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Safety in the battery design: the short circuit

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Abstract

The energy storage system is one of the key components of any electric vehicle powertrain. When lithium based energy storages are used it is important to investigate carefully the safety aspects, because the safety and cost were the main aspects which prevented the introduction of lithium ion in automotive application. This work describes the methods adopted in arsenal research for developing energy storage system for advanced electric power-train. The focus will be on lithium ion battery technology. The correct cell selection and its performance assessment could ensure the achievement of a performing and inexpensive energy storage system. But for ensuring the harmless of the energy storage system a safety concept and a consequent design should be also present. The present work shows the different requirements to take into account for the energy storage system design during the development of HEV and EV vehicles within arsenal research laboratories. Particular attention is given to the abuse conditions and their corresponding test methods during the development phase. The paper presents the safety concerns regarding the short circuit, its measurements method and the failure pathways. Results of short circuit abuse tests are analysed and indication regarding the design is given.

Keywords: Battery, Energy Storage, Lithium Battery, Safety, Short Circuit

1 Introduction

Lithium ion based energy storages offer flexible design and it could become an affordable inexpensive technology; this makes them interesting for automotive. From one side it is possible to design cells with outstanding gravimetric energy density (up to 150 Wh/kg at system level); these are suited for electric vehicle applications where the range is limited by the stored energy in the batteries. On the other side, keeping basically the same raw materials, it is possible to obtain a power optimised cell with few modifications on the cell design. In fact the chemistry principle and the active materials are basically unchanged, the charge carrier is still the lithium ion, the electrode materials are comparable, as well as the electrolyte and the separator. These high power cells can be used in hybrid electric vehicles mainly as power buffer during the acceleration and the regenerative braking phases, as energy source for the internal combustion engine last point shifting, and, when foreseen, for limited pure electric mode. These cells can achieve a power density of more a 4 kW/kg. In figure 1, the Ragone plot shows how the lithium ion technology, thanks its flexibility, covers a large area of the Ragone plot.

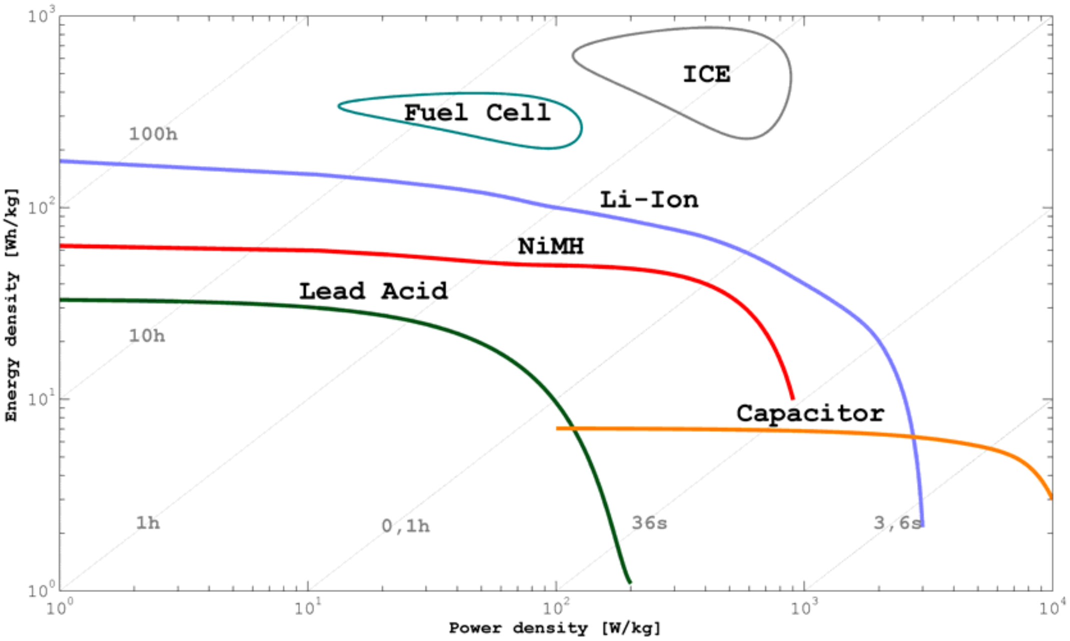

Figure 1: Ragone Plot

Even if the lithium ion batteries are so promising, this technology has been only to a limited extent implemented in automotive mass production, whereas in consumer application it has already replaced nickel metal hydrides batteries. One of the main reasons of the delay is the safety concern about lithium ion technology.
Safety of lithium technology depends on many factors, like: materials, manufacturing, cell and system design, and energy management.
The interactions between these factors make the management of the safety a complex task which should be investigate in detail.

2 High Power vs. High Energy Cell

Whereas in the Ragone plot are shown the different performances between energy and power lithium ion cells, table 1 shows the requirements for each application. It is evident that the battery plays different roles depending on the considered application. In an Integrated Starter Generator (ISG) powertrain or in mild hybrid electric vehicle (HEV) the energy storage system works mainly as power buffer, whereas in a battery electric vehicle (BEV) as energy provider for the motion. The most important parameter is the power/energy ratio. It could be notice that between the applications there are differences of about an order of magnitude (Table 1). Therefore based on the application should be designed and selected the suited cell, which at best fits the application requirments.

Table1: ESS specification for electric powertrain

Powertrain	**P/E**	**Energy [kWh]**	**Power [kW]**	**Voltage [V]**
ISG	>60	<0,6	<6	12
Mild HEV	30-80	<1	<15	12-42
Power HEV	20	<3	20 - 100	>150
Plug In HEV	7-12	5 - 20	<80	>200
BEV	2- 3	>15	20-60	>200

2.1 Cell design and configuration

Nowadays between energy and power cells the material differences are relative. Nowadays for achieving the different performances the designer usually plays on the cell geometry, the sections of the electrode collectors, the thickness of the active materials and so on.
Only to a limited extent the designer modifies the chemical compositions of the materials. Therefore it is important to identify which are the typical cell configurations for automotive application. In figure 2 the typical shapes of automotive cell is shown. On the right a cylindrical shape is shown, which it is usual in industrial and consumer applications and it is also proposed for automotive.

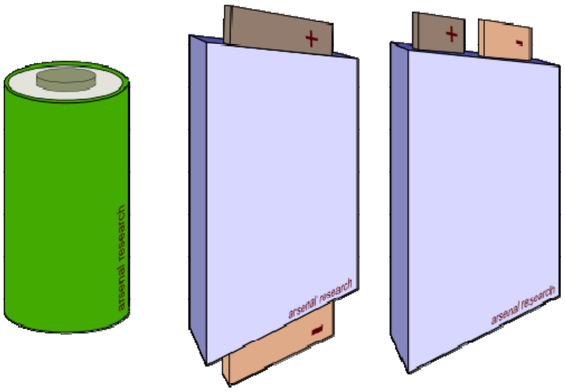

Figure 2: Automotive cell shapes

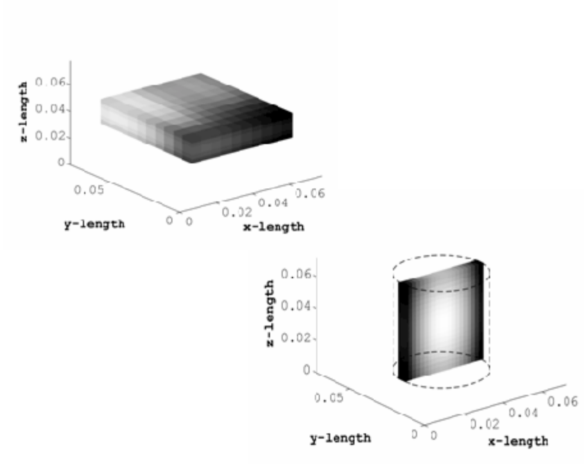

Figure 3: Thermal simulation of prismatic and cylindrical cell

The cylindrical shape offers the advantage of a rigid packaging, usually metallic, which, from the safety point of view, reduces the need for a strong module or system mechanical case. Besides, thanks to the metallic tin the cooling is facilitated, by the way it should be mentioned that the gradient in the cell is higher then in the other configurations, see in figure 3 the thermal simulation of such kind of cell. This temperature gradient, if excessive, could affect the ageing of the cell.

On the other side, cylindrical cells have the drawback that they require more volume. Therefore there are more suited for HEV application where the total Ampere-hours of the battery is limited.

In the middle and on the right side of figure 2 are shown two types of coffee bag cells. These shapes offer a higher surface area for cooling, but for achieving high energy density at system level and for cycling reasons, they are usually grouped together. In this system configuration only the edges of the cell and the tabs area available for exchanging heat with the external environment. Hence the tabs play a crucial role, they are the electrical contactor, so they must have the lowest possible resistance for avoiding power loss and heating. At the same time, they play as heating conductor for taking away the heat from the inner part of cell. Moreover, they are used as fixture points of the cell so they have to be mechanically resistant to a certain extent.

The different position of the tabs influences the thermal behaviour, in case of tabs on the same cell side the temperature gradient will be higher than in the other configuration, see also figure 3 where is depicted the temperature distribution of this kind of coffee bag configuration. Therefore, this configuration, the extreme right one, is more suited for energy cells where the losses are usually less due to the less demanding current profile and the lower power/energy ratio.

The last configuration, in the middle of figure 2, with tabs on the two opposite sides is more suited for power cells.

3 Triggers of the internal short circuit

The short circuit events could be triggered by different causes. Usually it is the punctual perforation of the separator which generates a local hot spot. This local hot temperature damages further the separator, especially in case of Polyethylene or Polypropylene separators, which undergo a shrinkage increasing the short circuit area and consequently decreasing significantly the internal resistance of the short circuit.

The perforation of the separator could be caused by an external mechanical puncture, as in case of a crash or a failure of the fixture system with consequent damage of the cell package. But it is also likely a short circuit due to internal breakdown of the cell. For instance, when an impurity is present in the cell, or in case of incorrect cell energy management design where the cell undergoes too quick charge phases with resulting lithium plating, which with the passing of time could perforate the separator triggering the internal short circuit.

4 Thermal Runaway as consequence of short circuit

With the term “thermal runaway” is meant a not controlled and irreversible increase of the internal cell temperature. There are different

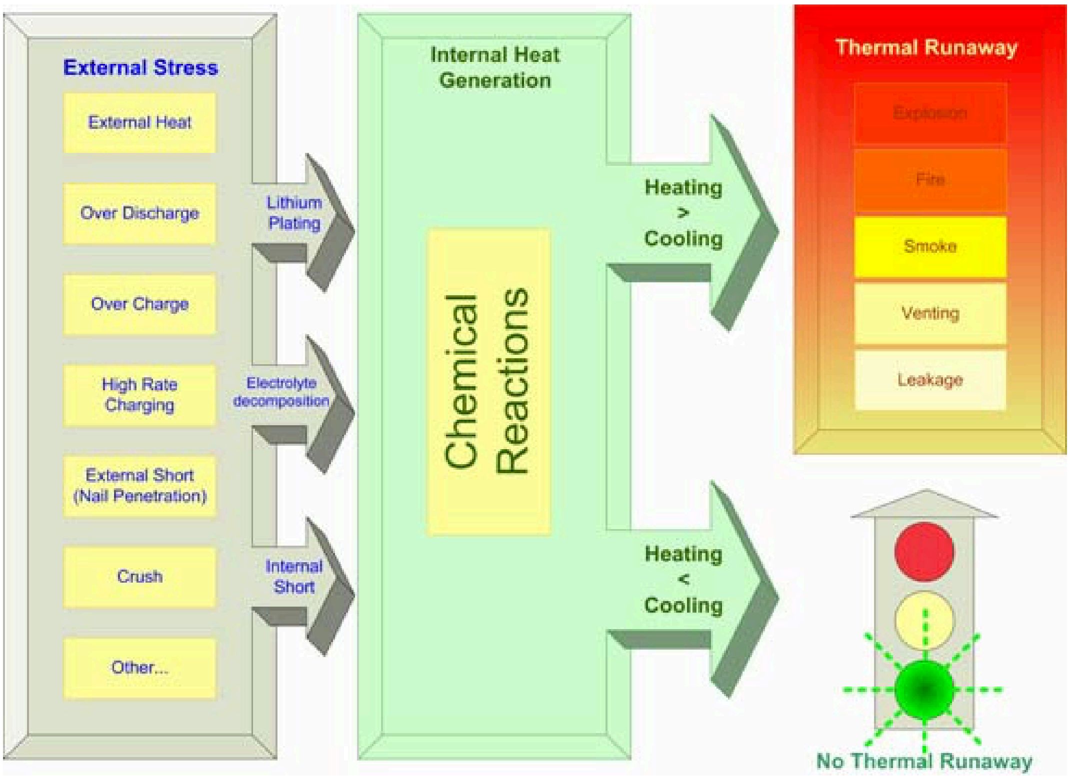

Figure 4 Thermal runaway pathway

events which triggers a thermal runaway. Generally, the thermal runaway takes place every time an over heat occurs and a critical temperature is exceeded. One of event which could trigger a thermal runaway is the short circuit event.

The reason why the thermal runaway should be always avoided is the likely chance of break down effect within a battery package. A cell may undergo a thermal runaway, and it could only in few improbable worst case explode or get burn, but also in case of not disruptive events its releases heat which it might trigger next cells increasing substantially the chance of disruptive event.

The critical temperature of the thermal runaway depends on the type of active material used for building up the cell. Nowadays the most critical components are the electrolyte, the separator and the anode active material. For instance in case of a carbon based anode, at temperature lightly above 115°C an exothermic reactions of the anode takes place. These reactions trigger other reactions, like the separator ones, the electrolyte one and at the end the cathode ones. All of them release heat. This heat should be dissipated otherwise the disruptive occur take place.

The figure 4 shows in detail the pathway from the causes to the thermal runaway event showing also the important role of the cooling system and the heat release rate. If the system is able to dissipate the generate heat then the hazardous consequences of a thermal runaway could be avoided.

For reducing the chance of thermal runaway the research is focusing in better monitoring system which should be able to identify in advance critical conditions. As well as the research is looking for better materials which are more chemically and thermally stable in abusive conditions, which do not form lithium metal and not release oxygen. Last but not least for reducing the chance of thermal runaway the research is focusing in not flammable electrolytes and in the introduction of shut down separators which are able in case of overheat to close the micropores for interrupting the ionic transport between the electrodes.

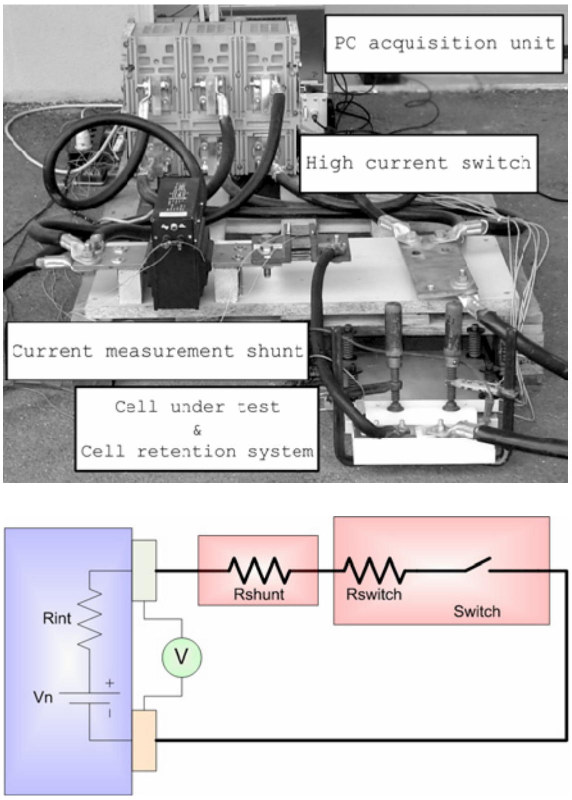

Figure 5 Short circuit test device

5 Short circuit test device

The measurement of short circuit in a reproducible and safe way is a complex task which requires a suited facility.

From one side the measurement equipment should be able to measure current of few thousand amperes, and at the same time it should be enough sensible and dynamic to detect correctly the peak currents at the beginning of the short circuit event. On the other side the power interrupter should be able to handle durable high short circuit currents, introducing together with the wiring as less as possible additional impedance to the system.

This special task is essential for obtaining comprehensive and useful results. In fact if the external resistance is too high the outcomes show currents lower, therefore more conservative, then the effective possible ones. Based on these outcomes are sized the fuse and the protection relays. Hence this incorrect assessment of the short circuit current brings to an underestimated sizing of the fuse and the protection switch units.

Regarding the wiring it is important to underline the issue of the contact between the electrode tabs and the external circuit. This contact is critical because an effective junction by simple pressing contact is difficult, a welding is also

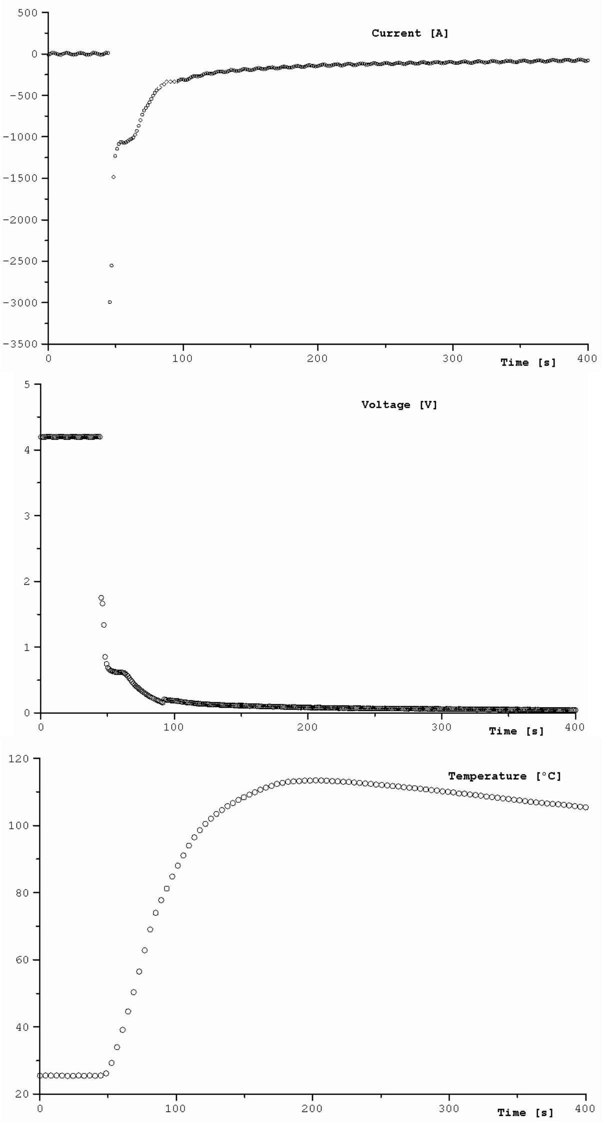

Figure 6 Example of short circuit test result

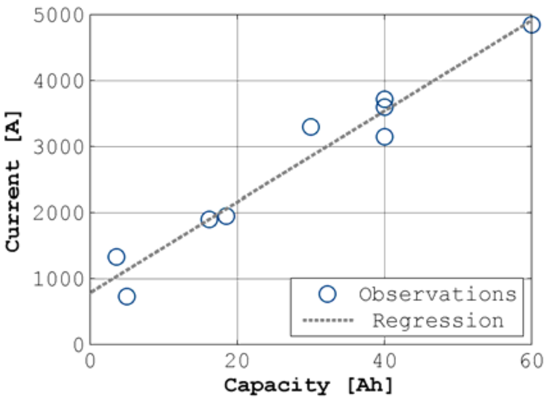

Figure 7 Cell size and short circuit peak current relationship

difficult because the heat could influence the result. A laser welding would be suited but of course at almost prototype development level it is usually not adopted.

In figure 5 is shown the short circuit test configuration, and its corresponding circuit schematics, used in arsenal research laboratories. However some devices are not shown in the picture, for instance the thermal camera which it is used for having a temperature images as supplementary input to the thermal sensor, the high speed camera, used for which it is useful when disruptive events takes place, or like the gas analysis unit for better understanding which reactions took place in case of venting or fire

6 Short circuit test results

In arsenal research have been tested different cell types (power optimized and energy optimized) with different cell sizes, and different shapes (cylindrical and prismatics), and, last but not least, various chemistries.

In figure 6 is presented the typical result in term of voltage and current of a short circuit test proceeded with the equipment previously described, the relative temperature trend is also shown. Here it is remarkable to notice how within few seconds the cell heats itself of about 100 degrees, however the temperature stays below dangerous values, so that it can be stated that the cell have withstood the abuse test.

7 Test result discussion

Only recently are available automotive ready for production cells. For that reason the abuse test on automotive cell is a quite new discipline where some aspects of the testing and the standard are still not completely defined.

7.1 Pressed cell vs. cell in free space

The standards for laminated cell do not specify in which configuration should be the cell tested. Up to our experience the cell shows different results depending on the test configuration. It is a fact that a cell tested in free space usually shows different abuse performance than a cell pressed into a battery package, mainly due to different cooling that they have.

Sometime the cell in free space shows worse performance then a pressed cell. This happen in case of overcharge test, whereas in case of short circuit due to the better cooling of the cell, in comparison to the pressed configuration, it could show better performances. For that reason, in our understanding it is advisable to proceed with the test in both configurations.

Regarding the difference between energy cells and power cells, it is still not possible to define well defined trends. The energy cell, due to the higher specific internal resistance shows higher specific heat than a power cell. On the other side the energy cell is bigger hence it has a bigger heat capacity where it can store the additional heat. So, chance by chance, depending on the cell, on the type, and the size of the electrode contacts the results could be different.

For instance, in case of not correctly designed electrodes, during a short circuit *hot spot* near the electrode contacting area could occur. This hot spot could trigger in some cases a thermal runaway, whereas in other cases only an electrolyte decomposition with gas evolution occurs with likely consequent venting.

Comparing the result of energy cell with power cell, the energy cell achieves a higher final temperature, but with a slower temperature rate, due to the bigger thermal capacity. A factor which plays against the energy cells is the capacity, thanks to the higher stored energy the short circuit lasts longer than in a power cell, where the short circuit event and the heating practically have an impulsive character.

7.2 Results generalisation

The designer engineer for reducing the ESS time and the cost development is interested in a simulation tool able to forecast the short circuit phenomena, in particular the peak current for sizing the switching units. The development of such a simulation tool for investigating the short circuits phenomena requires a CFD simulation approach. This requires a big effort because not linear electrochemical, electromechanical, and thermal phenomena take places, which to some extent are even not completely known.

Due to this extreme complexity, for solving the short circuit prediction problem also the empiric approach is investigated. The target of the arsenal research's research was to identify the parameters which mainly affect the short circuit phenomena.

On the base of the gained experiences in short circuits abuse tests it has been seen that one of main parameter is the ***short circuit peak current-capacity ratio.***

It has been seen that it is a useful parameter which could help the designer in the prediction of

short circuit peak current in the early design and sizing phase of the protection system.
Figure 7 shows the clear relationship between the size of the cell and the observed peak short circuits current. It has been also observed that to some extent the results are independent from the chemistry of the cell.

The power cells are usually small sized, from 1 up to 15Ah, they have low internal impedance, whereas the energy cell can even have a capacity above 50Ah, and they usually have an higher specific internal resistance.
For that reason the short circuit peak current-capacity ratio between the energy and the power cell is not spread.

7.3 Cell level test vs. module/system level test

Experience showed that short circuit tests at cell level are not exhaustive for assessing the short circuit power capability of a specific cell. A cell that withstands a short circuit test at cell level may fail in a short circuit module or at system level. This is even truer as the capacity of the cell increases.
The reason is that at cell level the internal capacity of the cell is comparable with the external short circuit wiring resistance. For that reason short circuit peak currents are limited.
As soon as the number of cells in series increases and at the same time the short circuit test equipment remains the same, the total internal resistance increase and the resistance of the test equipment gets always more negligible. So the problem that the test equipment resistance limits the peak short circuit current does not occur. Therefore, it is suggested to make the final sizing verification of passive elements like breakers, and contactors on the base of the results of module and system level short circuit tests.

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