Assessment of Potential Impacts of Fires at BESS Facilities

LITERATURE REVIEW | August 21, 2025

Prepared by Fire & Risk Alliance, LLC. for:
The American Clean Power Association

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Revision Notes:

			Authored:	Reviewed:	Approved:
Revision 0	August 21, 2025	Initial Release	JG, JM, MF	NR	NR

1 Executive Summary

Battery Energy Storage Systems (BESS) have become an essential component of modern energy infrastructure, supporting grid stability, renewable energy integration, and peak demand management. While concerns about fire hazards have been raised, historical data and scientific studies indicate that BESS remains a relatively safe technology with minimal environmental contamination risks. Furthermore, many reported fire incidents involved legacy systems that were designed, installed, and operational before the development and implementation of comprehensive national safety standards, such as NFPA 855 and UL 9540A.

This report provides an analysis of historical BESS fire incidents and, their causes, a review of the types of contaminants released, the extent of environmental impacts, and how advancements in safety regulations and technology have mitigated risks.

In none of the reviewed cases of environmental sampling related to the BESS fire events were contaminant concentrations found that would pose a public health concern or necessitate further remediation. This finding includes airborne contamination sampling conducted on-site, off-site, and within nearby communities, as well as relevant sampling of water from firefighting activities, automatic suppression system run-off, and groundwater testing in specific instances.

1.1 Historical Incidents: Context and Key Findings

A review of 35 documented large-scale BESS fire incidents in the United States (2012–2024) provides valuable insights into the evolution of ESS safety. These incidents occurred in 16 states, with California reporting the highest number (12). The following key trends emerged from the analysis:

- **Legacy System Involvement:** Many of these incidents involved early-generation BESS units that predate modern safety codes and lacked rigorous testing and integrated safety features.
- **Early Lifecycle Failures:** Nearly half (51%) of incidents reported the age of the system, with almost half of those incidents occurring within the first six months of operation, highlighting potential challenges during the commissioning and initial operational phases of BESS units.
- **Operational State at Time of Incident:** Among incidents where operational status was known, 69% of fires occurred during system use, while 17% took place during assembly, testing, or pre-commissioning.
- **Challenges in Root Cause Analysis:** Investigating BESS fires is complex due to the destruction of components at high temperatures. Available data suggests that failures primarily stemmed from system integration, construction, and assembly issues rather than fundamental battery chemistry concerns.
- **Advancements in Safety and Design:** Newer ESS units benefit from improved safety measures, such as advanced thermal management, suppression systems, and containment enclosures, significantly reducing the likelihood of large-scale incidents.

1.2 Case Studies of Notable BESS Fire Incidents

Several high-profile incidents illustrate the evolution of BESS safety and the limited environmental consequences of such fires. These incidents were also selected because they have published environmental impact assessments. Notable examples include:

- **Valley Center, CA (2022):** A small component-level BESS fire at a 560 MWh system. The fire was contained to a single module within a rack in one enclosure.

- **East Hampton, NY (2023):** A larger component-level fire at a 40 MWh system. The fire reportedly began as a result of a smoldering battery.

- **Surprise, AZ (2019):** A BESS enclosure fire and explosion in a 2 MWh system. Several firefighters were injured due to unexpected gas ignition and to date remains the sole incident in the US in which a person was injured.

- **Escondido, CA (2024):** A BESS enclosure fire at a 120 MWh system. The fire was limited to a single enclosure and had a duration of approximately 13 hours.

- **Lyme (Chaumont), NY (2023):** A BESS enclosure fire in a 15 MWh system. Four enclosures and two transformers were involved.

- **Melba, ID (2023):** A BESS enclosure fire that occurred in an 8 MWh system while in the pre-commissioning stage. The fire caused several battery stacks to be burned, and the fire had a duration of 3 days.

- **Warwick, NY (2023):** Two separate BESS fires occurred within 24 hours at a 36 MWh and a 17.9 MWh system. The BESS were allowed to consume themselves in a controlled manner, illustrating the shift in firefighting tactics from active suppression efforts to passive cooling of targets.

Table 1 summarizes the environmental sampling that was reported in the literature for each of the case studies selected. The documented record of environmental sampling performed for these events showed considerable variation in both the type of sampling conducted and the protocols employed, particularly concerning airborne contamination testing. Sampling was carried out by site personnel, HAZMAT first responders, and State and EPA personnel, often involving third-party consultants or testing laboratories.

Table 1: Summary of Environmental Sampling Performed at Case Study BESS Fires

Event #	Location	Date	Air	Soil	Water
1	Valley Center, CA	5-Apr-22	N/A	N/A	N/A
2	East Hampton, NY	31-May-23	X	X	X
3	Surprise, AZ	19-Apr-19	X	X	X
4	Escondido, CA	5-Sep-24	X		X
5	Lyme (Chaumont), NY	27-Jul-23	X	X	X
6	Melba, ID	2-Oct-23	X		
7	Warwick, NY	26-Jun-23	X	X	X

In addition to the case studies summarized above, a large indoor BESS fire occurred on January 16, 2025, involving a 1,200 MWh system at Moss Landing, CA. This facility, uniquely designed to operate within a historic, retrofitted former natural gas plant, is anomalous in several ways and would not be allowed under today's codes and standards. Accordingly, this incident is described separately in Appendix B and is not reflected in the conclusions of this report.

1.3 Regulatory and Scientific Assessments on Environmental Impact

- **ISO Standard 26367-1** provides a framework for assessing the environmental impact of fires.
- **EPA Risk Management Program** provides guidance on how to conduct off-site consequence analyses under the EPA's Clean Air Act and provides guidance both on establishing the worst-case scenarios for evaluation and data on a variety of toxic substances.
- **EPRI Guidance Documents**: The Electric Power Research Institute (EPRI) has published guidance on the available plume models that may be used for evaluating the potential airborne contamination from BESS fires and these guidance documents provide a modeling framework for performing air modeling simulations of BESS fires.
- **Community Risk Assessment Studies**: Studies performed by various engineering consultants model the spread of acid gases (HF and sometimes HCN and HCl) and conclude that acid gas emissions generally do not reach levels of concern beyond the immediate fire site. This conclusion is supported by limited large-scale BESS fire testing.

1.4 Environmental Impact Assessment

The environmental consequences of BESS fires have been a subject of increasing scrutiny. However, data from real-world incidents, experimental studies, and environmental monitoring efforts indicate that BESS fires have a minimal long-term environmental impact compared to other large industrial and structural fires.

1.4.1 Airborne Emissions from BESS Fires

A key concern in BESS fire events is the release of toxic gases, but studies indicate that emissions are largely confined to the immediate vicinity of the fire, with rapid dissipation and concentration reduction in open-air scenarios. It has also been shown that fires involving BESS share many similarities with conventional fires, particularly those involving plastics, in terms of combustion byproducts. This is because the materials that make up lithium-ion batteries—such as polymer-based separators, electrolytes, and enclosures—contain hydrocarbons and other organic compounds that produce similar combustion emissions when the materials are exposed to high temperatures. Key findings on airborne contaminants include:

- **Common Gases Released:** BESS fires primarily emit CO, CO_2, and volatile organic compounds (VOCs), and may emit other trace gases such as HF, HCN, or others depending on the battery chemistry and overall materials of construction of the BESS unit.

- **Limited Off-Site Impact:** Air sampling from past incidents has found that contaminant concentrations beyond the immediate fire scene do not pose a public health risk. For example, monitoring at the Escondido, CA and NY incidents showed no detectable hazardous concentrations in nearby communities and initial shelter in place and evacuation orders were generally lifted shortly after the measurements were taken.

- **Flammability and Gas Dispersion:** The rapid dispersion of gases in outdoor BESS fires limits the potential for widespread toxic exposure. Studies show that the local concentration of gases rarely reaches flammability limits in well-ventilated environments and toxic gases are rapidly diluted.

1.4.2 Soil and Water Contamination

Concerns about soil and water contamination primarily arise from firefighting suppression efforts, particularly when large volumes of water are used. However, available data from real-world incidents and testing does not support the notion of widespread contamination risks. Key findings include:

- **Firefighting Water Runoff:** The consensus best practice for response to a BESS fire is to allow the BESS to consume itself and provide cooling water to targets if needed. Unless there is direct suppression water applied to the BESS on fire, any cooling water applied will be similar to rain and no potential contaminants will be included in any runoff. While lithium-ion battery fires produce chemical byproducts, studies show that their solubility in water is low, limiting the potential for groundwater contamination if direct suppression efforts are performed. Additionally, standard stormwater management practices help prevent runoff from reaching natural water sources in the event that the fire department determines that suppression efforts are required.

- **Environmental Sampling Results:** In past BESS fire incidents where environmental sampling was conducted, water and soil samples did not reveal hazardous contamination levels requiring remediation.

1.5 Firefighting Strategies and Risk Mitigation

Lessons learned from BESS fire events have impacted the firefighting tactics and safety features for newer BESS installations and provided increased awareness of safety and environmental considerations.

1.5.1 Key Firefighting Considerations

The evolution of BESS firefighting strategies has led to a shift in approach, particularly in cases where deep-seated battery fires occur within enclosed containers. Fire suppression tactics now emphasize containment and cooling of targets rather than active suppression efforts, therefore reducing potential environmental impacts, particularly those associated with soil and water contamination.

- **Controlled Burn Approach:** Many fire departments now adopt a strategy of letting a burning BESS container consume itself rather than applying excessive amounts of water. This minimizes the potential runoff and reduces potential exposures to soil and water.

- **Regulatory Compliance:** Adherence to updated standards such as NFPA 855 and UL 9540A ensures that newer BESS installations include fire safety features designed to limit fire initiation and propagation, therefore reducing potential environmental impacts in the event of a fire.

1.5.2 ESS Safety and Environmental Considerations

While BESS fire incidents have raised safety concerns, it is important to contextualize these events within the broader landscape of industrial and energy-related hazards. Many documented BESS fires involved early-generation systems that predate modern safety standards. The implementation of robust national codes and advancements in ESS design have significantly improved fire safety and reduced risks.

Crucially, environmental monitoring data from real-world BESS fire incidents does not support claims of widespread contamination. Airborne emissions are short-lived and localized, soil and water contamination risks are minimal, and existing firefighting strategies further mitigate potential environmental harm.

As the BESS industry continues to evolve, adherence to best practices in system integration, commissioning, and fire protection will further enhance safety and environmental sustainability. With continuous ongoing research and advancements in technology, ESS remains a reliable and safe energy storage option.

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2 Introduction

Battery Energy Storage Systems (BESS) have become an essential component of modern energy infrastructure, supporting grid stability, renewable energy integration, and peak demand management. With the rapid introduction of BESS, concerns about the fire hazards associated with this equipment have been raised. To address these concerns, American Clean Power (ACP) has engaged Fire & Risk Alliance, LLC (FRA) to provide an independent analysis of historical Lithium-Ion (Li-Ion) Battery Energy Storage System (BESS) fire incidents and their causes, a review of the types of contaminants released, the extent of environmental impacts, and how advancements in safety regulations and technology have mitigated risks.

This report discusses the concerns related to BESS fires and the potential environmental impacts stemming from them. It is intended to provide an in-depth review of the available information, including case studies of past incidents and analysis of fire characteristics. By examining the causes, consequences, and mitigation strategies for BESS fires, the report aims to inform stakeholders and guide future safety improvements in the deployment of Li-Ion BESS systems.

3 Battery Energy Storage Systems

In recent years, the number of large and utility-scale BESS units has increased throughout the United States (US). These systems function by storing surplus power during lower demand periods and discharging it when electrical demand is elevated. As power demands continue to rise in the US, BESS units provide a highly effective method for energy storage and rapidly expanding electrical power capacity during peak demand periods.

According to the US Energy Information Administration (EIA), BESS capacity has increased drastically since 2021 and total installed US battery capacity exceeded 26 GW in 2024 [1]. Figure 1 shows the current and projected BESS storage capacity, in terms of total gigawatts.

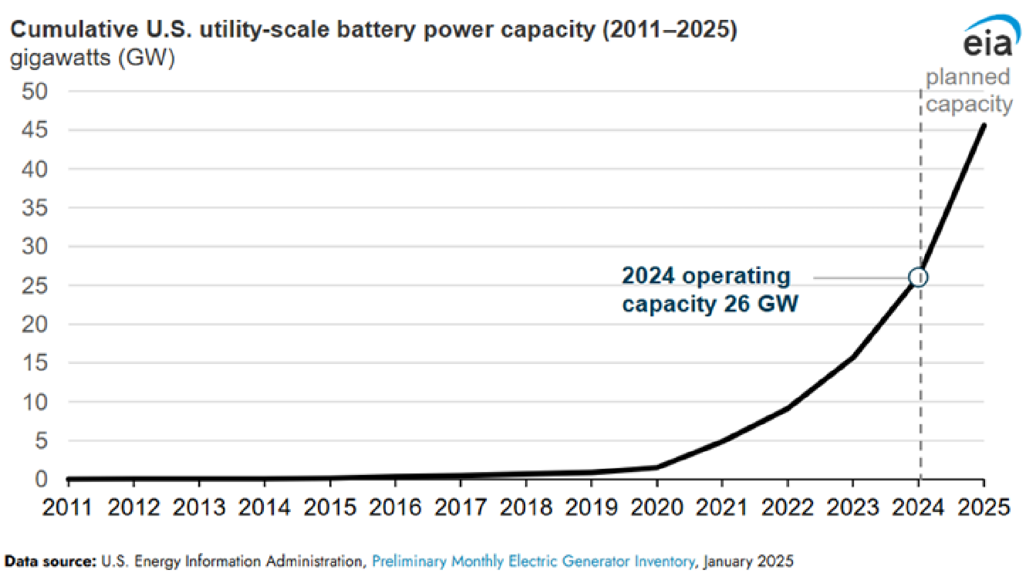


Figure 1: Cumulative Installed Battery Capacity in the US [1]

Utility scale BESS are typically installed near electrical substations or other utility plants to improve both the economic and power efficiency of the systems. The EIA defines large/utility scale energy storage to have "at least 1 MW of net generation capacity and are mostly owned by electric utilities or independent power producers to support the power grid" [2].

While renewable energy sources have contributed to the growth of BESS, BESS are increasingly being installed to provide grid stability, reduce the need for peak plants, and to take advantage of excess power generation from traditional power producers.

According to the DOE Global Energy Storage Database, there were 635 utility-scale Li-Ion BESS installations in the U.S. through the end of 2023 [3]. Cleanview reports that an additional 175 utility-scale BESS were built in 2024 [4]. Assuming from the DOE database data that 90-95% of new BESS installations in 2024 were Li-Ion BESS technology, the best approximation for the number of operating Li-Ion BESS facilities in the US at the end of 2024 is approximately 800.

4 BESS Fires

BESS fires remain a relatively uncommon but significant concern within the energy sector. As these systems continue to expand in deployment and capacity, understanding the characteristics of BESS fires is crucial for improving fire safety, emergency response, and system design. These fires can vary widely in duration, ranging from minutes to multiple days.

This section provides a brief overview of 35 documented large-scale BESS fire incidents in the US (listed in Appendix A of this report), examining key trends, common failure modes, and contributing factors, while Section 4.3 provides additional details on seven incidents in which environmental monitoring data was available. These incidents offer valuable insights into the fire risks associated with BESS technology and can serve to inform ongoing safety improvements.

4.1 Selection Criteria for Incident Analysis

The 35 incidents included in this review were selected based on specific criteria to ensure relevance to utility-scale BESS fire safety research. The inclusion criteria were:

- Fires occurring in the US
- Large/utility-scale, stationary BESS units[1]
- Lithium-Ion Battery (LIB) installations

The incidents occurred across 16 states, with California experiencing the highest number (12 cases) (Figure 2). In 10 states, only one incident was included. These fires spanned nine years (2012–2024) (Figure 3), though some years lacked reported incidents due to underreporting or data limitations [5, 6].

[1] A few exceptions were included: 3 transport-related incidents and 1 warehouse incident, in which additional plume data was available for review

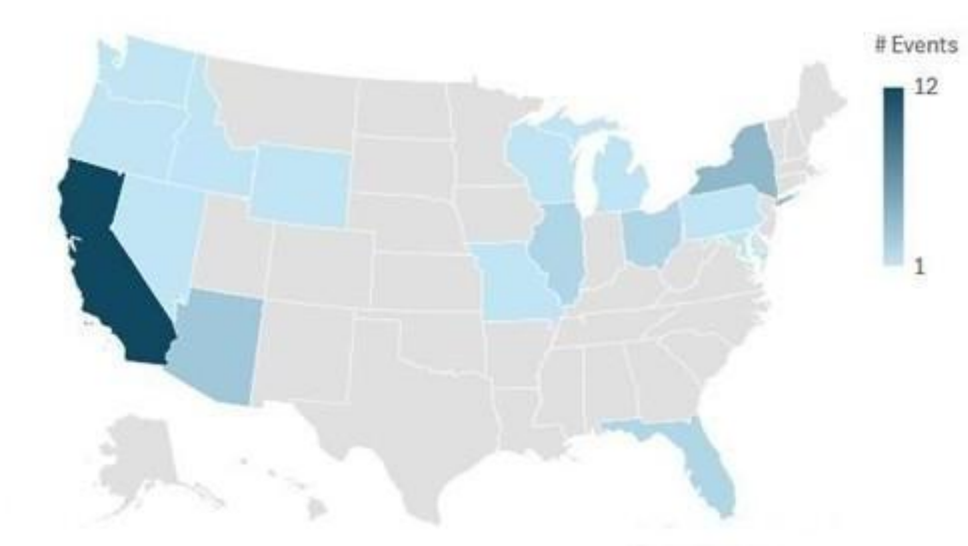


Figure 2: States in which Included Incidents Occurred[2]

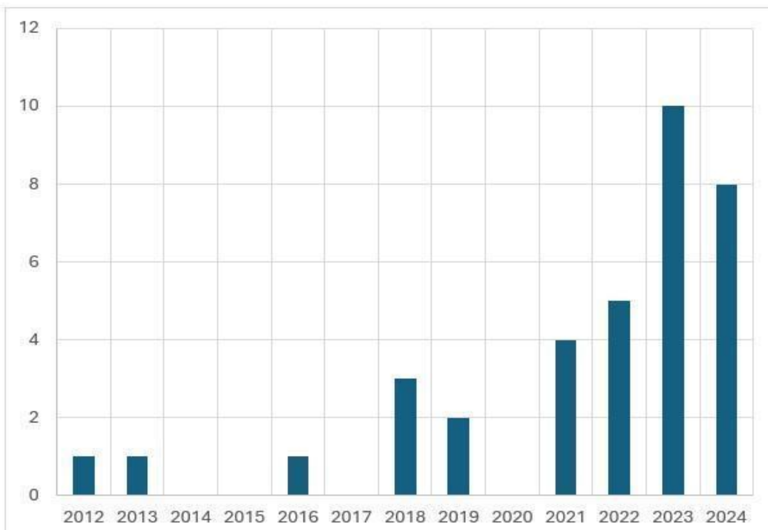


Figure 3: Number of Incidents Included in Analysis by Year[3]

4.2 Characteristics of BESS Fires

The analysis of historical incidents provides critical insights into the circumstances under which BESS fires occur. The following trends were observed:

4.2.1 System Age and Fire Occurrence

[2] Graphic created by FRA using data from [5, 6]

[3] Graphic created by FRA using data from [5, 6]

- Of the 35 incidents analyzed, 51% included data on the age of the BESS unit at the time of the fire (Figure 4). There were significantly more fires in BESS units that were early in the life cycle as compared to aged systems.

- Nearly half (44%) of the incidents with reported age occurred within the first six months of operation, suggesting that early-stage issues during assembly, installation, or pre-commissioning may play a significant role in BESS fire risk.

- The oldest system with a recorded fire was 7.6 years old (Escondido, CA, 2024) [5].

- This trend underscores the importance of improved quality control during manufacturing, commissioning, and initial operational phases.

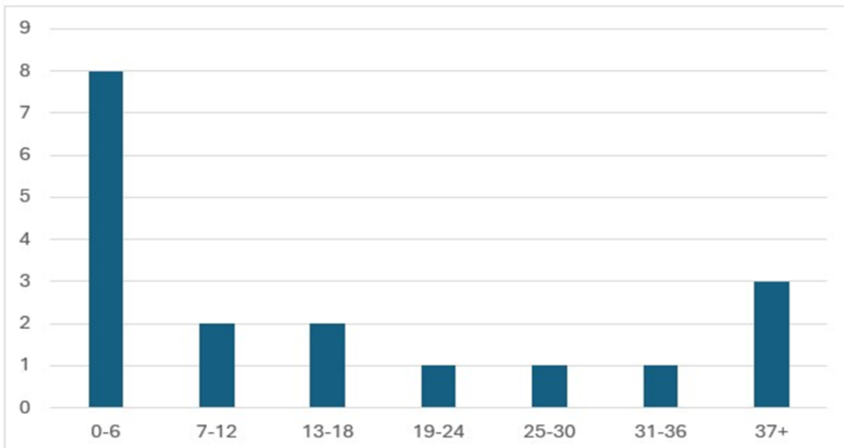


Figure 4: The Number of Fire Incidents by Age (Months) in Six-Month Increments[4]

4.2.2 Operational Status at the Time of Incident

As noted in Figure 5:

- 69% of fires occurred while the BESS was operational and in use.
- 17% of fires occurred during the assembly, testing, or pre-commissioning phase.
- Early-stage incidents highlight potential vulnerabilities in integration and commissioning procedures, necessitating improved testing, monitoring, and safety checks before systems are put into full operation [7].

[4] Graphic created by FRA using data from [5, 6]

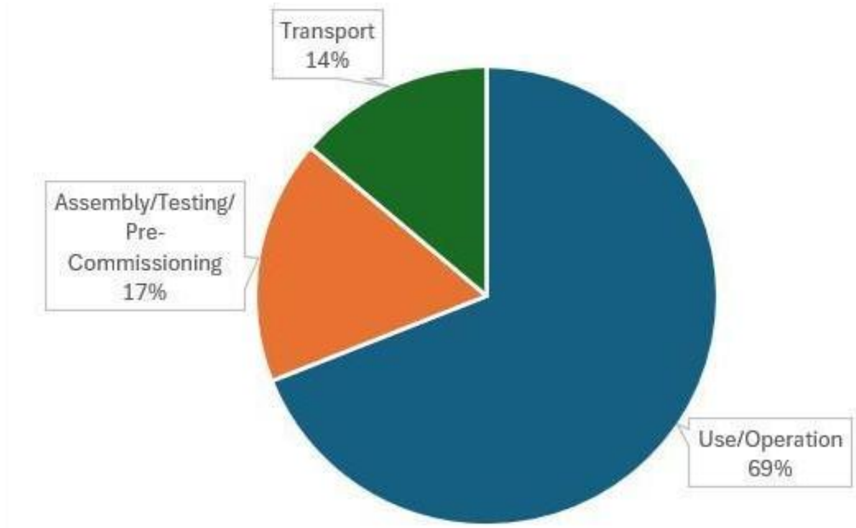


Figure 5: The Number of Incidents by the State of the BESS During the Fire Event[5]

4.2.3 Common Causes of BESS Fires

Determining the exact root cause of BESS fires can be challenging due to the destruction of evidence in high-temperature fire events and proprietary investigations that limit publicly available data. However, of the 35 incidents analyzed:

- 49% had a reported cause, with the most common being integration, assembly, or construction failures, followed by design-related failures (Figure 6).
- Manufacturing defects were cited in fewer cases, likely due to the difficulty in attributing these failures post-fire [7].
- Common Failure Categories (Based on EPRI and FRA Definitions) [7]:
  - Design Failures: Issues with planned system layout, cell or system-level design flaws, or insufficient safeguards against predictable misuse.
  - Manufacturing Defects: Flaws introduced during the production process, such as misassembled parts or foreign material contamination.
  - Integration, Assembly, or Construction Failures: Problems during installation, component compatibility issues, inadequate commissioning, or poor system integration.
  - Operational Failures: Failures occurring due to exceeding operational limits, such as incorrect voltage/current sensing or temperature threshold violations.
  - Physical Damage: Failures caused by mechanical impacts or external damage to the battery system (e.g., transportation-related incidents).

[5] Graphic created by FRA using data from [5, 6]

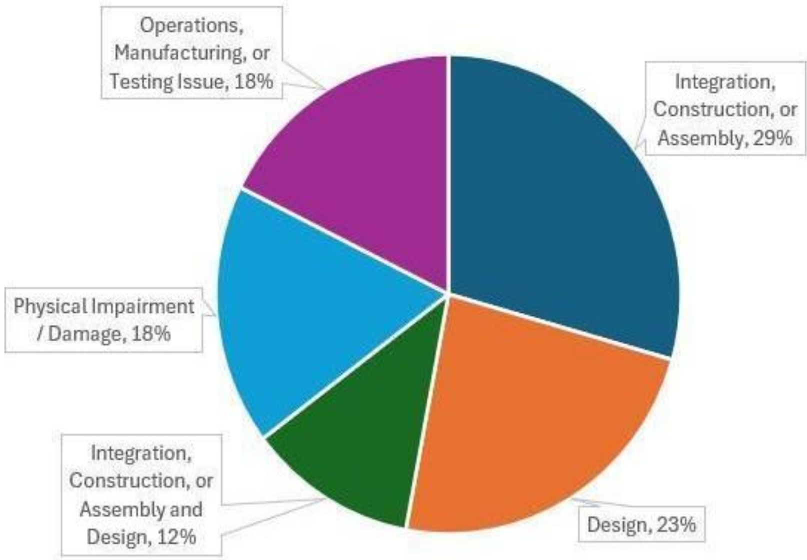


Figure 6: Number of Incidents by Cause[6] [7]

4.2.4 Failed System Components

Among the 35 incidents, 34% reported data on failed elements (Figure 7). The most commonly affected components were:

- Balance of Plant (BOP) Failures: These include wiring, busbars, enclosures, power conversion systems, fire suppression systems, HVAC, or liquid cooling systems.
- Control System Failures: Issues related to battery management systems (BMS), energy management systems (EMS), or communication/control circuit failures [7].
- Cell/Module: Failure in the LIB cell or module, usually beginning with short circuits that lead to thermal runaway. Failures can originate from poor cell design or incorrect installation.

[6] Incidents that occurred during transportation were considered physical damage.

[7] Graphic created by FRA using data from [5, 6]

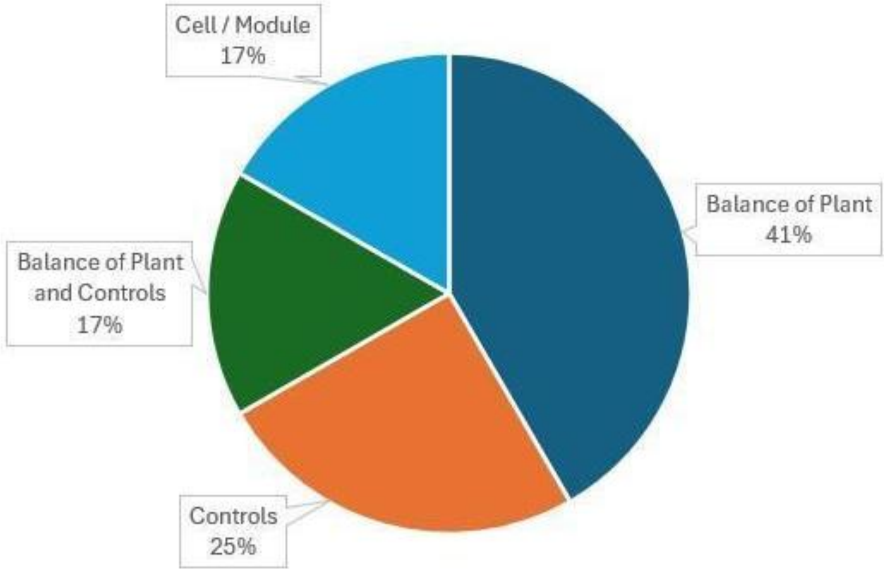


Figure 7: Number of Incidents by Failed Element[8]

Integration, assembly, and construction issues were the most frequently cited causes, aligning with the fact that BESS containers often integrate components from multiple manufacturers that may not have been designed or tested together for compatibility, leading to failed components. Failure in safety-critical components, such as cooling systems and fire suppression mechanisms, further emphasizes the importance of rigorous design, installation, and commissioning protocols.

4.2.5 Key Takeaways from Incident Analysis

- Most incidents involved legacy BESS systems that predate modern safety standards (IFC, NFPA 855, UL 9540A), underscoring the impact of regulatory improvements.
- Early-stage failures (within six months of operation) suggest a need for enhanced oversight during commissioning, installation, and integration.
- Fire incidents were predominantly linked to system design and integration failures rather than inherent flaws in LIB chemistry.
- A significant number of failures occurred in BOP components and control systems, highlighting the importance of improving system compatibility, safety interlocks, and failure detection mechanisms.

4.3 BESS Fire Case Studies

To better understand the characterization of BESS fires, 7 case studies are briefly presented. With the exception of the Valley Center, CA event, which is provided as an atypical example, these incidents have been selected because there is published data relating to air, water, and/or soil impacts for each of these events.

In addition to the case studies summarized above, a large indoor BESS fire occurred on January 16, 2025 involving a 1,200 MWh system at Moss Landing, CA. As of the drafting of this report, the investigation was

[8] Graphic created by FRA using data from [5, 6]

ongoing, and the environmental impact was being monitored closely. Due to the timing of this event, it was not formally considered in this study.

4.3.1 Valley Center, CA

On April 5, 2022, a fire occurred at a utility-scale BESS facility in Valley Center, California. This 560 MWh system, operational for about 2.4 months, was used for frequency regulation [5, 8]. The fire affected only one module, damaging a single rack within one container. The cause was traced to a design flaw in the controls, specifically a sensor fault that accidentally triggered the suppression system [9].

The fire was caused by an electrical failure within the controls. This failure produced some smoke, triggering the protection system, which operated successfully. The incident occurred at a new BESS facility and was quickly extinguished by the fire suppression system. According to the responding fire marshal, the safety (water suppression) systems appeared to have functioned correctly in terms of suppressing the incident. Additionally, the enclosure next to the affected one also shut down due to smoke detection as intended by the design of the safety system [5, 8]. Note that air, soil, and water contamination data was not available for this case study. It is provided solely as an example of a contained fire involving only one BESS module.

4.3.2 East Hampton, NY

A fire occurred on May 31, 2023 at a substation in East Hampton, New York. This BESS unit was 40 MWh and installed for grid stability. It was approximately 4.8 years old and in use/operational at the time of incident. The original reports of the incident recall a smoldering battery, which resulted in the shutdown of local roads and stopping train service for approximately one hour until the fire was contained [10]. NextEra, the manufacturer of the unit, confirmed that the "water-based fire suppression systems operated as designed and quickly contained the fire to the site," not requiring any further emergency response or external intervention [10]. There was no reported cause in any publicly released document nor were any available images found of this BESS fire incident.

4.3.3 Surprise, AZ

The April 19, 2019 incident in Surprise, Arizona resulted in the injury of multiple firefighters. Subsequently there have been extensive investigations undertaken post-incident by UL and Arizona Public Service (APS) [11, 12]. This fire event has been heavily considered in the subsequent development of fire protection and safety codes and standards and BESS firefighting procedures.

This BESS unit was slightly more than two years old at the time of the incident and was operational. It was installed at a substation to help with power supply and voltage regulation. The 2 MWh unit had NMC batteries, and the failure was traced to an internal manufacturing defect in a cell/module that caused a short circuit [5, 11, 12].

During the incident, fire alarms and the clean agent fire suppression system activated, but were unable to prevent or stop the cascading thermal runaway (TR) reaction in the BESS unit. Upon arrival on-scene, firefighters monitored temperatures and gas release from the venting batteries. Three hours after TR was initiated, firefighters opened a door to the battery container, allowing oxygen to enter. Within minutes, a powerful deflagration occurred, seriously injuring several firefighters [5, 11, 12].

Neither UL or APS's investigative reports provide pictures of the singular container on fire. Rather, both reports include photos of the damage after the incident, and UL's report features images of the incident upon arrival and just after firefighters opened the door to the unit during battery venting, which may be seen in Figure 8.

(a)

(b)

Figure 8: Images of the Surprise, AZ Fire.

(a) Conditions of the BESS site upon the firefighters' arrival. Venting can clearly be seen coming from the unit [11]

(b) Approximately 5 seconds after the responding firefighters opened the door to the BESS unit. As noted by UL in the report, high-density gases and vapors can clearly be seen in the photograph [11]

4.3.4 Escondido, CA

The Escondido incident was similar to that of Surprise in that both only impacted one container (see Figure 10). Both installations were at a substation, and both units were multiple years old, with the unit at Escondido being 7.6 years old [5, 13, 14]. Both incidents had air monitoring during the event performed by the responding firefighters, and resulted in evacuation orders for surrounding areas [5, 13, 14]. Escondido was a larger system at 120 MWh with 24 total containers on site. Surrounding unaffected containers were sprayed with water to avoid propagation instead of directly applying water to the affected container, which could have made the situation worse [5, 13, 14]. The affected container was left to burn itself out, taking about 13 hours total, and did not have a reported cause or failed element [5, 13, 14].

Figure 9a shows a clear image of the burning container, including dark smoke and flames [15]. Figure 9b shows a clear image of the burning container as part of the larger BESS facility [16]. It can be seen that firefighters are applying water from a distance to surrounding containers to avoid fire spread and are letting the involved container burn out [16].

(a)

(b)

Figure 9: Images of the Escondido BESS Container Fire

(a) Image shows fire contained to a single BESS container [15].

(b) Image shows application of cooling water to adjacent containers [16].

4.3.5 Chaumont (Lyme), NY

On July 27, 2023, a multi container fire occurred at a utility-scale facility in Lyme, New York (see Figure 10). The system was 4-5 months old and was operational and in use during the incident. An investigative report showed that the cause of the incident had to do with "the controls" [17, 18, 19] .There is minimal information regarding the specific design impairments and controls issue that led to this incident.

The system was 15 MWh and was collocated with a solar farm in a rural area [5]. During the event, four LIB storage containers and two transformers were damaged and produced large amounts of smoke [17, 18, 19]. A shelter-in-place order was issued for the surrounding community within one mile of the facility out of caution. The local fire chief intentionally chose not to put water on the flames due to knowledge that it would not put the fire out, and chose to let the battery burn itself out with full knowledge that it could take hours if not days to do so [17, 18, 19].

The Governor of New York, Kathy Hochul, was made aware of the situation and sent state emergency officials to assist local firefighters. She said that the fire caused "significant damage" to the system and that the smoke "may pose health risks" [17]. Officials monitoring the incident reported no toxic runoff into the water or contamination of the air that would pose health risks [17, 18, 19].

(a)

(b)

Figure 10: Images of the Chaumont (Lyme) BESS Fire Incident

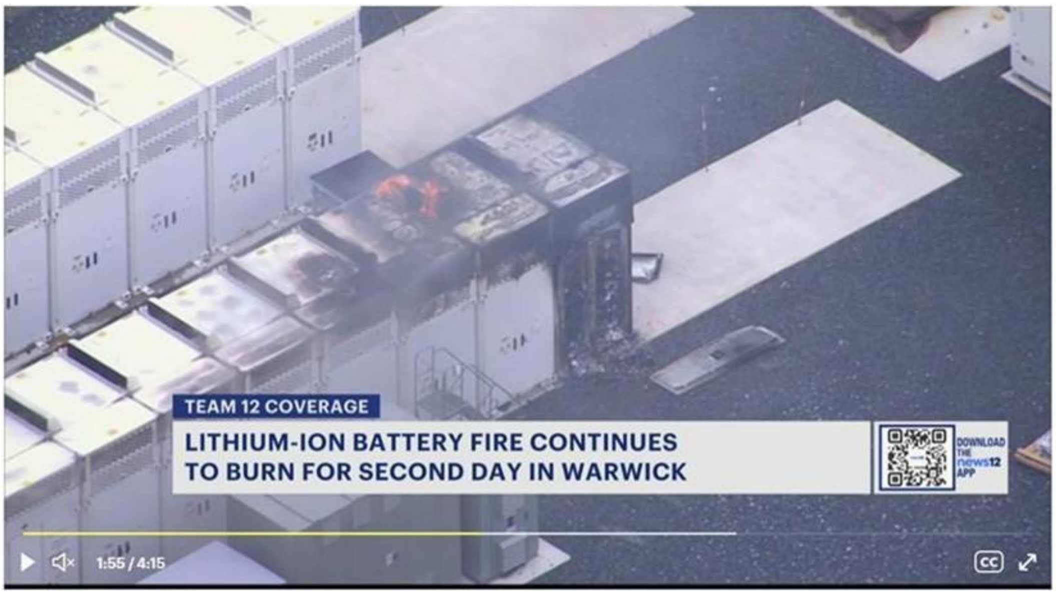
(a) An image showing burned containers emitting smoke and flames. The solar panels can also be seen in front of the BESS [19].

(b) A remote image showing the smoking BESS containers in the context of the whole site. Firefighters can be seen spraying water onto the adjacent containers from a great distance. [20]

4.3.6 Warwick, NY

Two independent fire events occurred on June 26 and June 27, 2023 in Warwick, New York (see Figure 11). On June 26, a fire alarm went off at a BESS site, activating the suppression system within the affected enclosures. A second incident on June 27 also resulted in the activation of the fire alarm at another BESS site [21]. The fire department responded and provided support for the battery fires [5]. The fire department allowed the fire to burn itself out and monitored air quality. The fires were believed to have been caused by damage to the batteries from a storm the previous night, though that was not confirmed [22]. Both were installed at substations for grid stability and were only several months old and in use/operational at the time of incident [5, 21].

(a)



(b)

Figure 11: Images of the Warwick, NY BESS Fires

(a) A single enclosure on fire can be seen at one of the units. It can also be seen that the fire was contained to the originally affected unit [22].

(b) A single enclosure on fire at the other BESS site. It can be seen that the gas build-up was strong enough to blow off the door of the enclosure [22].

4.3.7 Melba, ID

A fire at a BESS unit installed at a substation for distribution report occurred in Melba, Idaho on October 2, 2023. At the time of the incident, the system was in the pre-commissioning stage (not yet operational) [5]. The unit capacity was 8 MWh [5]. It was suspected that water intrusion led to a short-circuit, which caused excess heat production that eventually lead to ignition of the battery cells, with the fire spreading among battery segments until burning out [23]. 48 hours after the event, the temperature of the batteries was reported to be approximately 650 °F [24]. The fire burned out after three days, and the substation remained operational through the fire event with external road closures [23, 24]. Images of this incident may be found in Figure 12.

(a)

(b)

Figure 12: Images of the Melba, ID BESS Fire

(a) An image showing one side of the burning enclosure at the substation [24].
(b) Another angle of the burning BESS enclosure showing the other side burning [24]

5 Airborne Emissions from ESS fires

Estimating the effects of BESS fire-related effects requires two principal areas of analysis. The first area, covered in this section, addresses the generation of gaseous and particulate emissions from the malfunctioning BESS unit. The estimated conditions at the source are then used as input for the second part of the analysis. The second part assesses the transport of the gaseous and particulate emissions to estimate conditions away from the source. The second analysis is covered in the next section.

A review of toxic gas hazards and the potential for soil and water contamination requires an understanding of the gaseous and particulate emissions that are associated with BESS fire-related events. These events are associated with malfunctioning of a battery. These events may be limited to overheating of a battery with some venting of gases, while others may continue to TR and flaming combustion. The progression of these events and their consequences are depicted in Figure 13.

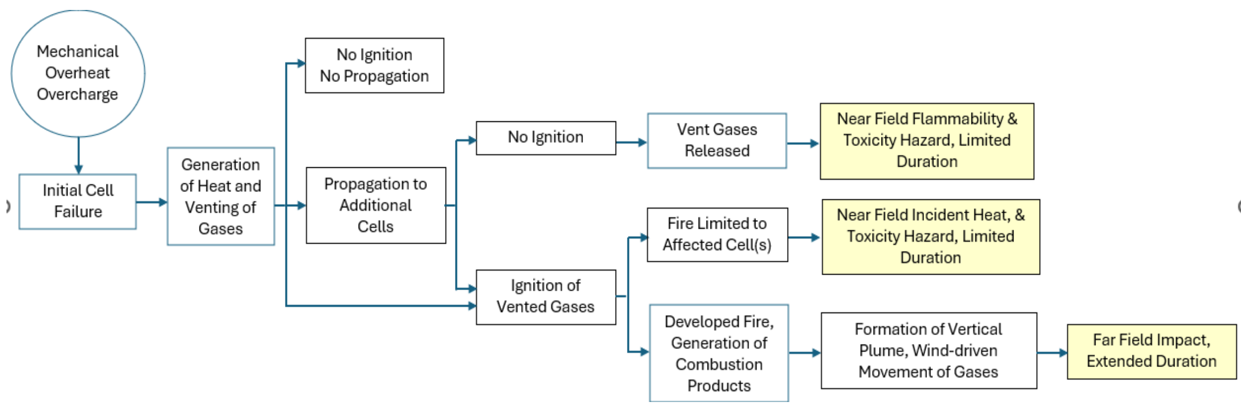


Figure 13: Event Pathways for Battery Malfunctions

These events may lead to TR where additional cells become involved. The process of TR involves the exothermic chemical decomposition of battery cell materials resulting in self-sustaining heat generation and temperature rise of the affected battery, leading to an increase in the rate of heat generation. The decomposition and temperature increase results in the generation of gases and particulate matter which are released from the battery cell. With sufficient temperature rise, the emitted gases will ignite and a fire may occur. The fire may develop to involve the electrolyte and container enclosing the battery. It should be noted that only a small number of battery failures will lead to TR and only a subset of those will lead to a fire.

The principal cause of a battery malfunction leading to TR is an internal short circuit. Examples of causes of short circuits include heating from external fires or other sources, physical damage, or overcharging. The process of TR includes several stages, including breakdown of the solid electrolyte interphase (SEI), reaction of the anode and electrolyte, reaction of the cathode and electrolyte and electrolyte decomposition. The cell temperatures associated with these stages are summarized in Table 2.

Table 2: Temperature Ranges for LIB Degradation (adapted from [25,26])

Temperature (°C)	Activity
>70	Li salt decomposition and reaction with solvent and solid electrolyte interphase (SEI).
90-130	SEI breaks down leading to anode-electrolyte reaction; low heat generation.
90-230	Li-electrolyte reaction occurs leading to gas production, e.g. ethylene, ethane and propane.
120-220	Electrolyte vaporizes, additional gas production, cell pressurization and initial venting. Separator melts at 270-370 °F.
160	Heat generation increases, transition from self-heating to TR. Second venting, with gases and particles emitted.
200-300	Electrolyte decomposition. Rapid temperature rise at TR, metal oxide cathode decomposes to produce oxygen and oxidation of electrolyte yielding carbon dioxide and water vapor.

Characteristics of the generated emissions depend on several factors, including the stage of the event, i.e. pre-TR, pre-combustion (non-flaming) TR, and post-combustion (flaming) TR. Given the variety of BESS unit designs found in utility-scale installations, the current state-of-the-art does not permit a universal description of the gaseous and solid emissions generated by these events. However, trends in emissions are evident following a review of numerous studies that have been conducted to analyze the gaseous and solid emissions generated. Many of these studies involved tests with single cells, though some experiments were conducted on modules or units [27, 28, 29, 30, 31, 32].

The gaseous and solid emissions released during an event can be described in terms of the chemical composition, total volume, and rate of production of the emissions. Each of these three qualities is dependent on the following five factors:

- Battery chemistry[9]
- Form of the battery
- State of charge (SOC) of the battery
- Stage of the event
- Cause of the malfunction/event

While numerous publications have appeared in recent years addressing emissions associated with TR, the information is still somewhat limited. A comprehensive description of the three qualities of emissions for every possible factor is not yet available. Further, regarding the information that is available, there are significant variations in the reported qualities within or between studies. These variations may be associated with differences in experimental procedures, quality control of batteries, or experimental uncertainty. As such, the most important takeaway of this review is the set of trends that have been reported in the literature. A second takeaway is that much research is still needed in order to provide definitive input information for predictive modeling.

[9] This report will principally address results from experiments with LFP and NMC chemistries given their prevalence in utility-scale BESS installations

5.1 Chemical Composition of Emissions

5.1.1 Gaseous Emissions

Several chemical species may be released as emissions. The gases commonly found in emissions released during TR are included in Table 3: Chemical Composition of Gas Emissions from LIB Degradation [25, 26, 33]. Batteries utilizing LFP and NMC chemistries generate more CO_2 and H_2 than other chemistries [26]. In experiments conducted by FRA on LFP batteries, 85-92% of the gas volume produced was composed of three gas species: H_2, CO_2 and CO with H_2 comprising the greatest percentage.

EPRI's review of gaseous emissions identified these trends relative to the generation of HF and CO [34]:

- Greater HF production is noted in LFP cells (as compared to NMC/LMO cells) and pouch cells as compared to cylindrical cells

- Greater CO production occurs when ignition originates internally versus externally[10]

Table 3: Chemical Composition of Gas Emissions from LIB Degradation [25, 26, 33, 34]

Carbon Monoxide (CO)	Dimethyl carbonate ($C_3H_6O_3$)
Carbon Dioxide (CO_2)	Ethyl methyl carbonate ($C_4H_8O_3$)
Hydrogen (H_2)	Diethyl carbonate ($C_5H_{10}O_3$)
Methane (CH_4)	Acrolein (C_3H_4O)
Ethane (C_2H_6)	Hydrogen fluoride (HF)
Propane (C_3H_8)	Hydrogen chloride (HCl)
Isobutane (C_4H_{10})	Fluoroethane (C_2H_5F)
Pentane (C_5H_{12})	Hydrogen cyanide (HCN)
Hexane (C_6H_{14})	Nitrous oxides (NOx)
Formaldehyde (CH_2O)	Sulfur dioxide (SO_2)
Acetylene (C_2H_2)	Phosphorus pentafluoride (PF_5)
Propylene (C_3H_6)	Phosphoryl fluoride (POF_3)
Benzene (C_6H_6)	
Butylene (C_4H_8)	
Toluene ($C_6H_5CH_3$)	

While a common set of gases, such as CO_2, CO, carbonates and H_2 are produced from all batteries [35], additional gases are produced depending on components of the battery such as the specific electrolyte.

[10] Experimentally obtained results of gas quantities depend on the experimental method. As such, the quantity of gas emissions in the field will depend on the details of the incident.

The gases produced by flaming batteries are relatively similar to those acquired from flaming ordinary combustibles such as wood, polymers and liquid fuels. Combustion of ordinary combustibles produces CO_2, CO, and an array of hydrocarbons. Depending on the composition of the fuel, other gases may be produced from fires involving these fuels. For example, the production of nitrogen-containing gases, such as NOx and HCN, are produced from fuels that contain nitrogen, SO_2 from fuels that contain sulfur, HCl and other chlorine-containing compounds from fuels that contain chlorine and fluorine-containing compounds from fuels that contain fluorine. The principal difference in the gaseous emissions from batteries to that of ordinary combustibles is the generation of H_2, which is not seen in the combustion of ordinary combustibles.

The list and proportions of gases generated from batteries undergoing TR is influenced by the State of Charge (SOC). At 0% SOC, more CO_2 is produced than CO, and only a few solvents are produced. The impact of SOC on the production of CO_2, CO, total hydrocarbons (THC) and H_2 on a prismatic NMC cell experiencing TR is presented in Figure 14 [36].

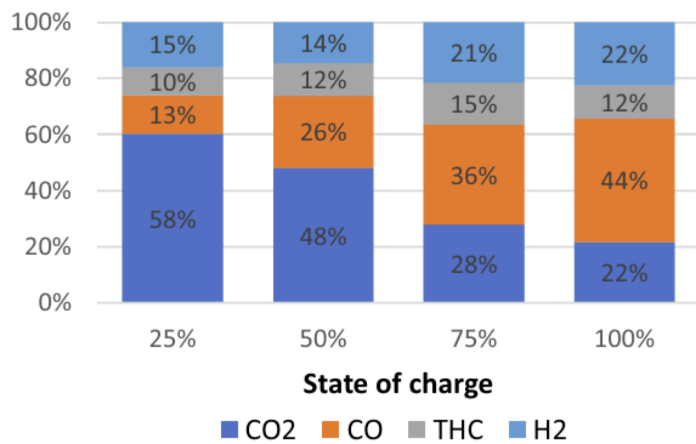


Figure 14: Impact of SOC on Proportion of CO_2, CO, Total Hydrocarbons (THC) and H_2 [36]

Increasing the SOC increases the rate of combustion which yields [36, 37, 38, 39, 40, 41, 42]:

- An increase in the quantity of gas production
- An increase of the number of different gas species emitted
- An increase in the concentration of H_2, especially for LFP cells.

The electrolyte in a LIB is flammable and generally contains lithium hexafluorophosphate ($LiPF_6$) or other lithium-salts containing fluorine. In the event of overheating, the electrolyte evaporates and vents from the battery cells. Emissions can include electrolyte vapors, especially if there is insufficient heat or oxygen for combustion to occur. In the case of overcharging LFP cells, up to 60% of emissions can be comprised of electrolyte [26, 33]. The most abundantly emitted gases that were associated with electrolytes were carbonates, such as ethyl methyl carbonate, diethyl carbonate or dimethyl carbonate. .

The fluorine content of the electrolyte and other parts of the battery, such as the polyvinylidene fluoride (PVdF) binder in the electrodes may form gases such as HF, phosphorus pentafluoride (PF_5) and phosphoryl fluoride (POF_3) at elevated temperatures [43]. The amount of HF produced per Watt-hour is approximately 10 times greater for the cell with the greatest capacity compared to a cell with the lowest capacity. This is likely due to differing amounts of electrolyte and filler materials being in the larger capacity cells.

Heated electrolytes in a cell may decompose resulting in the production of numerous compounds including CO, CO_2, CH_4, C_2H_4, C_2H_6 and H_2, HF, and C_2H_5F [25, 44].

While appreciable attention is given to the production of gases from battery incidents, it's important to note that some of these gases such as fluorine and HF are reactive and react with other components of the plume. While appreciable concentrations of these gases may be found near the source, significantly reduced concentrations will be found a short distance from the source [45].

5.1.2 Particulate Emissions

The composition of particulate emissions was discussed in several reports. Metal species found in the particles depended on cathode composition and otherwise did not depend on the cell chemistry [46]. In the experiments conducted NMC batteries, particulates were principally composed of nickel and copper, though some chromium and zinc were also found. Experiments with an NMC battery identified the following elements in solid particulates: nickel, cobalt, tin, silicon, phosphorus, manganese, lithium, copper, barium and antimony [47, 48, 49].

In experiments with 12 prismatic, Samsung SDI, 90 Ah, NMC cells, the anode was graphite, and the electrolyte was composed of organic carbonates with $LiPF_6$ salts [48]. The soot collected from their experiments was composed mainly of:

- Heavy metal-oxides of nickel, manganese, and cobalt (with similar mass proportions, in the range of 18-20%).
- Lesser amounts of the following were identified: lithium (3-4% by mass), fluorides (2.4% by mass), and chlorides (0.2% by mass) and small amounts of polyaromatic hydrocarbons (PAH).

NMC cells have been found to produce a greater number of particles than LFP cells [50]. Observing a greater number of particles likely means that particles were smaller than in releases with fewer particles. Particle sizes can range from less than 30 μm to 500 μm [49]. The mass distribution of particle sizes measured in one study in close proximity to the battery shortly before it reached TR is presented in Figure 15 [49].

The size of the particles and location of the measurement is relevant when considering the potential for airborne movement of the particles, with smaller particles staying airborne longer than larger particles. However, the size of the particles measured close to the source is likely to change. As the particles move away from the source, they are likely to agglomerate as their distance from the source grows, as is true of smoke particles produced by fires involving hydrocarbon fuels.

A distribution of airborne particle sizes as a function of particle count in repeated tests of NMC battery cells is presented in Figure 16 [47]. The mean particle size ranges from about 70 to 130 nm, which is also the size range noted for the greatest mass. These are smaller than those shown in Figure 16 as the data reported in Figure 15 was done downstream of the source and hence had settled out of the airstream.

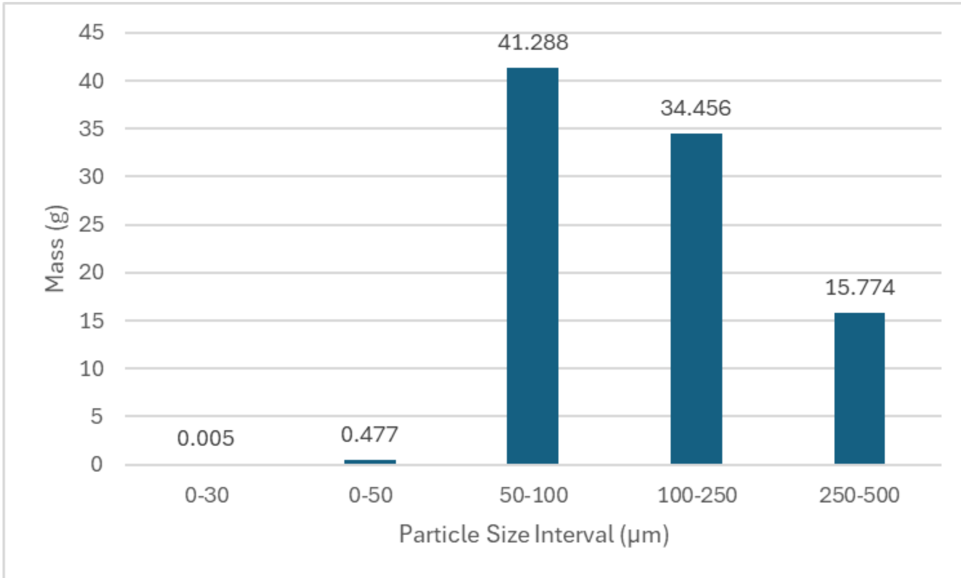


Figure 15: Mass of Particles Generated from Battery Emissions [49]

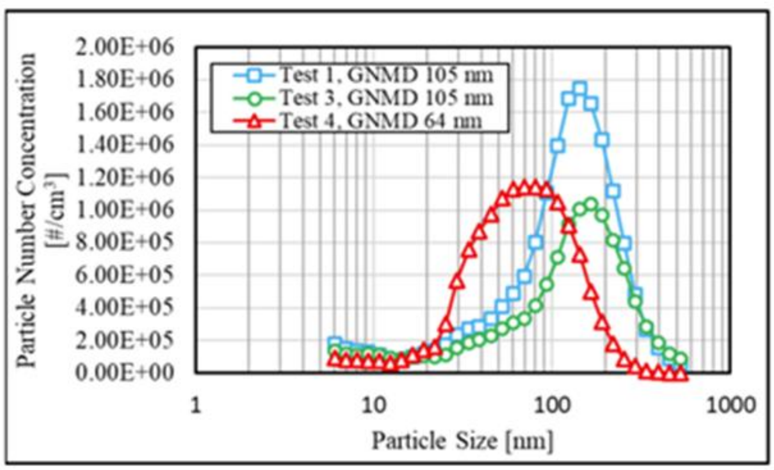


Figure 16: Airborne Particle Sizes [47]

5.2 Total Quantity of Gases Produced

The total volume of all gases produced has been shown to be dependent on battery chemistry, cell type, cell capacity and SOC [26]. Cell capacity and energy density affect TR as well as emitted gas volumes [50]. As a rough approximation, gas production is proportional to cell capacity, typically being in the range of 1 L/Ah to 3 L/Ah for any chemistry. More specifically, at 100% SOC, LFP cells generate a lesser volume of gas than NMC cells, being 0.4 L/Ah to 1.4 L/Ah versus 1.28 L/Ah to 21 L/Ah respectively. However, larger NMC prismatic cells (41 Ah) and LFP cells (5.5 Ah) have been shown to generate similar gas volumes, 1.64 L/Ah and 1.83 L/Ah respectively (in nitrogen) [51, 52].

The gas volume produced normalized by the cell capacity is presented in Figure 17 and Figure 18. As indicated in Figure 18, NMC pouch and NMC and LFP prismatic cells generate similar volumes of gas production and more volume than cylindrical cells of either chemistry.

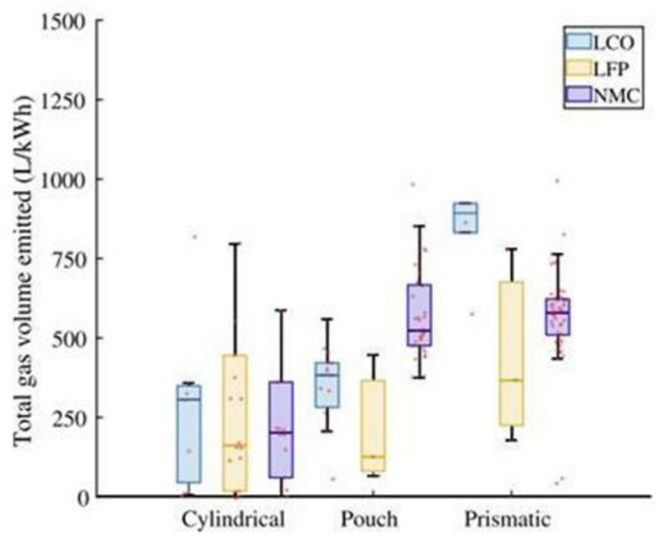


Figure 17: Influence of Cell Type on Gas Volume Produced [32]

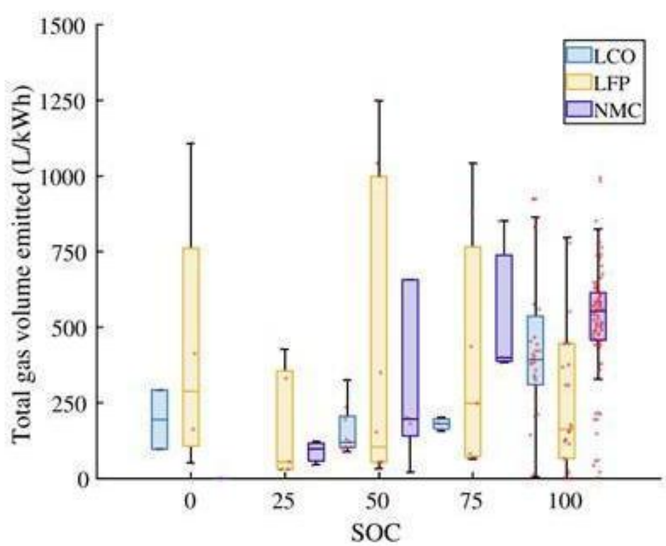


Figure 18: Influence of SOC on Gas Volume Produced [32]

Differences in the vent rate of gases resulting from different means of causing the battery to overheat in pouch and prismatic NMC cells are presented in Table 4 [53].

Table 4: Dependence of Gas Venting on Cause of Overheating [53]

	Overtemperature		**Overcharge**		**Nail Penetration**	
	Pouch	Prismatic	Pouch	Prismatic	Pouch	Prismatic
Vent Rate (L/s)	34	67	47	250	182	140
Normalized total vent gas (L/Ah)	1.56	1.56	2.79	2.65	1.71	1.77

Gas volume production is shown to increase as SOC increases for NMC [25, 54, 55, 56, 57] and LFP [40, 58] chemistries. While LFP cells at a greater SOC typically produce less off-gas than other chemistries, at lower SOC, gas volumes emitted from LFP cells tend to be comparable to those from other chemistries [36, 40]. Increased gas generation at a greater SOC is attributed to greater electrode potentials and more reactive cell materials [36]. As observed in Figure 18, the greatest increase in emissions occurs for SOCs greater than 50% [36, 54]

The occurrence of combustion is also believed to influence gas production in NMC cells. This is observed in the lab-scale tests with cells as well as those with modules. If the event is limited to a pre-combustion stage (at 0% SOC), more gas production is recorded [59]. In module tests, increased quantities of CO_2, HF, and NOx were observed with decreased quantities of methane, ethylene, CO, POF_3, carbonates, formaldehyde, and H_2 during flaming as compared to non-flaming combustion [29].

The volume of gases produced may be sufficient to be within their respective flammable range [33,39]. Experimental data of the four gases with the greatest concentration from an LFP cell undergoing TR is presented in Table 5.

Table 5: Volume of Emissions from NMC Cells of Five Gases [33] [11]

Gas Species	**Measured Range (vol %)**	**Flammable Range (% vol)**
Carbon Dioxide	18	N/A
Hydrogen	9	4-75
Ethane	3.9	3-12.5
Carbon Monoxide	1.9	12.5-74.0

The volume of gaseous emissions during TR from batteries of all cell types and chemistries depends on the battery capacity [26,55]. In general, the quantity of gas produced increases with cell capacity for all chemistries and cell types as depicted in Figure 19 [26]. .

[11]The absence of CO_2 from the table is likely due to the focus of the paper being on flammable gases. It's unclear why hydrogen was not included

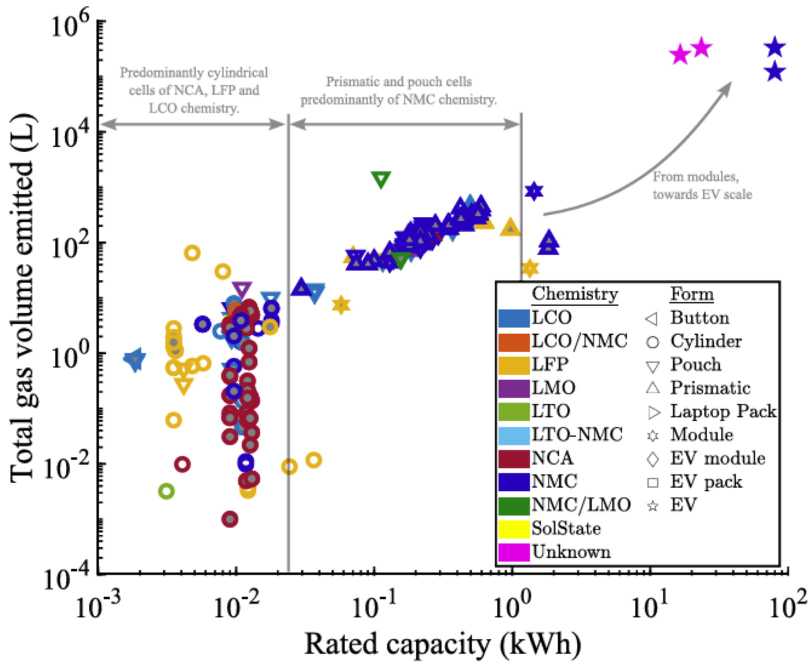


Figure 19: Relationship of Volume of Gas Production to Cell Type and Chemistry

Experiments measuring the gaseous emissions from 51 NMC cells undergoing TR found the principal gas components to be CO_2, CO and H_2 with average concentrations of 36.6%, 28.4% and 22.3% respectively [60]. The next most common gases were C_2H_4 and CH_4 with average concentrations of 5.6% and 5.3% respectively.

Table 6 provides a summary of results of selected gas species of emissions from TR of LIBs [47]. As indicated in the table, CO_2 and CO consistently comprise the greatest concentrations, though significant amounts of ethylene are also reported in some tests. Measurements taken to identify the presence of volatile organic compounds (VOCs) are presented in Table 7.

Table 6: Gas Emission Concentrations (ppm) [47]

	CO_2	CO	NH_3	CH_4	C_2H_4	HF	CH_2O
Test 1 (avg.)	578	30.3	0.5	10.4	25.9	2.3	3.5
Test 3 (avg.)	533	24.2	0.3	7.8	21	1.3	2.7
Test 4 (avg.)	1483	20.4	0.2	4.6	6.9	15.1	3.5
Koch et al. [60]	36.6	28.4	NA	5.3	5.6	NA	NA
Yuan et al. [58]	13.2	30.3	NA	10.5	NA	NA	NA
Sun et al. [61]	NA	14000	NA	NA	NA	NA	NA

According to EPRI [34], the emissions of battery cells of LFP chemistry contain fluorine compounds, which is produced as a result of the $LiPF_6$ electrolyte. The total volume of HF generated appears to be independent of the SOC as indicated in Figure 20. While the concentration of fluorine compounds can be appreciable in close proximity to the cell, given the reactivity of fluorine compounds, they will tend to react with other substances (including water vapor) or be absorbed into particulate matter. The rate of production of HF is presented in Figure 21 for a range of SOC's. As with other gases, the rate of production is dependent on the SOC, with greater release rates observed with increasing SOC.

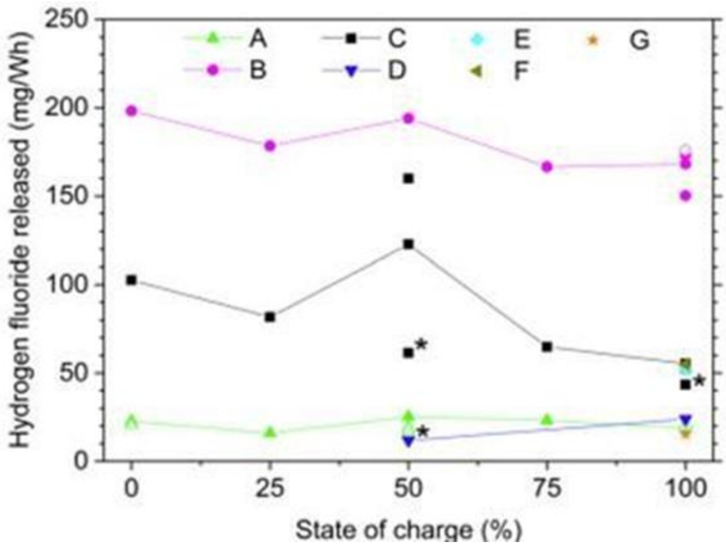


Figure 20: Influence of SOC on HF Production (Battery Types B-E have LFP Chemistry) [34].[12]

Masses of CO emissions from NMC and LFP batteries having a capacity of 0.01 kWh and SOC of 100% were [26]:

- NMC battery: 1.72 g of CO
- LFP battery: 0.19 g of CO

To put these CO mass production amounts into perspective, the CO emissions from the batteries can be compared to a small fire of pine wood having a heat release rate of 25 kW (comparable to that of a small trash can filled with wood chips). The same amount of CO is produced from this size fire of wood burning for the duration noted in Table 7.

Table 7: Comparison of CO Emissions from NMC and LFP 0.01 kWh Batteries (at 100% SOC) with Pine Wood

Battery Type	**CO Emissions from 0.01 kWh Battery (g)**	**Duration of 25 kW Fire with Pine Wood (sec)**
NMC	1.72	171
LFP	0.19	19

[12] Labels A-G relate to different battery chemistries: A=lithium cobalt oxide cathode and carbon anode, B-E= lithium-iron phosphate cathode and carbon anode. F= nickel cobalt aluminum oxide (NCA) and lithium aluminum titanium phosphate electrodes. G= laptop battery pack with unspecified battery chemistry.

The composition of the chemical species found in particle emissions in experiments with cells, arrays and modules is included in Table 8 [29]. The proportion of chemical species noted in the table is relatively consistent for all three sources, indicating that test results were not sensitive to the scale of the source. In another study, differences in the flow rates of gaseous and particulate emissions for different causes of overheating of LFP modules were utilized identified with overheating caused by overcharging producing a substantially greater flow rate for a wide range of particles [31,36].

Table 8: Comparison of the Composition of Emissions in Experiments with Cells, Arrays and Modules [28]

Element	Cell Test %	Array Test[13] %	Module Test %
Al	9	6	6
Co	23	20	23
Cu	0	0	0
F	11	19	9
Li	6	5	6
Mn	19	17	19
Ni	30	27	32
P	2	6	5

5.3 Impact of Gas Emissions

Potential concerns about emissions can be related to toxicity of smoke exposures, flammability and environmental damage. Table 9 summarizes the potential effects of emissions from BESS fires as well as fires from ordinary combustibles. The noted health concerns are most relevant to near field scenarios or where the exposure occurs in an enclosed space as is further described in Section 6 of this report.

Table 9: Potential Impacts of Emissions

Combustion Product	Primary Health Concerns
Carbon Dioxide (CO_2)	Contributes to greenhouse gas emissions but not hazardous at fire scene concentrations.
Carbon Monoxide (CO)	Toxic gas that poses immediate inhalation risks in enclosed spaces, in open air CO will dissipate rapidly.
Hydrogen Cyanide (HCN)	Toxic; common in fires involving synthetic materials like polyurethane foams and thermoplastics. Released in some BESS fires.
Hydrogen Fluoride (HF)	Released when fluorinated materials burn; a potential respiratory irritant.
Volatile Organic Compounds (VOCs)	Includes benzene, toluene, and other hydrocarbons; some are carcinogenic with prolonged exposure.
Particulate Matter (Soot, Carbonaceous Residues)	Can cause respiratory irritation and long-term health effects.

[13] The array test consisted of three cells arranged in parallel and separated by aluminum plates.

5.3.1 Flammability of Gas Emissions

The flammability of a gas release is assessed by comparing the concentration of the released gases to their flammability limits. When a mixture of gases is present, the flammability of the mixture can be assessed by accounting for the proportion of the mixture that each gas occupies and the flammability limit of that gas.

The flammability limits for gases commonly included in gas releases from batteries in TR were noted in Table 5. An ignition of the gases emitted is possible if the local concentration of the mixture of gases in proximity to an ignition source exceeds the lower flammability limit (LFL) of the gases. While some experiments have been conducted to determine whether the released gases reach a flammable range, the state-of-the-art does not permit calculating the range without test data for the specific unit in question [28, 39]. Further, a flammability assessment would need to consider the scenario of the event. The likelihood of flammability of a mixture decreases significantly if the gas mixture is in an unenclosed area because of the amount of dilution associated with a rising smoke plume.

5.3.2 Toxicity of Gas Emissions

The toxicity of the gas emissions depends on the scenario. If the emissions occur in an enclosed space, then a comparison of the emissions with toxicity limits is appropriate. For scenarios involving enclosed spaces, toxicity assessments can evaluate the consequence of an individual being exposed to gases in the same space as the malfunctioning battery. In these cases, the duration of the exposure of interest is likely to be short, being on the order of minutes, rather than hours, while they evacuate the space or are rescued by emergency responders prior to flashover of the space.

In contrast, if the emissions are released in an unenclosed space such as outdoors, the length of the exposure considered should include at least the amount of time for the battery event (i.e. hours while the battery or batteries are experiencing TR). In an outdoor application, the gases will be transported above the affected battery or batteries by a rising, buoyant plume. The plume will entrain air to dilute the gases in the plume. Rising even a short distance (10 m) will result in a substantial decline in the concentration of gases to reduce the toxicity of released gases in an unenclosed scenario. The gases will move horizontally as a result of wind and will be further diluted as they move in the downwind direction.

As such, the most significant concerns about the toxicity of gaseous emissions are associated with scenarios where the emissions are contained in an enclosed space and are short term. The enclosure may consist of a room housing the ESS or a BESS unit.

There are multiple approaches for assessing the toxicity of the exposure of a set of gases. The impact of exposure to any individual gas or combination of gases on individuals depends on the concentration of the gas(es) and the duration of the exposure. As such, threshold limits identified in every approach include a combination of gas concentration and duration. Toxicity assessment methods included in the literature are:

- Occupational Exposure Limits (OELs) are published by both the National Institute for Occupational Safety and Health (NIOSH) and the Occupational Safety and Health Administration (OSHA)
- The Emergency Response Planning Guideline (ERPG) established by the National Oceanic and Atmospheric Administration (NOAA)
- Acute Exposure Guideline Levels (AEGLs) developed by the National Research Council (NRC) and promoted by the EPA
- Immediately Dangerous to Life and Health (IDLH) referenced by NIOSH

- Threshold Limit Value by the American Conference of Governmental Industrial Hygienists (ACGIH)[14] OELs are established assuming exposure durations of 8 hours per day, 5 days a week, for 40 years. Given the long duration associated with this method, it is not the most relevant to assess exposure to a gas release from a battery event. As such, the remainder of this section will discuss approaches which are applicable to a short-duration exposure (i.e. 15 minutes or less)

The ERPG and IDLH approaches are more relevant to assessing the impact of short duration exposures.

The ERPG approach sets thresholds for a short-duration exposure of one hour. The ERPG levels are [62]:

- ERPG-3: maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects.
- ERPG-2: maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or other serious health effects or symptoms which could impair an individual's ability to take protective action.
- ERPG-1: maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing more than mild, transient adverse health effects or without perceiving a clearly defined objectionable odor.

The IDLH method from NIOSH provides an ability to conduct an analysis of a mixture of gases produced in battery fires. This method is based on adding the relative proportions of each gas concentration to its IDLH threshold.

For an analysis of the health impact of exposure of individuals located in a nearby community, AEGLs are often cited by the EPA. AEGLs are available for the following five exposure periods: 10 minutes, 30 minutes, 1 hour, 4 hours, and 8 hours, all relatively short durations. AEGL "levels" are dictated by the severity of the toxic effects caused by the exposure, with Level 1 being the least and Level 3 being the most severe. All levels are expressed as parts per million or milligrams per cubic meter (ppm or mg/m^3) of a substance above which it is predicted that the general population should not experience. Descriptions of the three AEGL levels are:

- AEGL Level 1: Notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.
- AEGL Level 2: Irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.
- AEGL Level 3: Life-threatening health effects or death.

As with the other methods described above, the established thresholds for exposure to gas emissions apply to exposures of "average individuals." People who are more sensitive, such as those who have respiratory or coronary conditions, infants, children, or the elderly will not be less likely to tolerate the noted threshold levels without adverse effects. While the AEGL approach purportedly considers exposure of susceptible individuals, it's unclear what basis (or adjustment) is used for that allowance.

The toxicity of many of the common chemical species that are included in combustion products from ordinary hydrocarbon fuels and batteries that are irritants are included in Table 10 [63].

[14] Because TLVs are not set or adopted by a regulatory authority, they are not further discussed in this report

Table 10: Irritancy of Combustion Products [63]

Irritant	RD50* (ppm) (Mice)	Severe Sensory Irritancy (ppm) (Humans)	30 Minute LC50 (ppm) (Mammal!)
C_3H_4O	1.7	1-5.5	140-170
CH_2O	3.1	5-10	700-800
Cl_2	9.3	9-20	100
SO_2	117	50-100	300-500
NH_3	303	700-1,700	1,400-8,000
HF		120	900-3,600
HCl	309	100	1,600-6,000
HBr		100	1,600-6,000
NO_2	349	80	60-250
Styrene	980	>700	10,000-80,000
Acetaldehyde	4,946	>1,500	20,000-128,000
Ethanol	27,314	>5,000	400,000
Acetone	77,516	>12,000	128,000-250,000

* RD50 is the concentration needed to reduce the respiratory rate by 50% in 50% of the subjects tested
! LC50 is the lethal concentration in 50% of the subjects tested

The results of an example tenability analysis conducted by EPRI [47] using data from a series of experiments conducted on an NMC battery using the IDLH and AEGL-2 thresholds are presented in Figure 21. The gases of interest for the toxicity assessment include CO_2, CO, NH_3, CH_4, C_2H_4, HF, and CH_2O. Of this group, the concentrations of CO, HF and CH_2O were greatest relative to their AEGL and IDLH thresholds. AEGL and IDLH thresholds for gases commonly released in battery incidents are included in an EPRI report [34].

Average concentrations of the gases over the noted time period are utilized in this review, being that these are more indicative of the sustained levels of gas concentrations. The AEGL-2 criteria are selected because these are the lowest AEGL thresholds that relate to significant health consequences, some of which may be irreversible. As indicated in Figure 21. all of the average concentrations are appreciably less than the IDLH levels. Relative to the AEGL-2 thresholds, none of the average gas concentrations exceed any of the respective AEGL thresholds.

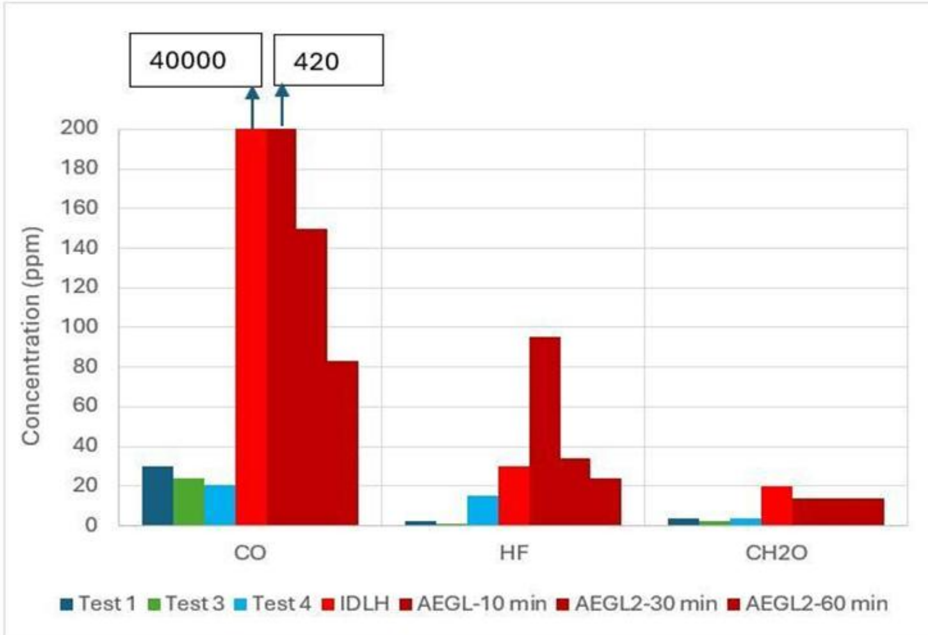


Figure 21: Example of Toxicity Assessment of Selected Gas Emissions from TR of NMC Battery

An approach used in tenability analyses in fire protection engineering for exposure of individuals to gases in an enclosed space is the fractional effective dose (FED) method. One advantage of the FED approach is it provides a means of assessing the impact of an exposure where the gas concentration varies with time. The FED method is most relevant to cases where the emitted gases are those which provide asphyxiating effects on people, i.e. CO, CO_2, and HCN, all of which are included in gaseous emissions from batteries. They are less proven to assess the impact of exposure to organic or inorganic irritants, such as formaldehyde, HF, and acrolein, all of which are produced in TR events. However, in short duration fire events, Levin suggested that accounting only for CO and CO_2 is highly successful in predicting lethality in fires [64].

5.3.3 Environmental Impact of Gas Emissions

The areas of potential environmental impact of gaseous and particle emissions from fire events is described in ISO 26367-3 [65]. The environmental impact of a selection of the gaseous and solid emissions produced in battery fires applying that approach is included in Table 11.

Table 11: Environmental Impact of Emissions from Battery Fires [65]

	Environmental Impact		
Emission	**Air**	**Water**	**Soil**
Halogenated Acids	X		
Nitrogen Oxides	X		
Sulfur Oxides	X		
Volatile Organic Compounds	X	X	X
Polycyclic Aromatic Hydrocarbons	X	X	X
Particulates	X	X	X

5.3.4 Rate of Production of Gaseous Emissions

From most sources, the peak rate of overall gas production, as well as that for CO, CO_2, and HF, has been shown to be proportional to the SOC [38, 55]. Results from experiments a pouch LFP cell are presented in Figure 22 [43]. The peak concentrations of HF occur simultaneously with flaming being observed. In that figure, the peak gas concentration for HF is relatively constant for SOCs of 50% or less but increases appreciably at SOCs of 75% and 100%. While there is a rapid increase in the concentration or rate of HF emissions at an early stage, the concentration of HF emissions decreases exponentially thereafter. A substantial amount of HF may be generated, ranging between 20 and 200mg/Wh of nominal battery energy capacity. In addition, cells with a capacity of 15–22 mg/Wh produced substantial quantities of phosphoryl fluoride (POF3), another potentially toxic gas, in some of the fire tests.

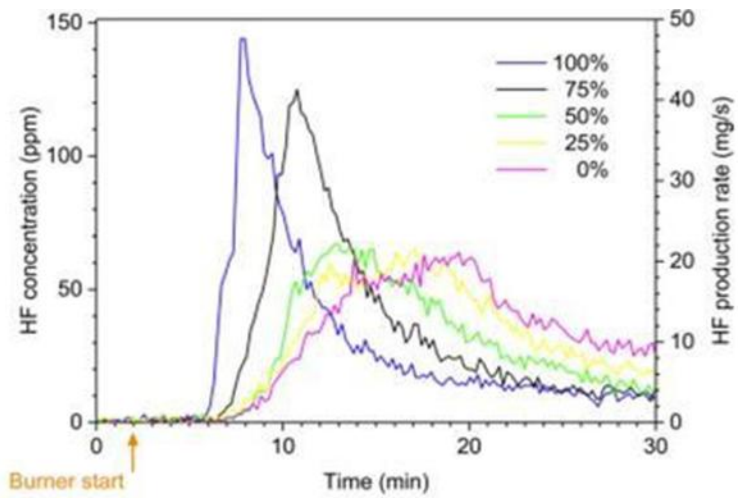


Figure 22: Transient Hydrogen Fluoride Production for Different SOCs [43]

In Figure 23, results of three replicate experiments (identified as “Type B,” repetition 1 and 2) (plus one additional experiment conducted with water mist, “repetition 3”) are presented. HF production varied significantly for LFP batteries with a 100% SOC, indicating the variability in outcomes from TR events, even when controls are in place to attempt repetition. While the production rate of HF is much less in repetition 1 than in the other two tests, the total volume of HF produced is reported to be similar in all three tests.

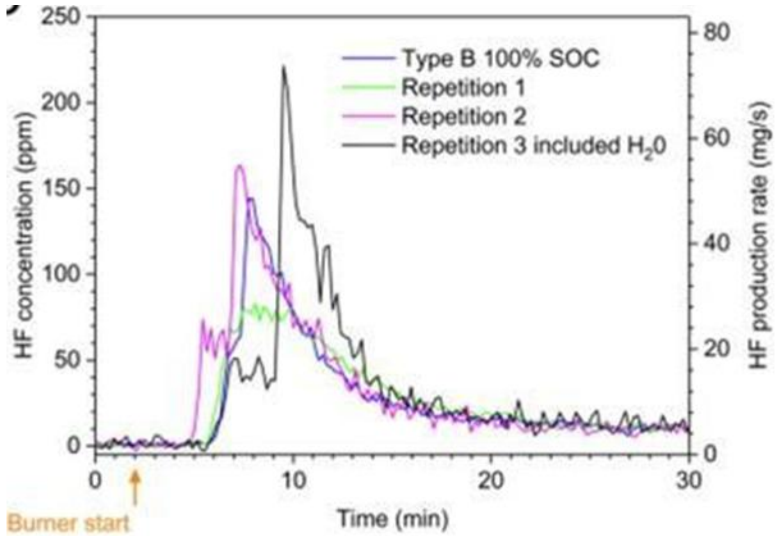
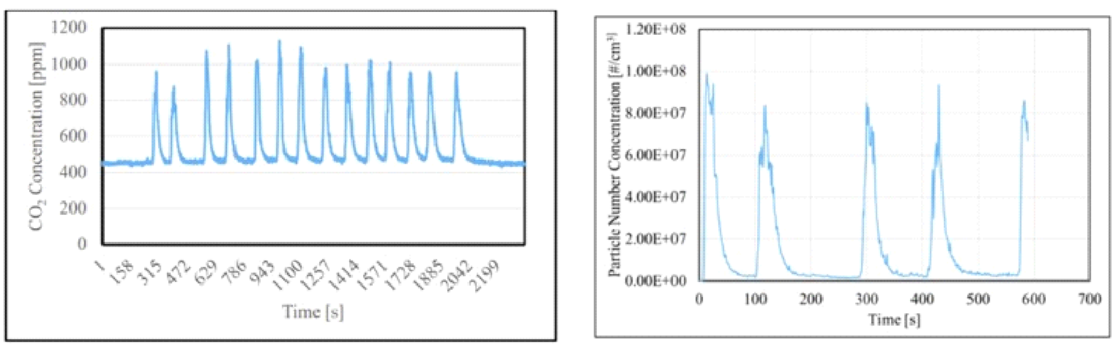


Figure 23: Transient Hydrogen Fluoride Production in Repetitive Experiments [43]

The time variation in the concentration of CO_2 (as an example of gaseous emissions) and particles from experiments by Larsson [43] is presented in Figure 24 The repeating peaks are evidence of a “puffing” type of response from the battery. The highly transient nature of such an event will be impractical to capture via computer simulations given the capabilities of currently used software.



(a) (b)

Figure 24: Transient Emissions of CO_2 and Particles [43]

6 Assessment of Containment Spread

The comprehensive nature of an environmental impact analysis for a fire involving a BESS unit is depicted in Figure 25 [66]. Smoke produced from a fire involving any commodity, including a BESS unit, will rise in a plume and include combustion gases such as carbon dioxide (CO_2), carbon monoxide (CO), water vapor, other gases, particulate matter (i.e. soot) and other condensed chemical species. The plume will continue to rise as long as it remains buoyant (i.e. is warmer than the surrounding air).

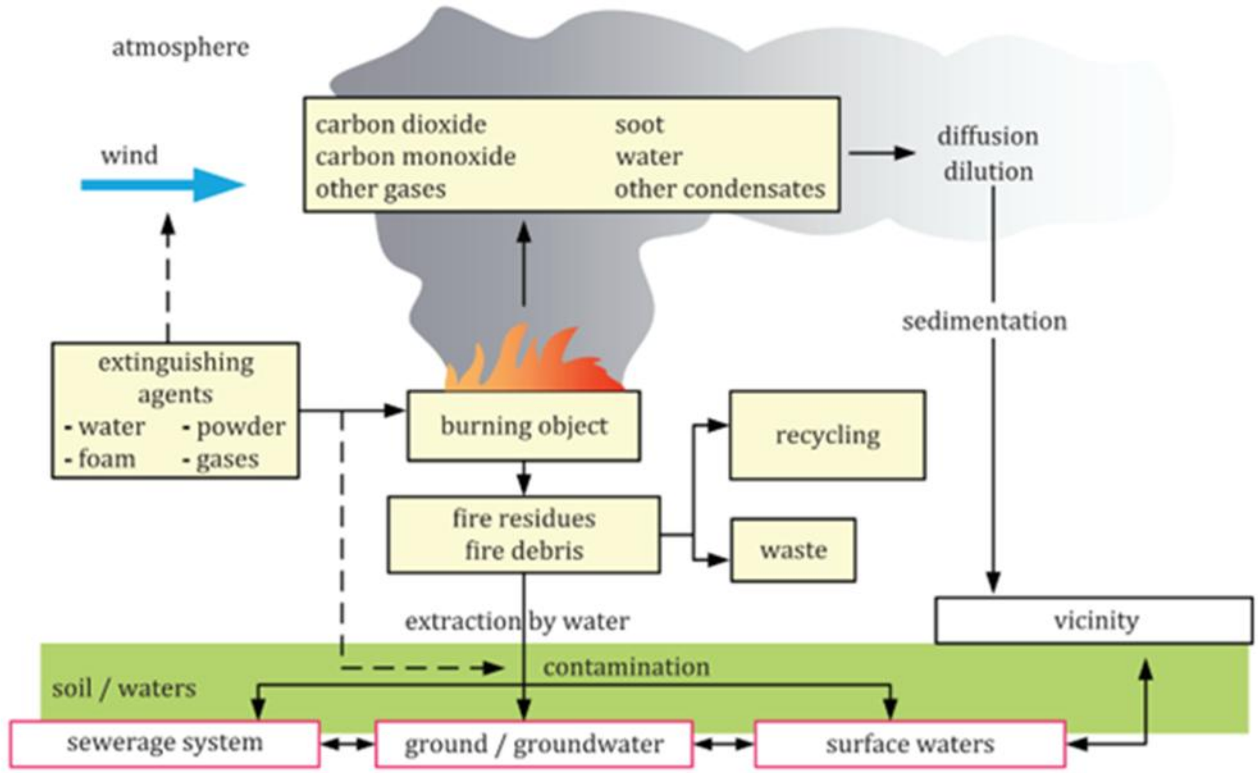


Figure 25: Pathways to Contamination from a Fire [66]

The rising plume will also entrain air which serves to dilute the combustion gases in the plume. The smoke from the plume will move horizontally due to wind (at any velocity) which will also include more entrainment and hence more dilution. While the plume disperses into the atmosphere as a function of distance, some dispersed particulates may deposit onto surfaces in the vicinity of the fire, which includes land and surface water.

Efforts to fight the fire using an extinguishing agent could cause some of the agent to be carried off by the plume or settle out on the ground some distance from the fire or runoff in the vicinity of the burning unit. Liquid extinguishing agents, such as water or foam, may carry some condensed items from the burning unit to soil, surface water, or ground water in the vicinity.

The issues surrounding the potential environmental impacts of fire events, particularly those associated with large industrial fires, are well established. Martin et al. present a comprehensive review of the issues associated with the environmental impact of fires and discusses many historically significant fire events, some of which resulted in significant environmental impact [67]. This review also provides a frame of reference for assessing the impact of BESS fires against historical precedent.

ISO Standard 26367-1, Guidelines for assessing the adverse environmental impact of fire effluents, provides an overview of the factors to consider when assessing the environmental impact of fires in general, and is also directly applicable to the assessment of BESS fire events [66]. Figure 26 is taken directly from Figure 1 of ISO Standard 26367-1 and graphically depicts the pathways for contamination.

As indicated in Figure 26, a burning object, including the case of utility-scale BESS equipment of varying fire size, emits a plume that can disperse airborne contaminants over a distance that depends on the relative buoyancy of the fire plume and wind speed during the event. The plume disperses into the atmosphere as a function of distance and some dispersed materials may deposit onto surfaces in the vicinity of the fire, which includes land and surface water.

Efforts to fight the fire using one of the various available extinguishing agents could cause local contamination by substances carried off with the extinguishing agent. Water-based extinguishing agents in particular can create the potential for contamination of local soil, surface water, and ground water due to direct agent run-off.

ISO Standard 26367-1 notes that short-term impacts from fire contamination occurring over a period of a few minutes to a few days, includes exposure arising from the atmospheric releases of asphyxiant and irritant gases. Short-term impacts to water include acute toxicity in run-off water, impacting aquatic habitats and species. It is noted that short-term impacts through deposition on land are unlikely.

Long-term impacts occur over a period of years after the fire and are experienced largely within the fire deposition zone and along impacted surface and groundwater. Long-term impacts are noted to be principally associated with persistent organic pollutants, metals, and other long-lived toxicants.

Another pertinent reference with relevance to the assessment of contaminant spread is the EPA's Risk Management Program Guidance for Offsite Consequence Analysis [68]. This document provides guidance on how to conduct off-site consequence analyses under the EPA's Clean Air Act and provides guidance both on establishing the worst-case scenarios for evaluation and data on a variety of toxic substances.

6.1 Spread of Airborne Contaminants

The spread of airborne contaminants can be assessed either through air sampling during or soon after a BESS fire event or through predictive modeling. As will be discussed in Section 7, often limited data is available from sampling gas concentrations within the plume in the immediate aftermath of an event, though sampling may commence within hours of the event and persist for days or weeks after the fire has been extinguished for the purposes of monitoring potential health hazards to the public.

6.2 Methods of Plume Spread Analysis

Air modeling simulations of the airborne plume spread from BESS fires are commonly used tools to assess airborne contaminant spread, both for the purposes of performing forensic analysis post-fire event and to perform predictive studies of the impact of an event. Predictive modeling is often integral to a community risk assessment (CRA), performed during the permitting and siting of a BESS installation.

An EPRI Technical Update published in 2020 summarizes the attributes of a range of the available models for use in this application, as may be seen in Table 12 [69].

Table 12: Plume Model Attributes (EPRI Table 1) [69]

Model	Dense Gas	Buoyant Plume	Chemistry	Terrain Impacts	Buildings	Spatial Scale	Setup Effort	Run Time	Public
IDEAL MODEL	Yes	Yes	Yes	Yes	Yes	Local	Easy	Fast	Yes
ADMS-5	Yes	Yes	Yes	Yes	Yes	Local-Regional	TBD	TBD	Licensed
AERMOD	No	Yes	No	Yes	Yes	Local	Easy	Fast	Yes
CALPUFF	No	Yes	Yes	Yes	Yes	Local-Regional	Medium	Moderate	Yes
CAMEO/ALOHA	Yes	No	Yes	No	No	Local	Easy	Fast	Yes
CMAQ	No	Yes	Yes	Yes	No	Local-Regional	Hard	Slow	Yes
CTDMPLUS	No	Yes	No	Yes	No	Local	Easy	Fast	Yes
FLEXPART	No	Yes	No	Yes	No	Regional	Easy	Fast	Yes
HPAC/JEM	Yes	Yes	Yes	Yes	Yes	Local-Regional	Medium	Fast	No
HYSPLIT	No	Yes	No	Yes	No	Local-Regional	Easy	Fast	Yes
Offshore and Coastal Dispersion Model	No	Yes	No	Yes	No	Local-Regional	Easy	Fast	Yes
Phast	Yes	Yes	No	No	Yes	Local-Regional	Medium	Fast	Licensed
SAFER / TRACE	Yes	Yes	Yes	No	TBD	Local	Easy	TBD	Licensed
QUIC-Plume LPDM	Yes	Yes	Yes	Yes	TBD	Local	Easy	Fast	No
SCICHEM	Yes	Yes	Yes	Yes	Yes	Local-Regional	Medium	Moderate	Yes
STILT	No	Yes	Yes	Yes	No	Regional	Easy	Fast	Yes
WRF-Chem	No	Yes	Yes	Yes	No	Local-Regional	Medium	Moderate	Yes
WRF-Fire	No	Yes	Yes	Yes	No	Local-Regional	Medium	Moderate	Yes

In 2022, in another Technical Update, EPRI further provided the demonstration of a modeling framework for performing air modeling simulations of BESS fires [70] EPRI chose the model SCICHEM (Table 12) for use in demonstrating the modeling framework. One of the reasons SCICHEM was selected was its stated ability to model chemical interactions and potential deposition of contaminants by the plume. This capability is only mentioned in the Technical Update and is not demonstrated. This literature review will later discuss the use of various models from Table 12 in published CRA reports. It should be noted that none of these studies use the models to predict deposition to remote surfaces (soil or surface water). Rather, they are used solely to predict airborne contaminant concentrations as a function of distance from the fire. EPRI recognizes this limitation and recommended that future work examine the impacts of atmospheric chemistry and deposition.

In the EPRI modeling framework's combustion simulations, two 8-hour fire release cases were simulated, having heat release rates of 1 MW and 10 MW [70]. For both cases, plume spread was assessed examining the spread of HF, with an assumed release rate of 100 mg HF per Wh, based on the work of Larsson [45] This release rate leads to a mass release of HF of approximately 13.9 g/s (50 kg/h) of HF over an 8-hour period. It is noted that this assumes battery racks burning in series, rather than parallel, in which case the release rates would be higher, but for a shorter period.

A third EPRI report published in 2024 discussed lessons learned from plume modeling of BESS fires [71]. The report notes that while plume modeling is not currently required in most jurisdictions, it was suggested for inclusion in NPFA 855, though it was not included due to outstanding uncertainties. While not mandated, the

EPRI report recommends plume modeling be performed when possible. The 2024 report goes on to highlight AERMOD, PHAST, SAFER/TRACE, and SCICHEM for further discussion and adds Fire Dynamics Simulator (FDS) to this list.

The 2024 EPRI white paper states that "due to their important driving effect on downwind exposures, emission rates during combustion and off-gassing are a key set of assumptions used in plume modeling. While results from a number of laboratory burn tests .... Are publicly available, a knowledge gap currently exists as to the emission rates from real-world incidents, including chemical and physical dynamic evolution of the emitted pollutants close to the source." It is further stated that "use of UL9540A test results as a total emitted chemical mass can be a good starting point for determining the source term." Because acid gas emissions data are not readily available from UL9540A test results, it is unclear if the 2024 report intends to recommend continued use of the HF scaling factors demonstrated in the previous EPRI reports. This discussion has bearing on the discussion of plume modeling in the upcoming BESS CRA reports.

Of further note in the 2024 EPRI white paper is the discussion that modeling scenarios may consider multiple phases of battery fire events, including the pre-combustion (off-gassing) phase, the combustion phase, and the suppression phase. As noted in the following section, the pre-combustion and combustion phases are common scenarios modeled in CRA reports, but no sources could be found modeling the suppression phase, likely due to the complexity of defining the source inputs to perform such a simulation. A final point in the scenarios considered by the 2024 EPRI white paper is the statement that depending on emissions assumptions, HCl may be a larger health concern than HF for the combustion case. This observation has also been corroborated by others [72]. It is asserted that with regard to human health considerations, prediction of HCl and HF is "likely protective for all other pollutants of interest" [71].

6.3 Plume Modeling in BESS (CRA reports)

The use of plume modeling has become prevalent in recent years to support the development of CRA reports, sometimes also called Offsite Consequence Analysis (OCA) reports.

Due to published accounts of BESS fires in recent years, a CRA report is often prepared to assist in siting efforts for new BESS sites and to address community concerns with the construction of new BESS sites in or near local communities, despite not currently being prescribed by NFPA 855. CRA reports are most often written as proprietary reports prepared for site owners or operators but are sometimes released into the public domain by the various jurisdictions.

For the purpose of illustrating the variability of these assessments, in the absence of prescriptive criteria or other guidance, three examples are included from the literature [73, 74, 75]. These three examples of plume analyses will be compared and contrasted to the approach typically used by FRA for proprietary BESS clients.

Table 13 shows a summary of the plume model used and the types of combustion products considered for evaluation in the plume spread analysis. It can be seen that while the EPRI modeling framework base case, CRA #0 [70] in Table 13, solely evaluated the spread of HF, the three public CRA examples [73, 74, 75] looked at both the spread of CO and HF. Additionally, two of the three modeling studies include consideration of HCN and HCl. It is noteworthy that the EPRI base case and all of the other examples in Table 13 used different plume models.

Table 13: Summary of Air Modeling Example Considerations

CRA#	Model	Parameter Evaluated					Event Modeled	
		CO	HF	HCN	HCL	LFL	Pre-Combustion (Off-Gassing)	Flaming Combustion
0	SCICHEM		X				X	X
1	AERSCREEN	X	X	X	X			X
2	AERMOD	X	X					X
3	ALOHA	X	X	X	X			X
4	PHAST	X				X	X	X

CRA #4 corresponds to the typical approach used by FRA, which includes modeling of CO and the extent of the LFL in the plume using PHAST. The approach used by FRA is based on extrapolation of data from UL9540A testing, as was noted in the 2024 EPRI white paper [71]. FRA has noted from its performance of large-scale BESS fire testing that while HF concentrations of concern have been observed in close proximity to the fire source, HF is not generally noted in concentrations of concern remote from the fire source. In performing this literature search, including the documentation of contaminant measurements taken in relation to the example BESS fire events summarized in Section 5, sources documenting acid gas measurements of concern remote from the fire event were not found.

An important observation when looking at each of the three published plume studies [73, 74, 75] designated as CRA #1, #2, and #3 in Table 13 was that the source emissions rates for the acid gases used in the modeling varied widely. This is based on different methods of scaling the amount of acid gas produced as a function of mass of batteries burned, derived from many of the same small scale testing sources of data summarized in Section 5 of this report. Of the acid gas source terms considered by the three reference studies, the highest generation rate cited by one of the studies was approximately 48 kg/h of HF for a duration of 24 hours [73] for a flaming combustion phase event. This generation rate appears to be similar to that used in the EPRI modeling framework base case and also cites the work of Larsson, et. al. [76], albeit from a different reference. The lowest cited rates of HF are up to two orders of magnitude lower, demonstrating the variability in using mass-scaled generation rates derived from small-scale testing.

Each of these studies only examined battery fire (flaming combustion) events and did not evaluate the pre-combustion (off-gassing) phase. The EPRI framework modeling base case (CRA #0) and FRA approach (CRA #4) both evaluated both pre-combustion and fire events.

6.4 Experimental Studies

While FRA is aware of large-scale testing that has been performed on BESS equipment and future testing that is planned on full-size BESS container units, currently, most of the experimental studies on which airborne contaminant spread assessments are based on are bench-scale in nature. Any future requirements incorporated into NFPA 855 pertaining to the testing of full-size BESS containers should yield more applicable results for assessing contaminant source terms for utility-scale BESS fires.

The 2024 EPRI White Paper [71] further notes that advancements in atmospheric concentration monitoring instruments, including unmanned aerial vehicles (UAVs), more commonly known as "drones", have been proposed to be outfitted with monitoring equipment to measure contaminants in real-time at various locations in the airborne plume and not just at ground monitoring locations.

6.5 Spread of Water-Borne Contaminants

The spread of water-borne contaminants from BESS fires is not well studied nor does the literature support this assertion; however, since this may be an issue of concern, it is discussed for completeness.

Throughout the literature, there are frequent mentions of concerns due to contamination present in firefighting water run-off, either due to the presence of automatic sprinkler systems or due to firefighting hose streams during suppression efforts. In the case studies discussed in this literature review, there are several mentions of soil contamination measurements made in areas where firefighting water runoff occurred. As depicted in Figure 26 of this report, there are also concerns expressed with the potential for contamination of underground water sources due to this run-off. In the specific case of the Escondido, CA fire event, sampling of well-water for properties near the BESS site was reported to take place for an unspecified period of time after the event, despite the fact that firefighting water was stated as being used only to provide exposure protection. No adverse outcomes were found in the literature associated with the well sampling.

Where contamination from fire water run-off is determined to be a concern, one means of mitigation would be to develop a comprehensive Soil and Water Management Plan. One notable example found in the literature, for a BESS site in Australia, identifies several potential mitigation controls including dust management, spill containment, drainage and stormwater management, and operational controls [77].

Recent developments in the firefighting tactics surrounding BESS fires have been noted in a 2023 EPRI White Paper titled "The Evolution of Battery Energy Storage Safety Codes and Standards" [78]. This white paper notes a significant shift in the firefighting philosophy associated with BESS fires. It also notes that while NFPA 855 mandates suppression for buildings and outdoor walk-in units, the requirement appears not to apply to outdoor units that cannot be entered, which is the case for most post-2020 utility-scale BESS installations. The realization that using water in an attempt to extinguish a deep-seated fire within a packed BESS container considers the volumes of water that would be used has driven a new "controlled burn" philosophy.

The "controlled burn" approach involves allowing the initial BESS unit to burn out in a controlled manner while protecting adjacent exposures. As noted by EPRI [78], the approach has several advantages:

- Issues with stranded energy and re-ignition are avoided.
- Flammable gases are consumed as they are released, eliminating the risk of explosion.
- By not using firefighting water on the fire itself, contaminated run-off and excessive water use are avoided.

The EPRI report notes that while laboratory testing identifies toxic compounds that are released by burning LIBs, these may be consumed internally, combusted, or may react to form other non-toxic compounds before being released to the environment. The report further notes that in recent events that were allowed to burn in a controlled manner, local monitoring has shown air quality to be at safe levels.

6.6 Availability of Predictive Models

The EPA website for Groundwater Modeling Research [79] summarizes a number of predictive models that may have the ability to be used to evaluate the potential for contaminated fire water run-off to reach groundwater sources. There were no sources identified in the literature that documented the use of predictive models for this application. Rather, the mentions of the potential for BESS fire water run-off to cause waterborne contamination was anecdotal and often reference the limited laboratory testing described in Section 7.

6.7 Experimental Studies

Two experimental studies were performed that report toxicity assessments of fire extinguishing water from LIB tests. Bordes, et al [80] performed small-scale testing using modules consisting of between 16 and 45 cylindrical prismatic cells. Quant, et al. [81] performed testing from large-scale battery and EV fire tests. Of importance in this documented test series are the tests where the battery alone was tested and thus the emissions do not contain the non-battery materials associated with the full EV test.

For the small-scale battery tests [80], the modules were induced into TR using a gas burner that was switched off, and overhead sprinklers were operated manually once TR was confirmed. The authors reported the presence of heavy metals such as Ni, Mn, Co, Li, Al, and polycyclic aromatic hydrocarbons (PAH) in amounts that could be potentially hazardous to the environment.

For the large-scale battery tests [81], one battery-only test was performed to compare the results of fire water runoff for the battery only to the full EV test. Overhead sprinklers were allowed to operate to extinguish the fire. Like the small-scale tests, the authors reported the presence of Ni, Mn, Co, and PAHs, but also noted the elevated presence of polyfluoroalkyl substances (PFAS) in the runoff. The authors also noted that after the battery test, the pack was opened and flushed with water, resulting in "a large increase of PFAS in the extinguishing water".

The EPRI 2024 White Paper [71] and other credible sources in the literature reference in particular the Quant, et al. paper [81] as evidence of the potential for potential contamination in fire extinguishing water used to fight battery fires. It is unclear whether the results of the noted experimental studies on contamination in firefighting water runoff can be extrapolated to be applicable to a utility-scale BESS fire, except to note that the presence of this concern would support the controlled burn philosophy to reduce the potential for water-borne contamination.

It is worthy of note that the results from the limited small-scale testing can be potentially misused to extrapolate very misleading results. One instance was found in the literature documenting an email transmittal from a concerned citizen in the wake of the East Hampton, NY fire [82], wherein the Quant paper [81] was used as the basis for an estimation that assumed rupture of all battery cells at the site and use of 2.2 million gallons of fire-extinguishing water, that then asserted it might be possible to see "a flow into the aquifer carrying PFAS 24,800 times the concentration level proposed in the EPA's National Primary Drinking Water Regulation." This would appear to be a gross overestimation and misuse of the available data.

7 Impact of Contaminant Spread

The BESS fire case studies described in Section 4.3 of this report were selected for discussion because they serve as examples of the relative fire severity and size of the fire event (component, single container, multi-container), but also (with one exception) were among the cases of the 35 U.S. BESS fires documented in the EPRI database that had documented assessments of air, water, and soil impacts.

One exception was the one component BESS fire example, occurring on April 5, 2022 in Valley Center, CA, for which a record of an environmental assessment was not found in the literature.

The summary of the environmental assessments performed for the BESS fire events described in the sections that follow demonstrate the variability in the type and amount of environmental testing performed and the time periods over which samples were collected.

7.1 East Hampton, NY – May 31, 2023

Subsequent to the East Hampton BESS fire event, surface wipe samples were taken from the interior of the building in which the BESS equipment was housed to investigate deposition from potential airborne contaminants from the fire [83]. Additionally, because the facility's automatic sprinkler system was allowed to run for approximately 30 hours to make sure the fire was fully extinguished, soil samples were taken at the exterior of the building to investigate the area where the sprinkler water run-off collected.

On June 14, a certified industrial hygienist took wipe samples from various interior items in the dedicated use building. The results of this testing were deemed inconclusive since there were no unimpacted background samples for comparison.

On July 13, and again on October 14, soil samples were taken to sample for 26 metals. This investigation showed no discernable difference in the concentration of the measured metals in the soil samples collected from the sprinkler water discharge area when compared to remote site background samples. Based on these results, no further remediation was required by the State of New York.

7.2 Surprise, AZ – April 19, 2019

APS hired consultants to conduct an evaluation of both on-site and off-site environmental and health impacts of the McMicken Battery Energy Storage System fire event [12]. The investigation involved collecting on-site samples, including soil samples, and performing off-site air dispersion modeling to evaluate the potential for off-site environmental impacts. Air monitoring during the event was part of the fire service's response [12].

On May 6-7, 2019, surface soil samples were collected from the ground around the BESS equipment and wipe samples from surfaces within the BESS container. The sampling data showed low concentrations of hazardous materials that were generally indistinguishable from background sampling data. The study concluded that no contaminants in excess of levels that would require remediation were detected and that additional groundwater or soil sampling was unnecessary.

Between May and September 2019, air dispersion modeling was conducted to determine if there was likely off-site deposition of contaminants via airborne transmission. Detailed information on the modeling assumptions was not found in the literature. The modeling concluded that particulate matter deposition via airborne transmission was minimal and confined to on-site locations near to the BESS fire event. Modeled off-site concentrations of contaminants were lower than federal and state guidelines and therefore additional off-site environmental investigations were not recommended.

7.3 Escondido, CA – September 5, 2024

San Diego County Fire Rescue, along with independent consultants, issued separate air quality and water run-off reports for the SDGE battery fire event [84, 85]. As documented in the air quality report [84], San Diego County Hazmat personnel conducted air monitoring over a period of four hours commencing 90 minutes into the event, at which time only normal products of combustion "consistent with a structure fire" were detected and at levels considered well below NIOSH and OSHA thresholds. A consultant began air quality monitoring later in the evening of September 5, concluding on September 7. These measurements consisted of measuring oxygen levels, concluding that any decrease in percentage "would indicate that there was some unknown gas in the atmosphere not able to be detected by monitoring equipment." Fluoride reactive test strips were also used to detect HF. At no time did oxygen deviate from normal levels nor was HF detected at any of the sampling locations.

As documented in the water quality report [85], the Escondido Fire Department used a defensive strategy focused on protecting adjacent structures by applying water to those structures during the fire event. Firefighting water run-off samples were collected on the evening of September 5 and sent to a third-party laboratory for analysis. The laboratory analysis found the pH of the water and metal concentrations was within normal or acceptable ranges. Low levels of barium, copper, and zinc were found that were determined not to pose significant environmental hazards and that there were no concerns with the run-off water entering the environment.

7.4 Chaumont (Lyme), NY – July 27, 2023

Over the five-day BESS fire event at the Convergent Energy facility, the New York State Office of Fire Prevention and Control (OFPC) performed air quality monitoring of nearby communities [83]. Additionally, due to the large volume of water applied to the fire over the duration of the event during fire suppression and control actions, a significant amount of fire fighting water run-off was noted and was a concern due to the presence of nearby residential wells. Ground water samples were analyzed for a variety of contaminants including volatile organics and metals. Additionally, samples were taken from 11 wells near the property that could be impacted by run-off. No apparent fire contaminants were identified in any of the ground water samples and the State Department of Health notified the potentially affected residents.

7.5 Melba, ID – October 2, 2023

Idaho Power contracted a consultant to provide air monitoring and sampling support in response to the Melba, ID BESS fire event. This was done to augment air sampling efforts being performed prior to the consultant's arrival on site by Idaho Power's industrial hygiene personnel.

Air monitoring was performed both during the multi-day fire event and consisted of real-time air monitoring both on-site and in the surrounding community. The consultant's report indicated that there were no detections of hazardous contaminants that exceeded "health-based action levels" and there were no contaminant detections observed by the air sampling, either by the consultant or Idaho Power staff, that would represent a public health concern [86].

7.6 Warwick, NY – June 26 and 27, 2023

The Orange County, NY HAZMAT Response Team responded to two independent events occurring one day apart in the town of Warwick, NY [83]. For each event they collected air samples to determine if hazardous materials were present and if measures to mitigate public exposure were required. In both cases, no elevated levels of toxic contaminants were reported to have been detected. Because no water was used to attempt to extinguish the fire at either location, there was no firefighting water runoff, and therefore no soil samples were taken due to the limited potential for off-site impacts.

8 Summary and Conclusions

This report provides an analysis of historical Li-Ion BESS fire incidents and their causes, a review of the types of contaminants released, the extent of environmental impacts, and how advancements in safety regulations and technology have mitigated risks.

In none of the reviewed cases of environmental sampling related to the BESS fire events were reported contaminant concentrations found that posed a public health concern or necessitated further remediation. This finding includes airborne contamination sampling conducted on-site, off-site, and within nearby communities, as well as relevant sampling of water from firefighting activities, suppression system run-off, and groundwater testing in specific instances.

In addition to the case studies summarized above, a large indoor BESS fire occurred on January 16, 2025 involving a 1,200 MWh system at Moss Landing, CA. As of the initial drafting of this report, the investigation was ongoing, and the environmental impact was being monitored closely. Due to the timing of this event, it was not formally considered in this study as no official environmental data had been released at the time of publication.

A Phase 2 supplement to this study will be performed that utilizes plume modeling to look at the expected contamination spread from representative BESS events consistent with the previous case study. This Phase 2 effort will look at both modeling performed commercially to support Community Risk Assessment (CRA) studies and other recently performed industry studies to compare and contrast modeling results and the source terms used.

9 Appendix A – Incident Database

Table 14 lists the BESS failure incidents noted in the EPRI / UL databases that were considered in the analysis presented in this report.

Table 14: 35 Incidents Included in Analysis

Location	Date
Flagstaff, AZ	11/26/2012
Port Angeles, WA	7/3/2013
Franklin, WI	8/10/2016
Beavercreek, OH	3/1/2018
Denton, MD	5/1/2018
Indio, CA	5/9/2018
Tualatin, OR	4/11/2019
Surprise, AZ	4/19/2019
Standish, MI	4/19/2021
Morris, IL	6/29/2021
La Salle, IL	7/19/2021
Moss Landing, CA	9/4/2021
Moss Landing, CA	2/13/2022
Valley Center, CA	4/5/2022
Chandler, AZ	4/18/2022
West Thumb Geyser Basin, Yellowstone, WY	9/6/2022
Moss Landing, CA	9/20/2022
Baker, CA	1/1/2023
Millvale, PA	1/30/2023
Jacksonville, FL	4/25/2023
East Hampton, Long Island, NY	5/31/2023
Warwick, NY	6/26/2023
Warwick, NY	6/27/2023
Tampa, FL	7/20/2023
Lyme, NY	7/27/2023
Valley Center, CA	9/18/2023
Melba, ID	10/2/2023
Columbus, OH	4/18/2024
Otay Mesa, San Diego, CA	5/15/2024
Santa Ana, CA	7/17/2024
Baker, CA	7/26/2024
Escondido, CA	9/5/2024
Nye County, NV	9/17/2024
San Pedro, CA	9/26/2024
Fredericktown, MO	10/30/2024

10 Appendix B – Moss Landing Fire Event

On January 16, 2025, a fire broke out in the 300 MW Vistra Moss Landing 300 facility in Monterey, CA, located within a converted, historic, generator hall on-site. According to the US Environmental Protection Agency[87], the fire damaged about 55 percent of the battery units in the facility. The fire was contained by the following day, although a less severe reignition occurred about a month later. The cause of the fire is still under investigation.

The EPA conducted air monitoring during the event and reported on January 18, 2025 that it had "not detected any risk to public health based on air monitoring data from stations near the Vistra Energy Battery Power Plant" [88]. The EPA noted that on the day of the event it had immediately deployed nine air monitoring stations for particulate matter and hydrogen fluoride. Post-incident environmental testing and monitoring information is summarized on the County of Monterey website [89] and the County has established a dashboard of test results [90]. The County has engaged independent environmental and toxicology consultants and is working towards a comprehensive Human Health Risk Assessment (HHRA), relying on lab data over field screening results.

It is worthy of note [91], that Moss Landing's design was "unique, globally, as a facility," given the design choice to concentrate rows of battery racks totaling 300 MW of capacity indoors in a 1950 era building and the use of nickel-manganese-cobalt (NMC chemistry) instead of the more common lithium-ion phosphate (LFP) chemistry. As noted, nearly all grid batteries installed over the past several years involve outdoor installations of modular containerized BESS designed with safety features to ensure that if a fire breaks out in one individual container it won't propagate to neighboring units.

In the soon-to-be-released 2026 edition [92] of NFPA 855, a new requirement for large-scale fire testing addresses a worst-case fire scenario, in which a developed fire condition is established in one battery unit and is not allowed to result in thermal runaway in adjacent units. Individual container sizes vary (typically 20-40 ft) with a capacity ranging from 1-5 MWh per container, as compared to the 300 MWh concentration of battery racks at Moss Landing.

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