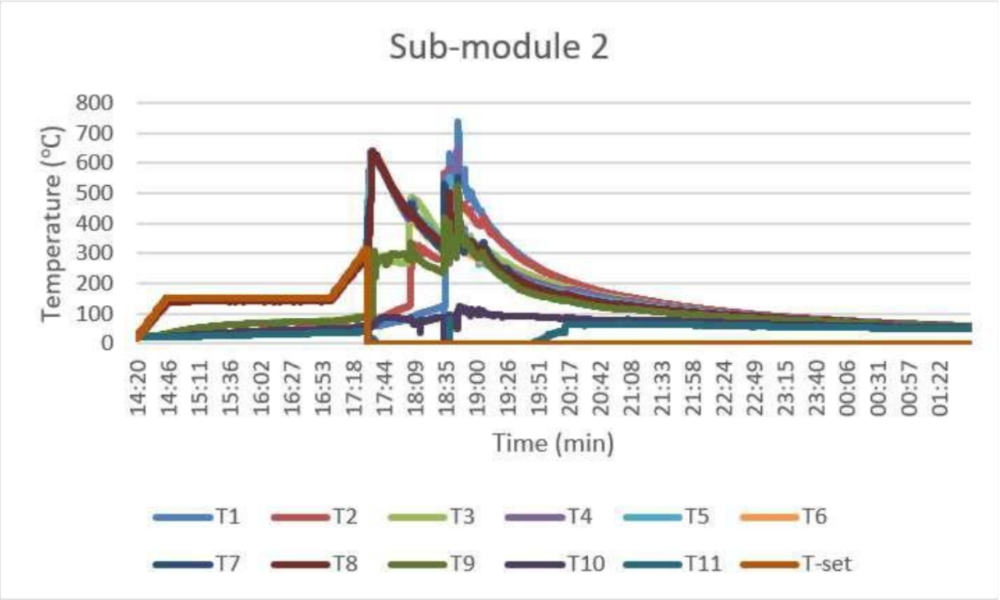


Figure 14: The temperature and voltage time history for cells 12 to 14 from the UL 9540A module test. This image taken was from the UL 9540A module-level test report [7].

The initiating cells were heated until thermal runaway occurred. The three initiating cells entered thermal runaway, which then propagated to four other cells. In total seven cells failed in thermal runaway, and five more cell cases were distorted [7]. External flaming was observed during the test, but not sparks or flying debris. Figure 15 shows the internal contents of the module after the test.

Figure 15: The internal contents of the module after the UL 9540A test. This image was taken from the UL 9540A module-level test report [7].

4.3 Unit Test

The UL 9540A unit test for unit models R286AL-121, R344AL-121, R573AL-123, and R688AL-123 is described in TUV Rheinland (Shanghai) Co., Ltd. report CN22216G 001 dated 3/19/2022. In this test, a unit comprised of six modules was tested [8]. 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 16, a diagram of the test setup is shown in Figure 17, and a picture of the test setup is shown in Figure 18.

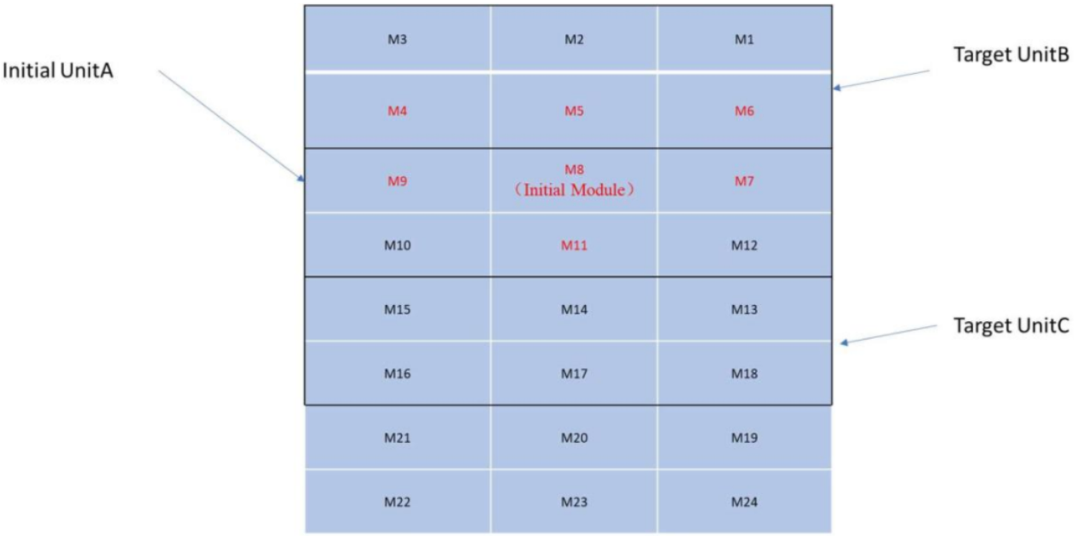


Figure 16: The initiating unit with the initiating module and target modules labeled. This image was taken from the UL 9540A unit-level test report [8].

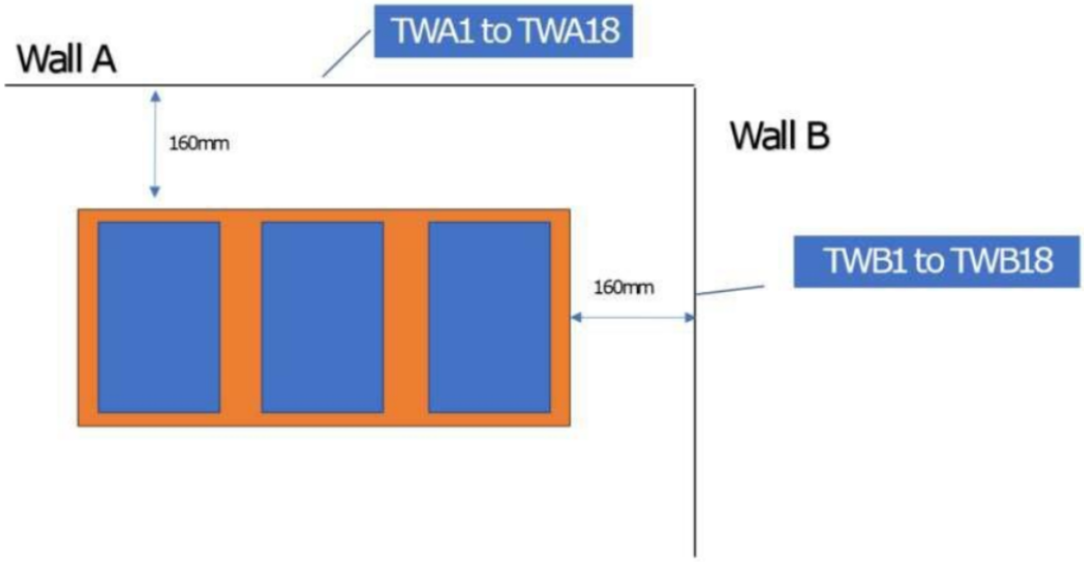


Figure 17: A diagram of the unit test setup. This image was taken from the UL 9540A unit-level test report [8].

Figure 18: A picture of the test setup. This image was taken from the UL 9540A unit-level test report [8].

Thermal runaway was initiated by activating the heaters on cells 11, 12, and 13 in sub-module 2 of the initiating module. Once thermal runaway began, the power to the heater was disconnected. Thermal runaway propagated from the three initiating cells to three other cells, making a total of six failed cells inside the initiating module [8]. Thermal runaway did not propagate outside of the initiating module. External flaming, sparks and debris were not observed.

5 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.

Two different heat release rates (HRR) were used to represent two different sizes of fire. The large HRR of 31.5 MW represents a full enclosure burning. This value was calculated using cell and module information from the UL 9540A cell and module tests [7] [6]. 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 3.15 MW was taken to be 10% of the large fire. This HRR was used to evaluate the consequences of a smaller fire in which the entire enclosure does not burn.

The non-fire scenario models the release of lithium-ion battery vent gas from a segment in the absence of burning. This scenario considers gas release without an active ventilation system. A gas release rate of 0.000285 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 [7] [6]. The calculation can be found in the appendix of this report. This gas release rate approximates the average release rate expected from seven failing cells as demonstrated in the module-level test. Actual gas release rates may be slightly above or below this value during portions of the thermal runaway process.

Each scenario assumes a steady-state release and was modeled for 300 seconds. The scenarios are summarized in Table 4. The wind speeds used in the models will be discussed in Section 5.1.

Table 4: Hidden Lakes BESS plume model scenarios.

Name	Wind Speed (m/s)	Mass Release Rate (kg/s)	HRR (MW)
Gas Release, Low Wind	1.5	0.000285	No Fire
Small Fire, Low Wind	1.5	0.174	3.15
Small Fire, High Wind	9	0.174	3.15
Large Fire, Low Wind	1.5	1.74	31.5
Large Fire, High Wind	9	1.74	31.5

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.

5.1 Model Setup

Computational fluid dynamics (CFD) models of possible toxic 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. 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 19.

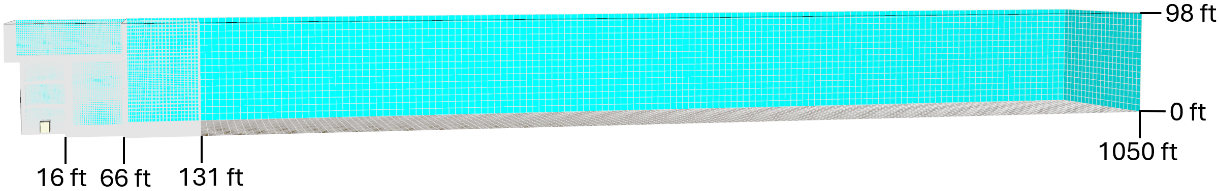


Figure 19: The model with the grid displayed. The grid varies in size from 0.25 m near the unit to 2 m starting 40 m away from the unit. The distances shown are measured from the front of the enclosure.

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 [29]. This wind speed was used in the model as well as the maximum wind speed for the Hidden Lakes BESS site, which is roughly 9 m/s or 20 mph (see Figure 7). High wind speeds occur approximately 0.5 to 1.2% of the time and 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.

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.

5.2 Results

Results were collected for battery vent gas concentrations (non-fire scenario) 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 20 shows the average vent gas and combustion product gas concentrations at 2 m (6.6 ft) above ground level at different distances downwind of the unit. Figure 20 shows that combustion product concentrations may remain elevated for a significant distance downwind of the unit if there are high winds. High wind speeds occur approximately 0.5 to 1.2% of the time at the Hidden Lakes BESS site. The large fire scenario with high wind has the highest combustion product concentrations up to approximately 300 ft from the unit, at which point the concentrations from the small fire scenario with high wind becomes greater. This figure also shows that for low wind scenarios, the battery vent gas and combustion concentrations are consistently at low levels a short distance outside of the battery enclosure. For the high-wind fire scenarios, overall combustion product concentrations are 270 ppm at 984 ft downwind from the unit, which is the end of the computational domain. 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. As the battery vent gas has a lower flammability limit (LFL) of 6.1% by volume (61000 ppm), the concentration of battery gas does not achieve a flammable condition beyond 2 m (6.6 ft) away from the BESS unit.

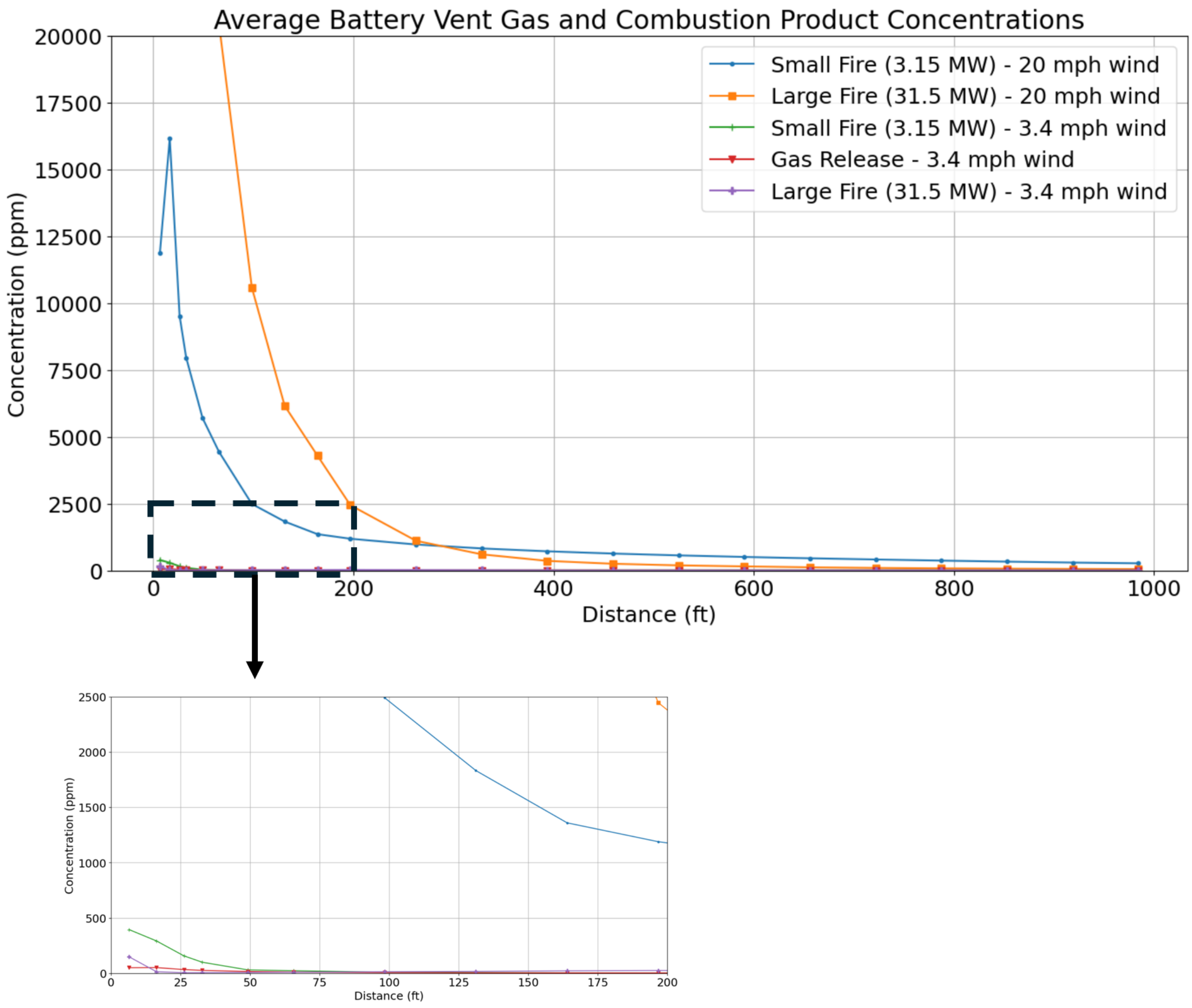


Figure 20: The average battery vent gas or combustion products concentration versus the downwind distance for different model scenarios.

Battery gas concentrations were very small away from the battery enclosure for the non-fire scenario, as shown in Figure 21.

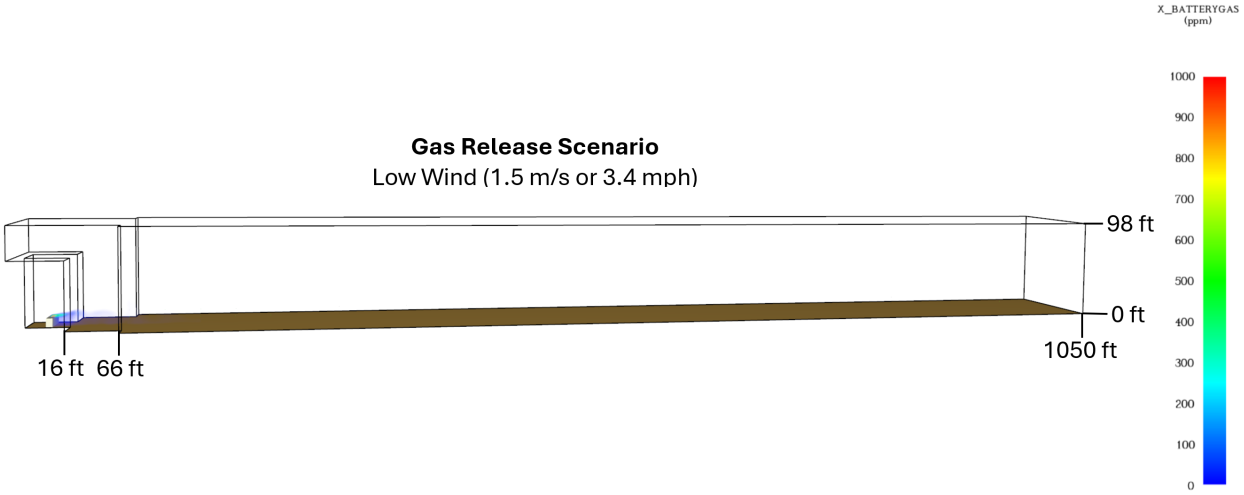


Figure 21: The model for a non-fire scenario with no ventilation and low wind speeds. X_BATTERYGAS is the concentration of battery vent gas in ppm. The distances shown are measured from the front of the enclosure.

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 22 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 23 shows that the combustion products rise immediately under low wind conditions.

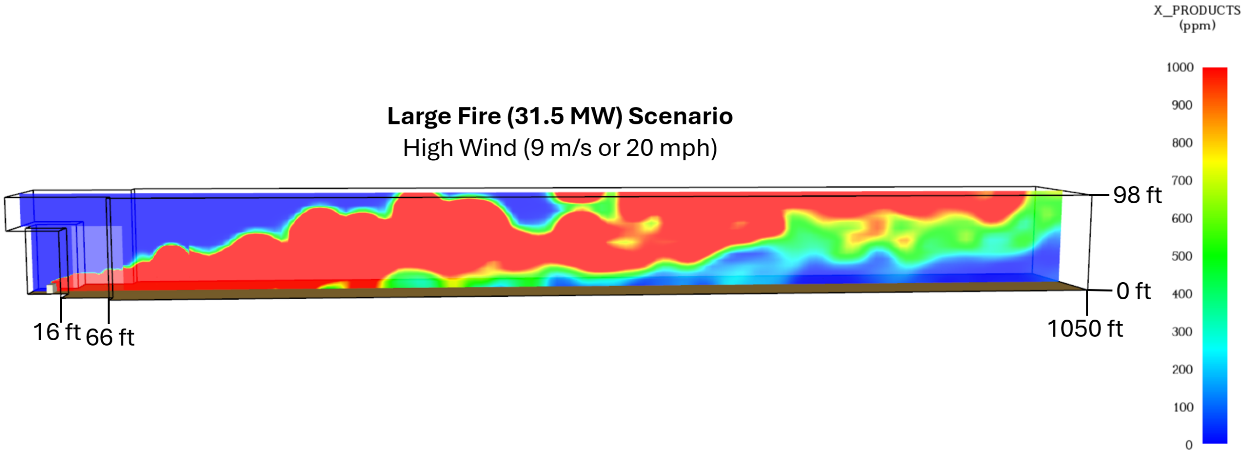


Figure 22: The model of a full unit fire with high wind conditions. In this scenario, the combustion products do not rise immediately due to high wind conditions, but they do rise over time while also mixing with air. X_PRODUCTS is the concentration of combustion products in ppm. The distances shown are measured from the front of the enclosure.

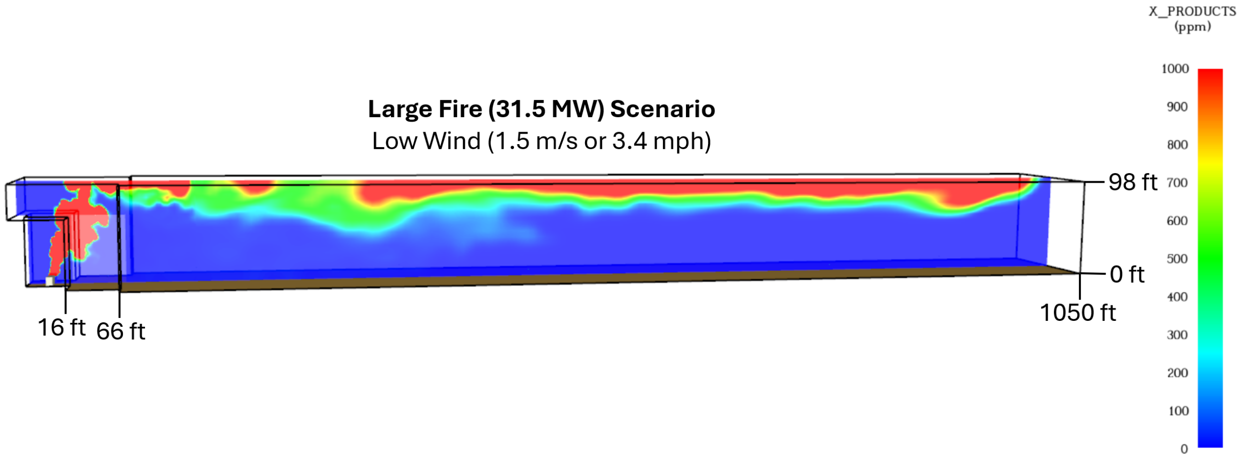


Figure 23: The model of a full unit fire with low wind conditions. In this scenario, the combustion products rise immediately and stay elevated for long distances. X_PRODUCTS is the concentration of combustion products in ppm. The distances shown are measured from the front of the enclosure.

Figure 24 shows that for a smaller fire with high winds, the combustion products stay near ground level for some distance before mixing occurs. Consequently, the combustion product concentration at 2 m (6.6 ft) from ground level far from the enclosure (greater than 300 ft away) is somewhat greater under high wind conditions for the small fire even though the overall combustion product concentration is greater for the large fire. 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 25.

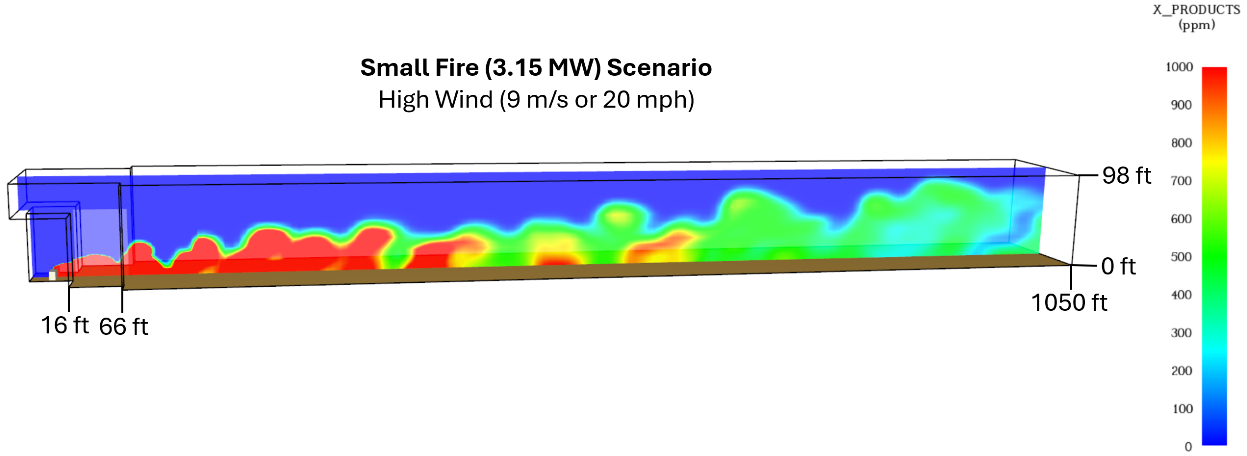


Figure 24: The model of a small fire with high wind conditions. In this scenario, the buoyant effects of the hot gas are partially overcome by the high wind such that the combustion products stay near ground level until mixing occurs. X_PRODUCTS is the concentration of combustion products in ppm. The distances shown are measured from the front of the enclosure.

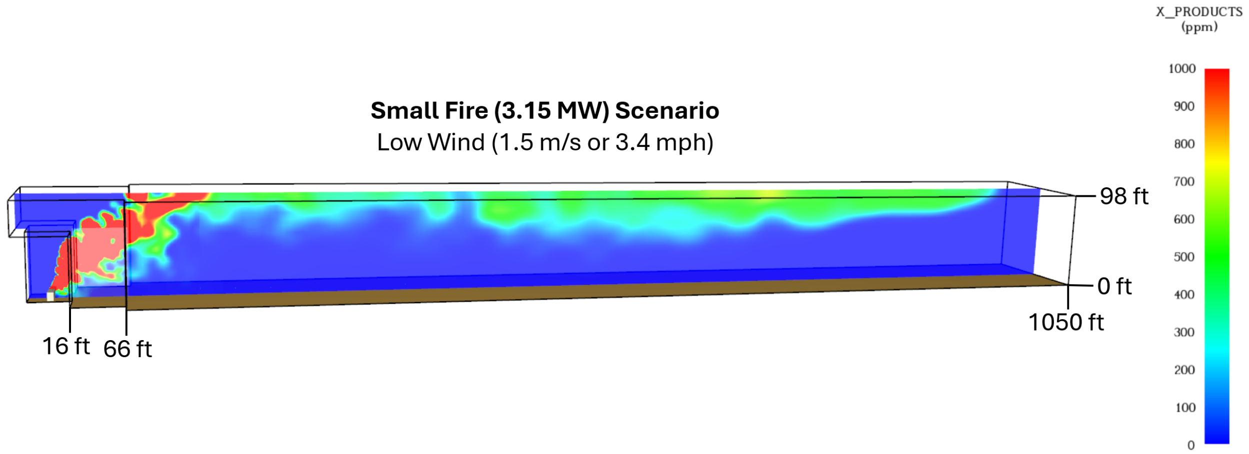


Figure 25: The model of a small fire with low wind conditions. In this scenario, combustion products rise to a lesser degree than in the large fire scenario. X_PRODUCTS is the concentration of combustion products in ppm. The distances shown are measured from the front of the enclosure.

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 listed the carbon monoxide concentration as being 7.53%. 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. The 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 both the gas release and fire scenarios is shown in Figure 26. The IDLH (Immediately Dangerous to Life and Health) level for carbon monoxide is 1200 ppm, the AEGL-3 (life-threatening health effects) level for a 30-minute exposure is 600 ppm, and the AEGL-2 (serious health effects) level for a 30-minute exposure is 150 ppm. Figure 26 shows that carbon monoxide concentrations exceed critical concentration levels only for fire scenarios with high wind speeds. High wind speeds occur approximately 0.5 to 1.2% of the time at the Hidden Lakes BESS site. Model results show that the carbon monoxide concentration may be immediately dangerous to life and health (above the IDLH level) up to approximately 5 m (16 ft), cause life-threatening effects (exceed the AEGL-3 level) up to approximately 12 m (39 ft), and cause serious health effects (exceed the AEGL-2 level) up to approximately 38 m (125 ft) from the burning enclosure. The EPA does not provide an AEGL-1 (temporary irritation) concentration for carbon monoxide.

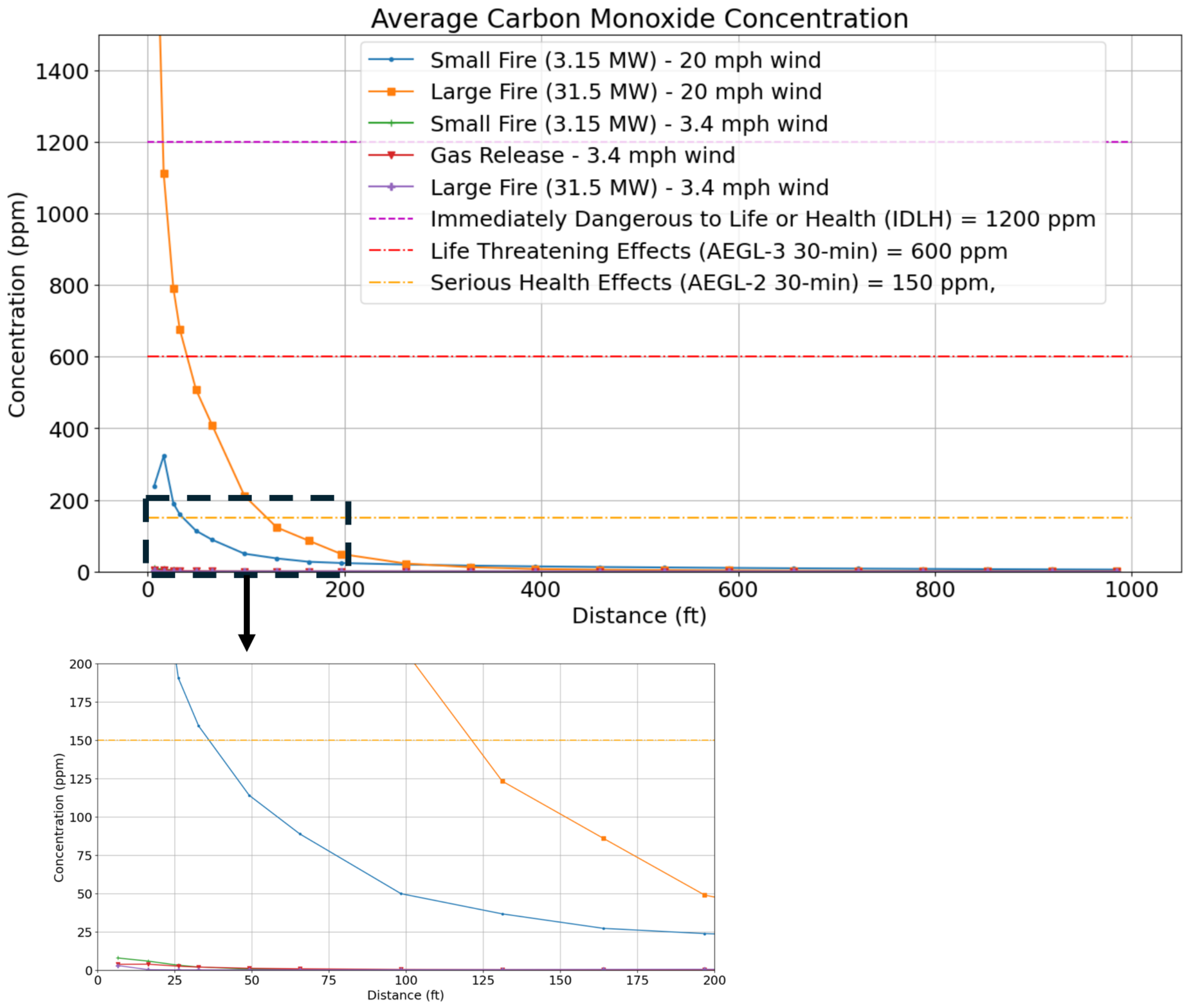


Figure 26: Average carbon monoxide concentrations as a function of distance for different battery vent gas or combustion product release scenarios. From this chart, we see that the carbon monoxide concentrations exceed critical levels only for fire scenarios with high wind. High wind speeds occur approximately 0.5 to 1.2% of the time at the Hidden Lakes BESS site.

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, 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 [9]. 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 may also 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 system.

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 Ruipu Energy Co., Ltd cells, the benzene and toluene concentrations were not measured.

6 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 7.53% 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 scenario 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 (exceed the IDLH level) up to 5 m (16 ft), cause life-threatening health effects (exceed the AEGL-3 level) up to 12 m (39 ft), and cause serious health effects (exceed the AEGL-2 level) up to approximately 38 m (125 ft) from the unit in a large fire scenario with high winds. High wind speeds occur approximately 0.5 to 1.2% of the time at the Hidden Lakes BESS 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. 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 may also 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. Similar fire-retardant plastics are commonly found in non-battery applications and may pose similar emission hazards during fire conditions. Other measured toxic gases make up only trace amounts of the battery vent gas. It is recommended that additional fire testing be performed in order to quantify what levels of hydrogen fluoride may exist for the PowerTitan. 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 [2] and publicly available maps indicate that the Hidden Lakes BESS is immediately surrounded by mostly open fields with some trees, but large neighborhoods and an RV park are in relatively close proximity. The nearest home is about 900 ft to the south of the site, and a gas station is 645 ft to the northwest. Notably, a group of schools is about 1.1 miles to the north of the site. The nearest home in League City is about 1200 ft north of the site (see Figure 6). Based on the model results, is it unlikely that the existing businesses or homes would experience critical concentrations of carbon monoxide in the event of a single BESS unit experiencing a failure event.

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.

Though such a situation is unlikely, officials may want to consider protective action guidance for this location in the event that people are nearby. 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, toxic exposure for occupants during an evacuation in proximity to the involved battery system is not likely to reach 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 27 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 Hidden Lakes BESS project site. These distances were measured from the outermost BESS enclosures. The modeled high wind speeds are 99th percentile based on the wind data from the Pearland Regional Airport weather station. Note that this figure does not consider possible hydrogen fluoride concentrations.

Maximum Distances for Toxicity Consequences with 99th Percentile 20 mph High Wind

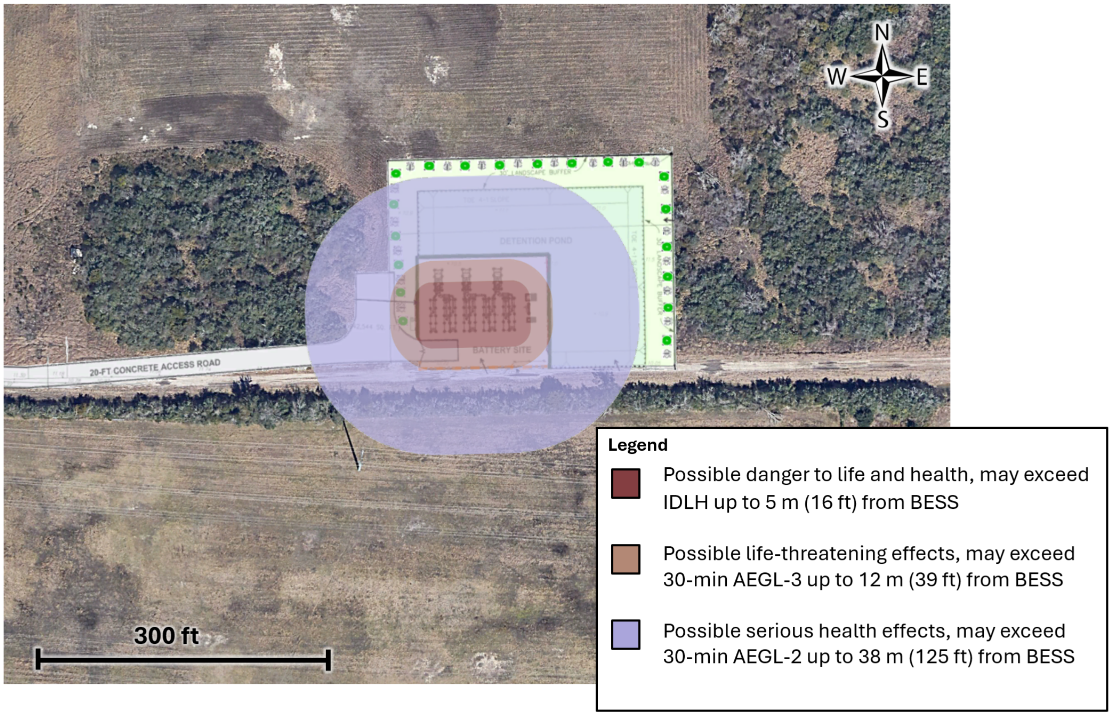


Figure 27: Satellite imagery of the immediate site surroundings with overlaid areas containing possible IDLH, AEGL-3, and AEGL-2 levels of toxic carbon monoxide gases with steady 9 m/s (20 mph) wind. This wind speed is 99th percentile based on the wind data from the Pearland Regional Airport weather station. No toxicity consequences were present for the modeled scenarios with low wind conditions. **Note that these buffers do not include possible hydrogen fluoride levels.** For the low wind scenarios, CO concentrations at 6.6 ft elevation do not exceed AEGL-2. Therefore, the map for the low wind scenario is not shown. This satellite image was taken from Google Earth 2024.

The buffers in Figure 27 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 28 shows a modeled plume for a high wind coming from the prevailing wind direction, which is south-southeast for the Hidden Lakes BESS site.

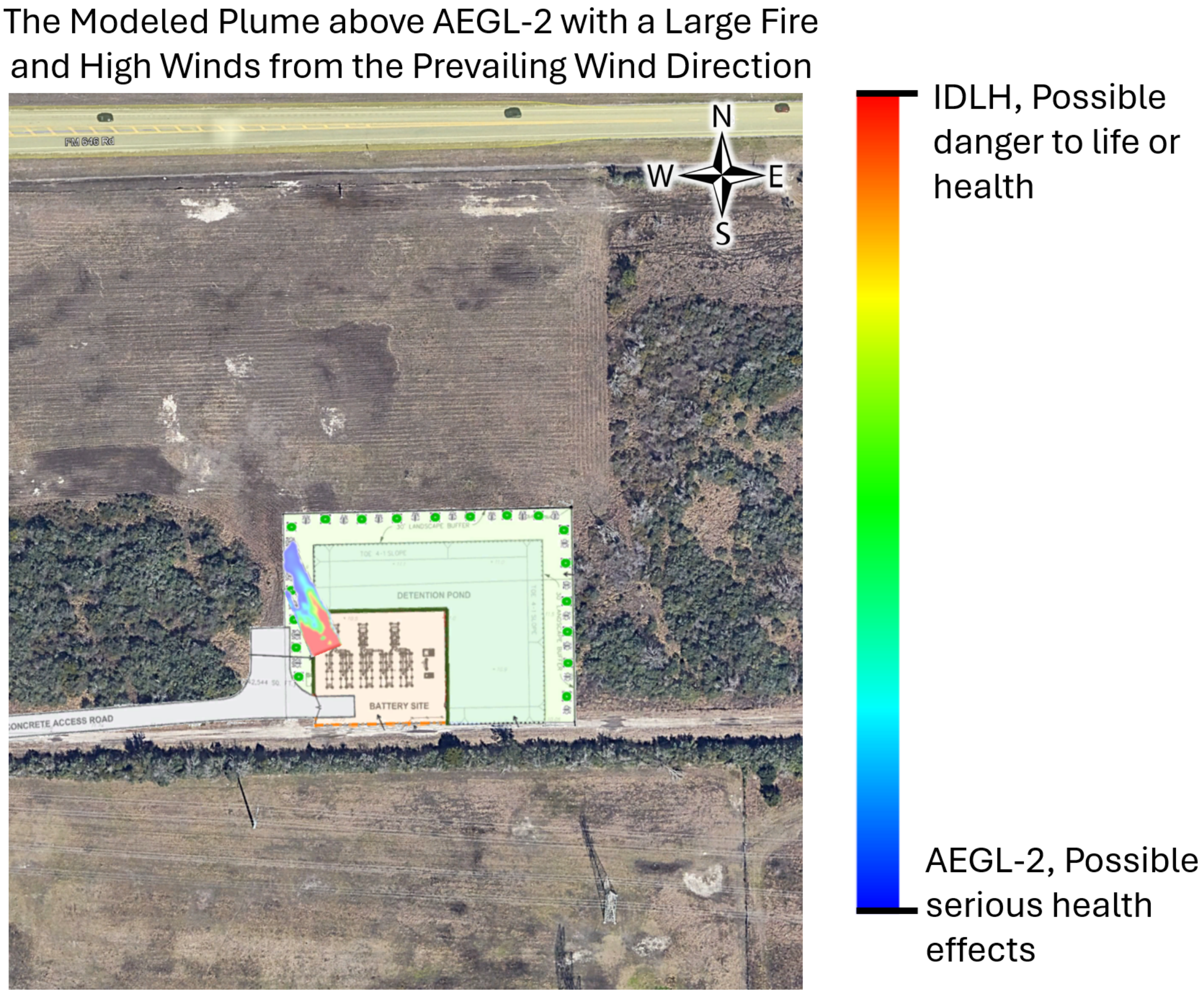

The Modeled Plume above AEGL-2 with a Large Fire and High Winds from the Prevailing Wind Direction

Figure 28: Satellite imagery of the immediate site surroundings with an overlaid plume that was modeled with 20 mph wind from the south-southeast. **Note that this plume does not include possible hydrogen fluoride levels.** Low wind scenario did not result in concentrations that exceed AEGL-2 and are not shown. This satellite image was taken from Google Earth.

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 and full unit fire 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, involvement of multiple units at the same time, or an inversion atmospheric condition. An inversion is a stable air mass where the air near the ground is cooler than the air above it rather than the usual condition of the air near the ground being warmer than the higher air. This can act to trap plumes and pollutants near ground level.

7 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.

References

[1] “Hidden lakes bess league city universal development application,” Tech. Rep., April 2024.

[2] “Hidden lakes revised layout for construction,” ALB Engineering Services, LLC, Tech. Rep., July 2024.

[3] “Hidden lakes electrical ifp,” Saber Power, Tech. Rep. 2308CG282-INDEX, July 2024.

[4] “Battery energy storage system manual,” Sungrow, Tech. Rep. ST2752-2293UX-US-SEN-Ver12-202204, July 1905.

[5] “Liquid cooling energy storage system cfd analysis,” TUVRheinland, Tech. Rep. CN22VHPH 001, April 2022.

[6] “Cell test report,” TUVRheinland, Tech. Rep. CN225QAV 001, January 2022.

[7] “Module test report,” TUVRheinland, Tech. Rep. CN22Q8G8 001, March 2021.

[8] “Unit test report,” TUVRheinland, Tech. Rep. CN22216G 001, March 2022.

[9] O. Willstrand, R. Bisschop, P. Blomqvist, A. Temple, and J. Anderson, “Toxic Gases from Fire in Electric Vehicles,” *RISE*, p. 240, 2020.

[10] 3M, “3M Novec-1230 Fire Protection Fluid Technical Data,” Feb. 2022. [Online]. Available: https://multimedia.3m.com/mws/media/124688O/3m-novec-1230-fire-protection-fluid.pdf

[11] D. Long, “BESS Failure Event Database - Storage Wiki,” Jul. 2021. [Online]. Available: https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database

[12] Garda, “Belgium: Battery fire and toxic smoke in Drogenbos November 11,” Nov. 2017. [Online]. Available: https://www.garda.com/crisis24/news-alerts/77816/belgium-battery-fire-and-toxic-smoke-in-drogenbos-november-11

[13] A. Blum, “Victorian Big Battery Fire: July 30, 2021,” p. 12.

[14] CFA, “Firefighters bring large battery fire near Geelong under control,” Aug. 2021. [Online]. Available: http://news.cfa.vic.gov.au/news/firefighters-bring-large-battery-fire-near-geelong-under-control

[15] rbb, “Brandenburg berät über Brandschutz für Solaranlagen,” Jul. 2021. [Online]. Available: https://www.rbb24.de/politik/beitrag/2021/07/brandenburg-neuhardenberg-brandschutz-batterie-solaranlage-feuerwehr.html

[16] RBB, “Hochgiftige Säure bei Brand von Stromspeicher ausgetreten,” Jul. 2021. [Online]. Available: https://www.rbb24.de/studiofrankfurt/panorama/2021/07/brand-solarspeicher-flugplatz-neuhardenberg.html

[17] M. Nafso, “All Clear for shelter in place advisory issued for Standish during hazardous materials fire,” Apr. 2021. [Online]. Available: https://www.abc12.com/2021/04/20/all-clear-for-shelter-in-place-advisory-issued-for-standish-during-hazardous-materials-fire/

[18] M. Urbanec, “No evacuations for battery fire at energy storage facility east of Grand Ridge Shaw Local,” Jul. 2021. [Online]. Available: https://www.shawlocal.com/mywebtimes/news/local/2021/07/19/no-evacuations-for-battery-fire-at-energy-storage-facility-east-of-grand-ridge/

[19] R. R. a. P. Vandell, “Fire crews tend to massive, smoldering battery in Chandler facility,” Aug. 2022. [Online]. Available: https://www.azcentral.com/story/money/business/energy/2022/04/21/fire-crews-tend-massive-smoldering-battery-chandler-facility/7405430001/

[20] D. Hill, “McMicken Battery Energy Storage System Event Technical and Recommendations,” DNVGL, Tech. Rep. 10209302-HOU-R-01, Jul. 2020, issue: 10209302-HOU-R-01. [Online]. Available: http://www.firefighternation.com/wp-content/uploads/sites/10/2020/07/document.pdf

[21] M. B. McKinnon, S. DeCrane, and S. Kerber, “Four Fireghters Injured In Lithium-Ion Battery Energy Storage System Explosion - Arizona,” p. 66.

[22] B. Gomez, “’It smells like glue.’ Lithium-ion battery fire at energy storage facility in Warwick burns for second day,” Jun. 2023. [Online]. Available: https://westchester.news12.com/fire-at-battery-storage-facility-burns-off-combustible-material

[23] D. A. Purser, “Combustion Toxicity,” in *SFPE Handbook of Fire Protection Engineering*, M. J. Hurley, D. Gottuk, J. R. Hall, K. Harada, E. Kuligowski, M. Puchovsky, J. Torero, J. M. Watts, and C. Wieczorek, Eds. New York, NY: Springer, 2016, pp. 2207–2307. [Online]. Available: https://doi.org/10.1007/978-1-4939-2565-0_62

[24] “29 CFR 1910.120 – Hazardous waste operations and emergency response.” [Online]. Available: https://www.ecfr.gov/current/title-29/subtitle-B/chapter-XVII/part-1910/subpart-H/section-1910.120

[25] “Immediately Dangerous to Life or Health | NIOSH | CDC,” Jul. 2020. [Online]. Available: https://www.cdc.gov/niosh/idlh/default.html

[26] O. US EPA, “Acute Exposure Guideline Levels for Airborne Chemicals,” Jul. 2022. [Online]. Available: https://www.epa.gov/aegl

[27] “Windrose plot for [lvj] pearland regional,” IEM, Tech. Rep. https://mesonet.agron.iastate.edu/sites/windrose.phtml?station=LVJnetwork=TX ASOS.

[28] “Windrose plot for [efd] ellington airpot,” IEM, Tech. Rep. https://mesonet.agron.iastate.edu/sites/site.php?station=EFDnetwork=TX-ASOS.

[29] U.S. EPA, “Risk Management Program Guidance for Offsite Consequence Analysis,” U.S. Environmental Protection Agency, Tech. Rep. EPA 550-B-99-009, Mar. 2009, issue: EPA 550-B-99-009. [Online]. Available: https://www.epa.gov/sites/default/files/2013-11/documents/oca-chps.pdf

A Appendix

1.1 Gas Release Rate

Since it was unclear exactly what times cells entered thermal runaway during the module test, the times smoke was released were used because these times resulted in a shorter time span than the "pop" times (making it more conservative). So, the time span was 17:29 to 18:44–taken from module test report page 16.

$$t_{modulepropagation} = 4500.00000 \text{ second}$$

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

$$V_{gascell} = 0.22000 \text{ meter}^3$$

Cells failed in module test

$$n_{cells} = 7$$

Average module release rate

$$r_{gasrelease} = V_{gascell} \cdot \frac{n_{cells}}{t_{modulepropagation}} = 0.22000 \text{ meter}^3 \cdot \frac{7}{4500.00000 \text{ second}} = 0.00034 \frac{\text{meter}^3}{\text{second}}$$

Density of the battery gas

$$\rho_{gas} = 0.83222 \frac{\text{kilogram}}{\text{meter}^3}$$

$$G = r_{gasrelease} \cdot \rho_{gas} = 0.00034 \frac{\text{meter}^3}{\text{second}} \cdot 0.83222 \frac{\text{kilogram}}{\text{meter}^3} = 0.00028 \frac{\text{kilogram}}{\text{second}}$$

$0.0002848032407816907\,3 \frac{\text{kilogram}}{\text{second}}$

B Revisions

Table 5: Document revision history.

Revision	Date	Description
0.1	September 18	Initial draft version submitted to client for review.
1.0	October 29	Final version with requested revisions.
1.1	November 15	Final version with considerations for site improvements
1.2	December 3 2024	Final version updated with new site plan