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Safety Issues Related to Stationary Electrochemical Energy Storage on Industrial Sites

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The present contribution discusses the safety issues related to stationary applications of electrochemical energy storage on hazardous industrial plants. Although only few accidents related to stationary electrochemical energy storage were reported, past accidents like the fire which occurred on a sodium-sulphur stationary system in September 2011 in Joso City (Japan) remind that the roll-out of such emerging technologies on industrial sites should be considered as both hazard sources and targets of potential domino effects.
Different technologies of stationary batteries exist, from low to high energy/power ratio, according to their intended use. These various technologies, together with the different configurations that can be expected on an industrial site, are addressed. A number of standards specify tests to evaluate the safety and abuse tolerance of batteries for mobile and stationary applications. Some of them can be viewed in parallel with the French approach for controlling major accident hazards on industrial sites. It appears that some tests may enable to exclude some events from the quantification of the annual probability of occurrence of an accident scenario, which can provide greater flexibility for the hazardous industrial sites.

1. Context

Several guidelines in reducing the production of greenhouse gases have been taken since the Kyoto Protocol ratified in 1997. Among others, the diversification of the energy mix through the development of renewable energy constitutes a major move. In Europe, wind and solar power are expected to reach respectively 33% and 10% of the total power demand in 2030 (IEC, 2012). However, these renewable energies represent intermittent production sources and issues such as hourly variations in demand and price have been raised to consider them as a sustainable alternative for the production of electricity.
In this context, electrochemical energy storage techniques enable to integrate higher levels of renewable energy sources and to achieve a better balance between demand and supply of electricity. Even if a number of electrochemical systems are already installed as stationary storage, this use is under development and its deployment is expected to increase in the coming years.

2. Stationary electrochemical energy storage

2.1 Technologies

The selection of the most relevant technology for a stationary application of electrochemical energy depends on many parameters such as available power, energy capacity, reaction time, efficiency, life cycle, system safety and cost. Secondary (rechargeable) batteries have a short reaction time (< 1 second), a medium discharge time from few minutes to several hours and withstand a number of charge/discharge cycles. Secondary battery technologies that can be used for stationary applications include lead-acid, nickel-cadmium (Ni-Cd), sodium based battery (Na-S, Na-NiCl2) and Li-ion. In 2011, the distribution of the electrochemical storage capacity established in the world is as follows: 400 MW of Na-S, 45 MW of Li-ion, 45 MW of lead-acid and 40 MW of Ni-Cd (EDF, 2011). The analysis of the current stationary electrochemical energy storage market shows that Na-S systems are already widely deployed, especially in Japan, due to their high energy density and that Li-ion technology is expanding rapidly for stationary applications due to both its high power density and its high energy density.

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2.2 Configurations

The battery allows managing fluctuations in demand, delivering frequency regulation, making more efficient use of the network (mitigation of congestion), providing emergency power supply for protection and control equipment, smoothing the power output provided by renewable energy sources, etc (IEC, 2011). Due to these various types of stationary applications, the battery energy storage system can be installed in a solar/wind farm or at substations, in a factory, a building, a hospital or a store or even in houses for residential application. For this latter, stored energy is about 3 kWh whereas it can reach several MWh in solar/wind power plants.

Stationary electrochemical energy storage can be used on industrial sites for different types of applications including telecom, emergency power supply, load leveling, utility switching or peak shaving. Na-S systems can be found in various industrial sites such as automotive factories, aircraft manufacturers, non ferrous metal manufacturers, tobacco factories, chemical plants, perfume factories, and sewage disposal plants (Fukushima, 2013). Na-S system power on these industrial sites is generally between 1 MW and 5 MW.

3. Safety issues on industrial sites

3.1 Large scale battery storage accidents

As they are quite new, only few accidents on large scale battery storages are reported. It's worth mentioning the accident of Joso City in Japan that occurred on September 21, 2011. A 2 MW Na-S storage located in an industrial site of carbide parts and tools manufacturing caught fire and burnt during several days (ARIA, 2011). The fire was fully extinguished on October 5, 2011. Considering the reactivity of the sodium with water, the extinguishing method consisted in covering the fireplace with sand and waiting for the quench of the fire. No injuries were reported as a result of this fire. The consequences of this incident were material damages and economic loss for NGK battery manufacturer which asked its customers to stop their facilities during investigations. NGK published a report on the cause of Na-S battery fire incident, safety enhancement measures and resumption of operations (NGK, 2012). The cause of the fire was attributed to the failure of one cell in one of the 40 battery modules. This cell had a breach and leaked hot molten material which flowed over the sand filler inside the battery module, causing a short circuit between battery cells which heated and in turn caught on fire (Figure 1). This fire spread to the whole battery module that released flames and hot molten material causing the fire to spread to modules installed above and below. Safety enhancement measures taken by NGK manufacturer included the addition of fuses and insulation boards between blocks in battery modules to prevent short circuits, the addition of anti-fire boards between modules to stop fire propagation to the whole battery (Figure 2) and the development of fire fighting strategy and means to assist fire crew.

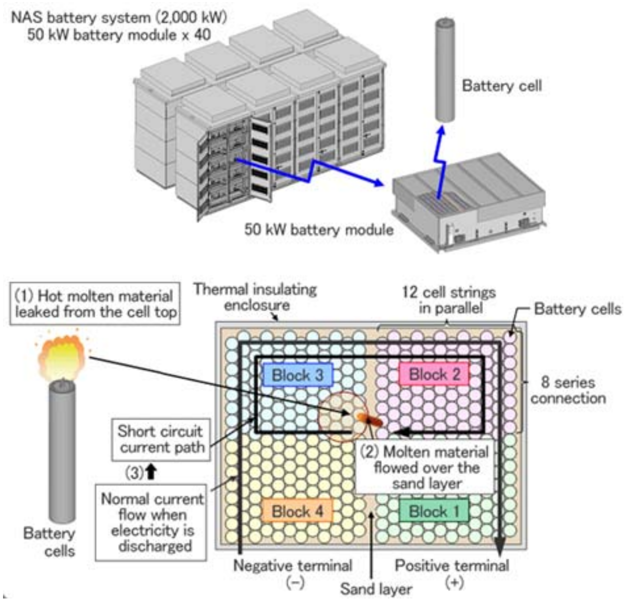

Figure 1 : Cause of fire in the 2 MW Na-S storage in Joso (Japan)

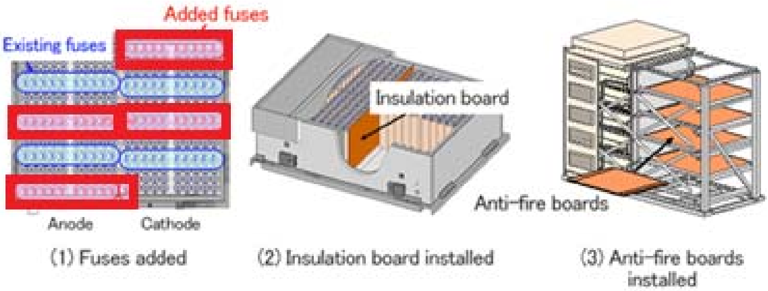

Figure 2 : Safety enhancement measures

3.2 Standards for safety of electrochemical energy storage

There are a number of standardized tests that evaluate the safety and abuse tolerance of batteries for electric or hybrid automotive applications, light electric rail applications, cellular phones and consumer electronic applications, etc. These standards have been established by numerous standardization bodies or test institutes such as UL, NEMA, SAE, IEEE, BATSO, TELCORDIA, JIS, EUCAR, INERIS, UN, IEC and ISO. All these standards rely on specific test methodologies that could be different even when considering the same application. Tests considered in these standards can be classified in 5 categories, which can be identified to accidental circumstances:

- Electrical tests (overcharge, short circuit, discharge, etc);
- Mechanical tests (impact, drop, crush, etc);
- Thermal tests (fire, heating);
- Environmental tests (altitude test, temperature cycling, etc);
- Specialized tests (insulation resistance, projectile).

A standard can be specific to one battery technology (Li-ion or Na-S for example) or can be more generic. Figure 3 gives an overview of the different tests of several standards that can be applied to automotive, consumer (mobile phone, laptop, etc) and industrial applications. This non-exhaustive list concerns non-stationary applications.

	UL					NEMA	SAE	IEEE		BATSO	Telcordia	JIS	INERIS	UN	IEC			ISO
Test Criteria Standard	UL 1642	UL2054	UL Subject 2271	UL Subject 2580	UL2575	C18.2M	J2464	IEEE 1625	IEEE 1725	BATSO 01	GR-3150	JIS C8714	ELLICERT D	Part II S38.3	IEC 62133	IEC 62281	IEC 62660-2	12405-1 & 12405-2
Applications*	C, A, I	C	A	A	C	C	A	C	C	A	C	C	A	C,A,I	C	C,A,I	A	A
External short circuit	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Abnormal charge	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Forced discharge	●	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●	●
Crush	●	●	●	●	●	●	●	●	●	●	●	●	●		●		●	
Impact	●	●	●	●		●		●	●					●		●		
Shock	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Vibration	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Heating	●	●	●	●	●	●	●	●	●			●	●		●		●	●
Temperature cycling	●	●	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●
Low pressure (altitude)	●		●	●	●	●		●	●	●		●	●	●	●	●		
Projectile	●	●	●	●				●	●									
Drop			●	●		●				●		●	●		●	●		
Continuous low rate charging												●			●			
Molded casing heating test						●												
Open circuit voltage						●												
Insulation resistance				●		●												
Reverse charge			●	●														
Penetration			●	●			●						●					
Internal short cicuit	●			●								●			●			
Immersion													●					
Fire											●		●					

*Automotive: **A**; Consumer (Mobile phone; Laptop etc.): **C;** Industry: **I**

Figure 3 : Existing standards for automotive, consumer and industrial applications (non-stationary)

There are also published safety standards that can be used to evaluate the safety of stationary energy storage systems. However, many of these standards specifically address more traditional technologies such as lead-acid or Ni-Cd batteries (IEC 62845-2, Telcordia GR-4228-CORE). There are IEC safety tests standards under development that address, among others, stationary Li-ion technology energy storage: IEC CD 62619 (not published), which covers industrial applications, and IEC 62897 (new approved work).
Some standards such as UL 1973 (Table 1) are not technology specific and cover all types of batteries technologies as well as electrochemical capacitors, for use in light electric rail (LER) applications and stationary applications. This standard also includes requirements for unique technologies such as flow batteries and sodium-based batteries.

Table 1 : Safety tests of UL 1973 standard

Standard	Safety tests
UL1973	Short circuit, overcharge, over-discharge, imbalanced charge, dielectric voltage withstand, continuity, temperature, failure of thermal stability system, temperature cycling, vibration*, shock*, drop, enclosure tests, water exposure, external fire, internal fire

* Only for LER applications

Finally, the standard UL 9540 under development is not battery specific since its covers all types of energy storage systems and is not based on a “test only” approach since it includes construction recommendations, performance verification, markings and instructions.
This analysis showed that standards addressing more recent stationary battery technologies (Li-ion) are under development and are not necessarily based on a risk assessment methodology that would consider the full scope of aggressions generated or imposed to the battery system. This is further addressed in paragraphs 3.4 and 3.5 below.

3.3 European regulation regarding major hazard accidents

As stated in paragraph 2.2, stationary electrochemical energy storage can be used on industrial sites for different types of applications. Some of those sites may be hazardous to the surrounding people and environment, because of their activity (e.g. petrochemical plants) or because of the electrochemical energy storage located on the site, whose constituents have flammable and toxic properties. If need be, the operation of the site is regulated under the Directive 2012/18/EU of July 4, 2012, on the control of major-accident hazards involving dangerous substances (also called Seveso III Directive). This Directive introduces a common European policy for the prevention of major industrial accidents, based on risk analysis, safety management systems, emergency plans, land use planning policies, and information to the public.
If the industrial site where stationary electrochemical energy is stored is covered by the regulation regarding hazardous facilities, it has to comply with several regulatory requirements. One of them can be the production of a safety report, which aims at demonstrating that major accident hazards and possible major accident scenarios have been identified and that the necessary measures have been taken to prevent such accidents and to limit their consequences for human health and environment.
Acceptance criteria have been developed based on the combination of the two following parameters: the annual probability of occurrence of the accident scenario and its severity. The quantification of those two parameters for each accident scenario identified is one of the tasks of the safety report. The basis of a safety report is the risk analysis, where all the accident scenarios that could potentially happen on the site are identified, together with their prevention and mitigation measures. This exercise is based on the mapping of the hazard potentials present on the site.
In the light of this, the electrochemical energy storage should be considered as a hazard potential when the risk analysis of the site is conducted. This activity should be assessed by itself, answering the question “what can happen to the storage?” It can also be a potential aggressor of other equipment, leading to a major accident scenario. For example, a liquefied petroleum gas sphere can be taken in a fire caused by the electrochemical energy storage.

3.4 Stationary electrochemical energy storage and major accident scenarios

Based on the past accident described in paragraph 3.1, the loss of containment of a cell is an undesirable event that can happen on stationary electrochemical energy storage. This event can lead to various dangerous phenomena, generating thermal or toxic effects according to the technology of the battery (e.g. Li-ion batteries can produce hydrogen fluoride in case of combustion). Those effects threaten both human health and environment. When conducting the risk analysis, questions regarding the causes of the loss of containment are raised. These causes can be external or internal to the site (Figure 4).

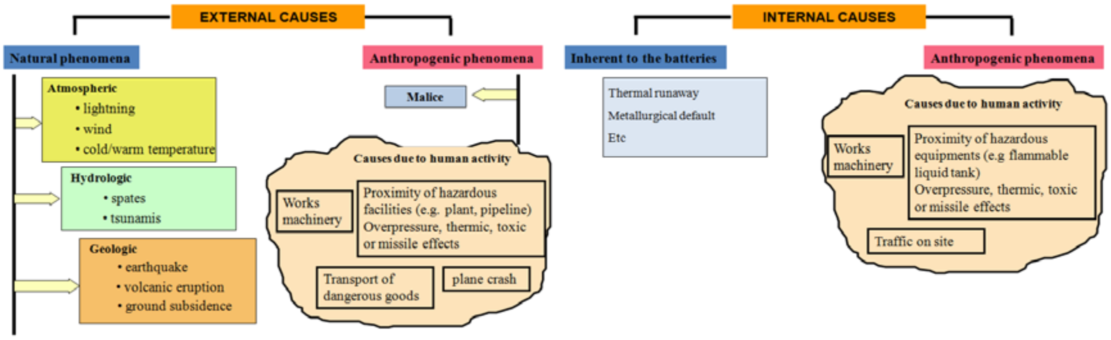

Figure 4 : External / Internal causes of loss of containment of electrochemical energy storage

Several methods exist to quantify the annual probability of occurrence of the dangerous phenomenon. The most precise one consists of quantifying all the causes (also called initiating events) that can lead to the loss of containment of a cell and a resulting dangerous phenomenon in terms of frequency of occurrence. The aggregation of those frequencies throughout the accident scenario (e.g. combination with safety barriers) leads to the determination of the probability of occurrence of the dangerous phenomenon.

Nevertheless, in the French regulation (Circular of May 10, 2010), it is clearly specified that some initiating events can be disregarded when the major accident scenario is to be quantified in terms of probability of occurrence. Regarding natural causes, the binding idea is the following: if the equipment has been conceived with regard to the corresponding regulation, the initiating event is not taken into account to assess the probability of occurrence of the accident scenario. For example, the initiating event “earthquake” can be excluded from the quantification process if the equipment has been conceived based on the seismic regulation. For the other types of initiating events, exclusion from the quantification process can happen if it has been demonstrated that the accident scenario is “physically impossible”. This approach consists in demonstrating that the conception of the equipment is ruled by a standard and that the conditions of use of the equipment cannot lead to aggressions higher than the ones described in the standardized tests procedures. The example developed in the next paragraph illustrates this approach.

3.5 Example

The standard UL 1973 evaluates the electric energy storage system's ability to safely withstand simulated abuse conditions (see Table 1). The defined requirements cover electric energy storage systems for use as energy storage for stationary applications and are not technology-specific. Table 2 describes, for a few examples, the nature of the tests performed on the energy storage system.

Table 2 : Examples of safety tests of UL 1973 standard

Safety tests of standard UL 1973	Short description	Results
Short circuit (§ 14)	The sample is to be short-circuited by connecting the positive and negative terminals of the sample with a resistive circuit load having a maximum total resistance of 20 mΩ.	The following events cannot be excluded: explosion, fire, combustible vapour concentrations, toxic vapour release, electric shock hazard, leakage, rupture, loss of protection controls
Impact (§ 27)	The sample is to be subjected to a minimum of three impacts of 6.8 J on any surface that can be exposed to a blow during intended use.	The following events cannot be excluded: explosion, fire, combustible vapour concentrations, toxic vapour release, electric shock hazard, leakage, rupture, loss of protection controls
External fire (§ 36)	The sample is subjected to a hydrocarbon pool fire for 20 minutes. The fuel used shall be heptane similar hydrocarbon fuel.	There shall be no explosion of the sample that results in projectiles falling outside a defined circular inner perimeter.
Internal fire (§ 37)	The sample is to be subjected to the internal fire test which consists of heating one internal cell that is centrally located within the system until thermal runaway.	There shall be no fire propagating from the system or explosion of the system.

These results, combined with the conditions of use of the system on the industrial site, could lead to exclude the initiating events “external fire” and “internal fire” respectively from the quantification process of the major accident scenarios “explosion” and “fire / explosion”. In other words, the annual probability of occurrence of the potential fire or explosion can be assessed without taking into account the causes “external / internal fire” since the electric energy storage system is designed to prevent an external fire and a single cell failure within the system from cascading into a fire and explosion. In this specific example, the other initiating events cannot be disregarded because the results of the safety tests run in the standard are non-compliant for the events explosion and fire.

4. Conclusions and perspectives

Stationary electrochemical energy storage on industrial sites can be the source of accident scenarios potentially leading to major consequences. If the industrial plant is to be regulated by the European policy for the prevention of major industrial accidents, it may have to produce a safety report where all the physically possible accident scenarios are identified through a risk analysis. The acceptance of the risk is based on the combination of the probability of occurrence of those accident scenarios and their severity.

Several methods exist for the quantification of the probability of occurrence of the identified accident scenarios. One of them consists of attributing a frequency of occurrence to each event initiating the scenario and propagating these data to get the final result. The present contribution shows that some initiating events could be excluded from this quantification process if the electrochemical energy storage system complies with some tests provided in acknowledged standards.

This work could be completed by a more in-depth study of all the existing standards for stationary applications of electrochemical energy storage on industrial sites and a thorough risk analysis of the use of those systems considering specific configurations. For example, it would be interesting to apply this approach based on the standard IEC CD 62619, which addresses, among others, stationary Li-ion technology energy storage for industrial applications.

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