Mitigating Risks of Explosion and fire for BESS (Battery Energy Storage System).

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***Abstract*—This presentation is talking about safety for energy stationary storage systems (BESS) with lithium-ion batteries and covers solutions for mitigating risks the effects of explosion and fire in a case of a thermal runaway.**

The topics covered will provide a better understanding of how passive solutions work, and the need to use them, in order to control the pressure wave, in case of an explosion, with a predetermined direction and ensure that the BESS does not collapse.
Although lithium battery technology is becoming increasingly safe, there is still a risk of explosion when this technology is used.

***Index Terms*— Active solution; Explosion Protection; NFPA 855 V 23; NFPA 68; NFPA 69; Passive solution; Thermal Runaway; UL9540a**

I. Introduction

The development of energy storage will increase in coming decades to reach 400 GW of storage globally in 2030 against 100 GW to date. [1]

Stationary storage systems use lithium-ion batteries which can present a risk of thermal runaway and lead to a severe fire and in some cases lead to an explosion.

A database [2] of BESS failure events exists and shows that since 2018, there have been 62 incidents leading to a fire or explosion on BESS, which represents an average of 10 serious events per year across the world.
Furthermore, in the majority of cases these accidents occurred on energy storage systems less than 3 years old.

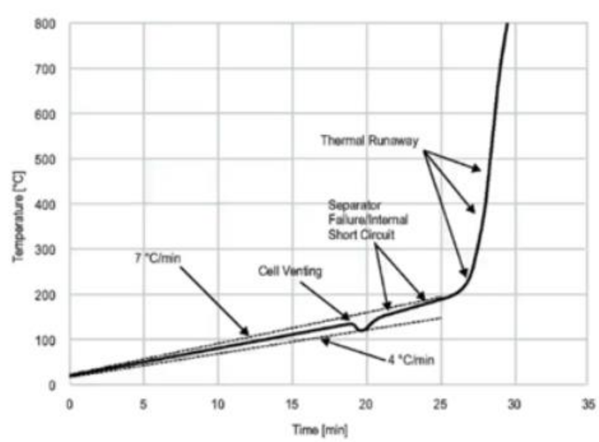
In view of the information recorded in this database, considering the massive deployment of energy storage projects, it is difficult to imagine that the number of accidents per year could decrease.

As shown by the BESS APs McMicken [3] accident occurred on 19 April 2019 in Arizona how it led to the complete destruction of the BESS, 8 firefighters were injured, 4 of them seriously during this incident.
The causes of this accident were due to a thermal runaway, with generation of flammables gases which led to an explosion.
The accident report made by DNV GL shows us that the BESS was not equipped with deflagration vent panels.
It explains clearly the importance to implement a protection solution to ventilate AND a **solution to protect against the effect of overpressure due to an explosion.**

II. Thermal Runaway

A. significance

A Thermal Runaway is a violent incident for the battery with electrochemical and exothermic reaction and creates a self-heating phenomenon



Ul 9540A - Figure 7.1
Illustrative Example of a Thermal Runaway
Temperature Curve

Thermal Runaway also produces toxic and flammable gases.

It is important to note also here that a battery fire caused by thermal runaway is not a conventionnal fire. It is a chemical fire and could burn without oxygen.

To quickly sum-up a thermal runaway in BESS:

Is Happening....

THIS....

INSIDE THIS....

B. Compostion of flamable Gas during thermal Runaway

The gas mixture generated during a thermal runaway contains hydrogen, which is a highly flammable gas. These gases in the correct concentration within the container can ignite upon contact with the heat of the batteries in their state of thermal runaway and lead to an explosion.

Cell Gas Composition:

Gas		Measured %
Carbon Monoxide	CO	11.191
Carbon Dioxide	CO_2	27.325
Hydrogen	H_2	48.013
Methane	CH_4	6.404
Acetylene	C_2H_2	0.107
Ethylene	C_2H_4	3.296
Ethane	C_2H_6	1.326
Propene	C_3H_6	0.948
Propane	C_3H_8	0.321
-	C4 (Total)	0.704
-	C5 (Total)	0.142
-	C6 (Total)	0.005
-	C7 (Total)	0.003
Benzene	C_6H_6	0.014
Ethyl Methyl Carbonate	$C_4H_8O_3$	0.201
Total	**-**	**100**

Table Extracted from test report UL9540a

It is important to remember here that all Lfp or Nmc type batteries chemistries currently available on the market can release flammable gases during thermal runaway. **In general, the H2 concentration is between 30% and 50%, depending on the specific technology chemistry.**

Unfortunately, we have seen validated UL9540a test reports from China showing thermal runaway cell tests without the presence of ANY flammable gas.
This cannot be correct and it is very important to understand that even with a UL9540a validated report, there is no such thing as 0 risk.

You should know that the concentration of flammable gases in a container cannot exceed 25% of the LFL. [4]

The study of the various UL9540a reports to which we have access shows us that the volumes of flammables gas generated by a single cell during a thermal runaway are very significant. The release of gas can be between 32L and 300L for only one cell depending on cell technology used.

Within an enclosure of BESS, the volume of free air is drastically reduced by the volume occupied by the battery modules. We have noted that in the majority of cases the volumes of flammable gases released by a partial quantity of cells in thermal runaway make it possible to reach or exceed the concentration threshold of 25% of the LFL.

III. Effects of an Explosion Without Protection

An explosion is an incident that generates 2 simultaneous phenomena: the production of a fireball accompanied by a sharp rise in pressure.
During an explosion, a fireball can be several dozen meters long and several metres wide.
The pressure can increase up to 12bar depending on the nature of the gas mixture.

Below we show values [5] of overpressure effects linked to an explosion with a maximum 0.300bar overpressure :

- 0.020bar = glass breakage
- 0.140bar =first lethal effects + damage on structure
- 0.300bar=very serious damage effect

To give another scale of values, for an explosion with a pressure rise of 1 bar, the pressure value applied to a wall is 10 tons per m².

IV. WHAT PROTECTION MEASURES FOR BESS

In terms of engineering solutions to be put in place, there are several strategies that can and should be used, either to "protect" or to "prevent".
This is in fact what NFPA 855 version 2023 states.
(§9.6.5.6.3 Nfpa 855 v23)

Our experience in the field of explosion protection, as well as our product developments with some of the largest OEMs in the world of stationary energy storage, allows us to indicate that the best protection for a BESS is a combination of Passive and Active solutions to meet both NFPA 68 and NFPA 69 requirements.

A. NFPA 855 V23 §9.6.5.6.3

9.6.5.6.3* ESS installed within a room, building, ESS cabinet, ESS walk-in unit, or otherwise nonoccupiable enclosure shall be provided with one of the following:

(1) Explosion prevention systems designed, installed, operated, maintained, and tested in accordance with NFPA 69
(2) Deflagration venting installed and maintained in accordance with NFPA 68

B. WHY NOT USE ONLY ACTIVE SOLUTION

NFPA 69 Active Protection Systems (e.g. Active Ventilation) are useful to ensure a concentration level below the 25% threshold mentioned in NFPA 855, **but can in no way protect against the effects of explosion-related overpressure, they are NOT designed to evacuate the blast from an explosion.**

In France we have seen cases of explosion on LFP battery without thermal runaway

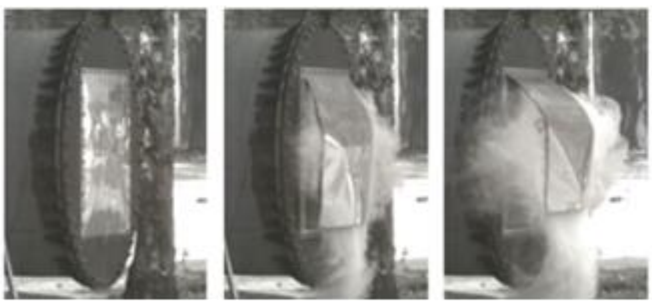
During the INES conference [6] focus on risk and protection of BESS presented in France in October 2022, the French emergency services SDIS73, made a statistic and showed that out of 20% of BESS accidents with severe thermal runaway, 5% will systematically lead to an explosion.

They therefore indicated, with reference to the accident [3] mentioned above in introduction, the importance of the installation of passive measures (NPFA 68) such as deflagration vent-panels.

C. WHAT IS A DEFLAGRATION VENT PANEL?

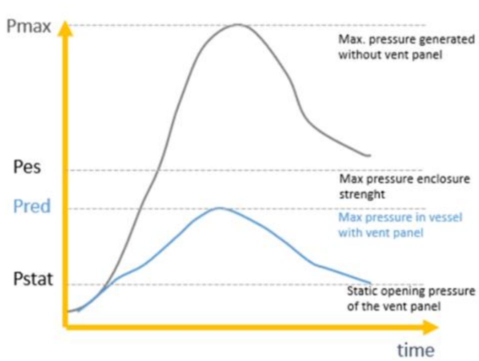
A deflagration vent-panel is a purposely weakened metallic membrane designed to open under the effect of a sudden rise in pressure.

This membrane serves as an engineered weak point, and allows, in the event of an explosion, release of the energy created by the deflagration and guarantees that the BESS structure resists the overpressure of the explosion.



Example of vent panel opening during an explosion.

1) Explosion Curve



The curve above is a representation of the effect of the explosion on a vent panel. The membrane activates when it reaches the opening value of the Pstat.

As can be seen on the blue curve, the pressure continued to increase until it reached the reduced pressure allowed by the enclosure to be protected, while guaranteeing to remain under the resistance value Pes of the container or enclosure to be protected

The blue curve is defined also by the vent surface of the panel used. This surface is determined by calculation according to NFPA 68

D. VENT PANEL SIZING

The discharge area (or vent area) required to protect a BESS enclosure is calculated in accordance with NFPA 68 -chapter 7 version 2018.
The vent surface must be calculated taking into account the combustion values of the gas mixture form the battery chemistry used on the BESS to be protected. Theses value are available from the UL9540a report used to test and validate the cells or batteries to be used on the BESS.

Important values to be identify in the UL9540a report for calculating the discharge area are as follows:

- **Su (m/s)** : fundamental burning velocity of gas-air mixture
- **Pu (kg/m3):** mass density of unburned gas-air mixture
- **Pmax (bar-g)** : the maximum pressure developed in a contained deflagration by ignition of the same gas-air mixture

The others important value to determine the discharge area are:

- **Pred (bar):** reduce pressure that the enclosure can withstand in the event of an explosion

I'm talking here only about the essential data that we must have access to, in order to carry out a specific calculation, of the relief area. Unfortunately, they are usually not provided by the OEM.

I draw your attention to the fact that NFPA 68 indicates values that can be used in the case of that these values are unknown. The problem is that using "unknown" values does not reflect the real nature of the thermal runaway that could occur and most of the time provide an oversized result.

I'd like to explain also, that an explosion due to thermal runaway, is a gas explosion. NFPA 68 is not a standard dedicated specifically for the gas explosion and has been created by the chemical industry. The calculation method considered in the NFPA68, is an approach based more on dust mixture, and its interpretation could be sometimes difficult to understand in term of result.
The safety for BESS, is currently leading by NFPA. In U.S NFPA 68 is the only standard available for explosion protection with Gas or Dust.

In term of calculation's method, and protection with passive solution, it would be possible to take another approach by considering the standard NF EN 14994.
This European standard NF EN 14994 is dedicated especially for the GAS Explosion.
The purpose of this standard, consider the KG value (in Bar.m/s) and the free air volume of gas mixture present within the vessel to be protected.

KG is similar than **KST** for dust, it corresponds to the velocity of explosion, and determine the rise of pressure **dp/dt.**
The KG like the burning velocity (Su) could be define by test in laboratory.

E. WHAT CRITERIA FOR THE CHOICE OF A DEFLAGRATION VENT PANEL?

A deflagration vent panel must be chosen in taken into account the following criteria (at least):

- Certified product
- The vent area must be defined according to a standard or simulation (NPFA 68, NF EN 14994, or CFD)
- The manufacturing process must include specific tests to guarantee the Pstat
- Could be insulated
- Must have a good water proof level (tested by a laboratory)

The concept of IP level on an explosion-proof panel intended for the protection of a BESS is also a very important characteristic.
Water ingress must not be able to entry within the container, otherwise it could cause a short circuit and lead to a severe fire [7]

F. CAN A DEFLAGRATION VENT PANEL AVOID AN EXPLOSION?

The purpose of a deflagration vent panel is not to avoid an explosion. It is designed to control the pressure wave in case of an explosion with a predetermined direction, and be also a guarantee of safety for first responder and firefighter…

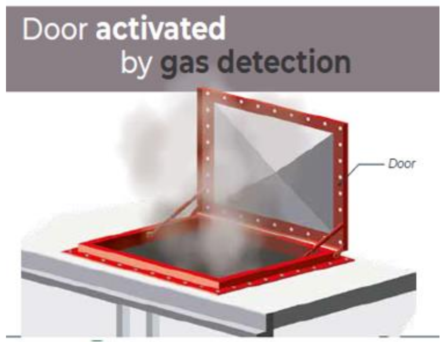
As i've explained above, the major problem in the event of thermal runaway is the creation of flammable gases which, in the event of excessive flammable gas concentration in the enclosure to protect, and could lead to an explosion.

The study of accidents, fires, and discussions that we had with the emergency services, led us to ask ourselves this question "Are the deflagration vent panel sufficient to protect BESS in the event of an explosion?"
The answer was clearly: NO.

This response led us to design an effective double security solution, which consists of the use of a door system, connected with gas detection.
Detection of both H2 and CO2 advised.

- 1st safety solution: **GAS VENTING**

When the thermal runaway gases are detected, this opens the door system and allows the BESS to be ventilated. This action creates natural ventilation and allows the release of concentrations of flammable gases present within the container, which could ignite on contact with the heat of the batteries and lead to an explosion. The goal being to remain below the concentration threshold of 25% of the LFL.



This helps meet certain requirements of **NFPA 69**.

- 2nd safety solution: **EXPLOSION VENTING**

We are talking here about a double safety solution, because this solution also includes a deflagration vent panel. It allows to release the effects of an explosion in the event of non-detection of thermal runaway gas, or a direct explosion.

This helps meet certain requirements of **NFPA 68**.

In terms of safety, the best place to position vents remains the "roof-top" installation.
With a roof-top installation, in the event of a fire or explosion, the flame and pressure are directly directed towards to the "sky".

This also helps to effectively combat the effects of propagation and protection of the immediate environment of the container subjected to an explosion or battery fire.

V. CONCLUSION

The consequences of thermal runaway can be serious with severe fires which in certain cases can lead to an explosion.

It must be remembered that the release of flammable gases from a cell can be very significant and quickly lead to a concentration level greater than 25% of the LFL being reached, and therefore lead to an explosion.

It is therefore important to understand that the protection solutions that are implemented in BESSs must integrate both passive and active solutions, which meet the requirements of NPFA 68 and NFPA 69.

As I said, passive solutions such as active ventilation are effective in prevention, but are not designed to evacuate the effects of excess pressure linked to an explosion.

It should also be understood that deflagration vent panels also contribute to the safety of emergency services, by drastically reducing the suppression effects that they could face during an event.

To conclude, the choice of a deflagration vent panel should not be made at random. It must be sized following a standard and taking into account the real characteristics of the mix of gases emitted during thermal runaway, which are validated on a UL9540a report.

An explosion-proof panel intended for the protection of BESS must also have intrinsic characteristics which take into account the environmental constraints of BESS, such as for example a good level of waterproofing.

VI. REFERENCES

[1] source : BloombergNEF

[2] souce : https://storagewiki.epri.com

[3] DNV GL – Document No.: 10209302-HOU-R-01, " McMicken Battery Enegy Storage Event Technical Analys and recommandations

[4] NFPA 855 §9.6.5.6.1.1

[5] Source : https://aida.ineris.fr/inspection-icpe/risques-accidentels/risque-explosion/risque-explosion

[6] https://www.ines-solaire.org/news/risques-incendie-des-applications-de-stockage-batteries-dans-le-batiment/

[7] Report : Elkhorn Battery Energy Storage System Fire of September 20, 2022 ESRG