# Safety of lithium-ion batteries

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*The European Association for Advanced Rechargeable Batteries*

## Foreword

Authors.

This publication has been prepared by RECHARGE aisbl.

The membership of **RECHARGE** includes suppliers of primary and secondary raw materials to the battery industry, rechargeable battery manufacturers, original equipment manufacturers, logistics partners and battery recyclers.

RECHARGE is following the continuously changing regulatory and legislative environment for rechargeable batteries and is a recognized expertise centre for advanced portable and industrial rechargeable battery technologies.

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# Content

# 1. Executive Summary

Lithium-ion battery safety has raised a large interest in the public in the recent years. This battery technology has been finding new markets since the years 2000. It is associated with the market development of cordless communication technologies and equipment such as cellular phones and portable computers, power tools and more recently tablets. In Europe it is the preferred battery technology for e-bikes, it is expected in the near future to be widely used in Plug-In Hybrid and full Electric Vehicles.

The number of rechargeable lithium-ion batteries used in cordless applications is well above one billion units per year and it is expected to grow in the mid-term. Despite the high safety standards used in the production of these batteries, several incidents have been reported, raising questions about the safety of this technology.

The aim of this document is to describe the risks associated with this technology, and how they are managed in order to guarantee a safe use of lithium-ion batteries. The following conclusions are drawn from this study.

1. **The safety protection is a fundamental function integrated in a lithium-ion battery**, minimizing the occurrence of the flammability hazard and its consequences by a combination of prevention, protection and mitigation systems:
   - **Prevention and protection** includes electronic protections, mechanical design and electric design incorporating the necessary redundancies to ensure the reliability of the safety protection: current and voltage control, state of charge and temperature management…
   - **Mitigation** systems reduce the consequences of defaults or abuse, e.g. internal shorts, temperature elevation, excess current, mechanical damage, through the usage of safety vents, heat protection or evacuation systems, mechanical protections…

2. **Product compliance with well established international or private standards** validate that the safety protection is adapted to the intended use. In addition, lithium-ion batteries have to be qualified for transport according to a UN safety standard, requiring manufacturers to comply with Safety Test requirements and a Quality Management System.

3. **The global approach to the hazard management has made the lithium-ion battery one of the safest energy storage systems**. Billions of electrical and electronic equipments powered by these batteries are used worldwide on a daily basis confirming that the safety of lithium-ion batteries is well managed.

4. **The major hazard offered by lithium-ion battery technologies is the evolution of a fire**, as a result of the flammability of the substances used in the battery.

A large majority of incidents reported recently found their origin in the following:

- Non-respect of UN provisions and packaging requirements prior to the transport of lithium-ion batteries.
- Cells assembly by non-professionals for innovative applications.
- Concentration of lithium-ion cells in non-controlled storage conditions or areas.

The lithium-ion battery Industry and RECHARGE are working at various levels of International and National Institutions to improve and guarantee the safety of lithium-ion batteries during use and transport while this battery technology is undergoing a strong market development.

## 2. Introduction

A lithium-ion battery is an electrochemical device optimized to store and release energy in the context of a specific application. All energy storage systems, whatever the system used, have a risk of unexpected environmental conditions or defaults which could create an accidental or uncontrolled energy release.

Specific environmental conditions are often used to test and characterize the stability of the energy storage system, defining the frontier between the acceptable conditions of use and the abusive conditions. In case of accidental abusive conditions or defaults producing some potential hazard occurrence, mitigations measures can be taken to avoid hazardous consequences. Using this information, products can be designed to control their safety with appropriate means both for the risk prevention and for the consequences mitigation while controlling any hazardous event during normal usage.

Table 1 below is describing some examples for different energy storage systems and the type of hazard they can offer. It appears that lithium-ion batteries have different behaviour compared to other battery technologies, requiring the use of suitable risk control and potential hazard mitigation, specifically relative to the so-called “thermal run-away” associated with a fire hazard. The aim of this document is to describe what are the risks associated with this technology, and how they are managed in order to guarante a safe use of lithium-ion batteries.

| Energy storage technology | Potential hazard | Hazard Prevention | Potential hazard control |
|---|---|---|---|
| Water storage (hydraulic systems, dams,..) | Rupture, water flows | Avoid corrosion and mechanical rupture | Manage water streams |
| Liquid fuels (gasoline, diesel, ethanol,…) | Fire, explosion | Avoid sparks, flames | Manage fire and fume emissions |
| Lead acid and Alkaline Rechargeable batteries | Hydrogen gas release (mainly in overcharge), explosion, Acid and Alkali release | Avoid battery electrical abuse (e.g. voltage control and protection) | Manage gas flow release, neutralize spillage of acid or alkali,… |
| Lithium-ion batteries | Combustible gas release, corrosive electrolyte release, fire | Avoid heat or flames, and battery electrical abuse. | Manage fire and fumes emissions, neutralize spillage of electrolyte. |

**TABLE 1. Examples of different energy storage systems and the associated potential hazard.**

# 3. Lithium-ion batteries: key features

## 3.1. Market and Applications

The lithium-ion battery technology is currently used in a large range of applications, both on the consumer, professional and industrial markets.

**Portable-Rechargeable**
- Electronic devices such as mobile phones, laptops and tablets
- Cordless Power Tools

**E-Mobility**
- Electric-Bikes
- Plug-In Hybrid Vehicles
- Electric Vehicles

**Stationary**
- Industrial Energy Power Stations
- Modular units for Grid Interface
- Supply of ancillary services to the electrical grid

**Others**
- Aeronautics
- Aerospace
- Military, Marine,…

Rechargeable lithium-ion batteries are primarily used in market segments where their high energy and power density as well as their superior cycling ability are requested.

As shown in Figure 1, prepared by AVICENNE, the future demand for lithium-ion batteries will be sustained in the portable market segment as well as in the E-mobility area.

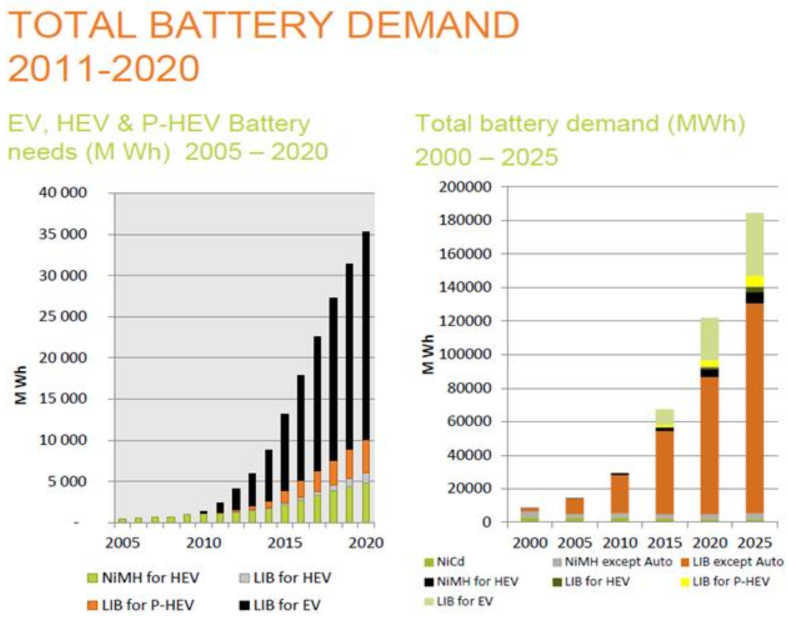


**FIGURE 1. Evolution of the production for lithium-ion batteries by application.**
*(source: Christophe PILLOT. AVICENNE. 2012).*

Lithium-ion batteries are the reference technology for plug-in and full-battery electric vehicles (PHEVs and BEVs) of the coming years. While other types of batteries, including lead-acid and nickel-metal hydride (in the first generation of the Toyota Prius hybrid) will continue to retain considerable market share in the short term, lithium-ion batteries are expected to dominate the market by 2017. Compared with other relevant battery types, lithium-ion batteries have the highest energy density as shown in Figure 2. Significant further improvements to the technology are expected in the coming years due to increases in the cell performance or via the battery engineering and design.

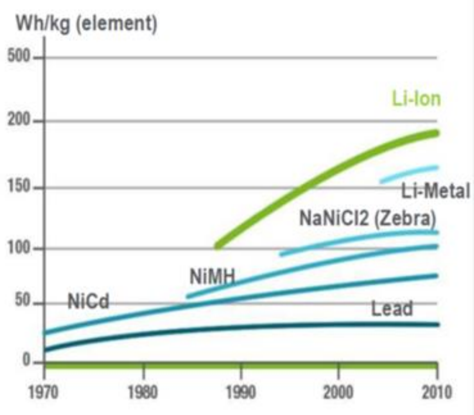


**FIGURE 2.** **Energy Density Range for various battery technologies.**
*(Source. DAIMLER 2011)*

In the future, there will be also high demand for these batteries in the energy storage sector.
Indeed, lithium-ion is also a technology of choice for large renewable energy farms in which smoothing functions are required along with ancillary services to the network (frequency regulation, primary power regulation), as both these requirements place a high demand on the battery cycling ability.

## 3.2. Chemistry and technology

### 3.2.1. A wide range of battery chemistries.

All lithium-ion technologies are based on the same principle: Lithium is stored in the anode (or negative electrode) and transported during the discharge to the cathode (or positive electrode) via an organic electrolyte. This principle is illustrated in Figure 3.

The most popular materials are graphite for the anode and a metal oxide for most of the cathode materials. The cathode material is based on Nickel, Manganese and Cobalt or made of iron phosphate. All of these materials have good lithium insertion or intercalation properties, allowing the storage of a large amount of electrical energy under a chemical form.

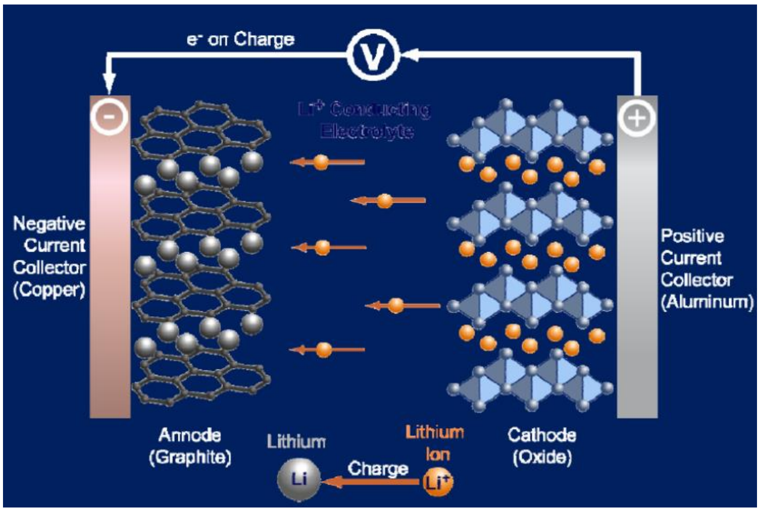


**FIGURE 3. The basic operation principle of lithium-ion batteries.**
*(Source : Exponent 2011).*

The selection of a battery technology depends on the application requirements regarding performance, life and cost, with each battery type providing specific functionalities. An illustration of the variety of properties offered by lithium-ion batteries is illustrated in TABLE 2 where the major components are detailed in a comparative presentation with the various battery technologies.

| Name | LCO | LNO | NCA | NMC | LMO | LFP | LTO |
|---|---|---|---|---|---|---|---|
| **Items** | Lithium Cobalt Oxide | Lithium Nickel Oxide | Lithium Nickel Cobalt Aluminium Oxide | Lihium Nickel, Manganese Cobalt Oxide | Lithium Manganese Spinel | Lithium Iron Phosphate | Lithium Titanate |
| **Cathode** | LiCoO2 | LiNiO2 | Li(Ni0,85Co0,1Al0,05)O2 | Li(Ni0,33Mn0,33Co0,33)O2 | LiMn2O4 | LiFePO4 | e.g.: LMO, NCA, … |
| **Anode** | Graphite | Graphite | Graphite | Graphite | Graphite | Graphite | Li4Ti5O12 |
| **Cell voltage** | 3,7 - 3,9V | 3,6V | 3,65V | 3,8 - 4,0V | 4,0V | 3,3V | 2,3 – 2,5V |
| **Energy density** | 150mAh/g | 150Wh/kg | 130Wh/kg | 170Wh/kg | 120Wh/kg | 130Wh/kg | 85Wh/kg |
| **Power** | + | o | + | o | + | + | ++ |
| **Safety** | - | o | o | o | + | ++ | ++ |
| **Lifetime** | - | o | + | o | o | + | +++ |
| **Cost** | -- | + | o | o | + | + | o |

**TABLE 2. The major components of lithium-ion batteries and their properties.**
*(Source: Daimler analysis, Nationale Plattform Eletromobilität, 2010)*.

### 3.2.2. The different types of cell geometry.

Lithium-ion cells are manufactured in accordance with various types of cell formats and geometries. Some of them are illustrated in Figure 4.a. and 4.b.

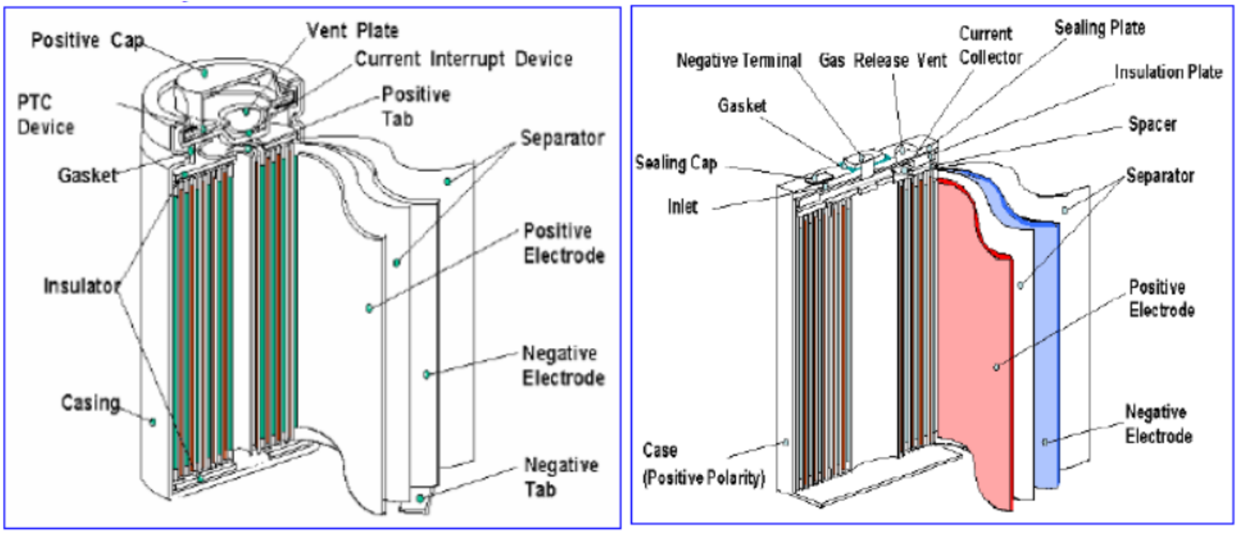


**FIGURE 4.a. Various type of cell formats: cylindrical and prismatic lithium-ion battery**

As illustrated in Figure 4a, hard case cylindrical or prismatic cells are produced: these cells are generally made of an aluminium can with laser-welded or crimped cover. They contain liquid electrolyte.

Soft case or « pouch cells » are also produced as shown in Figure 4b. These cells are using a thin aluminized plastic bag, glued with different type of polymers for the tightness. In general, they contain a gel or polymer electrolyte which justifies the qualification of “lithium-ion polymer” battery.

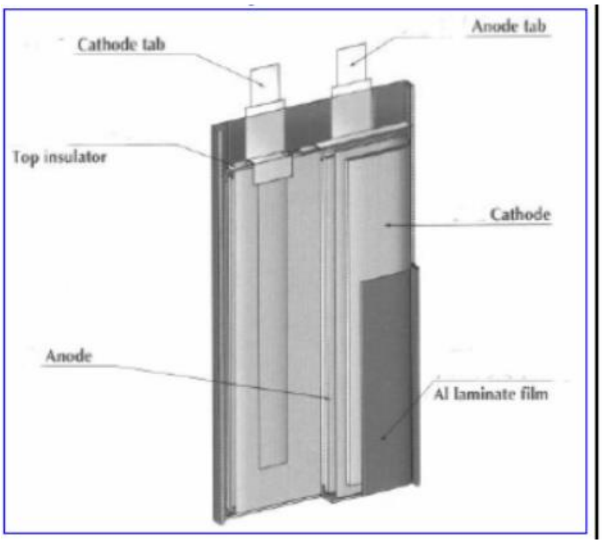
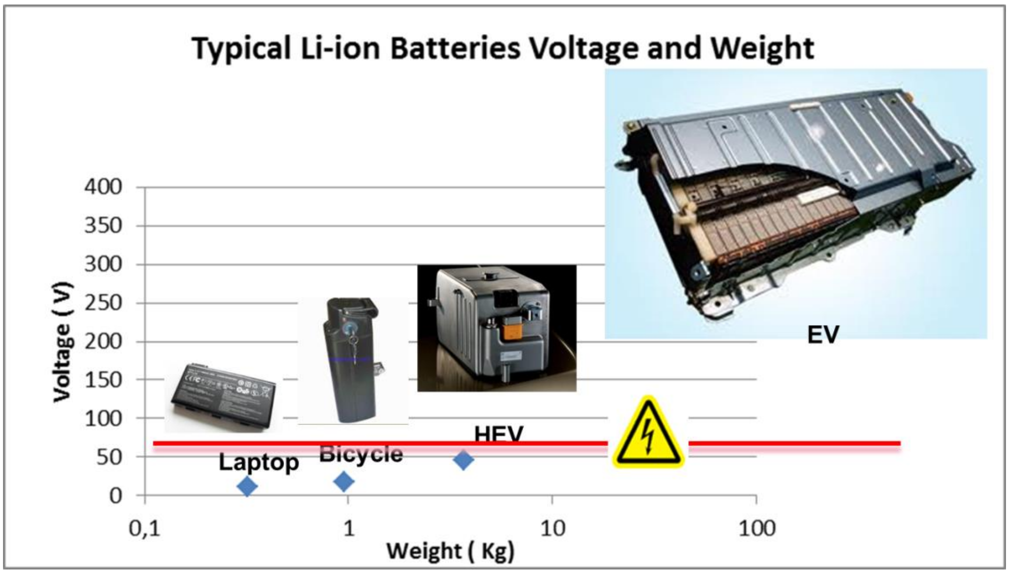


**FIGURE 4.b. Various type of cell formats: The pouch cell of a lithium-ion Polymer battery**

The cells are assembled to form battery packs and batteries, embedded in hard casing with electro-technical and electronic management systems (BMS). The final battery assembly (geometry and weight) and voltage is dependent of the cell type used and of their electrical assembly (series or parallel). The relation between battery weight and Voltage is illustrated in Figure 5 for several applications.



*Source : Recharge*

**FIGURE 5.** **Evolution of the weight of the battery with the voltage of the application.**

# 4 Lithium-ion battery hazards.

Safety assessment of a Lithium-ion battery requires the definition of the types of hazards they can offer, their occurrence probability and their consequences within the application.

## 4.1. The types of hazards.

As for any battery system, the Lithium-ion technology associates electrical risks and chemical risks. Depending on the environmental stress conditions, they can eventually create more or less dangerous consequences, called the potential hazards.

The potential hazards can be classified as below:

- The Chemical hazard
- The Electrical hazard
- Cumulative Electrical and Chemical hazards.
- High voltage (over 60 V-DC) hazard.
- Hazards due to loss of a function of the battery

### 4.1.1. The chemical hazard.

The substances contained inside the battery may present some chemicals risks. Although the battery is an article with no intended release of the substances during normal conditions of use, the case of accidental exposure has to be considered, in particular the rupture of casing due to mechanical damages, internal pressure, default,…. At this time, the following hazards may be observed.

- Spillage: hazard linked to the corrosive and flammable properties of the electrolyte.
- Gas Emission: hazard linked to the flammable properties of volatile organic substances.

The chemical risks associated with the direct exposure to the substances contained in the battery are exposed in the safety data sheet of the substances. A list of them is provided as an Annex to the Battery Information Factsheet prepared by RECHARGE (REF.1).

### 4.1.2. The Electrical Hazard.

Another type of hazard observed with all batteries is linked to the Electrical Energy content (according to the State of Charge).

**The current flow** through the battery in a conductive path is creating heat: this is known as the Joule effect. The heat generated by the electric current during charge /discharge processes is managed by a thermal management system.

In addition the battery has to be protected against high electrical currents and short circuits (internal, external or created by mechanical damage). Depending on the battery design, the heat created by these high currents may exceed the global battery cooling efficiency or create a local hot spot.

**The state of charge** needs to be controlled. The overcharge and over discharge generate unwanted reactions which are more exothermic than the normal one. They accelerate the temperature increase of the battery. In addition overcharge creates more chemical instability of some materials. This is the reason why electronic protection, generally based on voltage thresholds, is necessary for Lithium-ion batteries.

### 4.1.3. Cumulative effects (Chemical and Electrical).

In the case of energy storage systems like batteries, there is a potential cumulative effect of the chemical and the electrical hazards. In some specific circumstances it leads the so called “thermal run-away”. In case of a short-circuit, the Joule effect will increase the cell temperature to the point where the organic solvent leaves the cell via the vent. At this time any hot spot may induce a fire. The possible consequences of this cumulative effect are the following.

- Fire
- Toxic or harmful gas emission: CO, organic electrolyte,…
- Ejection of parts

The root causes of the thermal run-away are described in the parag 4.2.

### 4.1.4. High voltage (over 60 V-DC).

Large industrial or electric mobility batteries which are presenting a high voltage offer an additional hazard. Occupational Health recommendations fix a threshold at 60V for the electrical hazard of equipment in general and batteries in particular. In this case, the battery insulation loss may represent a direct danger to humans due to exposure to high voltage or high current: the usage of Lithium-ion batteries assembled to offer high voltage (over 60 V) has to respect the applicable electrical protection standards (terminals protection, insulation faults control to avoid exposure to dangerous battery voltage, etc…).

### 4.1.5. Loss of one (or more) of the battery service functions.

In many applications of industrial or mobility batteries, the control of the application relies on the battery power. A sudden loss of such a service function due to a battery failure can create a danger to the user. This hazard has to be analyzed in relation to each application.

## 4.2. Root causes of a thermal run-away.

It is important to understand the root causes of the potential hazards in order to define a specific and reliable risk management.

### 4.2.1. A materials issue.

The root cause of the thermal run-away is linked to the properties of the substances used in the battery. Indeed, Lithium-ion batteries contain several components which can under specific conditions react and generate heat or flames.

As shown in Table 3 below , the components used in a Lithium-ion cell are completely stable up to 80°C. At higher temperatures, the passivation layer called SEI ( Solid–Electrolyte Interface : a thin layer of carbonated compounds passivating the surface of the graphite negative electrodes) starts a progressive dissolution in the electrolyte, becoming significant at 120-130°C. Due to this mechanism, the electrolyte further reacts with the least protected surface of graphite, generating some heat.

| Temp (°C) | Reaction identified | Energy (J/g) | Comment |
|---|---|---|---|
| 120-130 | Passivation layer | 200-350 | Passive layer breaks<br>Solubilisation starts below 100°C |
| 130-140 | PE separator melts | -90 | Endothermic |
| 160-170 | PP separator melts | -190 | Endothermic |
| 200 | Solvents-$LiPF_6$ | 300 | Slow kinetic |
| 240-250 | $LiC_6$ + binder | 300-500 | |
| 240-250 | $LiC_6$ + electrolyte | 1000-1500 | |
| 200-230 | Positive material decomposition | 1000 | $O_2$ emission reacts with solvents |

*Values measured with differential scanning calorimetry on electrodes, may be partially representative of the reactions in the cell*

**TABLE 3. Thermal stability of components used in a Lithium-ion battery.**
*(SOURCE: Saft)*

Depending on the choice of components, the reactions onset temperature and the total energy of possible reactions can change. A well-known example is the selection of the positive active material: materials such as Lithium Nickel oxide or Lithium Cobalt oxide can decompose at high temperature and generate heat, while on the contrary Lithium Iron phosphate will not.

In addition, the energy of a given reaction may vary with the state of charge: for example, a discharged graphite negative electrode will not react with the electrolyte.

### 4.2.1. The Thermal Run-away mechanism.

The consequences of the heat evolution depends on the environment of the cells:

When the cells are in an environment where heat can be evacuated, the reactions described in § 4.2.1. will stabilize and cells will progressively cool down. This corresponds for example to batteries with cooling systems, or small batteries evacuating the heat through their external casing.

In contrast, when the heat cannot be evacuated (such has in a confined environment, or even worse, in a heated environment), the battery temperature will increase, and will reach a status where new reactions can start, generating even more heat.

This mechanism is called the "thermal run-away". As described in FIGURE 6 below, several reactions involving the separator, electrolyte and positive could be ignited with the temperature increase: consequently, the heating rate accelerates from less than a 1°C/minute to more than 100°C per minute.

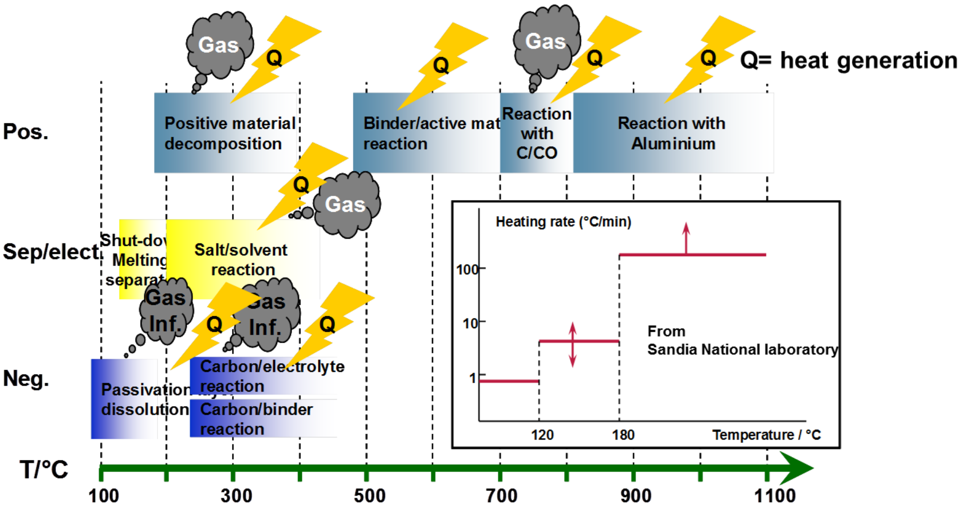


**FIGURE 6. Schematic representation of conditions leading to a “Thermal Run-away”**
*(Source: Saft)*

Without appropriate design to limit the run-away (such as venting, insulating layers,…), it can lead to a violent emission of gas and flames.

As explained above, the environmental reason creating the conditions of a thermal run-away can be the heat: this is the reason why it is recommended to protect Lithium-ion ion batteries from any heat sources.

The consequences of the thermal run-away are described in the next Chapter 4.3.

## 4.3. Hazard effects/consequences.

### 4.3.1. Gas emission during thermal run-away

During the run-away, several reactions occurr simultaneously. Their completion will depend on many factors:

- The heat and components generated by the competitive reactions,
- The state of charge,
- The size of the cells,
- The design of the cells (choice of the substances, efficiency of the protection components, etc..)
- The environment of the cells (efficiency of the cooling systems, local heat sources, atmosphere, etc…)
- Others.

Consequently, the information provided below on the consequences of a thermal run-away must be taken as general information. Each individual battery manufacturer should supply more accurate information on the consequences of a thermal run-away on its own battery systems.

The main consequences of the run-away are the emission of heat and gas which is flammable. The design of the cells and batteries generally integrates protections (like vents) in order to release gas without creating a risk of bursting the cells or batteries. In the same way, non-flammable plastics are used to avoid additional contribution of the plastic combustion to the heat generated. In TABLE 4, a list of gases emitted during the thermal run-away is supplied with indications of their relative concentration.

| Molecule | Concentration (%) |
|---|---|
| CO | #40 |
| $H_2$ | # 30 |
| $CO_2$ | # 20 |
| Methane | 7 |
| Ethylene | 3 |
| Ethane | 1 |
| Propylene | 1 |
| C4s and others | <1 |
| Including HF | #0,3 |

**TABLE 4. list of gases/substances emitted during the thermal run-away of a Lithium-ion battery**
*(SOURCE: Saft)*

The emitted gas contains Carbon Monoxide (CO), Carbon Dioxide (CO2) and Hydrogen (H2) as well as traces of Hydrogen Fluoride (HF).

### 4.3.2. Gas combustion

Depending on the gas emission temperature and the contact conditions with air, the gas can self-ignite in air, adding the thermal energy of this additional combustion process to the thermal run-away.

The gas self-ignition and combustion will be avoided when,

- the temperature of the exhaust gas remains below 350 to 400°C,
- the gas or the ambient atmosphere are sufficiently diluted with an inert atmosphere (in order to reduce the Oxygen/Hydrogen ratio below the combustible mix limit of 4%).

On the contrary, the gas combustion will happen when,

- the gas temperature is over 350 to 400°C when it comes in contact with air.
- The gas temperature is lower, but the combustion starts due to an ignition in presence of air (by another flame, a spark or a hot point).

In case of combustion in air, the emitted gas may have the composition detailed in Table 5, below.

| Molecule | Concentration (%) |
|---|---|
| N2 ( min) | #65 |
| CO | # 3 |
| $CO_2$ | # 27 |
| Other combustion residues | # 5 |
| Including HF | 10-100 ppm |

**TABLE 5. Indicative composition of gases emitted during the self-ignition of components of a Lithium-ion battery**
*(SOURCE:Saft)*

### 4.3.3. Heat generation during thermal run-away

Concerning the heat generation, the parameters used to characterize the severity of the event are the total heat release (in mega-Joules/kilogram of battery, MJ/kg) and the Heat Release Rate (HRR, in mega-Joules/battery surface unit, MJ/m2).

In case of run-away, the total heat release will depend of the reaction completion. In order to provide some quantitative information, the data presented below corresponds to the worst case scenario which includes gas combustion. These data have been measured on Lithium-ion batteries by several Institutions: INERIS, Sandia National Laboratory, Tiax and Saft ( REFERENCE 2,3,4 and 5). According to these studies, large variations can be observed depending on the cell design and other parameters such as composition of the electrodes, type of casing, plastics contents, etc…and the testing conditions.
In FIGURE 7, a comparison is supplied between the heat release from a Lithium-ion Battery and other combustible materials. The analysis of this FIGURE confirms that the maximum heat release rate is very comparable between a Lithium-ion battery and gasoline while the total heat released is much lower for the battery. This is particularly illustrated in Figure 8 where the total combustion energy per unit battery (kg) is compared with the same parameter for gasoline.

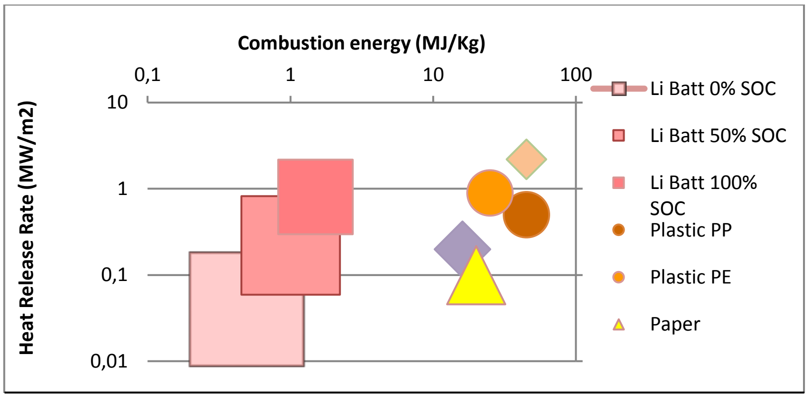
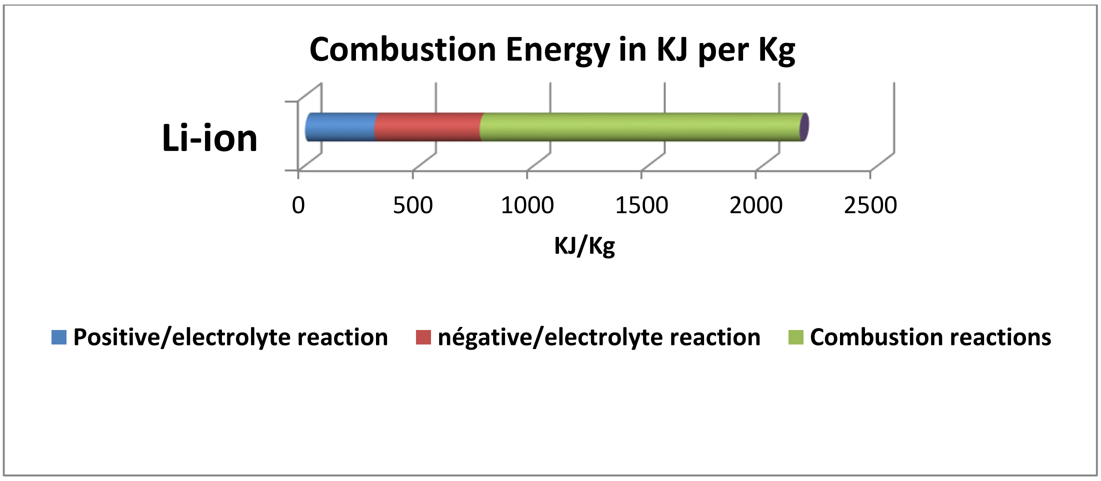


**FIGURE 7. Correlation between the heat release rate and the combustion energy for various materials including the Lithium-ion battery.** *(SOURCE: Recharge).*



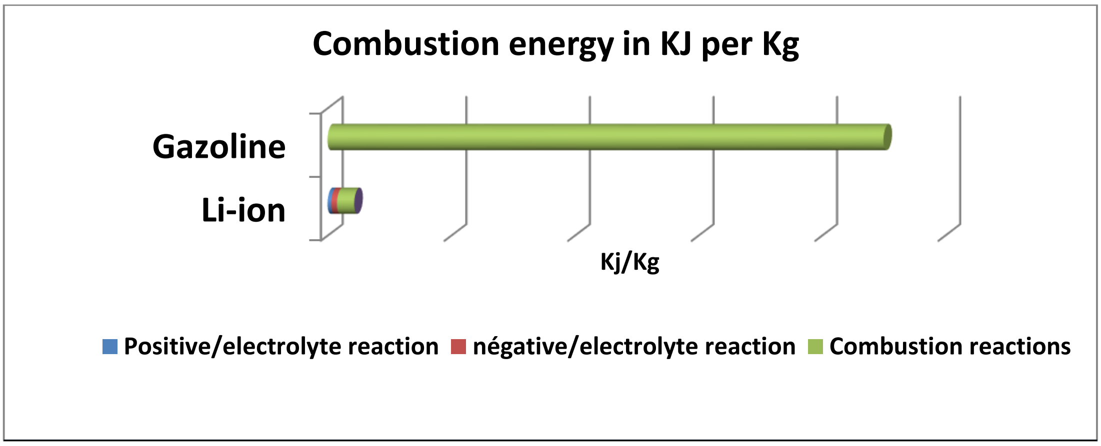


**FIGURE 8. Comparison between the combustion energy of components of a Lithium-ion battery and gasoline.** *(SOURCE:  Recharge).*

This type of information is very useful to size the protections for mitigation of the run-away consequences. In the same way, the knowledge of the risk of fire and associated fumes allows the appropriate measures to be taken to manage the consequences without creating an uncontrolled event.  This part is described in the paragraph 5 .

# 5. Lithium-ion battery safety management

## 5.1 Safety management approach

Potential hazards may not represent the same risk for the user, depending on the application: for example, fumes emissions may be considered as very dangerous in confined areas ( car, houses, etc…) but not in remote open spaces ( solar farms for example).

As illustrated in FIGURE 9 below, **Step 1** of the safety management approach starts with an analysis of the battery functions, and their interactions with the environment. This is called the "preliminary hazard analysis" and **"hazard identification".** At this stage, it is intended to cover all the aspects of the lifecycle: Design and qualification, Manufacturing, Transport, Use and End of Life. It results in a list of potential hazards for a given application, and the associated Safety Integration Level (SIL). The approach is coherent with the existing standard IEC 61508: "Functional safety of electrical/electronic/programmable electronic safety-related systems". In addition, the potential **failure mode** needs to be anticipated (**Step 2**).

The safety management will then consists in designing the product and the application in order to:

**A: Prevent the potential hazards (Step 3)**: this phase is called the "Hazard source control", it consists of setting up protections against the failure risks and/or the environment stressing condition: the **prevention** measures.

**B: Minimize the potential hazard and its consequences (Step 4):** this phase is called the " hazard control". Concerning the battery system, the event consequences can be minimized through **mitigation**:

- reduce sensitivity
- reduce reaction
- break reaction chain

Limiting consequences of the potential hazard on the environment is also an important avenue: this has to be developed in coordination with the application, in order to set efficient **protection** measures.
The global approach is resumed on the following scheme:

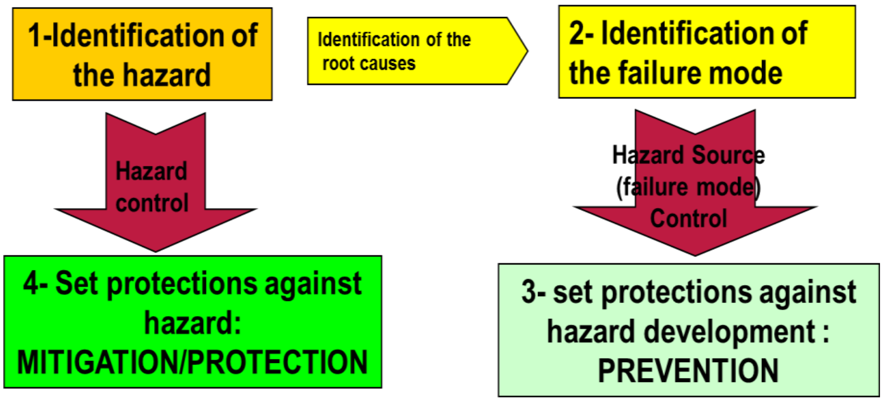
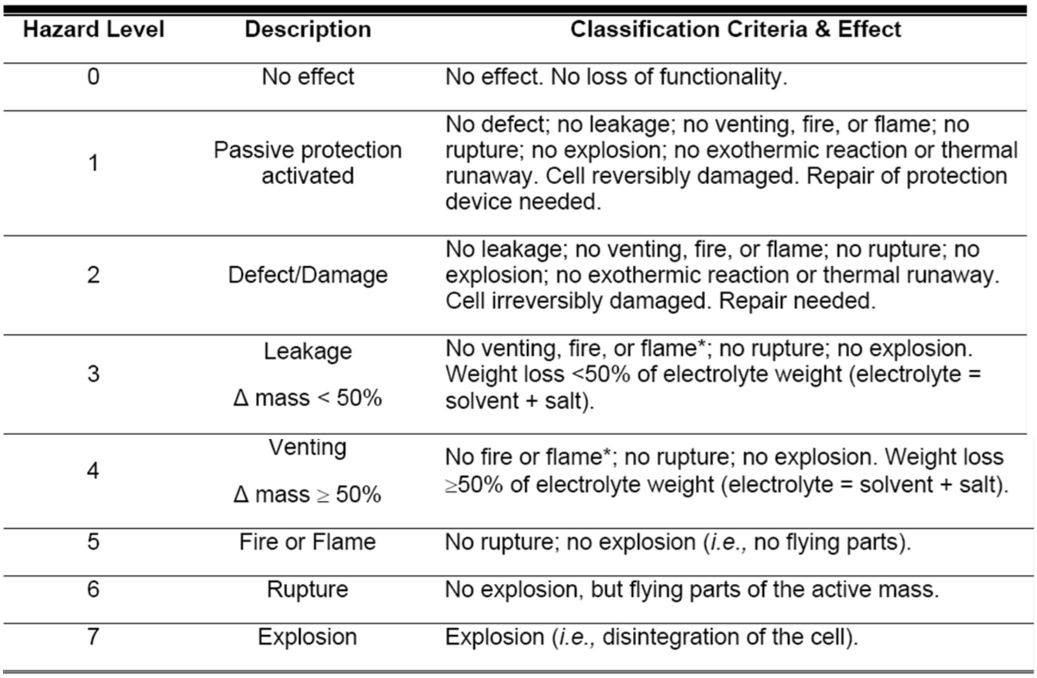


**FIGURE 9. Schematic approach to Hazard identification and remediation.**

## 5.2. Safety standards

EUCAR has developed a scale to define a level of danger for automotive applications. It is now widely used, as it helps describing the type of potential hazard observed with a Lithium-ion battery. The various hazard levels defined by EUCAR are described in the next Table.



| Hazard Level | Description | Classification Criteria & Effect |
|---|---|---|
| 0 | No effect | No effect. No loss of functionality. |
| 1 | Passive protection activated | No defect; no leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell reversibly damaged. Repair of protection device needed. |
| 2 | Defect/Damage | No leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell irreversibly damaged. Repair needed. |
| 3 | Leakage<br>Δ mass < 50% | No venting, fire, or flame*; no rupture; no explosion. Weight loss <50% of electrolyte weight (electrolyte = solvent + salt). |
| 4 | Venting<br>Δ mass ≥ 50% | No fire or flame*; no rupture; no explosion. Weight loss ≥50% of electrolyte weight (electrolyte = solvent + salt). |
| 5 | Fire or Flame | No rupture; no explosion (*i.e.*, no flying parts). |
| 6 | Rupture | No explosion, but flying parts of the active mass. |
| 7 | Explosion | Explosion (*i.e.*, disintegration of the cell). |

**TABLE 6. Various hazard levels defined by EUCAR for the use of a battery in an Electric Vehicle.**

In Table 6, level 4 is often considered as a “safe” behavior of the battery, particularly in the automotive application. Nevertheless, it should not be used as a general scale of hazards for other types of applications.

In general, there is a relationship between the level of event created by a battery and the severity of the environmental conditions. Logically, there is a threshold in all type of stresses (mechanical, thermal, electrical) above which the battery start reacting.

In order to specify the level and nature of stress, as well as the expected consequences, a large number of standards have been created either by international organism like UN, IEC or ISO or by private organizations.

These standards are based on two major types of tests.

- Some have as objective to test the battery’s robustness limits: they focus on the nature and intensity of stress possibly creating a potential hazard on a Lithium-ion battery. By example, the temperature resistance test is often specified at 130°C to 150°C, with exposure times for 10 to 60 Minutes, because it is close to the limit where these exposure conditions may ignite the battery. These tests are often called “abusive tests”.
- Other tests have the objective to validate the compatibility of the battery robustness with the application environment. Their focus is the test of the application stress on the battery: for example, vibrations tests simulating the expected vibrations during use in an automotive application.

Most of these standards also describe the expected tests results, with criteria defining the success of the test. This is intended to provide the safety guarantee for the considered application. International standards organizations have generated the following safety standards for Lithium-ion batteries (International Electrotechnical Commission (IEC) and International Organisation for Standardisation (ISO).

- IEC 62133-2 about safety requirement for portable battery cells.
- IEC 62660 about batteries for EV/HEV applications : 62660-1 : performances and 62660-2 : reliability.
- IEC 61427 about secondary cells and batteries for renewable energy storage
- ISO 12405 about test specifications for Lithium-ion traction battery packs and systems in Electric Vehicles

A series of requirements for each individual standard is described in Table 7.

| | UN | IEC | | | ISO |
|---|---|---|---|---|---|
| Test Criteria Standard | Part II S38.3 | IEC 62133 | IEC 62281 | IEC 62660-2 | 12405-1<br>12405-2 |
| 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 | | | | | |

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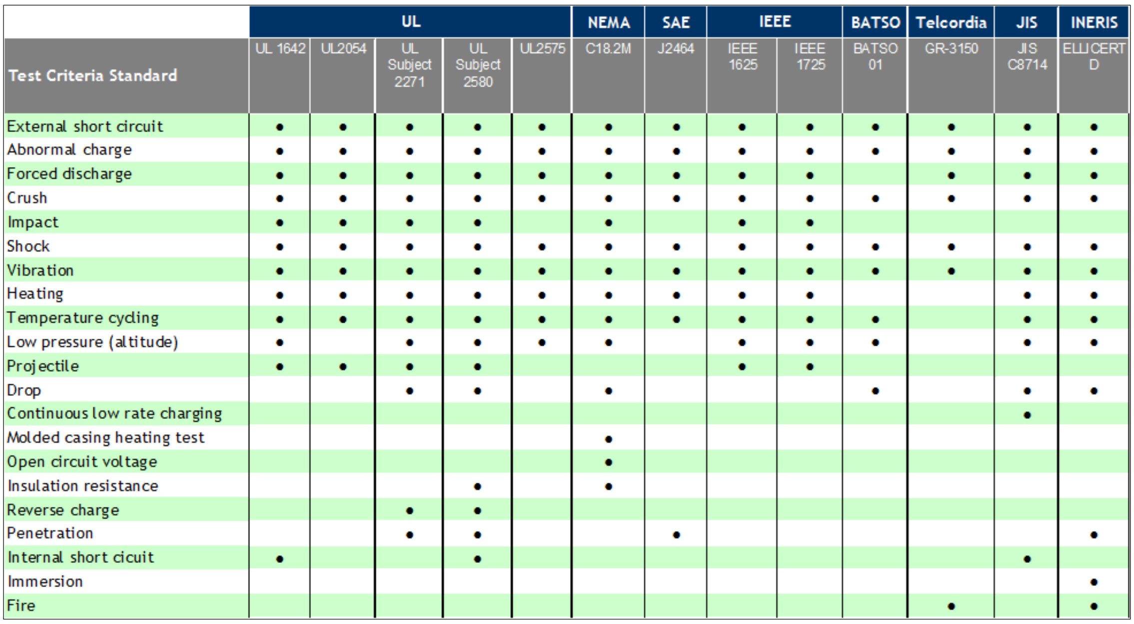
**TABLE 7. List of tests requirements for each individual standard**

Almost all of the IEC standards have been transposed into EN standards by CEN/CENELEC, the European standardisation body.

In addition, several groups of interest or private labels have created safety standards for Lithium-ion batteries. These are listed in Table 8.



| | UL | | | | | NEMA | SAE | IEEE | | BATSO | Telcordia | JIS | INERIS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **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 |
| 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 | | | | | | | | | | | • | | • |

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**TABLE 8. List of tests requirements for individual standard**

As indicated in Table 8, the types of abuse tests are very similar in most of the standards. The advantage is that the main usual safety risks of a Lithium-ion battery are checked in all standards, thus providing a protection to the user.

These standards may have some limitations.

- From the point of view of the application: the user must take care that the standard selected covers correctly the hazard in his own application (some application specific aspects may escape a general standard, possibly allowing unexpected stress of the battery).

- From the point of view of the product: large changes in the product designs between the different products manufacturers makes impossible to test all aspects of a product safety in a single standard. In addition, some products are designed to pass a standard: this may hinder some unexpected behavior.

Finally, the additional risk is about the inappropriate usage of a standard, which may give the battery user the feeling of purchasing a safe product, although the real safety risks have not been validated in practice. This risk can be covered with a preliminary hazard analysis, which will provide a more specific analysis of the real environment (see Figure 9 in § 5.1.).

## 5.3. Safety management tools

In practice, no “single device” is capable of fulfilling all the functions for the battery protection. The safety management is obtained with a combination of

- Technology and materials choices to optimize the performance versus reactivity of materials.
- Cell and battery design to optimize the robustness and resistance to environment stress.
- System design, fit and integration in the application.
- Quality product and process control to guarantee the manufacturing steps quality.

As a result, the global safety of a battery requires a much larger approach than the simple selection of materials showing some lower degree of reactivity. Indeed, fire incidents have already occurred with lithium-ion batteries using less reactive electrode materials such as Manganese Dioxide or Iron Phosphate cathode.

In Figure 10, we provide the description of some of the types of protections which are applied to Lithium-ion batteries. These protection systems can be applied at different levels.

| Level | **Prevention** (prevent the event) | **Mitigation** (minimize the event) | **Protection** (reduce consequences) |
|---|---|---|---|
| Cell | **Root causes** | X | X |
| Module/Battery | X | X | X |
| Application | X | | X |

**FIGURE 10. List of protection measures adopted at various levels.**

Depending on their size and application, lithium-ion batteries will use several of the following safety protection devices.

They are categorized in three main types.

**CELL HARDWARE**

- Cell-Level : Chemical Design Features (electrodes and separator materials)
- Case and Vent Design
- Current interrupt device

**SYSTEM HARDWARE**

- Electronics Hardware
    - Over-Voltage protection
    - Over-Temperature
    - Cell balancing circuitry
- Electrical Hardware
    - Fusing for over-current
    - Contactors
- Mechanical Hardware at module and systems level
    - Optimum thermal management (heat and fire)
    - Structural protection
    - Gas containment or evacuation systems

**SYSTEM SOFTWARE**

- Measurement of battery system characteristics
    - Cell/Pack voltage
    - Temperature
    - Current
    - Device feedback
    - Sensor validity
- Default or failure detection and appropriate control actions
    - Battery status and safety control software

Because they are sensitive to overcharge and deep discharge, all Lithium-ion batteries are protected against short-circuiting and have a voltage and current control. These protections are integrated to one or several printed circuit board (PCB) embarked within the battery.

As mentioned earlier, controlling and managing the temperature of the cells and the battery is one of the most important protection measure to be adopted.

In addition, particularly for large batteries, the Battery Management System (BMS) integrates in the software the control of key operational parameters during usage, including state of charge (SoC), current, voltage and the battery’s internal and ambient temperatures.

The redundancy of the control functions enhances the reliability of the global system. BMS technologies are constantly being developed to store comprehensive information about the battery use (battery information and traceability) and to regulate even more effectively. Current BMS have a communication system (such as a bus-can) to exchange information with the operating system. The global management of the battery can then be coordinated with the user need, including power and energy availability, or cooling systems control.

The mechanical design of the Lithium-ion cells is proven to be resistant to shocks and vibrations and they can be used safely in a large range of temperatures (typically between -20°C and +60°C). Their mechanical protection is largely ensured by the casing(s) of modules and/or of the battery..

The mechanical and electrical design of the battery depends for a large part on the applications constraints. According the usage specification, the battery is designed to be protected efficiently from usual environmental stress (e.g. external impacts, thermal shocks, etc…) while providing the best service. In addition, the adapted mitigation and protection of the potential hazards are incorporated in the mechanical design (vents, thermal protections against fire propagation, gas treatments, etc…). FIGURE 11 illustrates protections used in a laptop battery.

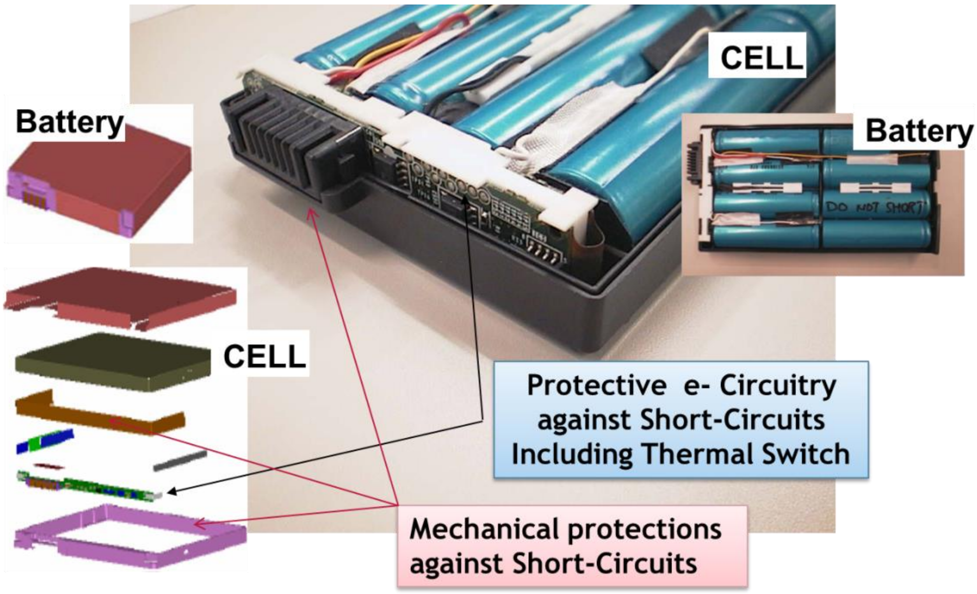

**FIGURE 11. Illustrations of system of protection against short circuits used in a Laptop battery pack.**

For the protection of the battery, organizational and environmental standards are applied by battery manufacturers ensuring that their manufacturing process is uniform and predictable, without anomalies that could cause safety problems later in the lifecycle. The protection against poor design or manufacturing defaults is generally controlled through the Quality Management systems (QMS). QMS applies directly to the design and manufacturing process, and allow companies to warranty its safety and effectiveness during the production of a battery.
The UN Model Regulation for the Transport of Dangerous Goods specifies that Lithium-ion batteries can only be offered for transport when ‘the manufacturer operates under a Quality Management Program’. In practice, this means that all major Lithium-ion battery manufacturers have to follow a QMS that encompasses both external standards and internal company requirements.

There are several important quality standards that a QMS should comply with:

- ISO 9001- A general set of international standards for the processes that create and control the product quality. The manufacturer must test whether the product meet design requirements, regulatory requirements as well as user needs.

- ISO 14001- The core international standard for designing and implementing an effective environmental management system. Helps companies to assess, manage and continuously improve their environmental performance.

- EMAS - A voluntary environmental management system overseen by the European Commission, with stricter requirements than ISO 14001 in several key environmental protection parameters.

## 6. Conclusion

Safety management is a fundamental measure for all Lithium-ion energy storage systems.

Lithium-ion safety is ensured by a combination of prevention, mitigation and protection systems:

- An application hazard analysis is necessary to adapt the design of the system for each specific application
- Protections are required at all levels: cell, module and battery. Lithium-ion batteries are equipped with electronic protections, mechanical design and electric design incorporating the necessary redundancies in the risk control chain to ensure the reliability of the safety functions

All Lithium-ion batteries are equipped with individual electronic protections to avoid electrical misuse (minimum and maximum voltage protection, current protection, etc…). Their mechanical design makes them resistant to shocks and vibrations and they can be used safely in a large range of temperature (typically between -20°C and +60°C). In order to guarantee the reliability of these protections, the necessary redundancies are introduced in the hazard control chain.

Global systems safety can only be ensured at system and application level. Large battery systems communicate with their operating system in order to coordinate the safety control with the user need, including power and energy availability, or cooling systems control.

In addition, the battery and systems are designed to mitigate the consequences of potential hazards, in order to face the situation of default or abusive usage. The design integrates for example specific vents to safely manage the fume exhausts, and large systems have thermal protections sized to limit the fire propagation.

The global approach to hazard management has made the Lithium-ion battery one of the safest energy storage systems. Billions of electrical and electronic equipments powered by these batteries are used worldwide on a daily basis confirming that the safety of Lithium-ion batteries is well managed.

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