BATTERY ENERGY STORAGE SYSTEMS EXPLOSION HAZARDS

October 2021

TABLE OF CONTENTS

INTRODUCTION

Lithium ion battery energy storage systems (BESSs) are increasingly used in residential, commercial, industrial, and utility systems due to their high energy density, efficiency, wide availability, and favorable cost structure. Unfortunately, a small but significant fraction of these systems has experienced field failures resulting in both fires and explosions. A comprehensive review of these issues has been published in the EPRI Battery Storage Fire Safety Roadmap (report 3002022540 [1]), highlighting the need for specific efforts around explosion hazard mitigation. EPRI also maintains a database of BESS failures [2].

Some BESS failures have resulted in significant consequences. These incidents have been widely reported in news media. In 2019, a 2-MWh lithium nickel manganese cobalt oxide (NMC) BESS in Surprise, Arizona, experienced an explosion that blew doors off their hinges, caused chemical and thermal burns to firefighters in full protective gear, and threw a firefighter 70 ft [3]. In 2020, an explosion at a 10-MWh system launched equipment fragments 70 ft in a Liverpool, UK, neighborhood [4]. In 2021 in China, while firefighters were focused on suppressing fire at one half of a 25-MWh lithium iron phosphate (LFP) BESS installation, an unexpected explosion occurred in the other half, killing two firefighters [5]. Continued research into BESS explosion hazards is needed, particularly better characterization of the quantity and composition of flammable gases released and the factors that cause a failure to lead to fire or explosion.

This white paper describes the basics of explosion hazards and the circumstances under which explosion of lithium ion BESSs may occur. The paper also discusses the quantity and species of flammable gases produced by thermal runaway and demonstrates a simple formula to determine how much energy stored in failing cells is required to create an explosion hazard for a given room volume. Owners, operators, building officials, and emergency responders can use this information to determine if there is a potential explosion hazard for a given quantity of batteries in a given volume.

BACKGROUND

GENERAL FIRE AND EXPLOSION HAZARDS

Both fires and gas explosions require fuel, oxygen, and an ignition source (heat), as shown in Figure 1. Some useful definitions follow:

- ***Explosion:*** Sudden violent release of energy usually accompanied by the generation of high temperatures and release of high-pressure gas. Types include
  - ***Deflagration*** – subsonic propagation of the combustion zone
  - ***Detonation*** – supersonic propagation of the combustion zone
- ***Overpressure:*** Transient air pressure, such as the shock wave from an explosion, which is greater than the surrounding atmospheric pressure.
- ***Lower flammability limit (LFL):*** Minimum concentration of fuel that can support a flame; fuel/air mixtures below the LFL are too lean to propagate a flame.
- ***Upper flammability limit (UFL):*** Maximum concentration of fuel that can support a flame; fuel/air mixtures above the UFL are too rich to propagate a flame.
- ***Stoichiometric concentration:*** Concentration where fuel is balanced with the oxygen in the available air to allow for complete combustion. The stoichiometric concentration is between the LFL and UFL.
- ***Enclosure:*** For BESS applications, enclosure refers to a confined space such as a battery module, an enclosed rack, a room, or an entire building.

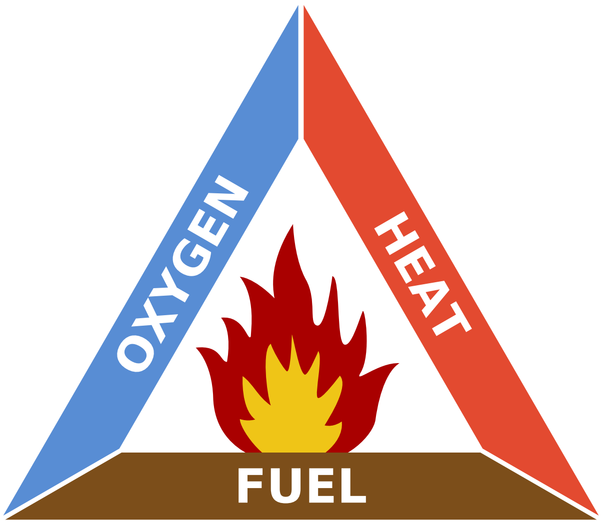

Figure 1 – Fire triangle

Although fires and gas explosions both contain fuel and air, several factors influence whether one or the other occurs, including the mixture of the fuel, confinement, and congestion. For a gas explosion to occur, a volume must exist where fuel and air are premixed and are within the flammability limits (LFL and UFL). Additionally, gas explosions require either confinement or congestion to create an overpressure. Confinement is provided by being located inside an enclosure. Congestion occurs when obstacles – such as pipes, ducts, conduit, and structural members – serve to accelerate the flame, leading to possible confinement effects.

The theoretical worst-case overpressure from a deflagration-type gas explosion is known as the maximum adiabatic explosion pressure (P_{max}). This occurs when a spatially uniform mixture with an optimum (near stoichiometric) mixture of fuel and air is burned inside a constant volume vessel (one that does not expand or vent to the outside). Since many deflagrations cause a large increase in temperature (often over 3000°F, ~1649°C), the overpressure for a deflagration in a sealed vessel exceeds 100 psig for most gases. However, this overpressure does not typically develop in common buildings, as most buildings fail at pressures below 1 psi. As vents, doors, windows, walls, or roofs fail due to overpressure, the pressure will be limited because the increased vent area allows excess gas to escape. Even with some venting, though, overpressure events can cause significant structural damage and possible collapse of the building itself and neighboring structures.

Since a small amount of gas will greatly expand due to a deflagration, it is possible to have a damaging explosion even when only a small fraction of the enclosure contains a flammable mixture. Known as a *partial volume deflagration*, this occurs when a fraction of the enclosure volume contains a flammable mixture and burning of this mixture is sufficient to produce a damaging overpressure.

BATTERY-SPECIFIC EXPLOSION HAZARDS

Large lithium ion battery systems such as BESSs and electric vehicles (EVs) pose unique fire and explosion hazards. When a lithium ion battery experiences thermal runaway failure, a series of self-reinforcing chemical reactions inside the lithium ion cell produce heat and a mixture of flammable and toxic gases, called battery vent gas. Cells can act as ignition sources, since their temperature can exceed 1600°F (~871°C), and they can eject glowing hot particles. Electrical arcing can also cause ignitions. In systems that contain multiple cells, thermal runway of one cell can induce thermal runaway in neighboring cells through conduction between adjacent cells as well as convection and radiation from hot battery vent gases. Depending on system design, thermal runaway may propagate from a single cell to the surrounding module, then into the rack, and finally to other racks and outside the system. Without proper mitigation, this can lead to fire, explosion, and/or toxic gas release consequences. The following section characterizes the explosion risk for lithium ion batteries.

BESS EXPLOSION RISKS

The magnitude of explosion hazards for lithium ion batteries is a function of the composition and quantity of flammable gases released during thermal runaway. Gas composition determines key properties such as LFL, burning velocity, and maximum explosion pressure directly related to the severity of an explosion event. Battery vent gas consists primarily of hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2) as well as an assortment of hydrocarbons such as methane (CH_4), ethylene (C_2H_4), and propane (C_3H_8). A number of studies have published data about battery vent gas compositions [6]–[14]. The quantity and composition of battery vent gas depends on the cell geometry, cell chemistry, cell form factor, state of charge (SOC) at failure, and how the battery failed.

The quantity of gas released will determine what types of deflagrations are possible given a certain enclosure volume. Generally, cells at a higher SOC release more flammable gas. The quantity of gas released by a cell in thermal runaway is commonly measured in mass,

moles, or volume at standard conditions such as standard ambient temperature and pressure (SATP), which is gas at 1 bar of pressure and 25°C (77°F). The gas volume released per cell energy (*r*) can be calculated by dividing the volume of gas released by the energy of the cell in watt-hours (Wh). Using the gas volume released per cell energy allows for estimation of the volume that can be released by a system of any size. For example, if a single cell test measures 0.6 L/Wh at SATP, then thermal runaway of every cell in a 1000-Wh module would be expected to release 600 L of gas at SATP.

LFL, UFL, maximum explosion pressure (P_{max}), and other important flammability properties such as maximum burning velocity (S_u) all depend on the composition of the battery vent gas mixture. Ranges provided by Archibald [11] based on a review of 21 compositions of battery vent gas taken from various cells at 100% SOC are shown in Table 1. These values come from experiments using NMC, LFP, lithium cobalt oxide (LCO), and lithium nickel cobalt aluminum oxide (NCA) chemistries in form factors including prismatic, cylindrical, and pouch. Given the limited amount of data available for different chemistries and form factors, it is premature to predict general trends in gas properties by chemistry or form factor. It is recommended that experimental data from the actual cells be used whenever available.

Table 1 – Lithium ion cell vent gas statistical properties of 21 varieties at 100% SOC (Archibald [11])

Parameter	Symbol	Mean	Min	Max	Units
Gas Volume Released per Cell Energy	r	0.40	0.12	0.63	l/Wh
Lower Flammability Limit	LFL	10%	5%	13%	
Upper Flammability Limit	UFL	47%	27%	60%	
Stoichiometric Gas Concentration	X_{st}	21%	11%	30%	
Maximum Pressure	P_{max}	7.85	6.44	8.95	bara
Burning Velocity	S_u	0.48	0.22	0.75	m/s

The minimum concentration of fuel capable of causing a partial volume deflagration (X_{pvd}) can be expressed as a ratio between the minimum volume of fuel (V_{f_pvd}) and the volume of the entire enclosure ($V_{enclosure}$) using the equation $X_{pvd}=V_{f\_pvd}/V_{enclosure}$. The value for X_{pvd} can be calculated using the stoichiometric fuel concentration (X_{st}), maximum explosion pressure (P_{max}), threshold absolute pressure that is considered damaging (P_{dam}), and initial absolute pressure (P_0) [15], [16]:

$$X_{pvd} = \frac{V_{f\_pvd}}{V_{enclosure}} = X_{st}\left(\frac{P_{dam} - P_0}{P_{max} - P_0}\right)$$

Using LFL along with the gas volume released per cell energy (r), it is possible to calculate the energy storage required (E_(sys_LFL)) to reach LFL if the gas were well mixed in the entire enclosure volume ($V_{enclosure}$):

$$EV_{LFL} = \frac{E_{sys\_LFL}}{V_{enclosure}} = \frac{LFL}{r}$$

This equation can also be used to calculate the energy stored required to reach UFL if the gas is well mixed in the entire enclosure volume:

$$EV_{UFL} = \frac{E_{sys\_UFL}}{V_{enclosure}} = \frac{UFL}{r}$$

Finally, the stored energy that would be required to cause a partial volume deflagration can be calculated. This is the minimum amount of energy stored in failing lithium ion cells that could theoretically cause a damaging explosion with a pressure of P_{dam}:

$$EV_{pvd} = \frac{E_{sys\_PVD}}{V_{enclosure}} = \frac{X_{pvd}}{r} = \frac{X_{st}}{r}\left(\frac{P_{dam} - P_0}{P_{max} - P_0}\right)$$

For example, for a cell with r = 0.6 L/Wh, LFL = 9%, UFL = 46%, and X_{pvd}=0.06%, it is possible to calculate the limiting energy storage per volume to reach partial volume deflagration, LFL, and UFL limits:

$$EV_{pvd} = \frac{E_{sys\_pvd}}{V_{enclosure}} = \frac{X_{pvd}}{r} = \frac{0.0006}{0.6L/Wh} = 0.001\frac{Wh}{L} = 0.028\frac{Wh}{ft^3}$$

$$EV_{LFL} = \frac{LFL}{r} = \frac{0.09}{0.6L/Wh} = 0.15\frac{Wh}{L} = 4.2\frac{Wh}{ft^3}$$

$$EV_{UFL} = \frac{LFL}{r} = \frac{0.46}{0.6L/Wh} = 0.77\frac{Wh}{L} = 22\frac{Wh}{ft^3}$$

This calculation can be made for the gas compositions provided by Archibald [11] to determine ranges for the minimum amount of energy stored per enclosure volume required for partial volume deflagration, LFL, and UFL (Table 2). This is done assuming that the pressure considered to be damaging (P_{dam}) is 0.02 barg or 0.29 psig.

Table 2 – Partial volume deflagrations, LFL and UFL calculated from empirical statistical data of 21 lithium-ion cell variants at 100% SOC

Parameter	Symbol	Mean	Min	Max	Units
Energy per Volume for Partial Volume Deflagration	EV_{pvd}	0.05	0.02	0.12	Wh/ft^3
Energy per Volume for Lower Flammability Limit	EV_{LFL}	6.6	3.3	16.3	Wh/ft^3
Energy per Volume for Upper Flammability Limit	EV_{UFL}	34.8	16.7	81.7	Wh/ft^3

EXAMPLES

The following section describes three instances of explosions caused by failures in lithium ion BESSs.

Experiment at University of Texas, Austin

At the University of Texas (UT) at Austin, an experiment was conducted with a single 94-Ah cell in a closet, as shown in Figure 2. Even though the cell was not capable of generating enough gas to fill the entire closet to LFL, a partial volume deflagration occurred and ruptured the closet before the cell had even finished venting flammable gas [11].

Electric Vehicle Failure in Montreal, Canada

In Montreal, Canada, a Hyundai Kona EV with a 64-kWh battery went into thermal runaway in a single car garage. The garage was estimated to have a volume of 2688 ft^3. This explosion caused damage to the garage and threw the garage door across the street (Figure 3) [17].

Figure 3 – Explosion Resulting from 64-kWh Hyundai Kona EV thermal runaway in a single car garage (photo courtesy Radio-Canada/ Mathieu Daniel Wagner) [17]

Figure 2 – Time lapse images of mannequin outside of drywall closet during explosion caused by single cell partial volume deflagration [11]

McMicken BESS in Surprise, Arizona

The final example is the McMicken BESS incident in Surprise, Arizona. In this incident, a single battery rack went into thermal runaway, filling the container with flammable gas. When first responders opened the container to investigate the failure, the incoming oxygen along with the presence of an ignition source caused a large explosion sufficient to blow two doors off their hinges and throw a firefighter 70 ft (Figure 4) [18].

Figure 4 – Image of lithium ion thermal runaway aftermath at Arizona energy storage site (photo courtesy of Peoria Fire-Medical Department) [18]

ANALYSIS

Table 3 shows the energy capacities and enclosure volumes for the examples described above. Compared to the values in Table 2, all these systems have sufficient energy density to make partial volume deflagrations possible.

Table 3 – Energy and Volume Data from Example Explosions

Example	Energy (kWh)	Enclosure Volume (ft³)	Volumetric Energy Density (Wh/ft³)
Single Cell in Closet	0.348	99	3.52
EV in Garage	64	2688	23.81
McMicken System (single rack)	74	~6000	~12
McMicken System	2000	~6000	~333

These examples are plotted on the graph in Figure 5, along with the minimum energy densities necessary for partial volume deflagrations, LFL, and UFL from Table 2. The minimum energy densities are represented by colored bands to show the statistical variation in gas production based on the available data. For example, the yellow color band represents the range for the minimum energy capacity per volume required to produce a partial volume deflagration. Anything above this colored band can also produce a partial volume deflagration.

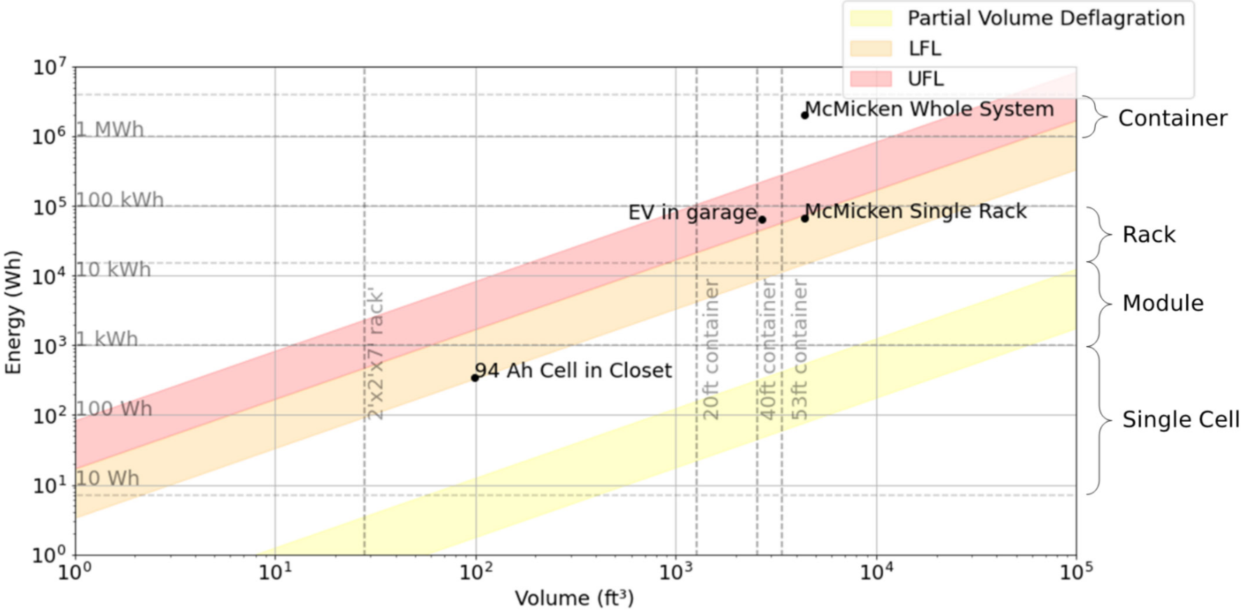

Figure 5 – Ranges of energy stored per enclosure volume required for partial volume deflagration, LFL, and UFL

For a given energy capacity and enclosure volume, Figure 5 can be used to develop a qualitative understanding of the inherent explosion risk in a system. For example, consider a 40-ft ISO container. With even a single 94-Ah cell, the energy density lies above the yellow band, indicating that there is a risk of partial volume deflagration should the cell fail into thermal runaway. As more cells are installed in the container, the energy density increases, moving the system from the yellow to the orange and red bands. When there is enough energy to reach LFL in the entire room volume, the risk of an explosion increases. This is because if the entire room volume can be filled to LFL, then an ignition source anywhere in the enclosure can start a deflagration. If the energy is sufficient to reach UFL in the entire volume, then the probability of an explosion again increases since introducing air later in the event could trigger an explosion. The McMicken explosion may be an example of this type of event.

Figure 5 also shows ranges for energy capacity for typical single cells, modules, racks and containers on the Y-axis. On the X-axis, volumes for a rack enclosure as well as 20-ft, 40-ft, and 53-ft containers are provided assuming that the containers are empty. These enclosure and container volumes can be used to estimate how much energy is required for different explosions given a certain container size. For example, for the 20-ft container, some single cells can cause partial volume deflagrations. For this same container, any module can cause a partial volume deflagration and – depending on the size of the module and gas composition – some modules could cause the entire container to reach LFL. A full rack in the 20-ft container can cause a partial volume deflagration; most full racks can reach LFL and many can exceed UFL for the entire container.

It is notable that all examples plotted in Figure 5 lie well above the partial volume deflagration band, indicating that energy densities in commercial energy storage systems are sufficiently high to generate explosions in the event of thermal runaway failure. However, though this graph shows that damaging explosions are possible; the actual distribution of gas in the real incident is more complex than these simplified cases. Experimental data from the specific cell type are necessary to understand gas evolution in detail. Additionally, the system design must be analyzed from a fire and explosion protection perspective to fully understand risk. Explosion mitigation solutions are discussed in the next section.

EXPLOSION MITIGATION SOLUTIONS

The previous section has shown that explosions are possible for many BESS installations. Building code requirements have not been sufficient to mitigate BESS explosion hazards given rapidly evolving technology and the time it takes to understand hazards, update older codes, and adopt new codes. For some existing installations, new understanding and industry developments within the BESS safety space may warrant reevaluation of explosion hazards and possible development of new safety practices or retrofitting of additional safety systems.

The goal of explosion mitigation is to avoid injuries and minimize other collateral damage due to explosions. To accomplish this, a hazard mitigation analysis (HMA) should be conducted. EPRI has published the Energy Storage Integration Council (ESIC) *Energy Storage Reference Fire Hazard Mitigation Analysis* (3002017136 [19]) document, which provides some guidance on HMAs. An HMA helps to determine if safety systems are sufficient to prevent or mitigate an explosion. The existence of safety systems, including fire suppression, does not mean that the explosion hazard has been properly mitigated. To assess the possibility of an explosion, analysis should determine whether flammable gas exhaust systems are sufficient to prevent damaging partial-volume or full-volume deflagrations. Test data can be useful to evaluate whether thermal runaway will propagate and what quantities of gas will be produced. The UL 9540A Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems provides a standard for such testing. BESS cells, modules, and racks – which are engineered to prevent the propagation of thermal runaway from cell to cell, module to module, and rack to rack – can be useful in limiting the volume of flammable gas released and can reduce the explosion hazard.

The National Fire Prevention Association (NFPA) Standard on Explosion Prevention Systems (NFPA 69) provides requirements for ventilation that can be used to exhaust flammable gases and thereby limit the concentration of flammable gases below LFL to avoid explosions. According to NFPA 69, if an explosion cannot be prevented, the explosion pressure must be reduced using venting to prevent structural collapse. NFPA 68 Standard on Explosion Protection by Deflagration Venting provides requirements for vents that allow pressure to be relieved should an explosion occur. To assess human exposure, the analysis should consider the occupancy of the

structure, ability to evacuate nearby populations, and emergency response plans. Sufficient distance in terms of the structure's siting should be provided to prevent injury and damage to nearby people and buildings. EPRI's *Battery Storage Explosion Hazard Calculator* (3002021076 [20]) provides tools for preliminary calculations for NFPA 68, NFPA 69, and outdoor pressure and thermal hazards.

CONCLUSIONS

Results of the analysis in this white paper show that for a 40-ft ISO container, thermal runaway of a single cell can produce enough gas to pose a partial volume deflagration risk. Energy densities of commercial BESSs are much higher, which increases explosion risk in the event of thermal runaway failures. The data and figures provided allow for a qualitative assessment of explosion risk for a given energy capacity and enclosure volume.

Continued research into BESS explosion hazards is needed, particularly better characterization of the quantity and composition of flammable gases released and how that release depends on chemistry, form factor, SOC, and failure mode. Although it is possible to develop models of explosion hazards, these models have not been validated against experimental data. Since explosion hazards greatly depend on the properties of the gas mixture involved, explosion experiments using battery vent gas are required to validate explosion models. The limits provided here define the minimum theoretical values required to produce specific explosion conditions. Further modeling and experiments would be necessary to more accurately determine practical limits at which explosions are expected to occur. Finally, there is a growing need for better guidance to define best practices and accepted performance for BESS explosion mitigation systems.

REFERENCES

1. *Battery Storage Fire Safety Roadmap.* EPRI, Palo Alto, CA: 2021. 3002022540.
2. *BESS Failure Event Database.* EPRI, July 22, 2021. https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database
3. M. B. McKinnon, S. DeCrane, and S. Kerber, *Four Firefighters Injured in Lithium-Ion Battery Energy Storage System Explosion - Arizona*, Underwriters Laboratories™, UL Firefighter Safety Research Institute: 2020, p. 66.
4. A. Colthorpe, "Fire at 20MW UK battery storage plant in Liverpool," *Energy Storage News*, accessed Aug. 3, 2021. https://www.energy-storage.news/news/fire-at-20mw-uk-battery-storage-plant-in-liverpool
5. "Accident analysis of the Beijing lithium battery explosion which killed two firefighters," *CTIF – International Association of Fire and Rescue Services*, accessed Aug. 3, 2021. https://www.ctif.org/news/accident-analysis-beijing-lithium-battery-explosion-which-killed-two-firefighters
6. A. R. Baird, E. J. Archibald, K. C. Marr, and O. A. Ezekoye, "Explosion hazards from lithium-ion battery vent gas," *Journal of Power Sources*, Vol. 446, p. 227257, Jan. 2020. doi: 10.1016/j.jpowsour.2019.227257
7. C. Essl, A. W. Golubkov, E. Gasser, M. Nachtnebel, A. Zankel, E. Ewert, A. Fuchs, "Comprehensive Hazard Analysis of Failing Automotive Lithium-Ion Batteries in Overtemperature Experiments," *Batteries*, Vol. 6, No. 2, June 2020. doi: 10.3390/batteries6020030
8. C. Essl, A. W. Golubkov, and A. Fuchs, "Comparing Different Thermal Runaway Triggers for Two Automotive Lithium-Ion Battery Cell Types," *J. Electrochem. Soc.*, Vol. 167, No. 13, p. 130542, Oct. 2020. doi: 10.1149/1945-7111/abbe5a
9. H. Webster, T. Maloney, S. Summer, D. Dadia, S. Rehn, and M. Karp, *Summary of FAA Studies Related to the Hazards Produced by Lithium Cells in Thermal Runaway in Aircraft Cargo Compartments*, U.S. Federal Aviation Administration, DOT/FAA/TC-16/37, June 2016.
10. R. W. Kennedy, K. C. Marr, and O. A. Ezekoye, "Gas release rates and properties from Lithium Cobalt Oxide lithium ion battery arrays," *Journal of Power Sources*, Vol. 487, p. 229388, Mar. 2021. doi: 10.1016/j.jpowsour.2020.229388
11. E. J. Archibald, *Fire & explosion hazards due to thermal runaway propagation in lithium-ion battery systems*, PhD Thesis, 2021.
12. A. W. Golubkov, S. Scheikl, R. Planteu, G. Voitic, H. Wiltsche, C. Stangl, G. Fauler, A. Thaler, and V. Hacker, "Thermal runaway of commercial 18650 Li-ion batteries with LFP and NCA cathodes – impact of state of charge and overcharge," *RSC Advances*, Vol. 5, No. 70, pp. 57171–57186, 2015. doi: 10.1039/C5RA05897J

13. A. W. Golubkov, D. Fuchs, J. Wagner, H. Wiltsche, C. Stangl, G. Fauler, G. Voitic, A. Thaler, and V. Hacker, "Thermal-runaway experiments on consumer Li-ion batteries with metal-oxide and olivin-type cathodes," *RSC Advances*, Vol. 4, No. 7, pp. 3633–3642, 2014. doi: 10.1039/C3RA45748F
14. V. Viswanathan and M. Paiss, "Safety Comparison of Li-ion Battery Technology Options for Energy Storage Systems," *IEEE Smart Grid, Safety Comparison of Li-ion Battery Technology Options for Energy Storage Systems*, Aug. 2020, accessed Apr. 01, 2021. https://smartgrid.ieee.org/newsletters/august-2020/safety-comparison-of-li-ion-battery-technology-options-for-energy-storage-systems
15. R. A. Ogle, "Explosion hazard analysis for an enclosure partially filled with a flammable gas," *Process Safety Progress*, Vol. 18, No. 3, pp. 170–177, 1999. https://aiche.onlinelibrary.wiley.com/doi/10.1002/prs.680180310
16. R. Zalosh, "Flammable Gas and Vapor Explosions," in *SFPE Handbook of Fire Protection Engineering*, eds., M. J. Hurley, D. Gottuk, J. R. Hall, K. Harada, E. Kuligowski, M. Puchovsky, J. Torero, J. M. Watts Jr., and C. Wieczorek. New York, NY: Springer, 2016, pp. 2738–2765. doi: 10.1007/978-1-4939-2565-0_69
17. G. H. Ruffo, "Hyundai Kona Electric Explodes, Blows Hole in Garage: Cause Unknown," INSIDE EVs, July 28, 2019. https://insideevs.com/news/362202/hyundai-kona-electric-explodes-canada/
18. J. Roman, "ESS SPECIAL REPORT: Learning from Surprise," *NFPA Journal*, July 26, 2021. https://www.nfpa.org/News-and-Research/Publications-and-media/NFPA-Journal/2021/Fall-2021/Features/ESS
19. *Energy Storage Integration Council (ESIC) Energy Storage Reference Fire Hazard Mitigation Analysis.* EPRI, Palo Alto, CA: 2019. 3002017136.
20. *Battery Storage Explosion Hazard Calculator v1.0.* EPRI, Palo Alto, CA: 2021. 3002021076.

ACRONYMS

BESS	Battery Energy Storage System
EV	Electric Vehicle
HMA	Hazard Mitigation Analysis
ISO	International Organization for Standardization
LCO	Lithium Cobalt Oxide (battery)
LFL	Lower Flammability Limit
LFP	Lithium Iron Phosphate (battery)
NCA	Lithium Nickel Cobalt Aluminum Oxide (battery)
NFPA	National Fire Prevention Association
NMC	Lithium Nickel Manganese Cobalt Oxide (battery)
SATP	Standard Ambient Temperature and Pressure
SOC	State of Charge
UFL	Upper Flammability Limit

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI.

THE ELECTRIC POWER RESEARCH INSTITUTE (EPRI) PREPARED THIS REPORT.

Note

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

EPRI RESOURCES

Dirk Long, *Senior Technical Leader*
650.855.2662, dlong@epri.com

Energy Storage

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI members represent 90% of the electricity generated and delivered in the United States with international participation extending to nearly 40 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; Dallas, Texas; Lenox, Mass.; and Washington, D.C.

Together . . . Shaping the Future of Energy™

3002022706 October 2021

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

© 2021 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute and EPRI are registered marks of the Electric Power Research Institute, Inc. in the U.S. and worldwide.