
# Plume Analysis

## Racho Viejo Battery Energy Storage System
## Santa Fe County, New Mexico

**July 14, 2025**
**Revision 0**


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## Rancho Viejo Battery Energy Storage
## Santa Fe County, New Mexico

July 14, 2025
Revision 0

**Project Location:** 4125 NM-14
Santa Fe, NM 87508

**Coffman Project Number:** 241470

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# EXECUTIVE SUMMARY

This report documents the air plume simulation modeling effort conducted to assess potential fire/thermal runaway related hazardous material releases from the Rancho Viejo battery energy storage system (BESS) facility. This analysis seeks to improve the understanding of the potential downwind flash fire, explosion and toxicological hazard during a battery failure incident. This report describes the analysis methodology, release scenarios, environmental conditions, modeling inputs, human health criteria and modeling results for the air plume study.

The Rancho Viejo Solar project, located in Santa Fe County, New Mexico, features a 192 MWh BESS yard which includes 38 AES model CEN-E5S BESS enclosures. The facility is located in a remote area with the currently closest off-site occupiable structure being located approximately 1.4 miles from the edge of the BESS yard.

## ANALYSIS METHODOLOGY

Phast air plume modeling software was used to simulate three battery failure scenarios to evaluate the possible health effects, flash fire hazard and potential explosion overpressures.

The analysis included evaluation of one pre-combustion phase gas release scenario and two combustion phase gas release scenarios. The pre-combustion phase thermal runaway scenario is intended to represent the gas release prior to flaming combustion or where ignition of the flammable gases never occurs. The limited and full involvement, combustion phase scenarios are reflective of battery failure events after ignition of thermal runaway gases occurs. The limited involvement scenario assumes a long duration event which consumes roughly half of the battery modules within the enclosure. The full involvement combustion phase scenario assumes a short duration, higher heat release fire event which consumes all the battery modules within the enclosure.

The health effects of the resulting gas plumes were evaluated using combined gas PAC-2 limits which generally accounts for exposure of unprotected persons, including sensitive individuals, to accidental releases of chemicals into the air. The health impacts are also evaluated at the combined gas EPRG-2 limits which do not account for sensitive individuals. The flash fire hazard was evaluated at the 25% of the lower flammable limit (LFL), LFL and upper flammable limit (UFL) concentrations. The potential explosion overpressure was evaluated at the 0.1 barg, 0.2 barg and 0.3 barg limits.

## ANALYSIS RESULTS

Plume modeling results of the pre-combustion phase scenario indicates that gas concentrations will exceed the limit required to cause health effects in unprotected persons, including sensitive individuals, distances closer than 86’-0” from the affected unit(s). The pre-combustion event scenario results in a flashfire hazard at distances closer than 6’-0” and does not pose a discernable vapor cloud explosion hazard.

Plume modeling results for combustion phase fire scenarios indicate that gas concentrations will exceed the limit required to cause health effects in unprotected persons, including sensitive individuals, at a distance closer than 1306’-0” from the affected unit(s) for the limited fire involvement case and 2256’-0” for the full fire involvement case.

## MAJOR ANALYSIS ASSUMPTIONS AND LIMITATIONS

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

1. Emission rate assumptions thermal runaway scenarios are based on an extension of UL9540A cell level testing data and emission rates published in literature. The emission rates in an actual event may vary from these values.
2. The final fate and transport of contaminates after the atmospheric concentrations have reduced below the toxic endpoints is not considered. This analysis specifically evaluates when gases are sufficiently dispersed into the atmosphere to a concentration below the identified toxic endpoints.
3. Additional contaminates beyond those considered in this analysis may be released during actual fire events. These may include materials currently known or may someday be determined to have negative health effects.
4. This analysis assumes all flammable gas released during flaming thermal runaway scenarios are fully consumed and not available to contribute to flash fire or explosion events.
5. Additional gases may be released outside of those directly considered in this analysis. These additional materials may act to dilute the effects of the gases that are considered in this analysis.
6. Battery fires are known to release contaminates in a variety of forms including, particulates (e.g. soot), aerosols and gases. This analysis considers all contaminants released are in the gas form only.
7. The emission rates assumed in this study are highly dependent upon the rate of thermal runaway / fire propagation from cell to cell. The scenarios developed in this analysis attempts to establish the bounds of the rate of thermal runaway propagation, however, variations beyond those considered in this analysis may exist.
8. This analysis attempts to consider worst case weather conditions but may not capture all extreme weather conditions that may be possible. The effect of rainout is not considered in this analysis.
9. All thermal runaway / fire events are assumed to occur when cells are at a 100% SOC.

**Note: The battery failure scenarios considered in this analysis represent conservative estimates of the maximum plausible consequences from battery gas dispersion plumes. All scenarios considered in this analysis assume ideal conditions to facilitate the largest release and minimal effectiveness of provided safeguards. While assessing the likelihood of these events is beyond the scope of this report, it is expected that, when hazard mitigation systems operate as intended, the actual consequences of any failure would likely be significantly less severe. The provided safeguards and mitigations are described in detail in the project Hazard Mitigation Analysis.**

## TABLE OF CONTENTS

## ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| AEGLs | Acute Exposure Guideline Levels |
| AHJ | Authority Having Jurisdiction |
| AICHE | American Institute of Chemical Engineers |
| BESS | Battery Energy Storage System |
| EPRGs | Emergency Response Planning Guidelines |
| FED | Fractional Effective Dose |
| HMA | Hazardous Mitigation Analysis |
| HRR | Heat Release Rate |
| LFL | Lower Flammable Limit |
| O&M | Operations and Maintenance |
| PAC | Protective Action Criteria |
| PCS | Power Conversion System |
| PPE | Personal Protective Equipment |
| SOC | State of Charge |
| SVOC | Semi-Volatile Organic Compounds |
| STP | Standard Temperature and Pressure |
| TEELs | Temporary Emergency Exposure Limits |
| UFL | Upper Flammable Limit |
| VCE | Vapor Cloud Explosion |
| VOC | Volatile Organic Compounds |

# 1.0 INTRODUCTION

This report documents the air plume simulation modeling effort conducted to assess potential fire/thermal runaway related hazardous material releases from the Rancho Viejo battery energy storage system (BESS) facility. During abnormal conditions, the lithium-ion batteries used in battery energy storage systems can potentially experience thermal runaway, which may release flammable and toxic gases that can ignite. This analysis seeks to improve the understanding of the potential downwind flash fire, explosion and toxicological hazard during a failure incident, to support effective planning and emergency response.

This report describes the analysis methodology, release scenarios, environmental conditions, modeling inputs, human health criteria and modeling results for the air plume study.

## 1.1 ANALYSIS GOALS AND OBJECTIVES

The purpose of this analysis is to establish the potential on-site and off-site flash fire and toxicological exposure hazards as a result of lithium-ion battery failure events. Events involving non-flaming thermal runaway and events which include flaming combustion will both be considered. Potential impacts of exposures will be evaluated assuming no personal protective equipment (PPE) is in use.

**Note: The battery failure scenarios considered in this analysis represent conservative estimates of the maximum plausible consequences from battery gas dispersion plumes. All scenarios considered in this analysis assume ideal conditions to facilitate the largest release and minimal effectiveness of provided safeguards. While assessing the likelihood of these events is beyond the scope of this report, it is expected that, when hazard mitigation systems operate as intended, the actual consequences of any failure would likely be significantly less severe. The provided safeguards and mitigations are described in detail in the project Hazard Mitigation Analysis.**

# 2.0 FACILITY DESCRIPTION

## 2.1 PROJECT SITE

The Rancho Viejo Solar project site is located south of Sante Fe County, New Mexico near New Mexico State Road 14. The BESS yard will be located on the northeast corner of the project site. Other notable areas on the project site include an electrical substation, an O&M building and contractor laydown areas. Figure 1 shows the project vicinity map.

The BESS yard is approximately 2.3 acres in size and will have a nominal total energy capacity of 192 MWh. The BESS yard will include a total of 38 AES CEN-E5S BESS enclosures, 19 power conversion system (PCS) units and an emergency generator. The proposed layout of the BESS yard is shown in Figure 2.


**Figure 1** – Rancho Viejo Solar Project Vicinity Map

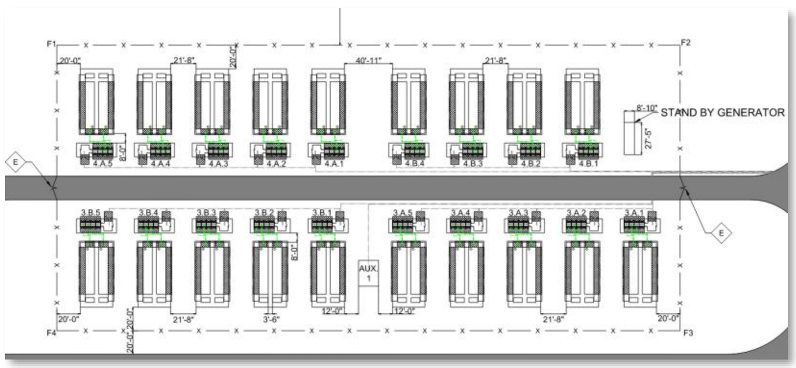


**Figure 2** – BESS Yard Layout

## 2.2 BESS SYSTEM EQUIPMENT

The AES CEN-E5S BESS enclosure incorporates lithium-ion battery modules, power electronics, and a battery management system. All components are pre-assembled within a non-occupiable ISO container enclosure. A rendering of the exterior of the enclosure is shown below in Figure 3. Details of the AES CEN-E5S enclosure are as shown in Table 1. Additional details regarding the CEN-E5S enclosure can be found in the Preliminary AES Rancho Viejo Hazardous Mitigation Analysis (HMA).

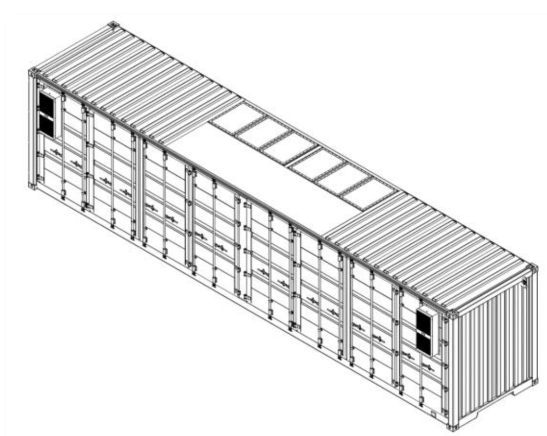

**Figure 3** – Rendering of AES CEN-E5S Enclosure

| Table 1: E5S BESS System Specification Summary | | | |
|---|---|---|---|
| ESS System Manufacturer: | | AES | |
| ESS Model #: | | CEN-E5S | |
| ESS Electrical Ratings: | | 8,068 kWh | |
| ESS Max Voltage: | | 1494 Vdc | |
| ESS Enclosure Dimensions: | | 40’-0” (L) x 8’-0” (W) x 9’-6” (H) | |
| ESS Layout / Construction: | | Non-Occupiable, Non-Walk-in<br>252 Modules per enclosure | |
| **Cell** | | **Module** | |
| Manufacturer: | Samsung SDI CO LTD | Manufacturer: | Samsung SDI CO LTD |
| Model No: | CP1495L101A | Model No: | E5S (MS3204L101A) |
| Electrical Rating: | 3.68 Vdc, 145 Ah | Electrical Rating: | 110.4 Vdc, 290 Ah |
| Chemistry: | $LiNiCoALO_2$ | Cells per Module: | 60 |
| Format: | Prismatc | Module Dimensions: | 388 x 1751 x 155 mm |

## 2.3 SURROUNDING AREAS AND KEY POINTS OF INTEREST

Potentially occupied areas adjacent to the Rancho Viejo BESS yard are shown in Figure 4, below. The facilities Operations and Maintenance (O&M) building, electrical substation and laydown areas are located between 170’-0” and 1000’-0” from the nearest edge of the BESS yard (See Figure 4 inset). These areas are within the control of the Rancho Viejo facility.

The closest off-site currently occupied areas is the Rancho San Marcos neighborhood residential area to the southwest of the facility and the Eldorado neighborhood residential area to the east of the facility. The nearest property edge of both of these residential zoned areas are more than 1.4 miles from the edge of the BESS yard. The closest off-site areas to the north and west which are currently occupied are more than 2 miles from the nearest edge of the BESS yard.

The area located approximately 1 mile north of the BESS yard is zoned as Planned Development which may be further developed at some point in the future.

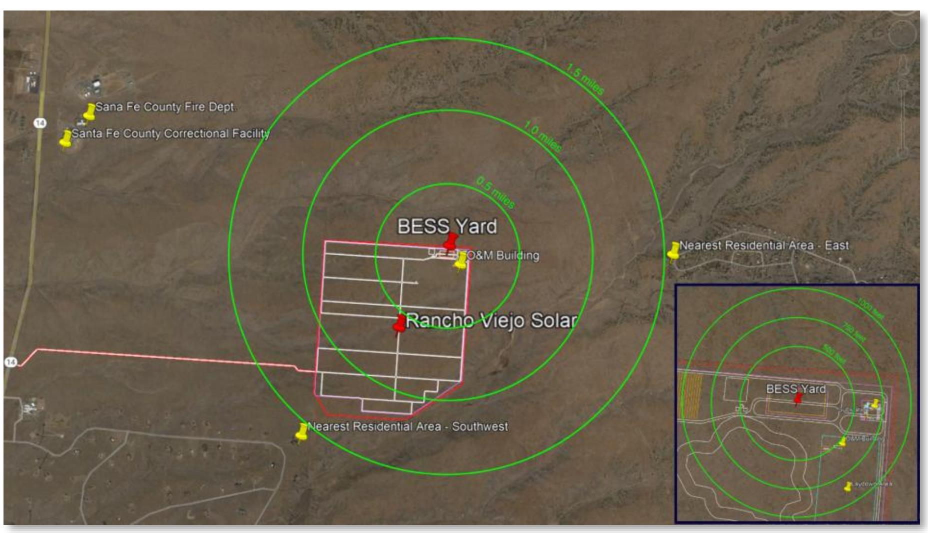


**Figure 4** – Occupied Areas Adjacent to BESS Yard
(Inset shows areas within 1000 feet from the center of the yard)

# 3.0 HAZARD ANALYSIS AND EVENT SCENARIOS

## 3.1 HAZARD ANALYSIS

When in thermal runaway, lithium-ion batteries can release large amounts of flammable and toxic gases. When battery failures occur in conditions similar to those simulated in the UL 9540A cell level test, up to 423 L of gas is expected to be release from each cell involved in the incident. During the initial stages of an incident, prior to ignition, the released gases include primarily hydrogen (H), carbon monoxide (CO) carbon dioxide ($CO_2$) and various hydrocarbons. The gases released during thermal runaway are expected to migrate from the enclosure to the outside environment via open deflagration vents, gaps in the enclosure structure and any enclosure access doors open at the time of the incident. When these gases are released to the environment they pose a potential toxicological, flash fire and explosion hazard to persons in the vicinity of the gas plume.

When ignition of the gases released during the initial thermal runaway event occurs, the resulting fire tends to consume a large amount of the flammable gases but the combustion of thermal runaway gases is expected to produce several toxic gas species, including, but not limited to hydrogen fluoride (HF), carbon monoxide, sulfur dioxide (SO2), hydrogen cyanide (HCN), nitric oxide (NO) and hydrogen chloride (HCl) [1] [2]. The production rate of these gases is primarily dependent upon the fire size and ventilation conditions. Similar to pre-combustion situations, the gases released during combustion events are expected to be released from the enclosure to the outside environment via open deflagration vents, gaps in the enclosure structure and any enclosure access doors open at the time of the incident.

In both the pre-combustion and combustion situations described above, the atmospheric dispersion of the released gas species will be dependent upon the atmospheric stability, wind speed and direction, height and buoyancy of gas release, major topography and landscape type as well as nearby structures.

A delayed ignition of an accumulated cloud of flammable gases outside the enclosure may result in either a flash fire or vapor cloud explosion (VCE) depending upon the conditions present at the time of ignition. A flash fire is the combustion of a flammable vapor and air mixture in which the flame passes through the mixture at a rate less than sonic velocity so that negligible damaging overpressure is generated [3]. Flash fires are typically characterized by a “wall of flame” progressing out from the point of ignition until the whole of the flammable cloud has burned; flash fires typically occur where the flammable gas cloud is in an unconfined and uncongested region where there is a delay between release and ignition [4]. If conditions are sufficient to accelerate flames to high velocities the result is a VCE. While the main consequence of a flash fire is direct flame contact, the main consequence of a VCE is an overpressure.

## 3.2 EVENT SCENARIOS

The following event scenarios have been developed to support the stated goals and objectives of this analysis given the review of hazards provided in the previous section. Table 5 in Section 5.5 provides a summary of the key parameters used to characterize each scenario described below.

The three event scenarios described below are intended to bound the maximum credible events that may occur at the facility, both in duration, fire size and emissions release rates. The scenarios are not necessarily intended to represent the most probable battery failure scenarios. Industry experience suggests that the level of hazard posed by the most frequent BESS battery failure events is somewhat less than the event scenarios considered in this analysis.

### 3.2.1 Scenario #1 - Pre-Combustion Phase

Event Scenario #1 considers a non-flaming thermal runaway scenario. This scenario is reflective of both the initial stages of a fire event, in the moments prior to ignition, and events where ignition of thermal runaway gases never occur due to the action of safety systems or insufficient energy to ignite the gas cloud.

This scenario assumes an initial thermal runaway event, involving a limited quantity of cells, similar to what is included in UL9540A testing. Propagation of thermal runaway is assumed to be via thermal abuse to adjacent cells. Thermal runaway propagation is assumed to be limited to the quantity of cells in a single module as sufficient heat transfer to continue propagation to additional modules is assumed to require flaming combustion.

During the UL9540A module level testing, thermal runaway propagated to all 60 cells in a module within a duration of 230 minutes. As the module level test included flaming combustion, it is recognized that a non-flaming event will have a longer duration associated with lower emission rates. Therefore, Event Scenario #1 assumes a thermal runaway event involving a single module over a 230-minute duration.

This scenario assumes that the event occurs while the batteries are at 100% state-of-charge (SOC). This is considered conservative as the gas volume vented during thermal runaway is proportional to the SOC [5].

This analysis will evaluate the toxic gas, flash fire and explosion overpressure hazard posed by this scenario.

### 3.2.2 Scenario #2 – Combustion Phase with Limited Fire Involvement

Event Scenario #2 considers a thermal runaway event involving combustion. This scenario reflects the expected conditions of Event Scenario #1 after ignition of the gas cloud has occurred. The quantity of gas released and gas buoyancy will be dependent upon the fire conditions and size. The provided safety barriers as described in the Coffman prepared Preliminary HMA report tend to make larger fire events less probable as compared to smaller incidents. Event Scenario #2 is intended to characterize the lower bound of a fire event, while Event Scenario #3 is intended to capture the behavior of the upper bound of what may be expected during a fire event.

The fire in Event Scenario #2 is expected to consume all batteries on one side of the enclosure fire separation (132 modules) over an 8-hour duration. This event is reflective of a ventilation limited fire occurring within the enclosure where enclosure integrity is intact with gas and other fire effluents being released to the outside environment via open deflagration vents, gaps in the enclosure structure. The 8-hour duration also aligns to the “let-it-burn” firefighting strategy that may be employed by emergency responders, where the fire is relatively contained to a single enclosure and a life hazard is not immediately present [6].

This analysis will evaluate toxic gas hazards only, as the flammable gases being released are assumed to be burned in the fire. The ventilation limited nature of the fire in Event Scenario #2 is anticipated to result in higher yields of toxic gases as compared to well-ventilated fire conditions.

### 3.2.3 Scenario #3 – Combustion Phase with Full Enclosure Fire Involvement

Event Scenario #3 considers a thermal runaway event involving combustion of the entire enclosure. The fire in this scenario is expected to consume all batteries over a 1-hour duration. This event is reflective of a fuel limited fire where the enclosure doors are open during a failure event or where the deformation caused by heat load from the fire event has significantly enlarged gaps in the enclosure structure to allow for additional ventilation to the fire. The fire is assumed to have breached the enclosure with flames and active combustion occurring outside of the enclosure itself. The 1-hour fire duration represents the fastest rate of fire propagation and the largest fire heat release rate anticipated.

This analysis will evaluate toxic gas hazards only, as the flammable gases being released are assumed to be burned in the fire. The increased fire size anticipated in Event Scenario #3 is expected to result in increased gas buoyancy as compared to the fire in Event Scenario #2.

## 4.0 MODELING METHODOLOGY

This project utilizes computer-based modeling to evaluate the near- and far-field impacts of the atmospheric dispersions associated with the gas release scenarios described in the previous section. Scenario modeling will compare the predicted dispersions against toxicological exposure limits, the flash fire hazard potential and potential deflagration overpressure limits.

### 4.1 SOFTWARE SELECTION

Based on the scenarios described in Section 3.2, the modeling software should be capable of modeling both positive and neutral buoyant plumes as well as dense gas plumes. Modeling should incorporate wind, temperature, humidity, atmospheric stability, terrain, and chemical parameters.

Phast (Version 9.0) atmospheric dispersion modeling software by DNV-GL was selected for this project. Phast utilizes an integral type Gaussian model. Phast evaluates different types of hazards (depending on the release scenario), toxicity, flammability, thermal radiation, and overpressure. Phast produces a threat zone estimate, which shows the area where a particular hazard (such as toxicity or thermal radiation) is predicted to exceed a specified level of concern at some time after the release begins. Phast is able to determine a threat zone under different weather and wind scenarios.

Phast is software that has been validated using experimental data by a number of individuals and organizations for both passive and heavy gas dispersion [7] [8].

EPRI identified Phast as one of three models that are suitable for modeling hazardous material releases from BESS fires in their analysis of currently available plume modeling tools [7]. Two potential limitations are noted regarding the use of Phast. Phast does not account for chemical reactions occurring within the plume. The chemical and physical evolution of gases and particles emitted to the atmosphere is beyond the scope of this project. Additionally, EPRI also notes that the research needed to appropriately evaluate this phenomenon as a current industry knowledge gap [7]. Phast also faces limitations when downwind obstacles, such as buildings, are considered. Terrain effects may be accounted for and building downwind effects may be simulated but large obstructions cannot be directly considered. Given the landscape and minimal number and size of buildings in the target area, this limitation is assessed to be not applicable to this project.

## 5.0 MODELING INPUTS

### 5.1 EMISSION RATES

#### 5.1.1 Scenario #1 - Pre-Combustion Phase Emission Rate

The pre-combustion phase scenario considers flammable and toxic gases vented from lithium-ion battery cells just prior to and after thermal runaway has occurred. Cell level UL9540A testing includes the collection of thermal runaway gases from a cell in an inert atmosphere to determine both the volume and composition of gases released. For the cells used in the E5S enclosure, gas composition is determined via gas chromatography. The gases collected in UL9540A cell level testing include $H_2$, CO, $CO_2$ and various hydrocarbons. UL9540A testing also found that 423 L of gas was released from a single cell during thermal runaway at 100% SOC under test conditions at standard temperature and pressure (STP). Scenario #1 assumes all gas is released from one lithium-ion battery module (60-cells) over a 230 minute duration.

The main constituents of thermal runaway gas include the gases measured in UL9540A testing. In wet gas, there will also be condensable components such as electrolyte solvent vapor and water. Studies have also suggested that there may be hundreds of other gas components that can be of toxicity concern, however data on these additional components is unavailable [9]. These additional gases are likely present in significantly lower concentrations as compared to those included in the UL9540A testing. One recent study published on the gases released during thermal runaway suggests that when combined, these other gases may amount to less than 5% of the total gas released during thermal runaway [10].

Hydrogen fluoride is another gas of potential concern. HF is not reported with UL9540A testing results. While HF gas can theoretically be produced, it reacts quickly to form other species [10]. A recent literature review article, which reviewed multiple studies, found that only one study has detected HF from a thermal runaway gas release in an inert environment [2]. However, this study used Fourier-Transform spectroscopy (FTIR) to monitor concentrations in real time before HF could react with other elements [11]. The lack of HF gas being reported when gas chromatography is used suggests that the HF gas may react quickly and not be present in major quantities within the plume, therefore, HF gas is not considered in the pre-combustion phase scenario. HF gas emissions are included in the combustion phase scenarios in relatively large quantities.

### 5.1.2 Scenario #2 – Combustion Phase with Limited Fire Involvement Emission Rate

When ignition occurs in well-ventilated environments, the flammable gases released from the battery cells, as measured in UL9540A testing, are generally consumed in the combustion process producing several other toxic gas species. Literature cites the battery fire gases of which are of a toxicity concern are CO, HF, HCl, HCN, $NO_X$ and $SO_2$ [9]. Phosphoryl fluoride ($POF_3$) has also been detected, but its toxicity level is not known [12]. As emissions from battery fires are not typically collected during UL9540A testing or other full scale fire testing, values from cell research as reported in scientific literature are used. The yield of toxic gas species values reported for well-ventilated fires used from this analysis are obtained from a literature review paper which summarizes the results of 11 separate studies. These values are provided in Table 2 [2]. Given that the reported values in literature do differentiate between battery chemistries, upper quarter tile values are used. A review of the literature data also suggests that the yield of some gas species is higher at lower SOC values. To reflect the worst case conditions the highest upper quarter tile values from literature were used regardless of the reported SOC.

It is recognized that under-ventilated fires will result in a higher yield of toxic products as compared to well-ventilated fires. The SFPE Handbook of Fire Protection Engineering classifies the range of toxic products evolved during flaming combustion into three main categories with respect to the relationship between ventilation and yield [13]. Halogen acid gases including HF and HCl remain nearly constant regardless of ventilation. Products which depend upon efficient oxidation such as $CO_2$, water vapor and nitrogen oxides ($NO_2$ and $NO_2$) have reduced yields when subject to under-ventilated conditions. To account for the reduced yields of NO and $SO_2$, the median literature reported values for well-ventilated fire are used in lieu of the upper quarter tile values. Products of inefficient combustion are expected to increase. A study of the yields of CO in fires in under-ventilated conditions suggested that CO yields are approximately four times larger than for well-ventilated fires [14]. This increased rate of CO production is further supported by the data provided in Table 62.20 of the SFPE Handbook of Fire Protection Engineering [13]. Another recent study regarding HCN determined that the yield may be up to nine times larger for fires in under-ventilated conditions as compared to well-ventilated conditions [15]. The gas yield values used in this analysis for under-ventilated conditions are shown in Table 2.

Scenario #2 assumes a fire involving 132 modules over an 8-hour duration. The assumed emission rate over this duration is shown in Table 2.

| Table 2: Estimated Pre-Combustion Phase Emission Rates (Scenario #2) | | | | |
|---|---|---|---|---|
| **Gas** | | **Well-Ventilated Battery Fire Yield per Literature (g/Wh)** | **Corrected for Under-ventilated Conditions (g/Wh)** | **Gas Emission Rate (g/s)** |
| Hydrogen Fluoride | HF | 0.0720 | 0.0720 | 10.57 |
| Carbon Monoxide | CO | 0.1300 | 0.5200 | 76.30 |
| Sulfur Dioxide | $SO_2$ | 0.0160 | 0.0130 | 1.91 |
| Hydrogen Cyanide | HCN | 0.0056 | 0.0504 | 7.40 |
| Nitric Oxide | NO | 0.0140 | 0.0090 | 1.32 |
| Hydrogen Chloride | HCl | 0.0300 | 0.0300 | 4.40 |

### 5.1.3 Scenario #3 – Combustion Phase with Full Enclosure Fire Involvement Emission Rate

Scenario #3 utilizes the same well-ventilated fire condition literature data as described in the above section. In this scenario the entire module is assumed to be consumed over a 1-hour duration. The emission rates used for Scenario #3 are shown in Table 3.

| Table 3: Estimated Pre-Combustion Phase Emission Rates (Scenario #3) | | | |
|---|---|---|---|
| **Gas** | | **Well-Ventilated Battery Fire Yield per Literature (g/Wh)** | **Gas Emission Rate (g/s)** |
| Hydrogen Fluoride | HF | 0.0720 | 161.36 |
| Carbon Monoxide | CO | 0.1300 | 291.34 |
| Sulfur Dioxide | $SO_2$ | 0.0160 | 35.86 |
| Hydrogen Cyanide | HCN | 0.0056 | 12.55 |
| Nitric Oxide | NO | 0.0140 | 31.38 |
| Hydrogen Chloride | HCl | 0.0300 | 67.23 |

## 5.2 GAS RELEASE HEIGHT, VELOCITY AND TEMPERATURE

For the pre-combustion scenario, the gas emissions are assumed to be released from the enclosure at ambient temperature. The effective release height is assumed to be consistent with the height of the enclosure. Anecdotal accounts of pre-combustion thermal runaway events suggest that the gas released is generally cool with little vertical movement, hanging around as a white fog [16]. It is assumed that the hot gases released from battery cells in this scenario, rapidly cool as they expand and mix with the air within the enclosure. Without the heating from combustion, the gas release temperature when gases leave the enclosure is anticipated to be minimally elevated from the normal conditioned air temperature within the enclosure. Based on this, for Scenario #1, a vertical velocity of 1 m/s is assumed with a gas release temperature of 28°C at a release height of 2.67 m (9'-6").

For the combustion phase scenarios, the effective release height, velocity and temperature are all dependent upon the average heat release rate (HRR) of the associated fire. Given the previously assumed fire duration and quantity of battery cells to be consumed in the fire, an approximation of the total heat release may be used to ascertain the average fire HRR. Average total heat release values for NCA batteries can be found in scientific literature. Analysis of data available from a study which reviewed lithium-ion fire meta-data, suggests a total heat release to electrical energy ratio of 12 may be appropriate [17]. Application of this ratio, given the quantity of cells to be consumed and previously discussed fire durations results in a 6,300 kW fire HRR for the limited fire involvement scenario and a 96,800 kW fire HRR for the full enclosure scenario.

Turbulent fire plume theory calculation methods may be used to estimate the gas release characteristics using the fire HRR. These calculation methods are described in the SFPE Handbook of Fire Protection Engineering Chapter 13 [18]. These equations are summarized below

$$z_0 = 0.083Q^{2/5} - 1.02D_e \tag{1}$$

$$z_l = 0.234Q^{2/5} - 1.02D_e \tag{2}$$

$$T_{cp} = T_o + 9.1\left(\frac{T_o}{gc_p^2\rho_o^2}\right)^{1/3}\frac{Q_c^{2/3}}{(z-z_o)^{5/3}} \tag{3}$$

$$u_o = 3.4\left(\frac{g}{c_p\rho_oT_o}\right)^{1/3}Q_c^{1/3}(z-z_o)^{-1/3} \tag{4}$$

where

$z_o$ = distance to virtual origin (m)

$Q$ = fire HRR (kW)

$D_e$ = effective fire diameter (m)

$z_l$ = limiting elevation (m)

$T_{cp}$ = absolute centerline plume temperature at elevation z, (K)

$T_o$ = absolute ambient temperature (K)

$c_p$ = specific heat of plume gas (1.0 kJ/kg-K)

$\rho_o$ = density of ambient air (kg/m$^3$)

$g$ = acceleration of gravity (9.81 m/s$^2$)

$Q_c$ = convective HRR (kW) $Q_c = 0.7Q$

$z$ = distance above base of fire (m)

$z_o$ = distance to virtual origin (m)

$u_o$ = velocity at plume centerline

For Scenario #2, the gas release height is assumed to be the height of the enclosure, the resulting plume temperature is 486°C. The vertical velocity is shown to be approximately 1 m/s. Given the fire HRR for Scenario #3, flames are assumed to be exiting the enclosure. Applying equations (1) through (4) results in a flame height and effective gas release height of 19.05 m, a plume temperature of 486°C and an upwards velocity of 1.68 m/s.

## 5.3 ATMOSPHERIC CONDITIONS

Known weather conditions for the project site are given in Table 4 as obtained from 2021 ASHRAE Climate Design Conditions utilizing the closest weather station to the project site in Santa Fe, NM.

| Table 4: Site Weather Conditions | |
|---|---|
| Average Temperature | 11.4°C |
| Maximum Temperature (5-year) | 37.0°C |
| Average Relative Humidity | 47% |
| Average wind speed | 4.0 m/s |

Weather conditions at the time of the release have a major influence on the extent of dispersion. The primary factors are the wind speed and atmospheric stability. Atmospheric stability is an estimate of the turbulent mixing of the atmosphere. Stable atmospheric conditions lead to the least amount of mixing and unstable condition to the most. The atmospheric conditions are normally classified according to six Pasquill stability classes, denoted by letters A through D. Stability class A represents the least stable conditions while F represents the most stable. The Pasquill stability classes are correlated to wind speed and the quantity of sunlight.

The highest modeled concentrations in off-gassing and fire scenarios occur during calm wind conditions; the concentrations become disproportionally higher as zero wind speed is approached [1]. Increasing winds act to dilute gas plumes faster with larger quantities of air. Common atmospheric wind speed conditions used for consequence analysis studies are D at 3 m/s and F at 1.5 m/s as these generally relate to the worst case scenario when evaluating the effects of plume dispersion [19]. This is also generally in alignment with the guidance provided in the EPRA Risk Management Guidance for Offsite Consequence Analysis document [20]. The sensitivity analysis described in Section 8.0 of this report determined that 2.0 m/s wind speeds generate worse case conditions at class F stability conditions for Scenarios #1 and #2, while 1.5 m/s is worse case for Scenario #3. This analysis will evaluate scenarios at stability class D at a wind speed 3 m/s and stability class F at a wind speed 2.0 m/s for Scenarios #1 and #2, and at stability class D at a wind speed 3 m/s and stability class F at a wind speed 1.5 m/s for Scenario #1.

In alignment with the recommendations EPRA Risk Management Guidance for Offsite Consequence Analysis document this analysis will model all scenarios at a 50% relative humidity and at the highest daily maximum temperature [20].

## 5.4 SURFACE ROUGHNESS

The roughness of the ground surface contributes to mixing in the atmosphere by causing boundary layer turbulence. It also has an effect on the wind speed profile. The Phast model utilizes a single value for surface which must be estimated based on the prevailing geographic features. The project area is characterized by a mix of grassland and desert-like features. Literature research indicates that this type of terrain can be associated with a surface roughness parameter between 0.10 and 0.30 m [19] [21]. The surface roughness value of 0.10 m is defined by flat lands, few trees, long grass, fairly level grass plains. The surface roughness value of 0.30 m is defined in literature as being defined by open areas with great overgrowth and scattered houses. The 0.10 m Phast surface roughness parameter is assumed in the model. A sensitivity study of this parameter was completed as discussed in Section 8.0.

## 5.5 SUMMARY OF MODELING INPUTS

| Table 5: Modeling Input Variable Summary | | | | | | |
|---|---|---|---|---|---|---|
| **Scenario Name** | **Scenario #1**<br>Pre-Combustion Phase | | **Scenario #2**<br>Combustion Phase with Limited Fire Involvement | | **Scenario #3**<br>Combustion Phase with Full Enclosure Involvement | |
| **Quantity of Modules Involved in Scenario** | 1 | | 132 | | 252 | |
| **Release Duration** | 3.83 hours (230 minutes) | | 8 hour (480 minutes) | | 1 hour (60 minutes) | |
| **Gas Release Data** | | | | | | |
| **Emission Rates (g/s)** | Flammable Gases | 1.2459 | HF | 10.57 | HF | 161.36 |
| | | | CO | 76.30 | CO | 291.34 |
| | Non-Combustible Gases | 0.3324 | $SO_2$ | 1.91 | $SO_2$ | 35.86 |
| | | | HCN | 7.40 | HCN | 12.55 |
| | | | NO | 1.32 | NO | 31.38 |
| | | | HCl | 4.40 | HCl | 67.23 |
| **Average Fire HRR** | -- | | 6,300 kW | | 96,800 kW | |
| **Release Temperature** | 28°C | | 486°C | | 486°C | |
| **Vertical Release Velocity** | 1 m/s | | 1 m/s | | 1.68 m/s | |
| **Effective Release Height** | 2.67 m (8’-9”) | | 2.67 m (8’-9”) | | 19.05 m (62’-6”) | |
| **Weather Conditions** | | | | | | |
| **Pasquil Stability Class and Windspeed** | Class D at 3 m/s (6.7 mph)<br>and<br>Class F at 2 m/s (4.5 mph) | | Class D at 3 m/s (6.7 mph)<br>and<br>Class F at 2 m/s (4.5 mph) | | Class D at 3 m/s (6.7 mph)<br>and<br>Class F at 1.5 m/s (3 mph) | |
| **Ambient Temperature** | 37°C | | 37°C | | 37°C | |
| **Relative Humidity** | 50% | | 50% | | 50% | |
| **Surface Roughness** | | | | | | |
| **Surface Roughness** | 10 cm – Low Crops<br>Occasional large Obstacles | | 10 cm – Low Crops<br>Occasional large Obstacles | | 10 cm – Low Crops<br>Occasional large Obstacles | |

## 6.0 HUMAN HEALTH CRITERIA

This analysis assesses the potential toxicological, flash fire and explosion hazard posed to humans that result from the hazardous material releases described in Scenarios #1 through #3. The basis for this evaluation is described below.

### 6.1 TOXICITY

A variety of toxic endpoints are available for evaluating how members of the general public would be affected if they are exposed to a particular hazardous chemical in an emergency response situation. Three commonly applied exposure guidelines include the following:

- Acute Exposure Guideline Levels (AEGLs) – AEGLs are used by emergency planners and responders as guidance in dealing with rare, usually accidental, releases of chemicals into the air. AEGLs are expressed as specific concentrations of airborne chemicals at which health effects may occur. They are designed to protect sensitive individuals including elderly, children, and other individuals who may be susceptible. Acute exposures are single, non-repetitive exposures that don't exceed 8 hours.

- Emergency Response Planning Guidelines (EPRGs) – ERPGs estimate the concentrations at which most people will begin to experience health effects if they are exposed to a hazardous airborne chemical for 1 hour. Sensitive members of the public are not covered EPRGs and may experience adverse effects at concentrations below the ERPG values.
- Temporary Emergency Exposure Limits (TEELs) – TEELs estimate the concentrations at which most people will begin to experience health effects if they are exposed to a hazardous airborne chemical for a given duration. The TEEL methodology uses available levels of concern and manipulates current data using a peer-reviewed, approved procedure in order to establish the TEELs as opposed to AGELs and EPRGs which are derived from extensive reviews of animal and human studies. As a result AGELs and EPRGs are recognized as better public exposure guidelines [22].

Each of the above-mentioned guidelines can be referenced at one of three levels (i.e. AEGL-1, EPRG-2, etc). Generally, these tiers are as follows:

- First-tier – This exposure level may result in temporary, non-disabling effects.
- Second-tier – This exposure level may result in disabling (escape impairment) effects.
- Third-tier – This exposure level may result in life-threatening effects.

This analysis evaluates exposures at the second-tier level.

AGEL values are not available for all materials considered in this analysis. Therefore, the Protective Action Criteria (PACs) values will be used. The PACs dataset is a hierarchy-based system of the three public exposure guideline systems described above: AEGLs, ERPGs, and TEELs. The PACs hierarchy favors the following hierarchy for establishing toxic endpoint values where available, (1) Final and interim 60-minute AEGLs, (2) EPRGs and (3) TEELs. PAC values are provided on the same three tier system as described above.

The PAC-2 values for the materials of concern identified for each of the three scenarios considered in this analysis are as shown in Table 6. PAC values were obtained from the PAC Chemical Database as maintained by the U.S. Department of Energy [23]. With the exception of NO, all PAC database values are based on the AGEL values which are applicable to sensitive individuals. To provide additional context to tis analysis EPRG-2 values are also considered in this analysis and are reported in Table 6. EPRG-2 values are applicable to the general public but do not include the effects to sensitive individuals. EPRG-2 values were obtained from the CAMEO database [24].

| Table 6: Substance Toxic Exposure Limits | | | |
|---|---|---|---|
| Gas | | PAC-2 Value (ppm) | EPRG-2 Value[1] (ppm) |
| **Scenario #1 Gases** | | | |
| Hydrogen | $H_2$ | 230000 | 230000 |
| Carbon Monoxide | CO | 83 | 350 |
| Methane | $CH_4$ | 230000 | 230000 |
| Ethylene | $C_2H_4$ | 6600 | 6600 |
| Ethane | $C_2H_6$ | 230000 | 230000 |
| Carbon Dioxide | $CO_2$ | 40000 | 40000 |
| Propylene | $C_3H_6$ | 2800 | 2800 |
| Propane | $C_3H_8$ | 17000 | 17000 |
| Benzene | $C_6H_6$ | 800 | 150 |
| **Scenario #2 & 3 Gases** | | | |
| Hydrogen Fluoride | HF | 24 | 20 |
| Carbon Monoxide | CO | 83 | 350 |
| Sulfur Dioxide | $SO_2$ | 0.75 | 3 |
| Hydrogen Cyanide | HCN | 7.1 | 10 |
| Nitric Oxide | NO | 12 | 12 |
| Hydrogen Chloride | HCl | 22 | 20 |

[1] Hydrogen, Methane, Ethylene, Ethane, Carbon Dioxide, Propylene, Propane and Nitric Oxide do not have EPRG-2 values therefore for PAC-2 values are used as a conservative approach.

The individual substances listed in Table 6 form complex mixtures which must be considered when evaluating toxicology. For mixtures, three different situations are recognized. Substances in a mixture may have a synergistic effect, where the presence of one substance causes another to produce a much greater toxic effect. Additive substances are where the effects of individual substances have an additive effect. The effects of individual substances also may be neither additive nor synergistic [25].

For the purposes of this analysis, all effects are assumed to be either synergistic or additive in nature. Where effects are additive, the overall exposure limit is given by Equation 5 [25].

$$\frac{1}{L_{mix}} = \sum_{i=1}^{n} \frac{Y_i}{L_i} \tag{5}$$

where

$L_{mix}$ = exposure limit for mixture (ppm) [PAC-$2_{mix}$ or EPRG-$2_{mix}$]

$Y_i$ = mole fraction of component $i$

$L_i$ = exposure limit for component $i$ (ppm) [i.e. PAC-$2_{HF}$ or EPRG-$2_{HF}$]

Synergistic effects must also be accounted for. The multi-gas fractional effective dose (FED) models, as described in the SFPE handbook of Fire Protection engineering account for several known synergetic effects of the gases considered in this analysis [13]. The FED calculation model identifies the following relevant synergistic effects.

- Additive Fractions – Fractions of lethal doses of all typical fire gases except $CO_2$ are directly additive.
- Effect of $CO_2$ – The main effect of $CO_2$ is considered to be a multiplicative event on the rate of uptake of other gases depending on the extent of $CO^2$ driven hyperventilation.
- Effect of HCN and $NO_x$ – A correction for the protective effect of NO on HCN toxicology due to methemoglobin formation can be made for their additive effect.

Equation 5 is modified as follows to account for these synergistic effects.

$$\frac{1}{L_{mix}} = \left(\frac{Y_{HNC} - Y_{NO}}{L_{HCN}} + \sum_{i=1}^{n} \frac{Y_i}{L_i}\right) \times VCO_2 \tag{6}$$

where

$L_{mix}$ = exposure limit for mixture (ppm) [PAC-$2_{mix}$ or EPRG-$2_{mix}$]

$Y_{HCN}$ = mole fraction HCN

$Y_{NO}$ = mole fraction NO

$Y_i$ = mole fraction of component $i$ [all other components other than HCN and NO]

$L_{HCN}$ = exposure limit for HCN (ppm)

$L_i$ = exposure limit for component $i$ (ppm) [all other components other than HCN and NO]

$VCO_2$ = multiplication factor for $CO_2$ driven hyperventilation [see SFPE Handbook for more information]

Table 7 shows the gas mixture toxic exposure limits for each scenario as calculated using Equation 6.

**Table 7: Gas Mixture Toxic Exposure Limits**

| Scenario | PAC-2 (ppm) | EPRG-2 (ppm) |
|---|---|---|
| **Scenario #1** Pre-Combustion Phase | 201 | 847 |
| **Scenario #2** Combustion Phase with Limited Fire Involvement | 16 | 28 |
| **Scenario #3** Combustion Phase with Full Enclosure Involvement | 16 | 28 |

## 6.2 FLASH FIRE

The flash fire flame envelope is considered equal to the lower flammable limit (LFL) contour in which expansion of the cloud during combustion is not typically considered [3]. For the purposes of this analysis, the flame envelope is considered to be between the upper flammable limit (UFL) and 25% of the LFL. This approach incorporates an additional safety factor and and exceeds the combustible concentration limits recommended by American Institute of Chemical Engineers (AICHE) [19]. The LFL of the mixture was determined utilizing Phast. Phast calculates the LFL by utilizing Le Chatelier's Mixing Rule which accounts for the LFL of each mixture component and the amount that component consists of in the total mixture.

Inside the flame envelope the probability of death is equal to one due to the high level of heat radiation and the ignition of clothing and buildings. Outside the flame envelope of a flash fire the heat radiation is assumed to be low (on the order of a few tenths of a second) and the probability of death equal to zero

[4] [19]. Dispersion modeling was conducted using Phast to calculate the extent of the unconfined flammable vapor cloud.

## 6.3 VAPOR CLOUD EXPLOSION

The impact to humans from a VCE type explosion is based primarily on the peak pressure (over pressure) developed during the explosion. The *Guidelines for Quantitative Risk Assessment "Purple Book"* as developed by the Dutch organization for applied scientific research and AICHE's *Guidelines for Consequence Analysis of Chemical Releases* book both provide information regarding the probability of death due to VCE events. Probability of death information from these sources are shown in Table 8 [19] [3]. Where information is available the probability of death of community individuals located both indoors and outdoors as a result from a VCE is given.

**Table 8: Pressure Effects for a Vapor Cloud Explosion**

| Explosion Overpressure | Probability of Death | |
|---|---|---|
| | Indoor Population | Outdoor Population |
| Greater than 0.3 barg (4.35 psi) | 100% | 100% |
| 0.2 barg (2.90 psi) | 50% | |
| Between 0.3 barg (4.35 psi) and 0.1 barg (1.45 psi) | 2.5% | 0% |
| Less than 0.1 barg (1.45 psi) | 0% | 0% |

Outdoors, a higher overpressure is usually required to cause significant harm or fatalities, as the open environment allows the pressure to dissipate more easily. However, indoors, the risk is increased due to the potential for building collapse, flying debris, and shattered windows. Enclosed spaces can amplify the effects of the blast, leading to a higher probability of injuries or fatalities for people inside buildings.

In relation to damage to structures, at an overpressure endpoint of 0.1 barg (1.45 psi) windows of a building may break and persons exposed may be knocked down. Structures exposed to 0.2 barg (3 psi) side-on overpressure or higher 0.3 barg (4.35 psi) may suffer major damage with fatalities reaching up to 50% [19].

Based on the potential of harm to both humans and structures, this analysis evaluates the explosion overpressure at the 0.3, 0.2 and 0.2 barg contours.

# 7.0 PLUME ANALYSIS RESULTS

The Phast generated plume modeling results are shown in the following report section.

## 7.1 SCENARIO #1 - PRE-COMBUSTION PHASE RESULTS

Scenario #1 assumes a non-flaming thermal runaway event propagating throughout a single module over a 230-minute duration while at 100% SOC.

### 7.1.1 Toxicity

Two toxic endpoints (PAC-2 and EPRG-2) of the combined gas mixture were evaluated at two windspeed / atmospheric stability conditions.

Figure 5 shows the side view of the toxicity gas cloud under Class D atmospheric stability with a 3 m/s wind condition while Figure 6 shows the gas cloud extents under Class F atmospheric stability with a 2 m/s wind condition. In both figures, the blue line represents the PAC-2 (201 ppm) boundary and the green line represents the EPRG-2 (847 ppm) boundary.

Figure 7 and Figure 8 show the top view of the gas cloud toxicity effect zone at the Class D at 3 m/s and Class F at 2 m/s atmospheric conditions. Both top view figures are shown at the reference height where the PAC-2 boundary extends furthest from the release point. As shown in Figure 5 and Figure 6, the toxic effect zones are not anticipated to drop below the typical breathing height of 6'-0".

As shown in the figure below, gas concentrations for Scenario #1 are expected to exceed PAC-2 limits up to 86'-0" and EPRG-2 limits up to 33'-0" from the release location. The results generally indicate that the elevations below the typical breathing height of 6'-0" would not be anticipated to exceed the identified toxic endpoints, however as described in Section 8.0 of this report the 86'-0" PAC-2 and 33'-0" EPRG-2 limits should be applied at ground level.

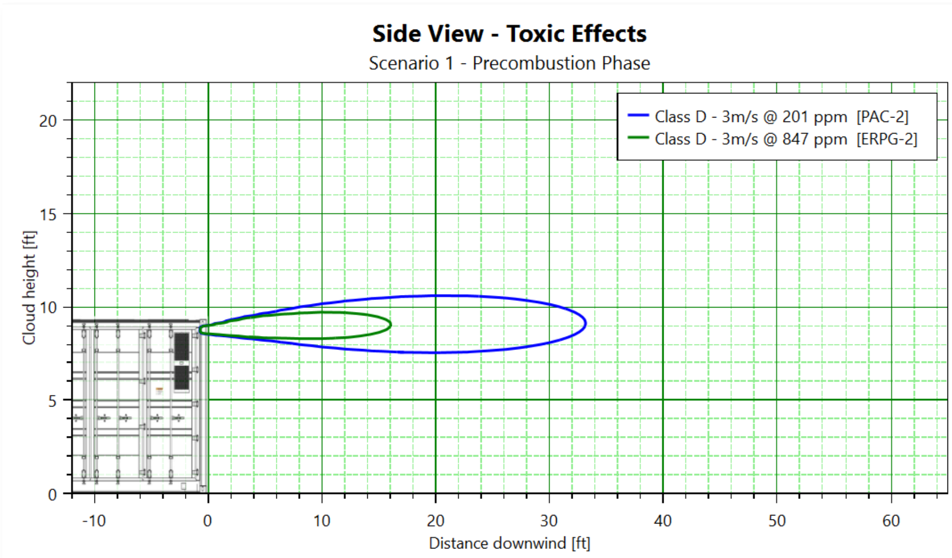


**Figure 5** – Scenario #1 Toxic Gas Cloud (Class D at 3 m/s Atmospheric Conditions) Side View

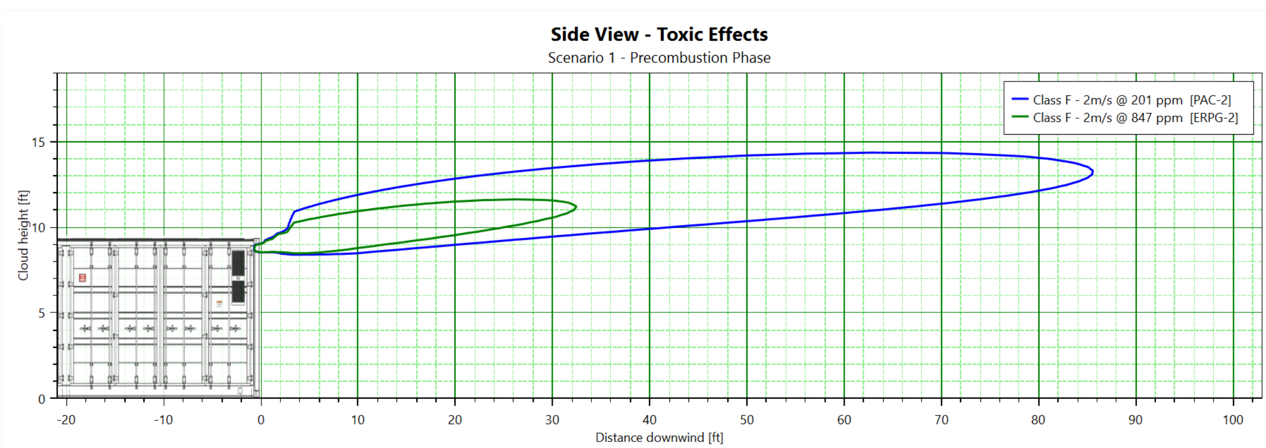


**Figure 6** – Scenario #1 Toxic Gas Cloud (Class F at 2 m/s Atmospheric Conditions) Side View

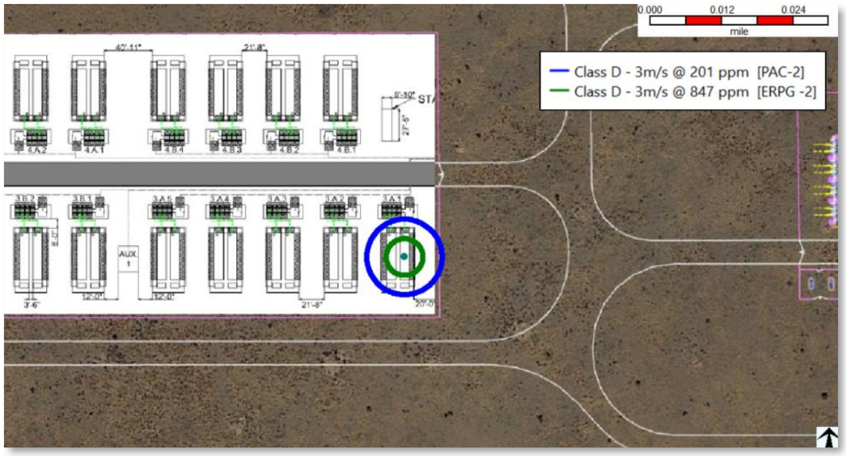


**Figure 7** – Scenario #1 Toxicity Effect Zone (Class D at 3 m/s Atmospheric Conditions)
Top View at 9’-0” Height

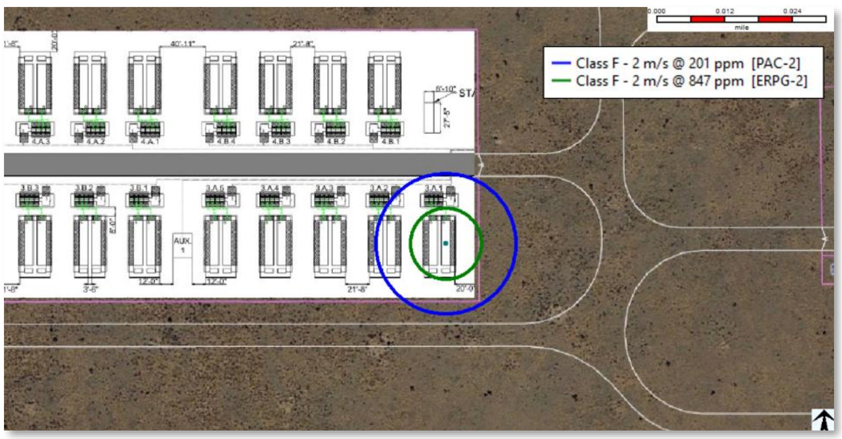


**Figure 8** – Scenario #1 Toxicity Effect Zone (Class F at 2 m/s Atmospheric Conditions)
Top View at 11’-0” Height

### 7.1.2 Flash Fire

Three flammable endpoints (UFL, LFL and 25% of the LFL) of the combined gas mixture were evaluated at two windspeed / atmospheric stability conditions.

Figure 9 shows the side view of the flammable gas cloud under Class D atmospheric stability with a 3 m/s wind condition while Figure 10 shows the gas cloud extents under Class F atmospheric stability with a 2 m/s wind condition. In both figures, the red line represents the UFL boundary and the green line represents the LFL boundary and the blue line represents the 25% of the LFL boundary.

Figure 11 and Figure 12 show the top view of the gas cloud toxicity effect zone at the Class D at 3 m/s and Class F at 2 m/s atmospheric conditions. Both top view figures are shown at the reference height where the PAC-2 boundary extends furthest from the release point and at the 6‘-0” height.

As shown in the figures below, flammable gas concentrations for Scenario #1 are expected to exceed the 25% of the LFL limits 6’-0” from the release location.

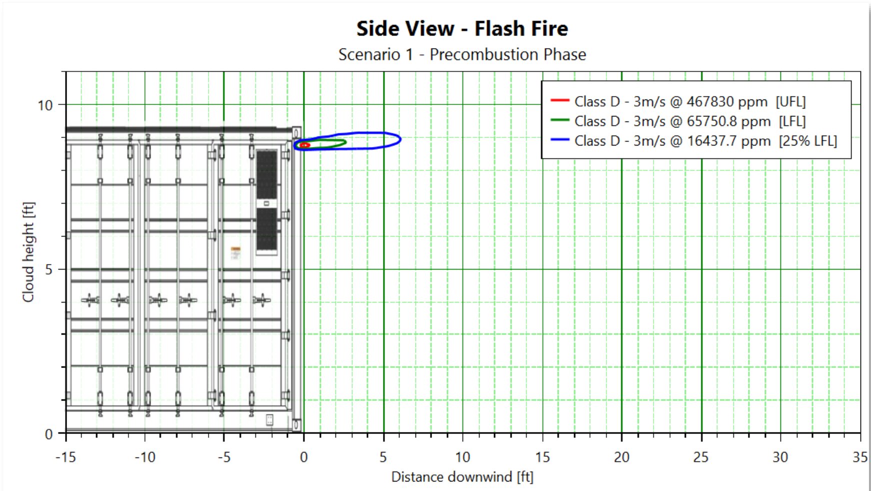


**Figure 9** – Scenario #1 Flammable Gas Cloud (Class D at 3 m/s Atmospheric Conditions) Side View

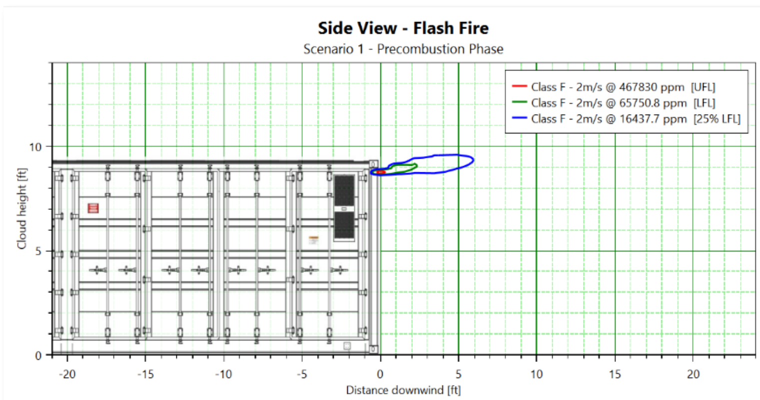


**Figure 10** – Scenario #1 Flammable Gas Cloud (Class F at 2 m/s Atmospheric Conditions) Side View

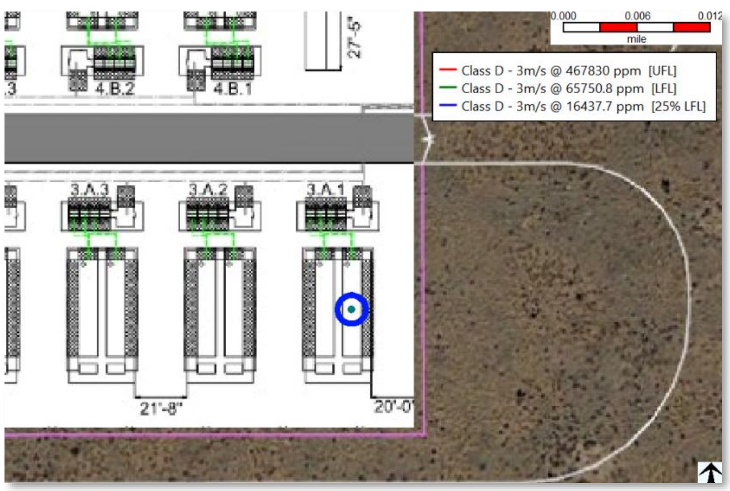


**Figure 11** – Scenario #1 Flammability Effect Zone (Class D at 3 m/s Atmospheric Conditions) Top View at 9'-0" Height

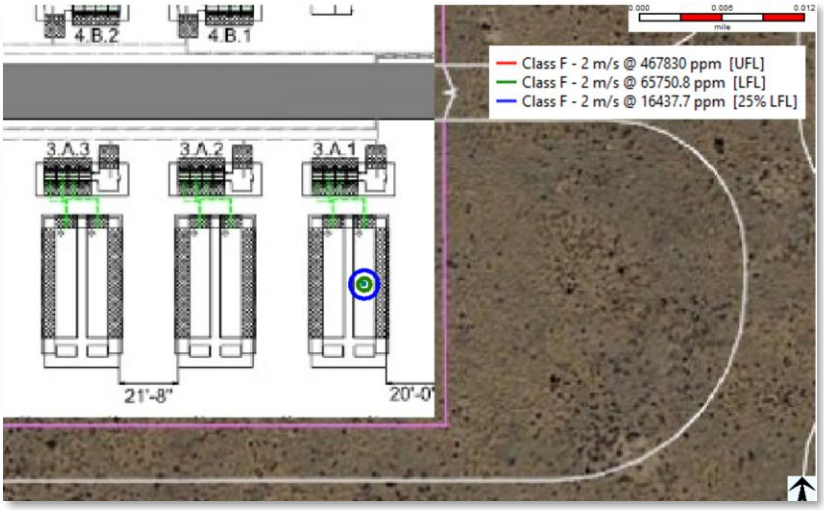


**Figure 12** – Scenario #1 Flammability Effect Zone (Class F at 2 m/s Atmospheric Conditions) Top View at 9'-0" Height

### 7.1.3 Vapor Cloud Explosion

The Phast results indicate that insufficient quantities of gas are not present to calculate an overpressure for Scenario #1.

## 7.2 SCENARIO #2 - COMBUSTION PHASE WITH LIMITED FIRE INVOLVEMENT RESULTS

Scenario #2 assumes a flaming thermal runaway event that consumes 132 modules over a 8-hour duration while at 100% SOC.

This scenario includes an evaluation of toxicity only as all flammable gases are assumed to be combusted in the associated battery fire.

### 7.2.1 Toxicity

Two toxic endpoints (PAC-2 and EPRG-2) of the combined gas mixture were evaluated at two windspeed / atmospheric stability conditions.

Figure 13 shows the side view of the toxicity gas cloud under Class D atmospheric stability with a 3 m/s wind condition while Figure 14 shows the gas cloud extents under Class F atmospheric stability with a 2 m/s wind condition. In both figures, the blue line represents the PAC-2 (16 ppm) boundary and the green line represents the EPRG-2 (28 ppm) boundary.

Figure 15 and Figure 16 show the top view of the gas cloud toxicity effect zone at the Class D at 3 m/s and Class F at 2 m/s atmospheric conditions. Both top view figures are shown at the reference height where the PAC-2 boundary extends furthest from the release point and at the 6'-0" height.

As shown in the figure below, gas concentrations for Scenario #2 are expected to exceed PAC-2 limits up to 1306'-0" and EPRG-2 limits up to 812'-0" from the release location. The results generally indicate that the elevations below the typical breathing height of 6'-0" would not be anticipated to exceed the identified toxic endpoints at distances exceeding 550'-0", however as described in Section 8.0 of this report the toxic boundaries should be applied at ground level.

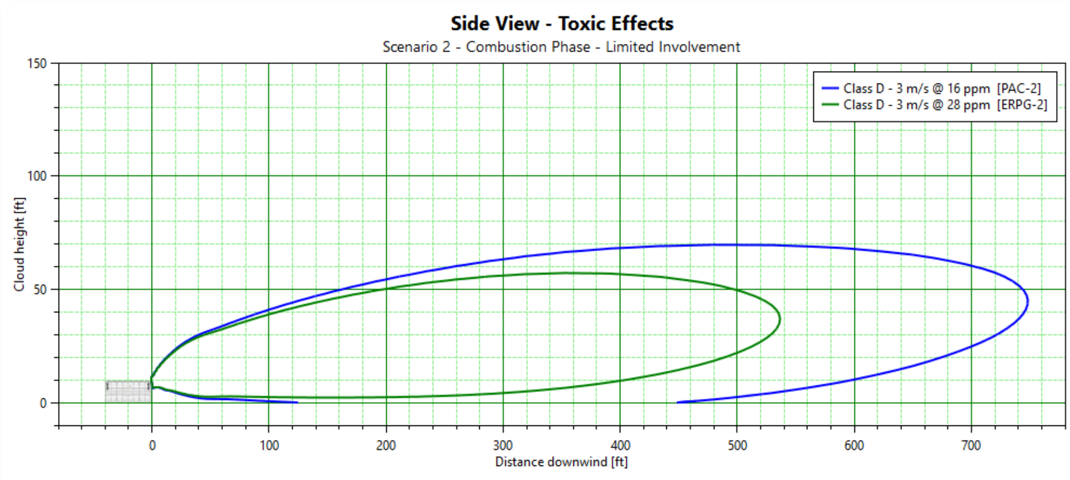


**Figure 13** – Scenario #2 Toxic Gas Cloud (Class D at 3 m/s Atmospheric Conditions)
Side View

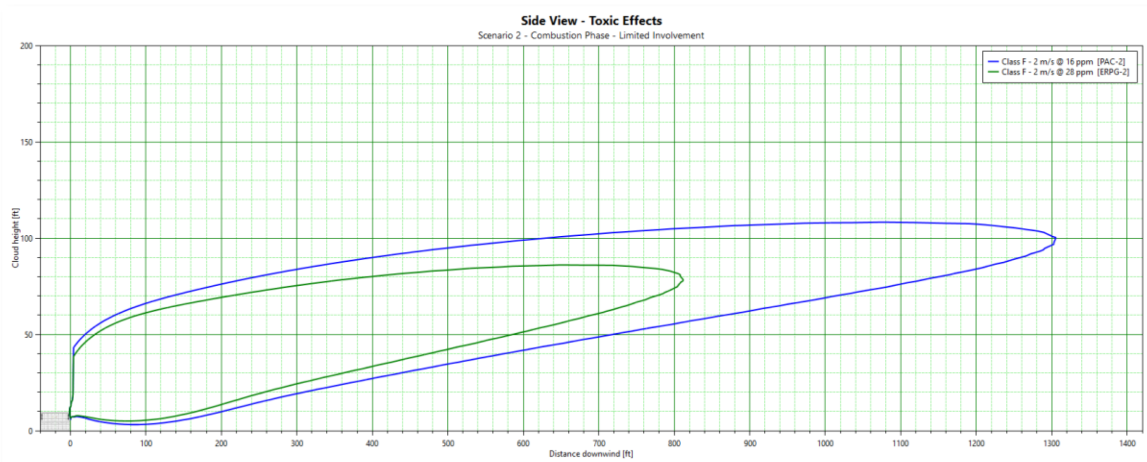


**Figure 14** – Scenario #2 Toxic Gas Cloud (Class F at 2 m/s Atmospheric Conditions)
Side View

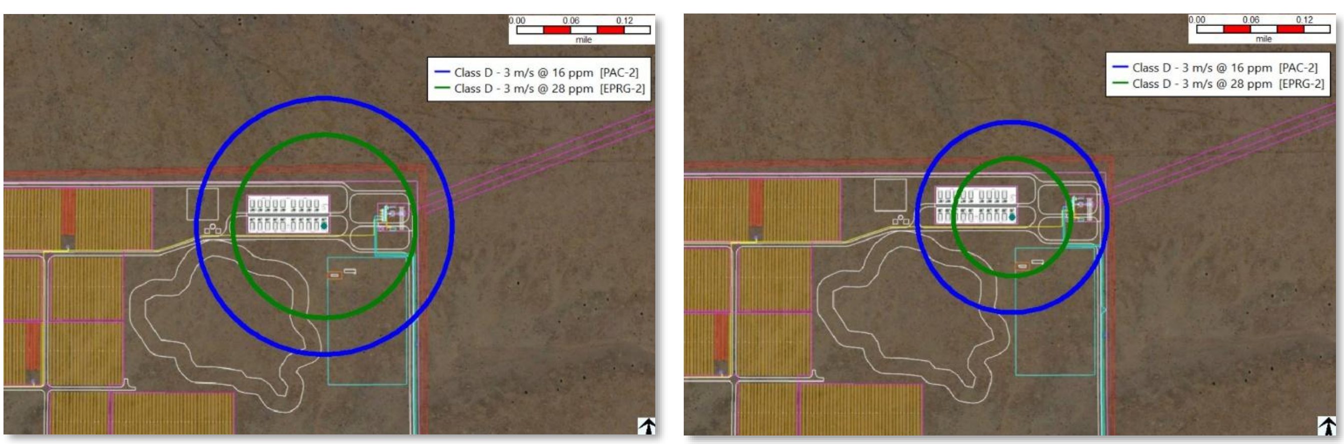


**Figure 15** – Scenario #2 Toxicity Gas Cloud (Class D at 3 m/s Atmospheric Conditions)
Left Image: Top View at 40'-0" Height, Right Image: Top View at 6'-0" Height

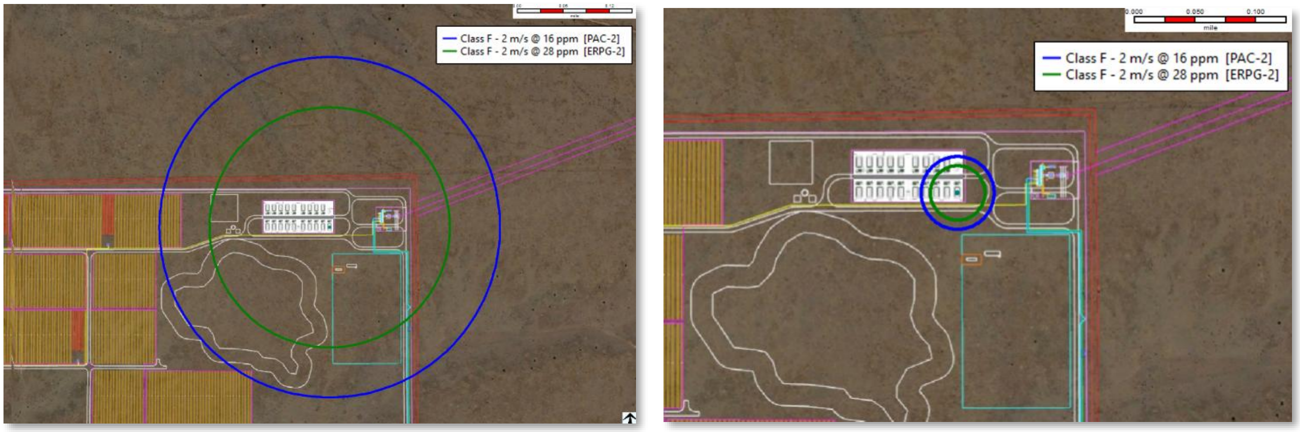


**Figure 16** – Scenario #2 Toxicity Gas Cloud (Class F at 2 m/s Atmospheric Conditions)
Left Image: Top View at 80'-0" Height, Right Image: Top View at 6'-0" Height

## 7.3 SCENARIO #3 - COMBUSTION PHASE WITH FULL FIRE INVOLVEMENT RESULTS

Scenario #3 assumes a flaming thermal runaway event that consumes all modules within a single enclosure (252 modules) over a 1-hour duration while at 100% SOC.

This scenario includes an evaluation of toxicity only as all flammable gases are assumed to be combusted in the associated battery fire.

### 7.3.1 Toxicity

Two toxic endpoints (PAC-2 and EPRG-2) of the combined gas mixture were evaluated at two windspeed / atmospheric stability conditions.

Figure 17 shows the side view of the toxicity gas cloud under Class D atmospheric stability with a 3 m/s wind condition while Figure 18 shows the gas cloud extents under Class F atmospheric stability with a 1.5 m/s wind condition. In both figures, the blue line represents the PAC-2 (16 ppm) boundary and the green line represents the EPRG-2 (28 ppm) boundary.

Figure 19 and Figure 20 show the top view of the gas cloud toxicity effect zone at the Class D at 3 m/s and Class F at 1.5 m/s atmospheric conditions. Both top view figures are shown at the reference height where the PAC-2 boundary extends furthest from the release point. As shown in Figure 17 and Figure 18, the toxic effect zones are not anticipated to drop below the typical breathing height of 6'-0".

As shown in the figure below, gas concentrations for Scenario #3 are expected to exceed PAC-2 limits up to 2256'-0" and EPRG-2 limits up to 1720'-0" from the release location. The results generally indicate that the elevations below the typical breathing height of 6'-0" would not be anticipated to exceed the identified toxic endpoints, however as described in Section 8.0, the 2256'-0" PAC-2 and 1720'-0" EPRG-2 limits should be applied at ground level.


**Figure 17** – Scenario #3 Toxic Gas Cloud (Class D at 3 m/s Atmospheric Conditions) Side View

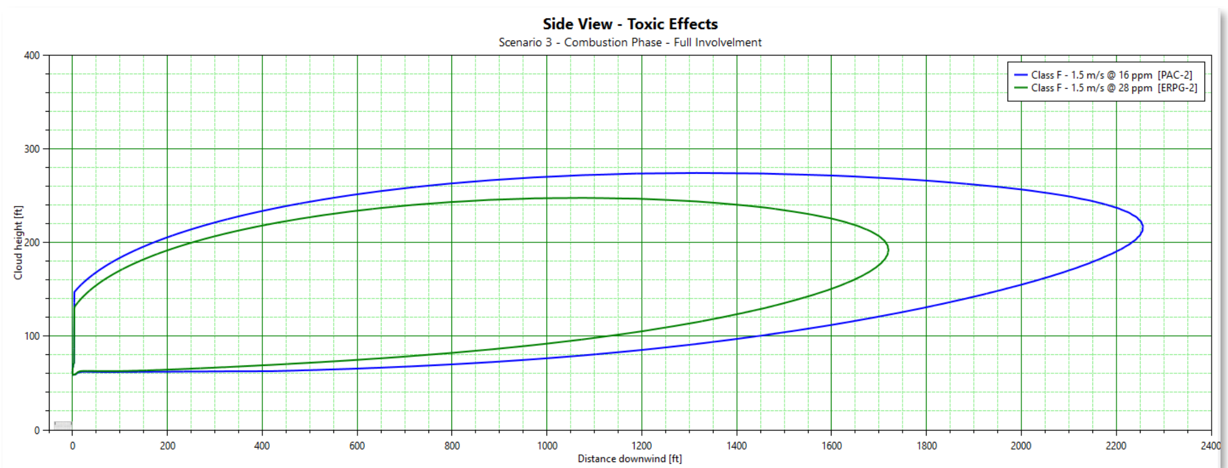


**Figure 18** – Scenario #3 Toxic Gas Cloud (Class F at 1.5 m/s Atmospheric Conditions) Side View


**Figure 19** – Scenario #3 Toxicity Gas Cloud (Class D at 3 m/s Atmospheric Conditions) Top View at 135’-0” Height

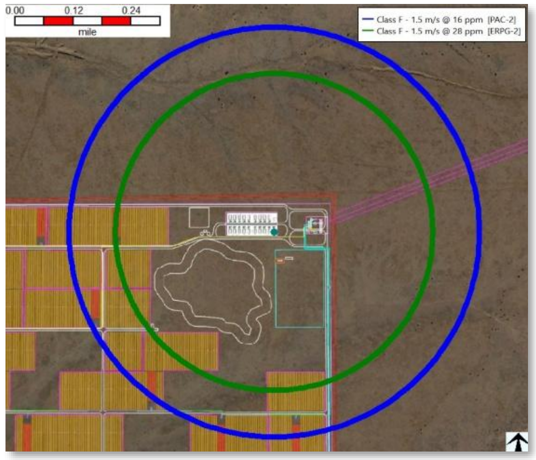


**Figure 20** – Scenario #3 Toxicity Gas Cloud (Class F at 1.5 m/s Atmospheric Conditions) Top View at 195'-0" Height

## 7.4 MODELING RESULT SUMMARY

Table 9 shows a summary of the distances from the point of release where gas concentrations are expected to be reduced below the toxic, flammable and explosion over pressure endpoints.

| Table 9: Modeling Result Summary | | | |
|---|---|---|---|
| **Endpont** | **Scenario #1** Pre-Combustion Phase | **Scenario #2** Combustion Phase with Limited Fire Involvement | **Scenario #3** Combustion Phase with Full Enclosure Involvement |
| **Toxicity** | | | |
| PAC-2 | 86'-0" | 1306'-0" | 2256'-0" |
| EPRG-2 | 33'-0" | 812'-0" | 1720'-0" |
| **Flash Fire** | | | |
| 25% of LFL | 6'-0" | N/A | N/A |
| LFL | 2'-0" | N/A | N/A |
| UFL | <1'-0" | N/A | N/A |
| **Vapor Cloud Explosion** | | | |
| 0.1 barg | 0'-0" | N/A | N/A |
| 0.2 barg | 0'-0" | N/A | N/A |
| 0.3 barg | 0'-0" | N/A | N/A |

## 8.0 SENSITIVITY AND UNCERTAINTY ANALYSIS

Two elements in the plume modeling process are identified as either uncertain or heavily influencing the calculation results, surface roughness and atmospheric conditions (wind and atmospheric stability).

The sensitivity of surface roughness on the plume analysis results was directly evaluated. The plume modeling assumes a surface roughness parameter of 0.10 m in Phast. The next lower surface type that may be selected in Phast is 0.03 m. As this value is associated with open flat terrain with few isolated objects, it does not appear to be appropriate based on the geographic features present at the site. Various models included in this analysis were ran with the next higher surface roughness option in Phast, of 0.25 m. Models with this higher surface roughness option were found to result in a reduction in endpoint distances from the release point. The 0.10 m surface type option is therefore considered to be the conservative selection.

The plume modeling results are considered to be highly sensitive to atmospheric conditions. To evaluate the sensitivity of atmospheric conditions, each scenario was ran at a wide variety of wind speed and atmospheric stability conditions, see Figure 21 through Figure 23, below. A review of these figures shows that the toxic end points extended furthest from the release points under Class F atmospheric stability with a 2 m/s wind conditions for Scenarios #1 and #2 and Class F atmospheric stability with a 1.5 m/s wind condition for scenario #3. It can also be observed that the gas plume drops lower to the ground at other atmospheric stability and wind combinations. Based on this observation, toxic limits are assumed to be applied at ground level. This is consistent with the recommendations found in the EPRA Risk Management Guidance for Offsite Consequence Analysis document [20].

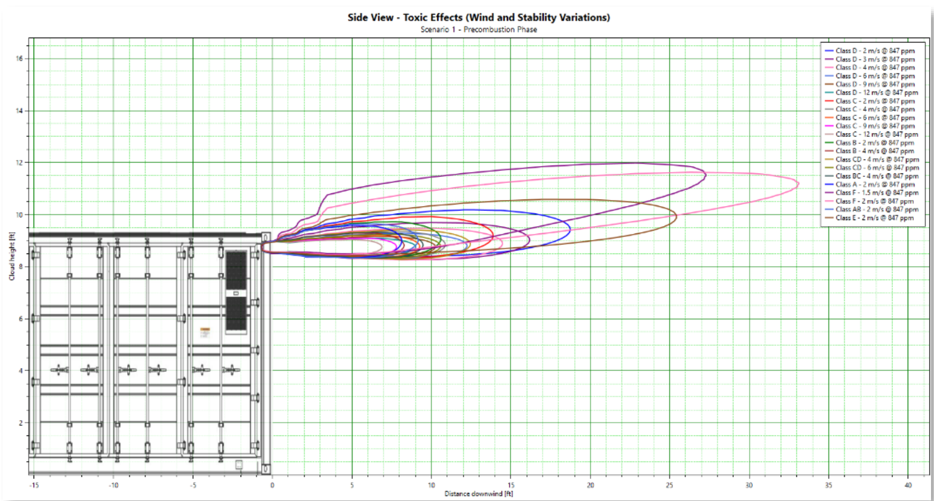


**Figure 21** – Scenario #1 Toxic Gas Cloud Atmospheric Variations

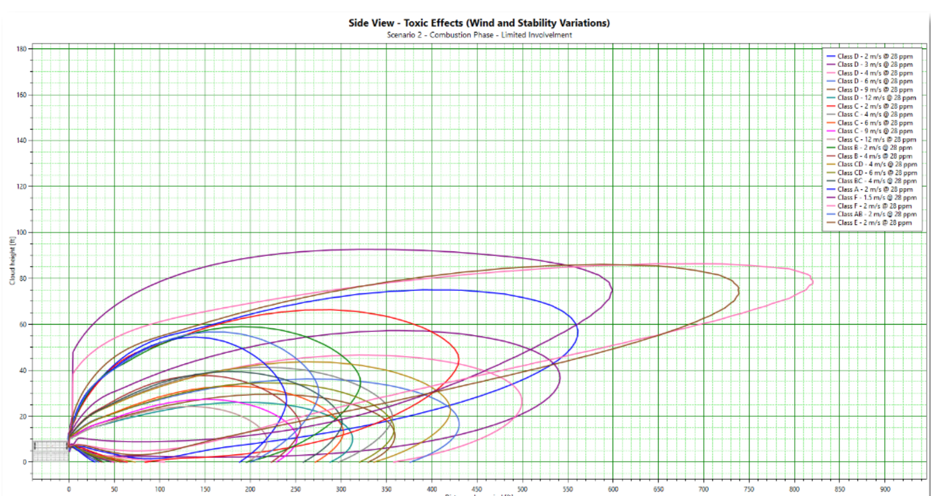


**Figure 22** – Scenario #2 Toxic Gas Cloud Atmospheric Variations

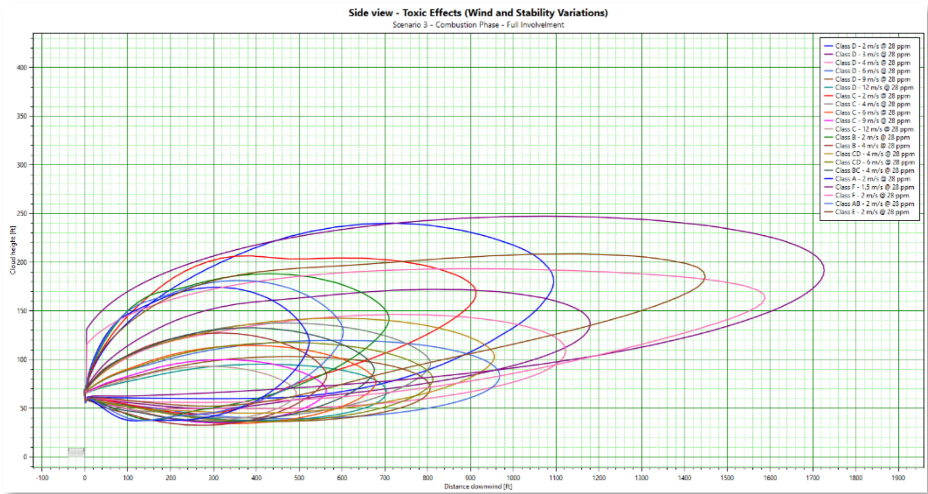


**Figure 23** – Scenario #3 Toxic Gas Cloud Atmospheric Variations

## 9.0 MAJOR ANALYSIS ASSUMPTIONS AND LIMITATIONS

- **Emission data availability** – Emissions data available from full scale testing of the batteries used for this project is limited to the data provided in UL9540A cell level testing. Emission rate assumptions for non-flaming thermal runaway scenarios are based on an extension of cell level data. Emission rate assumptions for flaming thermal runaway scenarios are based entirely on emission rates published in literature. The emission rates in an actual event may vary from these assumed values.

- **Fate and transport not evaluated** – Fate refers to the ultimate end result of a contaminate after it has been released into the environment. This can involve various transformations, including physical transformations, biological transformations or chemical reactions with other substances. Transport is the movement of contaminates within a given medium and across interfaces between water, soil, sediment, air, plants, and animals. This analysis specifically evaluates when gases are sufficiently dispersed into the atmosphere to a concentration below the identified toxic endpoints. The final fate and transport of contaminates after the atmospheric concentrations have reduced below the toxic endpoints is not considered.

- **Additional contaminates not evaluated** – Additional contaminates beyond those considered in this analysis may be released during actual fire events. These may include materials currently known or may someday be determined to have negative health effects. Materials such as heavy metals, semi-volatile organic compounds (SVOC) and volatile organic compounds (VOC) other than those already considered in this analysis are either confirmed or are suspected to be produced during battery fires; however, consensus as to their health effects, emission rates and how they should be handled in gas dispersion studies has not yet been established. These materials are therefore considered outside the scope of this analysis.

- **Full consumption of flammable gas during fire events** – This analysis assumes all flammable gas released during flaming thermal runaway scenarios are fully consumed and not available to contribute to flash fire or explosion events.

- **Dilutes not considered** – Additional gases may be released outside of those measured in UL9540A testing and those listed in Table 2 through Table 3. These additional materials may act to dilute the effects of the gases that are considered in this analysis. This dilution effect would be expected to reduce the consequences estimated in this analysis.

- **Single Phase Release** – Battery fires are known to release contaminates in a variety of forms including, particulates (e.g. soot), aerosols and gases. This analysis considers all contaminants released are in the gas form only.
- **Assumed thermal runaway events** – The emission rates assumed in this study are highly dependent upon the rate of thermal runaway / fire propagation from cell to cell. The rate of propagation is highly variable based on a variety of conditions that can't be predicted prior to an incident. The scenarios developed in this analysis attempts to establish the bounds of the rate of thermal runaway propagation, however, variations beyond those considered in this analysis may exist.
- **Rainout and Weather** – This analysis attempts to consider worst case weather conditions but may not capture all extreme weather conditions that may be possible. The effect of rainout is not considered in this analysis.
- **100% state of charge** – All thermal runaway / fire events are assumed to occur when cells are at a 100% SOC. The quantity of gas released per cell is generally trends to be higher at higher SOC values.

## 10.0 CONCLUSION

This analysis reviewed three battery failure scenarios. The pre-combustion phase thermal runaway scenario is intended to represent largest credible release prior to ignition of flaming combustion or the largest credible release that may occur if ignition of the flammable gases never occurs. The plume modeling results indicate that gas concentrations will exceed the limit required to cause health effects in unprotected persons, including sensitive individuals, at a distance of 86'-0". The pre-combustion event scenario results in a flashfire hazard at distances closer than 6'-0" and does not pose a discernable vapor cloud explosion hazard.

Two combustion phase scenarios were evaluated; these models are reflective of battery failure events after ignition of thermal runaway gases occur. The limited involvement scenario assumes a longer duration event which consumes roughly half of the battery modules within the enclosure. The full involvement scenario assumes a shorter duration, higher heat release fire event which consumes all the battery modules within the enclosure. The limited involvement fire scenario is intended to represent a typical large scale battery enclosure fire, while the full involvement fire scenario is reflective of the largest credible fire event. The plume modeling results indicates that gas concentrations will exceed the limit required to cause health effects in unprotected persons, including sensitive individuals, at a distance of 1306'-0" for the limited fire involvement case and 2256'-0" for the full fire involvement case.

## 11.0 REFERENCED PROJECT DOCUMENTATION

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

- 30% Civil, Structural and Electrical Rancho Viejo Solar Utility Drawings, Revision 3, Dated July 2, 2024
- 30% Electrical Rancho Viejo Solar Utility BESS Drawings, Revision 1, Dated August 11, 2023
- Draft Preliminary HMA report – Rancho Viejo Solar Utility, Revision A, Dated July 24, 2024
- *UL 9540A Report – Cell Test Report* (Project No. 4790746849), Issued July 7, 2023
- *UL 9540A Report – Module Test Report* (Project No. 4790351859), Issued July 10, 2023
- *UL 9540A Report – Unit Test Report* (Project No. 4790648531), Issued June 28, 2023
- *UL 9540A Report – Installation Test Report* (Project No. 4790648557), Revised July 7, 2023

## 12.0 QUALIFICATIONS AND LIMITATIONS STATEMENT

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

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