

A Design Study of Lithium-ion as a Storage Medium for Automotive Applications

by Bruce Baird

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A Design Study of Lithium-ion as a Storage Medium for Automotive Applications

Final Dissertation Report

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Abstract

This report provides a complete design analysis of a lithium-ion battery pack for use in an electric ATV. The report evaluates the alternative battery types commonly used in the automotive industry and provides a detailed explanation for the chosen chemistry lithium-ion. The chemistry of the battery cells is explained, and testing was carried out to determine the real capacity of available to purchase consumer batteries. Material selection is researched and analysed. A variety of different materials can be used as both the enclosure and internal components of the battery pack. In most cases a combination of materials are used for different components. These include plastics, steel, aluminium, fibre glass and composite materials such as carbon fibre. When selecting a material, it is important to establish the requirements of the component it is being used for. With ESS (Electrochemical Storage System) design, the factors taken into consideration are its strength, electrical conductivity,

mass and thermodynamic properties such as thermal conductivity, thermal expansion and melting points. The balance of safety and performance must be carefully evaluated. Due to the heat emitted by the cells the materials chosen within the ESS should dissipate the heat evenly throughout the pack to prevent any 'hotspots'. If a hotspot is detected on the cells a cooling method will need to be established as this can lead to thermal runaway

Contents

List of Figures.....	5
List of Tables.....	6
1 Introduction.....	7
1.1 Brief history of electric motors.....	7

1.2	Why use electric propulsion?	8
1.3	Will electric vehicles prevail?	8
1.4	Objective of dissertation	9
1.5	Aims	9
2	Literature Review	10
2.1	Battery operating principles	10
2.2	Battery cell chemistries	10
2.3	Parameters for evaluating battery performance	12
2.3.1	Capacity	12
2.3.2	Voltage	12
2.3.3	Power	13
2.3.4	Energy Density	13
2.4	Lithium-Ion Battery design	13
2.4.1	Cell materials	13
2.4.2	Cell internal construction	15
2.4.3	Cell form factor	15
2.4.4	Dangers of lithium-ion	16
2.5	Battery housing design	18
2.5.1	Materials	18
2.5.2	Module design	19
2.5.3	Safety features	20
2.5.3.1	BMS hardware	20
2.5.3.2	Balancing	21
2.5.3.3	Thermal control	21
3	Timing plan	23
4	Methodology	24
4.1	Testing	24
4.1.1	Cell testing	24

4.1.2	Material testing.....	24
4.1.2.1	Puncture.....	24
4.1.2.2	FEA.....	27
4.2	Results.....	27
4.3	Recommendations for further work.....	31
5	Conclusion.....	32
6	References.....	33

List of Figures

Fig.1 – Joyner ATV battery formation.....	9
Fig.2 – Diagram to show charge & discharge of lithium-ion cell.....	10
Fig.3 - Internal construction of 18650.....	15
Fig.4 - Example of 18650 by Samsung.....	15
Fig.5 - Example of generic pouch cell.....	15

Fig.6 - Image to show battery pack of Tesla Model S.....	18
Fig. 7- Specimen of fibre reinforced polymer honeycomb.....	24
Fig.8 – Cross-section of fibre reinforced polymer.....	25
Fig.9 – Cross section of aluminium honeycomb.....	25
Fig. 10 Drop-weight Impact equipment.....	26
Fig.11 – Specimen with penetration hole visible on top layer.....	27
Fig.12 Specimen with deformation to bottom layer visible.....	27
Fig.13 - FEA model showing deformation of topside.....	28
Fig.14 - FEA model showing deformation of underside.....	28
Fig.15 – Pouch Enclosure with heat sink.....	29
Fig.16 – 18650 Battery module with heat sink.....	29
Fig.17 – Front side of enclosure.....	30
Fig.18. – Rear side of enclosure.....	30
Fig.19 – Finished design of the Pouch ESS with lid removed.....	30
Fig.20 – Finished design of the 18650 ESS with lid removed.....	31

List of Tables

Table 1 – Table to compare commonly used battery chemistries in the automotive industry.....	10
Table 2 – Table to compare Nickel-metal chemistries.....	11
Table 3 – Table to compare commonly used lithium chemistries in cell manufacture.....	14

Table 4 – 18650 single cell test.....

Table 5 – 18650 parallel cell test.....

Table 4 – Pouch cell test.....

1. Introduction

1.1 Brief History of Electric Vehicles

There is a varying consensus on who first created an electric vehicle. Hungarian inventor Anyos Jedlik created an electric motor to power a small carriage in 1828, this is believed to be the first working electric vehicle. The first practical electric vehicle that could be mass produced was designed by Thomas Parker a British inventor who was responsible for electrifying the London Underground. It grew in popularity as alternative gas and steam engines were loud and produced pollutants, although the harm of the pollutants was necessarily known the smell was off putting so the electric vehicle became popular in cities.

By the 1900's electric vehicles contributed to a third of all vehicles in the USA.

In 1901 the world's first hybrid vehicle was manufactured by Porsche using a gas engine and electricity stored in a battery. It was the mass production of Ford's Model T and the discovery of cheap crude oil that saw the decline in popularity of the electric vehicle and by 1935 they had practically disappeared. The low price of crude oil and the improvement of ICE (Internal Combustion Engine) kept the attention away from alternate fuel sources.

In 1971 the lunar rover powered by electricity raised the profile of electric power for transportation once more. CitiCar produced by Sebring-Vanguard made more than 2000 models however, by the end of the 70's the low range of these vehicles allowed ICE to regain complete popularity.

In 1990 legislation created in California, USA by the Californian Air Resources Board (CARB) prohibited any manufacturer selling cars there unless they offered a zero-emission alternate to ICE, this was called the ZEV (Zero Emission Vehicle) mandate, this forced companies such as General Motors to produce either an all-electric or hydrogen fuel cell vehicle. One of the best examples of an all-electric vehicle produced as a result of the mandate was the EV1 was created by GM, using a lead-acid battery as a storage medium saw the EV1 achieve a range of 60 miles on a full charge. Although sceptics claimed this range was not enough to merit the vehicles long-term viability the average daily commute for Americans at the time was only 29 miles. Continued lobbying and lawsuits from the automotive manufactures, oil industry and even the US government saw the legislation revoked in 2003. The vehicles were not sold but leased and when the ZEV mandate was overturned the vehicles were recalled and subsequently destroyed leaving little trace they ever existed. (Paine, 2006)

In 2000, Toyota produced the Prius which became the first mass produced hybrid. In 2006 Elon Musk started Tesla Motors and produced the Tesla Roadster, based on the chassis of a Lotus Elise it was a luxury electric sports car capable of a 200+ mile range and a 0-60mph of 3.7. The first plug-in hybrid was manufactured by GM in 2010, the Chevy Volt. As investment was made into the charging station infrastructure electric and plug-in hybrids became feasible to everyday commuters due to better range and with the lowering cost of producing batteries many car manufactures developed their own hybrid and electric models. (AMERICAN ENERGY DEPARTMENT, 2019)

1.2 Why use electric propulsion?

The automotive industry is being pressured by government and environmental agencies to adopt cleaner technologies for use in vehicles. This is not only due to climate change as a result of increasing CO₂ levels in our atmosphere, but the industry is also trying to lose its reliance on non-renewable fossil fuels. These fuels not only produce CO₂ when burned and extracted but there is a limited supply globally and as we approach the limit, the price will not only drastically increase but global political instability will increase as the remaining global reserves are in locations with unstable economies and governments.

"The large number of automobiles in use around the world has caused and continues to cause serious problems for the environment and human life. Air pollution, global warming,

and the rapid depletion of the Earth's petroleum resources are now problems of paramount concern". (M. Ehsani – 2010). It has been 9 years since M. Ehsani published that statement and in that time the global population has increased by almost a billion people with very little being done with legislation until recently. We are now seeing a rapid change in legislation restricting emissions.

1.3 Will electric vehicles prevail?

A combination of electric motors and a rechargeable storage medium can be used to propel a vehicle. There is a distinct difference between the efficiency of an ICE system compared to a full electric system. Conventional gasoline vehicles only convert about 17%–21% of the energy stored in gasoline to power at the wheels, whereas an electric vehicle converts about 59%–62% of the electrical energy from the grid to power at the wheels. Although there is no emissions or harmful products produced by an EV during operation the source of the electricity used to charge the vehicle may have emissions and contribute to global CO₂ levels. If the source of the electricity is from clean energy i.e. Solar, wind or nuclear then there is no carbon footprint from operating the EV. If, however the source is from dirty energy i.e. burning fossil fuels, then the vehicle will directly contribute. Main factors that contribute to consumers adoption of electric vehicles are cost, availability, range and charging infrastructure. Ultimately consumer anxiety will determine the success and demand of EVs, it is still such a new technology with very little public knowledge on the benefits of all-electric. This consumer anxiety will fade as more manufactures produce EVs and they become more mainstream. Motorsport has had a big influence on car sales in the past with consumers opting for vehicles that perform well in divisions such as Touring Cars or the WRX world rally championship. Both championships have announced an all-electric series in 2020 which should boost the popularity of EVs. The end is drawing near for ICE both in motorsport and with general consumers. ICE will inevitably be phased out and possibly even HEV's too, the question is what will replace them? Currently the legislations is pointing towards zero emission vehicles becoming standard so the most likely solution now is EVs.

1.4 Objective of dissertation

The University of Wales owns and operates a Joyner ATV fitted with two electric motors on each rear wheel. Currently there are 4, 12V lead acid batteries acting as the storage medium. The main objective is to design an alternative storage medium to power the two electric motors. A research study will be carried out to determine best battery chemistry that can be used to provide a larger capacity than is currently available increasing run time.



(Fig.1 – Joyner ATV battery formation)

In Fig 1 we can see the location placement of the current 4 lead acid battery packs. Each pack weighs 32.5kg totalling 130kg. As they are fitted at the rear the weight distribution is currently 31% - 69%, this has a negative effect on handling as the optimum is 50% – 50%. The current battery packs are securely fitted in a purpose-built frame just behind the driver's seat and are connected in series to generate 48 volts. The new battery packs will ideally share the same outer dimensions as the current lead acids so the purpose-built frame can continue to be used. Safety is the most important driving factor of this project so the location of the batteries must not jeopardise the safety of the driver in the event of a collision. Due to the complexity and hazardous nature of many of the available battery chemistries the cells will not be designed but purchased. Once the chemistry is chosen a further study will be carried out to determine the most suitable cell type. The cells must be tested to ensure they match the manufacturers stated specifications. As the minimum requirement is producing a battery pack with a greater capacity than the lead acids the results of the tests will determine how many cells are needed within each pack. The design for the battery pack will be created using a CAD (Computer-aided Design) software package and FEA (Finite Element Analysis) will be performed to ensure the structural integrity of the battery pack in the event of a collision. To evaluate the accuracy of the FEA, testing will be performed on a variety of materials. There is no set budget for the battery pack however cost should be taken into consideration as cells and safety components can be very expensive compared to lead acid batteries and the performance benefit should outweigh the added cost.

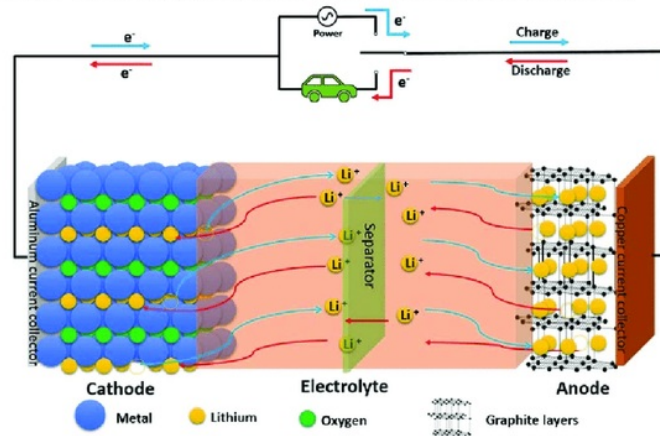
1.5 Aims

- Research the available battery chemistries to determine the most suitable for use in a battery pack for an ATV.
- Research the design of current battery packs used for automotive applications including safety features.
- Establish the requirements for the battery pack and outline the specifications the pack must be built to using previous research to provide realistic parameters.
- Create a design for the pack adhering to the required specifications using CAD.
- Perform testing on the materials to be used and the battery cells using both FEA and real-life testing.
- Perform an appraisal of the design including a cost analysis and the requirements for manufacturing the pack.
- Evaluate the improved performance of the ATV using the new battery pack.

2. Literature Review

2.1 Battery operating principles

A battery is a device which stored chemical energy can be converted to electricity and used as a power source. Batteries usually consist of a positive (anode) and negative (cathode) electrode divided by a separator which is typically soaked with an electrolyte solution containing disassociated salts. Ions are forced from the anode to the cathode through the electrolyte solution when charging and from the cathode to the anode when discharging. A current collector material that is coated in anode and cathode material allows the current to flow from the battery to the circuit.



(Fig.2 – Diagram to show charge & discharge of lithium-ion cell)

2.2 Battery cell chemistries

(Table 1 – Table to compare commonly used battery chemistries in the automotive industry)

Battery Type	Specific Energy (Wh/kg)	Energy Density (Wh/l)	Specific Power (W/kg)	Cycle Durability
Lead-Acid	33–42	60–110	180	500–800
Lithium - ion	100–265	250–620	~250–340	400–1200
Li - ion Polymer	100–265	250–730	~250–340	400–1200
Nickel-Metal Hydride	60–120	140–300	250–1,000	500–2000
NiCd	40–60	50–150	150	2,000

Lead Acid

This has been the most used battery chemistry in the automotive industry. For standard ICE vehicles the battery provides power for engine starting, lighting and ignition (SLI). As power is drawn from the battery the capacity is reduced and the vehicles alternator replenishes this lost power using the engine. The lead acid battery comprises of lead plates that compose the anode and cathode and a sulfuric acid electrolyte that the plates are submersed in. The positive and negative plates are usually separated using a plastic divider to prevent an internal short-circuit. This became the most popular storage medium due to its relatively low cost to manufacture and its recyclability potential. There is very little need for a higher energy density battery for ICE vehicles as a lead acid can provide for SLI functions adequately. Its low cycle life is a result of the lead plates 'flaking' due to the corrosive properties of the sulphuric acid, this reaction also causes gassing and as a result the battery needs regular service and refilling. (Warner, 2015)

Although the sulphuric acid is hazardous to human health if it comes in contact with the skin or is inhaled, the lead acid battery is seen as a safe storage medium as it will not ignite or explode with heavy use or in the event of a collision. The drawbacks of this medium are its low energy density and its low cycle life as can be seen in Table 1. Although the earliest EVs used lead acid it is not suitable for today's EVs due to the weight implications from its low energy density. There is still potential for this medium to be used in HEVs however this is

only due to its low cost, as the cost to manufacture other mediums is lowered we will see lead acid technology being phased out of the automotive industry for EVs and HEVs.

Lithium-ion

This has become the most popular chemistry for both electric/hybrid automotive applications and personal electronics in recent times due to several factors. Because of the high energy density, it is possible to achieve a much higher capacity than lead acid or nickel-metal based chemistries of equal volume. It has a low self-discharge rate and can achieve more cycles in its life cycle. It is important to note that the life cycle can be extended by not discharging the lithium-ion battery to 0% SOC. If instead the battery is discharged to 20% SOC the battery can achieve up to a thousand more cycles. (Warner, 2015)

As Table 1 shows, lithium-ion has the highest specific energy and energy density of the chemistries which is why it is the most commonly used in EVs.

The Tesla Model S is currently the best example of an all-electric vehicle, it has the option of a 70kWh and 90kWh battery pack. It uses 18650 NCA cells of 3.4Ah. For the 90kWh pack it uses 7616 cells in a liquid cooled battery pack. It can still achieve a real range of 225 – 440 miles.

Nickel-Metal Chemistries

The following are all considered nickel metal-based chemistries;

Nickel Metal Hydride - NiMH

Nickel Cadmium – NiCd

Nickel Zinc - NiZn Nickel Hydrogen – NiH₂

(Table 2 – Table to compare Nickel-metal chemistries)

Chemistry	NiMH	NiCd	NiZn	NiH ₂
Specific Energy (Wh/kg)	30-80	40-60	70-110	50-65
Energy Density (Wh/L)	140-300	50-150	130-350	55-110
Specific Power (W/kg)	250-1000	150	280-2500	-
Power Density (W/L)	400	210	420-7000	-
Volts Per Cell	1.2	1.2	1.6	1.2
Cycle Life	500-1500	1000-2000	300-900	2000
Self-Discharge (% per month)	30%	20%	20%	-
Operating Temperature Range (°C)	-20 to +60	-40 to +60	-20 to +50	-

These chemistries are compared in Table 2. Nickel metal based chemistries have a higher specific energy and energy density than lead acid and can provide more cycles over the life cycle of the cell however these chemistries suffer from memory effect lowering the potential capacity over time if full discharge and charge cycles are not full cycles. If the cell is discharged to 20% remaining capacity before it is then recharged or continually only charged to 80% capacity before use and this happens regularly the chemistry adapts and the available capacity will then be lowered even when the cell is fully charged lowering the capacity to the most commonly used level. To overcome this phenomenon the cell must be completely discharged before charging and fully charged before use. In practice this can be problematic as most applications will not have the exact same run time each use requiring extra use just to completely discharge the cell which can prove wasteful. These chemistries also suffer from a higher self-discharge rate than lead acid and lithium-ion so extra charging is required if the cell is left inactive. For these reasons Nickel-metal based chemistries are not seen as suitable for fully electric automotive applications have only gained a popular foothold in the consumer electronic markets such as laptops and mobile phone, this is due to the lower number of cells required, lower cost of production vs lithium-ion cells and the shorter expected life-span of the product.

2.3 Parameters for evaluating battery performance

2.3.1 Capacity

Is defined as the amount of charge that can be stored per unit of mass of the electrode material and is measured in Amp Hours (Ah). The capacity of the battery will determine what duration of time the battery can output power for. If two identical cells are connected in a parallel formation the total capacity will be doubled. To further increase the capacity to the desired level more cells can be connected in parallel. Parallel formations do not require cell balancing to charge or discharge each cell evenly. This happens automatically as any number of cells connected in parallel will act as one cell. It is important to note that if one cell has a slightly lower capacity than the other cells in a parallel formation the total capacity will be the lowest capacity cell times the total number of cells, e.g. if 4 cells connected in parallel each have a capacity of 3000 mAh the total capacity is 12,000 mAh or 12 Ah. If one cell drops to 80% capacity the total capacity will become 9600 mAh or 9.6 Ah. This will need to be considered when designing a battery pack as there may be variations in actual capacity due to manufacturing techniques of the cells so more cells may be needed to achieve the required capacity. As aging occurs the capacity of the cell is reduced, the aging can be accelerated through high ambient temperatures surrounding the cell, it is then important when designing a battery back to ensure that the ambient temperature surrounding the cell is even across all cells. The aging and balancing process will be discussed in more detail later in the document. (Andrea, 2010)

2.3.2 Voltage

Voltage is the electrical potential difference between two places in a circuit. It is effectively the pressure within a circuit. It 'pushes' charged electrons (current) from a power source, such as a battery to a device that carries out 'work' such as illuminating a light or driving a

motor. Measured in Volts (V) the standard for most commonly found lithium-ion cells is 3.7V nominal. With battery cells there are three types of voltage stated by the manufacturer, nominal voltage, maximum voltage and cut-off voltage. The nominal voltage is measured at the mid-point between fully charged and fully discharged. This is the advertised voltage a manufacture will specify. Maximum voltage as the name suggests is the maximum voltage the battery can output and cut off voltage is the minimum voltage the battery will get to before potential damage is done to the battery cell. When power is drawn from cell voltage will reduce as the capacity is reduced. This is an important factor when designing the battery pack as it will reach a point where the voltage is too low to operate the motor without causing irreversible damage to the cell.

2.3.3 Power

Power can be calculated by multiplying the voltage by the current in a circuit. An important factor of evaluating a cell's performance is its C rate. It is the rate that battery can charge/discharge its entire energy (power) in relation to its capacity. It is measured in relation to a 1 hour discharge, it can be best described using the following example, a cell with a capacity of 1000 mAh and a 1C rate will charge/discharge its's entire nominal capacity in one hour, so 1 Amp in one hour. If the same cell had a 2C rate it would charge/discharge its's entire capacity in 30 mins, and a 0.5 rate would take 2 hours.

2.3.4 Energy Density

This is the measurement of how much energy per mass a battery can provide. The two different measurements for this are watt hour per kilogram (Wh/kg), referred to as Gravimetric Energy Density and watt hour per litre (Wh/L) referred to as Volumetric Energy Density. In automotive applications where weight has a direct relation to the performance of the vehicle the energy density of a cell becomes extremely important. If a cell with a lower energy density is used and the performance needs to remain the same more cells will be required increasing the overall weight of the battery pack lowering the power to weight ratio of the vehicle.

2.4 Lithium-Ion Battery design

2.4.1 Cell materials

The main components of a lithium-ion cell are;

Anode – Most commonly a copper foil coated in the active anode material

Cathode – Most commonly an aluminium foil coated in the active cathode material.

There are various chemistries used for the anode and cathode materials, the most used are;

LMO-Lithium Manganese Oxide - LiMn_2O_4

NCA - Lithium Nickel Cobalt Aluminium Oxide - LiNiCoAlO_2

LFP - Lithium Iron Phosphate - LiFePO_4

LTO - Lithium Titanate - $\text{Li}_4\text{Ti}_5\text{O}_{12}$

LCO - Lithium cobalt oxide - LiCoO_2

NMC - Lithium Nickel Manganese Cobalt Oxide - LiNiMnCoO_2

(Table 3 – Table to compare commonly used lithium chemistries in cell manufacture)

Cathode Chemistry	LFP	LMO	LTO	LCO	NCA	NMC
Specific Energy (Wh/kg)	80-130	105-120	70	120-150	80-220	140-180
Energy Density (Wh/L)	220-250	250-265	130	250-450	210-600	325
Specific Power (W/kg)	1400-2400	1000	750	600	1500-1900	500-3000
Power Density (W/L)	4500	2000	1400	1200-3000	4000-5000	6500
Volts Per Cell	3.2-3.3	3.8	2.2-2.3	3.6-3.8	3.6	3.6-3.7
Cycle Life	1000-2000	500	4000	700	1000	1000-4000
Self Discharge (% per month)	1%	5%	2-10%	1-5%	2-10%	1%
Cost (per kWh)	£300-£1000	£300-£700	£500-£1500	£200-£350	£500-£800	£400-700
Operating Temperature Range (°C)	-20 to +60	-20 to +60	-40 to +55	-20 to +60	-20 to +60	-20 to +55

Separator – Keeps the anode and cathode separated, often a thin piece of plastic or ceramic. The hydrocarbon electrolyte solution is often corrosive so the separator must be able to withstand this corrosion to keep the two halves of the electrode separate to avoid an internal short-circuit. Polypropylene and polyethylene are the most commonly used plastics. The benefit of using ceramic is its ability to withstand higher temperatures while reducing the internal resistance of the cell improving safety and performance.

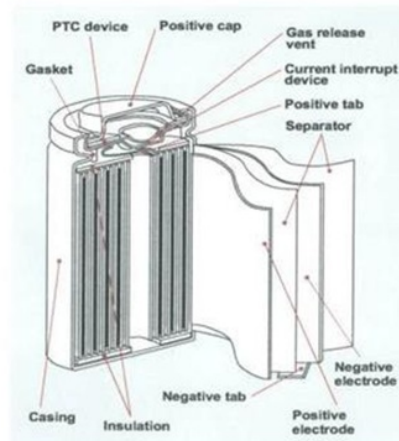
Electrolyte – This conductive solution allows the lithium-ion cells to pass between the anode and the cathode, usually in liquid form however some manufactures use a gel solution to reduce the potential to ignite during failure once thermal runaway has taken place. Commonly a Hydrocarbon mixture consisting of alkyl carbonates is used. There is also research being undertaken to produce a solid electrolyte, but this is still in early stage of development and not currently used in the manufacture of cells.

Housing/Outer Case – Usually a hard metal or soft metal foil and in some circumstances plastic enclosures are used.

2.4.2 Cell internal construction

Due to the pressure within the cells a material that can withstand the force must be used for the outer shell of the cell. Vent holes are located at the top of the cell to release pressure if the build-up becomes too great preventing damage to the internals of the cell. A 'jelly-roll' is inserted within the outer shell, this jelly roll comprises of the anode, cathode, separator and electrolyte. Regardless of the cell form factor this is standard design for lithium-ion cells. Various manufactures include safety devices within the cell, CIDs (Current interrupt devices) are common to prevent damage to the cell if the voltage drops below safe operating range. The internal construction of an 18650 cell can be seen in Fig.3.

Lithium ion Battery Construction (Cylindrical)



(Fig.3 - Internal construction of 18650)

2.4.3 Cell form factor

Cylindrical battery cells are the most used lithium-ion battery cells, the 18650 is the most commonly purchased cell. The 18650 is named in relation to its dimensions, 18mm in diameter and 65mm in length. Slightly larger than the AA type cylindrical cell that has a dimension of 14mm diameter and 50mm in length. Many rechargeable consumer electronics use this standardised cell size much the same as the AA is common place for non-rechargeable electronic devices. Some automotive manufactures such as Tesla use the 18650-cell due to the added protection of the hard metal casing and the wide availability of the cell.



(Fig.4 - Example of 18650 by Samsung)

Pouch cells are becoming more popular as they can be scaled up in size reducing the total number of cells needed in a battery pack. These pouch cells are already common place in portable consumer electronics such as mobile phones and laptops. This is because there is a greater need within these devices to reduce the thickness of the cell allowing for a thinner device. This type of cell does not have the added protection of a hard metal outer case, so considerations need to be made during the design process to ensure adequate protection of the cell to prevent piercing or deformation.



(Fig.5 - Example of generic pouch cell)

2.4.4 Dangers of lithium-ion

As the demand for lithium-ion batteries has increased, so too has the reported fires and explosions caused by this chemistry. The probability of a lithium-ion battery catching fire is very low, by best estimates it is predicted 1 in 1 million – 1 in 10 million batteries will fail causing a fire or explosion, although this is a low probability the potential damage it can cause to human life is great if the failing battery is located on an aeroplane or in a vehicle. 'Thermal Runaway' is the term used to describe the process of the irreversible chain reaction that happens once the battery has exceeded its safe operating range. Every manufacturer of lithium-ion cells will list its own safe limits but as a rule the potential for thermal runaway can occur after the cell has reached 60°C, if the temperature increases to 100°C thermal runaway is almost inevitable. Once the battery has entered a thermal runaway phase all its stored energy is suddenly released increasing the temperature of the cell to around 400°C in most cases. At this temperature, the device the cell is fitted to would likely ignite further increasing the danger to life. Conventional means of firefighting do not work with lithium fires as it can burn without oxygen and cannot be extinguished with water or other common firefighting liquids and foams. There are ways to reduce the chance of thermal runaway and slow the spread of the fire once started but currently there are no methods of completely extinguishing a lithium quickly once started. This has created problems with transporting batteries as strict guidelines need to be met especially if the transportation method is aviation.

The most common causes of thermal runaway are imperfections in the manufacturing process causing an internal short-circuit during normal use, overcharging past the manufacturer's specifications, excessive currents when charging and discharging and deformation of the cell through puncture or excessive stress. The design of the device or pack the cell is occupying can also cause thermal runaway and as a result the cooling of the pack is extremely important. Hardware can be used to monitor the cells within a pack and deactivate the cells if they begin to operate outside of safe operating ranges, this is explained further in Chapter 2.4.4 – Safety features. Ultimately the capacity of the individual cell that experiences thermal runaway will determine how severe the risk is. The large pouch style cells can have a capacity ten times greater than a regular 18650 cell. If failure occurs within this larger capacity cell this can translate to an instant energy release ten times greater than the regular cell, in this instance there is a much greater chance that the energy released will cause the neighbouring cells to experience thermal runaway or damage other components within the battery pack. If larger capacity cells are used there should be ample spacing between the cells or added safety features to mitigate this risk. Unfortunately, there is no easy solution to mitigate the risk involved with selecting cell size, there are benefits and drawbacks with each alternative, smaller capacity cells may have a lower risk factor if thermal runaway occurs but there are more connections between the cells due to the higher number of individual cells, this increases the risk of a connection failure which could induce cell failure. (Andrea, 2010)

The other danger associated to lithium-ion is the same with any energy storage medium, risk of electrocution. Due to the high voltage of a battery pack, precautions should be incorporated into the design to prevent the risk of electrocution for both handling the battery pack and servicing the pack.

2.4.5 Current applications for Lithium-ion batteries

Lithium-ion has now become the preferred storage medium for numerous applications ranging from small power banks used to charge USB devices to back-up storage mediums used in aerospace. Any application that requires a storage medium can use lithium-ion. There are obvious applications that have low weight requirements such as ebikes, electric skateboards, mobile phones etc.. however, with the lowering cost of the cells many applications are adopting this technology due to the high energy density and cycle life.

2.5 Battery housing design

2.5.1 Materials

A variety of different materials can be used as both the enclosure and internal components of the battery pack. In most cases a combination of materials is used for different components. These include plastics, steel, aluminium, fibre glass and composite materials such as carbon fibre. When selecting a material, it is important to establish the requirements of the component it is being used for. With ESS (Electrochemical Storage System) design, the factors taken into consideration are its strength, electrical conductivity, mass and thermodynamic properties such as thermal conductivity, thermal expansion and melting points. The balance of safety and performance must be carefully evaluated. Due to the heat emitted by the cells the materials chosen within the ESS should dissipate the heat evenly throughout the pack to prevent any 'hotspots'. If a hotspot is detected on the cells a cooling method will need to be established as this can lead to thermal runaway. This can be achieved by changing the materials within the ESS to allow for better heat dissipation, this will be discussed in greater detail in chapter 2.4.4.5 – Thermal control.

Before materials are selected it is imperative that the designer is aware of all the conditions the ESS is subject to. If the ESS is located on the outside of the vehicle there is a greater necessity for structural strength of the enclosure as it is not protected by the vehicle's chassis or outer-shell. For this situation there is also the need

to have a sealed enclosure to protect the internals of the ESS from environmental hazards such as rain and dust, this could potentially cause an internal short circuit leading to cataclysmic failure. If the ESS was located within the 'cab' of the vehicle this is no longer an issue and the design could incorporate less material lowering the weight and cost of the ESS. In a normal road EV



(Fig.6 - Image to show battery pack of Tesla Model S)

the total weight of the ESS is considerable to achieve a good driving range. The battery pack in a Tesla Model S has a mass of 540kg contributing to just over a quarter of the cars total curb weight of 2100kg. This battery pack can be seen in Fig.6. To improve performance the centre of gravity must be brought down, so the packs are fitted as low as possible, this is now common in EV design. This has proved to be a safety issue with debris hitting the underside of the ESS and piercing the enclosure causing thermal runaway and subsequently the complete destruction of the vehicle. Although it could be argued that this was not normal operating conditions the enclosure clearly lacked the required strength.

Vibrational stress will reduce the life of an ESS and can potentially cause damage to the electrical components and battery cells. The best way this can be mitigated is by using foam or a 'spongy' material in locations that are the most vulnerable.

As metals are conductive a coating should be applied to the internal side of the enclosure when using steel or aluminium, this will prevent the grounding or shorting of the battery cells or electronics. This coating acts as an insulator. An adhesive film placed on the inside of the enclosure can be used to achieve this.

If the strength of the enclosure is not deemed adequate reinforcement such as ribbing can be applied without altering the enclosure material. Using FEA will determine if the design has sufficient structural strength providing the potential forces acting on the ESS are calculated correctly. (Warner, 2015)

2.5.2 Module design

The term battery module is used to describe an assembly of lithium-ion cells. As there could be thousands of cells within ESS and there are various reasons to divide these cells into manageable assemblies. The module will consist of the lithium-ion cells and safety hardware such as thermal management components and holders or bus bars. Some of these safety features will have a maximum number of cells that can be managed limiting the number of cells to be used within a module. When using 18560 the stated voltage is usually 3.7V, for automotive applications the required voltage of the ESS will be much higher depending on the requirements of the motors and any on-board electronics, lights, stereo, alarms etc... With the required voltage known the number of cells mounted in series or parallel can be calculated, usually a module will consist of cells mounted in parallel to increase the capacity of the module then the module is connected in series to other modules to increase the voltage of the ESS up to the required level. By designing a module like this there are fewer connections between cells, it is common practice to use a low resistance metal plates to connect the cells to one another within the module then the module is connected to other modules using wire, the thickness of the wire will be selected based on the load it will be transferring, this is important to calculate correctly as if its too thin there is a risk factor associated and if it's too thick it will add unecicary resistance to the ESS reducing performance. (Andrea, 2010)

Serviceability is also considered during module design, in some instances the plates used to connect the cells within a module are spot welded, this will reduce any risk of bad connections and wear on the connectors, however this will increase the cost of servicing the ESS if a cell was to fail or prematurely age as each individual cell cannot be replaced. The more cells used within a single module will exacerbate this issue. Alternatively, the module can be designed using mechanical components to interlock the cells using bolts and nuts. This allows individual cells to be replaced when they have reached the end of their life cycle or have experienced failure. The safety of the ESS can be compromised using this method as excessive vibrational stress can cause the connections to loosen over time increasing the chance of an internal short-circuit. If the ESS is regularly maintained this can be prevented. There is an added cost to using fasteners and added weight implications.

Depending on the cells to be used the module design can add protection to the cells if the enclosure was to fail from excessive stress. Factors such as vibrational stress can be incorporated into the module design to mitigate the stress transferred to the internal components of the ESS and the cells. Module design can incorporate plastic holders that can be used to keep the cells in position, when using plastics it is important to establish what level of elasticity can be expected of the life cycle of the cells as this can affect the connectors between cells. Conversely when metal plates are selected there is a chance that the cells may grow dimensionally with age and the metal connecting plates will not increasing the pressure between them.

2.5.3 Safety features

2.5.3.1 BMS hardware

The Battery Management System (BMS) is the central control unit of the ESS. It comprises of any hardware placed within the ESS to control safety features, this can include Printed Circuit Boards (PCB), temperature sensors, fuses switches etc.. The main requirement of the BMS is to ensure that the cells are not operating outside their safe operating range. It can achieve this by monitoring the temperature and voltage of each cell. There is software that manages these components to provide an automated safety system. The BMS protects against over-charging, over-discharging, short-circuiting, low temperatures and high temperatures. The functionality of the BMS depends on the topography of the ESS design, if there is an active cooling and heating system the BMS will use attached temperature sensors to engage and disengage the cooling system as a when is required to keep the ESS at optimal operating temperature. By incorporating a BMS into the ESS design gauges can be connected allowing the operator to see how the battery pack is performing by displaying load, remaining capacity temperature etc.. An advanced BMS will communicate with the motor controller, sending and receiving data with the ability of reducing or completely isolating the voltage provided by the ESS. The software that controls it is a set of complex algorithms based on mathematical formulae and calculations that determine the cells state of health. Many BMS systems are 'off the shelf' however they will need to be programmed to operate effectively with the components chosen for the ESS. These systems are specific to the chemistry used within the cells so cannot be used with alternative chemistries. (Andrea, 2010)

It is not a requirement to fit a BMS system to an ESS and some EVs used for racing applications do not utilise one however these vehicles are only designed to last a single race or season before the equipment is replaced. For most automotive applications the total lifespan of the ESS is important, because of warranty and reputation implications an ESS should be designed to last for 8 – 15 years. It is then essential to fit some form of BMS. The level of sophistication of a BMS can vary widely across manufactures however in essence it is required to improve the life span of the ESS and mitigate risk factors.

The design of the BMS is an important factor as there are advantages and disadvantages of each design. Some systems use a centralised design whereby all the cells are connected to the main board which monitors the status of each cell. This can require a large amount of wiring which has its own safety implications. Other systems use a distributed topology where 'slave' boards are placed on each module and connected to the mainboard, this reduces the wiring risks however it can increase the cost of the ESS as more boards are required. The requirements of the boards will determine their cost. In all cases the BMS will require programming to ensure the safety hardware is engaged when certain criteria are met.

2.5.4.2 Balancing

To achieve maximum performance from the ESS and increase its life cycle cell balancing must be achieved. A module's performance and capacity are determined by the weakest cell that is connected. If one cell has a lower capacity when it reaches its lowest SOC it will need to deactivate to avoid failure, in doing so this will deactivate the entire module even when there is a higher SOC in the other connected cells. The more cells that are incorporated into an ESSs design the greater the requirement for balancing. When cells are connected in parallel they can achieve self-balancing as the cells become one larger cell, as a result if a module is comprised of a number of cells in parallel the balancing is only necessary between modules. Balancing must occur during both charging and discharging.

There are predominantly two methods of cell balancing, active and passive. With a Passive system the cell with the highest SOC needs to limit the flow of current into the cell to allow the other connected cells to increase their SOC to the same level. This is achieved by converting the current into heat energy that is then dissipated into the pack wasting the excess energy. Usually this is achieved using a resistor that is incorporated into the slave or main board, the resistor will need to be of adequate size and can be used for multiple cells however this can only work for one cell at a time. The advantage of passive balancing are the low cost compared to an active system. The disadvantage is the waste of energy reducing the efficiency of ESS, the heat that is dissipated can also prevent a problem if the ESS does not have an adequate cooling function. As only one cell can be balanced per resistor the total time of balancing the entire ESS is increased.

In an Active Balancing system, the cell with the highest SOC moves the charge to the lower SOC cells until all the cells are balanced. The electronics required to perform this task will need to be attached to each cell or into the slave boards depending on the topology of the BMS. The obvious advantage of this design is that the excess energy is not wasted so the efficiency is improved, and no extra heat is generated. This system has a much higher cost than passive systems and extra hardware must be incorporated into the ESS design increasing the space required and the weight of the ESS.

Current research indicates that the benefits of using an active system do not outweigh the added cost implications. "There have been a lot of evaluations of both systems over the past few years; however, current studies do not show the long-term benefits of using an active balancing system". (Warner, 2015).

2.5.4.3 Thermal control

As a general rule of thumb for lithium-ion batteries, they should be maintained as the same temperature range that humans find comfortable, around 23°C. For most lithium-ion cells the optimal temperature range is between 10 and 35°C. In this range under normal operating conditions no reduction in life to the cells would be expected. Below this range the electrolytes may begin to freeze and the impedance is increased within the cell resisting the flow of ions so reducing the performance and capacity of the cell. Above this range the cell chemistry can become unstable and the risk of thermal runaway is increased. (Warner, 2015)

The main function of a Thermal Management system is to ensure that all the cells within a ESS are at a near constant temperature while under load. Although there are various methods that this can be achieved the main principle behind all these methods are to move heat away from the cells through a medium and direct the heat out of the pack. The three main factors to consider when designing a thermal management system is;

- *Where in the world the vehicle is likely to be used* – different outside temperatures will determine whether the pack requires heating or cooling and to what level. A location with a high ambient temperature will translate to the cells having a higher ambient temperature before use so increasing the maximum temperature they will achieve under load. The ability to use the outside ambient temperature to cool the pack is also reduced.
- *The duty cycle the ESS will operate under* – higher load requirements will cause a higher operating temperature of the cell.
- The chemistry being used within the cell – different chemistries have alternative optimal and safe operating ranges and perform differently under higher loads.

The three types of heat transfer that need to be considered in the design are convection, conduction and radiation. Conduction occurs when two objects are in direct contact with one another. Similar to conduction, convection is the transfer of heat from a fluid to a solid material. Radiation is the transfer of electromagnetically charged thermal particles from one source to another usually through air.

When designing the thermal management system it is vital to consider all sources of heat within the pack, the main sources are the cells due to the chemical reaction occurring within the cells and any electronics within the pack that emit heat. The method chosen for balancing the cells will have an influence on the heat generated by the electronic components. The most common forms of cooling an ESS are fans, heat-sinks and radiators or a combination off all. The Tesla Model S uses a radiator system to pump anti-freeze fluid through the internal heat-sinks, this is a very effective way of controlling the temperature as the BMS can alter the temperature of the fluid that is passed through the ESS. This is a significant advantage if the pack is to be used in an environment with a large fluctuation in ambient temperatures as heated liquid can also be passed through the heat-sinks to increase the temperature of the cells to ensure they are at optimal temperature in cold environments. The disadvantage of this system is the high cost of implementing the system and the safety risk of passing a liquid through an electrical device. Extra precautions need to be made in the design process to insure this liquid does not come into contact with the electrical components during excessive stress or as the equipment reaches the end of its life cycle. This may require additional maintenance to ensure all piping and connections are secure. (Andrea, 2010)

Fans used to extract heated air from within the ESS or induct cold air from outside the ESS can be an excellent method of cooling and are often found in electrical devices such as computers and laptops. These, however, can only be used when there is not the necessity for a sealed ESS. If the ESS is exposed to environmental factors like weather the sealing of the enclosure needs to remain paramount. As the fan induces cold air it will also induce any particulates in the air such as dust, this can present a fire hazard if dust is to collect within the ESS so appropriate filtration systems will need to be in place to mitigate this risk

Another method of cooling which can be referred to as passive cooling is the use of specific materials within the ESS that will dissipate the heat generated by the cells throughout the ESS and away from the cells. This is usually achieved through heat-sinks located in hotspot areas and materials connected to the outer enclosure allowing the ambient temperature to cool the enclosure and subsequently cool the connected materials. With this method all the focus is placed on the property of the materials used, each material has a different ability to absorb heat and have different safe temperature ranges. It is obviously a bad idea to use materials with a low melting point in place you would anticipate high levels of heat transfer.

3 Timing plan

4 Methodology

4.1 Testing

4.1.1 Cell testing

The manufactures specifications for the cells have been verified through individual testing of the cells. Although these cells are not used in the final design the test gives a good indication of how much each cell can vary from the listed specification.

Using automotive headlight bulbs the cells have been drained at a consistent level to establish the exact capacity of each cell and compare this data with the provided data from the manufacturer.

A circuit was created between the bulb and the cell, using a multimeter voltage readings were taken in 10 minute increments to establish the capacity of the cell and at what point the cell reaches 0% SOC. This study was carried out for both the pouch cell and the 18650.

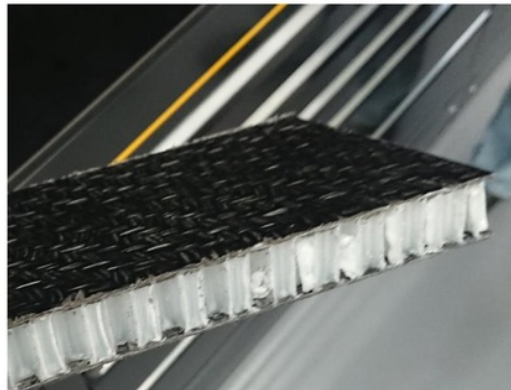
A further study was performed on the 18650 cells to establish how the capacity changes when mounted in parallel and to evaluate the level of self-balancing achieved. As there is only one pouch cell available for testing this could not be performed however the principle remains the same for each battery type.

Using the 18650s in a series configuration a test was carried out to prove that balancing is required within the design

4.1.2 Material testing

4.1.2.1 Puncture

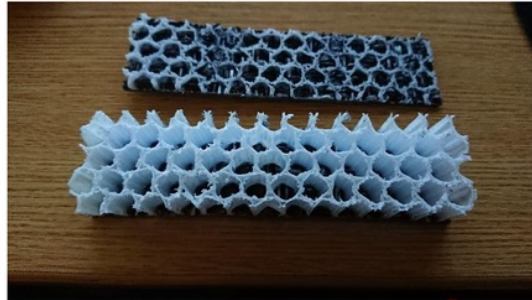
A faculty member of The University of Wales suggested that a honeycomb composite material could be used for the enclosure of the ESS, with no data on the material properties, testing was required to determine the properties and the subsequent feasibility of using this material. A specimen of this material was donated and can be seen in Fig.7. The sample is considered a fibre-reinforced polymer comprised of two composite sheets with a thickness of 2mm each, one sheet has a smooth outer finish whilst the other sheet has a textured finish. In both cases the sheets use woven strands to reinforce the material without adding excess mass similar to carbon fibre, these woven strands are then laminated to provide the required outer texture whilst keeping the woven strands in place.



(Fig. 7– Specimen of fibre reinforced polymer honeycomb)

The two sheets are glued to the internal honeycomb structure giving the material its sandwich formation, see Fig . It was not possible to determine the exact dimensions or shape of the honeycomb as the quality of manufacture is poor as can be seen in Fig.8. Normally a hexagon

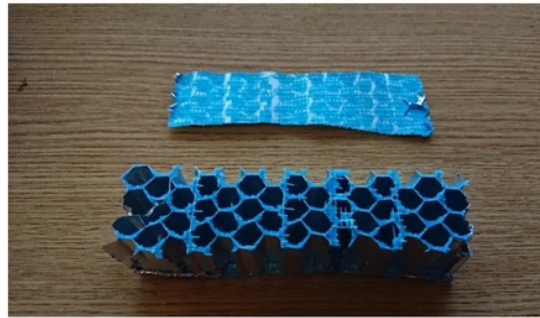
structure is used and it does appear this was attempted however the plastic used in this structure only has a thickness of 0.2mm so deformation has occurred when manufacturing, this deformation has also been exacerbated when removing the top layer from the specimen. The author of this report does not believe this will have much of an effect on the overall strength properties of the specimen as there is very little space between the 'hexagons' keeping the



(Fig.8 – Cross-section of fibre reinforced polymer)

structure secure. The overall thickness of this specimen is 22mm.

As an alternative to the composite honeycomb material, an aluminium honeycomb structured specimen was also tested to establish its suitability for the enclosure material. This specimen comprises of two 1mm thick aluminium sheets glued to an internal aluminium honeycomb structure. Removing the outer layer has caused some deformation of the honeycomb structure, this is seen in Fig.9 . The overall thickness (Fig.9 – Cross section of aluminium honeycomb) is 26mm.



(Fig.9 – Cross section of aluminium honeycomb)

Due to the limited available supply of the material and the destructive nature of the testing only two tests were performed on the composite material, one test was carried out with drop-weight impact equipment and the second test was carried out with a tensile stress testing apparatus. It was only possible to perform the drop-weight impact test on the aluminium specimen as the deformation caused by this test limited further testing. The results can be viewed in Chapter 4.2 – Results.

Drop-weight Impact Testing

The assembly of this testing equipment can be seen in Fig.10.

1. Release Mechanism.
2. Impactor Head Supporting Frame.
3. Impactor Head with Adjustable Weight.
4. Impactor Tip.
5. Anti-Rebound Mechanism.
6. Specimen Supporting Fixture.
7. Power Supply
8. Drop height Reference Measuring Point
9. Safety Leash
10. Rest Springs

(Drop-Weight Impact Equipment User Manual, Pagano, 2017)



(Fig. 10 Drop-weight Impact equipment)

The specimen is fixed to the supporting fixture using clamps, the weight and impact point size are then selected. In the start position the impactor tip is 1 metre above the fixed specimen with an initial speed of 0m/s. Once the release mechanism has been activated the impactor tip falls at free-fall acceleration (approximately 9.8 m/s^2) achieving a final speed of impact at 4.43 m/s . For both specimens, the test was carried out twice using the same parameters to ensure comparability between the two material types. One test using a 2.3Kg weight and the second using 5Kg weight. In all instances the height of the impactor tip is 1 metre and the diameter of the impactor tip is 17mm.

The conservation of energy principle stipulates that energy cannot be created or destroyed, only transferred from one form to another. This principle allows one to determine the potential gravitational energy of an object and its kinetic energy just before impact. By measuring the deflection after impact, the total force applied to the specimen can be calculated. This calculated force can then be used in an FEA simulation to accurately model the material tested. The equations used can be seen below;

$$PE = mgh \quad v = \sqrt{2gh} \quad KE = \frac{1}{2}mv^2 \quad \text{Average Impact Force} = \frac{1}{2}mv^2/d$$

Where;

PE : Potential Energy in Joules

m: mass of the object in Kilograms

h: height of the object in metres

v: velocity of the object in metres per second

KE: Kinetic Energy in Joules

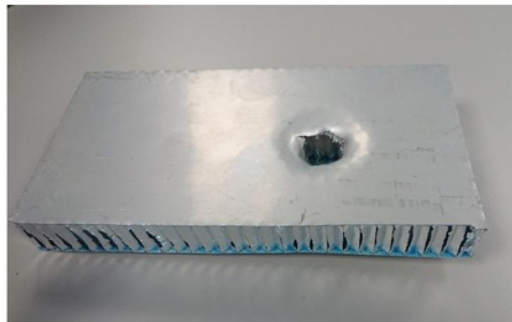
d: distance of deflection in metres

4.1.2.1 FEA

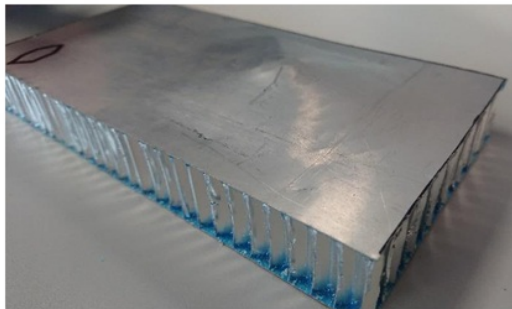
To verify the puncture tests an FEA analysis was performed. The specimens used were re-created in Solidworks using the exact dimensions. The bottom support plate was also modelled to get the most accurate test results possible. Using the equations above it was calculated that the total force applied on the specimen when a 5kg weight was dropped from 1m was 742N. This force was applied across the impactor tip with a 17mm diameter. Using this force in Solidworks it was possible to produce the same deformation as was calculated in the real-life test. This can be seen in the results section below.

4.2 Results

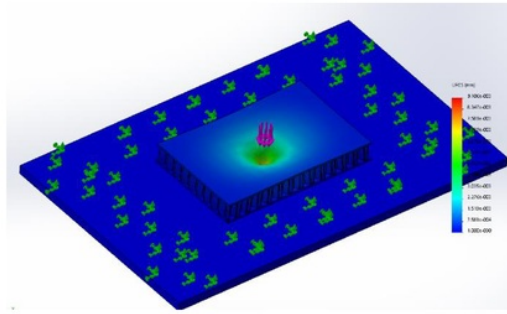
The aluminium honeycomb specimen experienced a 6.6mm deformation and a partial tear on the top surface when a weight of 2.3kg was dropped from 1m. In the subsequent test using a 5kg weight the deformation measured was 8.9mm and full penetration was recorded with complete failure of the honeycomb. In Fig.11 we see the top section of the aluminium honeycomb with the penetration hole clearly visible. In Fig.12 the bottom section of the specimen is shown with the indentation from the final test using a 5kg weight. Although the bottom section did not experience full penetration this would have caused damage to any internal components of the ESS had it been used for the outer housing. The FEA of the top layer result can be seen in Fig.13 and the bottom layer can be seen in Fig.14. The same test was performed on the fibre reinforced polymer. In the first test using a 2.3kg weight there was a deflection of 0.7mm and left no visible damage on the specimen. The second test using a 5kg weight produced a deflection of 0.95mm. This second test did leave a slight tear in the surface but this was only in the laminate coating and did not breach through to the fibres. This would not have reduced the strength of the specimen significantly as the honeycomb and fibre were completely intact.



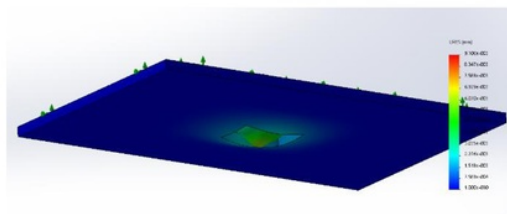
(Fig. 11 – Specimen with penetration hole visible on top layer)



(Fig. 12 Specimen with deformation to bottom layer visible)



(Fig. 13 - FEA model showing deformation of topside)

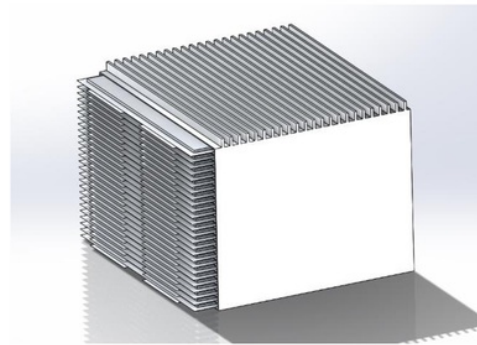


(Fig. 14 - FEA model showing deformation of underside)

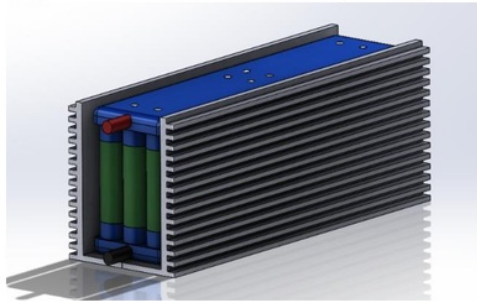
4.3 Design

There are several parameters that were incorporated in this design phase. As the battery pack is being designed for an all-terrain vehicle the requirements are slightly different than if the design was for a road vehicle. The ATX has no body-work surrounding the current location where the lead-acid batteries are fitted, instead there is an exposed roll-cage with a purpose-built frame attached to hold the batteries secure. As a result, the battery packs are completely exposed to the environment, so the most important design implication is that the new packs have been completely sealed and weather proof to an IP6 rating. This has reduced the cooling methods that could be used. Not only is rain an issue but using the vehicle off road may involve driving through large pools of water so it was essential that the pack upholds the IP6 rating. Seals are located on the inside of the removable cover to ensure it maintains an IP6 rating.

Currently the required 48V drawn from the motors is derived by four 12V lead-acids connected in series. The original plan was to design four 12V lithium-ion battery packs however this was not possible due to the number of cells required in each housing. There was not ample space within the 12V housing to incorporate all the cells required without jeopardising the safety of the pack due to the heat produced. There was also an issue achieving 12V from each pack. To achieve 12V from a 3.7 lithium-ion cell it would require either three or four cells in series, as 3.7V is only the nominal voltage with the maximum at 4.2V this presents a problem. Three cells in series would only provide 11.1V at they're nominal rating, although would still run the motors it would put added strain on the cells and would reduce the run time of the ATV as the minimum cut-off voltage would be achieved sooner. In contrast if four cells were mounted in series the nominal voltage would be 14.8V from each housing. With four 14.8V packs the total voltage would be 59.2V, the motor controller is specified to 48V and although it has a function to slightly reduce the incoming voltage this is only the nominal voltage so the maximum voltage when fully charged would put strain on the motor controller and potentially damage it. For these reasons one 48V ESS was designed by using 13 cells in series to achieve a nominal voltage of 48.1. The larger pack uses less material for the housing than four 12V packs would and the increased space within the pack mitigates the need for active cooling. This not only has a cost advantage but will reduce the maintenance implications and providing the design provides ample cooling it will reduce the safety implications of running liquids through the pack. As the IP66 rating needed to be upheld there was no possibility of adding external fans to the design without jeopardising this rating. As such the cooling is considered passive with extra consideration placed on material selection and design incorporating heat sink structures where possible. These heat sinks can be seen on the battery module enclosures in Fig.15 and Fig.16



(Fig. 15 – Pouch Enclosure with heat sink)



(Fig. 16 – 18650 Battery module with heat sink)

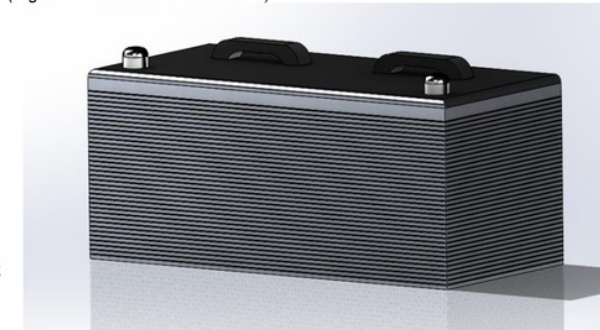
With a wide range of lithium-ion cells available to purchase of various specification and dimensions two types were identified as being the most suitable for this application. Testing battery cells requires specialist equipment, so the chosen battery cells have been selected due to the wide range of data available on their properties. A design using the common 18650s has been carried out along with large pouch cells with a 32 Ah capacity. To get to the target of 120Ah for the pouch cells it was necessary to mount four cells in parallel, this provides 128Ah per module. To achieve the 48V required 13 modules needed to be connected in series achieving a nominal voltage of 48.1. The total number of cells required for the pouch design is 52. The chosen 18650 cells have a capacity of 3600mAh, each module comprises of 39 cells giving a total capacity per 140.4Ah. With 13 modules connected in series the output voltage is 48.1 as they are 3.7V cells.

The designs were compared, and the best method selected. The criteria for selecting the design was based on cost to produce, performance of the battery pack and the total weight of the packs as this will affect the performance of the ATV.



(Fig.17 – Front side of enclosure)

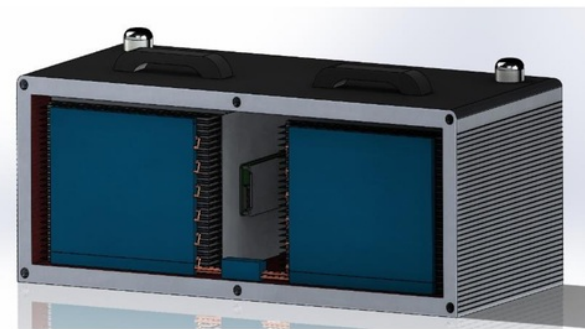
The ATV is located in South Wales / UK and this will be the primary location that the vehicle will be used in. The temperature range of this location is between -10°C and 35°C , these are extreme ranges and these maximum and minimum temperatures may only occur one day of the year, the common temperature range is 0°C – 25°C . This has reduced the cooling and heating requirement. To keep the temperature of the ESS down fins have been incorporated into the design of the enclosure on the outside, this works by increasing the surface area so allowing more contact from cold air. These can be seen in Fig.17 and Fig18.



(Fig.18. – Rear side of enclosure)

As the ATV will be used off-road there were a few extra implications this has had on the design. Operating a vehicle on road usually translates to a smooth ride with little vibration caused. The nature of off-road use means there is a much greater chance of vibration and heavy impact caused by navigating uneven ground at speed and potentially jumping. Because of this, foams are used throughout the design to mitigate this stress on the internal components of the ESS.

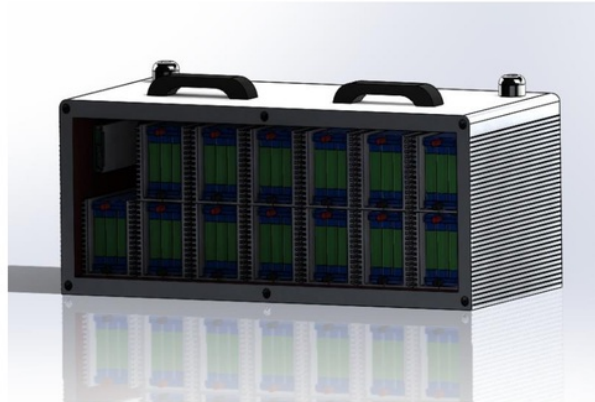
To help protect the connections from vibration most of the connecting plates are sealed within plastic enclosures, this also mitigates the risk of short circuits in the event of an accident. These plastic enclosures can be seen in Fig.19.



(Fig.19 – Finished design of the Pouch ESS with lid removed)

A BMS was sourced that can handle 13 modules in series at 48V. It can be fitted within the housing and offers balancing for both charging and discharging and also monitors the health of the cells to ensure none are operating outside their safe ranges. This BMS also has temperature sensors built in to monitor the temperature within the housing and the ability to shut down the ESS should the temperature rise above safe levels. Each module is wired to

the BMS in a centralised system reducing the overall wiring. With both the pouch design and the 18650 design it is possible to interchange cells without having to replace the entire module, this will keep the cost of maintenance down however the screws that hold the modules together will need to be checked regularly to ensure the safety of the device. Fuses are mounted on the inside of the removeable enclosure so that there is no current being supplied once this is removed to mitigate the risk of electric shock.



(Fig.20 – Finished design of the 18650 ESS with lid removed)

4.4 Recommendations for further work

Further testing is required to ensure the safety and life-span of the ESS design. A small scale model should be built using fewer cells to perform a vibrational analysis. This would ensure that connectors and fittings have been designed to a standard that will endure the stresses placed on the ESS once it has been fitted to the ATV. A full thermal analysis should be performed taking data from real-life tests that can be used in conjunction with a computer program such as Ansys. This would allow the user to see how heat is dissipated throughout the housing and would indicate if there are any hot spots. The design could then be modified to ensure these hot spots are limited and do not cause any safety concerns. If it was found that the housing lacked the required cooling further studies could be performed to determine if it was possible to achieve this without drastically modifying the housing design. Some manufactures use the wheel design to help cool brakes in high performance vehicles. This could be done with the ATV however it may lack the required top speed to generate enough air flow.

5 Conclusion

The design of the housing is sufficient to function however there are limitations to the design as a result of limitations to the study. Unfortunately, it was not possible to get my designs to mesh sufficiently to perform a thermal study. This study is vital to ensure the ESS performs as intended for the required duration. Currently the design is based only on research, if it were possible to perform a thermal study there could have been modifications made to the design to allow for better cooling if it were required. The material samples provided would need to have further testing to ensure their suitability however it is unlikely they would be the best option. The weight saving they provide would not outweigh the risk factor of using them. The glue that holds the honeycomb structure would not maintain its integrity as the temperature is raised beyond the normal operating ranges. If the BMS was to fail or there was a collision that caused a short circuit within the ESS, thermal runaway could occur in one or many of the cells. If that were to occur there would be potential for that heat to transfer into the housing which would cause the glue to fail or possibly ignite. Ultimately safety should be a greater concern than performance. Lithium-ion is so inherently dangerous that the prime function of the housing should be to reduce the risk to the driver. The aluminium honeycomb did not perform well in the puncture test in comparison to the fibre-reinforced polymer. Although it is lightweight, this will not be reflected into considerably better performance if it were used. As an ATV is for all terrain it's components should be of a greater strength than a normal road car. The fibre-reinforced polymer would be a better option, but it lacks the ability to conduct heat away from the internals of the ESS. This is a vital function of the housing is a passive cooling system is used. If an active cooling system was used the cost of the cooling system would outweigh the performance benefit from using this material.

6 References