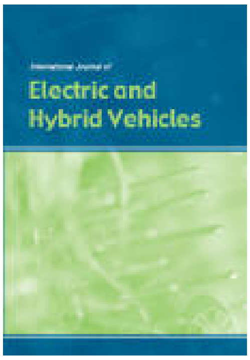


International Journal of Electric and Hybrid Vehicles

ISSN online: 1751-4096 - ISSN print: 1751-4088
https://www.inderscience.com/ijehv

Criteria and integration limitations for cells and thermal management in EV battery pack design: a review

Iban Retolaza, Ander Avila-Limia, Iban Díaz, Maite Elkoro

DOI: 10.1504/IJEHV.2022.10050670

Article History:

Received:	18 December 2021
Accepted:	18 April 2022
Published online:	17 February 2023

Criteria and integration limitations for cells and thermal management in EV battery pack design: a review

Iban Retolaza*, Ander Avila-Limia and Iban Díaz

Department of Mechanical Systems Design,
Ikerlan Technology Research Centre,
P.J.M. Arizmendiarrieta, 2, Arrasate/Mondragón,
20500, Gipuzkoa, Spain
Email: iretolaza@ikerlan.es
Email: ander.avila@ikerlan.es
Email: idiaz@ikerlan.es
*Corresponding author

Maite Elkoro

Design Innovation Center (DBZ),
Faculty of Engineering,
Mondragon Unibertsitatea,
Loramendi, 4, Arrasate/Mondragón,
20500, Gipuzkoa, Spain
Email: melcoro@mondragon.edu

Abstract: Transportation methods are changing, and electric vehicles (EVs) may replace to some extent combustion ones in the short-term. Nevertheless, new EVs technology does not transmit so much reliance due to its safety issues and limited range. Hence, in this paper, an introduction is made to outline EV's current state and safety problems, and it aims to give an overall view of the different available solutions to design a battery pack (BP) and their limitations. Due to the extension of the criteria to design a BP, this paper is focused on the cells (types, integration in the BP, and joining methods) and the thermal safety of the system [how to detect a thermal runaway (TR), battery thermal management systems (BTMSs) and cooling strategies] from the point of view of the implementation to the BP. Finally, some features that limit BP designs in which more research is needed have been identified.

Keywords: electric vehicle; EV; electromobility; battery pack; lithium-ion battery; design criteria; cell joining; cell compression; thermal safety; thermal runaway; battery thermal management system; BTMS.

Reference to this paper should be made as follows: Retolaza, I., Avila-Limia, A., Díaz, I. and Elkoro, M. (2023) 'Criteria and integration limitations for cells and thermal management in EV battery pack design: a review', *Int. J. Electric and Hybrid Vehicles*, Vol. 15, No. 1, pp.1–21.

Biographical notes: Iban Retolaza is a Mechanical Engineer from the École Polytechnique Fédérale de Lausanne (EPFL) University in 1998. In 1998, he joined Ikerlan, working as a researcher in the Department of Mechanical Systems Design. He collaborates in national and EU research projects. His current research interests include DfX methodologies for large size and long-life products with special emphasis on its application to industrial projects materials and also on the design of battery packs.

Ander Avila-Limia is a Technical Engineer in Industrial Design from the Mondragon Unibertsitatea. He is currently studying for his MS in Industrial Engineering from the Mondragon Unibertsitatea and working as a research assistant in Ikerlan. His current research interest is electrical energy storage and is focused on the design of battery packs.

Iban Díaz is a Mechanical Engineer from the Institut National de Sciencies Apliquées (INSA) University, Toluose in 2000. In 2000, he joined Ikerlan, working as a researcher in the Department of Mechanical Systems Design. He collaborates in national and EU research projects. His current research interests are electrical energy storage and focused on the design of battery packs.

Maite Elkoro is a Lecturer and researcher at the Mondragon Unibertsitatea (MU) in the Department of Diseinu Berrikuntza Zentroa (DBZ). She holds a degree in Industrial Design and Product Development and later a Master's in Strategic Design of Products and Services, both from the Mondragon Unibertsitatea. In addition, she has participated in several research projects within the DBZ-MU in collaboration with companies belonging to sectors such as automotive, machine tools, education, etc. She has previously worked in the field of production engineering in CAF and in European research and transfer projects related to the promotion of STEMs, entrepreneurship, design thinking and human centred design. Her current research interests include projects related to the environment and circular economy for Social Economy companies.

1 Introduction

Electromobility is a word that has become common in everyday life. Electric vehicles (EVs) are more affordable than ever before. In 2020 there was an increase of 58% in EV sells and 93% more energy capacity was developed (Kolesnikova and Adamas Intelligence, 2020). Nowadays, Li-ion batteries (LIBs) are the most used ones in the automotive industry, due to their high energy density, high cycle life, and high efficiency (Srinivasan, 2008). They have been enhanced since they were commercialised in the early '90s, and in 2023, it is expected that the cost of the kWh will be below \$100/kWh owing to the research concerning this technology (Henze, 2020). These improvements have inspired carmakers to put faith in EVs. Nevertheless, the governments have also been crucial in this change. For example, Regulation (EU) 2019/631 issues that every manufacturer must have an emission average below 95 g CO_2/km among its annual car sales (the same as 4.1 l petrol/100 km) since 2020 (European Parliament, Council of the European Union, 2019). These policies are part of a process to remove combustion car sales in 2035.

Despite this boost to LIBs, these batteries have several limitations and issues that must be cleared up to become the flagship battery cell type in the future. EVs store energy in battery packs (BPs) consisting of interconnected individual battery cells (Perner and Vetter, 2015). Safety is one of the toughest challenges for LIBs to deal with. As a new technology, it is hard to reassure people, and it is harder if EVs are involved in several accidents because of the battery every year.

A LIB can fail if it suffers different types of abuses in its lifetime. The most common mechanical damages are the loads that the assembly must withstand in a vehicle (Stephens et al., 2017). The resistance of the housing to projections of debris or the impact that may suffer in a crash should be considered. Moreover, the random vibrations due to irregularities in the asphalt can generate great fatigue and wear that affect the structure of the BP and the ageing of the cells. Hence, the parts of the system must be well fixed and protected (Zwicker et al., 2020).

This system also needs to manage its thermal behaviour. The hardest issue to achieve is to keep the cells within their limited operating temperature range of 15–35°C (Pesaran et al., 2013; Pesaran, 2002). It must be borne in mind that, in the different connections that are made among cells or modules, there is a resistance in which energy losses are generated by the Joule effect (Zwicker et al., 2020). This heat can result in a rise in temperature inside the battery that is not favourable for it, therefore, an attempt should be made to achieve the smallest possible resistance. This attempt should go with the efficient cooling of the system not to exceed this range. Additionally, having considerable temperature differences within a module is also something that should be avoided ($\Delta T < 5°C$) (Pesaran et al., 2013; Pesaran, 2002), since the uneven thermal expansion that two adjacent cells or two materials can undergo. If they come into contact, plastic deformations or fractures will be generated.

Temperatures above 70–100°C must not be achieved due to the risk of starting a thermal runaway (TR) (Khateeb et al., 2005). This is one of the most important phenomena to avoid in a BP. It is an abrupt exothermic reaction that will produce fire and gases (Börger et al., 2019; Chidambaranathan et al., 2020). Another way to begin a TR is by electrical incidents. The most common ones are an internal or external short-circuit and BP's overcharging or over-discharging. The aforementioned mechanical issues can also start a TR.

Because of the breadth of the topic, this paper is focused on the cells (types, integration in the BP and joining methods) and the thermal safety of the system (how to detect a TR, battery thermal management systems (BTMSs), and cooling strategies) from the point of view of the implementation to the BP. This paper aims to alleviate such concerns at battery designing. The different solutions to fulfil BP's requirements are summarised, with their limitations. In this way, an overall view of the current state of different solutions to design a BP is given.

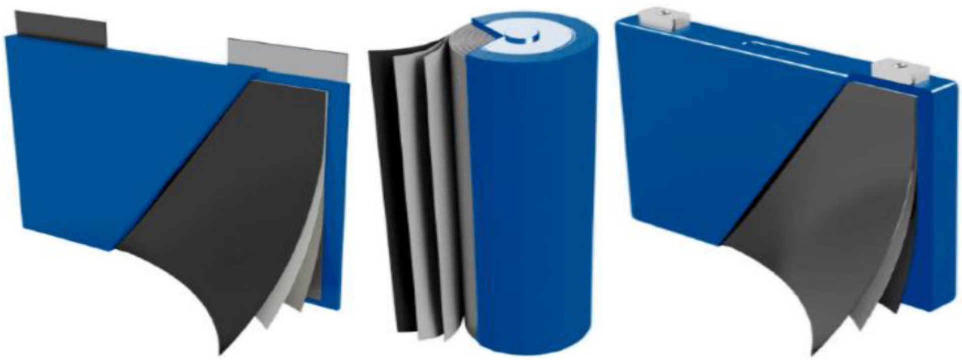
2 Cell integration

The cell is the electrochemical reference unit (Thomas, 2011). A BP is formed by gathering several cells and joining them in series or parallel to achieve a desired voltage and current.

2.1 Cell types

These cells can be classified into three groups regarding their shape. These groups are cylindrical cells, prismatic cells, and pouch cells.

Figure 1 Cell types, (a) pouch (b) cylindrical (c) prismatic (see online version for colours)



(a) (b) (c)

Source: Löbberding et al. (2020)

2.1.1 Cylindrical cells

The cylindrical cell, as its name suggests, is shaped like a cylinder. These cells are made up of a hard casing, usually made of nickel-plated steel, in which the electrolyte and the active material (anode and cathode) can be found rolled up. This shape helps to control internal stresses that can arise during charging and discharging cycles due to expansion of materials or generation of gases (Das et al., 2018). These cells usually have a very low capacity, approximately 2–3 Ah (Flash Battery, 2020). In addition, the sizes are standardised. The most used cells are 18,650 (Ø18 mm and 65 mm high) and 21,700 (Ø21 mm and 70 mm high).

One of the biggest issues with this type of cell is the loss of volume when some of them are gathered. The optimal use of space packaging circles is generated with a hexagonal lattice (Weisstein, 2021). Even with this configuration, about 10% of the volume is not used.

2.1.2 Prismatic cells

Prismatic cells also have a hard shell, but their size is not standardised. They are shaped like a cuboid and vary in length, width, and height depending on the model and manufacturer. Inside the case, the active materials are also rolled, but in this case, ending with a shape that adjusts to the volume of the housing (Christen et al., 2017). Its shape is ideal for the optimisation of space since there is almost no waste of volume when some cells are gathered. The terminals of these cells are usually found on the same face, but far from each other.

2.1.3 Pouch cells

Pouch cells are soft shell cells. They are shaped like a bag and their most frequent shape is rectangular. The active materials inside are interspersed with each other (Raccichini et al., 2019). These types of cells are the lightest, but their drawback is their changing shape. In charging/discharging cycles they swell up and their size varies, making that tolerance an important factor when designing. The size increases by 6% compared to their resting shape (Lee et al., 2003).

The terminals of these cells do not follow a specific configuration. They are located on the edges of the bags, but you can find cases with both terminals at the same edge or opposite edges.

2.2 Cell integration in the BP

As well as different cell types exist, there are also different ways to structure these cells in the BP. Proper cell integration must be done to ensure the requirements that the BP must withstand.

2.2.1 Topology

The internal topology of the BP is classified according to the number of packaging levels it has. There are three different ways to arrange the cells in the BP: modular, cell-to-pack (CTP), and cell-to-chassis (CTC).

Table 1 BP topologies regarding the packaging levels

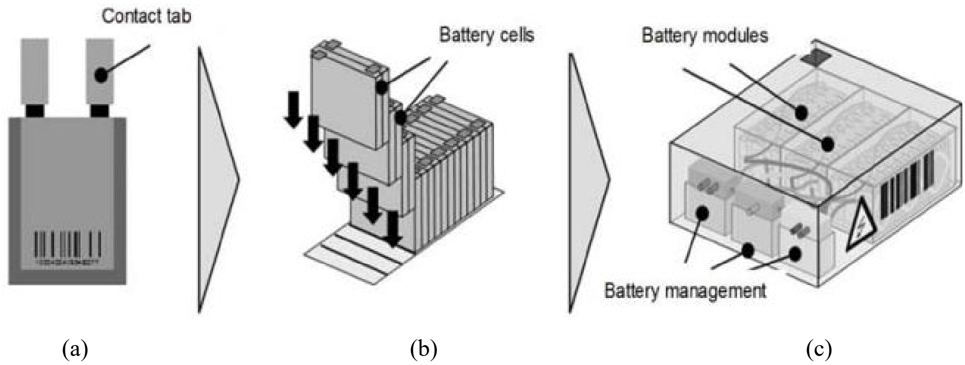
Topologies	*Cell*	*Module*	*Pack*	*Application*
Modular	✓	✓	✓	✓
CTP	✓		✓	✓
CTC	✓			✓

The structure of the BPs seems challenging. It consists of different packaging levels one inside the other one. The modular topology is based on several cells interconnected and packaged in modules. Then these modules are interconnected simultaneously and packaged in a structure or pack. Finally, this structure is installed in the application. Thus, four packaging levels are identified: cell, module, structure, and application.

CTP topology is similar to the modular one, but it removes the module level. Instead, all the cells are packaged in the structure, becoming a three-level BP.

Finally, the CTC topology removes another level of packaging. This strategy packages the cells directly in the application. US Patent 20210159567A1 (Ruddell et al., 2020) reveals a redesigned chassis to create a compartment for the cells and to be able to insert them there. In this way, they eliminate the structure level and the function of storing the cells is added to a part of the application that already has its functionality, such as the chassis, creating a structural BP. The system only has two levels: cell and application.

Figure 2 BP packaging levels, (a) cell (b) module (c) pack



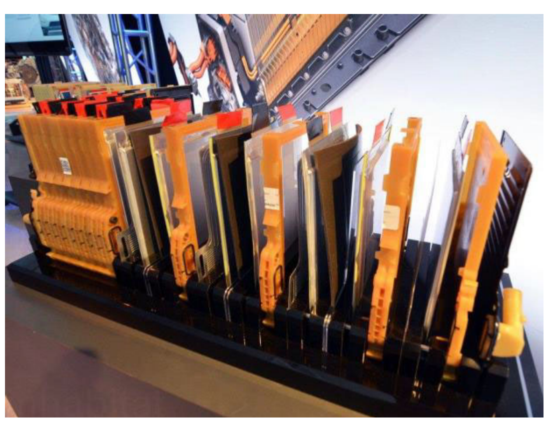
Source: Kampker et al. (2016)

The main difference among these topologies is the subsequent maintenance of the BP and its weight and volume. The more levels removed, the less weight and volume it will have. Consequently, if all the cells are gathered in the same place, it will be more difficult to repair any failure. However, when they are structured in groups, the issue is easier to identify and fix.

2.2.2 Cell compression

On one hand, if pouch cells are used in a BP, it has been observed that they are normally assembled compressed. As they do not have a solid casing, they have little mechanical stability and, therefore, require consistent packaging to favour their operation and safety. The packaging of pouch cells usually consists of interspersing the cells with compression pads, cold plates, or some good thermal conductive material and plastic frames. This packaging turns into compression in the cells which is usually obviated when analysing their lifespan. However, when designing a system, it is essential to know how compression affects the cell, how much pressure should be exerted, and how it should be applied.

Figure 3 Disassembled module of a Chevy bolt EV BP (see online version for colours)



Source: Fehrenbacher (2015)

On another hand, it can be broadly concluded that the effect of the compression in cell's efficiency is parabolic. There is an ideal or optimal pressure and if it is exceeded, it worsens, even having worse performance than without applying any type of compression (Mussa, 2018; Zhao et al., 2017). A slight compression can favour the lifespan of the cell by reducing the losses that occur in each cycle of the cell, helping to maintain contact between the anode, electrolyte, and cathode, and avoiding the delamination of these layers (Müller et al., 2019; Mussa et al., 2018). However, the impedance of the cell increases with increasing pressure, decreasing its power and capacity (Barai et al., 2013). The challenge is in the characterisation of the ideal pressure.

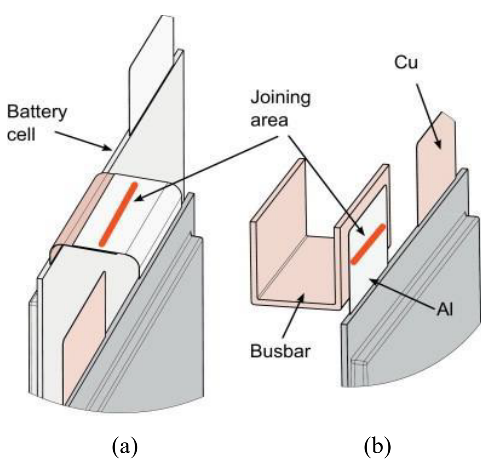
According to Barai et al. (2013), after comparing compressions of 0.02 MPa, 0.04 MPa, and 0.08 MPa in pouch cells, at 25°C the only compression that improves the performance of the cell is 0.02 MPa. They also confirm that at 45°C the cell should be without compression to work properly. However, Müller et al. (2019) compare different fixed and flexible compressions and conclude that the optimal fixed pressure is 0.08 MPa and the flexible one is 0.42 MPa. Nevertheless, Zhao et al. (2017) conclude that a much higher fixed compression, 0.32 MPa, is favourable for the cell. These disparate conclusions insinuate that each different cell has its own optimal compression, and for that reason, a generic ideal compression cannot be defined.

In addition, due to the swelling up of the cells in the charging/discharging cycles and the permanent deformation that they suffer, the applied compression would increase over time. Barai et al. (2017) begin an experiment with a 5 ksi compression, and it increased with a peak increase of 74% after 150 cycles, and 199% after 1,200 cycles.

2.3 Cell joining methods

A BP has many different connections since it is a complex device: closing the casing, fixing the modules, positioning the cells, etc. All these joints vary according to the design, but there is a connection that occurs in all cases and that is the most important to achieve a correct operation: the connection between cells.

Figure 4 Different types to carry out battery connections, (a) tab-to-tab connection (b) tab-to-busbar connection



Source: Solchenbach et al. (2014)

To achieve the necessary energy in the battery connections are made between the cells depending on the configuration. These joints can be of two types: tab-to-tab or tab-to-busbar (Das et al., 2018). Self-evidently, tab-to-tab connections are the ones in which two cells' tabs are joined directly, and in tab-to-busbar connections, the cell tabs are connected to a busbar.

These connections can be done by different methods. The most common ones are ultrasonic welding (UW), resistance spot welding (RSW), laser beam welding (LBW), wedge bonding (WB), and mechanical fastening (MF). The feasibility of each method concerning the cell type is shown in Table 2. Each joining process has its advantages and disadvantages and they are broken down below.

Table 2 Feasibility of cell joining methods regarding the cell type

	UW	*RSW*	*LBW*	*WB*	*MF*
Cylindrical	◐	●	●	●	○
Prismatic	◐	●	●	●	●
Pouch	●	◐	●	○	●

Notes: ●: feasible, ◐: acceptable and ○: not possible.

2.3.1 Ultrasonic welding

UW is a joining process that generates heat by friction between two or more materials. The process is done using a sonotrode and an anvil. The anvil is a fixed structure in which the material is placed and the sonotrode is the moving tool that contacts the materials generating pressure and vibrations at a certain frequency and this way generating friction (Brand et al., 2015). This friction generates plastic deformations in the pieces and consequently the welding between the materials.

UW is mainly used with pouch cells since reaching both sides of the tabs is possible and the process can solder multi-layered foils (Das et al., 2018). This technique is possible with prismatic and cylindrical cells, nevertheless doing it on a large scale is more difficult, due to the complexity in fixing the cells to transmit the vibration and make a good joining.

The biggest limitation with this type of welding is hard materials since they do not work well with friction. However, it is the best process for welding dissimilar materials (Das et al., 2018). It is not recommended to make multiple welds with this method in the same area, since the vibration of a second weld can damage the first one (Zwicker et al., 2020). Weld parameters are very important as well, too much pressure or too much welding time can create an excessive deformation, not creating a good weld (Brand et al., 2015).

Brand et al. (2017) analysed the contact resistance of different joining methods in battery cells. UW seems to have the bigger resistance. In order to reduce it, the joining area has to be increased.

2.3.2 Resistance spot welding

RSW is a joining method by electrical current. To make this type of welding, two electrodes or a two-tipped electrode is necessary. An electric current is conducted from one electrode to the other or between the two tips and passes through the pieces to be joined. The electrical resistance of the materials causes heat until they reach their melting point (Brand et al., 2015). When the two materials are in a liquid state and subsequently solidify, a union will be generated between the pieces.

The biggest problem in this process is the joining of dissimilar materials, since each one, having different melting points, can lead to the case that one reaches its boiling point before the other melts, creating voids and achieving a very low-quality joining (Das et al., 2018). Another problem in this process is the difficulty of welding materials with little electrical resistance. This makes it difficult to generate heat and they are usually materials that cannot be welded using this process.

However, there is a strategy called projection that can solve these problems. This is based on creating deformations in one of the materials to generate smaller contact areas (Das et al., 2018). Hence, all the current is conducted through these specific points, concentrating the generation of heat there and obtaining connections that, otherwise, would not be possible.

This process could be considered the least professional because it is not widely seen in the industrial field, but it is widely used in DIY projects due to the low price of the equipment necessary to carry out the process. Moreover, the generated connections have a quite small contact resistance, and it can be easily reduced by welding more spots in the connection (Brand et al., 2017).

Concerning the cell type, the most common is to use it with cylindrical cells, although it is not dismissed for prismatic cells or pouches.

2.3.3 Laser beam welding

The LBW process is the most versatile since the laser beam can be moved arbitrarily creating any shape in the joint (Brand et al., 2015). In this way, the shape can be optimised for each case. If the welding conditions are good, it is an expeditious process, being able to do up to 54 welds per min (Amada Weld Tech, 2020); in addition to its accuracy, thanks to being able to focus the laser on a specific point. The only thing that must be considered is that the materials to be joined are well fixed and in contact with each other. Unlike UW and RSW, where pressure is applied to the material to ensure contact, here it is welded at a distance from the materials. The air gap that can be left between the materials cannot be welded, so fastening is important.

Despite all its advantages, the process has a great disadvantage: reflective materials such as copper, which is widely used in electrical conduction due to its low resistivity, cannot be duly welded. The reflection of the laser in these materials can damage the surrounding areas (Zwicker et al., 2020) since it tends to reflect red light. As the laser is commonly this colour, the material does not manage to absorb enough energy to be able to weld properly. Therefore, this is a great challenge today for which different solutions are emerging.

Green laser welding has been developing for a few years. The wavelength goes from being 1,064 nm for the red laser to 532 nm for the green laser, achieving high-quality and much more controlled results when welding these types of materials (Amada Weld Tech, 2020).

Another solution that has been found is the high-power adjustable ring mode (ARM) fibre laser (Coherent, 2021). This laser emits a beam of light composed of a ring and a core in which it can divide the laser power between these two areas with a certain configuration according to the need to achieve welding in conditions that would not otherwise be possible.

If a high-quality connection is achieved, it will have low contact resistance. This resistance is reduced by increasing the welded area (Brand et al., 2017). For example, a connection done by two parallel seams has less contact resistance than a connection done by a unique seam.

2.3.4 Wedge bonding

The process of WB is based on the joining of two pieces by welding one or more wires between them. This process is used for joining different components on PCBs; however, it is innovative within batteries. It became known in the industry because Tesla patented this idea in 2006 (US Patent 20100216010A1) (Straubel et al., 2007) and applied it to the BP of some of its models.

The WB is done using a wedge (Powell and Palomar Technologies Inc., 2014). This wedge is the one that positions the cable, welds it, and cuts it. This cable is welded using friction, with the same principle explained previously in the UW.

One of the advantages of this process is that the welded wire can work as a safety feature in the system. Defining a specific diameter to the wire to be welded can make it work as a fuse. In the event of an overload or short circuit in the system, in which a current greater than that specified passes through it, the wire will break, isolating electrically that cell from the rest. For example, making the connections with a copper wire with a diameter of 0.5 mm would suppose a fuse of 35 A (Hesse Mechatronics, 2017). In case of needing very large currents, there is an alternative: ribbon bonding. It is the same process as WB, except that instead of welding a wire, it welds a ribbon.

This virtue is a double-edged sword. Although the function of the fuse is to protect the integrity of the BP, the method of protecting it is by heating the wires. These losses due to the Joule effect are energy losses for the battery and the temperature that rises inside it. For this reason, the operation of the system must be properly tested in case this process is used.

2.3.5 Mechanical fastening

The fixing and joining by this method are done mechanically. This is a great advantage since it is a cold process which means that the cell will not suffer in the joining process by the heat input into battery cells.

There are different strategies for joining two cells mechanically. One of them and the most typical is by nuts and bolts. This process is widely used in prismatic cells, installing threads on their terminals and nuts to fix the joints. Clinching is also a possibility. In pouch cells, for example, two tabs could be clinched (Das et al., 2018). Another option is the mere compression to hold cells with a force applied to the terminals.

MF has low contact resistance (Brand et al., 2017). This resistance can be reduced by polishing fasteners' contact surfaces. This way more area will be in contact to conduct electricity.

3 Thermal safety

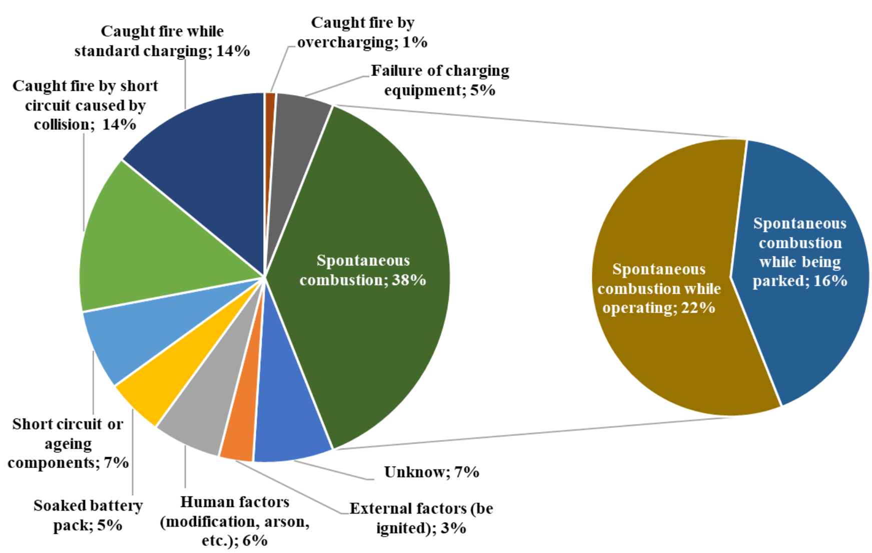
As aforementioned, LIBs are the most widely used energy storage systems because of their specific energy and specific power ratio. These characteristics are very important when it comes to design since, in many cases, the aim is to optimise the weight. However, these batteries need to face a big problem: their safety.

Most batteries heat up in use because the heat they generate is greater than the heat they dissipate (Börger et al., 2019). This gives rise to two of the main problems in the battery: the exceeding of the allowed temperature during charging or discharging and irregular temperature distribution in the system that generates punctual deteriorations (Chidambaranathan et al., 2020). If this temperature rise is not counteracted, it can damage the cell and even cause a TR.

TR is one of the major threats in BPs. TR is an exothermic chain reaction that occurs when a critical temperature is exceeded and heat is generated uncontrollably. If there is no way to extract it, the internal temperature of the cell will increase rapidly with irreversible damage (Börger et al., 2019; Chidambaranathan et al., 2020). Along with this temperature rise, gases also start to be exhausted uncontrollably, which can increase the internal pressure of the system with the danger of generating an explosion.

Current applications demand higher energy density than any previous one and this leads to an increase in the number of cells in the pack (Kim et al., 2019). This, in turn, limits the spacing between cells, and if one cell suffers a TR, it affects the rest more easily. This is what is known as thermal propagation (TP); the sequence of multiple TRs in a system triggered by the TR of a single cell (Börger et al., 2019). Additionally, the term TP is also used for heat transfer between adjacent cells.

Figure 5 A study of 101 xEV fires' causes up to 2019 (see online version for colours)



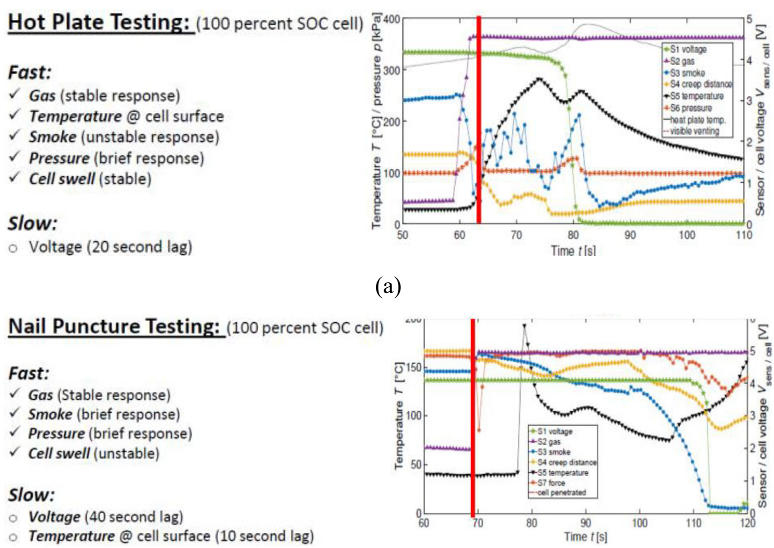
Source: Amphenol (2021)

As mentioned in the introduction, the EV industry has been booming in recent years. This increase in sales has made visible some previously mentioned security issues. Figure 5 shows data from a battery fire report. It classifies several EV fire incidents according to the TR initiation.

38% of the accidents identified were the result of spontaneous combustion in the battery, without knowing the apparent causes. As a result of these accidents, in recent years, the regulations to be considered when bringing this type of product to the market have increased. China has decreed three standards regarding this sector and its safety (GB 18384 2020, GB 38031 2020, GB 38032 2020) (Yu, 2020). In Europe, in 2018, a new standard was published: the Global Technical Regulation No. 20 on the safety of EVs (UN GTR 20) (United Nations, 2018). These two standards cover the whole EV, from some criteria for product design to the tests that they must successfully pass before bringing to the market. For example, the European standard specifies the duties that the vehicle must meet concerning cell electrolyte projection, battery retention, and electrical isolation of the chassis in the event of a collision.

Concerning the thermal safety of the vehicle, both agree that the vehicle must warn its occupants of a thermal problem five minutes before the hazard reaches the occupants' cabin so that they have enough time to safely exit the vehicle. The problem is identified as TP due to the TR of a single cell.

Figure 6 Readings of different sensors two TR tests, (a) hot plate testing (100% SOC)* (b) nail puncture testing (100% SOC)** (see online version for colours)



(a)

(b)

Notes: *the line labelled with 'visible venting' indicates the time when a venting was visible outside the battery housing. **the vertical line indicates when the trigger cell is fully penetrated.

Source: Koch et al. (2018)

3.1 Detection of a TR

As a result of these regulations, the importance of the sensorisation of the internal behaviour of the battery to early detect a TR appears. There are different ways to detect the onset of a TR in the system. Koch et al. (2018) carries out a test using six different indicators to predict which would be the best option. The indicators are voltage drop, gas generation, heat generation, smoke generation, pressure, and cell swelling. The TR of a cell is forced by two processes accepted by the aforementioned regulations: overheating and nail penetration of one of the cells. In Figure 6 the obtained results are observed.

In both cases, the gas seems to be the best option for TR detection thanks to its stable signal and, in contrast, the voltage seems to be one of the worst since its signal delays 10 and 20 seconds respectively in the detection.

3.2 Thermal management strategies

There are different strategies for the implementation of thermal management in BPs. These strategies define if the heat will be dissipated with an active or passive strategy, if the BP is cooled directly or indirectly, from which part of the BP the heat is dissipated.

3.2.1 Active/passive cooling

First of all, it is specified whether the cooling is to be active or passive. Passive cooling means that the environment in which the system is cooled will not be forced. However, if it is done actively, an external power supply is needed to move the environment (Kim et al., 2019). For example, in the case of air cooling, fans are used to move the air. This makes it more effective. Passive cooling can be used in BP with low C rates as they will not need to dissipate as much heat.

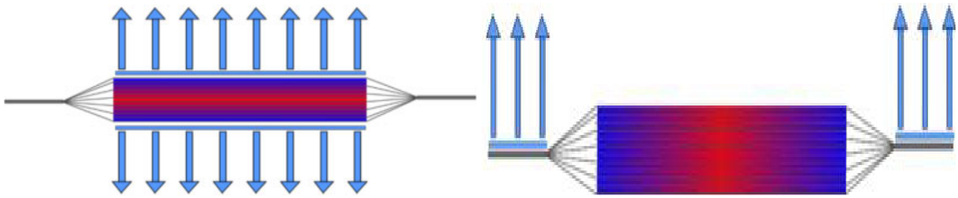
3.2.2 Direct/indirect cooling

Another specification is whether the cooling is done directly to the system or indirectly. Direct cooling refers to being in contact with the part to be cooled directly (Kim et al., 2019). This strategy is not always possible due to the accessibility of the area. Otherwise, it could be cooled indirectly. This method tries to move the heat to a more accessible area and cool it from there. This strategy can be seen in typical pouch cell modules, for example, due to the difficulty of dissipating heat directly from several pouch cells. In these BPs the heat is moved to a side of the module created by frames and then dissipated from that part.

3.2.3 Tab cooling

A strategy that is not seen much in the industry, but that can be used is the cooling from the terminals or tab cooling. Imperial College London has conducted several investigations and argues that it can benefit battery life, especially in pouch cells (Hales, 2019). By cooling from the terminals, a smaller temperature difference is achieved between adjacent layers of active material, resulting in better cell performance. However, it is not always a useful strategy because depending on the requirements of the BP it may not be efficient enough, since if the cooling covers more area, it will be more efficient. To know if this strategy is viable or not, researchers are trying to identify a new feature called cell cooling coefficient (CCC) with which the feasibility of tab cooling can be calculated.

Figure 7 Thermal gradient representation in, (a) surface cooling (b) tab cooling (see online version for colours)



(a) (b)

Source: Hales (2019)

3.3 *Battery thermal management systems*

BTMSs are extra systems that are added to the BP. They deal with cooling to dissipate heat from the battery and heating to increase the cell temperature when it is too low to maintain a proper operating temperature (95). The solutions are mainly focused on cooling the system as high temperatures entail a major hazard.

In addition, BTMSs must meet requirements such as compactness, lightweight, low cost, high reliability, easy maintenance, low parasitic power consumption, and simple packaging for use in EVs (94). Different solutions are available.

3.3.1 *Intumescent material*

Intumescence is the effect of volumetric growth (expansion) of a substance under the effect of heat. The physical phenomenon of this quality deals with the formation of a foamy layer of carbonised materials that works as a thermal barrier to combustion and smoke (Lacosta Berna, 1991). This material can appear in different formats such as paints, plastics, foams, or rubbers. The best-known application is the coating given to structural steel to protect it in fires (Catalá and Comité Productos Protección Pasiva, 2015).

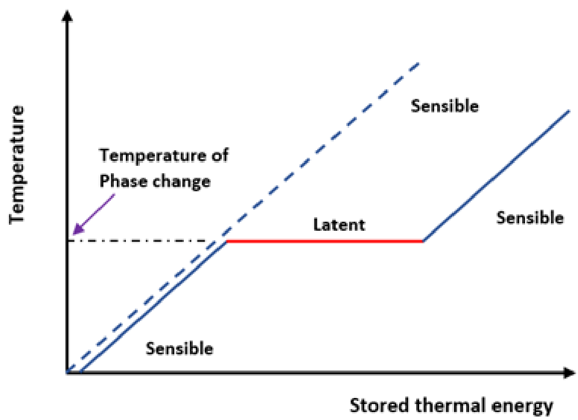
Materials of this type usually have a very low thermal conductivity ranging from 0.1 to 0.4 W/m·K (Luangtriratana et al., 2018). This means that the heat from the fire cannot damage the material to which an intumescent layer is applied. All the heat is absorbed by the charred material which expands. This layer usually expands at critical temperatures ranging from 100–150°C (Lacosta Berna, 1991). As it is used in steel, it can also be used in a BP to protect the cells, the housing, or other specific area from degeneration or even melting. Nevertheless, this protective coat has an issue. The thermal conductivity of the materials is reduced when this intumescent material is applied, so heat will be more difficult to dissipate.

3.3.2 *Phase change material (PCM)*

These materials have another interesting property for thermal management. They can store or release large amounts of heat when their phase is changed, and this phase change can occur at a desirable temperature (Wang et al., 2016). Such materials are introduced into BPs to heat or cool the system with this energy.

In Figure 8 the characteristic curve of a PCM is observed, which shows the reaction of the PCM when it reaches its melting point. It can be seen how the temperature rise slows down during the period in which the PCM is making the phase change (Joshy et al., 2020). Something similar would happen with the temperature of the system. The reverse operation would be the same. Lowering the temperature would also slow down the process because of the energy absorbed by the PCM in heating, which would now be dissipated as heat.

Figure 8 A schematic of sensible and latent heat storage principles of PCMs (see online version for colours)



Source: TK and Raj (2018)

PCMs' main problems are low thermal conductivity, additional weight, as well as leakage problems. Due to its low thermal conductivity heat accumulations can appear during normal or aggressive operations. Because of that, the PCMs must be well-positioned.

3.3.3 Heat pipe

The heat pipe can transport large amounts of thermal energy over considerable distances and at high speed without external energy. For this purpose, the structure only consists of an airtight container and a fluid. It has an evaporation section, an adiabatic section, and a condensation section. The heat source is brought into contact with the evaporation section. This heat will cause the internal fluid to evaporate and due to the pressure difference, it will move to the condensation section through the adiabatic section. There the fluid condenses by heat transfer with the outside. Once in a liquid state, it returns to the evaporation section thanks to capillarity. This process causes the heat from the source, in this case, the BP, to be effectively transported to another place where it is dissipated (Kim et al., 2019).

3.3.4 Fins

Fins are protruding elements that are used in multiple applications to increase the heat transfer surface area (Spakovszky and Waitz, 2007). Convection heat transfer is proportional to the area in contact with the environment. Therefore, fins are designed to increase this contact area and therefore increase the heat transfer. The material of the fin usually has high thermal conductivity to promote convection. It is widely used in air cooling systems to improve the efficiency due to air's low thermal conductivity.

3.3.5 Air cooling

This BTMS can be performed by natural convection by letting the ambient air cool the BP, or forced convection, moving the air around the system (Chidambaranathan et al., 2020). If the convection is forced, the system is more efficient than if it is natural, since the air is constantly renewed, but it supposes a parasitic load to the BP. Blowing air by a fan or a wind tunnel over the cells (direct air cooling), or fins connected to the cells (indirect air cooling), is probably the simplest and most cost-effective way to regulate the system temperature (Arora, 2018). In order to optimise the air-cooling system, the air inlet and outlet channels have to be well-designed and positioned. Locating the air inlet and outlet on opposite sides and avoiding the unidirectional flow are strategies to improve the cooling efficiency (Zhao et al., 2021).

Table 3 Compatibility of different materials with cooling liquids

		Water	*Ethylene glycol*	*Propylene glycol*	*Mineral oil*	*Refrigerants*	*Dielectrics*
Polymers	Commodity plastics	●	●	◐	●	○	◐
	Engineered thermoplastics	●	●	◐	●	● to ○	◐
	Elastomers	●	●	●	●	● to ○	● to ○
Metals	Aluminium	◐	●	◐	●	●	●
	Brass (plated)	●	●	◐	●	●	●
	Copper	◐	◐	●	◐	●	●
	Stainless steel	●	◐	◐	●	●	●

Notes: ●: recommended (little or no potential for chemical reaction), ◐: good option (minor potential for chemical reaction) and ○: not recommended (mild to severe chemical reactions).

Source: Langer and Sekeroglu (2021)

3.3.6 Liquid cooling

Compared to air, liquid has higher thermal conductivity and specific heat and, therefore, BTMS developed with liquid can be up to 3,500 times more efficient than those with air (Arora, 2018). The liquids typically used are water, mineral oils, or other refrigerants. There are mainly three ways to do liquid cooling:

1 Circulating liquid through different jackets or tubes in contact with the system.

2 Circulating liquid through a cold plate. Cold plates are thin pieces of metal with one or more flow channels inside, through which the fluid circulates, and which are placed in contact with the system. This solution is one of the most popular because it does not require great difficulties in design.

3 Immersing the system in the fluid itself. In this case, it must be taken into account that the liquid must be a dielectric. Compared to the first method it is more effective since the liquid is in contact with a larger surface of the system.

When using a liquid, the chemical compatibility of the liquid with the materials with which it will be in contact must be considered. Table 3 shows the compatibility limitations of the most commonly used liquids.

4 Conclusions

This paper has given an overview of the current state of the BP design concerning the cell integration in the BP and its thermal safety. A BP is not a one-size-fits-all system. There are a lot of features to choose regarding its requirements as cell type, cell's configuration, how they will be joined, the BTMS. The target must be clear since the beginning due to the limitations of each choice.

Regarding the cell integration in the BP following limitations must be taken into account:

- More packaging levels your BP has, more easily will be fixed, but the heavier it is and more volume it has.
- If pouch cells are used, applied compression is a feature to be considered. An optimal compression seems to exist for each cell which increases cells' lifespan, but excessive compression worsens cell's efficiency. More research is needed for the characterisation of the optimal compression as it cannot be calculated.
- Minimal contact resistance must be sought. As each cell interconnection has a contact resistance is important to be as small as possible to lose the minimum energy and not to heat the BP. More research is needed to characterise this resistance.

Concerning the thermal safety of the BP following limitations must be considered:

- Regulation regarding BP's safety is changing as these systems are optimised. Nowadays, the most important limitation is that the vehicle must warn its occupants of a thermal problem five minutes before the hazard reaches the occupants' cabin so that they have enough time to safely exit the vehicle. The problem is identified as TP due to the TR of a single cell. More security issues seem to appear in the future.
- The best indicator for TR detection seems to be the generated gas in the BP. It returns an instant and homogenous signal as soon as the TR is initiated. Voltage drop seems to be the worst indicator.
- Tab cooling strategy uniforms adjacent active material layers' temperature and it improves cell efficiency.

- PCMs have potential to support another system in a hybrid BTMS but positioning is key due to their low thermal conductivity. More research is needed in increasing their thermal conductivity.

Acknowledgements

This project was financed by the Basque Emaitek Plus 2020-program which is a partnership of the Basque government and the Cooperative Research Centres (CRC). Partners within this project comprise IKERLAN Technology Research Center and Mondragon University.

References

Amada Weld Tech (2020) *Solutions in e-Mobility | Battery Manufacturing*, Amada Weld Tech [online] https://amadaweldtech.com/solutions-in-emobility-webinar/ (accessed 10 March 2021).

Amphenol (2021) 'Advancements in cell thermal runaway detection – charged EVs', in *Charged Virtual Conference – EV Engineering*, October.

Arora, S. (2018) 'Selection of thermal management system for modular battery packs of electric vehicles: a review of existing and emerging technologies', *J. Power Sources*, Vol. 400, pp.621–640 [online] https://doi.org/10.1016/J.JPOWSOUR.2018.08.020.

Barai, A., Guo, Y., McGordon, A. and Jennings, P. (2013) 'A study of the effects of external pressure on the electrical performance of a lithium-ion pouch cell', in *2013 International Conference on Connected Vehicles and Expo, ICCVE 2013 – Proceedings*, IEEE Computer Society, pp.295–299 [online] https://doi.org/10.1109/ICCVE.2013.6799809.

Barai, A., Tangirala, R., Uddin, K., Chevalier, J., Guo, Y., McGordon, A. and Jennings, P. (2017) 'The effect of external compressive loads on the cycle lifetime of lithium-ion pouch cells', *J. Energy Storage*, Vol. 13, pp.211–219 [online] https://doi.org/10.1016/J.EST.2017.07.021.

Börger, A., Mertens, J. and Wenzl, H. (2019) 'Thermal runaway and thermal runaway propagation in batteries: what do we talk about?', *J. Energy Storage*, Vol. 24, p.100649 [online] https://doi.org/10.1016/J.EST.2019.01.012.

Brand, M.J., Kolp, E.I., Berg, P., Bach, T., Schmidt, P. and Jossen, A. (2017) 'Electrical resistances of soldered battery cell connections', *J. Energy Storage*, Vol. 12, pp.45–54 [online] https://doi.org/10.1016/J.EST.2017.03.019.

Brand, M.J., Schmidt, P.A., Zaeh, M.F. and Jossen, A. (2015) 'Welding techniques for battery cells and resulting electrical contact resistances', *J. Energy Storage*, Vol. 1, pp.7–14 [online] https://doi.org/10.1016/j.est.2015.04.001.

Catalá, P. and Comité Productos Protección Pasiva (2015) *Los Recubrimientos Intumescentes Para La Protección Pasiva Contra Incendios En Fuegos Celulósicos (I)*, Tecnifuego-Aespi [online] https://www.tecnifuego.org/los-recubrimientos-intumescentes-para-la-proteccion-pasiva-contra-incendios-en-fuegos-celulosicos-i (accessed 6 April 2021).

Chidambaranathan, B., Vijayaram, M., Suriya, V., Sai Ganesh, R. and Soundarraj, S. (2020) 'A review on thermal issues in Li-ion battery and recent advancements in battery thermal management system', *Mater. Today Proc.*, Vol. 33, pp.116–128 [online] https://doi.org/10.1016/J.MATPR.2020.03.317.

Christen, R., Rizzo, G., Gadola, A. and Stöck, M. (2017) 'Test method for thermal characterization of Li-ion cells and verification of cooling concepts', *Batteries*, Vol. 3 [online] https://doi.org/10.3390/batteries3010003.

Coherent (2021) *HighLight ARM Fiber Lasers*, Coherent [online] https://www.coherent.com/lasers/fiber/highlight-fl-arm (accessed 9 March 2021).

Das, A., Li, D., Williams, D. and Greenwood, D. (2018) 'Joining technologies for automotive battery systems manufacturing', *World Electr. Veh. J.*, Vol. 9 [online] https://doi.org/10.3390/wevj9020022.

European Parliament, Council of the European Union (2019) *Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 Setting CO_2 Emission Performance Standards for New Passenger Cars and for New Light Commercial Vehicles, and Repealing Regulations (EC) No. 443/2009 and (EU) No. 510/201*.

Fehrenbacher, J. (2015) *2016 Chevy Volt Battery Pack, Inhabitat – Green Design, Innovation, Architecture, Green Building*, Inhabitat [online] https://inhabitat.com/we-test-drove-the-new-2016-chevrolet-volt-and-heres-the-scoop/jill-chevy-volt-2016-test-drive-12/ (accessed 5 April 2021).

Flash Battery (2020) *The Best Lithium Cells for Industry*, Flash Battery [online] https://www.flashbattery.tech/en/cells-lithium-batteries-industrial/ (accessed 23 February 2021).

Hales, A. (2019) *The Effects of Thermal Gradients in Automotive Battery Packs Balancing Strategy*, Imperial College London.

Henze, V. (2020) *Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh | BloombergNEF*, Bloom, 2020 Batter. Price Surv. [online] https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/ (accessed 18 February 2021).

Hesse Mechatronics (2017) 'Wire bonding for EV batteries and inverters: application and process tips from Hesse Mechatronics', in *Charged EVs*.

Joshy, N., Hajiyan, M., Siddique, A.R.M., Tasnim, S., Simha, H. and Mahmud, S. (2020) 'Experimental investigation of the effect of vibration on phase change material (PCM) based battery thermal management system', *J. Power Sources*, Vol. 450 [online] https://doi.org/10.1016/j.jpowsour.2020.227717.

Kampker, A., Heimes, H.H., Ordung, M., Lienemann, C., Hollah, A. and Sarovic, N. (2016) 'Evaluation of a remanufacturing for lithium ion batteries from electric cars', *Int. J. Mech. Mechatronics Eng.*, Vol. 10, pp.1929–1935 [online] https://doi.org/10.5281/ZENODO.1128215.

Khateeb, S.A., Amiruddin, S., Farid, M., Selman, J.R. and Al-Hallaj, S. (2005) 'Thermal management of Li-ion battery with phase change material for electric scooters: experimental validation', *J. Power Sources*, Vol. 142, pp.345–353 [online] https://doi.org/10.1016/j.jpowsour.2004.09.033.

Kim, J., Oh, J. and Lee, H. (2019) 'Review on battery thermal management system for electric vehicles', *Appl. Therm. Eng.*, Vol. 149, pp.192–212 [online] https://doi.org/10.1016/J.APPLTHERMALENG.2018.12.020.

Koch, S., Birke, K.P. and Kuhn, R. (2018) 'Fast thermal runaway detection for lithium-ion cells in large scale traction batteries', *Battery*, Vol. 4, 16pp [online] https://doi.org/10.3390/BATTERIES4020016.

Kolesnikova, A. and Adamas Intelligence (2020) *State of Charge | EVs, Batteries and Battery Materials 2020 H2*.

Lacosta Berna, J.M. (1991) 'Introducción a la tecnología de los materiales intumescentes', *Mapfre Segur. – Madrid*, Vol. 43, pp.41–49.

Langer, E. and Sekeroglu, K. (2021) *Liquid Cooling and the Chemical Compatibility Imperative Understanding Coolants and Components' Materials of Construction – and their Interaction Tech Guide*, CPC, No. 5012 [online] https://www.cpcworldwide.com/Portals/0/Library/Resources/Literature/Guides/CPC-ChemicalCompatibilityTechGuide.pdf (accessed 30 March 2021).

Lee, J.H., Lee, H.M. and Ahn, S. (2003) 'Battery dimensional changes occurring during charge/discharge cycles – thin rectangular lithium ion and polymer cells', *J. Power Sources*, Vols. 119–121, pp.833–837 [online] https://doi.org/10.1016/S0378-7753(03)00281-7.

Löbberding, H., Wessel, S., Offermanns, C., Kehrer, M., Rother, J., Heimes, H. and Kampker, A. (2020) 'From cell to battery system in BEVs: analysis of system packing efficiency and cell types', *World Electr. Veh. J.*, Vol. 11, 77pp [online] https://doi.org/10.3390/WEVJ11040077.

Luangtriratana, P., Kandola, B.K., Duquesne, S. and Bourbigot, S. (2018) 'Quantification of thermal barrier efficiency of intumescent coatings on glass fibre-reinforced epoxy composites', *Coatings*, Vol. 8 [online] https://doi.org/10.3390/COATINGS8100347.

Müller, V., Scurtu, R-G., Richter, K., Waldmann, T., Memm, M., Danzer, M.A. and Wohlfahrt-Mehrens, M. (2019) 'Effects of mechanical compression on the aging and the expansion behavior of Si/C-composite|NMC811 in different lithium-ion battery cell formats', *J. Electrochem. Soc.*, Vol. 166, p.A3796 [online] https://doi.org/10.1149/2.1121915JES.

Mussa, A.S. (2018) *Durability Aspects of Fast Charging, Mechanical Constraint, and Inhomogeneity in Lithium-Ion Batteries*, KTH Royal Institute of Technology School of Engineering Sciences in Chemistry, Biotechnology and Health.

Mussa, A.S., Klett, M., Lindbergh, G. and Lindström, R.W. (2018) 'Effects of external pressure on the performance and ageing of single-layer lithium-ion pouch cells', *J. Power Sources*, Vol. 385, pp.18–26 [online] https://doi.org/10.1016/J.JPOWSOUR.2018.03.020.

Perner, A. and Vetter, J. (2015) 'Lithium-ion batteries for hybrid electric vehicles and battery electric vehicles', *Adv. Batter. Technol. Electr. Veh.*, pp.173–190 [online] https://doi.org/10.1016/B978-1-78242-377-5.00008-X.

Pesaran, A., Santhanagopalan, S. and Kim, G-H. (2013) 'Addressing the impact of temperature extremes on large format Li-ion batteries for vehicle applications (presentation), NREL (National Renewable Energy Laboratory)', in *30th International Battery Seminar*, Florida.

Pesaran, A.A. (2002) 'Battery thermal models for hybrid vehicle simulations', *Journal of Power Sources*, pp.377–382, Elsevier [online] https://doi.org/10.1016/S0378-7753(02)00200-8.

Powell, J. and Palomar Technologies Inc. (2014) *Ball Bonding vs. Wedge Bonding* [online] https://www.palomartechnologies.com/blog/bid/206846/ball-bonding-vs-wedge-bonding (accessed 11 March 2021).

Raccichini, R., Amores, M. and Hinds, G. (2019) 'Critical review of the use of reference electrodes in Li-ion batteries: a diagnostic perspective', *Batteries* [online] https://doi.org/10.3390/batteries5010012.

Ruddell, S., Madawala, U.K. and Thrimawithana, D.J. (2020) *US 20210159567A1 – Integrated Energy Storage*.

Solchenbach, T., Plapper, P. and Cai, W. (2014) 'Electrical performance of laser braze-welded aluminum-copper interconnects', *J. Manuf. Process.*, Vol. 16, pp.183–189 [online] https://doi.org/10.1016/j.jmapro.2013.12.002.

Spakovszky, Z.S. and Waitz, I.A. (2007) *Unified: Thermodynamics and Propulsion*, MIT Open Courseware [online] https://web.mit.edu/16.unified/www/FALL/thermodynamics/notes/node128.html (accessed 24 February 2021).

Srinivasan, V. (2008) 'Batteries for vehicular applications', *AIP Conf. Proc.*, Vol. 1044, p.283 [online] https://doi.org/10.1063/1.2993726.

Stephens, D., Shawcross, P., Stout, G., Sullivan, E., Saunders, J., Risser, S., Sayre, J. and National Highway Traffic Safety Administration (NHTSA) (2017) *Lithium-ion Battery Safety Issues for Electric and Plug-in Hybrid Vehicles*.

Straubel, J., Lyons, D., Berdichevsky, E., Kohn, S. and Teixeira, R. (2007) 'System and method for fusibly linking batteries' (accessed 16 March 2021).

Thomas, B.R. (2011) *Linden's Handbook of Batteries*, 4th ed., McGraw-Hill Education, New York.

TK, G., Raj, V. (2018) 'Use of phase change material (PCM) for the improvement of thermal performance of cold storage', *MOJ Curr. Res. Rev.*, Vol. 1, pp.49–61 [online] https://doi.org/10.15406/MOJCRR.2018.01.00010.

United Nations (2018) *Global Technical Regulation on Electric Vehicle Safety (EVS)*, GTR, No. 20.

Wang, Q., Jiang, B., Li, B. and Yan, Y. (2016) 'A critical review of thermal management models and solutions of lithium-ion batteries for the development of pure electric vehicles', *Renew. Sustain. Energy Rev.*, Vol. 64, pp.106–128 [online] https://doi.org/10.1016/J.RSER.2016.05.033.

Weisstein, E.W. (2021) *Circle Packing* [online] https://mathworld.wolfram.com/CirclePacking.html (accessed 22 February 2021).

Yu, S. (2020) *New Chinese Safety Standard for Batteries of Electric Vehicles* | Obelis Group [online] https://www.obelis.net/news/new-chinese-safety-standard-for-batteries-of-electric-vehicles-gb-38031-2020-standard/.

Zhao, G., Wang, X., Negnevitsky, M. and Zhang, H. (2021) 'A review of air-cooling battery thermal management systems for electric and hybrid electric vehicles', *J. Power Sources*, Vol. 501 [online] https://doi.org/10.1016/J.JPOWSOUR.2021.230001.

Zhao, Y., Patel, Y., Hunt, I.A., Kareh, K.M., Holland, A.A., Korte, C., Dear, J.P., Yue, Y. and Offer, G.J. (2017) 'Preventing lithium ion battery failure during high temperatures by externally applied compression', *J. Energy Storage*, Vol. 13, pp.296–303 [online] https://doi.org/10.1016/J.EST.2017.08.001.

Zwicker, M.F.R., Moghadam, M., Zhang, W. and Nielsen, C.V. (2020) 'Automotive battery pack manufacturing – a review of battery to tab joining', *J. Adv. Join. Process.*, Vol. 1 [online] https://doi.org/10.1016/j.jajp.2020.100017.