Approaches for Evaluating Potential Human Health Consequences of Utility-Scale Lithium-ion Battery Failures

3002021634

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Technical Update, September 2021

EPRI Project Manager

A. Rohr

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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ACKNOWLEDGMENTS

The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

Gradient
1 Beacon St., 17th Floor
Boston, MA 02108

Principal Investigators
A. Lewis
T. Manidis

This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Approaches for Evaluating Potential Human Health Consequences of Utility-Scale Lithium-ion Battery Failures. EPRI, Palo Alto, CA: 2021. 3002021634.

ABSTRACT

Battery energy storage systems (BESS) are a key facet of green energy initiatives, but it is critical that these systems are designed, operated, and decommissioned in a safe manner, and that any adverse human health concerns related to these developing technologies be fully explored. One of the key health concerns with BESS, and in particular with lithium-ion batteries (LIBs), is the possibility of failure leading to thermal runaway and the resultant release of toxic gases, as well as fire and explosion.

While many individual research efforts to inform the potential impacts of a thermal runaway event are ongoing, and related provisions are in development for building codes and standards (*e.g.*, National Fire Protection Agency [NFPA] Standard 855) (NFPA, 2020a), the industry currently lacks a robust framework for evaluating potential health risks to workers, the community, and first responders associated with LIB failure. Moreover, there are no current regulatory requirements or other industry standards in the United States (US) related to the assessment of human health risks should a LIB failure occur.

This report introduces concepts that can be used to develop a framework for evaluating potential human health risks associated with LIB failures. The report relies heavily on a quantitative risk assessment (QRA) methodology that is used to assess industrial accidents, mainly outside the US, while also taking more US-centric risk assessment approaches and principles into account. The battery safety concepts in this report build on the larger effort EPRI is undertaking to ensure that the widespread implementation of BESS, which are critical to current and future energy infrastructure, is done in a way that maximizes safety and minimizes adverse effects to human health and the environment. The results of this work will be used in future EPRI battery fire safety R&D and communicated more broadly to the industry and stakeholder organizations.

Keywords
Lithium-ion battery
Energy storage
Human health
Quantitative risk assessment

Deliverable Number: 3002021634

Product Type: Technical Update

Product Title: Approaches for Evaluating Potential Human Health Consequences of Utility-Scale Lithium-ion Battery Failures

PRIMARY AUDIENCE: Electric utilities interested in using lithium-ion batteries (LIBs) in energy storage systems (ESSs).

SECONDARY AUDIENCE: Storage solution providers, occupational health and safety practitioners, and other energy and environmental stakeholders and researchers.

KEY RESEARCH QUESTION

As utilities and other entities expand their energy storage capacity and utilization of LIBs, there is a need to understand the practices used to evaluate the human health risk to workers and the public from chemical gas releases, explosions, and fire associated with LIB failures. No standard process or guidance currently exists to inform such an assessment. This work represents a critical first step in developing a scientific framework for evaluating the potential human health risks of an LIB failure at a utility-scale ESS.

RESEARCH OVERVIEW

This report introduces concepts that can be used to develop a scientific framework for evaluating potential human health risks (for workers and the public) associated with LIB failures. The proposed approach integrates quantitative risk assessment (QRA) methodology, which is commonly used outside the United States (US) to assess industrial accidents, with more US-centric risk assessment approaches and principles. The key steps of QRA (hazard analysis, frequency analysis, consequence analysis, and risk evaluation and conclusions) are outlined in the report. The applicability of each QRA step to the risk evaluation of LIB failure is discussed, including what LIB-specific information is required, as well as the existing key data gaps. An example of a QRA conducted for LIB ESSs is provided in the report, and further research needs are also addressed.

KEY FINDINGS

- Guidance and standards for evaluating the potential human health consequences associated with LIB ESSs are lacking.
- Although QRA was developed more generally for other types of industrial activities and facilities, it offers a promising framework for evaluating the potential human health consequences of an LIB-related chemical gas release, explosion, and/or fire. QRA examines the consequences of gas emissions, explosion overpressure, thermal radiation, and flammability potential – all of which are issues relevant to LIB failures.
- While the concepts underlying QRA seem well suited to quantifying the risks and potential impacts of LIB failure, more investigation is needed to understand how this framework can be used to make reliable and actionable decisions specific to utility-scale LIB ESSs.
- Some key areas that require more research and analysis include the rate of failure at utility-scale LIB ESSs, fire and explosion dynamics, and suitable risk benchmarks.

WHY THIS MATTERS

A key concern with LIB ESS implementation is the potential impact to human health as a result of chemical gas releases, explosions, and/or fire that can occur in the unlikely event of thermal runway or other LIB failure. A framework to assess possible human health consequences will support the safe deployment of LIB ESSs, reduce barriers to implementation, and help inform the appropriate response of first responders to chemical gas releases, explosions, and/or fire at LIB ESSs.

HOW TO APPLY RESULTS

This report presents a way to consider risk (*e.g.*, explosion overpressure) and health (*e.g*., exposure to toxic gas) for the implementation of LIBs in ESSs. It can also help inform priority data needs that if addressed could help develop more reliable safety assessments.

LEARNING AND ENGAGEMENT OPPORTUNITIES.

Participate in Program 197, Environmental Aspects of Fueled Distributed Generation and Energy Storage, and collaborative supplemental projects, such as Fire Prevention and Mitigation Phase II (https://www.epri.com/research/products/000000003002022509).

EPRI CONTACTS: Annette Rohr, arohr@epri.com, 425-298-4374. Stephanie Shaw, sshaw@epri.com, 650-565-8931

PROGRAM: P197 Environmental Aspects of Fueled Distributed Generation and Energy Storage

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

ACRONYMS AND ABBREVIATIONS

AEGL	Acute Exposure Guideline Level
AIChE	American Institute of Chemical Engineers
AIHA	American Industrial Hygiene Association
ALARP	As Low As Reasonably Practicable
ALOHA	Areal Locations of Hazardous Atmospheres
CCPS	Center for Chemical Process Safety
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
EPRI	Electric Power Research Institute
ERPG	Emergency Response Planning Guideline
ESS	Energy Storage System
ETA	Event Tree Analysis
FEMA	Federal Emergency Management Agency
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
GPM	Gallon Per Minute
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
HVAC	Heating, Ventilation, and Air Conditioning
IDLH	Immediately Dangerous to Life or Health
IEEE	Institute of Electrical and Electronics Engineer, Inc.
ISO	International Organization for Standardization
kWh	Kilowatt-Hour
LC_{50}	Median Lethal Concentration
LEL	Lower Explosive Limit
LFL	Lower Flammability Limit
LFP	Lithium Ferrophosphate
LIB	Lithium-ion Battery
MW	Megawatt
NFPA	National Fire Protection Association
NIOSH	National Institute for Occupational Safety and Health
NMC	Nickel-Manganese-Cobalt

NOAA	National Oceanic and Atmospheric Administration
OSHA	Occupational Health and Safety Administration
PAC	Protective Action Criteria
PHA	Process Hazard Analysis
ppm	Parts Per Million
psi	Pounds Per Square Inch
psig	Pounds Per Square Inch Gauge
QRA	Quantitative Risk Assessment
RIVM	Rijksinstituut voor Volksgezondheid en Milieu
RMP	Risk Management Plan
SLOD	Significant Likelihood of Death
SLOT	Specified Level of Toxicity
STEL	Short-Term Exposure Level
TEEL	Temporary Emergency Exposure Limit
UK	United Kingdom
UK HSE	United Kingdom Health and Safety Executive
US	United States
US DOD	United States Department of Defense
US DOT	United States Department of Transportation
US EPA	United States Environmental Protection Agency
V&W	Netherlands Ministry of Transport, Public Works, and Water Management
Wh	Watt-Hour

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1 INTRODUCTION

Stationary and mobile energy storage capacity is a key facet of green energy initiatives, but it is critical that any adverse human health concerns related to these developing technologies be fully explored. One of the key health concerns with energy storage systems, and in particular with lithium-ion batteries (LIBs), is the possibility of failure leading to thermal runaway and the resultant release of toxic gases, as well as fire and explosion. Although LIB fires are considered "statistically rare," the potential risks are significant due to the differences in "initiation, spread, duration, toxicity, and extinction" of LIB fires compared to other fire hazards (Bravo Diaz *et al*., 2020).

While many individual research efforts to inform the potential impacts of a thermal runaway event are ongoing, and related provisions are in development for building codes and standards (*e.g.*, National Fire Protection Agency [NFPA] Standard 855) (NFPA, 2020a), the industry currently lacks a robust framework for evaluating potential health risks to workers, the community, and first responders associated with LIB failure. Moreover, there are no current regulatory requirements or other industry standards in the United States (US) related to the assessment of human health risks should a LIB failure occur.

This report introduces concepts that can be used to develop a framework for evaluating potential human health risks associated with LIB failures. The report relies heavily on a quantitative risk assessment (QRA) methodology that is used to assess industrial accidents, mainly outside the US, while also taking more US-centric risk assessment approaches and principles into account.

This report is organized as follows:

- Introduction to LIB Fires (Section 2.1)
- Identifying a Risk Framework for LIBs (Section 2.2)
- Key Steps in QRA (Section 3)
  - Hazard Analysis (Section 3.1)
  - Frequency Analysis (Section 3.1)
  - Consequence Analysis (Section 3.2)
  - Risk Evaluation and Conclusions (Section 3.3)
- Tools and Guidance Documents (Section 4)
- Example Risk Assessments (Section 5)
- Data Gaps and Uncertainties (Section 6)

The battery safety concepts in this paper build on the larger effort the Electric Power Research Institute (EPRI) is undertaking to ensure that the widespread implementation of energy storage systems (ESSs), which are critical to current and future energy infrastructure, are implemented in ways that maximize safety and minimize adverse effects to human health and the environment. Key EPRI research on this topic includes:

- Identifying battery failure modes and improving battery reliability (EPRI, 2019a, 2021);
- Conducting life cycle assessments to assess the overall environmental impact of ESSs, with an emphasis on end-of-life-cycle options (Pellow *et al*., 2020; EPRI, 2019b,c);
- Understanding the characteristics of ESS fires, possible combustion products, and the nature of chemical releases from ESSs (EPRI, 2020a-d); and
- Evaluating the potential for occupational, general population, and ecological exposures to chemicals used in ESSs throughout the ESS life cycle (EPRI, 2018a,b, 2019d).

The results of this work will be used in future EPRI fire safety efforts, such as the Battery Energy Storage Fire Prevention and Mitigation Project Phase II, and communicated more broadly to the industry and stakeholder organizations.

2
OVERVIEW

2.1 Introduction to LIB Fires

Stationary LIB ESSs are comprised of large quantities of high-density LIB modules, which pose a risk of fire, explosion, and toxic gas emission if they undergo thermal runaway. The higher the energy density of the battery, the greater the electrical energy that can be stored in it. Without proper hazard mitigation technologies installed, thermal runaway propagation in LIBs with higher energy density is more likely, and therefore, the risk of fire spread among modules and beyond is greater (Bravo Diaz *et al*., 2020).

Despite some of the similarities shared between LIB failures and industrial accidents (*i.e*., types of chemicals released, infrequency of incidents), there are unique aspects of LIBs that differentiate LIB ESS failures, including the magnitude of chemical emission rates, the potential for multi-cell/module/rack propagation, and extended active burning or reignition potential. Therefore, methodologies or tools commonly used to assess risk in industrial settings will require optimization to accommodate LIB-specific data, especially related to chemical emissions and fire dynamics. For example, the University of Washington found that the production of hydrogen fluoride from a LIB failure is proportional to the amount of electrical energy stored in the LIB; therefore, although the types of gases released during LIB failures are similar to those released from plastics fires, the high volume and energy density of ESS LIBs have the potential to increase the severity of risk when they fail (UW, 2018).

Risk associated with LIB fires is also unique in that these fires require different extinction measures than first responders have traditionally used. LIBs need to be ventilated and cooled to stop thermal runaway and prevent reignition, which can occur hours to days after the initial suppression of a LIB fire (Bravo Diaz *et al*., 2020; Chieh, 2021). DNV GL (2017) suggests that responders ensure the LIB temperature is stable for 60 minutes before ventilating. In NFPA 855 (Standard for the Installation of Stationary Energy Storage Systems), ventilation is described as "critical" during fire suppression, because removing flammable gas emissions and combustion "significantly improves the effectiveness of suppression" (NFPA, 2020a).

Water is often recommended for suppressing LIB fires and subsequent cooling. NFPA 855 states that water is the "agent of choice" in fires involving LIBs, as it is the most effective cooling measure (NFPA, 2020a). NFPA 855 requires minimum water flow densities for sprinkler systems of 0.3 gallons per minute (GPM) per square foot but notes that a greater sprinkler density may be "necessary to provide an adequate level of protection… for some lithium-ion battery ESS designs" (NFPA, 2020a). Interestingly, an insurance company (Allianz Global Corporate & Specialty) suggests that 500 GPM of water be available for at least 2 hours for fire protection associated with LIB ESSs (AGCS, 2019).

Because LIB size and density are important factors to consider for fire suppression, optimal methods for extinguishing and cooling for LIB fires will be battery specific. DNV GL (2017) has calculated the GPM of water requirement based on battery size (per kg) and energy density (per kilowatt-hour [kWh]). According to DNV GL (2017), an average of 0.1 GPM/kg, or 0.99 GPM/kWh, is required to extinguish and cool a LIB fire. In order to adjust for energy density, one can divide the GPM/kg by the energy density (watt-hour [Wh]/kg) and multiply by 1,000 Wh/kWh (DNV GL, 2017). Although water suppression is the recommended method of extinction, it does not negate the shock hazard or toxic gas emissions associated with LIBs (DNV GL, 2017; Chieh, 2021). According to NFPA 855, LIBs can "continue to generate flammable gases during and after extinguishing" (NFPA, 2020a). In a study conducted by DNV GL (2017), battery modules submerged in water for over 30 minutes still generated carbon monoxide. In addition, water suppression may damage the battery system or short out undamaged modules, resulting in an electrical hazard (DNV GL, 2017; Chieh, 2021).

2.2 Identifying a Risk Framework for LIBs

Understanding the frequency of risks from LIB failures, as well as the nature of the related human health impacts, is an important area of research. Significant research has been conducted to identify the factors that may cause LIB failure, as well as preventative measures that may mitigate failure (Bravo Diaz *et al*., 2020; EPRI, 2019a). However, little work has been done to identify methods or approaches for evaluating human health consequences for workers, nearby community members, or first responders after a failure has occurred. Documentation of firefighting approaches and consequences, including human health impacts, are sometimes now reported by the first responder agencies. Risks post-failure can be viewed as a function of both how often a failure can potentially occur as well as the severity of impacts from such a failure in relation to human receptors.

The concepts addressing risk from catastrophic LIB failure broadly fall under an analysis scheme termed "quantitative risk assessment" (QRA). The results of a QRA can be used to inform decisions related to LIB ESS facility design, worker safety, emergency planning, land use planning, and insurance coverage. These assessments can vary by objective and level of complexity, but generally aim to assess impacts to human health and property associated with toxicity from gas or firewater release, flammability, thermal radiation, and explosion overpressure.

QRA has been widely adopted in Europe and in other countries and regions outside the US (*e.g*., the United Kingdom [UK], the Netherlands, Singapore, Australia, Hong Kong), where a number of regulatory agencies use QRA methodologies to assess risk associated with potential industrial accidents (US DOT, 2020; UK HSE, 2001; RIVM and V&W, 2005; Wardman *et al*., 2017; Nivoliantou, 2002; Pasman and Reniers, 2014). UK and Dutch regulatory agencies are particularly active in developing QRA methodology and applying that methodology to regulations (UK HSE, 2001; RIVM and V&W, 2005). Norway published new guidance in 2019 (Lloyd's Register Consulting - Energy AS, 2019). In the US, QRA has been introduced as a tool for ensuring industrial accident safety (US NRC, 1983; Nivoliantou, 2002; AIChE, 2000; ABS, 2020), and aspects of QRA are integrated into assessments that are required for facilities storing large amount of chemicals under the provisions of Title 40 Part 68 (Chemical Accident Prevention; US EPA, 2021). More recently, Sandia National Laboratories recommended that the

United States Department of Transportation (US DOT) adopt a QRA approach when evaluating risks associated with the transportation of hazardous materials in railcars (US DOT, 2020).

To comply with the Chemical Accident Prevention provisions, the United States Environmental Protection Agency (US EPA) has issued technical guidance that embodies the concepts of QRA (US EPA, 2009a). The American Institute of Chemical Engineers' (AIChE) Center for Chemical Process Safety (CCPS) has also developed guidance on QRA for managing industrial processes that involve chemicals (AIChE, 2000). Outside of these guidance documents, much of the existing QRA guidance is industry specific. For example, there is an International Organization for Standardization (ISO) standard that addresses the installation of liquefied natural gas (ISO, 2015). As described in Section 4 of this document, ongoing innovation and development of QRA methodology is driven by proprietary software tools developed by private consulting companies. However, there are publicly available resources that can be used to aid in industrial accident risk assessment, such as Areal Locations of Hazardous Atmospheres (ALOHA), a tool developed by the National Oceanic and Atmospheric Administration (NOAA) (see Section 4 for more information on guidance and tools).

QRA methodology has been developed to answer these key questions:

- What can cause a failure?
- At what frequency does a failure occur?
- When something fails, what is the risk?
- Given the frequency and severity of the failure, is the risk acceptable?

These key questions are answered in the context of a QRA framework using hazard analysis, frequency analysis, consequence analysis, and risk evaluation and conclusions. These methodologies are summarized in Figure 2-1 but are also detailed in Sections 3.1-3.4 of this report.

Hazard Analysis	**Determine possible modes of failure and safeguards (*i.e.*, threats, barriers, and consequences)** • Example: The EPRI (2019) Bowtie Analysis
Frequency Analysis	**Identify quantitative information on the frequency/probability of failures** • Electrical, mechanical, thermal, and human errors defined during hazard analysis
Consequence Analysis	**Measure adverse effects from chemical releases, blast overpressure, heat radiation, and fire** • Public and proprietary modelling software that measures human impacts and property damage
Risk Evaluation	**Calculate risk to relevant human receptors** • Involves identifying appropriate health-based benchmarks and methodologies for expressing risk (*e.g.*, nature and extent of health impacts/fatalities per year)
Risk Conclusions	**Establish tolerable/acceptable risk levels** • Examines individual and societal risk

Figure 2-1
Summary of Quantitative Risk Assessment (QRA) Framework Methodologies

The purpose of this report is to introduce methodologies and LIB-specific factors that will need to be considered when characterizing the potential impacts of LIB ESS failure. While there has been an initial attempt to use QRA concepts for LIB applications (see Section 4), this should be considered a developing science. Although many of the existing QRA methodologies have been successfully implemented by other industries and QRA tools are becoming more sophisticated, further research will be needed to optimize tools to model more reliable results for LIBs. Further, the industry needs to consider how modeled data will be used to inform decisions, both with respect to what risk levels are considered acceptable and what types of decisions the results will inform. Outside the US, QRA appears to play a role in land use planning and plant design to minimize human health impacts. However, it can also be used to improve and benchmark safety technologies and processes.

3
KEY STEPS IN QUANTITATIVE RISK ASSESSMENT

3.1 Hazard Analysis and Frequency Analysis

The first step in QRA is to identify potential failure modes that can lead to an accident and the safeguards that are available to mitigate these adverse events. This is broadly referred to as process hazard analysis (PHA) and is associated with a number of different qualitative methodologies (*e.g.*, hazard and operability study [HAZOP], "what if?" analysis) (US EPA, 2009b). Once this step is completed, a more detailed, semi-quantitative or quantitative frequency analysis can be performed. In qualitative frequency analyses, more general probability principles are applied. For example, in a safety assessment of LIBs using the failure mode and effect analysis (FMEA) method, Xuan *et al*. (2016) used a generalized law called Heinrich's law, which combines both severity and frequency, to determine accident probability for LIBs. According to Heinrich's law, "for every 300 unsafe behaviors performed, there are 29 minor accidents and 1 serious accident" (AMS, 2017).

In QRAs, fault tree analysis (FTA) and/or event tree analysis (ETA) are more commonly used to assess the frequency of undesired events (*i.e*., battery failure, fire, or explosion). FTA and ETA are both qualitative models that can be modified to be quantitative if data are available. FTA focuses on an "undesired event," which is the top event in the fault tree, and identifies the possible causes of that event, depicting "the logical interrelationships of basic events that lead to the undesired event" (US NRC, 1981). Conversely, ETA starts with an "initiating event," and instead of defining the relationships among more minor events that lead to an undesired event, ETA defines the consequential events from the initiating event by laying out the "sequences of events linked by conditional probabilities" (Paté-Cornell, 1984). According to Paté-Cornell, (1984), "event trees can handle better notions of continuity (logical, temporal, and physical), whereas fault trees are most powerful in identifying and simplifying failure scenarios." Therefore, ETA is used more as a mitigating tool rather than a preventative tool. Although these models are different, they are often used in tandem, which is referred to as a "bowtie" analysis technique.

Bowtie analysis is routinely used in the maritime, oil and gas, and utility industries. EPRI (2019a) has specifically developed a bowtie analysis method for LIBs that detailed the threats of, barriers to, and consequences of LIB failure (an example of which is provided in Figure 3-1).

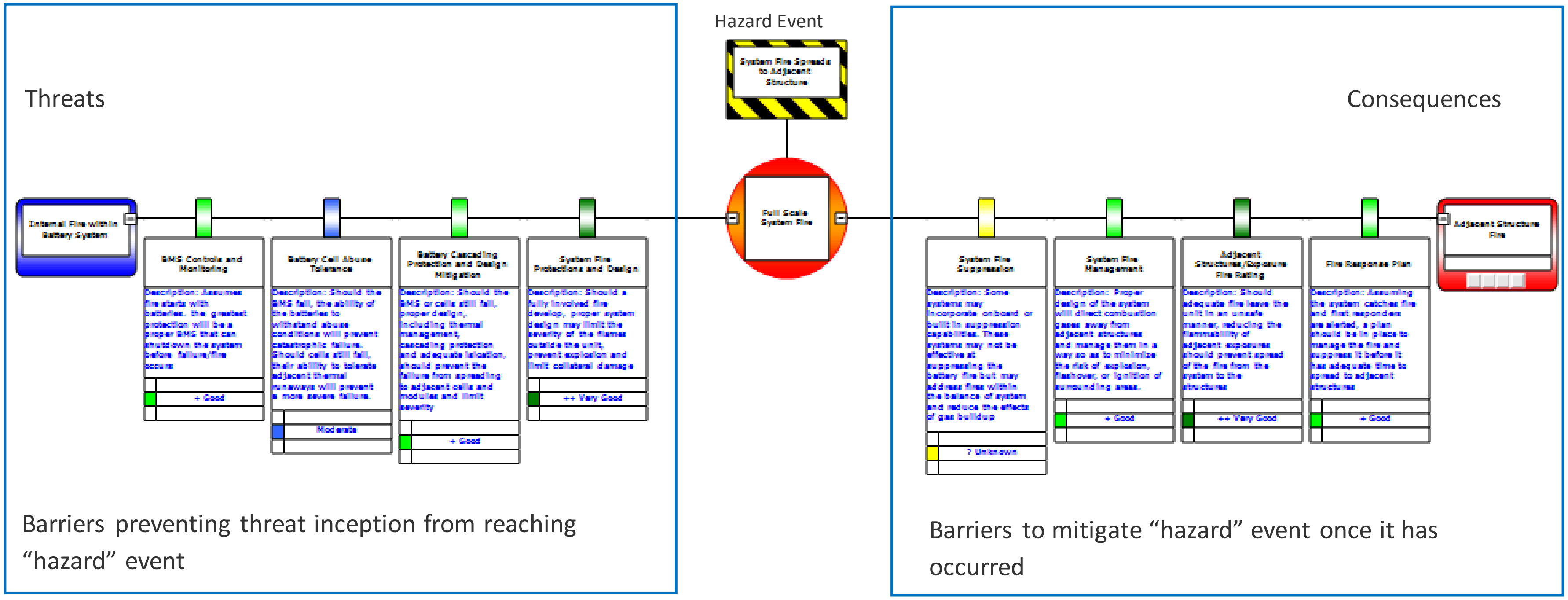

Figure 3-1
Bowtie Analysis from EPRI (2019a)

Because a detailed bowtie analysis has already been completed for LIBs, this report will not focus on this step in the evaluation framework. However, it is important to appreciate that this analysis is critical for defining the relationship between LIB failure modes and mitigation measures, and thus is a necessary first step in the QRA for understanding the potential risks associated with LIB fires and explosions.

3.1.1 Example of Frequency Analysis and Data Availability

Quantitative data, such as historical reliability data or data from incident databases, can be used in frequency analyses. As data specific to LIBs are limited or unavailable, most existing assessments rely on reliability data from other industries. DNV GL has attempted to conduct frequency assessments specific to LIBs and published its results in two reports: "Quantitative Risk Analysis for Battery Energy Storage Sites" (DNV GL, 2019a) and "Technical Reference for Li-ion Battery Explosion Risk and Fire Suppression" (DNV GL, 2019). These assessments rely on data collected by the Institute of Electrical and Electronics Engineers (IEEE, 1995) and CCPS (2015). The IEEE (1995) reliability data were collected from surveys and analyses of electrical equipment (*i.e.*, electrical failure). CCPS (2015) collected reliability data from various chemical process industries, and also used expert judgment to derive failure probabilities for a number of scenarios. DNV GL applied the information from these sources in its LIB failure frequency assessment to account for factors such as human error, thermal failure, and process control failure.

DNV GL (2019a,b) assigned a mechanical failure probability of 0.01 per year to a single LIB module. It was explained that this assumption was based on the six sigma process, which is an approach used by companies to meet a performance standard of 3.4 defects per million opportunities (or in this case, 3.4 failures per million modules) (de Mast and Bisgaard, 2007). It is not clear, however, how the mechanical failure probability of 0.01 per year was calculated from this generic assumption.

DNV GL (2019a,b) calculated fire occurrence frequency for LIBs using a sequential approach that considers the frequency of fires in a single cell, then multiple cells, then the whole battery module, and then multiple battery modules. The safeguard factors in place at each level of the sequence (single cell, multi-cell, single module, and multi-module) are multiplied together to calculate the probability of fire. Figure 3-2 and the associated equation illustrates the occurrence frequency method used to calculate the frequency of each threat individually, where F = Frequency, IE = Initiating Event, FE = Frequency Event, and S = Safeguard. The individual fire probabilities for each threat are then added together, resulting in the final probability.

$$F_{IE} \times S_{1.1} \times S_{1.2} \times S_{1.3} = F_{FE1}$$
$$F_{FE1} \times S_{2.1} \times S_{2.2} = F_{FE2}$$
$$F_{FE2} \times S_{3.1} \times S_{3.2} \times S_{3.3} = F_{FE3}$$

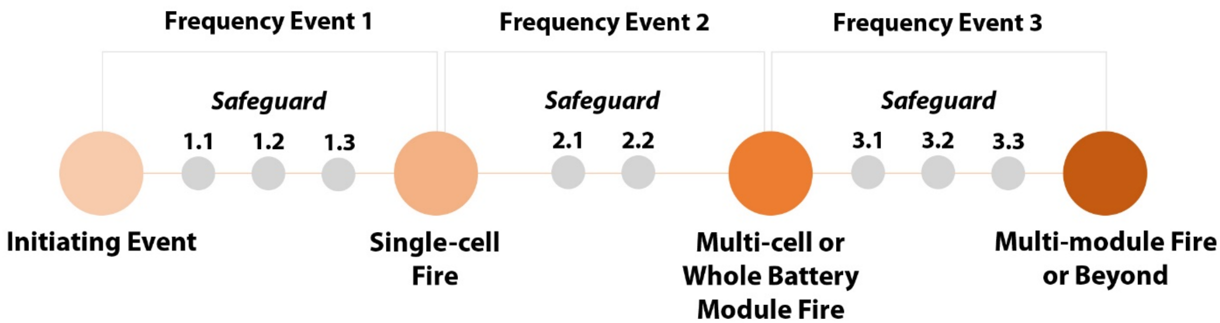

Figure 3-2
Occurrence Frequency Methodology for Individual Threats

In DNV GL's QRA for battery energy storage sites, the authors concluded that the probability of failure in one single-cell LIB with no safeguards in place or other on-site mitigating factors is "once in 10 years to once in 100 years, depending on the number of batteries and the electrical equipment (inverters or transformers)" (DNV GL, 2019a). In most scenarios, multiple safeguards are in place, and therefore, this is considered a conservative estimate. According to DNV GL (2019a), event trees and QRAs have shown that when all the safeguards are accounted for, the probability of LIB failure probability resulting in a fatality is 1×10^{-5} per year (once in 100,000 years) for an individual from the surrounding community and 1×10^{-6} per year (once in 1,000,000 years) for an individual worker at the facility, respectively. Although DNV GL (2019b) admits that "these are very uncertain numbers for a generic system," the authors point out that their analysis shows how fire occurrence frequencies vary depending on the barriers in place, and stresses that the absence of certain barriers can greatly increase fire occurrence frequency. Therefore, it is important to calculate fire and explosion occurrence frequency based on individual systems and the associated barriers that are in place. According to DNV GL (2019b), "explosions are considered to have the same threats and causes as fires in a battery system and would be a separate branch in the 'event tree' (delayed ignition)… and many of the same barriers apply to prevent explosion." Therefore, DNV GL (2019b) considers the frequencies associated with explosions to be "similar or of lower order of magnitude as the fire frequencies." More information on this QRA is provided in Section 5 of this report.

It unclear whether DNV GL's (2019a) estimated probability of LIB failure resulting in a single fatality (1×10^{-5} to 1×10^{-6} per year) is reflective of real-world occurrence probability. LIB ESS deployment continues to increase. ESSs also provide other important ancillary services that are in need, such as frequency regulation. In the last 10 years, a number of fires associated with LIB ESSs have been reported, including in 2012 at a 1.5-megawatt (MW) facility in Flagstaff, Arizona; in 2016 in Franklin, Wisconsin; and in 2017 at a 6-MW facility in Drogenbos, Belgium (AGCS, 2019; Chieh, 2021). In South Korea alone, 23 fires at LIB ESS facilities were reported between August 2017 and 2019 (Chieh, 2021). At one 10-MW facility in Kahuku, Hawaii, two fires occurred in 2011 less than 2 months apart and a third fire occurred in 2012 (AGCS, 2019). In 2019, in Surprise, Arizona, a battery exploded unexpectedly, injuring eight firefighters, one of whom had life-threatening injuries and four of whom had severe burns (NFPA, 2020b). According to the NFPA (2020b), the failure rate for LIB cells has been estimated to be between 1 in 10 million and 1 in 40 million, "depending on the quality of the manufacturing." However, because LIB ESSs "may have 100,000 battery cells or more within the installation," NFPA estimates the failure rate per LIB ESS to be much higher, stating that "as many as 1 in 100 containers on average could experience a failure in one of its battery cells" (NFPA, 2020b).

3.2 Consequence Analysis

In the consequence analysis portion of a QRA, stakeholders select the risk endpoints of interest and use modeling tools to quantify the impacts from a failure. The types of impacts that are typically quantified and that are relevant to LIB failure are those that occur from the release of chemicals, overpressure from an explosion, fire, and thermal radiation (US EPA, 2009c; NOAA, 2013a; UK HSE, c. 2009). These impacts are primarily assessed with respect to their impact on human health or fatalities, but property damage or other economic endpoints can also be evaluated. In general, consequence modeling will estimate impact severity over a geographic area. Sample outputs from ALOHA, which can be used to conduct such an analysis, are demonstrated in Figure 3-3. Panel A of Figure 3-3 demonstrates the threat zone (in miles) associated with thermal radiation from a vapor explosion, and Panel B of Figure 3-3 shows the concentration (in parts per million [ppm]) for a generic gas release downwind of a vapor explosion.

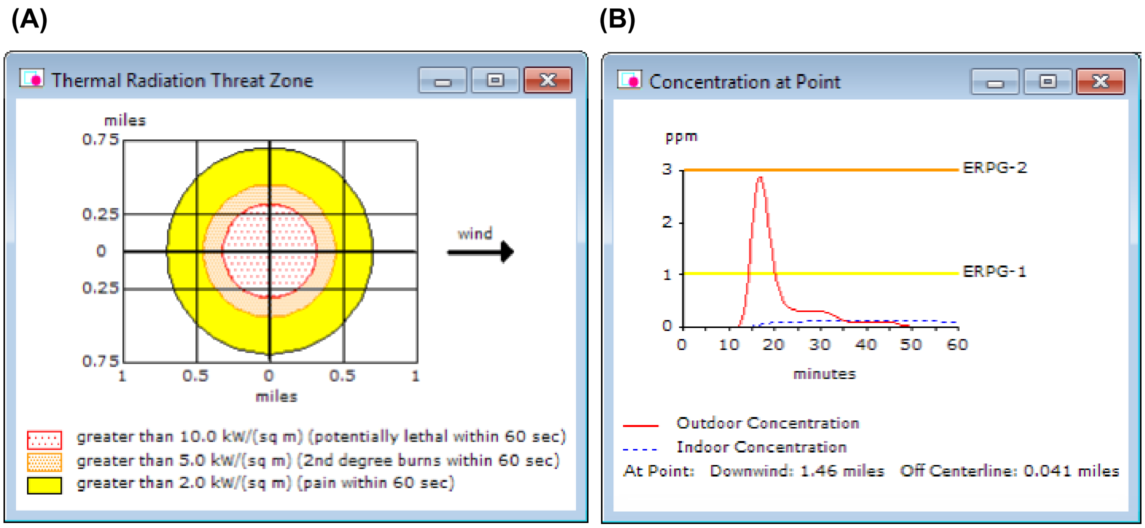

Figure 3-3
ALOHA Model Outputs for Thermal Radiation Shown as Threat Zone in Miles (Panel A) and Toxic Gas Concentrations (ppm) Over Time (Panel B)

Source: NOAA (2020a).

It is important to appreciate that consequence evaluation is accomplished with sophisticated dispersion models, some of which are publicly available, but many of which are proprietary. ALOHA is of particular importance because it was developed by NOAA and is publicly available. It is also one of the recommended models to use for consequence evaluation under the provisions of the US EPA Accidental Release Risk Management Plan (referred to as the Risk Management Plan or RMP herein; US EPA, 2009c).

The sections below provide an overview of the basic approaches that are common to these models, but the specifics of each model differ. It is also noteworthy that many of these models have been developed for (and consequently are better validated for) industries with a longer history (*e.g.*, oil and gas, nuclear energy). While the underlying features of many of the models make them amenable to use for assessing the impacts of LIB failure, there may be opportunities to optimize these models for risk evaluations of the technology of interest. Some of the available models and their basic capabilities are described in Section 4.

The sections below describe some of the key "consequences" relevant to LIB failures that are evaluated under QRA. These sections describe the nature of each consequence and how that consequence is measured to assess risk (*i.e.*, risk benchmarks), and also provide some preliminary information on LIB-specific data that may inform future modeling. For the purposes of this report, we have focused on the consequences and risk benchmarks implemented in the ALOHA model. However, other resources, particularly from Europe, contain alternative information that can be used for each of these endpoints. For example, the United Kingdom Health and Safety Executive (UK HSE) has published substantive guidance on methods and data for evaluating consequences in a QRA (UK HSE, c. 2021a).

3.2.1 Chemical Releases During a LIB Fire

Overview

A key endpoint in consequence analysis is the modeling of chemical releases from an accident or failure. Models are used to estimate concentrations of gases released during a fire or explosion over a specific time period and area. These models focus on the acute inhalation risk to nearby human receptors during an active release, which is usually assessed over a period of 30 minutes to a few hours. The types of models that can be used to estimate chemical gas releases are described in Section 4, and some of these models have been described in detail by EPRI (2020b). Currently, there is very little research or even theoretical modeling to demonstrate the relationship between LIB fires and the expected concentrations of various chemicals released from these that are present at downwind distances. However, because the chemical releases associated with LIB failure (*e.g.*, hydrogen fluoride and carbon monoxide) overlap with those associated with other types of fires and explosions (*e.g.*, oil and gas explosions, plastics), there is at least some practical understanding that the chemicals released during LIB failures have the potential to travel large distances and cause injury.

Research has identified multiple chemicals that have the potential to be released during LIB failure (see Table 3-1), but carbon monoxide has emerged as the chemical that is likely to constitute the most significant release (by volume) from LIB failures, and hydrogen fluoride has emerged as the chemical that has the potential for the most significant adverse impacts following LIB failure because of its well-known toxicity (DNV GL, 2017, 2019b; Kong *et al*., 2018; UW, 2018; Baird *et al*., 2019). Even low cutaneous exposures to hydrogen fluoride can cause serious systemic toxicity (MacPherson, 2021). An overview of the available information on flammability, health hazard, and reactivity potential as classified by NFPA for chemicals associated with LIB failure is presented in Table 3-2. Without more practical evaluation experience, it is not yet possible to understand if risk associated with LIB failures could be appropriately characterized by a small set of sentinel chemicals released during a failure or if a comprehensive assessment of all possible releases will be necessary to characterize risk potential.

Table 3-1
Chemical Releases from LIB Failures

Chemical Name	CAS No.	Reference
Benzene	71-43-2	EPRI (2020e)
Carbon Dioxide	124-38-9	EPRI (2020e); UW (2018); Baird *et al*. (2019)
Carbon Monoxide	630-08-0	EPRI (2020e); UW (2018); Chieh (2021); Baird *et al*. (2019)
Ethane	74-84-0	Kong *et al*. (2018)
Ethylene	74-85-1	Kong *et al*. (2018)
Hydrochloric Acid/Hydrogen Chloride	7647-01-0	EPRI (2020e); Chieh (2021)
Hydrofluoric Acid/Hydrogen Fluoride	7664-39-3	EPRI (2020e); UW (2018); Chieh (2021)
Hydrogen Cyanide	74-90-8	EPRI (2020e); Chieh (2021)
Hydrogen Sulfide	7783-06-4	Chieh (2021)
Methane	74-82-8	Kong *et al*. (2018); Baird *et al*. (2019)
Nitrogen Dioxide	10102-44-0	EPRI (2020e)
Propane	74-98-6	Baird *et al*. (2019)
Sulfur Dioxide	7446-09-5	EPRI (2020e); Chieh (2021)
Toluene	108-88-3	EPRI (2020e)

Notes:
CAS No. = Chemical Abstracts Service Number; LIB = Lithium-ion Battery.

Table 3-2
NFPA Hazard Classifications for Chemicals Associated with LIB Failure

Chemical of Concern	CAS No.	NFPA 704 Hazard Identification System for Emergency Responders			
		Flammability		Health Hazard	Reactivity
		Flash Point	NFPA Code Description	NFPA Code Description	NFPA Code Description
Benzene	71-43-2	Below 100°F	3 Can be ignited under almost all ambient temperature conditions	2 Can cause temporary incapacitation or residual injury	0 Normally stable, even under fire conditions
Carbon Monoxide	630-08-0	Below 73°F	4 Burns readily. Rapidly or completely vaporizes at atmospheric pressure and normal ambient temperature.	3 Can cause serious or permanent injury	0 Normally stable, even under fire conditions
Ethane	74-84-0	Below 73°F	4 Burns readily. Rapidly or completely vaporizes at atmospheric pressure and normal ambient temperature.	1 Can cause significant irritation	0 Normally stable, even under fire conditions
Ethylene	74-85-1	Below 73°F	4 Burns readily. Rapidly or completely vaporizes at atmospheric pressure and normal ambient temperature.	2 Can cause temporary incapacitation or residual injury	2 Readily undergoes violent chemical changes at elevated temperatures and pressures
Hydrochloric Acid/ Hydrogen Chloride	7647-01-0	–	0 Will not burn under typical fire conditions	3 Can cause serious or permanent injury	1 Normally stable but can become unstable at elevated temperatures and pressures
Hydrofluoric Acid/ Hydrogen Fluoride	7664-39-3	–	0 Will not burn under typical fire conditions	4 Can be lethal	1 Normally stable but can become unstable at elevated temperatures and pressures
Hydrogen Cyanide	74-90-8	Below 73°F	4 Burns readily. Rapidly or completely vaporizes at atmospheric pressure and normal ambient temperature.	4 Can be lethal	1 Normally stable but can become unstable at elevated temperatures and pressures

Table 3-2 (continued)
NFPA Hazard Classifications for Chemicals Associated with LIB Failure

Chemical of Concern	CAS No.	NFPA 704 Hazard Identification System for Emergency Responders			
		Flammability		Health Hazard	Reactivity
		Flash Point	NFPA Code Description	NFPA Code Description	NFPA Code Description
Hydrogen Sulfide	7783-06-4	Below 73°F	4 Burns readily. Rapidly or completely vaporizes at atmospheric pressure and normal ambient temperature.	4 Can be lethal	0 Normally stable, even under fire conditions
Methane	74-82-8	Below 73°F	4 Burns readily. Rapidly or completely vaporizes at atmospheric pressure and normal ambient temperature.	2 Can cause temporary incapacitation or residual injury	0 Normally stable, even under fire conditions
Nitrogen Dioxide[a]	10102-44-0	–	0 Will not burn under typical fire conditions	3 Can cause serious or permanent injury	0 Normally stable, even under fire conditions
Propane	74-98-6	Below 73°F	4 Burns readily. Rapidly or completely vaporizes at atmospheric pressure and normal ambient temperature.	2 Can cause temporary incapacitation or residual injury	0 Normally stable, even under fire conditions
Sulfur Dioxide	7446-09-5	–	0 Will not burn under typical fire conditions	3 Can cause serious or permanent injury	0 Normally stable, even under fire conditions
Toluene	108-88-3	Below 100°F	3 Can be ignited under almost all ambient temperature conditions	2 Can cause temporary incapacitation or residual injury	0 Normally stable, even under fire conditions

Notes:

CAS No. = Chemical Abstracts Service Number; LIB = Lithium-ion Battery; NFPA = National Fire Protection Association.

Source: The National Oceanic and Atmospheric Administration (NOAA) Computer-Aided Management of Emergency Operations (CAMEO) Chemicals Database (NOAA, 2021).

(a) Possesses oxidizing properties.

(b) Reacts violently or explosively with water.

The inputs needed to estimate chemical emissions will vary by modeling software. However, some key inputs include chemical-specific vapor pressure sand emission rates. Deposition characteristics have also been measured, which could help characterize possible human exposures from post-fire deposition, although whether contact with deposited dust is a meaningful exposure pathway has not been well studied.

Example data for chemicals relevant to LIBs are presented in Table 3-3 through Table 3-5. A more comprehensive evaluation of the available data for use in modeling should be undertaken when beginning a consequence analysis, which would be most efficiently accomplished in the context of a specific modeling tool or set of tools. This is because the inputs (and sometimes units) for a specific endpoint may vary by tool and depend upon the complexity of the evaluation being undertaken.

Table 3-3
Vapor Density of Key Chemical Releases

Chemical of Concern	CAS No.	Vapor Density (Relative to Air)	Source
Benzene	71-43-2	2.77	NTP (1992)a
Carbon Monoxide	630-08-0	0.97	CDC (2019 221-4986)
Hydrochloric Acid/ Hydrogen Chloride	7647-01-0	1.268	US EPA (1998)a
Hydrofluoric Acid/ Hydrogen Fluoride	7664-39-3	0.7 at 65°C and 2.6 at 20°C	ILO and WHO (2017 221-5002)
Hydrogen Cyanide	74-90-8	0.94	ILO and WHO (2018 221-5001)
Nitrogen Dioxide	10102-44-0	1.58	US EPA (1998)a
Toluene	108-88-3	3.14	NTP (1992)[a]

Notes:

CAS No. = Chemical Abstracts Service Number; LIB = Lithium-ion Battery.

(a) As cited in the National Oceanic and Atmospheric Administration (NOAA) Computer-Aided Management of Emergency Operations (CAMEO) Chemicals Database (NOAA, 2021).

Table 3-4
Dry Deposition Velocity of Key Chemical Releases

Chemical of Concern	CAS No.	Dry Deposition Velocity (cm/s)	Source
Hydrochloric Acid/ Hydrogen Chloride	7647-01-0	0.4-6.9	Harrison et al. (1989 221-4999)
Hydrofluoric Acid/ Hydrogen Fluoride	7664-39-3	1.6-3.7	Sehmel (1984 221-5066)
Hydrogen Sulfide	7783-06-4	0.015-0.38	
Nitrogen Dioxide	10102-44-0	1.9	
Sulfur Dioxide	7446-09-5	0.04-7.5	

Notes:

CAS No. = Chemical Abstracts Service Number; LIB = Lithium-ion Battery.

Table 3-5
Emission Rates for Key Chemical Releases

Chemical of Concern	CAS No.	30-Minute Release Rate (kg/s)
Carbon Monoxide	630-08-0	2.00E-07
Hydrochloric Acid/ Hydrogen Chloride	7647-01-0	2.36E-07
Hydrofluoric Acid/ Hydrogen Fluoride	7664-39-3	1.74E-07
Hydrogen Cyanide	74-90-8	1.74E-07

Notes:

CAS No. = Chemical Abstracts Service Number; LIB = Lithium-ion Battery.

Source: DNV GL (2017, Table 2).

Chemical Emissions Benchmarks

To characterize risk potential for chemical exposures, estimated chemical emissions need to be compared to toxicity benchmarks protective of human health. Several agencies have developed benchmark values that are relevant to gas releases during a LIB failure. Most modeling programs allow users to customize the toxicity benchmarks used in an analysis, and while the selection may depend on the evaluation's objective, ALOHA (NOAA, 2016) recommends the following hierarchy of sources in decreasing order of importance:

- Acute Exposure Guideline Levels (AEGLs);
- **Emergency Response Planning Guideline (**ERPG) values;
- Protective Action Criteria for Chemicals (PACs); and
- Temporary Emergency Exposure Limits (TEELs)

Health-based benchmarks have been developed to reflect three levels of risk: acute exposures that cause mild effects, more serious effects, and life-threatening effects. A complete description of the various values that can be used to assess acute risk are presented Table 3-6. Table 3-7 presents examples of health-based guidelines for chemicals associated with LIB failure. Table 3-8 presents the PAC values for the chemicals associated with LIBs identified in existing literature. Note that there may be multiple values for each level of risk based on different exposure times. Immediately Dangerous to Life or Health (IDLH) values are also used as a health benchmark, particularly when values from other sources are not available. Although these health-based benchmarks were all developed in the US, they have global acceptance.

To characterize risk of various gases, the user-selected benchmark can be directly compared to modeled emissions. Depending on the benchmark selection, different effect severities can be evaluated.

Table 3-6
Key Sources of Human Health Toxicity Benchmarks for Acute Inhalation Exposures

Acute Guideline	Description
Acute Exposure Guideline Levels (AEGLs)	**Developed by US EPA, AEGLs are generally considered some of the most current, well-researched values.** **The three levels of AEGLs and their definitions are presented below:** **"AEGL-3** is the airborne concentration, expressed as parts per million (ppm) or milligrams per cubic meter (mg/m^3), of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death. **AEGL-2** is the airborne concentration (expressed as ppm or mg/m^3) of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape. **AEGL-1** is the airborne concentration (expressed as ppm or mg/m^3) of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic nonsensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure. All three tiers (AEGL-1, AEGL-2, and AEGL-3) are developed for five exposure periods: 10 minutes, 30 minutes, 60 minutes, 4 hours, and 8 hours" (NOAA, 2019a).
Emergency Response Planning Guidelines (ERPGs)	**Developed by the** American Industrial Hygiene Association (AIHA) Emergency Response Planning Committee (NOAA, 2019b). **"ERPG-3** is the maximum airborne concentration in air below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects**.** **ERPG-2** is the maximum airborne concentration in air 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** is the 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" (NOAA, 2019b). Each ERPG is developed to reflect 1 hour of exposure (NOAA, 2019b).
Protective Action Criteria for Chemicals (PACs)	**The PACs are a hierarchy publicly available exposure guidelines, a database of which is maintained by the United States Department of Energy (US DOE) (NOAA, 2020b). The hierarchy of PACs is as follows:** **"1. Final, 60-minute AEGL values (preferred)** **2. Interim, 60-minute AEGL values** **3. ERPG values** **4. TEEL values" (NOAA, 2020b).** **Each chemical in the PAC database has values that reflect mild (transient) effects (PAC-1), more severe (irreversible) effects (PAC-2), and life-threatening effects (PAC-3) (NOAA, 2020b).**

Table 3-6 (continued)
Key Sources of Human Health Toxicity Benchmarks for Acute Inhalation Exposures

Acute Guideline	Description
Temporary Emergency Exposure Limits (TEELs)	**Developed by US DOE Subcommittee on Consequence Assessment and Protective Actions (SCAPA). As the name suggests, TEELs for a specific chemical should only be used temporarily until AEGLs or ERPGs are developed for that chemical (NOAA, 2020c).** **"TEEL-3** is the airborne concentration (expressed as ppm [parts per million] or mg/m^3 [milligrams per cubic meter]) of a substance above which it is predicted that the general population, including susceptible individuals, when exposed for more than one hour, could experience life-threatening adverse health effects or death. **TEEL-2** is the airborne concentration (expressed as ppm or mg/m^3) of a substance above which it is predicted that the general population, including susceptible individuals, when exposed for more than one hour, could experience irreversible or other serious, long-lasting, adverse health effects or an impaired ability to escape. **TEEL-1** is the airborne concentration (expressed as ppm or mg/m^3) of a substance above which it is predicted that the general population, including susceptible individuals, when exposed for more than one hour, could experience notable discomfort, irritation, or certain asymptomatic, nonsensory effects. However, these effects are not disabling and are transient and reversible upon cessation of exposure" (**NOAA, 2020c**). Each TEEL is developed to reflect 1 hour of exposure (**NOAA, 2020c**).
Immediately Dangerous to Life or Health (IDLH) Values	Developed by the National Institute for Occupational Safety and Health (NIOSH, 2019b), for the protection of workers in occupational settings. NIOSH provides only one IDLH value per chemical, which is derived as described below. "IDLH values are established (1) to ensure that the worker can escape from a given contaminated environment in the event of failure of the respiratory protection equipment and (2) to indicate a maximum level above which only a highly reliable breathing apparatus, providing maximum worker protection, is permitted" (NIOSH, 2019).

Table 3-7
Health-Based Guidelines for Key Chemical Releases

Chemical of Concern	CAS No.	IDLH Value (ppm)	ERPGs (ppm)			10-Minute AEGLs (ppm)			4-Hour AEGLs (ppm)		
			1 (Mild Effects)	2 (Serious Effects)	3 (Life-Threatening Effects)	1	2	3	1	2	3
Benzene	71-43-2	500	50	150	1,000	130	2,000	9,700	18	400	2,000
Carbon Monoxide	630-08-0	1,200	200	350	500	NR	420	1,700	NR	33	150
Hydrochloric Acid/ Hydrogen Chloride	7647-01-0	50	3	20	150	1.8	100	620	1.8	11	26
Hydrogen Cyanide	74-90-8	50	NA	10	25	2.5	17	27	1.3	3.5	8.6
Hydrogen Sulfide	7783-06-4	100	0.1	30	100	0.75	41	76	0.36	20	37
Hydrofluoric Acid/ Hydrogen Fluoride	7664-39-3	30	2	20	50	1	95	170	1	12	22
Nitrogen Dioxide	10102-44-0	13a	1	15	30	0.5	20	34	0.5	8.2	14
Sulfur Dioxide	7446-09-5	100	0.3	3	25	0.2	0.75	30	0.2	0.75	19
Toluene	108-88-3	500	50	300	1,000	67	1,400	10,000	67	310	1,800

Notes:

AEGL = Acute Exposure Guideline Level; ERPG = Emergency Response Planning Guideline; IDLH = Immediately Dangerous to Life and Health; NA = Not Appropriate; NOAA = National Oceanic and Atmospheric Administration; NR = Not Recommended Due to Insufficient Data; ppm = Parts Per Million.

Source: The National Oceanic and Atmospheric Administration (NOAA) Computer-Aided Management of Emergency Operations (CAMEO) Chemicals Database (NOAA, 2021), unless otherwise indicated.

(a) Source is NIOSH (2017).

Table 3-8
Protective Action Criteria (PAC) for Key Chemical Releases

Chemical of Concern	CAS No.	PAC (ppm)		
		1	2	3
Benzene	71-43-2	52a	800a	4,000a
Carbon Monoxide	630-08-0	75	83a	330a
Ethane	74-84-0	65,000b	230,000b	400,000b
Ethylene	74-85-1	600	6,600c	40,000b
Hydrochloric Acid/ Hydrogen Chloride	7647-01-0	1.8a	22a	100a
Hydrofluoric Acid/ Hydrogen Fluoride	7664-39-3	1a	24a	44a
Hydrogen Cyanide	74-90-8	2a	7.1a	15a
Hydrogen Sulfide	7783-06-4	0.51a	27a	50a
Methane	74-82-8	65,000b	230,000b	400,000b
Nitrogen Dioxide	10102-44-0	0.5a	12a	20a
Propane	74-98-6	5,500a,c	17,000a,d	33,000a,b
Sulfur Dioxide	7446-09-5	0.2a	0.75a	30a
Toluene	108-88-3	67a	560a	3,700a,c

Notes:

AEGL = Acute Exposure Guideline Level; CAS No. = Chemical Abstracts Service Number; ERPG = Emergency Response Planning Guideline; LEL = Lower Explosion Limit; LIB = Lithium-ion Battery.

Source: US DOE (2021).

(a) Corresponds to 60-minute AEGL value.

(b) PAC value is ≥LEL.

(c) PAC value is ≥10% LEL but <50% LEL.

(d) PAC value is >50% LEL but <100% LEL.

The values presented in the tables above are applicable to all individuals, including the general public. Many of these values, however, were specifically developed to protect workers during an unintended release (*e.g.*, ERPGs developed by the American Industrial Hygiene Association [AIHA] and IDLHs developed by the National Institute for Occupational Safety and Health [NIOSH]). Acute occupational exposure values developed by the Occupational Health and Safety Administration (OSHA) (*i.e.*, short-term exposure levels [STELs]) have not been included in this table); these values are generally considered outdated and not based on the best-available science. Consequently, QRA frameworks do not typically use the short-term toxicity benchmarks developed by OSHA.

As an alternative to these benchmarks, a UK HSE guidance document identifies different approaches for quantifying possible fatalities from chemical exposures (UK HSE, c. 2021a). This agency provides guidance on developing Specified Level of Toxicity (SLOT) values and Significant Likelihood of Death (SLOD) values for chemicals. As described in the guidance, a

SLOT is an exposure that will cause fatality in a few susceptible individuals (*i.e.*, fatality rate of 1-5% in exposed individuals) and cause severe distress and injury in others (UK HSE, c. 2009). A SLOD value, on the other hand, is an exposure that will result in a significant risk of death (*i.e.*, an approximate 50% fatality rate in exposed individuals). SLOT and SLOD values should be developed based on the best available toxicity data while taking into account uncertainty factors associated with the data (UK HSE, c. 2009). These values are also adjusted with respect to time (UK HSE, c. 2021).

Chemical Deposition Risk and Toxicity Benchmarks

Although not modeled by current software, another chemical exposure resulting from LIB failure that could affect human health is residual deposition that can occur post-fire. Particulates generated during a LIB fire can contain a variety of metals, including, lithium, nickel, manganese, and cobalt. The potential for exposure to these residues could provide an ongoing source of chronic exposure to a workplace or residential neighborhood affected by a LIB fire.

In the aftermath of the 2001 World Trade Center attack, US EPA developed a methodology for evaluating risk from exposure to residential dust (US EPA Region II, 2004). In one of the initial steps of this methodology, the Agency developed conservative screening levels for contaminants that would protect against health effects from incidental ingestion and dermal contact with dust. This approach could potentially be adapted to assess longer-term risks from the deposition of metals that may occur after a LIB fire or explosion. Because the benchmarks were developed for residential exposures, they would need to be adapted to be protective of worker exposures.

3.2.2 Explosion Overpressure

Overview

Overpressure, also known as a blast wave, is the pressure released after an initial explosion (NOAA, 2019c). Human impacts from overpressure can include damage to internal organs or the ear drums. It can also cause forceful physical displacement of receptors within close proximity. For example, in one of the most recent examples of a thermal runaway incident at an Arizona site, several first responders sustained severe injuries (*e.g.*, traumatic brain injury, a collapsed lung, broken bones, laceration of the liver) when they were propelled up to 70 feet following the explosion of a LIB ESS (Scanlon, 2020).

Overpressure can also cause damage to nearby structures and buildings. This can cause further injury to humans should parts of damaged structures become dislodged or collapse. Overpressure is generally characterized by the propagation speed of the flame front and the mass of fuel involved in the reaction (NOAA, 2013a).

Specific overpressures associated with LIB fires are not well characterized. A 2019 review article noted a lack of experimental data on LIB explosion strength (Baird *et al*., 2019). However, this article does present modeling results that offer some perspective on possible overpressures associated with different LIB types over a range of air-to-fuel ratios. Depending on conditions, these estimated overpressures ranged from approximately 5.5 to 8.5 bar (approximately 80-120 pounds per square inch [psi]) in the immediate vicinity of the LIB. The relationship of these overpressures to battery size is not apparent from the information presented in the article.[1]

Overpressure Benchmarks

In ALOHA's technical guidance, NOAA (2019c) presents a table (see Table 3-9) outlining the relationship between overpressure (measured in pounds per square inch gauge [psig][2]) and expected damage (to both human health and physical structures), citing Lee's 1980 publication *Loss Prevention in the Process Industries, Vol. 1*.

Table 3-9
Damage/Injury Overpressure Benchmarks

Overpressure[a] (psig)	Expected Damage
0.04	Loud noise (143 db); sonic boom glass failure.
0.15	Typical pressure for glass failure.
0.40	Limited minor structural damage.
0.50-1.0	Windows usually shattered; some window frame damage.
0.70	Minor damage to house structures.
1.0	Partial demolition of houses; made uninhabitable.
1.0-2.0	Corrugated metal panels fail and buckle. Housing wood panels blown in.
1.0-8.0	Range for slight to serious laceration injuries from flying glass and other missiles.
2.0	Partial collapse of walls and roofs of houses.
2.0-3.0	Non-reinforced concrete or cinder block walls shattered.
2.4-12.2	Range for 1-90% eardrum rupture among exposed populations.
2.5	50% destruction of home brickwork.
3.0	Steel frame buildings distorted and pulled away from foundation.
5.0	Wooden utility poles snapped.
5.0-7.0	Nearly complete destruction of houses.
7.0	Loaded train cars overturned.
9.0	Loaded train box cars demolished.
10.0	Probable total building destruction.
14.5-29.0	Range for 1-99% fatalities among exposed populations due to direct blast effects.

Notes:

db = Decibel; psig = Pounds Per Square Inch Gauge.

Source: Lees (1980 as cited in NOAA, 2019c).

(a) According to the National Oceanic and Atmospheric Administration (NOAA, 2019c), "[t]hese are peak pressures formed in excess of normal atmospheric pressure by blast and shock waves."

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[1] The paper does note that the modelling was based on an experiment using a 201 spherical vessel.

[2] Pounds per square inch gauge (psig) differs from pounds per square inch (psi) in that the former is relative to atmospheric pressure.

The information presented in Table 3-9 can be used for customization in ALOHA or other models and was used to set the default overpressure values and associated damage implemented in the ALOHA model (see Table 3-10).

Table 3-10
Damage/Injury Overpressure Benchmark Defaults

Overpressure (psi)	Injury/Damage
8	Destruction of buildings
3.5	Serious injury likely
1	Shatters glass

Notes:
psi = Pounds Per Square Inch.
Source: NOAA (2019c).

3.2.3 Thermal Radiation

Injury can also occur in the form of burns from the heat generated during a LIB failure. This would be most relevant to those in close proximity to a LIB fire, including first responders. A number of studies have assessed the heat-generating potential associated with LIB failure, but a limited number have specifically examined utility-scale LIB ESSs. To provide some perspective, Wang *et al*. (2019) measured the heat release rate of two types of utility-scale LIBs (lithium ferrophosphate [LFP] and nickel-manganese-cobalt [NMC]). In this controlled experiment, which tested small samples[3] of each cathode type, Wang *et al*. (2019) determined that the normalized heat release rates in the immediate vicinity (*i.e*., in the small experimental apparatus) of LFP and NMC batteries were 1,426.2 and 2,910.3 kW/m^2, respectively. This small experiment is useful for a comparison of thermal radiation profiles between battery types, but significantly more research is currently needed to understand the thermal radiation profile of an actual utility-scale sized battery.

Benchmarks to assess injury from thermal radiation have been established. In a table in ALOHA's technical guidance, NOAA (2013b) presents benchmarks that correspond with the time it takes for physiological effects to occur following direct thermal radiation exposure to bare skin (see Table 3-11). NOAA states that the source of the information in this table is the *Handbook of Chemical Hazard Analysis Procedure*, which was published by the Federal Emergency Management Agency (FEMA), US DOT, and US EPA in 1988.

[3] The samples were on the scale of centimeters. For example, the LFP cathode was 13.52 × 2.95 × 22.05 cm).

Table 3-11
Damage/Injury Thermal Radiation Benchmarks

Radiation Intensity (kW/m^2)	Time for Severe Pain (seconds)	Time for Second-Degree Burns (seconds)
1	115	663
2	45	187
3	27	92
4	18	57
5	13	40
6	11	30
8	7	20
10	5	14
12	4	11

Note:
Source: FEMA *et al*. (1988, as cited in NOAA, 2013b**).**

Similar to overpressure, the information presented in Table 3-11 was used to set the three default values implemented in ALOHA (see Table 3-12).

Table 3-12
Damage/Injury Thermal Radiation Benchmark Defaults

Radiation Intensity (kW/m2)	Injury
10	Potentially lethal within 60 seconds of exposure
5	Second-degree burns within 60 seconds of exposure
2	Pain within 60 seconds of exposure

Notes:
kW = Kilowatt.
Source: **NOAA (2013**b).

3.2.4 Flammability Potential

Most consequence analysis programs also take into account the potential for chemical emissions to undergo a secondary explosion. This would occur under conditions in which a specific emitted chemical was present above its lower explosive limit (LEL)[4] (also referred to as a lower flammability limit [LFL]) and was exposed to an ignition source (*i.e*., spark, other fire, *etc*.). Many of the chemicals released from LIB fires are flammable. Flammability hazards classified by NFPA are presented in Table 3-2, and the LELs available for these chemicals are presented in Table 3-13. Baird *et al*. (2019) provide a review of studies measuring the percentage of

[4] The LEL is the lowest chemical-specific concentration (expressed as percentage) that is capable of becoming a fire in the presence of an ignition source.

flammable gas released during a LIB failure, which varies by battery type and state of charge. At 100% state of charge, the amount of flammable gases released following a LIB failure can be over 50% of their respective LELs.

Table 3-13
Lower Explosive Limits (LELs) for Key Chemical Releases

Chemical of Concern	CAS No.	LEL (%)
Benzene	71-43-2	1.4
Carbon Monoxide	630-08-0	12.0
Ethane	74-84-0	2.9
Ethylene	74-85-1	2.75
Hydrogen Cyanide	74-90-8	5.6
Hydrogen Sulfide	7783-06-4	4.3
Methane	74-82-8	5
Propane	74-98-6	2.1
Toluene	108-88-3	1.27

Notes:

CAS No. = Chemical Abstracts Service Number; LIB = Lithium-ion Battery.

Source: the National Oceanic and Atmospheric Administration (NOAA) Computer-Aided Management of Emergency Operations (CAMEO) Chemicals Database (NOAA, 2021).

The ALOHA model uses 60% of the LEL of each chemical to define the area of concern (NOAA, 2013a). The rationale for using a benchmark that is lower than the LEL is based on the observation that even if the time-averaged concentration of a gas is below its LEL, the gas concentration may exceed its LEL during isolated periods of time and or in distinct locations (NOAA, 2013a).

3.3 Risk Evaluation and Risk Conclusions

3.3.1 Risk Evaluation

Under a QRA paradigm, risk is typically measured as the probability of a fatality over a certain time period (*i.e.*, the annual fatality rate), but it can also be used to look at non-fatal injuries and property damage. Risk results can be expressed as individual risk or societal risk. Individual risk measures the probability of fatality/injury (expressed as the number of fatalities per year) for an individual worker or community member from a specific facility/operation/location. Risks to workers and community members are evaluated separately. Individual risk tolerance benchmarks have been developed by numerous regulatory agencies, but the values developed by UK HSE are commonly used in QRA assessment (UK HSE, c. 2021a; Dunjo *et al*., 2016; AIChE, 2009b). Societal risk considers population density in the vicinity of an accident and is measured as the probability of a fatality (expressed as the number of fatalities per year) to the group of workers at the facility/operation or the population living or working within the vicinity of the facility. These levels have also been set by global regulatory agencies (AIChE, 2009b).

In QRA modeling programs, individual risks are often calculated using probit functions, which translate chemical-specific consequence intensity and exposure time into a probability of a fatal consequence. For example, in the case of chemical releases, chemical-specific probit equations are used to estimate the chemical concentration that can cause death over a specific exposure duration. Empirically, the probit functions are based on median lethal concentrations (LC_{50} values, *i.e*., concentrations that cause death in 50% of exposed experimental animals). Probit functions are available for many of the key chemical emissions that would be associated with LIB fires (*e.g*., hydrogen fluoride, carbon monoxide). Probit functions are also available for heat radiation and blast overpressure. The general probit equation is presented below (UK HSE, c. 2009):

$$Y = k_1 + k_2(\ln V) \qquad \textbf{Eq. 3-1}$$

where:

Y	=	Probability (1-99%) of fatality/damage.
k1/k2	=	Probit constants.
V	=	Product of the intensity (raised to a hazard-specific expense) and time.

Probit constants are available from a number of different resources. The Dutch Rijksinstituut voor Volksgezondheid en Milieu (RIVM, 2015) provides guidance for developing probit functions for hazardous chemical inhalation exposures. As explained below in Section 3.3.2, probit results can be compared to individual risk benchmarks established by public health authorities to determine acceptable risk.

For evaluating societal risk, F-N curves are commonly used. F-N curves are a visual representation of the frequency of an event (F) *vs.* the predicted number of people harmed by that event (N). In essence, they combine information on the frequency of an event (or series of events) and the potency of the event to calculate a predicted level of harm. Harm can be expressed as an injury, fatality, or any measure of damage for which the relationship between the exposure and the outcome has been quantified. F-N curves are common result outputs used by modeling programs and are plotted against information on acceptable risk tolerances. While F-N curves can be relatively flexible and cover a whole range of endpoints, the health-based benchmark information presented in Section 3.2.1 is often used to calculate the deaths, injuries, and damages associated with accidents. More information on the development and functionality of F-N curves and example F-N curves are presented in Appendix A of the AIChE CCPS's "Guidelines for Developing Quantitative Safety Risk Criteria" (AIChE, 2009a).

Reliable information on the frequency of a failure is needed to produce F-N curves. However, it is possible to assess risk without considering the event occurrence probability. While such an approach runs contrary to the principles of QRA, it is more consistent with traditional risk assessment practices in the US. Under this more familiar US risk assessment paradigm, a level of concern (*i.e*., the benchmarks described in Section 3.2.1) can be compared to a modeled exposure to determine if risk exists. For example, one could model hydrogen fluoride emissions assuming a LIB failure has occurred and determine the area where the modelled emissions exceed the ERPG-1, -2, and -3 values for hydrogen fluoride to define the population that would be expected to experience mild, severe, and fatal effects from the modeled exposure.

3.3.2 Establishing Risk Tolerances Under QRA

One of the main reasons the QRA paradigm is focused on calculating the probability of an individual fatality over a certain time period is because the tolerable risk levels established by key regulatory agencies that promote QRA are in the form of acceptable numbers of deaths per year. Specifically, the QRA framework relies heavily on the individual risk levels established by the UK HSE (2001, c. 2021b), which established a set of acceptable risk levels for industrial accidents. The UK HSE (2001) has set a maximum tolerable risk level of 1×10^{-3} and 1×10^{-4} fatalities per year for workers and the general public, respectively. In other words, the probability associated with fatality for a specific facility needs to be lower than 1 in 1,000 and 1 in 10,000 for workers and for members of the general public, respectively. The practical implication of these levels is that facility construction will not be permitted (or will require the implementation of further risk reduction measures) when risk exceeds these levels.

The UK has also established broadly acceptable criteria (*i.e.*, 1×10^{-6} deaths/year for both workers and the general public) (UK HSE, 2001). Facilities with these lower fatality probabilities are generally considered to have a negligible risk of fatalities and can be constructed without further evaluation using QRA.

A risk that falls between the maximum tolerable and broadly acceptable risks is subject to a risk-benefit analysis to demonstrate that the facility's/operation's risks are "as low as reasonably practicable (ALARP)" (UK HSE, c. 2021b). According to UK HSE (c. 2021b), "this involves weighing a risk against the trouble, time and money needed to control it," and, in practical terms, involves a demonstration that all reasonable risk reduction measures have been taken that are "not grossly disproportionate" to the benefits achieved by the measure. While the UK seems to have pioneered this concept, many countries have developed conceptually similar approaches, including Australia, Brazil, and the Netherlands. A full review of tolerable limits set by other agencies is reviewed and summarized in Appendix B of the AIChE CCPS "Guidelines for Developing Quantitative Safety Risk Criteria" (AIChE, 2009b). A more recent publication (Dunjo *et al*., 2016) also summarizes the different individual and societal risk levels set by global regulatory agencies, with some additional comments on how the risk levels are applied to decision making.

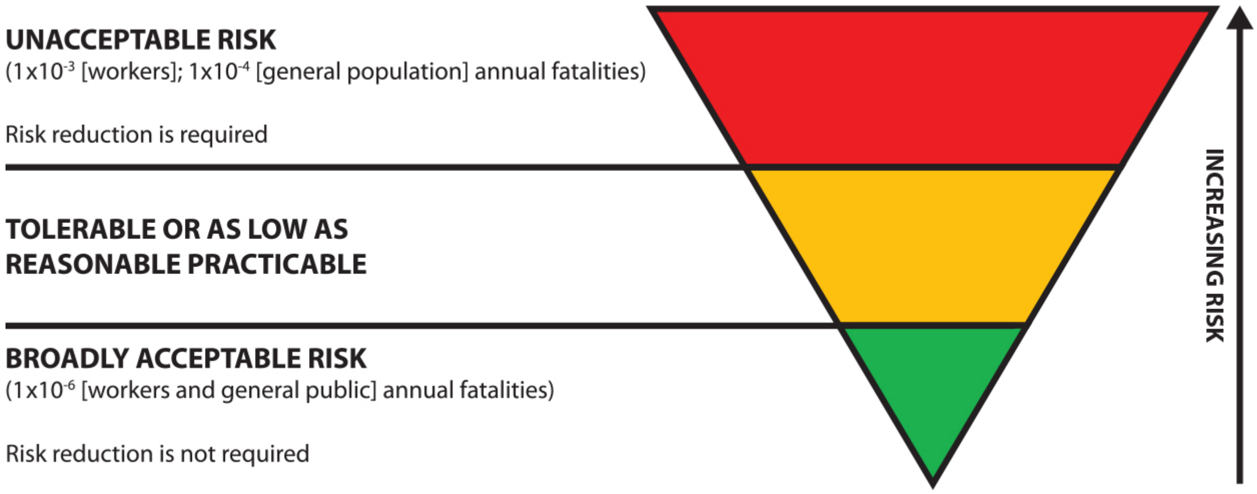

Figure 3-4
Generally Accepted Risk Benchmarks for Quantitative Risk Assessment (QRA) Developed by the United Kingdom Health and Safety Executive
Modified from Figure 1 of UK HSE (c. 2021c).

As with criteria for individuals, societal risk benchmarks have been set by different organizations, which vary by approach and risk tolerance. The upper tolerance criteria generally range from 1×10^{-2} to 1×10^{-4} (cumulative frequency of fatalities per year) (AIChE, 2009b).

While the concept of ALARP (*i.e.*, a regulatory impact analysis) underlies most federal regulations, ALARP is generally not a concept used on a facility- or site-specific basis in the US. Risk assessments in the US tend to operate with more of a "bright line" concept – *i.e.*, is a facility associated with a risk concern or not. While the Nuclear Regulatory Commission was one of the pioneers of establishing acceptable risk benchmarks, in general, the US lacks a framework for demonstrating risk acceptability for industrial accidents based on economic considerations (Dunjo *et al*., 2016; US DOT, 2020). Some municipalities in California (*e.g*., Santa Barbara) have well-developed QRA methodologies and have set acceptable risk benchmarks (Dunjo *et al*., 2016). Also, the NFPA has set acceptable fatality frequencies to set land use limitations for facilities that handle liquefied natural gas (Dunjo *et al*., 2016). According to Dunjo *et al*. (2016), the United States Department of Defense (US DOD) published an acceptable fatality rate of 1×10^{-4} fatalities per year for operations in which explosives are handled. As noted earlier, the US DOT is current considering appropriate QRA methodologies and risk benchmarks for the transportation of hazardous materials in railcars (US DOT, 2020).

4
TOOLS AND GUIDANCE DOCUMENTS

The steps involved in QRA can be complex. In particular, the consequence analysis involves calculating gas releases, thermal radiation intensity, and overpressure over time and space. Risk estimates involve integrating the consequence data with information on failure probabilities. Because of these complexities, several modeling programs are available to support QRAs. These tools range in sophistication and complexity, and more research is needed to identify the tool that is most suited to assessments of LIB failure events or to determine whether a new tool will need to be developed specifically for such assessments. It is noteworthy that many of these tools can assess human health endpoints as well as property damage. While some tools are publicly accessible, most are proprietary and can only be accessed and used for a fee. An overview of QRA software as well as tool examples are presented in Appendix A of *In Offshore Risk Assessment: Principles, Modelling and Applications of QRA Studies (Second Edition)* (Vinnem, 2007). The sections below provide a brief overview of some of the tools that currently exist to accommodate steps in the QRA process.

4.1 Frequency Analysis

As described in Section 3.1, the frequency of LIB failures can be assessed using FTA or ETA. These analyses can be conducted using fault tree, event tree, or fault tree and event tree software tools, such as those listed in Table 4-1.

Table 4-1
Frequency Analysis Tools

Type	Model	Access	Provider
Fault Tree	CARA	Licensed	Safetec Nordic
Event Tree	RISKMAN	Licensed	PLG
Fault Tree and Event Tree	RiskSpectrum	Licensed	RELCON

Note:
See Appendix A of Vinnem (2007) for more details.

4.2 Consequence Analysis

Consequence analysis, which is described in Section 3.2, can be conducted using empirical or computational fluid dynamics (CFD) models. Although the tool ALOHA is referenced throughout the report, there are a number of available tools that offer features or allow for input customization to estimate chemical gas, fire, and explosion risk for more specific or complex scenarios (*e.g.*, multiple buildings, site mapping). Examples of these tools are provided in Table 4-2. To see the difference in the level of detail provided by ALOHA *versus* these other, more sophisticated modeling tools, one could compare the outputs from ALOHA, such as the example outputs presented in Figure 3-3, with example outputs in the software brochures for these other tools, such as EFFECTS (Gexcon AS, 2020a) and FRED (Gexcon AS, 2020b).

Table 4-2
Consequence Analysis Tools

Model Type	Tool	Modeling Capabilities			Access	Provider	Website
		Gas	Fire	Explosion			
Empirical Model	SCICHEM	X			Public	EPRI	https://www.epri.com/research/products/1025626
Empirical Model	ALOHA	X	X	X	Public	US EPA	https://response.restoration.noaa.gov/oil-and-chemical-spills/chemical-spills/aloha
CFD Model	OpenFOAM	X	X	X	Public	Open Source	https://openfoam.org
Empirical Model	PHAST	X	X	X	Licensed	DNV	https://www.dnv.com/software/services/phast/phast-module-multi-component-extension.html
Empirical Model	TRACE	X	X	X	Licensed	Safer Systems	https://www.safersystem.com/safer-trace-v10-2-release
Empirical Model	FRED	X	X	X	Licensed	Shell Global Solutions	https://www.gexcon.com/products-services/shell-fred-software
Empirical Model	EFFECTS	X	X	X	Licensed	TNO	https://www.tno.nl/media/10741/effects-brochure.pdf
CFD Model	FLACS	X	X	X	Licensed	GEXCON	https://www.gexcon.com/products-services/flacs-software

Notes:

ALOHA = Areal Locations of Hazardous Atmospheres; CFD = Computational Fluid Dynamics; EPRI = Electric Power Research Institute; FRED = Fire, Release, Explosion and Dispersion; PHAST = Phylogenetic Analysis with Space/Time; US EPA = United States Environmental Protection Agency.

4.3 Risk Evaluation

The risk evaluation step of a QRA, as described in Section 3.3, can be conducted using a number of tools, including RISKCURVES (licensed by TNO), SAFETI (licensed by DNV GL), and SHEPHERD (licensed by Shell Global Solutions). Essentially, these tools synthesize frequency and consequence data to generate risk profiles over a geographic area. Risk can be presented as a societal risk map, potential loss of life, or fatality curves (*i.e.*, F-N curves). Example outputs of societal risk maps showing individual risk contours modeled by RISKCURVES and SAFETI are provided in their associated software brochures (Gexcon AS, 2020c; DNV GL, 2018). An example output of a societal risk map showing total risk contours and an example output of an F-N curve modeled using SHEPHERD are provided in the SHEPHERD software's brochure (Gexcon AS, 2020d).

4.4 Key Guidance Materials

While there are no QRA guidance documents specific to assessing LIBs ESS events, the guidance documents below are key resources for understanding the general QRA process, the types of modeling inputs required to assess impacts, and the different risk benchmarks. While some of the resources below describe the entire QRA process (*e.g.*, AIChE, 2000; RIVM and V&W, 2005), some are focused on the consequence analysis modeling and risk evaluation components (*e.g.*, AIChE, 1995; US EPA, 2009c). These resources are also referenced throughout this report.

- **AIChE CCPS:** Guidelines for Consequence Analysis of Chemical Releases, 1995 (AIChE, 1995).
- **AIChE CCPS:** Guidelines for Chemical Process Quantitative Risk Analysis, Second Edition, 2000 (AIChE, 2000).
- **AIChE CCPS:** Guidelines for Developing Quantitative Safety Risk Criteria, 2009 (AIChE, 2009c).
- **RIVM and the Netherlands Ministry of Transport, Public Works, and Water Management (V&W):** "Guideline for Quantitative Risk Assessment 'Purple Book,'" 2005 (RIVM and V&W, 2005).
- **Norwegian Directorate for Civil Protection (DSB):** "Guidelines for Quantitative Risk Analysis of Facilities Handling Hazardous Substances," 2019 (Lloyd's Register Consulting - Energy AS, 2019).
- **UK HSE:** "Reducing Risks, Protecting People: HSE's Decision-Making Process," 2001 (UK HSE, 2001).
- **US EPA:** "Risk Management Program Guidance for Offsite Consequence Analysis," 2009 (US EPA, 2009c).

5 EXAMPLE ASSESSMENTS

Example QRAs are available for a large variety of industrial facilities, but QRA application to assessing ESS, or for that matter electric vehicle, platforms is not widespread (AcuTech Consulting Group, 2016; WorleyParsons Infrastructure & Environment, 2015). This is likely a function of the developing nature of the LIB ESS industry and the fact that existing QRA models are not optimized to handle LIB failure dynamics. Nonetheless, one example of a LIB-specific QRA was conducted by DNV GL, the results of which were published in a white paper (DNV GL, 2019a). Section 5.1 provides a brief overview of QRA application across other industries, and Section 5.2 details the DNV GL QRA performed specifically for LIBs and evaluates its limitations.

5.1 QRA Application

In the US, the consequence analysis component of QRA is largely performed in the context of the US EPA Risk Management Plan (also referred to as the Risk Management Program), which is part of the 1990 Amendments to the Clean Air Act (US EPA, 2020a, 2009a). The purpose of the RMP is to establish a process for understanding risks from chemical accidents (US EPA, 2009a,c, 2020a). The results of RMP assessments are used to inform local fire, police, and emergency response personnel responding to chemical accidents and to communicate potential risks to community members (US EPA, 2020a).

Among other requirements, the RMP requires stationary facilities that store large volumes of specific chemicals[5] to conduct a hazard assessment (US EPA, 1999, 2009a, 2021). Facilities must submit an emergency response plan based on their evaluation every 5 years.

The general methodology outlined in the RMP has been used sporadically in states and municipalities in the US (see examples below). The hazard assessment prescribed in the guidance is similar to a QRA consequence analysis. US EPA guidance for these assessments calls for different levels of analyses depending on the facility type (US EPA, 2009a,c, 2021). In almost all circumstances, the first step of a hazard assessment is to perform a "worst-case analysis," which is a relatively prescriptive screening analysis to determine the extent to which off-site populations could be affected by an accident (US EPA, 2009a). Under certain circumstances, the guidance for hazard assessments allows for further refinement through an "alternative scenario assessment" (US EPA, 2009a,c). Depending on the outcome of the assessment, further action could be required, including accident prevention programs as well as additional hazard assessment, management, and emergency response (US EPA, 2020a).

US EPA has provided industries with a very straightforward computer program to assist with screening calculations using the principles outlined in the US EPA's guidance for off-site consequence analysis (US EPA, 2009c, 2020b). RMP*Comp™ is a high-level screening model with limited consideration of facility-specific information (US EPA, 2020b). ALOHA (discussed

[5] Specific chemicals and threshold quantities are specified in Appendix A to 40 Code of Federal Regulations (CFR) Part 68.130 (US EPA, 2021)

in Sections 3.2 and 4.2 of this report) is another publicly available tool, which is more sophisticated than RMP*Comp™ and can be implemented in RMP analyses to calculate worst-case and alternatives analyses. However, in the context of modern consequence modeling analysis, ALOHA is not as sophisticated as commercial consequence modeling tools, which can be used when more refinement is needed (see Section 4.2). More research is required to understand whether ALOHA can sufficiently capture the characteristics and consequences of LIB failure, or if commercially available consequence modeling tools would better help to accomplish public health protection goals.

It is important to note that these US regulatory risk assessments do not incorporate frequency data and, consequently, do not derive predicted risk (*i.e.*, estimated fatalities), whereas QRAs conducted outside of the US more often calculate frequencies of adverse events and develop quantitative risk estimates. Example RMP hazard assessments, as well as more detailed QRAs that go beyond the provisions of the federal- or state-mandated assessments, are identified below. These publications are publicly available and can be accessed *via* the links in the reference list.

- <u>Example RMP Hazard Assessments:</u>
  - **Medical Device Company (California, US):** This RMP hazard assessment was conducted to support a permit related to the on-site storage of toxic chemicals. The assessment used RMP*Comp™ and ALOHA to model the potential consequences of an accidental release of chemicals stored at the site (EXP and Otis Institute, 2018). The analysis showed that the facility would not "impact public or environmental receptors" (EXP and Otis Institute, 2018).
  - **TowerJazz Semiconductor Facility (Newport Beach, California, US):** An off-site consequence analysis was conducted consistent with the RMP's requirements for a proposed semiconductor facility. Both RMP*Comp™ and ALOHA were used to define the areas of concern for various possible chemical releases and to determine if any facility modifications were needed to provide a proper buffer zone between the facility and the general public (The Planning Center, 2012).
- <u>Example QRAs:</u>
  - **NW Innovation Works (Washington, US):** A QRA was conducted for a proposed methanol plant to "address risks of the proposed plant to onsite employees and the offsite community from an accidental release from the methanol production, storage and vessel loading operations" (AcuTech Consulting Group, 2016). This assessment used PHAST for consequence modeling and SAFETI to calculate risks (AcuTech Consulting Group, 2016).
  - **Tahrir Petrochemicals Complex (Ain Sokhna, Egypt):** A QRA was conducted for a proposed petrochemical plant. Consequence analysis modeling was conducted using PHAST. The methodology presented in this report provides a good example of a full QRA conducted using best practices (WorleyParsons Infrastructure & Environment, 2015).

5.2 LIB-Specific Assessment

DNV GL published the results of its QRA for LIB ESSs in a white paper titled "Quantitative Risk Analysis for Battery Energy Storage Sites" (DNV GL, 2019a). DNV GL has also published a "Technical Reference for Li-ion Battery Explosion Risk and Fire Suppression" document, which outlines some of the underlying principles it used in its QRA for LIB ESSs (DNV GL, 2019b). In the first step of the assessment, DNV GL presents a PHA, which implements methodologies captured by more qualitative frameworks like Hazard Identification (HAZID) or FMEA, to address the potential frequency and severity of risks posed by LIB ESSs (DNV GL, 2019a). DNV GL (2019a) also presents a high-level bowtie analysis. This analysis, which provides more information on the threats of, barriers to, and consequences of LIB failure, is similar in concept to the work conducted in EPRI's bowtie hazard analysis (EPRI, 2019a), but is significantly less detailed.

The DNV GL (2019a) report builds on their high-level bowtie analysis and presents a simplified LIB QRA applicable to workers and the general public. In general, the analysis relies on quantitative information for the probability of failure, the amount of time receptor populations are within a fixed distance to a LIB, and information on how safeguards can reduce the probability of failure. These factors are multiplied together to quantify the likelihood of fatality among workers and the public from a LIB failure. This frequency of failure calculation process was detailed in Section 3.1.1 of this report.

DNV GL's QRA approach lacks details or information on underlying analyses. The QRA is mainly presented in the form of an example assessment applicable to isolated circumstances. In the example assessment, workers are assumed to be on site and residents are assumed to live 30 feet downwind of a 40 MWh ESS that experiences a heating, ventilation, and air conditioning (HVAC) failure. Other information and assumptions used in the analysis are described below.

- **Failure Rate:** DNV GL presents information on the probability of LIB failure associated with electrical, mechanical, and thermal issues, as well as human error (DNV GL, 2019a,b). This information stems from DNV GL's own research as well as information from a CCPS (2015) publication titled "Guidelines for Imitating Events and Independent Protection Layers in Layer of Protection Analysis." The report also presents information on the reduction of failure rates based on the presence of a variety of safeguards related to HVAC failures (DNV GL, 2019a), for which DNV GL relied on the CCPS (2015) publication as well as the IEEE (1995) publication (this information was described in more detail in Section 3.1.1). The safeguards considered included the presence of battery management systems that can isolate battery racks, redundant HVAC units, HVAC failure alarms, and an active fire suppression system.
- **Presence Factor:** The presence factor reflects the proportion of time a human may be within 30 feet of the LIB ESS. As a worst-case scenario, the DNV GL (2019a) assessment assumes a resident is always present 30 feet downwind of the LIB ESS. A worker is assumed to be present in the LIB facility 10% of the time, which is noted to be an overestimate (DNV GL, 2019a). No source is provided for this information, but it seems to reflect reasonable worst-case estimates, based on professional judgment. However, the presence factor should be adjusted on a case-specific basis to reflect population density.
- **Fatality Probability:** In this assessment, the fatality rate was set at 100%. This assumption reflects modeling results that show carbon monoxide will be present in the area of interest (*i.e.*, 30 feet downwind of the LIB ESS facility) in concentrations above the ERPG-3 level for carbon monoxide. DNV GL provides no supporting quantitative modeling information. It can be inferred from the report that DNV GL (2019a) used its proprietary software, PHAST, to model the consequences related to chemical releases (including carbon monoxide,

hydrogen fluoride, hydrogen cyanide, and benzene), flammability, and overpressure. The authors do not present modeling assumption or inputs for their analysis.

The DNV GL (2019a) assessment presents scenario-estimated risks both with and without safeguards. Without safeguards, the risk from an HVAC failure, the individual risk to a LIB technician (*i.e.*, worker), and the risk to the general public all fell in the "intolerable" ranges (*i.e.*, they were above the individual risk benchmarks set by UK HSE [2001, c. 2021b] [described in Section 3.3.2] of 1×10^{-3} for workers and 1×10^{-4} for the general public). When safeguards to protect HVAC integrity were considered, risk to the general public fell into the "tolerable" region and worker risks fell into the "broadly acceptable" range.[6]

The DNV GL (2019a) assessment represents an important first step in developing an approach to quantitatively assessing the possible health consequences of a LIB failure. However, because high-quality, relevant information needed for reliable modeling is still lacking, the results of the analysis are uncertain and are not broadly applicable (*i.e.*, they only relate to a certain size of battery under specific conditions). Additionally, the basis for some of the assumptions in the analysis lack details. Some specific limitations to the evaluation are described below.

- As noted by the authors, the methodology used to characterize failure frequency is generic and the numbers used for failure frequency are very uncertain (DNV GL, 2019b). In terms of reliability data, DNV GL (2019a,b) relied on an HVAC failure rate (from overheating due to a process control failure) of 1 in 10 years. The applicability of this value to LIB HVAC systems is not clear. In addition, DNV GL (2019a,b) cites reliability data from the 1995 version of "IEEE Recommended Practice for the Design of Reliable and Commercial Power Systems" (IEEE, 1995), even though an updated version was published in 2006.
- The QRA assumed that the LIB ESS being assessed consisted of several hundred racks (multiple containers) of LIBs that can store 40 MWh each. It is unclear from the reported modeling how many cells/racks fail or are affected and how that relates to the rate of carbon monoxide release.
- The report does not provide details about the modeling that was used to predict chemical air concentrations downstream of the LIB failure, simply stating that under a worst-case scenario, carbon monoxide "could go" 30 feet downwind of the LIB ESS (DNV GL, 2019a). It is unclear what the concentration of carbon monoxide (or other chemical releases) might be at distances further from the LIB ESS following a LIB failure. This is a limiting assumption, because the assessment is based on the fact that the fatality rate would be 100% at this 30-foot distance. Other distances and health endpoints were not examined. It would be useful to include the modeled distance at which carbon monoxide and other chemicals would not be considered a risk with respect to fatality or health endpoints. This would provide some important perspective on the extent of the area of concern after a LIB failure.
- The QRA only examined chemical releases. The potential health impacts from overpressure, flammability, and heat radiation were not evaluated. In the QRA, DNV GL (2019a) calculated individual risk for workers and the general public, then compared these to the risk

[6] Without safeguards, the calculated probability of a fatality of a worker (technician) is 0.01 per year and the probability of a fatality among the public is 0.01 per year. With safeguards, the calculated probability of a fatality of a worker (technician) is 1×10^{-6} per year and the probability of a fatality among the public is 1×10^{-5} per year.

benchmarks established by UK HSE (2001). While this is a common approach in QRA, additional analyses may be more useful for QRA application in the US. For example, it may be useful to know the population density around a LIB ESS and how that could influence total fatality. Also, as noted earlier, it would be useful to know potential health impacts other than fatality and how those effects change at different distances from a LIB ESS.

6
DATA GAPS AND UNCERTAINTIES

QRA is a well-established methodology used routinely in a variety of industries to understand potential risks to workers and surrounding communities associated with accidental chemical releases, fires, and explosions from facilities and operations. Because these risks are shared between industrial accidents, the concepts that underlie QRA seem well suited to quantify the risks and potential impacts of LIB failures. However, more investigation is needed to understand how this framework can be used to make reliable and actionable decisions specific to potential large-format LIB risks. Some key areas requiring more research and analysis include the following.

- QRA relies heavily on being able to quantify accident rates. However, frequency or occurrence data specific to LIBs are limited or unavailable. The only existing identified QRA used reliability data from other industries, such as electrical equipment data (IEEE, 1995) or data from various chemical process industries (CCPS, 2015). Due to limited LIB-specific reliability data, it is unclear whether existing frequency analysis assessments would be reflective of real-world occurrence probabilities, especially because the presence of LIB ESSs is rapidly increasing with the demand for new energy storage facilities. The NFPA (2020b) cites failure rates for LIBs between 1 in 10 million and 1 in 40 million; however, the NFPA itself estimates the failure rate per LIB ESS to be much higher, stating that "as many as 1 in 100 containers on average could experience a failure in one of its battery cells" (NFPA, 2020b).
- There are a plethora of available tools, albeit mostly proprietary, that can be used to support the different components of QRA. Existing hazard tools seem particularly well suited for understanding the threats of, barriers to, and consequences of LIB failures. However, it is not yet clear how well existing consequence analysis modeling software will perform for assessing large-format LIBs specifically. While there are similarities between LIB fires and other types of fire, including the types of chemicals released, infrequency of incidents, *etc*., which likely make these models useful, the unique aspects of LIB failures (*i.e.*, unique chemical emission rates, the potential for multi-cell/module/rack propagation, and extended active burning or reignition potential) will need to be further explored in the context of these tools. Many of the more sophisticated tools will likely require optimization to accommodate LIB-specific data, especially related to chemical emissions and fire dynamics. The best approach may be leveraging existing models to develop a LIB-specific tool.
- Some research has already been conducted to characterize the nature and extent of chemical releases from LIB fires. Many of these studies have been limited to single-cell LIBs and have not assessed container or facility scales as the investment cost is prohibitive. This information is critical for reliable modeling of chemical concentrations that can cause adverse effects downwind of a LIB failure. With more information, there may be ways to streamline risk analyses and only focus on those chemicals that would pose the most significant risk.
- Far less work has been done to characterize the overpressure intensity associated with LIB failure. More research in this area is needed to better understand how LIB explosions may

compare to other types of industrial accidents, and to determine if current models can accurately predict associated effects.

- Global regulatory agencies have established annual acceptable fatality rates associated with industrial accidents when citing new facilities and for general land use planning. To date, the US has assessed possible fatality rates associated with accidents more qualitatively and has not yet established any "bright line" criteria. However, a series of health-based benchmarks for chronic chemical exposures has been established by US EPA (2020c). These benchmarks are not always based on fatality and, in fact, are usually based on the manifestation of adverse health effects (even if these are not fatal) (US EPA, 2020c). For the siting of LIB ESSs in the US, some thought will need to be given to whether a quantitative or qualitative approach should be implemented for assessing risk for such facilities.
- Consistent with QRA methodology, this report focuses on the immediate human health consequences during and in the immediate aftermath of a LIB failure. Therefore, this report has not meaningfully contemplated any long-term risks of LIB fire or explosions, such as metal particulates/residues that can settle in/and around buildings and nearby residences after emergency events, or the infiltration of metals and/or solvents into groundwater during fire suppression. These ancillary risks require further investigation.

7
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