LITHIUM ION BATTERIES FOR HYBRID AND ELECTRIC VEHICLES – RISKS, REQUIREMENTS AND SOLUTIONS OUT OF THE CRASH SAFETY POINT OF VIEW

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ABSTRACT

The main focus of the current development projects in the automobile industry is on the vehicles with an alternative power train such as hybrid vehicles and electric vehicles. The first hybrid and battery electric vehicles are already available. Companies are working on a final "roll out" for all vehicle classes with high pressure. With the use of these new technologies, some safety issues and risks could take place.

For these kinds of vehicles, the use of lithium ion batteries seems to be the most common approach out of the range and performance point of view. Because of the existing risks, special safety systems have to be developed and included.

How do these existing risks influence the passive safety level of a vehicle and what has to be done to reduce the post crash severity? Within this paper, an overview of the risks of the lithium-ion-technology like chemical and electrical risks that are dependent on the several used chemistries will be given, as well as an overview of the worldwide requirements and existing test configurations. I will discuss the solutions as to why these risks are relevant for the vehicle crash safety, what kind of reactions could take place in a crash event and how the existing battery component tests compare with the common vehicle crash test characteristics. The results of a statistical research according the relevant crash configurations based on the GIDAS- and NASS-databases will be shown, as well as an investigation according to the packaging positions of the lithium ion batteries in the vehicles. Finally an overview of some approaches used by manufacturers concerning crash safety will be given.

A concept of an approach to assess the safety level of a lithium hybrid battery of an electric and hybrid vehicle will be shown. This method includes the used cell form and cell chemistry as well as other influencing factors. It should be noted that the used crush pulses of battery component tests are different when compared with the vehicle crash tests and the characteristic of real world accidents.

A possible finding is that it is necessary to develop and integrate systems that guide the released energy (in a worst case assumption for a crash) of the batteries in a direction away from the vehicle and the occupants. This means to stiffen and weaken the housing of a battery according to the packaging and to include passive cooling systems, which could be helpful after a crash event. This approach is different compared to existing approaches, which are based on using a very stiff housing to protect the battery cells. This may work for smaller batteries, but could be very dangerous for bigger ones.

This study is limited to electric and hybrid vehicles, in which lithium ion batteries are used. To gain the first results, only a small set of available lithium ion battery cells could be used.

INTRODUCTION

It is expected that in 2020 1.000.000 battery electric vehicles will be on the roads in Germany – the German government and the automobile industry defined this goal. Other countries defined goals as well, so the raising of the technology of electric and hybrid vehicles can't be stopped.

All of the manufacturers are still working on vehicles with electric powertrains. They are used in mild hybrids, plug-in hybrids as well as in battery electric vehicles. All of these concepts include a high-voltage system and a high-voltage battery, which can base on several available technologies.

A detailed description of these technologies will not be given because they should be known very well.

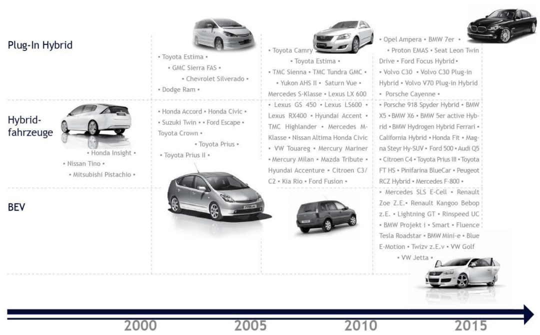

Figure 1: Overview of existing and planned vehicles with electric power train

Different forecast give the information, that in 2015 more than 2.5 up to 10 million vehicles with electric power train will be existing and in use.

LITHIUM ION BATTERY TECHNOLOGY – A SHORT OVERVIEW

Because of their characteristics and behavior lithium ion batteries seem to have the biggest potential for the use in electric and hybrid vehicles. A high energy density combined with a high power output is typical for them compared with other battery technologies like lead acid or nickel metal hydrid. This leads to more compact and low weight battery systems.

As energy storage device in laptops lithium ion batteries are well known and in use since a couple of years.

Because of the higher power density compared with other battery technologies a higher efficiency of the power train can be reached. This results in a lower fuel consumption of hybrid vehicles or in a wider range of electric vehicles.

The so called "memory effect" does not exist for lithium ion batteries.

At the moment the produced numbers of lithium ion batteries for electric vehicles are relatively low; but for the future much bigger sales numbers are expected, which can result in much lower costs and prices.

One milestone for the success of the lithium ion technology was the first series produced system for a hybrid vehicle, which is part of the power train of the Mercedes "S400 Hybrid".

Lithium ion batteries for electric vehicles consist of the cells, the housing with the vehicle interfaces, the cooling system as well as the battery management system.

Figure 2: Parts of a battery system [1, 2]

There are existing different concepts for the single cells, but even if they are cylindrical, prismatic or according to the pouch-concept they consist of an anode, cathode, separator and electrolyte.

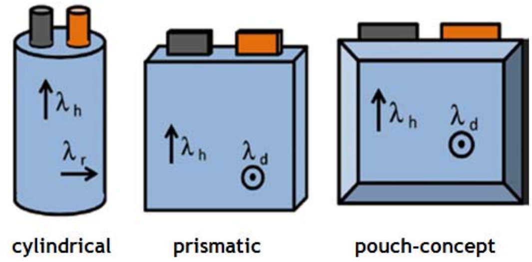

Figure 3: Concepts for single cells [1, 2]

RISKS AND DANGERS OF THE LITHIUM-ION-TECHNOLOGY

The following potential risks and dangers that exist through the use of lithium ion batteries:

- electric danger (short-cut)
- fire and explosion
- danger out of chemical reactions and dangerous goods
- thermal danger out of high temperatures
- mechanical danger because of the higher weight of the battery components

Starting with the assumption that an electric vehicle is „self-safe“ after leaving the factory, electrical risks like short cuts or electric shocks can be caused and initiated by failures of the high voltage system or by physical impacts from the outside, like it happens in a vehicle crash.

In addition these dangers can be caused by misuse or human error of a mechanic, technician or hobby assembler.

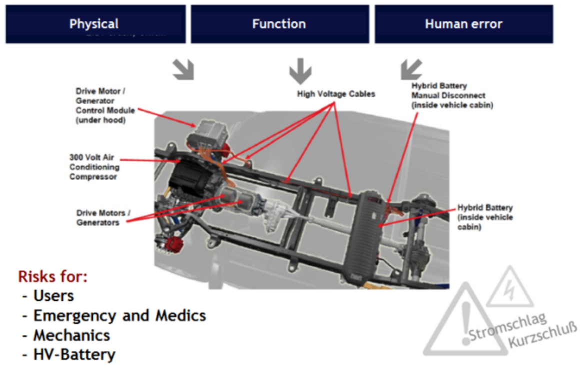

Figure 4: Risks and potential dangers of high voltage systems [3]

Out of the point of view of the high voltage battery potential defects can be caused out of internal and external short cuts, cell aging processes, overcharging and over-discharging, external high temperature or crash events as well.

All of it can cause reactions inside of the battery which can lead to overheating and fire, to the destruction of the separator or to a thermal runaway.

In addition deflagration and explosion are possible, if there is a local gas concentration and an ignition by spark will take place.

Dangerous chemical substances can escape from the component housing as well.

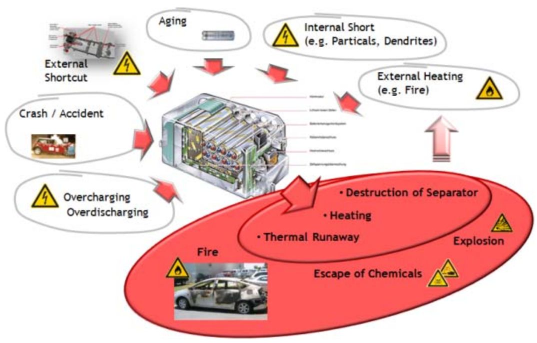

Figure 5: Risks by the high voltage battery [4, 5]

Vehicles which are delivered to the costumer have to be so called „self safe“. That means that by

technical solutions a complete contact and electric arc protection is realized and can be assumed.
Out of this no special risks by the used technology have to be expected as long as the vehicle will be used inside of the defined and allowed limits.
If manipulation of the technical systems takes place, the safety cannot be guaranteed for this case.
That these risks exist and occurring accidents can be seen in the following figure showing electric shock that took place during a Formula 1 race.

Figure 6: Accident during a formula 1 race caused by electric shock of the KERS system [6]

LEGAL REQUIRMENTS AND REGULATIONS OUT OF THE SAFETY POINT OF VIEW

Requirements and regulations are existing on different levels; out of the point of view of the vehicles, the battery systems and the single cells as well. There are requirements from out of the vehicle crash safety, there are regulations concerning the transport, storage and the recycling of lithium ion batteries. In addition there are requirements according to the high voltage safety and the safety at work.

The well known legal requirements out of the vehicle safety point of view are the ECE-R100 and the FMSS 305 respective SAEJ 1766.
The ECE-R 100 describes the requirements according to the approval of electric vehicles in Europe, but it doesn't include any crash requirements. For the crash the vehicles have to meet the crash requirements of the conventional vehicles. Most of the OEM's have special internal requirements, for example the there has to be a protection according to short cuts or fire after a crash test.
The FMVSS 305 and the SAE J 1766 are requirements according to the post crash characteristics of hybrid and electric vehicles. After a crash test according to the impact configurations of the FMVSS 208 the occupants have to be protected against electrical shock and fire. In addition the leakage of electrolyte is limited.
To meet these requirements the electrical components and wires have to be packaged in crash protected areas. In addition the high voltage system usually will be disconnected after a crash event.

There are other legal requirements existing for lithium ion batteries like the UN manual of test and criteria for the transport of dangerous goods. To transport lithium ion batteries in general without exceptions it is needed to pass a test series of in sum 8 tests for the cells and the modules. This test series includes vibration test, temperature and pressure test as well as overcharging, shock and external short test. To pass the test it is not allowed that a fire, explosion, abnormal heating, leakage of electrolyte or a mass reduction takes place.

Other requirements according to storage, recycling and safe handling exist as well, but this depends on the local conditions. For Germany a special safety concept for a development or production site has to be defined and implemented.

Overview Battery Tests

Component test configurations for an evaluation of the crash safety of battery systems are already under development.

There are several test procedures existing, mainly developed and provided by several institutes like VDA, Sandia, UL, ISO, Batso and so on, but most of them were developed years ago for the safety of transport and handling of cells and batteries focused on the use by the costumer in applications like notebooks.

These test procedures consist out of shock, drop, crush, squeeze and penetration test and are very similar from institute to institute.

Most of the test results don't give enough information according to the crash safety of a battery, even if the battery passed all the tests erase. The load characteristic of the test compared with a real crash pulse is completely different and not comparable.

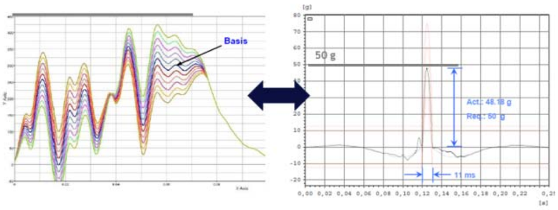

Figure 7: Comparison of crash pulse and safety test pulse (drop test, example) [7]

A different test configuration was developed and introduced by the TÜV Süd in Germany. In these tests different impactor types with a maximum weight of 550 kg will hit and probably penetrate a battery with a velocity of max. 55 kph and an energy input of max. 60 kJ.

The Chinese regulation QC/T 743-2006 is a requirement according to component tests for lithium ion batteries for electric vehicles with a "nominal voltage 3.6V for secondary cell and *n*x3.6V for module (*n* is number of batteries)" [8].

It contains of a couple of tests on cell and battery system level which addresses issues like aging, cycle life, storage, vibration or safety.

Out of the safety point of view several tests have to be done. On the cell level as well as on battery system level over-discharging, over-charging, short circuit, falling heating, squeezing and the needle punch test are part of the requirement. To pass the test a fire or explosion doesn't take place during or after the test.

Especially the squeeze test is quite difficult to pass. On cell level the cell has to be squeezed until the battery case cracks or an internal short takes place. On battery system level the battery module has to be squeezed in a first step to 85% of the original size. In a second step the battery module should be squeezed to 50% of its original size. For the squeezing a special squeezing device should be used.

In addition there are several internal OEM impact test configurations and requirements existing, which have to be met.

The statistical relevance of all of these test configurations according to the real world accident scenario is not verified.

Finally it has to be accepted that it is a myth to believe that the batteries are safe because the passed the tests. In the past all of the battery types passed the required tests (UL and so on) but the history shows that even if they past the tests accidents took place [9]. Some other myths like "ceramic separator solves the problem" or "non flammable electrolytes are the solution for a better safety" are shown in the following figure. These statements about the myth were given at a battery conference in 2010.

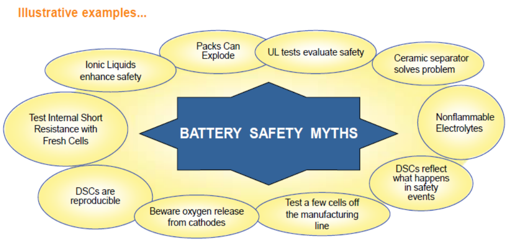

Figure 8: Myth of battery safety [9]

STATISTIC OVERVIEW

In 2009 were 51.8 million vehicles recorded. (according to the data of the German departure for statistic [10]) By the police were 2.3 million accidents registered. Out of this approximately 89,500 accidents were with bigger material damage only and 311,000 accidents with bodily injury.
69 percent of the accidents with bodily damage took place inside of urban areas.

Based on the fact that currently approximately 30,000 HEV's and 1,600 EV's are in use in Germany and a predicted number of 1 million EV's in 2020 it seems to be impossible to predict a realistic accident statistic of HEV's and EV's.
It is for sure that percentage of involved HEV's and EV's will be low. In addition it is for sure that these vehicles – especially the EV's – will be used in urban areas. Because of the speed limits there the crash severities and velocities can be predicted at a lower level.
But it is for sure as well that vehicles with an alternative power train will be involved in accidents in the future.
Out of a statistical analysis basing on the German GIDAS-database crash velocity below 50 kph have to be expected.

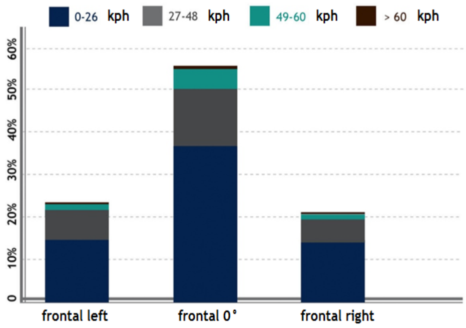

Figure 9: impact velocity for frontal accidents

In result it seems to be that intrusions and penetrations of the batteries will not take place that much. Most of the vehicles are designed to avoid these reactions.
It will be much more important to understand the reaction of the batteries according to acceleration impacts at different levels and directions.
In addition it is needed to answer the question from which acceleration impact level the battery has to be assessed as "defective", for example in result of an low speed crash and without any damage or penetration of the battery housing.

SAFETY CONCEPTS FOR LITHIUM ION BATTERIES

Because of the special characteristics and risks of the battery technology additional safety concepts for the lithium ion batteries only were developed. These safety concepts are working on the three levels cell chemistry, cell and battery system. In addition the protection of the battery system in the vehicle influences the whole safety level.
On the level of the cell chemistry it is important which kind of material for the cathode, the anode, the separator and the electrolyte is chosen. The used combination defines the thermal stability, the lifetime, the charging- and discharging characteristic as well as the reaction during a

physical impact from the outside. It is well known that in china for example lithium iron phosphate is used as material for the cathode. It is the try to get a safer battery by the price of less energy performance.

The choice of the chemistry is important for a possible fire fighting as well. Not every extinguishing media will work well for the used chemistry; sometimes the effect can be worse.

On the level of the cells the design of the housing and the implementation of several safety technologies like a safety vent are defining the safety characteristic. The cell housing protects against impacts and intrusions.

For the battery system the design of the housing is important as well. In addition the battery management system controls and checks the performance (temperature, current, voltage, isolation etc.) of the battery during the use.

The position and the package of the battery as well as integrated additional protection and deformation elements are responsible for the vehicle safety level. A deformation of the battery housing has to be avoided. For the case of a deformation an explosion or a fire can take place.

It has to be taken into account that the position of the battery can influence the dynamic behavior of the vehicle because of the additional weight and the different center of gravity.

Out of this the crash behavior can be different compared with conventional vehicles.

The positioning of the battery is important for the fire fighters and emergency aid too. Is the battery packaged under the hood it is not complicated to extinguish the fire. It is much more difficult if the battery is positioned in the rear part of the vehicle or directly in the middle under the vehicle.

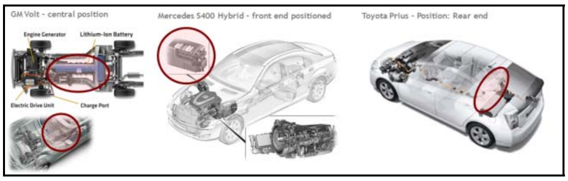

Figure 10: Current packaging and positions of high voltage batteries in vehicles [11, 12, 13]

Finally the chosen cooling system is important for the safety as well. It takes care for the optimal temperature. The temperature is one of the most important factors for the aging behavior of a lithium ion battery. The age of a cell is another important factor according to the failure sensitivity and with it on the risk level of the battery.

At last it should be noted that it is quite common to provide the fire departments with information about the vehicle, the position of the emergency disconnect device, the position and type of the used battery as well as information about the position of the high voltage harness.

DEFINITION AND ASSESSMENT OF A BATTERY SAFETY SYSTEM

The decision for a battery system depends on several factors. First it is needed to define the characteristics like range, power, capacity, volume, weight and the expected cost. Out of this the decision for the used technology, cell chemistry, cooling system, stability of the housing and so on has to be made.

After the first draft of a concept is finished an assessment according to the safety level should be done. This starts with the assessment of the used cell, the behavior during acceleration, penetration, charging and discharging, pressure and temperature.

Unfortunately it is not well known how the reaction of the cells under acceleration effects is. It is recommended to start further investigation according to this issue. A kind of a "landscape", which describes the cell chemistry, the acceleration level and the duration would be helpful to get an overview about the risks and reaction and which levels of acceleration have to be avoided. Out of this the risk for the cells can be assessed. Afterwards a decision for the used cell technology can be made.

In a third step and by knowing the risk level of the cells the safety devices for the cells can be chosen as well as the safety devices for the module. This includes the cell control parameters, the complexity of the battery management system as well as safety vents, the stability of the housings and the packaging.

In last and fifth step the safety devices for the vehicle have to be defined. This includes the kind of the cooling system (liquid or air), the positioning in the vehicle and the implementation of additional crash elements or deformation zones to reduce the acceleration effects. Special constructions like stiffer bars or a cooling system, which works in a passive way during and after the crash, could be very helpful to reduce the overall damages.

Afterwards the battery system should be tested according to the relevant test specifications.

If the target couldn't be reached and the system safety is less than required even if the best available technology was chosen for the modules and vehicles, changes on the cell chemistry have to be done.

With this method it should be possible to develop a safe battery system. The required "acceleration landscape" should be available for several cell chemistries and types within the next years and has to be improved permanently.

CONCLUSION

The use of lithium ion batteries in vehicles is not only important for the future of the e-mobility, it is the key. It doesn't matter for which kind of vehicles it will be used – electric vehicles or hybrid vehicles are possible as well.

There are several risks existing like chemical risk or electrical risk. It is important to understand the technology and the reactions of the material, the cell and the system during an accident. With this knowledge it is possible to design a safe system. An approach for a method is introduced within this paper.

Today's safety technology bases on four levels – the chemical material level, the cell level, the battery module level and the vehicle level. All of these levels are responsible for the final safety level, but they depend on each. An excellent safety rating on one level only doesn't guarantee an excellent safety rating for the whole system.

Out of statistical data's of real world accidents it seems to be more important to focus on the accelerations than on the intrusions. The battery modules are usually positioned in an area inside of the vehicle where an intrusion is less likely. That's why it is recommended to generate a landscape for the different cell technologies (the material and chemistry is included) and their behavior during different acceleration loads in duration and amount.

In addition there are a lot test requirements existing. Currently these requirements are not comparable with the expected load characteristic of vehicle accidents or crash events. Out of this it is needed to define more realistic component tests.

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