# BESS Part 4: Flammable Hazards of BESS Failures

By Aníbal Morones, PhD

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This article is the fourth in BakerRisk's six-part series on Battery Energy Storage System (BESS) hazards (previous articles can be found here). The first article described ways in which lithium ion (Li-ion) batteries can fail, followed by a discussion of challenges assessing the reliability of such a rapidly-evolving technology. The third article discussed potential mitigation strategies for BESS facilities. This article discusses the consequences of catastrophic failure in a BESS.

The combustible materials used to build battery cells are contained in a casing that prevents exposure to air. Nevertheless, under certain conditions, batteries can produce flammable and/or explosive atmospheres and pose related risks. This article describes basic concepts of combustion that aid in the analysis of consequences of fires and explosions associated with BEES failures.

During normal operation, useful energy is cycled in and out of a battery cell when powering a load or recharging the battery. Some heat is generated inside battery as a byproduct of the reversible reactions that facilitate such cycling of energy. Thermal management is key to the battery health, as high temperature enables irreversible degrading reactions that release more heat and permanently affect the performance. Improper dissipation of generated heat, or an external heat source are just two of the several modes of failures (for more information click here) that can generate a build-up of temperature in a battery cell. Once the temperature rises above the thermal runaway critical point, the heat is generated spontaneously through the aforementioned irreversible reactions at a quicker rate that it can be dissipated until destruction of the battery occurs and possibly the rupture of the casing. The strength of the casing and the internal gas volume within are factors in burst intensity. The weakest of the structural components and connections in the casing will control the pressure at which the casing fails. As battery casings are not typically designed as pressure vessels and the interior volume is mostly occupied by solids, the bursting of casing itself is unlikely to be of major consequence.

With the battery casing integrity lost, air may come in contact with flammable materials, such as the electrolyte solvent and gaseous decomposition products formed during the thermal runaway. The released gas is composed of a mixture of hydrogen, carbon dioxide, and carbon monoxide with traces of light hydrocarbons. Exposing these flammable materials into air means that all the elements (fuel, oxidizer, and a competent ignition source) required for a fire are present. Fire increases the chances of cascading runaway, but it is not it a necessary condition. Cascading runaway was observed in a severe incident where a clean fire suppressant agent prevented open flames to exist.[1,2]

Figure 1 examines different paths in which the materials expelled from a Li-ion cell may be transformed into one or more damaging effects through different modes of combustion. Strictly speaking, all flames happen in the gas phase, even if the fuel is originally in a different state. If the fuel is already in gas phase and thoroughly mixed with air, the combustion regime is referred to as a pre-mixed flame. When fuel and air are physically separate, the flame establishes near the contact surface of the reactants. This mode of combustion is called a diffusion flame. A diffusion flame may supply the heat necessary to gasify and/or melt the fuel entering the reaction zone if the fuel is not in the gas phase already. Pool fires, jet fires, and candle flames are examples of diffusion flames. See Figure 2 for examples of diffusion and premixed flames in the context of battery failures.

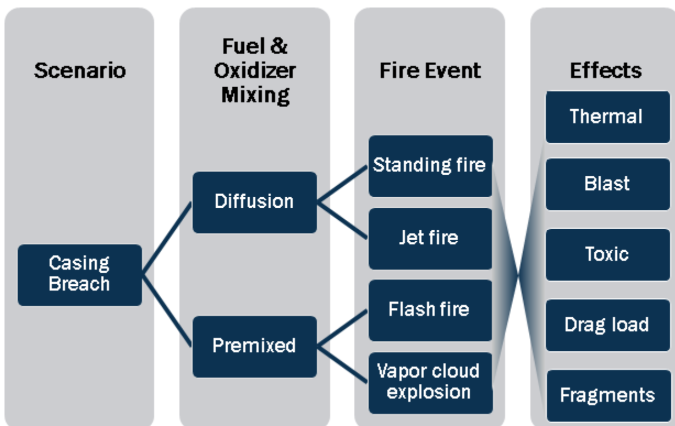


**Figure 1. Failure hazards of Li-ion batteries**

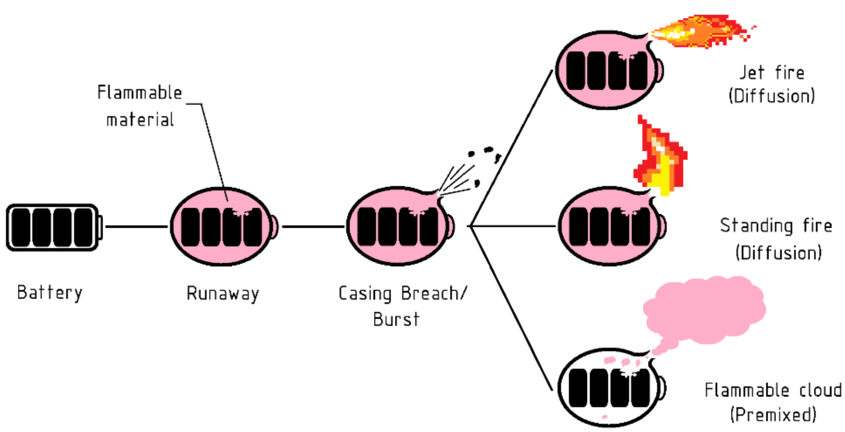


**Figure 2. A possible line chain of events during runaway**

[1] DNV GL Energy Insights USA, McMicken Battery Energy Storage System Event Technical Analysis and Recommendations, in Technical Support for APS Related to McMicken Thermal Runaway and Explosion. 2020.

[2] McKinnon, M.B., S. DeCrane, and S.I. Kerber, *Four Firefighters Injured In Lithium-Ion Battery Energy Storage System Explosion - Arizona*. 2020, UL Firefighter Safety Research Institute.

Pre-mixed flames can also be formed during battery failures. If a battery cell off-gases decomposition products that are allowed to mix with ambient air prior to finding an ignition source, then a flammable premixed cloud may be created. In pre-mixed flames, the reactants are already in contact and therefore the flame advances unhindered by the intermediate steps such as mixing, and/or evaporation sometimes present in diffusion flames. In addition, the flame front of pre-mixed flames is not bound to the contact surface of fuel and oxidizer, so it can grow to encompass the extent of the reactant field. This readiness for reaction means that pre-mixed flammable clouds have the potential to convert the chemical energy into thermal energy very quickly resulting in a flash fire or a deflagration explosion[3]. Deflagrations are pre-mixed flames that stay subsonic, such as flash fires and vapor cloud explosions. Thermal run-away in Li-ion batteries has the potential to produce deflagrations.

Flash fires are typical of clouds consumed in open, uncongested spaces. No overpressure or blast is expected from a flash fire. Flashfires have been observed in prior catastrophic battery failures (e.g. *Electric bus bursts into flames, sets nearby vehicles on fire in China* | South China Morning Post (scmp.com)).[4]

Under certain conditions that can create sufficient turbulence, the combustion of premixed flammable clouds can occur so rapidly that a vapor cloud explosion occurs producing a perceptible blast wave. Reactivity, concentration, and turbulence strongly influence the rate at which a deflagration consumes the available fuel and oxidizer (usually air). The energy associated with unintended deflagrations scales the size of the flammable cloud. If the cloud is large enough to engulf nearby structures and equipment, the interaction with these objects could intensify the reaction rate. In general, any obstruction or body immersed in the cloud stirs turbulence as the deflagration front wraps around it. These objects are collectively called "congestion" in the context of unintended flammable releases. The more congestion, the more turbulence is created resulting in quicker energy release resulting higher overpressures.

A vented deflagration is a special type of vapor cloud explosion that occurs within an enclosed structure, which ultimately fails (hopefully in a designed fashion) and allows the flammable cloud/combustion event to vent to the outside environment. This venting relieves the pressure applied to the inside of the structure. To describe vented deflagrations, it is useful to describe the effect of heat addition to a rigid closed volume (isochoric). A finite quantity of gas molecules held captive at constant volume have density $\rho$ and will maintain that density as long as none of the molecules are allowed to enter or leave the space. Temperature, $T$, and pressure, $p$, of the gas are linked in this type of constant-volume system. For ideal gases, pressure is proportional to temperature with the factor $\rho R$, where $R$ is the ideal gas constant. This relationship is depicted in Figure 3. If heat is added to an isochoric system, both pressure and temperature increase. Combustion could be the source of the heat that increases temperature of gas trapped inside of a closed volume.[5]

[3] "Explosion" is used in this text in colloquial sense of the word and is synonymous with blast.

[4] https://www.scmp.com/video/china/3136069/electric-bus-bursts-flames-sets-nearby-vehicles-fire-china

[5] The molecule count in combustion is not necessarily conserved as atoms in reactants may arrange in products in such way thar results in net change of molecule quantity. For the sake of simplicity, this discussion assumes the molecule count stays relatively constant, which is fair for many cases of combustion in air, since inert nitrogen molecules make up most of the molecules.

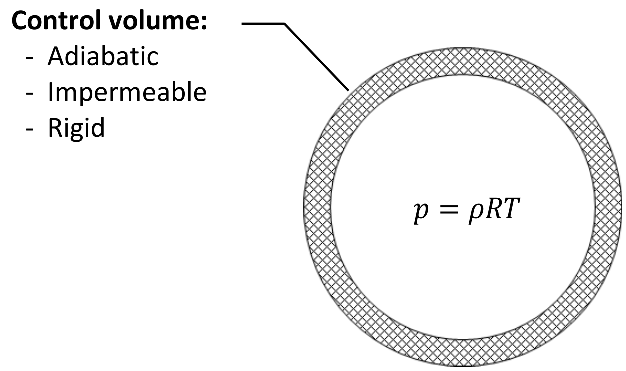


**Figure 3. Illustration of Isochoric System**
**Pressure scales with temperature with ratio $\rho R$**

Figure 4 presents a pressure trace of a confined combustion test in a laboratory. The vessel was filled with gaseous fuel and oxidizer at 1 atmosphere before sealing it. The mixture was then ignited, and the instruments recorded peak pressure of about 8 atmospheres before thermal losses to the walls of the test vessel cooled the vapor space and forced the gas pressure to gradually decay (solid line in Figure 4). While a pressure vessel in a laboratory can be made to handle the maximum pressure developed by confined combustion, buildings and structures are seldom built to withstand such loads.[6]

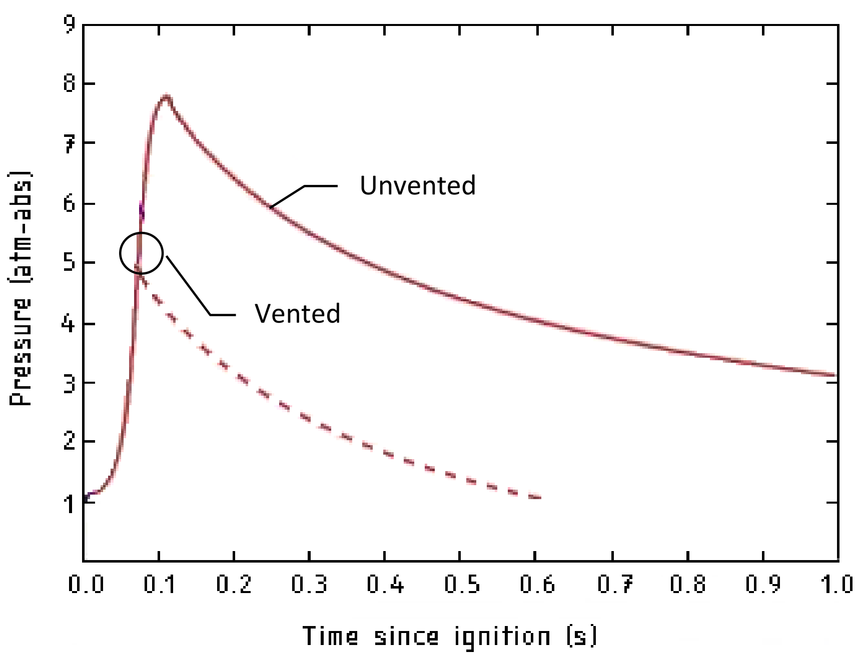


**Figure 4. Pressure traces of confined combustion**

[6] https://www.click2houston.com/news/2017/04/24/lithium-batteries-causes-train-car-explosion-in-ne-houston/

Typically, a space that initially contains an internal combustion event will fail due to the increase in internal pressure and breach to allow gases to escape and reduce further pressure escalation (dotted line in Figure 4). The failure of the structure creates blast wave, fireball ejection, and possibly debris throw. The gases leaving the confided volume do so at high speed and can exert significant drag loads on nearby objects. Internal deflagrations and venting have been reported in catastrophic incidents involving battery energy storage systems, sometimes with fatal consequences.[7]

Batteries have been observed to fail catastrophically for a variety of reasons.[8] While there is a fair degree of uncertainty on how and when a battery system may fail, the effects described above can be reasonably bounded and modeled. Once the effects have been assessed, the consequences to structures, equipment, and/or personnel are estimated to determine risk. Part 5 in this series will cover the assessment of damage caused by catastrophic hazards and address considerations for mitigation design.

7 Accident analysis of the Beijing lithium battery explosion which killed two firefighters | CTIF - International Association of Fire Services (https://www.ctif.org/news/accident-analysis-beijing-lithium-battery-explosion-which-killed-two-firefighters)

8 https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database