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Safety Enabling Technologies – The case of Li-ion batteries for automotive applications

Relatore/i

firma del relatore (dei relatori)

prof. Demichela Micaela

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Candidato

firma del candidato

Priyanka Krishna Kumar

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List of Figures:

List of Acronyms:

DMC	Dimethyl Carbonate
DEC	Diethyl Carbonate
EC	Ethyl Carbonate
EMC	Ethyl-Methyl Carbonate
PE	Polyethylene
PP	Polypropylene
EV	Electric Vehicles
HEV	Hybrid Electric Vehicle
PHEV	Plug-in Hybrid Vehicle
ICE	Internal Combustion Engine
SOC	State Of Charge
CID	Circuit Interrupt Device
SEI	Solid Electrolyte Interphase
PVDF-HFP	poly(vinylidene fluoride-hexafluoropropylene)
TPP	triphenyl phosphate
TFP	tris-(2,2,2-trifluoroethyl) phosphate
TDP	diethyl phosphate
BMP	bis(2,2,2-trifluoroethl)-methylphosphate
PCM	Phase Changing Material
BTMS	Battery Thermal Management System
EG	Expanded Graphite
BMS	Battery Management System

List of Symbols

SiO_2	Silica
$LiCoO_2$	Lithium Cobalt Oxide
$LiMn_2O_4$	Lithium Manganese Oxide
$LiFePO_4$	Lithium Iron Phosphate
Li	Lithium ion
Cu	Copper

Abstract

Lithium-ion batteries are being used in electric vehicles as a main energy source, since they are light weight, have low energy density, provide better battery efficiency and higher energy output. The depletion of fossil fuels has led to electric energy as the alternate source for automotive industry. The safety of lithium-ion batteries is questionable and extensive research is being done to improve the safety conditions of the battery. This lack of safety hinders the advancements of electric vehicle technologies involving lithium ion batteries. The use of electric vehicles is increasing and are going to dominate the automobile industry in coming years. The safety of the vehicle involving lithium ion battery is a key concern. Fire and explosion of lithium-ion batteries causes fire in the vehicle and sometimes could cause loss of lives. For this reason, the people are sceptical about the safety of the battery powered electric vehicles. This thesis focuses mainly on the different safety strategies that could be employed to ensure the safe and secure performance of the lithium-ion battery. Furthermore, the causes of fire and explosion in lithium-ion batteries are studied and analysed. Thermal runaway has proven to be the main cause of fire and explosion in lithium-ion battery, this thesis also focuses on the preventive techniques that could be employed to overcome thermal runaway process and ensure safety of the battery. Also, the Affordability and cost analysis of lithium ion batteries are studied. From the data obtained with the research study, SWOT analysis for lithium-ion batteries and SWOT analysis for electric vehicles powered by lithium-ion batteries are done in this thesis.

Keywords: Lithium-ion battery, Thermal Runaway, Safety, Prevention of thermal runaway, SWOT analysis.

1. Introduction:

Recent advancements in automotive technologies have made transportation sophisticated. Travelling long distance has become a day to day routine and millions of vehicles travel across states each day, all over the world. The demand for fossil fuel has increased due to the increased production and use of automobiles. Increased use in fossil fuel has resulted in various climatic changes and health hazards due to the gas emission from the automotive vehicles. Greenhouse gases are the mainly emitted from automobiles that use fossil fuel as energy source. The increased use of fossil fuels has resulted in its rapid depletion and the need to protect it for future use.

The need to conservatively use fossil fuels can be achieved by using an alternative energy source for automotive transportation. Electric vehicles have played a major role in 1900's. Even though it had some drawbacks, it is a very good and steady form of energy. The main drawback faced in electric vehicles was the battery capacity. With very limited battery capacity, the vehicle was allowed to travel in contained speed and covered less distance. The cost also played a major role, in order to have good battery capacity the cost and weight of the vehicle multiplied. If the electric vehicles produced in 1900's were to be compared with the recent advancements in automotive industry, it would not stand a chance in efficiency and comfort. With the recent advancements in battery technology, the electric vehicles are brought back to life and are also able to meet the needs of current life.

Lithium-ion batteries are the most commonly used battery source of electrified vehicles and are also used in various commercial applications. Li-ion batteries are used in electric vehicles (EV), hybrid- electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV). The cost of the electric vehicles are a bit higher compared to fuel vehicles. Some countries have started decreasing the production rate of petrol and diesel automobiles. In states which are highly affected by global warming are trying to control the effect by increasing the use of electric vehicles. Lithium ion batteries also have some major disadvantages that can cause fire and explosion to the automobile.

It is vital to create a safe and secure battery system to overcome the disadvantages and to facilitate improved efficiency. This thesis work is focused on understanding the effects of lithium-ion battery, safety concerns, fire or explosion and to discuss the prevention methods.

1.1. Evolution of electric vehicles:

Electric vehicles have been in use since early 1900's, the main disadvantage of the combustion engine vehicle was overcome in the electric vehicle by providing a battery start instead of the traditional crank shaft technique. The electric vehicles were first manufactures resembling a cart with four wheel, the cost was so high and was only used by dignitaries and government officials. The battery capacity of electric vehicles was so minimum and could only cover less distances in between charging. As the cities started developing it was very hard to travel long distances in electric vehicles, since there were no charge points in between and it takes hours for full charge. Electric vehicles were also very costly compared to combustion vehicles and was not easily affordable. Most of the electric cars were leased and electric carts were used in golf courses.

Figure 1: 1903 Baker Electric – There is no steering wheel. It was steered with a tiller, visible above in front of the driver's seat on the left of the vehicle [1].

The discovery of lead acid battery for combustion vehicles lead to the decline of sales and production of electric vehicles by 1920. The crank shaft technique used earlier for staring the vehicles was replaced by lead acid battery. The combustion vehicles were produced with closed body and a next generation level of comfort was introduced in the automobiles. Recharging the electric vehicles took a long time, but in the combustion vehicles it was easy to refill the fuel tank in less than 5 min and continue the trip. In combustion vehicles it was easy to go faster from the start and it had fuel bunks in between cities. As fuel was easily available, the production of electric vehicles was stopped for many years. Now we have reached a limit for fossil fuels and there is an urge to protect the available fuels. The invention of lithium ion batteries has made it easy to meet the needs of the users. Since lithium has no memory effect and are lighter, it is easy to use more cell packs for more battery power. Now the electric vehicles are able to cover a maximum distance of nearly 300 kilometers in between charges. The implementation of electric car charge points are in process to provide easy access for users.

Figure 2: Tesla Model S electric car [2].

The electric cars with lithium batteries are affordable not like the electric cars that were produced in 1900's. For more battery efficiency and power the cost increases and a lot of research is being made on electric car batteries. Though lithium ion batteries have various advantages and has made life simpler, it also has safety concerns that are fatal.

The prediction of the increased use of electric vehicles is done in many developed countries. Some countries are predicted to ban the purchase of internal combustion engine vehicles, a sample of the countries can be seen in the figure. If the sales of Internal Combustion Vehicles is banned as announced by the countries, the sales and production of electric vehicles will be very high and will become a basic mode of transportation. The increased demand for electric vehicle and the mass production of battery pack will lead to the reduced cost of lithium ion batteries. The cost of electric vehicles will become affordable by common man. It is the responsibility of the countries to install charging stations for easy access and to create comfortability for the people.

Country	Current government proposals to ban ICE only vehicle sales
China	Actively considering and studying a ban
France	2040
Germany	2030
India	2030
Ireland	2030
Israel	2030
Netherlands	2030
Norway	2025
Scotland	2032
UK	2040

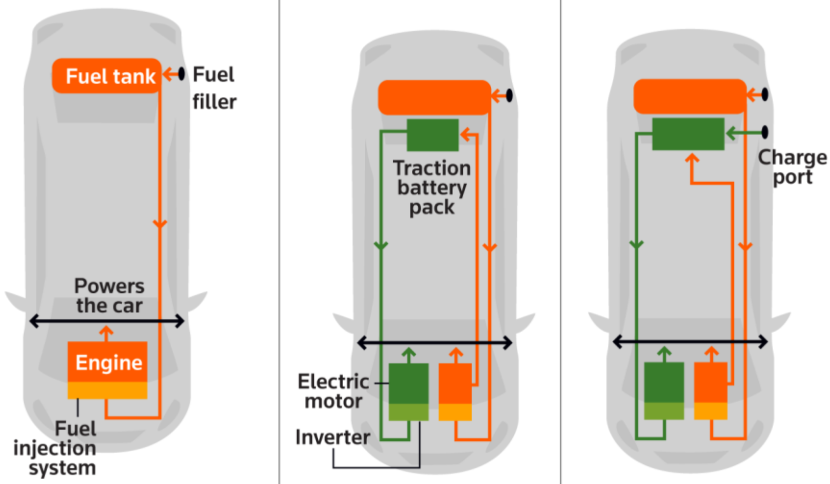
Figure 3: Proposal of countries to ban sales of Internal Combustion Vehicles [3].

1.2. Types of Electric Vehicles:

The introduction of electric vehicles in the automotive industry has occurred in many stages and in different types. The Internal Combustion Engine vehicles (ICE) have been the first and foremost choice in the automotive industry for a very long time, the addition of electric motor in the ICE is a type of electric vehicle known as Hybrid Electric Vehicles (HEVs). In HEVs the vehicle has both the engine and the motor and if the fuel in the vehicle is completely dry, the stored electric energy is used for transmission of the vehicle. The HEVs have a fuel tank and a battery for the electric motor. In the HEVs the battery for the electric motor is charged internally through the working of the engine. The general structure of the HEVs can be seen in figure. Some sample models of HEVs are Toyota Camry Hybrid, Honda Accord Hybrid, Toyota Avalon Hybrid, Kia Optima Hybrid, Ford Fusion Hybrid, Chevrolet Malibu Hybrid, etc.

Types of electric vehicles

CONVENTIONAL VEHICLES	HYBRID ELECTRIC VEHICLES	PLUG-IN HYBRID ELECTRIC VEHICLES	ALL-ELECTRIC VEHICLES
Use internal combustion engines. Fuel is injected into the engine, mixing with air before being ignited to start the engine.	Powered by both engine and electric motor. The battery is charged internally through the engine.	Battery can be charged both internally and externally through outlets. Run on electric power before using the engine.	Powered only by electric motor with no engine. Have large traction battery and must be plugged externally to charge.



Consumption: Fuels	Fuels	Fuels and electricity	Electricity
Driven by: Engines	Engines primarily, motors secondarily	Motors primarily, engines secondarily	Motors
Advantages: Easy to refuel, long driving range and high speed	Easy to refuel, less fuel consumption, less emissions	Easy to refuel, less fuel consumption, less emissions	Environmentally friendly, low maintenance, government support
Disadvantages: More emissions, high cost of fuel	Less power, heavier weight of the car	High price, limited models to choose from, heavier weight	Lack of charging stations, short driving range and low speed, heavier weight

Figure 4: Types of Electric Vehicles [3].

The next development after the HEVs is the Plug-in Hybrid Vehicles (PHEVs). In the plug-in hybrid vehicles, the vehicle uses both the electric motor and the internal combustion engine, the difference from the hybrid vehicles is that there are two options to charge the vehicle. It can run on the combustion engine or the electric motor. The PHEVs have a fuel tank and a battery, the fuel tank is filled with combustion fuel and the battery is charged through the external port in a charging station. The electric motor is the primary source of transmission and the combustion engine is used as backup. It has environmental advantages and less fuel emission and consumption. The general structure of the plug-in hybrid vehicles is shown in figure 4. Some sample models of PHEVs are Hyundai Sonata PHEV, Hyundai Ioniq PHEV, Volvo XC90 AWD T8 PHEV, Cadillac CT6 PHEV, Kia Niro PHEV, etc.

The total environment friendly, emission free vehicles is the complete Electric vehicles. In the electric vehicles the main source of power is the electric battery which can be recharged in a charging station. The electric battery pack runs the electric motor and does not use any engine as in internal combustion vehicles. The battery size in the electric vehicles is very huge than the batteries in PHEVs or HEVs. The battery size is needed in order to completely power the vehicle and to cover distances. The general structure of electric vehicles is shown in figure 4. Some sample models of electric vehicles are Tesla Model 3, Audi e-tron, Jaguar I-pace, Porsche Taycan, Ford Focus Electric, Nissan Leaf, etc. Lot of advancements in battery technology is being researched at a very good pace. The future of the automotive industry depends upon the electric vehicles and it is the next available energy source.

2. Lithium-Ion Battery:

Lithium ion battery comprises of a cathode (positive electrode), an anode (negative electrode), electrolyte and a separator. The separator is porous and it facilitates the transfer of lithium ion during the charge and discharge process. During discharge the lithium ions are transferred from anode to cathode through the porous separator. The separator ensures that the cathode and anode do not come in contact. There are also different types of separators, polyethylene (PE) or polypropylene (PP) are commonly used separators. The electrolyte is a mixture of organic solvents, Li-salt and a number of additives. During electrical charge the lithium ions are transferred from cathode to anode through the separator. The collectors present in the anode (using copper) and cathode (using aluminium) are used to conduct current. The charge and discharge process of a lithium battery is shown in figure 5.

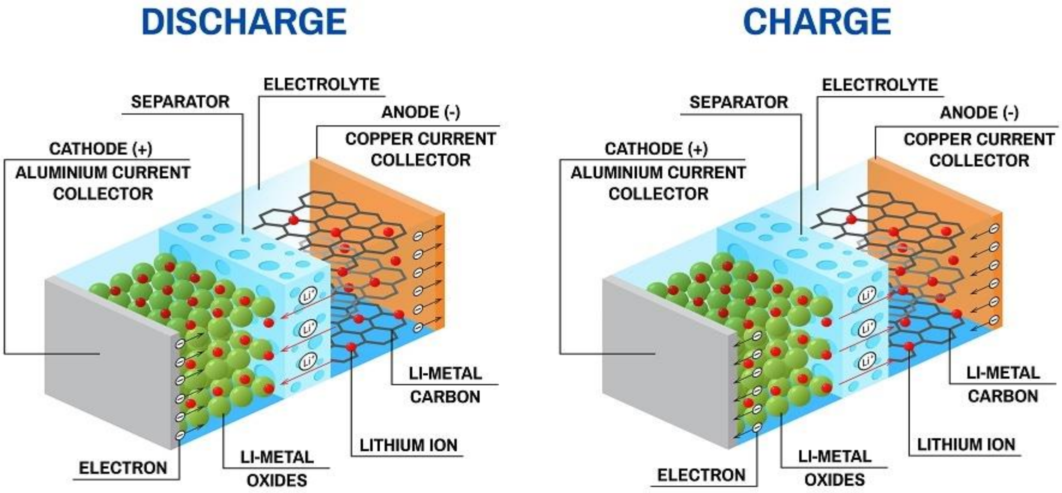


Figure 5: The charge and discharge process in Li-ion batteries [4].

Lithium-ion batteries have a family of battery chemistries that employ various combinations of anode and cathode materials. The performance of the battery and capacity also depends on the different battery chemistry. Lithium-ion cells are most extensively used for rechargeable batteries. Lithium-ion batteries are used in various commercial applications such as cell phone, laptop computers, digital cameras, electrified vehicles and for stationary energy storage in electrical grids. The most important properties of Li-ion batteries are the possibility of fast charging, long lifetime and also the battery has no memory and low maintenance. There are also some drawbacks to Li-ion batteries in terms of safety. The electrolyte is flammable and has limited temperature and voltage ranges. If the Li-ion battery is short-circuited or exposed to high temperature, exothermic reactions can be triggered, resulting in self-enhanced raise in temperature loop known as “Thermal Runaway” that can lead to battery fires and explosion [5].

Li-ion batteries are increasingly used in electrified vehicles such as electric vehicles (EV), plug-in hybrid electric vehicles (PHEV) and hybrid electric vehicles (HEV). The battery sizes differ based on the type of electrified vehicle. Battery failure can be caused due to many reasons such as short circuit, external abrasion, internal short circuit and so on. The lithium ion batteries are used in packs for electrified vehicles. The effect of failure is greater compared to a single lithium-ion battery cell.

2.1. Lithium-ion battery electrochemistry:

For better efficiency and improved working of the battery different cathode and anode materials are used. The cathode and anode materials must support intercalation process of the lithium ion particles. When the lithium ion battery undergoes charging or discharging process the lithium ions are transferred from the cathode to anode and from anode to cathode. The lithium ions position themselves in the vacant structure of cathode and anode respectively, this process is called intercalation. Extensive research is carried on the cathode and anode materials in order to increase the life cycle of Li-ion batteries and to provide safety of the battery in terms of electrochemistry.

2.1.1. Cathode materials:

The detailed study of cathode materials is very important to understand the aging process of the battery and improve its life cycle. The principles required for cathode materials are as follows [6]:

- The discharge reaction should have a large negative Gibbs free energy (high discharge voltage) [6].
- The host structure must have a low molecular weight and the ability to intercalate large amount of lithium (high energy capacity) [6].
- The host structure must have a high lithium chemical diffusion coefficient (high power density) [6].
- The structural modifications during intercalation and de-intercalaltion should be as small as possible (long cycle life) [6].
- The materials should be chemically stable, non-toxic and inexpensive [6].
- The handling of materials should be easy [6].

In this chapter the suitable cathode materials, their capacity is discussed.

2.1.1.1. Lithium Cobalt Oxide ($LiCoO_2$):

Lithium Cobalt Oxide ($LiCoO_2$) remains to be one of the most commonly used cathode material for commercial batteries. The structure of intercalation of CoO_2 in between Li ions can be seen in figure 6. The realizable capacity of $LiCoO_2$ is limited between 140-160mAh.g^{-1} [7]. Cathode materials are trusted to maintain the thermal stability of the battery, the capacity and thermal stability of lithium cobalt oxide is achieved with the help of coatings such as $AlPO_4$ [8]. Lithium cobalt oxide can be synthesised following two processes, low temperature synthesis methods and high temperature synthesis methods. The deintercalation/intercalation reactions of Li have a low potential in LT-$LiCoO_2$ than HT-$LiCoO_2$ and is also highly reactive with the electrolyte and has low transport rate [8]. The main drawback of $LiCoO_2$ is its cost, the cost is so high and cobalt is highly toxic and easily reactive with the electrolyte.

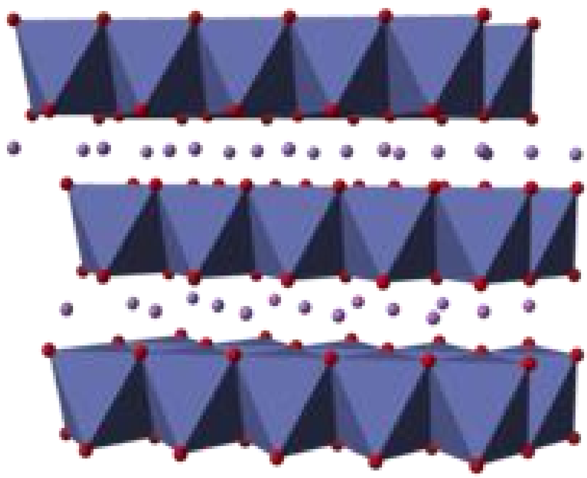


Figure 6: Layered structure of $LiCoO_2$ [9].

2.1.1.2. Lithium Manganese Oxide ($LiMn_2O_4$):

Compared to the above mentioned Lithium cobalt oxide the specific capacity of Lithium manganese oxide is less. Cost of Lithium manganese oxide is cheap compared to cobalt oxide. The advantages of manganese are that is has a higher discharge voltage, less cost compared to nickel and cobalt and has good thermal stability when overcharged and maintains stability. Lithium manganese oxide is employed in a cubic spinel structure, though it has advantages, it has lower specific capacity and lower power compared to the layered structure of nickel oxide and cobalt oxide. In order to make the cost as an advantage, extensive research is being carried out on lithium manganese oxide.

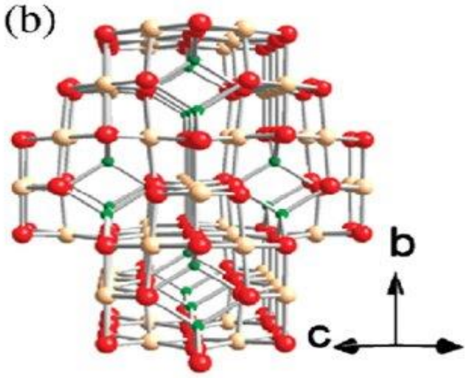


Figure 7: Cubic Spinel structure of Lithium Manganese Oxide ($LiMn_2O_4$) [10].

2.1.1.3. Lithium Iron Phosphate ($LiFePO_4$):

Iron is available abundantly and has basic advantages that qualify it to be used as cathode material for lithium ion batteries. The advantages are iron has low toxicity, low cost and is easily available. $LiFePO_4$ has a very different structure from other lithium ion chemistries, its intercalation mechanism involves phase changing and has a thermal specific capacity of 170mAh.g^{-1}. A $LiFePO_4$/C composite material with a nano-carbon wire network has been shown to have excellent high rate performance, achieving 129 mAh.g^{-1} at a 10C rate and retaining over 90% of its capacity after 400 cycles at 10C [11].

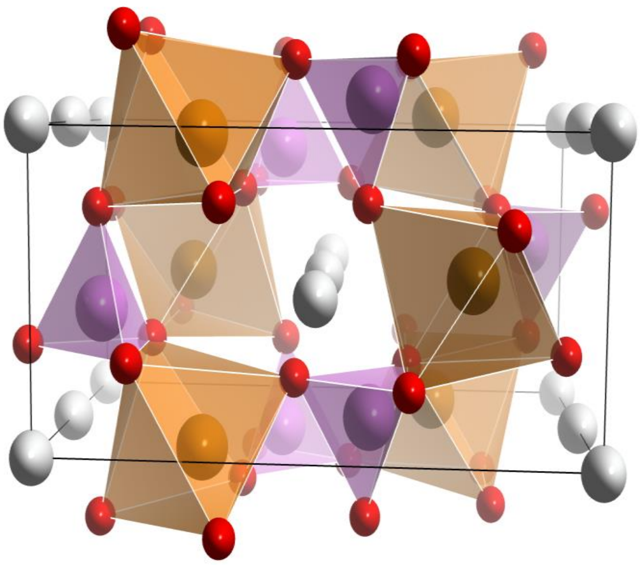


Figure 8: Lithium Iron Phosphate cell structure ($LiFePO_4$) [12].

2.1.2. Anode Materials:

Silicon based electrode, tin based electrode, transition metal based electrodes and carbon based electrode are the most commonly used anode materials. The incorporation of graphene provides stability in extreme environmental conditions, though graphene has low theoretical capacity, its incorporation with anode materials gives good electrical conductivity. Tin based materials have higher specific capacity compared to graphite, but if lithium metal plating occurs in the anode, the depletion of the material is huge in volume and can easily lead to thermal runaway. Silicon based electrodes along with graphene increases the transport capability of lithium ions and the electrons, the release of by-products of silicon weakens the strength of the electron transfer. Silicon is the first alternative for carbon cased anode material. Transition based metal oxide electrodes have high storage capacity of lithium ions, during charging and discharging the volume of lithium ions increase. To overcome the excess lithium production, graphene is incorporated with the electrode. Extensive research is being carried on in order to improve the working of the anode and to avoid lithium metal plating in the anode.

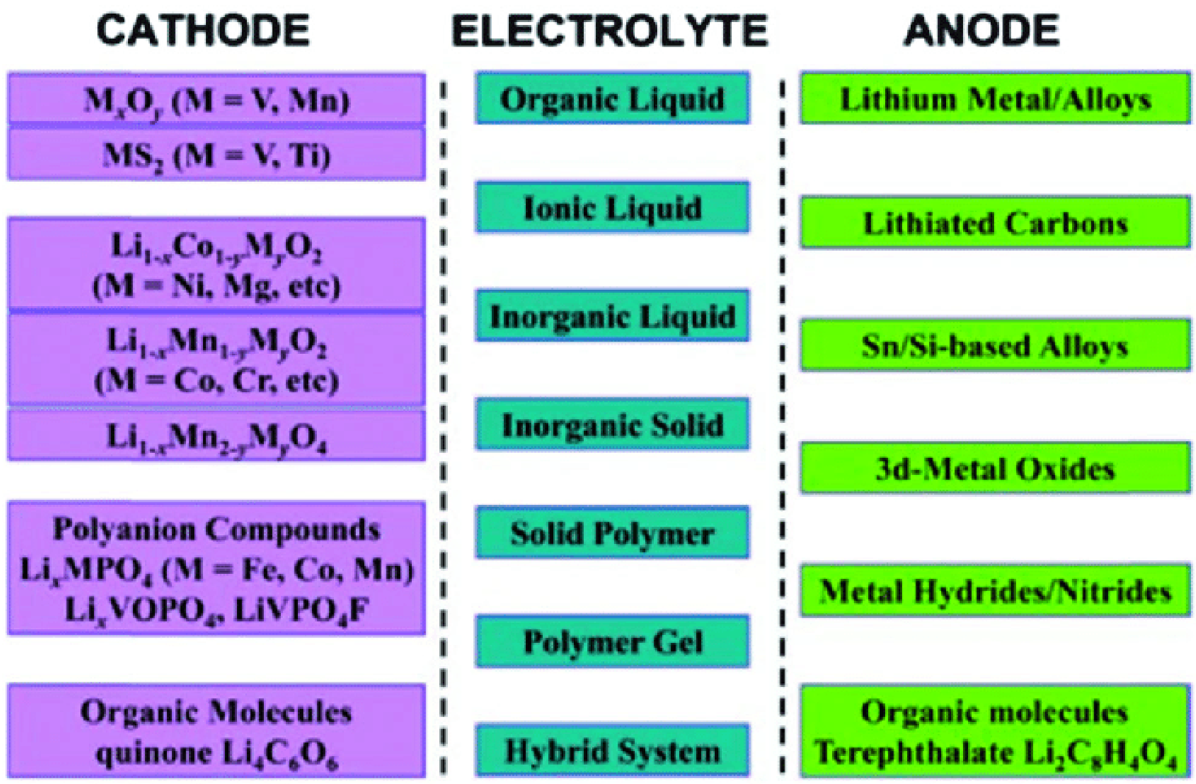


Figure 9: List of different types off cathode, anode and electrolyte materials for lithium-ion batteries [13].

2.1.3. Electrolyte:

Electrolyte is a very important component in any battery. It helps in transferring electrons from positive electrode to negative electrode. In lithium ion batteries, the electrolyte helps in the transfer of lithium ions between the electrodes. A good electrolyte must have high ionic conductivity, low reactivity with other cell components, low toxicity a large window of electrochemical voltage stability (0-5V), and be thermally stable [14]. The role of liquid electrolytes in lithium-ion cells is to act as an ionic conductor to transport lithium-ions back and forth between positive and negative electrodes as the cells are charged and discharged [15]. Some commonly used electrolytes in lithium-ion battery are, dimethyl carbonate (DMC), diethyl carbonate (DEC), ethylene carbonate (EC) and ethyl-methyl carbonate (EMC). The electrolyte used should be chemically stable and be able to conduct lithium salts.

The ideal properties for an electrolyte are as follows [16,17]:

- Large electrochemical window, at least 4.5V for lithium-ion cells with high voltage cathodes.
- High Li^+ conductivity over a wide temperature range.
- Retention of the electrode/electrolyte interface during cycling when the electrode particles are charging their volume.
- Good chemical and thermal stability.
- Low toxicity and low prices.
- Safe materials, preferably non-flammable and nonexplosive.

There are different types of electrolytes such as organic liquid electrolytes, ionic liquids, polymer electrolytes, inorganic solid electrolytes and hybrid electrolytes. Among these organic electrolytes are the most commonly used.

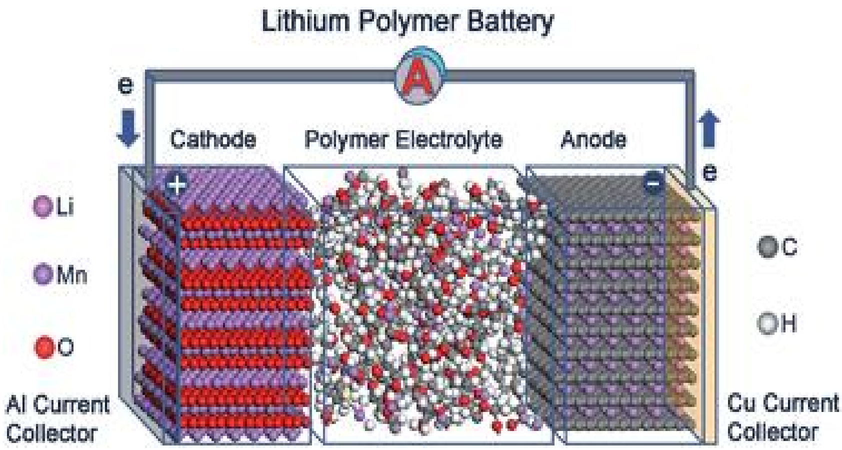


Figure 10: The structure of an electrolyte in a lithium battery [18].

2.1.4. Separators:

Separators are a very important part in the structure of a lithium-ion battery. The separator separates the positive and negative electrode from making direct contact with each other. The separators are made porous in order to facilitate the transfer of lithium ions between the electrodes during the process of charging and discharging. The working of a separator is very important for the smooth working of the battery. The problems that occur due to the faulty working of the separators and the methods to prevent them are seen in chapter 4. The property of the separator should not change during the process and intensive research is being carried on in this field.

The requirements for a good working separator are as follows[19]:

- Electronic insulator [19].
- Minimal electrolyte (ionic) residence [19].
- Mechanical and dimensional stability [19].
- Sufficient physical strength to allow easy handling [19].
- Chemical resistance to degradation by electrolyte, impurities, and electrode reactance and products [19].
- Effective in preventing migration of particles or colloidal or soluble species between the two electrodes [19].
- Readily wetted by electrode [19].
- Uniform in thickness and other properties [19].

Figure 11: Polyethylene (PE) and Polypropylene battery separators for lithium-ion battery material [20].

Wettability is also a basic requirement for a separator, the separator should easily wet in the electrolyte and the chemical properties of the electrolyte should not be changed and should be retained permanently. The different types of separators are, microporous separators, nonwoven separators, ion exchange membrane separators, supported liquid membrane separators, polymer electrolyte separators, solid ion conductor separators. The most commonly used separator in lithium-ion batteries are polyethylene (PE) and polypropylene (PP) which are microporous membrane separators. All lithium based batteries use nonaqueous electrolytes because of the reactivity of electrolyte's stability at high voltage [19]. Lithium secondary batteries can be classified into three types, a liquid type battery using liquid electrolytes, a gel type battery using gel electrolytes mixed with polymer and liquid, and a solid type battery using polymer electrolyte [19].

2.1.5. Current Collectors:

The current collectors are present in both the negative and positive electrodes. Copper is used a current collector in the negative electrode and aluminium is used as a current collector in the positive electrode. When the battery is discharged the lithium ions are transferred from the anode to cathode resulting in the creation of charge in the positive aluminium current collector. The current is then transferred to the device that uses the battery. When the battery is charged the reverse reaction occurs and the lithium ions are transferred from the cathode to anode resulting in the creation of charge in the negative copper current collector. Copper and aluminium are used in the respective electrodes due to their electrochemical stability at 3V and 3.5 – 5V respectively. The current collectors are thin foils and the electrodes are coated around them. In the figure, the orange thin line is used to represent the thin foil of copper current collector in negative electrode and the aluminium current collector in the positive electrode.

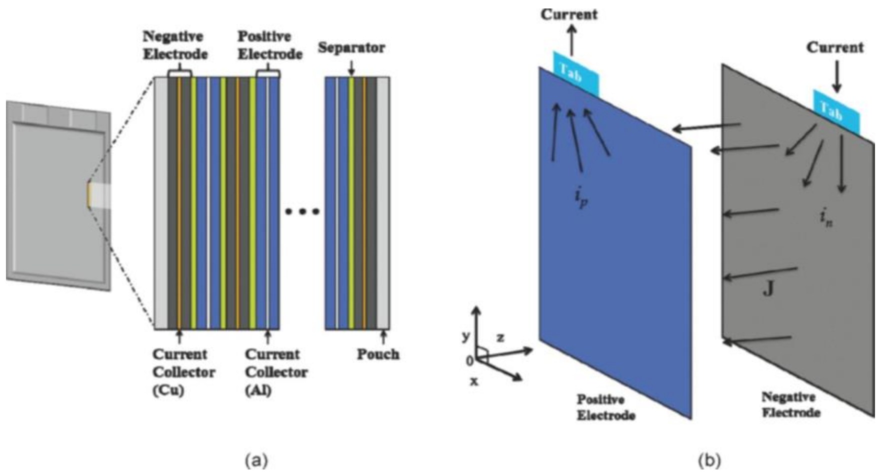


Figure 12: The modelling of a lithium-ion battery [21].

Current collectors play a major role in rechargeable lithium-ion batteries. Different current collectors can make a difference in the performance of lithium-ion batteries. Lee et al. [22] demonstrated that cycle-life of the silicon-graphite composite electrode had significantly been improved by using a Cu current collector with a modified surface morphology [23]. Wang et al. [24] reported that a porous silicon-carbon anode on a carbon fiber current collector had superior overall capacity, cycle ability, and rate capacities [23]. The efficiency of the current collectors reduces with the increased number of cycles. The current collectors also undergo natural corrosion and cracking. It is important to choose the current collector based on the chemistry of the electrodes.

2.2. Cost Analysis of Lithium-ion Batteries:

The cost of any vehicle or technology always depends on the demand and supply of the product. Cost of electric vehicles continued to remain as one of the main disadvantages. With the development in technology sector, the realisation of global warming, and the invention of lithium-ion batteries have resulted in the drop of the cost of electric vehicles.

The main and most costly component in the electric vehicle is the battery pack. The cost of the battery pack is proportional to the capacity of the batter pack. In order to provide good travel distance, good speed and smooth driving batteries with more kWh are preferred.

In simple terms the affordability of the electric vehicle depends on the cost of the battery pack used during manufacturing. Bloomberg New Energy Finance has provided a graph on the decrease of the cost of batteries since 2010 [25].

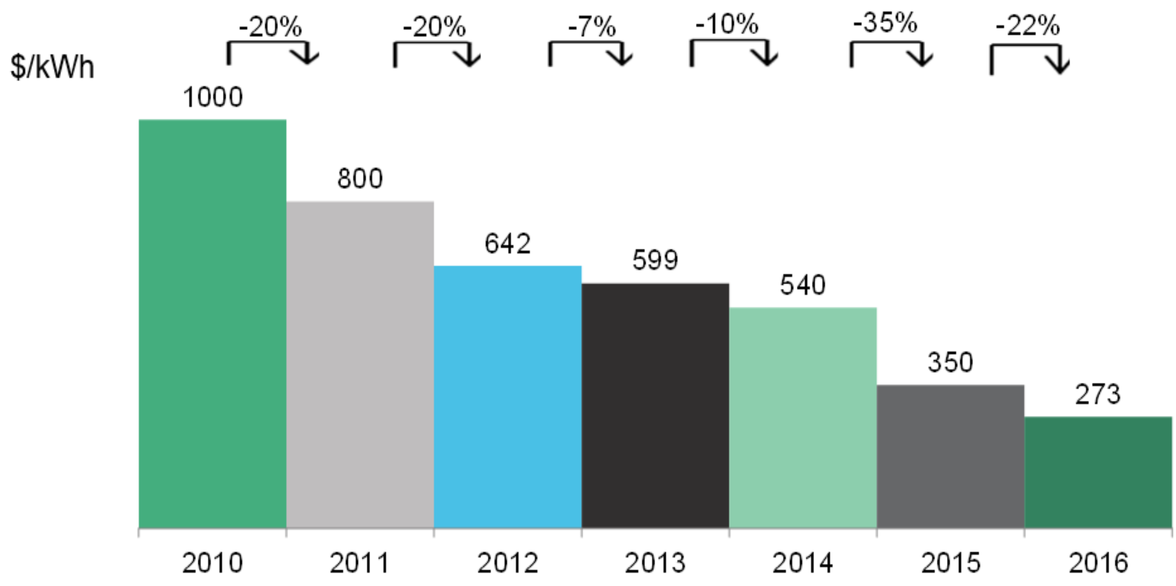


Figure 13: BNEF lithium-ion battery price survey, 2010-16 ($/kWh) [25].

Lithium-ion battery prices have fallen 73% since 2010. For the last two years, the change was propelled mostly by technology improvements (largely in energy density) and factory overcapacity, which resulted in growing competition between major battery manufacturers [26]. The diminishing cost of lithium-ion battery packs is the driving factor behind the falling cost of BEVs [26].

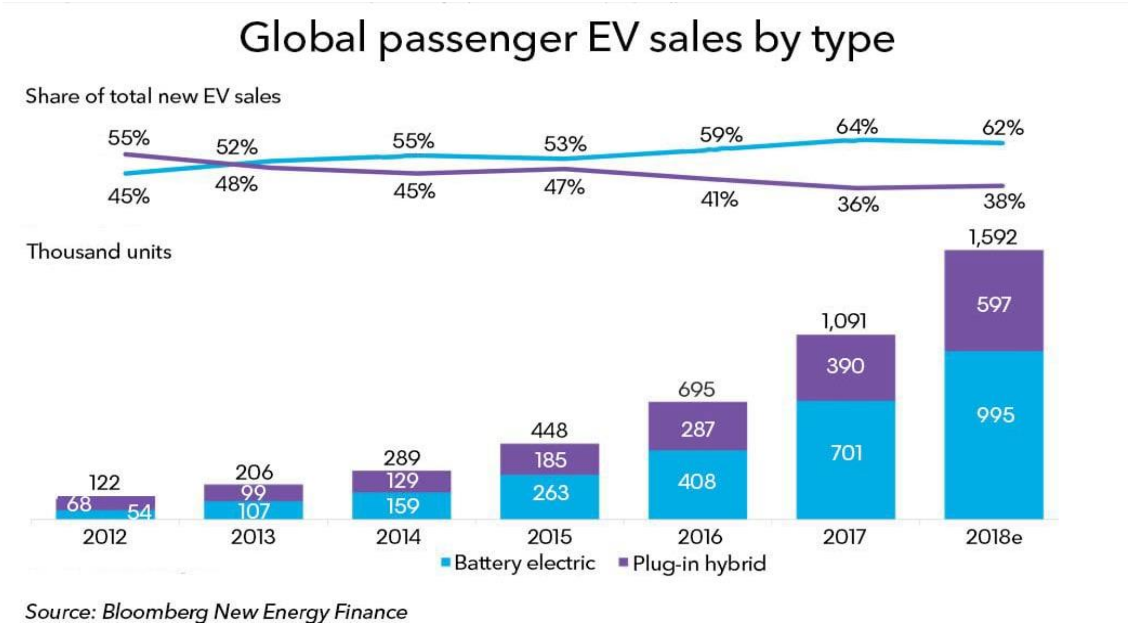


Figure 14: The sales of battery electric vehicles and plug-in hybrid vehicles is shown [27].

The sales of electric vehicles (both plug-in and battery) is very high in the recent years as seen in the above figure 14. The growth of plug-in electric vehicles is more in percentage compared to the growth of battery electric vehicles. The reduction in the cost of lithium-ion battery price is considered a main reason for the increase in the sales of electric vehicles.

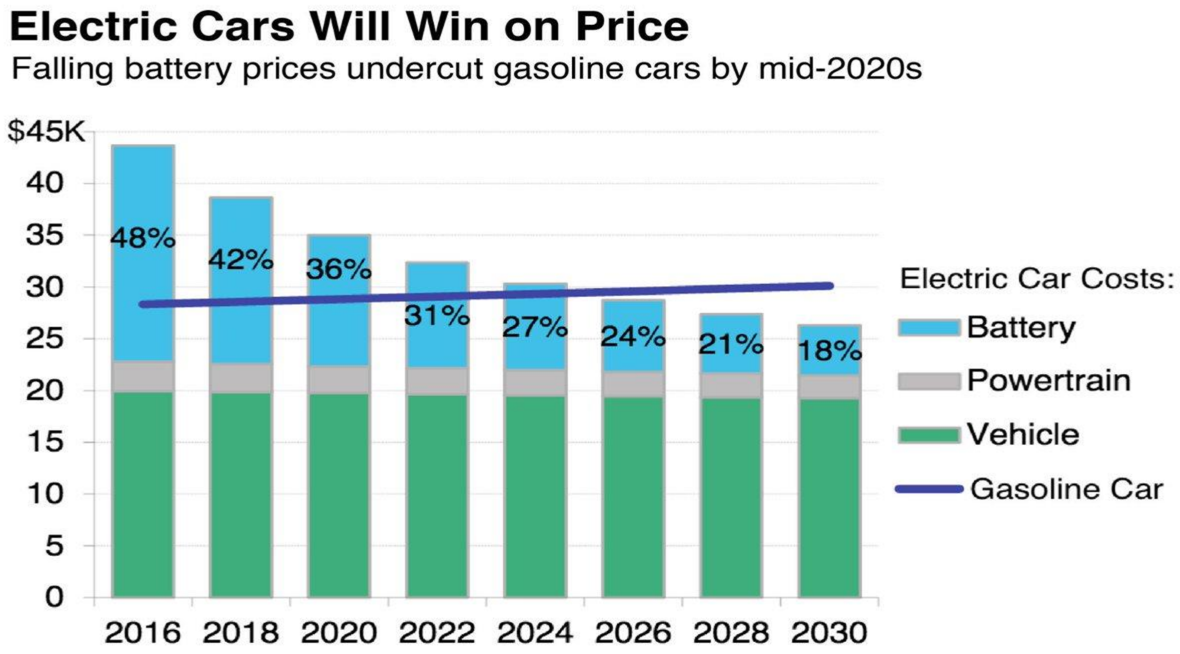


Figure 15: The price range of electric cars in the following years [28].

As the cost of electric car batteries declines the cost of the electric vehicles is proposed to be less than the normally affordable gasoline vehicles. The most polluted countries in the world have started implementing higher use of electric vehicles compared to combustion vehicles. This results in increase in sales of the vehicles. The world is looking for the adoption of electric vehicle as the major source of transportation. With the increase in demand the lithium-ion batteries are mass produced and the prices tend to go low based on the production and sales of the batteries.

3. Safety concerns with Li-ion battery:

The usage of Li-ion batteries in electric vehicles has become a main safety concern. The electrolyte in Lithium battery is flammable and volatile. The main parts required for a fire triangle (heat, oxygen and combustible material) in case of overheating are already present inside the battery without any external effect. The overheating of the electrolyte can be caused by an internal or external short circuit, external penetration, abusive damage to the battery, etc.

Reports of incidents involving electric vehicles (EV) have resulted in fire and damage of the vehicles. In 2013, Tesla Model S (BEV) battery fire was caused when the driver hit the road debris at high speed. The fire was a result of penetration from beneath the battery pack. In 2014, the National Highway Traffic Safety Administration investigated the fires and did not find any defect trends, but Tesla did voluntarily choose to reinforce the underbody of their cars with arming plates in order to lower the frequency and the effect of hitting road debris. Although Tesla strengthened the battery shield on its new and existing cars, in August 2016, a Tesla electric car caught fire in France during promotional tour.

Figure 16: A Tesla model S car caught fire due to lithium-ion battery explosion [29].

In May 2011, a Chevrolet Volt caught fire three weeks after crash test. In October 2012, Hurricane Sandy caused the flooding of a harbour in New Jersey, causing 16 brand new Fisher karma PHEV to catch fire. The flood lasted for several hours causing salt water intrusion to the batteries. Other incidents caused by Fisher Karma cars were, the car caught fire in a supermarket parking lot once the driver got out of the car and also fires during charging. Uneven separators, poor conductivity, high and low temperatures are also some reasons for car fire.

The main cause of fire in the Li-ion battery is Thermal Runaway. There are several processes to prevent thermal runaway from occurring. If all the methods taken by the company to protect the battery fails, like extreme accident that causes huge damage to the battery and the car, the thermal runaway process cannot be prevented and results in a fire and sometimes explosion of the vehicle. There are also chances of fire with the use of fossil fuel but the battery chemistry of Li-ion has many reasons which can cause the fire and the necessary ingredients required for a fire triangle are present within each cell of the battery pack.

Figure 17: Fire of a Tesla S car at charging station in Norway [30].

The accident shown in the figure 17 was reported in Norway in 2016. It is said that a Tesla S electric vehicle caught fire while the car was charging at the supercharger charging station at Norway. Nobody got hurt during the incident. This is a typical example for a car fir while undergoing charging. The temperature effects on an electric car during charging can be analysed in this figure. The effects and reasons of failure of an electric vehicle due to low temperature can be seen in chapter 3.1.1.1 .

3.1. Failure modes of lithium battery:

In this section we will discuss the possible reasons for failure of a lithium ion battery. Failure in a lithium-ion battery can be either non-energetic or energetic failure. Some non-energetic failure (considered as benign failures) possibilities are loss of capacity, internal impedance increase (loss of rate capability), activation of a permanent disabling mechanism like CID, shut down separator, fuse, or battery pack permanent disable, electrolyte leakage with subsequent cell dry-out, and cell swelling [31]. Some other non-energetic failures can be resulted due to different types of damages to the cell. Energetic failure always refers to thermal runaway, which causes excessive heat release and exothermic reactions. The more energy stored, more rapidly the energy is released during thermal runaway process. Thermal runaway is considered energetic failure due to its very high energy density when compared with other cell chemistries and the cell contains flammable electrolyte, thus not only store electrical energy in the form of chemical energy but also they store appreciable chemical energy in the form of combustible materials [31].

3.1.1. Temperature Conditions:

Temperature control is a very important parameter for lithium battery. Extreme low temperature and extreme high temperature affects the battery and can cause explosion or causes permanent damage to the battery. In normal conditions lithium ions are present in both cathode and anode, when charged or discharged the lithium ions are transferred from cathode to anode and vice versa.

3.1.1.1. Low temperature:

When the temperature goes to -15 ºC or less than that, there is a possibility of anodes and cathodes freezing. There are some inbuilt heating elements in some high cost and well-designed batteries, to avoid the problem. If the battery does not support this problem or is not equipped to solve the situation, the mobility of the ions in the battery is not as same as the normal working condition. When the battery is charged there is reduced reaction rate and the since the ions do not transfer or flow at the desired rate, the lithium ions get deposited in the negative electrode and do not release back from the negative electrode, causing the deposition of metallic lithium resulting in anode lithium plating [32]. As seen in the figure 18 when lithium plating occurs, the lithium ions settle in the anode causing a metallic lithium plate. This creates high resistance and the normal working of the battery is affected. When the discharge process occurs the lithium ions are supposed to be transferred from anode to cathode, due to lithium metallic plating, the lithium ions from other regions continuously keep transferring and causing dendrites in anode.

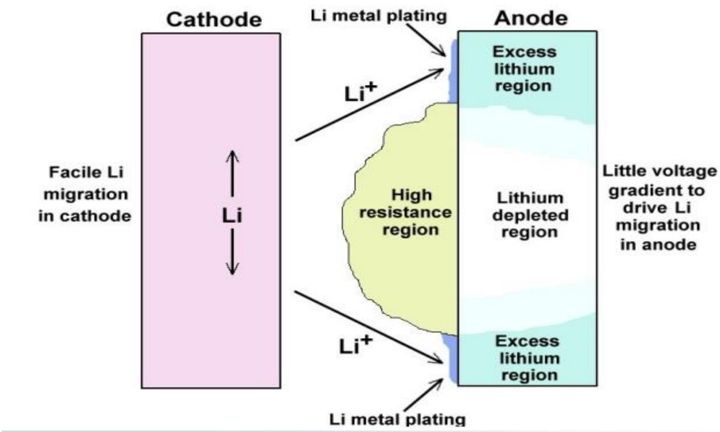


Figure 18: Anode lithium plating in Li-ion battery cell [33].

When lithium plating occurs on the anode, the number of lithium ions for transfer is reduced and eventually results in short circuit. The electric vehicles produced for use in countries with low temperature need to ensure the protection measures to avoid lithium plating. The safety concerns of electric vehicle in low temperature countries can be seen in chapter 3.

3.1.1.2. High temperature:

When the temperature rises to 40ºC or greater than that, there is a possibility for increased reaction rate. This is based on the Arrhenius law, increased reaction rate causes increased mobility of lithium ions producing more current. The heat production rate during the charge and discharge is higher. If the dissipated heat is not properly let out of the battery pack, heat accumulation occurs and leads to Thermal Runaway. A detailed description about thermal runaway is given in chapter 4.

3.1.2. Electrical Abuse:

For every lithium ion battery chemistry there is a cut-off voltage limit for both charging and discharging, they play a key role during charging and discharging of the battery.

3.1.2.1. Overcharging:

The cut off voltage is present for the safe working of the battery. When the battery is charged for a long time and if the voltage limit goes across the safe voltage the chemical reactions inside the cell are disturbed. Most cells charge to 4.20V/cell with a tolerance of

+/50mV/cell, safety concern arises if charged beyond 4.20V/cell [34]. When the cell is fully charged, continuous supply of charge to the cell produces heat from the cell. The released heat has to be vented out, if the heat gets accumulated it results in undesirable pressure and heat. The safe voltage is set to mainly serve this purpose, if it does not work then it leads to thermal runaway and cause fire or explodes. Overcharging can be prevented by setting cut off voltage even in the charger.

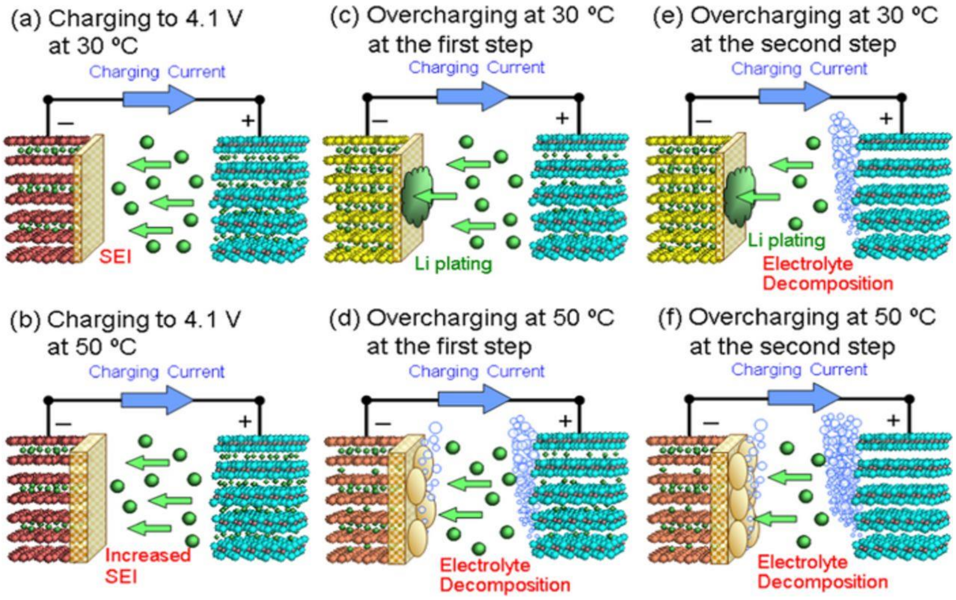


Figure 19: The charging and overcharging results can be seen in two different temperature variations [35].

In the above figure 19, the charging conditions for a battery working in 30ºC and 50ºC temperature conditions is observed. The impact of overcharging can be observed evidently in the second step at 30ºC, the lithium plating in the anode and electrolyte decomposition leads to thermal runaway in the battery. The same process happens on the battery undergoing overcharge at 50ºC [battery operated in high temperature conditions]. The damaged caused to the battery due to overcharging is multiplied with the increase in temperature. The intensity of solid electrolyte interphase, and electrolyte decomposition is highly increased with high temperature.

3.1.2.2. Over-Discharging:

Over discharge happens when the battery charge is very low and is not used for several days. The internal temperature and ac impedance suffered an abnormal increase almost immediately when the current is applied [36]. When the battery is charged after overdischarge, the accelerated increase of temperature and impedance accumulates the heat, resulting in the dissolution of anode and gas leaks and swelling of cells. Overdischarge does not directly lead to thermal runaway as seen in overcharging, but it leads to the depletion of anode and impacts the impedance and internal temperature, resulting in capacity loss and might cause internal short [36]. Even though the reaction does not occur right away, the battery is damaged and will not be suitable for use.

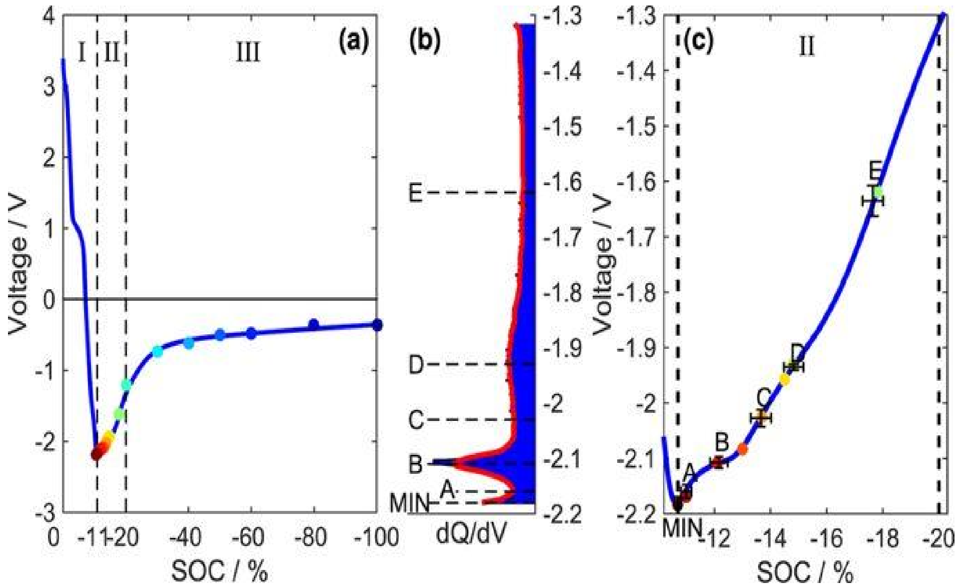


Figure 20: Voltage analysis during overdischarge [37].

3.1.2.3. External Short Circuit:

External short circuit in a lithium ion battery occurs when the battery undergoes unnatural changes in its surroundings. The occurrence of external short circuit has nothing to do with the physical design or the internal chemistry of the lithium ion battery. Some reasons for lithium ion battery to undergo external short circuit are the intrusion of salt water in the battery, when the conductors of the battery (negative and positive conductor) come in direct contact with each other, or damages due to battery collision. In December 2018, hundreds of Maserati cars caught fire in Savona, an Italian city. The fire was caused due to floods in the north western area. The fire was due to the intrusion of salt water inside the car batteries, one of the causes for external short circuit. When a battery is affected by external short circuit the current drops to zero when the cell discharges. The heat produced at the time of external short circuit is not much, but the heat gradually decreases. In the case of larger cells in heat transfer occurs slowly due to external short circuit due to their high energy capacity, leading to the increase in internal heat in the battery. This initiates the thermal runaway process in the battery and results in fire and explosion. External short circuit is more likely to occur due poor packaging for battery transportation and also when the battery is damaged due to collision of vehicles.

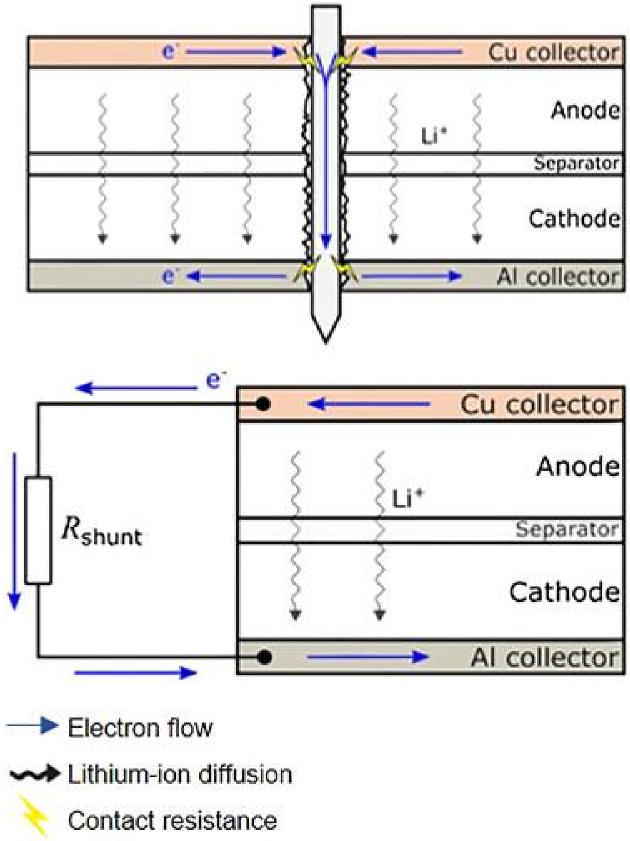


Figure 21: Internal and External short circuit in a lithium ion battery cell [38].

In the figure 21, the first representation is for the induced internal short circuit in a lithium ion battery cell, it is achieved by nail penetration. The second representation is for the induced external short circuit, it is achieved by connecting the positive and negative conductors directly with each other. The resistor R shunt is used to allow controlled current and helps to test external short circuit in the battery.

3.1.3. Internal Short circuit:

One of the main reasons for the occurrence of thermal runaway in a battery is internal short circuit. When internal short circuit occurs, heat is generated in the cell due to the increased propagation of negative electrode. The heat gets accumulated in the battery and if not dissipated properly leads to thermal runaway and causes fire and explosion. Internal short circuits are caused by many reasons; the most common reason is anode lithium plating.

The possible schematic for internal short circuit in a lithium-ion cell is shown in figure 22. The anode with the copper current collector is separated from the cathode with aluminium current collector through a separator.

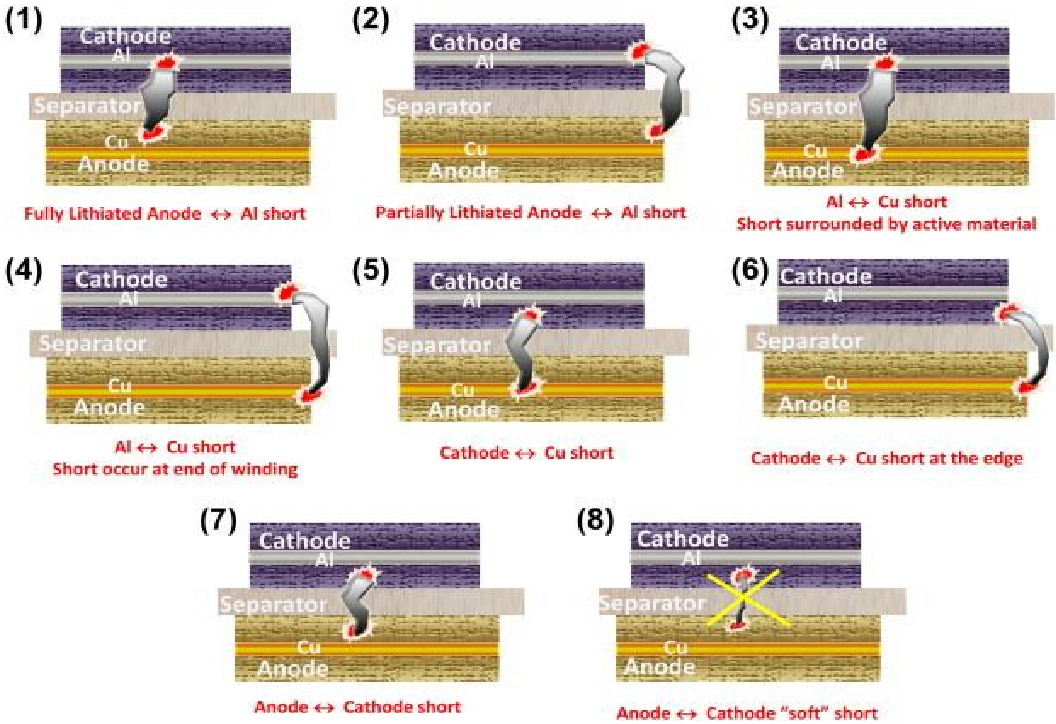


Figure 22: Schematic showing various internal short scenarios occurring in Li-ion cell. Assumptions include high SOC and hard shorting for case 1-7. Case 8 refers to "soft" shorting [39].

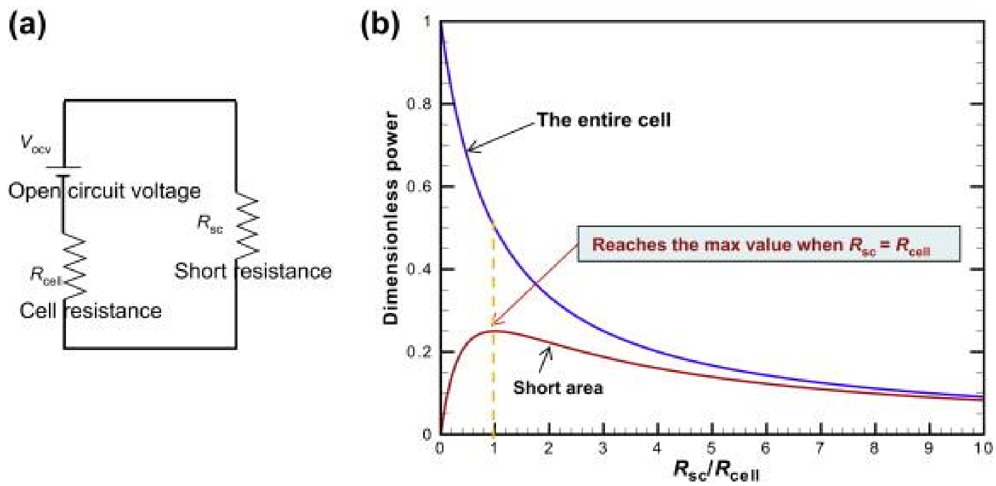


Figure 23: (a) Equivalent circuit of an internal short. (b) Simulation of power generation as a function of variation in short and cell resistance during internal short. The maximum power generated in the short area is when the cell resistance equals the internal short resistance [39].

When internal short occurs in a cell, local hot spots are created, these spots promote the depletion of negative electrode and allow heat accumulation. Once the heat starts accumulation the cathode provides oxidation reaction and releases oxygen inside the cell. During this process if the cell is vented or comes in contact with the atmosphere, it results in explosion [39]. It is possible to prevent the problem if the lithium electrolyte contained some components that could sustain the hot spots.

3.1.4. Mechanical Abuse:

Mechanical abuse leads to internal short circuit and results in thermal runaway. The impact of mechanical abuse can either occur immediately or propagate slowly and react after some time. When the failure is subtle the failure creates a flaw in the cell and it reacts after repeated number of operation cycles leading to thermal runaway. The occurrence of mechanical abuse is high during accidents or heavy impact on the electric vehicle. When a battery undergoes mechanical abuse, the electrodes are the main part that gets impacted. If the impact occurs on the edges of the electrode the chances of the battery to undergo thermal runaway are higher compare to the damage caused in the surface of the electrodes. The dormant mechanical abuse can become a point in the electrode or separator degradation and when the number of operating cycles increases it leads to anode lithium plating or a hole in the separator, causing them as reasons for thermal runaway in the battery [31]. In order to satisfy good working conditions of the battery chemistry it is necessary to undergo mechanical abuse tests. Detailed descriptions about the test that can be carried out on the battery are seen in chapter 5. Mechanical abuse is one of the main reasons for fire or explosion of electric vehicles that have met with accidents. When the car hits debris or undergoes impact due to collision of two vehicles, the battery is either penetrated or impacted and internal short circuit occurs. When the impact occurs the thermal runaway process is initiated and the damage occurs in a concentrated place or propagates throughout the batter based on the impact and results in fire and explosion of the electric vehicle. Some of the reported accidents (due to mechanical abuse) involving electric vehicles are mentioned in chapter 3.

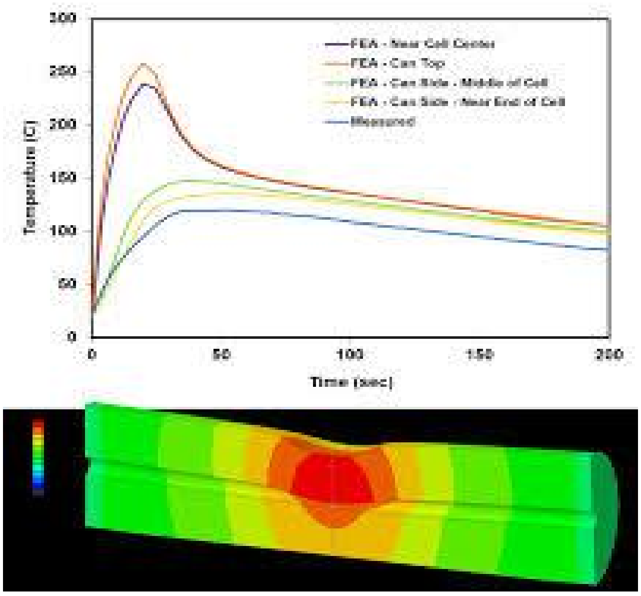


Figure 24: Thermal response to mechanical abuse [40].

In the figure 24, in the top the comparison of the FEA model predictions of the cell temperature vs. measured values. In the bottom the temperature profile when the temperature reaches maximum [40], the estimated values and the obtained values are plotted in the graph according to the research reference paper.

In some cases the impact on the battery can leave damages to the battery but the failure of the battery might not be noticeable. The placement of the battery in the electric vehicle has proven to be a great risk concern. All the car manufacturing companies provide enhanced safety measures for the battery pack.

3.1.5. Manufacturing Defects:

The battery packs are designed in order to protect or prevent in case of mechanical, thermal abuse. Even beyond the preventive measures provided in the battery failure tend to occur and results in thermal runaway. Extensive research is being carried out to figure out the cause of failure due to manufacturing defect. According to exponents, the lithium-ion battery packs with mature protection electronics packages, the majority of thermal runaway failures in the field are caused by faults related to cell manufacturing [31]. There are numerous flaws that can occur during the manufacturing that can ultimately result in the failure of the batteries. Some examples of manufacturing defects are as follows, defects in cell raw materials, defects in electrode coatings, contaminants introduced during assembly process, and misplaced, misapplied, or damaged components [31]. If there are any manufacturing defects present in the cell, it is evident during charging the cell. The defects in the cell will cause self-discharge in the point. When the battery is charged, the defect or short tends to draw energy continuously which will in-turn increase the heat and initiates thermal runaway process. There are a number of flaws that could occur during manufacturing of a battery and most of them react only when the battery is charged. Another major manufacturing defect can be seen in the anode of the battery, the defect leads to lithium plating and dendrites in the anode. The formation of more number or dendrites results to internal short circuit and leads to thermal runaway in the battery. The defect due to anode plating is also identified during or directly after charging, the reasons for the phenomenon are [31]:

- Lithium dendrite formation occurs during charging; thus, shorting of dendrites (which will provide highly localized heating that could potentially trigger other exothermic reactions) is most likely to occur during charging [31].
- Charging provides electrical energy to the cell raising its SOC, and susceptibility to thermal runaway [31].
- Charging provides energy to any shorting point within a cell. If a shorting point was present in a cell prior to charging, it may have caused the cell to self-discharge before sufficient heat was generated to induce thermal runaway. However, when attached to a charger, a short may draw energy continuously until thermal runaway is initiated [31].

The failure of lithium-ion batteries due to manufacturing defects are so minute and there are various reasons for the fault to occur. The defect can be caused at any stage of battery manufacturing. Since most of the defects are known only when the battery is charged, it is advisable to avoid charging of newly manufactured batteries in mass production area.

4. Thermal Runaway Process:

The thermal runaway process affects the battery voltage, temperature and pressure. Thermal runaway process is caused by several reasons, such as internal or external short circuit, overcharging the battery, unexpected chemical reactions. Thermal runaway is the most dangerous impact in lithium-ion battery. Most of the incidents involving electric vehicles are caused due to thermal runaway. When a problem occurs in the lithium-ion battery, the temperature starts rising, it increases to approximately 130-150ºC, the organic components are not stable and generate more heat [41]. Once the heat starts accumulating the separator begins to melt and uncontrolled temperature increase occurs within seconds. Other than temperature changes, there is no other notable changes or spikes to indicate the initiation of thermal runaway and create awareness.

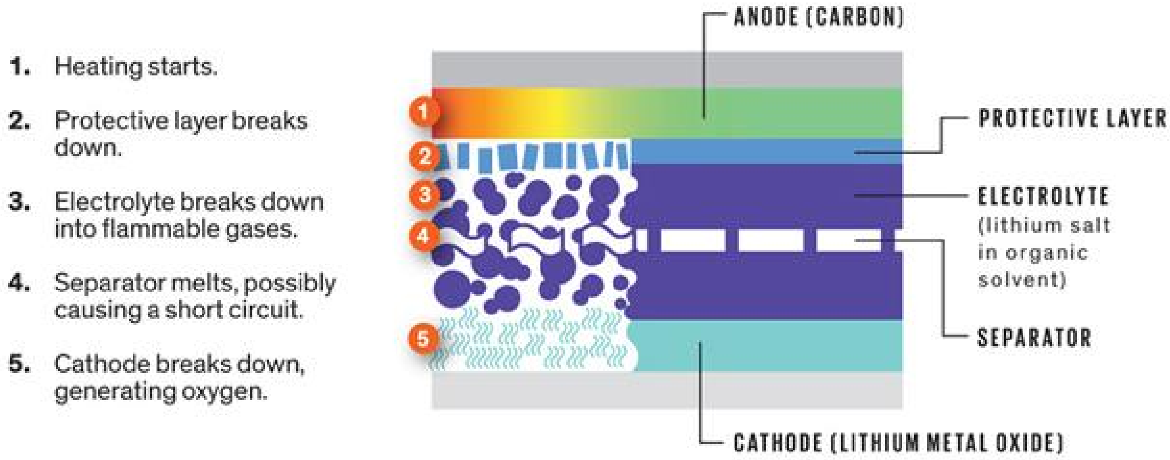


Figure 25: Thermal runaway process [42].

The uncontrolled heat accumulation has to be taken care of or the battery goes into a positive feedback loop of heat increase resulting in fire and explosion of the battery. In electric vehicles battery packs are used, wherein each pack contains more number of lithium cells. When a thermal runaway occurs in one battery due to the emitted heat the neighbouring batteries are affected. The impact of a single Li-ion cell is much less compared to an electric vehicle battery pack.

The thermal runaway follows a mechanism of chain reactions, during which the decomposition reaction of the battery component materials occurs one after the other [43]. The abusive conditions for the occurrence of thermal runaway are electrical, mechanical, thermal abuse and also internal and external short circuit.

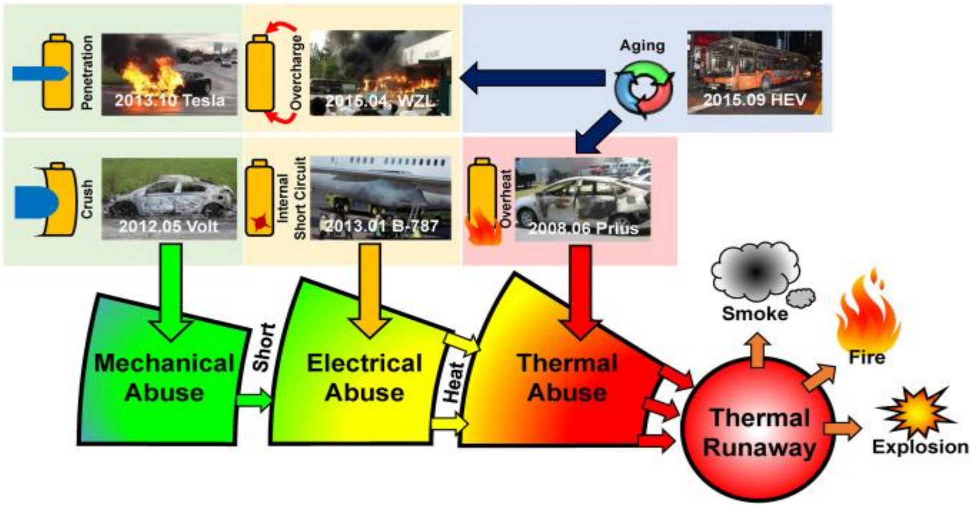


Figure 26: The possible abuse conditions for thermal runaway [43].

In figure 26 the process of thermal runaway occurrence due to mechanical abuse is shown. First the battery undergoes mechanical abuse either by penetration (a Tesla model S car accident is shown in the picture) or crushing (a Volt car accident is shown in the picture) of the battery. Mechanical abuse leads to the internal short circuit (a Boeing-787 accident is shown in the picture) or external short circuit or overcharge of the battery also known as electrical abuse. When the battery undergoes internal short circuit or overcharge the heat accumulates and the temperature of the battery rises uncontrollably leading to thermal abuse. If a battery cell in the battery pack undergoes thermal runaway the temperature for the neighbouring cells increases, the sudden increase in temperature initiates thermal runaway. Exposure to acute heat induces thermal runaway in a cell, this leads to thermal abuse in the battery and the heat propagates throughout the battery pack. Thermal abuse can also be seen due to flame attack and exposure to hot gases. Finally resulting in thermal runaway causing fire and explosion of the battery, and also causing explosion in the electric vehicle in which the battery is used.

The impact or severity of the thermal runaway process depends on factors like state of charge (SOC) of a cell (how much electrical energy is stored in the form of chemical potential energy), the environmental temperature, cell chemistry, cell size, electrolyte volume, etc. [31]. The most impact occurs when the cell is fully charged, some of the impacts are as follows:

- Increase in cell internal temperature.
- Increase in cell internal pressure.

- Cell venting.
- Gases let out during cell venting may ignite.
- Ejection of cell contents
- Thermal runaway might propagate to adjacent cells.

The preventive measures for thermal runaway in a multi cell pack must be done with caution. The multi cell packs are used in electric vehicles and the explosion or fire in battery pack due to thermal runaway might become very dangerous for the people inside the vehicles. The impact of a battery pack is very high compared to a single lithium-ion battery cell.

4.1. Thermal Runaway Breakdown Process:

When thermal runaway occurs in the lithium-ion battery the breakdown process can be classified as decomposition of solid electrolyte interphase, melting of separator, reaction between negative material and electrolyte, decomposition of electrolyte and reaction between positive material and electrolyte. These processes are triggered and set in motion when a battery starts to undergo thermal runaway.

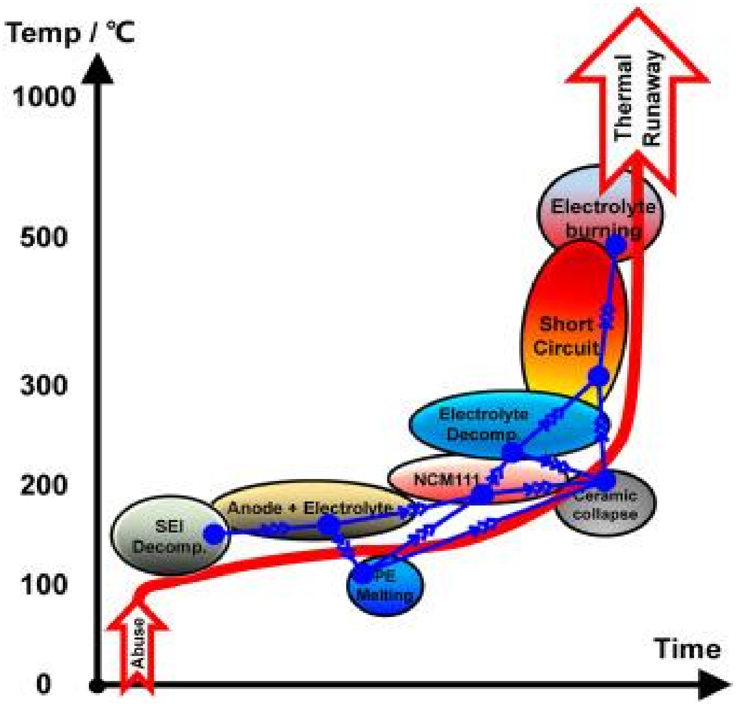


Figure 27: The breakdown process due to thermal runaway [44].

In the figure, the thermal runaway process is triggered by an abuse in the battery pack. The abuse starts the breakdown process which will lead to thermal runaway. The steps in which the breakdown process is clearly mentioned in the figure 27 and the detailed description of each stage is seen below.

4.1.1. Decomposition of Solid Electrolyte Interphase (SEI):

Solid Electrolyte Interphase (SEI) is formed on the negative electrode because the electrolytes are not stable at the electrode during charging. When the decomposition takes places the particles form a solid layer on the negative electrode. When the number of cycles of charging and discharging increases, the thickness of the SEI layer increases. The formation of SEI layer has some advantages such as, it prevents further loss of electrolyte material and also maintains good cycle ability. When the SEI layer has formed it reacts with the lithium ions and electrons and suppresses the growth of the SEI. The passage of lithium ions to the negative material through the SEI layer is not a problem. Lithium ions can easily pass through the SEI layer and get intercalated in the negative electrode during the charging and discharging process. The formation of SEI layer further facilitates the smooth functioning of the battery with increased cycle ability. The SEI layer keeps getting layered but the rate of thickening of the layer is very slow.

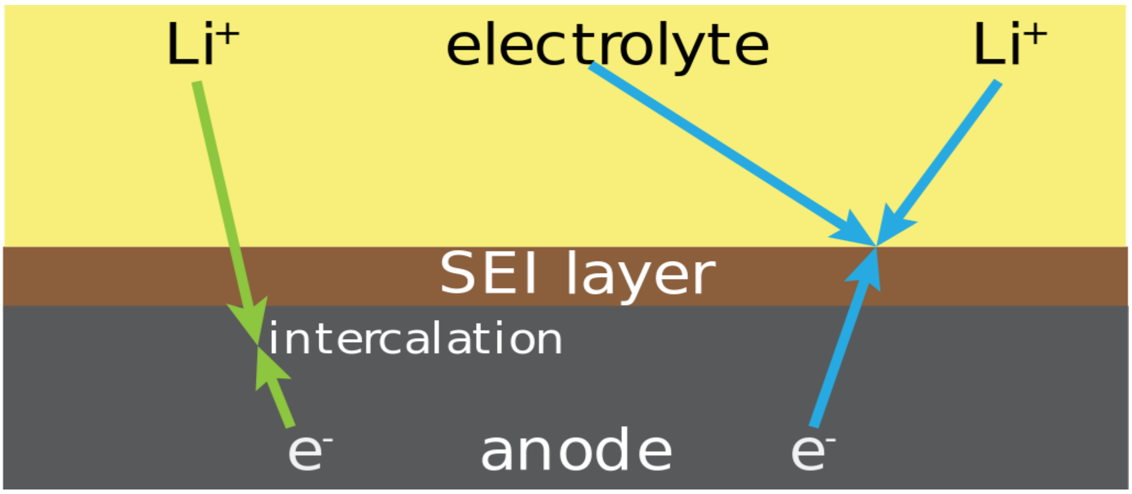


Figure 28: Formation of SEI layer in the negative electrode [45].

The formation of the SEI Layer is clearly explained in the figure 28. Solid Electrolyte Interphase also occurs on the positive electrode but is not as efficient as the negative electrode and is very thin layer. The SEI layer allows the passage of lithium ions to and fro from anode, in some cases it does not happen properly which leads to the formation of dendrites in the anode. After dendrites are formed, there is high chance for the occurrence of thermal runaway after some charge and discharge cycles of the battery.

As the thermal runaway process is initiated in a lithium-ion battery, a series of process take place within the cell before it either results in fire or explodes. The first affected is the SEI layer. When the heat starts accumulating in the battery the transfer resistance in the SEI layer is increased, when such resistance is formed even more heat is produced during the transfer of lithium ions. The dissolution of SEI layer begins at around 80ºC. The SEI layer begins to breakdown due to the heat generated in the battery, the time taken to reach the exothermic state depends on the stability of the SEI layer. The SEI layer is thermally unstable, the decomposition of SEI layer marks the starting of the thermal runaway process.

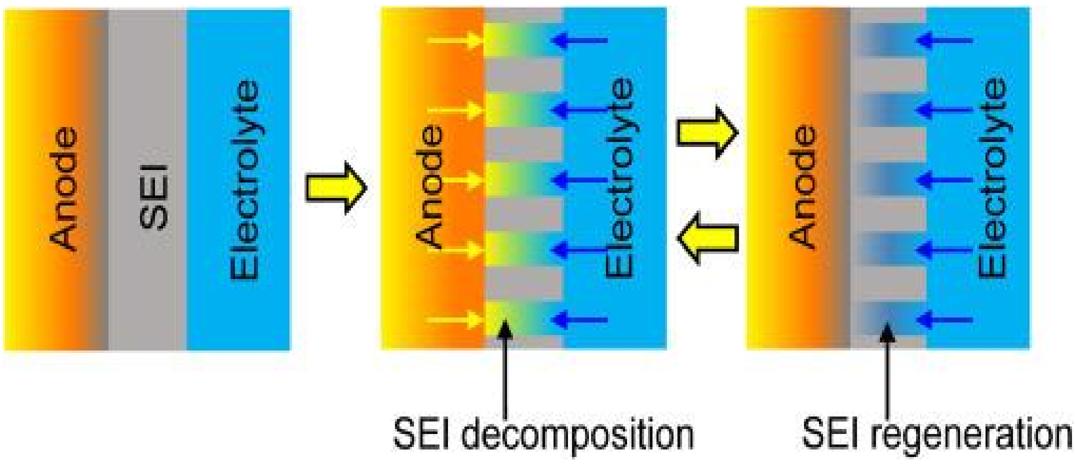


Figure 29: SEI layer decomposition and regeneration process [44].

4.1.2. Reaction between negative material and electrolyte:

The negative electrode is not directly in contact with the electrolyte once the solid electrolyte interphase is created. The SEI provides a passivation layer thus not disturbing the working process of the anode. When thermal runaway is initiated in the lithium-ion battery, the SEI layer is decomposed and the anode comes in direct contact with the electrolyte. The reaction of the negative electrode with the electrolyte is an exo-thermal reaction, results in the increase of temperature in the lithium ion battery cell. The interaction between the anode and electrolyte results in the decomposition of the electrolytes. The capacity of the electrolytes starts fading due to the impurities present in the electrolytes. At around 110ºC the organic solvents start to break and result in the release of hydrocarbon gases [46]. This does not result in fire because the gases are not in contact with the atmosphere or is not in contact with oxygen. The temperature and pressure inside the cell is increased. The temperature raised in the battery due to this reaction is almost equal and nearing the melting point of the separator. If the cell was designed with a proper venting system it would help in eliminating the heat inside the cell and prevent the melting of the separator. If the venting process fails to dissipate the heat from the cell at this point, the temperature rises above the melting point of the separator and initiates the separator melting process.

4.1.3. Melting of Separators:

The decomposition of SEI layer leads to the additional increase in temperature. As the temperature keeps increasing inside the battery, it reaches the melting point of the separator. The separator shut down process gets activated and tries to prevent the battery from thermal runaway. When the temperature inside the cell reaches to about 135ºC, which is beyond the melting point of the separator, the separator starts to melt. Since the temperature is too high, the separator shutdown does not withstand. It can only hold based on the chemical component used as a separator. When the separator is melted the positive and negative electrode tend to come in contact with each other and result in internal short circuit in the cell. Intensive research is being carried out to find a separator which can withstand very high temperature and prevent thermal runaway.

4.1.4. Reaction between positive material and electrolyte:

The electrolyte reacts also with the positive electrode and results in the decomposition of positive electrode. The cathode is generally made up of oxidants and when the temperature reaches nearly 200ºC the cathode breaks and tend to release the oxygen present in them. The cathode releases oxygen as a result of oxidants present in the electrode material. When the oxygen is released in the lithium ion battery cell, it comes in contact with the hydrocarbons released from the negative electrode during the second breakdown process. This results in the production of gas or heat inside the cell. This is also an exo-thermal reaction. The cathode materials used in electric vehicles exhibit greater heat during thermal runaway process, resulting in the extensive decomposition of positive electrode materials, further increasing the battery temperature.

4.1.5. Decomposition of Electrolyte:

When the cathode (positive electrode) is decomposed it comes in contact with the impurities in the electrolyte. Most of the impurities are known to be combustible in nature. This generates additional heat in the cell and also forms gas in the cell. The cathode becomes more porous during the thermal runaway process due to the formation of gas as a result of interaction between the cathode and the electrolyte. As the temperature keeps increasing the separator does not hold and it ruptures. The positive and negative electrode come in direct contact with each other and results in internal short circuit of the lithium-ion battery.

The breakdown process of the battery takes place in this manner, the time taken to attain thermal runaway once the process has initiated depends on the protective and preventive measures made during each process. The advancements in separators are enabling them to withstand to very high temperatures. If cell venting is provided in the battery mechanism then the generated gas can be let out in the process of interaction between positive material and the electrolyte. Sometimes the thermal occurs immediately or it takes some hours or days to show symptoms in the battery.

4.2. Thermal Runaway Prevention Techniques:

As we know that thermal runaway is a very dangerous and life threatening issue in lithium ion batteries inbuilt prevention techniques are very important. In this section we will discuss about the available vital prevention techniques.

4.2.1. Separators:

The lithium cell structure consists of cathode (positive electrode), anode (negative electrode), a separator and an electrolyte as seen in chapter 2. The role of a separator is very important in a lithium-ion cell, the most commonly used separators are polyethylene (PE) and polypropylene (PP). The separator is a porous material, it facilitates the transfer of lithium ion (Li^+) from anode to cathode and vice versa, during charge and discharge. The main purpose of the separator is to keep the anode and cathode away from contact. The anode materials do not directly react with the cathode materials, only the lithium ions transferred through the porous separator comes in contact with each other. When the thermal runaway process is initiated in a battery, the heat accumulates inside the cell causing the separator to melt, once the separator melts both the anode and cathode come in contact with each other causing internal short circuit in the cell. The separator acts as an insulation material to prevent internal short circuit in the cell.

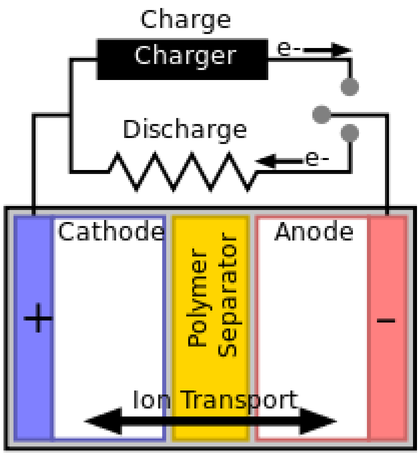


Figure 30: lithium cell structure with separator before thermal runaway [47].

In order to maintain the safe working of the battery a polymer separator is used. The porous polymer separator is made to close the pores and block the transfer of lithium ions once heat is generated in the cell. Each polymer separator has its own melting point and the when the battery temperature nears to the maximum melting temperature of the separator, the pores are closed, this process is called separator shutdown. The closed separator blocks the transfer of cathode and anode particles when the temperature inside the battery is high and prevents immediate internal short circuit in the battery. The melting points of different separators are as follows, polyethylene (PE) is 140ºC and polypropylene (PP) is 160 ºC [48]. As soon as the separator shuts down the process inside the battery does not stop or the heat does not reduce. The separator holds the integrity of the cell and not lead to internal short which will lead to thermal runaway.

The separator should be able to withstand the heat and not melt again, if it does not hols and the temperature is too high than tolerable, the separator melts and the negative and positive electrodes come in direct contact and cause internal short circuit [49]. This can be most commonly seen in single layer polymer, the chances of holding the heat in a single layer is quite hard. To solve this, the batteries can be equipped with triple-layered polymer separator (PE is sandwiched between two layers of PP), also ceramic materials are included in the polymer material, the ceramic/polymer composite separator can hold stable for a long time and has high melting point than single layer polymer separator [50].

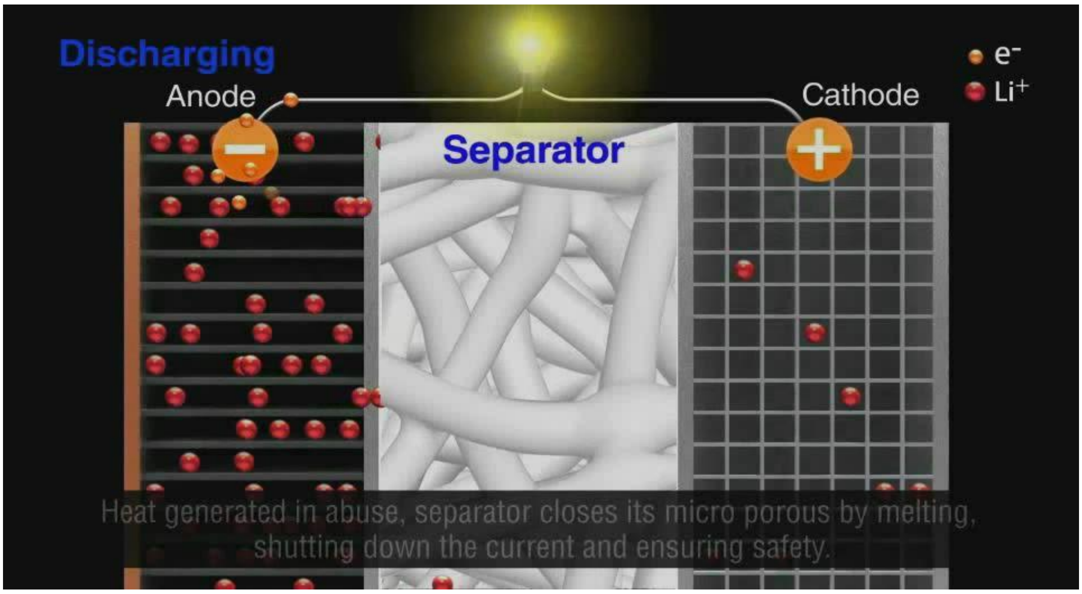


Figure 31: The separator melts and the closure of pores in the polymer is shown [51].

In the multi-layered polymer, the different materials have different melting point. For example in PE sandwiched between two PP polymer, the melting point of PE is less than that of PP. The internal layer of the polymer separator first closes the pores and restricts lithium transfer, if the temperature keeps raising and if it gets near the melting point of the outer polymer layer, the pores of outer polymer layer starts closing and holds for a longer time than the single layered polymer. Lee et al. [52][53] explored a new silica(SiO_2) nanoparticle/polyvinylidene fluoride-hexafluoropropylene coated polyethylene terephathalate (PET) nonwoven composite separator for a lithium-ion battery as a promising alternative to a commercialized polyethylene (PE) separator.

4.2.2. Cell Venting:

Cell venting is a process in which the excess internal heat produced in the battery is released to maintain the integrity of the battery. When shutdown separators are used, there are chances for the heat to get accumulated and to cause the separator to melt and cause internal short circuit. With the use of cell vents the accumulated heat can be released slowly and reduce the pressure inside the battery. When the temperature rises in the battery flammable gases and organic electrolyte accumulate in the battery, when they directly come into contact with the atmosphere explosion occurs. With the help of cell vents, the flammable substances can be released uniformly and can avoid explosion.

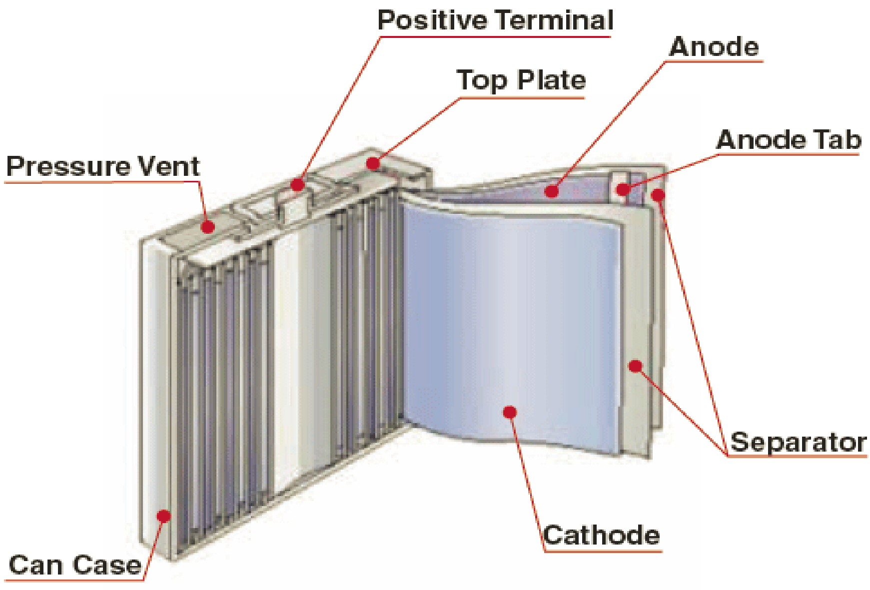


Figure 32: The pressure vent enables the cell venting process [54].

The venting of the gases and the heat occurs in seconds, and the designed vent in the battery must be able to accommodate the process in less time. Mier et al. [55] found that not only gases vented, but also the electrolyte and even solids were vented out, the venting generated a shock wave which indicated high rate of gas venting. The reaction of the gases with the atmosphere during thermal runaway can be made subtle and not cause much damage using cell venting. The pressure vent seen in figure 32 is opened when the heat starts accumulating and releases the excess heat and flammable gases from the battery.

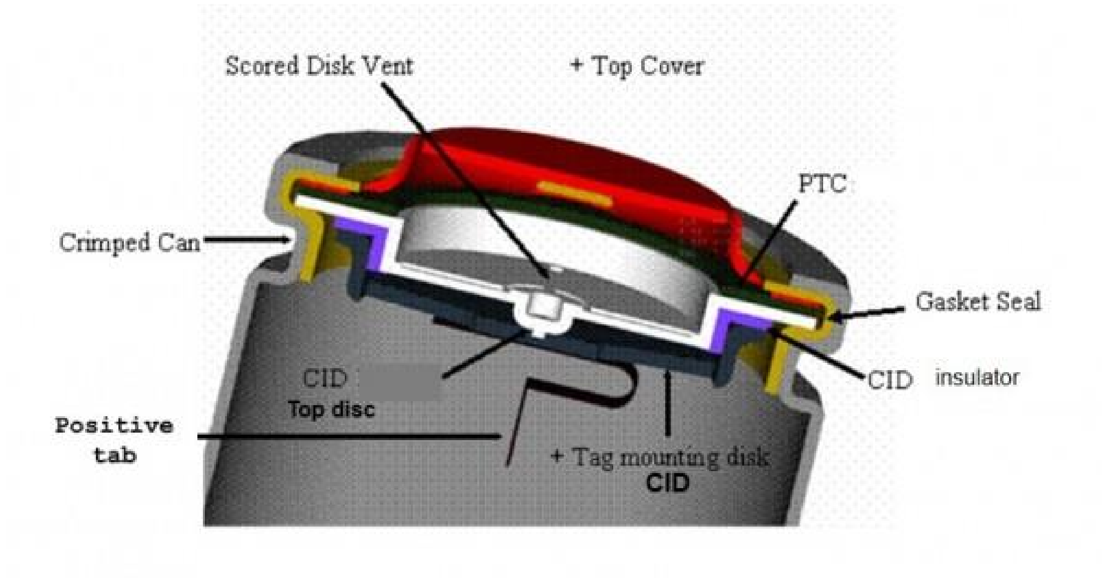


Figure 33: Cell venting mechanism in a lithium-ion battery [56].

The pressure vent releases the hot gases, a CID (Circuit Interrupt Device) is used in some designs to eliminate the positive electrode connection and a CID insulator protects the circuit interrupt device from getting damaged during the process. The internal protective devices are PTC, CID, Tab/lead meltdown, Bimetallic disconnects. The external protective devices are diodes, PTC/polyswitch, thermal fuses, circuit boards with specialized wire traces [56].

4.2.3. Flame Retardants:

When thermal runaway occurs in a lithium ion battery, it mainly escalates due to the gas, heat and pressure accumulation inside the battery. The first component to get affect inside the battery is the electrolyte. The solvent in the electrolyte is a mixture of cyclic and non-cyclic carbonate solvents. The cyclic solvents have high flash points i.e. they can withstand heat and high temperature better than non-cyclic solvents with low flash point. When the electrolyte is starts experiencing the heat, the solvents and inorganic lithium salt in the electrolyte release flammable gases. The flash points of some of the non-cyclic solvents are as follows: diethyl carbonate (DEC) 33ºC, dimethyl carbonate (DMC) 15ºC and methyl ethyl carbonate (EMC) 22 ºC [57].

Techniques are being developed in order to facilitate the control of heat and temperature by adding some additives to the electrolyte. These additives are called flame retardants, they are used to control the heat and to prevent any mishap. The main purpose of the flame retardant is to maintain the normal working of the battery and to prevent thermal runaway. The flame retardant should not chemically participate in the working of the battery i.e. the chemical component added as flame retardant has to be inert to the working of the battery. The addition of flame retardants will affect the battery efficiency but without flame retardants the explosion is unavoidable and cause damage to the vehicles.

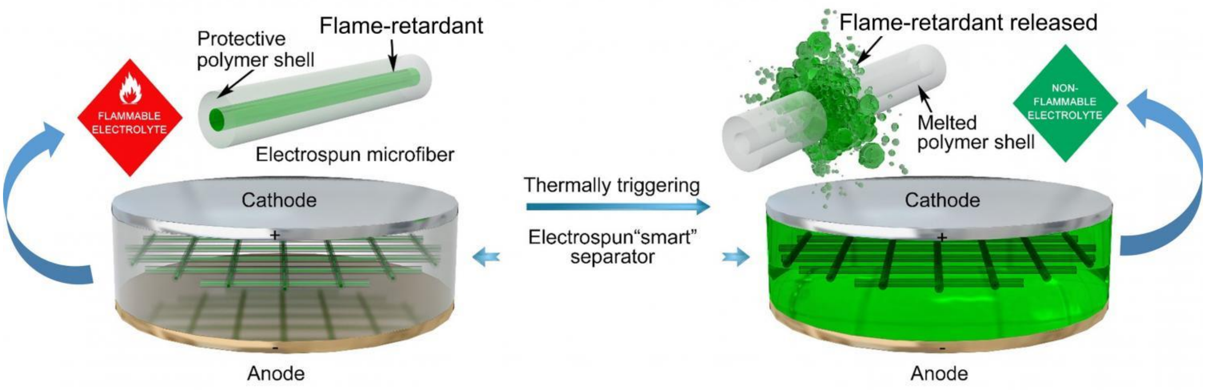


Figure 34: Schematic of the "smart" electrospun separator with thermal-triggered flame-retardant properties for lithium-ion batteries [58].

Kai Liu et al. [58] have fabricated a novel electrospun core-shell microfiber separator with thermal-triggered flame-retardant properties for the safety of lithium ion batteries. As seen in the above picture, the flame retardants are encapsulated within the microfibers that are fabricated by electrospinning, the core consists of the triphenyl phosphate (TPP) a popular flame retardant and the shell is composed of poly(vinylidene fluoride-hexafluoropropylene)(PVDF-HFP) [58]. Since the flame retardant is encapsulated it does not come in direct contact with the chemical components of the battery and the integrity of the flame retardant is maintained. The melting point of PVDF-HFP is nearly 160 ºC, when the temperature starts rising, the PVDF-HFP layer melts and releases the flame retardants present in the core. When the flame retardants are released it reduces the internal temperature and prevents the release of flammable gases from the electrolyte and stops thermal runaway.

Xu et al. [59] synthersized tris-(2,2,2-trifluoroethyl) phosphate (TFP), bis(2,2,2-trifluoroethl)-methylphosphate (BMP), and (2,2,2-trifluoroethyl) diethyl phosphate (TDP). They investigated the flame-retarding ability and electrochemical properties of the additives. The electrolyte conductivity was not altered and had excellent electrochemical properties, TFP had overall best performance than BMP and TDP [59].

4.3. Thermal Protection:

Thermal energy in the form of heat is the first and foremost reason for the failure of a battery or any electric component. When the battery undergoes charging or discharging process it tends to heat up during the process. When the battery level goes less than half of its capacity, it tends to dissipate energy at a faster rate and heat up the lithium ion battery cell.

When the electric vehicle is operated in high temperature regions, the heat produced in the battery and the heat from the external makes the performance of the battery less effective and may lead to damage of the battery resulting in failure. In order to ensure the safe working of the battery a thermal management system is very important. The main factor in lithium ion batteries is they tend to produce more heat and especially during aging of the battery. Compared to plug-in electric vehicles and hybrid electric vehicles the battery energy is very high in battery electric vehicles, the charge and discharge cycles are very deep in electric vehicles. The thermal management is not only required in high temperature regions it also plays a major role in providing efficient working in all temperature conditions. The temperature affects battery [60]:

- Operation of the electrochemical system [60].
- Round trio efficiency [60].
- Charge acceptance [60].
- Power and energy availability [60].
- Life and life-cycle cost [60].

The temperature affects or decides he battery power capability and also limits the driving range of the electric vehicle. The continuous degradation in the power and energy of the battery determines the required size and capacity of the battery based on the environment it is used. Heat generated in the cell has to be dissipated out of the lithium ion battery pack, the fundamental methods of managing the heat are convection, radiation and conduction. Based on the use and need of the type of thermal management for the battery any method can be opted as shown in figure 35. The internal thermal management methods are mechanical-level enhancement and embedded micro-channels. The external thermal management methods are active thermal management, passive thermal management and hybrid thermal management. The commonly opted technique in electric vehicles to manage heat emission is active thermal management and passive thermal management. Thermal management constantly uses electricity in order to ensure the thermal range of the battery even when the car is parked.

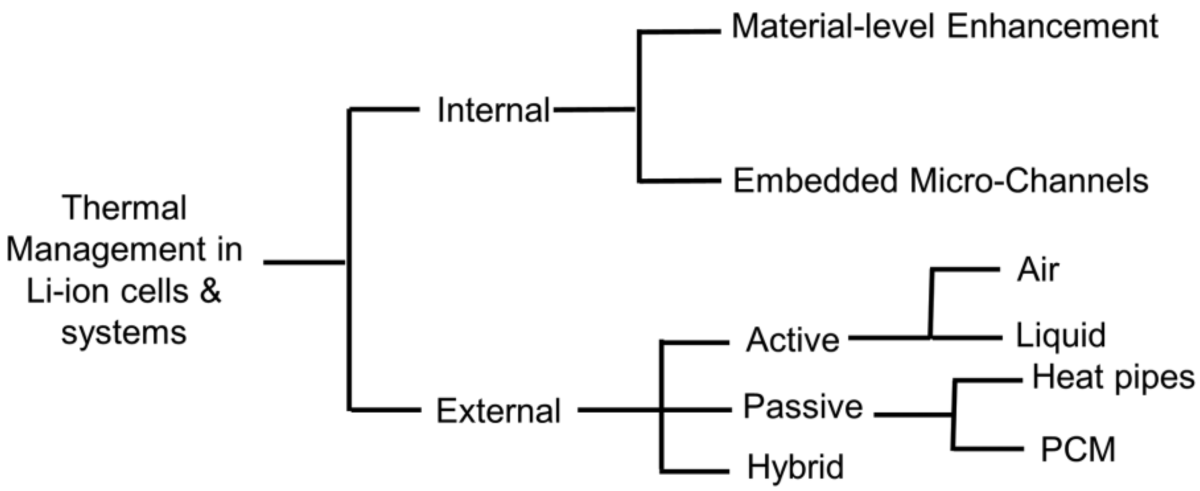


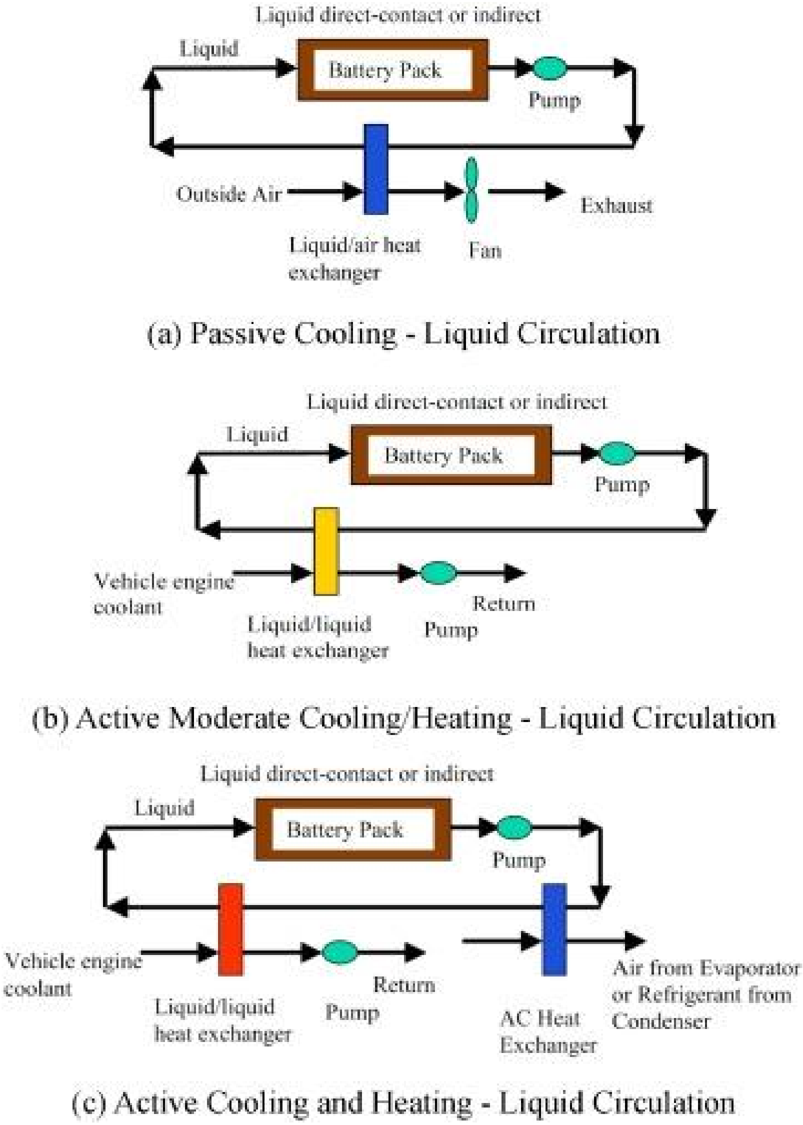
Figure 35: The different types of thermal management [61].

Active thermal management can be achieved by using air or liquid as cooling agents and passive thermal management is achieved by using heat pipes or PCM (phase changing materials). The Hybrid thermal management technique is under intensive research in which both the active and passive thermal management techniques are combined for better results. If the thermal environment in the lithium ion battery is not taken care of in a proper way it leads to early aging of the battery and damages the performance of the battery.

Conduction – conduction is the process by which heat flows from an area of higher temperature to one of lower temperature within a single medium – solid, liquid or gas – in an attempt to equalize thermal differences [62].

Convection – convection is the transfer of heat between a solid surface and a fluid (gas or liquid) due to the bulk motion of the fluid. In the case of convection, ambient air absorbs heat from a nearby heated surface. It becomes warmer than the surrounding air and rises. Cooler air replaces the warmer air and a natural flow occurs [62].

Radiation – Radiation heat transfer results when thermal energy in the form of electromagnetic waves is emitted from a body due to its temperature. Emission and absorption is determined by the temperature and surface condition of the radiating source, and the temperature of the surrounding environment [62].



(a) Passive Cooling - Liquid Circulation

(b) Active Moderate Cooling/Heating - Liquid Circulation

(c) Active Cooling and Heating - Liquid Circulation

Figure 36: Thermal management [63].

In the figure 36, (a) represents the schematic working of a passive cooling thermal management system using liquid cooling circulation, (b) represents the schematic working of an active moderate cooling /heating thermal management system using liquid cooling circulation, (c) represents the working of an active cooling and heating thermal management system using liquid cooling circulation.

In order to determine the thermal management technique required for a system the thermal resistance of the system is checked based on the total heat generated. The lithium ion battery cell has spatial distribution for the generated heat, in this case it is important to analyse the conductivity of the cell to know the heat inside the cell [61].

The thermal management technique used in any lithium-ion battery cell is defined as Battery Thermal Management System (BTMS). The main function of the BTMS is to regulate the temperature of the battery system and to achieve a uniform temperature across each battery cell and between cells in the module or pack, principally during high current rate charging and discharging processes [64]. An effective design of BTMS helps to enhance the battery performance, lifetime and effectiveness, and to reduce the size, complexity, weight and the cost of the battery [64].

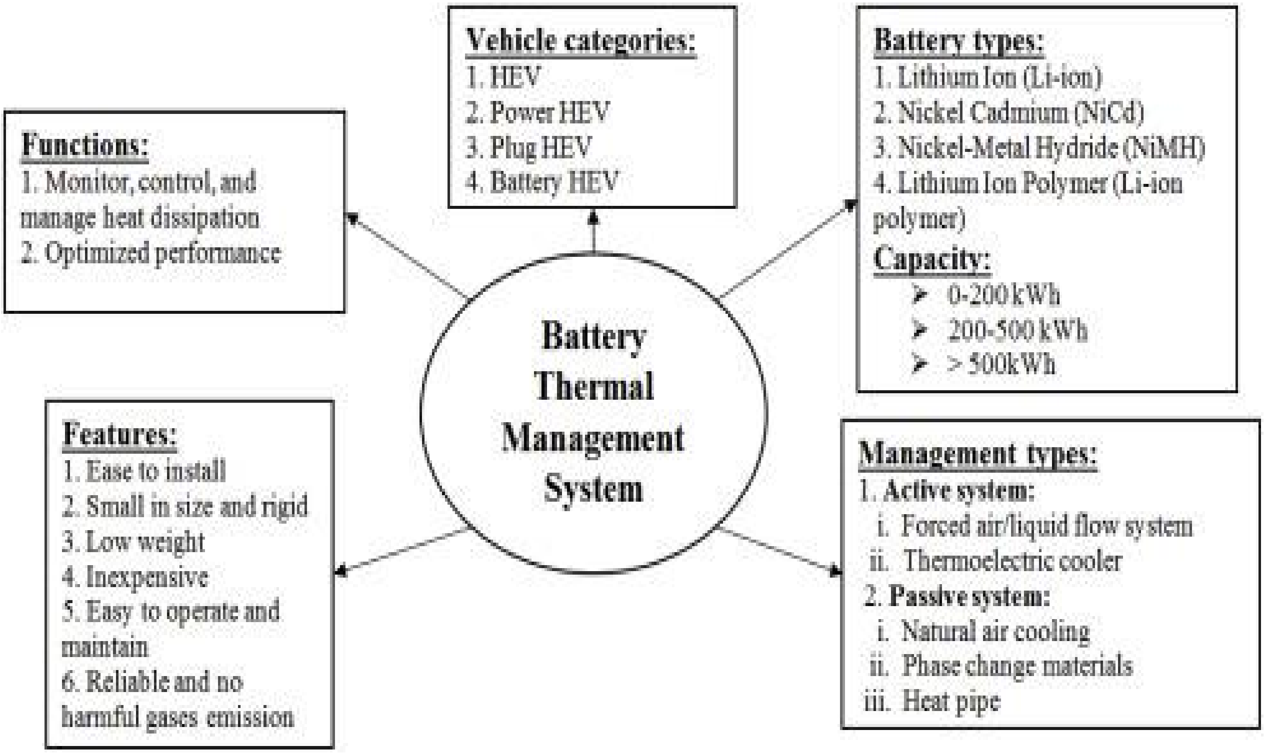


Figure 37: Battery Thermal Management System [65].

4.3.1. Passive Thermal Management:

Passive thermal management is achieved with the help of already existing systems and does not require additional cooling system installed in the battery. These cooling methods rely on the process of conduction, convection and radiation. Passive thermal management can be easily established in a system and is the cost effective. Some common methods to implement passive thermal management are by using heat sinks, heat spreaders, and thermal interface materials. Passive thermal management techniques ae advised for systems with minimum heat generation. As the rate of heat generation increases the nature of dissipation of the heat has to be quick and is better to adopt active thermal management.

4.3.1.1. Phase Change Material:

Phase Change Material (PCM) is used for Battery Thermal Management System (BTMS) and come under the passive thermal management category. PCM is mostly preferred for PHEVs and BEVS as they produce more heat in the battery while charging or discharging. The thermal conductivity of PCM is quite low and the heat produced in the material needs to be removed quickly. Techniques like the encapsulation of PCM inside metal foam is used to improve the thermal conductivity of the material and the metal foam's meatal is often made of aluminium, copper or graphite composite [66].

The PCM are positioned in between the battery cells and they absorb the heat produced in the battery during charging or discharging of the battery. The stored heat is either removed as the excess heat from the battery or it can also be used to maintain the temperature of the battery greater than room temperature in cold environment. It can be very helpful in the cold climate and increase the efficient working of the battery. A fully developed PCM based Battery Thermal Management System (BTMS) has been done for electric scooter and the model of the battery is seen in figure 38.

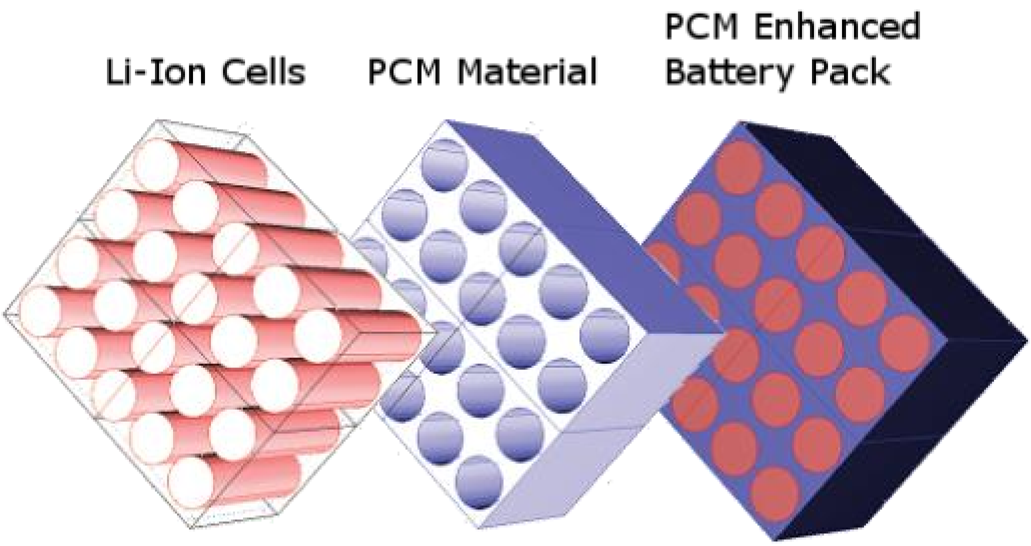


Figure 38: Phase Change Material for Electric Scooter [67].

The advantage of PCM is that they have good cycling ability, compactness and high latent heat [68]. The thermal conductivity, latent heat and the melting temperature are very important for a phase change material. Paraffin is tested to have these components and is the most commonly used material for phase change material (PCM) but lacks thermal conductivity which is quite a problem [69]. In order to overcome the drawback in paraffin composite PCM is used. The composite uses aluminium or copper foam placed on either sides of PCM. Graphene-enhanced PCM are used in order to overcome the thermal conductivity of PCM, the thermal conductivity resulted to be 60 times higher than that of paraffin [68]. Incorporating expanded Graphite (EG) in the matrix, called the graphite matrix, helps in the thermal conductivity of paraffin [70][69]. The graphite matrix structure can be seen in the figure 39.

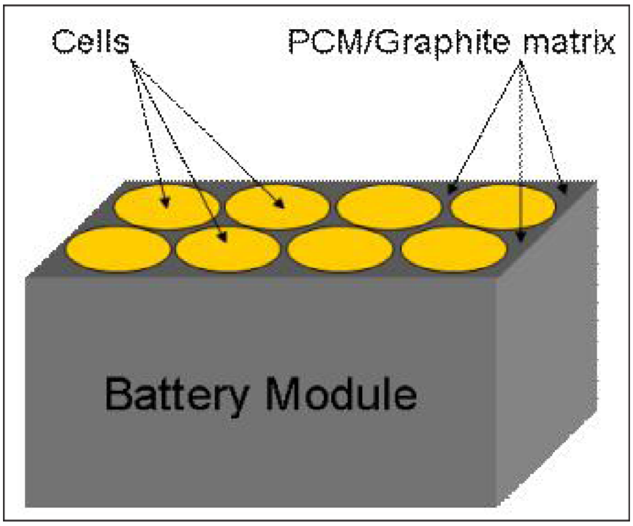


Figure 39: PCM/Graphite Matrix [71].

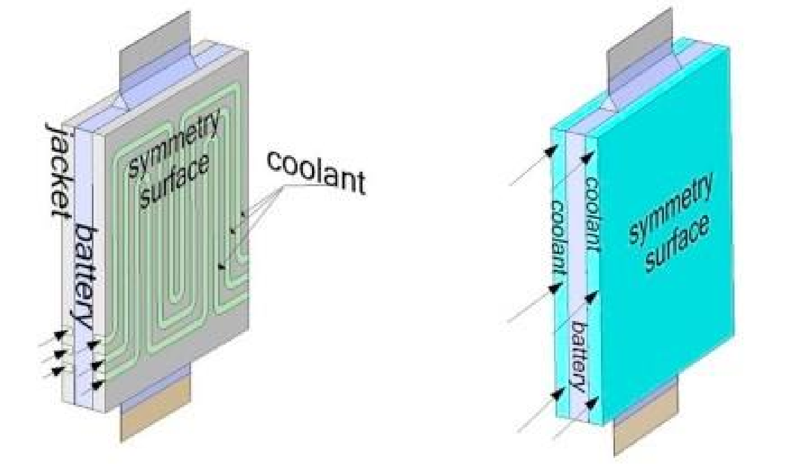
PCM also has several uses in hybrid thermal management and it is the first option in the form of passive thermal management. Though PCM is efficient in removing excess heat from the battery, extreme temperature conditions in the battery can cause the thermal management system to fail.

4.3.2. Active Thermal Management:

Active thermal management involves the use of external energy introduced in the system in order to remove the heat inside the battery pack. The use of external energy helps in fast removal of heat from the system and uses the process of convection. The use of external energy introduces complexity in the system and increases the expense of the thermal management system. It is expensive than the passive thermal management system. Active thermal management can be realised using forced air cooling, forced liquid cooling, and solid-state heat pumps.

4.3.2.1. Liquid Cooling:

Liquid cooling is one of the most widely used Battery Thermal Management System (BTMS) in electric vehicles. The liquid cooling is mostly preferred for PHEVs and BEVs. Liquid cooling is not preferred in HEVs (Hybrid electric vehicles). In the plug-in hybrid vehicles and battery electric vehicles the amount of heat dissipated is very high compared to hybrid electric vehicles, liquid cooling helps in fast dissipation of generated heat in the battery. Liquid cooling shows a heat transfer coefficient 1.5 to 3 times greater than air cooling and requires smaller cell to cell gap than air cooling [64]. While using liquid cooling the factors such as leakage and corrosion has to be noted. Liquid cooling also adds on weight to the battery pack.



(c) Configuration of indirect liquid cooling (d) Configuration of direct liquid cooling

Figure 40: Liquid Cooling Thermal Management [66].

The advancement in liquid cooling technology can be seen in the use of cold plates, which are thin metal plates that includes one or more internal channels through which the liquid flows. The use of cold plates has increased efficiency than the direct flow of liquid in the internal structure of the battery, and also reduces the quantity of liquid used and shows a reduced amount of consumed power. Investigations and research works are been carried out in the cold plate to analyse the performance of the cold plates, the to study the maximum heat removal rate and temperature uniformity of the cell. Jin et al. [72] investigated ultra-thin mini-channel performance by comparing the oblique structure to the conventional channel and shows that high performance was obtained with oblique structure. The positioning of the cold plates (cell level or pack level) in the battery module also plays a major role in efficient working of the thermal management. The cold plates are cooled external through inlet/outlet valves and the cold plates are sophisticated with micro-channels which facilitate internal coolant flow. Oblique cold plates and straight cold plates have been tested to obtain best results. Oblique cold plates prove to have more efficiency compared to straight cold plates [68].

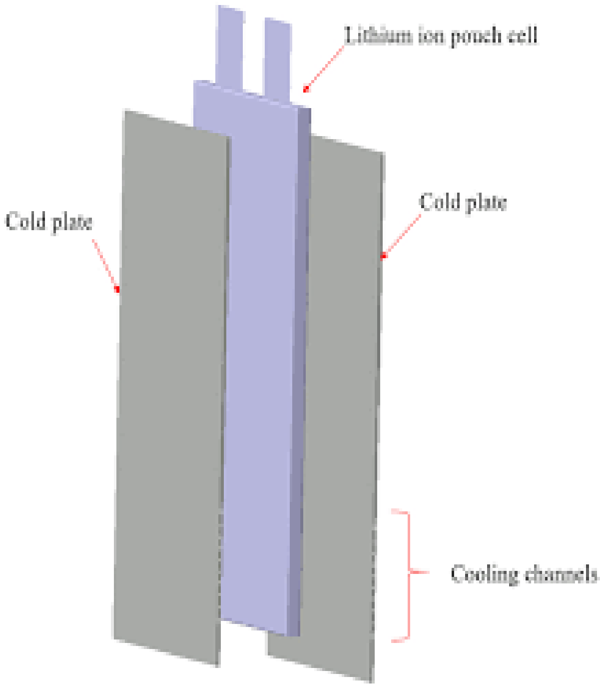


Figure 41: The use of cold plate for liquid cooling [73].

In the figure 41 the cold plates are placed on either side of the lithium ion battery pouch cell. The inlet and outlet valve for cooling is indicated as the cooling channels in the figure 41. The two extensions in the lithium ion pouch cells are the negative and positive tabs of the battery.

4.3.2.2. Air Cooling:

Air cooling can be used for both passive and active thermal management, in active thermal management technique special components are used along with the battery to provide heating or cooling based on the weather conditions (hot or cold temperature). In order to reduce the heat dissipated in the battery during the discharging or charging process of the battery, air is passed through the air channels designed in the battery pack as BTMS (Battery

Thermal Management System). The introduction of air channels in the battery increases the size of the battery. The volume of air required to reduce the heat inside the battery is very high compared to liquid cooling technique, which can cool the battery pack at a faster rate than air cooling. The rate of heat removal depends on facts such as the chemical and physical structure of the battery, rate of heat generation, usage of the battery based on the powertrain of the vehicles, the heating and cooling demands, etc. [74]. The advantages of air cooling is that it is light weight (does not add so much weight as in the case of liquid cooling), low cost and has a long life. The use of air as a cooling systems generates more noise in the vehicle compared to liquid cooling and also required increased size of the battery to allow the passage of air through the air channels.

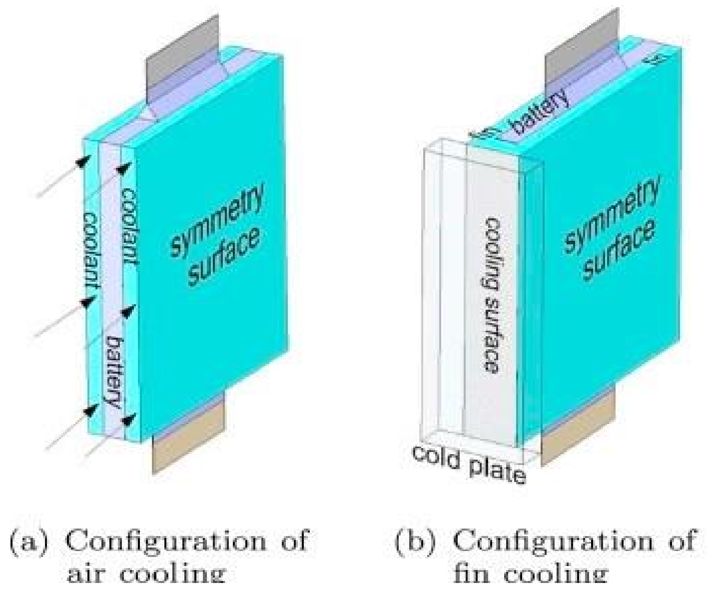


Figure 42: Air cooling thermal management [66].

As seen in the figure 42, air cooling is done in different ways, direct cooling and indirect cooling. In indirect cooling a fin mechanism is used in which thermal conductivity metal plates are placed in the between the battery cells and the air does not directly reach the battery cells. In the direct air cooling mechanism the air reaches the battery cells directly. The direct battery cooling battery structure can be seen in figure 42(a). The indirect air cooling technique using fin cooling structure can be seen in figure 42(b). A detailed structure of the fin cooling technique can be seen in figure.

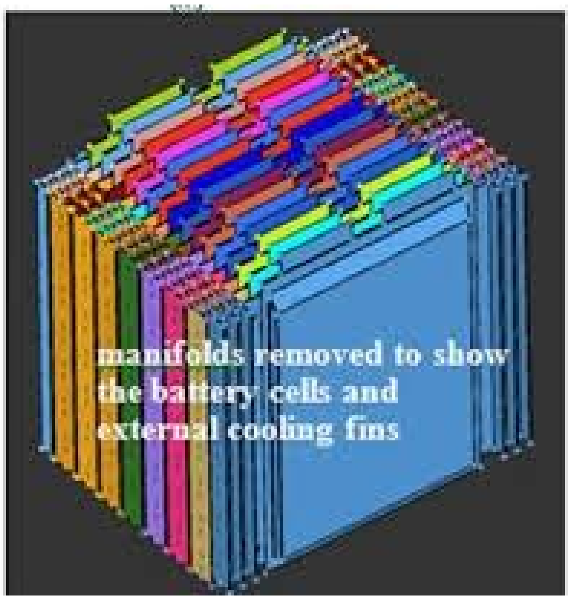


Figure 43: A internal structure of the battery pack without the outer case [75].

The fins in the exterior are connected to the cooling plates in between the cells and are cooled indirectly through them. Aluminium is the mostly commonly used metal for the production of fins and the cooling plates.

4.3.3. Hybrid Thermal Management:

Hybrid Thermal Management is a combination of passive and active thermal management techniques. PCM has many advantages as a cooling technique but due to its passive heat absorption there are chances of the battery to over heat and undergo thermal runaway. In order to use PCM as efficient as possible it is combined with active cooling to help the removal of passive heat in the battery. The use of PCMs along with active water cooling, forced air cooling and the air cooling using heat pipes have all been researched. The use of a specific technique remains with the designer and the requirements of the automotive vehicle. A lot of research in hybrid thermal management is being carried out.

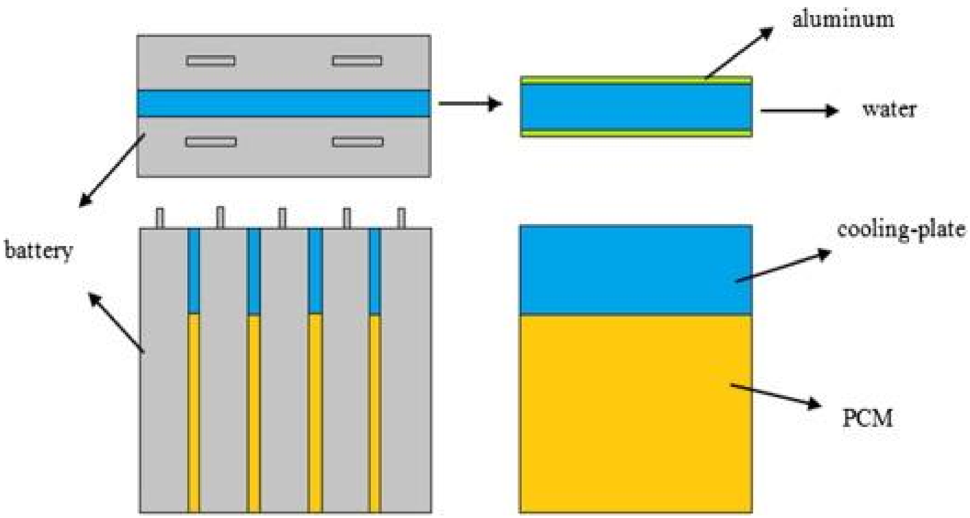


Figure 44: PCM/water cooling plate [76].

Figure 44 shows the hybrid thermal management technique by the use of PCM with water cooling plate for thermal management [76].

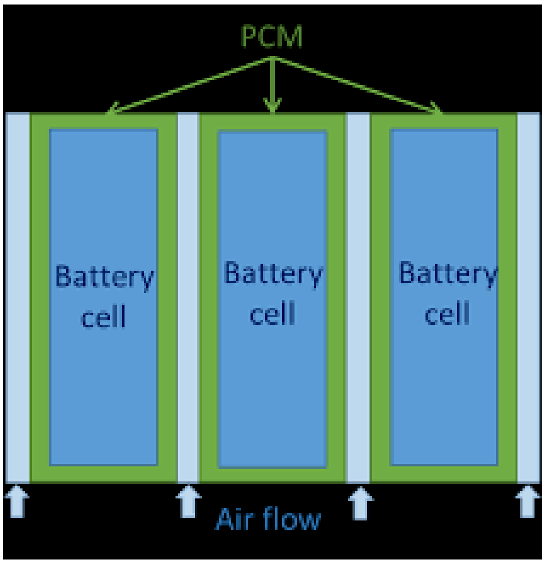


Figure 45: PCM/forced air cooling [77].

Figure 45 shows the model representing three prismatic battery cells surrounded by a layer of PCM and forced air cooling [77].

5. Tests for Lithium-ion Battery:

Lithium-ion batteries can be tested for various aspects and various categories based on their use. The main aspect of the tests are to check the stability of the battery under the test conditions and to improve the nature of the battery chemistry or protection of the battery parameters to avoid battery failure. The tests are also pushed to the maximum level to check the condition in which the battery fails and to make changes in the battery if possible. The tests are very important to understand the working of the battery pack and to be aware of the possible conditions of battery failure. The most commonly done tests are electrical tests, mechanical tests, and environmental tests. A detailed description about the types of test that can be carried out under each category is given in this chapter.

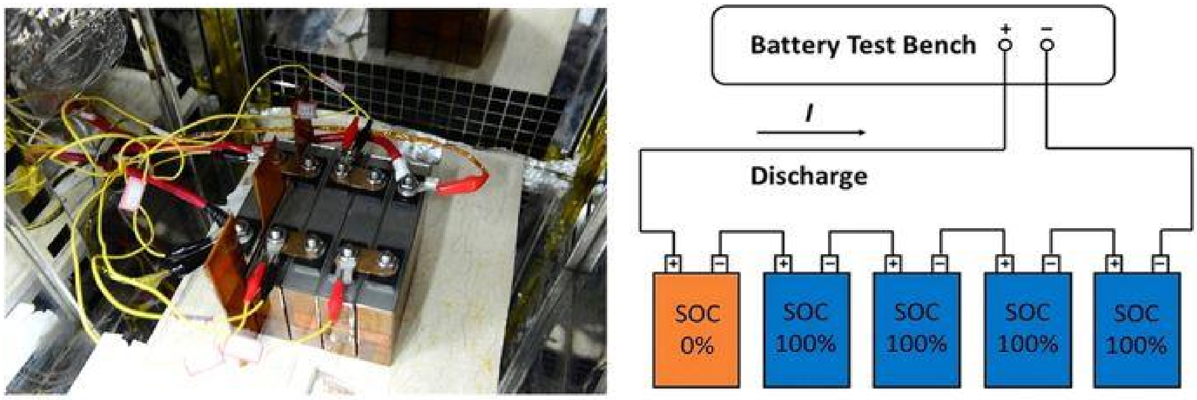
5.1. Electrical Test:

Electrical tests are carried on the lithium-ion battery cells in order to protect the electrical integrity of the cell. Overcharge/overdischarge, external short circuit and internal short circuit are some of the electrical damages to the cell. The tests to check the electrical integrity are seen below.

5.1.1. Forced Discharge or Overdiscgare Test:

The forced discharge or overdischarge test is carried out with a specific number of cells connected in series. The battery charge of each cell is noted or all the cells are charged to the same level. For this test the batteries are connected in series. The test is carried out by discharging the battery beyond the cut off voltage of the battery and maintain the battery in the discharged state for a prolonged time. The goal is to create an imbalance in the series connected battery pack, which results in a short-circuit [78]. If the battery is stable and does not result in thermal runaway, the battery has passed the test (not one cell of the battery pack was impacted due to overdischarge). If the even one cell explodes or catches fire during the test it does not pass the test and the battery cell has to be re-evaluated until it passes the test.

The overdischarge test is generally carried out in an explosion-proof chamber and the batteries are placed in the test bench. Rui et al [79] performed the forced discharged test with the experimental setup as shown in figure 46.



(a) (b)

Figure 46: Experimental setup of the forced discharge or overdischarge test [79].

In the figure 46 (a) shows the test bench of the batteries connected in series for overdischarge test, (b) represents the circuit connection diagram of the overdischarge test [79].

5.1.2. External Short Circuit Test:

The external short circuit test is carried out by connecting the positive and negative terminal of the battery directly with each other. While the test is conducted a resistor is connected between the terminals in order to contain the power supply. The circuit diagram for an external short circuit test is seen in figure 21, is connected with the resistor Rshunt to control the power supply. The controlled power supply allows us to diagnose the batteries behaviour. The resistor is connected between the positive and negative terminals externally for a defined period of time. If the battery is equipped with fuse or protective systems they disable the passage of current for a period of time. This test allows us to determine the ability of the battery to withstand a maximum current flow condition without causing an explosion or fire [78].

5.1.3. Abnormal Charging Test:

The abnormal charging test is carried out by charging the battery beyond its 100% capacity. When a battery is overcharged internal short circuit occurs and the battery explodes or catches fire. If the battery does not explode or catch fire it passes the test and the battery is safe. Abnormal charging test can also be overcharging test and is conducted in an explosion proof chamber to contain the results.

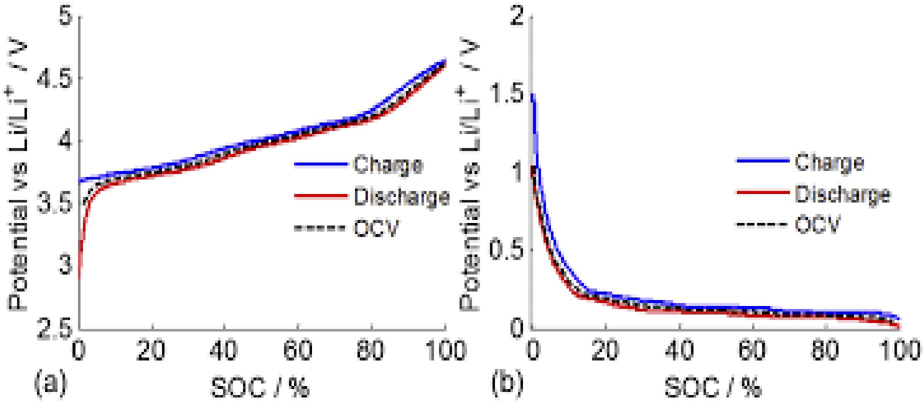


Figure 47: The overcharging and capacity fading of the battery is shown in the graph [80].

5.2. Mechanical Test:

Mechanical tests are done to a lithium-ion battery cell to analyse the withstanding capacity or the mechanical integrity of the battery. The battery can undergo mechanical situations like crush, vibration, impact and penetration and damage the integrity of the battery. Tests to analyse the working of the battery and check the protection circuit of the battery are seen below.

5.2.1. Crush Test:

The crush test is carried out by crushing the lithium ion battery cell with an applied force, that is applied by two plates. The battery cell is placed in between the plates and then crushed. The force that is generally used for the crush test is 13 kN. To pass this test the battery does not explode or catch fire under the applied force condition.

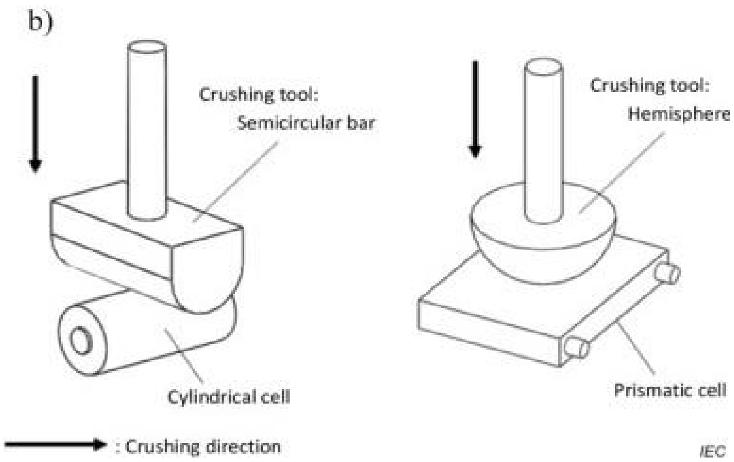


Figure 48: Crush test for lithium-ion battery cell [81].

5.2.2. Vibration Test:

Vibration test for the lithium-ion battery is very necessary due to the application of the battery in electric vehicles. The vibration test can be carried out by applying a simple harmonic motion at a specific amplitude, with variable frequency and time [78]. The test also helps in understanding the long term effect of vibration to a battery pack. With the help of vibration test the durability of the battery based on the vibration impact can also be obtained [81]. If the battery does not ignite or explode the battery passes the test.

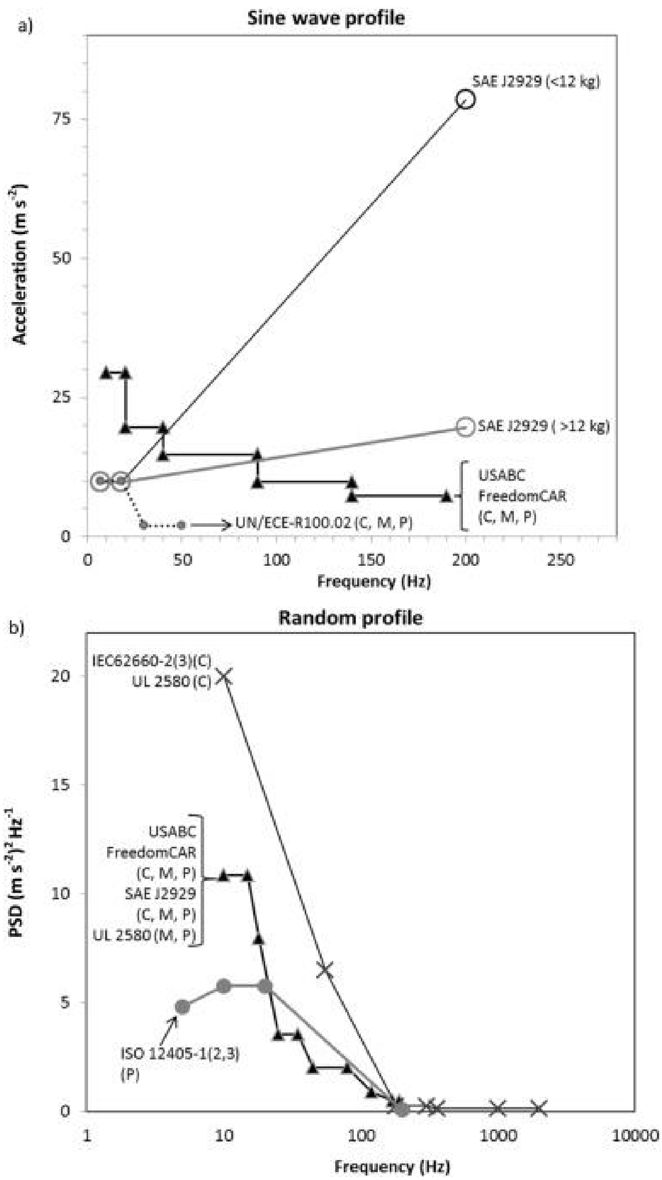


Figure 49: Vibration test a) sine wave profile b) random profile [81].

5.2.3. Nail Penetration Test:

The nail penetration results both mechanical and electrical damage in a battery. A Sharp pointing rod is inserted in the battery with a certain force at a certain constant speed [81]. As the nail penetrates the cell it damages the separator and the electrodes are compromised causing short circuits and heat release [81]. As in a battery cell there are many electrode layers combined together, the impact can be noticed in a short duration.

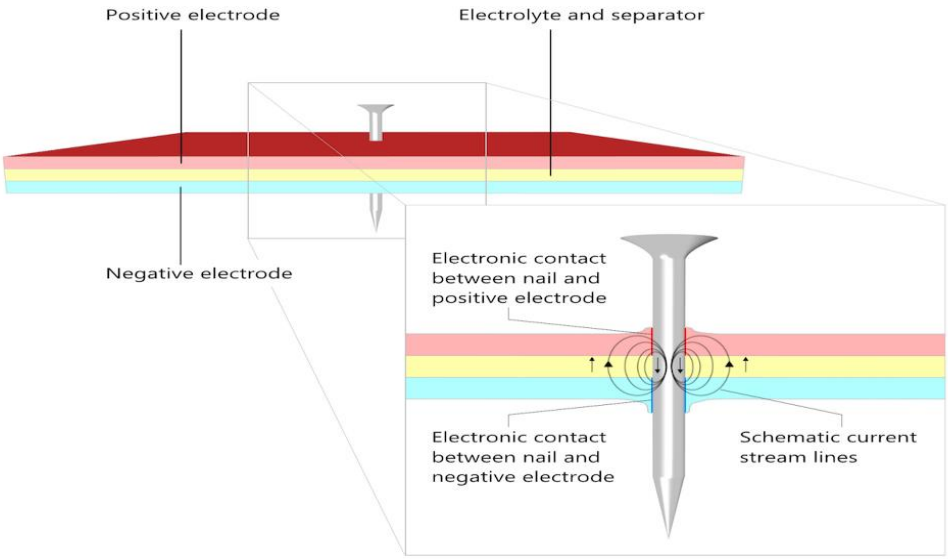


Figure 50: Nail Penetration test [82].

5.3. Environmental Test:

Environmental tests are carried out to make sure better working of the battery when exposed to abnormal environmental conditions. The working of the battery and the protection circuit under these circumstances are seen below.

5.3.1. Thermal Shock Test:

The thermal shock test focuses on the expansion and contraction of the cell due to the exposure of the cell to sudden changes in temperature (example a heated garage, transport) [81]. For the test the battery cell is exposed to two temperature limits and held at each limit for a period of time [81]. The temperature limits are extreme hot and extreme cold conditions. If the cell does not explode or catch fire the battery cell passes this test.

5.3.2. Extreme Cold Temperature Test:

The main objective of this test is for the extreme cold countries and to analyse the working of the battery in such scenarios. When the temperature is too low, there is higher possibility of dendrite formation in the anode and the electrolyte has poor conductivity. USCBC:1999 [83] describes a matrix for charging at normal primary charge rate for the specific system and discharging at 1C down to various depths of discharge 20,50,60,80,100% at the following temperatures:-40,-20,0 and 25º. The test shall be stopped if abnormal conditions or physical damage to the cell becomes evident [81].

6. Battery Management System:

Battery Management System (BMS) is an electronic system that controls a rechargeable battery pack or cell pack. BMS is a critical part of the electric vehicle powertrain. The BMS is most widely employed in electric vehicles to manage the charge/discharge of the lithium ion battery. BMS is needed because of the non-linear nature of the charge/discharge of the lithium ion battery. The BMS can accurately calculate the current in the battery and monitor the state of charge because lithium ion battery can be damaged by simply overcharging or undercharging. BMS consists of many different circuits inbuilt, each circuit is responsible for a specific operation. The modules responsible for measuring the voltage of each cell and measuring the temperature of the battery pack are called slave BMS modules. The slave BMS modules communicate with the master BMS module about the state of charge of the battery, temperature, rate of charge/discharge, flow of current in/out of the battery pack etc. The BMS displays the state of charge of the battery to the driver and it can also communicate with other powertrain subsystems using CAN Bus serial communication.

The BMS also has the capability to balance the charge between the poorly charged cell and the heavily charged cell. When the cells are overcharged, the BMS connects the overcharged cells to the load circuit to dissipate the excess charge to save the battery from damaging. BMS automatically disconnects the battery pack from the charger when they are fully charged, thus avoiding overcharging. The battery management system must. be configured to each different battery pack and according to the powertrain configuration [84].

7. Proposed SWOT Analysis:

Lithium-ion battery technology being the major power source of electric vehicles and automotive industry, the safety of the battery remains a main issue. SWOT analysis framework helps in analysing the strength, weakness, opportunities and threats of the lithium ion battery and its application in the automotive industry. SWOT analysis is mainly used for an organisation, person, component or product to get a clear purpose and understanding [85]. SWOT analysis provides a clear understanding of the strengths and weakness of the product. The main components of SWOT analysis are classified into Internal Environment (Strength and Weakness) and External Environment (Opportunities and Threats) [85]. Strength mainly focuses on the advantages and the positive aspects of the component. Weakness focuses on the disadvantages and the negative aspects of the product. Opportunities and Threats are related to the effects of the system when released to the environment (used in applications), foreseeing the opportunities and threats helps in the betterment of the product.

7.1. SWOT Analysis of Lithium-Ion Battery:

STRENGTH	WEAKNESS
- High energy density - Low maintenance - Diverse battery chemistry - Long cycle life - Light weight - Self-discharge - No memory effect	- Ageing - Cost - Require protection circuit - Sensitive to temperature - Transportation - Deep discharge cycles
OPPORTUNITY	**THREAT**
- Applications in automobiles - Promising energy source	- Flammable - Battery failure - Environmental conditions

Strength:

- **High energy density:** The power capacity of a battery is directly proportional to its energy density. Lithium ion battery having high energy density provides long lasting and stable power. The high energy density plays a vital role in the use of lithium-ion battery in electric vehicles [86].
- **Low maintenance:** Since lithium-ion batteries have no memory effect they require less maintenance compared to other rechargeable batteries.
- **Diverse battery chemistry:** Since lithium-ion has different battery electro-chemistry it can be used for various applications. Lithium-ion batteries are widely used in many application from products like cell phone, …….., electric vehicles.
- **Long cycle life:** The lithium-ion battery facilitate long cycle life, which enables hundreds of charge and discharge cycles.
- **Light weight:** Lithium ion batteries are light weight and helps in the use of many portable devices. Though they are light in weight, they provide high energy density and are compact to use. Many number of lithium-ion cells are combined together in a battery pack and used in electric vehicles.
- **Self-discharge:** Lithium-ion batteries have low self-discharge, they can hold charge for a longer time compared to other rechargeable batteries. Low self-discharge increases the number of charge/discharge cycles.
- **No memory effect:** Unlike other rechargeable batteries, the lithium-ion battery does not have to be completely discharged before recharging. Lithium ion battery has no memory effect.

Weakness:

- **Ageing:** The degradation of the lithium-ion batteries is not much different from other rechargeable batteries. The ageing depends not only on the duration (no. of days), it also depends on the number of charge/discharge cycles.
- **Cost:** The cost of the lithium-ion batteries remains a major disadvantage for electric vehicles. Compared to other rechargeable batteries, the cost of lithium-ion battery is 40% higher [86].
- **Require protection circuit:** Lithium-ion batteries require protection from overcharge and over discharge. The current in the battery needs to be maintained. In order to ensure the safe working of the battery, protection circuit is incorporated in the battery.

- **Sensitive to temperature:** High temperature affects lithium-ion batteries when they are used or operated. High temperature results in faster degradation.
- **Transportation:** Transporting lithium-ion batteries is a very big disadvantage, there are several accidents involving the transport of lithium-ion batteries.
- **Deep discharge cycle:** Deep discharge cycles damages the battery and they require on-board circuit to manage the battery during discharge [87]. The addition of the on-board circuit increases the cost of the battery.

Opportunity:

- **Applications in automobiles:** The recent advancements have increased the efficient of electric vehicles due to the use of lithium-ion batteries. The sophistication and distance criteria are well developed. Advanced lithium ion batteries play a major role in the use of electric vehicles.
- **Promising energy source:** With the increased awareness of global warming and degradation of fossil fuels, lithium-ion battery is a promising energy source. Increased production of electric vehicles directly increases the production of lithium-ion batteries. Electric vehicles are foreseen to be the future of automobile industry.

Threats:

- **Flammable:** The composition of lithium-ion battery poses a threat of fire when the battery is damaged or when the electric vehicle meets with an accident. The fire may lead to explosion in the case of transportation of the batteries.
- **Battery failure:** There are many failure modes for lithium-ion batteries; a detailed description is given in chapter 3.1. When the battery fails, it undergoes thermal runaway process and results in fire of the battery. When used in large number as in the case of electric vehicles, if one battery cell fails it might not be noticeable until most of the cells are damaged.
- **Environmental conditions:** Environmental conditions need to be considered mainly in the lithium-ion battery, it might lead to a very serious threat. The environmental conditions such as extreme heat and extreme cold affect the battery. Preventive measures must be provided in the battery used in these regions.

7.2. SWOT analysis of electric vehicles powered by lithium-ion battery:

STRENGTH	WEAKNESS
- Eco-friendly - Cheaper to run - Smooth to operate	- Safety issues - Batteries and battery change are expensive - Lack of charging infrastructure - Too long to charge
OPPORTUNITY	**THREATS**
- Rising fuel cost - Banning of ICE cars - Alternative option for fossil fuel	- Limited advancements in battery technologies - Alternative fuel

Strength:

- **Eco-friendly:** electric vehicles do not have any emission problems, therefore they do not pollute the environment. Increased use of electric vehicles help to fight environmental degradation.
- **Cheaper to run:** the cost of charging the vehicle is very cheap compared to the cost of fossil fuels. The maintenance of electric vehicles are also very cheap compared to ICE vehicles.
- **Smooth to operate:** the noise of the engine is very less and the transmission is very smooth.

Weakness:

- **Safety issues:** lithium-ion batteries are unstable under certain environmental conditions, the chances of battery failure is high and may result in fire and explosion of the vehicles.
- **Batteries and battery change are expensive:** Lithium-ion batteries are still one of the expensive batteries in the market. Electric vehicles need large set of battery packs and hence the cost is high.
- **Lack of charging infrastructure:** The consumer base for the electric vehicles are yet to be covered. Therefore lack of consumers results in lack of charging infrastructure for the electric vehicles.

- **Too long to charge:** The time taken for charging the lithium-ion battery used in electric vehicles is very long. This is a disadvantage compared to the refuelling of ICE cars. This is due to the fact that lithium-ion batteries have to be chemically excited in order to charge.

Opportunity:

- **Rising fuel cost:** For the past decade, the world has seen a rapid rise of the fossil fuel cost. The rise in fuel cost can be used as a selling point for electric vehicles.
- **Banning of ICE cars:** Fossil fuels cause emission of greenhouse gases which affects the environment to a greater level. Increasing pollution is causing health hazards all over the world. In order to prevent global warming, many countries are planning to ban the sales of ICE vehicles.

Threats:

- **Limited advancements in battery technologies:** Battery technologies for electric vehicles are still under development. Lithium-ion batteries having its own issues cannot be relied upon completely.
- **Alternative fuel:** Development of hydrogen fuel cell powered vehicles and development of alternative fuels can be a threat to the advancements of electric vehicles that use lithium-ion battery.

8. Conclusion:

Based on the estimated use of electric vehicles in the coming years and the affordability due to reduced cost, the need for low cost, highly efficient lithium-ion batteries is increasing. Although lithium-ion batteries have safety concerns and are easily flammable, they have proved to be very efficient and can give high output power with high battery capacity. Extensive research is being carried out all over the world in order to make the use of lithium-ion batteries safe and non-flammable. The recent trend in the electric vehicle market saw an increase in the sales of electric vehicles with the decrease in price. Based on the cost analysis, the electric vehicles are becoming cost efficient and affordable.

In order to understand the safety problems of lithium-ion battery, a detailed study about the modes of failure of the lithium ion batteries under different conditions were discussed in this thesis.

Thermal runaway process being the main hazard for the lithium-ion batteries, study of the breakdown process of the battery during thermal runaway, helps us to analyse and understand the basis of lithium-ion battery fire. Different prevention techniques to protect the battery from undergoing thermal runaway have been discussed. Protection of lithium-ion batteries from thermal runaway being the main concern, extensive research is being carried out in this field.

Some of the available testing methods to test the battery efficiency and the battery electrochemistry have been discussed and a description of the test process is studied. The different test categories such as electrical test, mechanical test and environmental test were reviewed and different test conditions are explained. Battery management system has become an essential electronic module in every electric vehicle. The BMS monitors the charge/discharge of the lithium-ion batteries and communicates the battery status to the driver and to other power train components. BMS also measures the bulk current flowing in and out of the battery pack. A brief study about the battery management system was done.

The detailed study about the cost benefit analysis, safety concerns, causes and prevention techniques, for the prevention of fire and explosion in lithium-ion batteries is achieved in this thesis. This could be used for further research study related to safety of lithium-ion batteries.

Based on the research study, SWOT analysis of lithium-ion batteries and SWOT analysis for electric vehicles powered by lithium-ion batteries is done in this thesis.

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