This project was supported by the Centre for Global Eco-Innovation and is part financed by the European Regional Development Fund.

**Thermal Modelling of the LiNa Battery**

By

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In collaboration with

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**Abstract**

The project involves the thermal analysis of the Lina battery. Due to the high operating temperature, it is necessary to apply insulation to the battery model. Various types of insulation were applied at different thicknesses to give an idea of which performs the most effectively. Another part of the project involved applying heaters to the model; this is to maintain the high operating temperature when it is out of operation. An additional consideration that was taken into account is when the battery is running at high power. Therefore it is important to find a balance between keeping the battery hot and avoiding over-heating. The final part of the project involves bringing together battery packs into a system that would be suitable for an electric vehicle.

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## **Introduction**

The development of battery technology is an area of research of extreme importance towards combating climate change. Competent technology has the ability to allow the movement away from fossil fuel usage in numerous industries. One of the main contributors towards greenhouse gas emissions is the production of electricity. The industry is entering a transitional stage from the use of fossil fuel energy towards renewable energy; however, there is still a long way to go. According to the Department for Energy and Climate Change (DECC), the UK’s dependency on fossil fuels is reducing but a huge bulk of 84.5% of energy is still produced in this way (Hope, 2019). This figure represents the UK alone; on a global scale, it is likely to be higher due to the lack of resources available to enable the movement towards renewable energy in less developed countries.

There is a vast abundance of renewable energy available to harness, with the Sun alone continuously providing the Earth with 35,000 times the amount of energy required for electricity worldwide (Llorens, 2019). The quality and availability of battery storage is a major limiting factor for the expansion of renewable energy. The U.S. Department of Energy (DOE) is currently exploring energy storage strategies in order to accelerate the use of wind and solar power. SunEdison CEO Ahmad Chatila said at an annual summit, “the most important technology we can develop right now is storage” (Irfan, 2019). This is important as the electricity supply within the grid must match with the demand, in order to avoid power outages. Renewables without storage are deemed unreliable and inefficient due to the unsteadiness of energy outputs. The energy from renewable power plants must be stored in large industrial battery systems, so that companies such as The National Grid can control the energy outputs, ensuring that the power consumption is reliable and efficient (Good Energy, 2014). There is a lack of suitable batteries on the market for large-scale power plants. However, there is currently an enormous amount of research into battery storage technology, which could be suitable for storing renewable energy.

There are some examples of large-scale battery systems that have been put into operation around the world, which provides a useful comparison of the pros and cons of the different systems. The Amplex Group in the United Arab Emirates implemented a unique battery storage system; they used a sodium-sulfur based storage, with a capacity of 350MWe, for grid stabilization, voltage support, frequency regulation, power quality, load shifting and energy arbitrage. The same group also developed and employed a system in West Virginia, USA. This was a lithium-ion based system with capacities of 32MWe and 8MWe, which was used for a large-scale wind integration by providing frequency regulation and wind energy smoothing (greentechmedia, 2013). Another example which has notable significance for large-scale storage is the planned Rubenius battery energy system in California, USA. The system will have a huge capacity of 1000MWe and will encompass an area of 1,416,400m2. This system will use sodium-sulfur based technology to store energy from large scale solar and wind integration (Poullikkas, 2013) (Kumagai, 2012). The samples of electricity storage systems stated are just a select few; the number of these stations is increasing around the world. This project looks at the LiNa battery, which is a developing technology that could one day have applications in the renewable electricity storage industry. It is beneficial to compare various industrial storage systems and to consider the best application for each one, whether it be large scale or smaller scale solutions.

The other region that the improvement of battery technology has vast implications is the automotive industry. There are a number of issues associated with electrical vehicles (EV), one of the major problems being the charging of the batteries. The lack of charging stations is an obvious issue; however, the growth of the market for EVs is likely to have a direct relation to an increasing number of charging stations. Another problem with charging is the length of time it takes and the range of charging times at different stations, consumers need quick and reliable energy if they are to move away from the convenience of petrol/diesel engines (Schaal, 2019). The other big issue related to the development of EVs is the limited battery storage. One study compared investments in fast electrical charging and in longer battery ranges. While both are highly important, it was established from research that investments in longer battery ranges were much higher (Funke, 2019). The logic behind the higher investments could be due to the favorability of EVs and their capability of travelling for long distances without the need for charging. If the charging of the car took around 5-6 hours, it might suit consumers as charging could be completed overnight, and the battery range would be substantial for travel in the daytime. However, this can only be implemented on a large scale if the number of charging stations increases dramatically, which is expected to take place over the next decade.

Most big car companies are currently exploring suitable battery types for the development of EVs, to make the most of the growing market. Currently the most widely used type is lithium-ion storage, which is now considered the standard for EVs. Compared to other mature battery types such as lead-acid and nickel metal hydride (NiMH), the lithium-ion holds advantages. Significantly, lithium-ion batteries have an excellent specific energy (140Wh/kg) and energy density, when compared to the specific energy of lead-acid (34Wh/kg) and NiMH (68Wh/kg). However, the lithium-ion technology is far from perfect. With lithium being a relatively rare material, it is expensive technology and there are safety concerns related to overcharging and overheating of the battery. The Tesla Model S utilizes a lithium ion battery and there have been instances where fire has broken out due to fluctuating charges or damage to the battery (Mok, 2019). The risk of fire is however relatively low considering the large market; it was recorded that there were 2,089 Tesla Model S EVs registered in the UK alone (Bus, 2019). Other brands of EVs with a huge presence in the UK, such as the Nissan Leaf and the Mitsubishi Outlander also use lithium-ion based batteries. This shows the dominance it has on the EV market and it demonstrates that they are currently the most viable replacement for petroleum-based engines. The big issues to be addressed with lithium batteries relate to resource depletion and waste management. It is likely that there are alternative batteries that could work just as well or even better. This project looks into a possible substitute that could be beneficial for combating the issues involved with lithium-ion technology.

There are a number of environmental and health concerns associated with batteries. A large amount of raw materials including both metals and non-metals are consumed during the manufacturing process. Batteries account for a large percentage of worldwide consumption of certain materials, such as lead (85%), cadmium (75%), cobalt (50%), and lithium (46%) (Dehghani-Sanij, 2019). The increasing production of batteries for a number of markets is leading to resource depletion, and therefore a rise in price of the materials required. It also leads to a higher demand for mining, which brings its own environmental concerns. Batteries generate pollutants such as greenhouse gas emissions, toxic fumes and hazardous waste during its lifetime from production to disposal. Currently most are sent to landfill at the end of useful life as recycling waste batteries and recovering metals is a relatively expensive process to carry out safely. However, as battery production and disposal is increasing, it is becoming more necessary to recycle the materials (Dehghani-Sanij, 2019). It is important to consider the environmental effects throughout the lifetime of a battery during design, so that they can be produced, used, and disposed of in an environmentally friendly way. This project studies technology with a sodium-nickel chloride core, which is commonly known as a ZEBRA battery. However, the company that this research contributes towards, Lina Energy, have modified the cell design to improve the batteries efficiency. One of the big advantages of the sodium-nickel chloride core is the fact that the materials are much more readily available in terms of abundance and cost. There are also advantages associated with the ease of manufacture, and the battery has a good energy density and efficiency. The Lina battery aims to provide as an alternative, which could rival other battery storage technology that currently dominate the industry.

1. **Aims and Objectives**

The Lina battery operates at a high temperature range from 160℃ - 300℃. This means that there are some factors within the design that must be considered, which may not usually be of concern for most battery types. For example, it is important to explore suitable insulation materials that can be applied to a battery pack, to keep the battery hot when it is not in operation. The aim is to ensure the temperature remains within the operating temperature limits for a large length of time, so that the battery does not always rely on the use of a start-up battery to achieve the correct temperature. The motivation behind this is to ensure the battery is readily available for use for an extended amount of time. A wide range of insulation types were applied to the battery design at altered thicknesses starting at 10mm up to 50mm, increasing in 5mm increments. These thicknesses represent a suitable size range for an individual battery pack. It was important to explore a range of insulation materials; these included ceramic fibre boards, ceramic blankets, insulating gels and more. Thermal simulations completed on the Abaqus platform allowed for results that provided useful information relating to the insulation, such as the specific amount of time that the model takes to cool from the maximum operating temperature (300 to the minimum operating temperature (160℃), and then towards the sink temperature, which was set at room temperature (25℃). This is beneficial for the project as it provides the specific time that the battery temperature remains within the operating limits, and the specific point that heating could be required. It also provides an idea of the most suitable insulation materials and thicknesses in order to retain the high temperatures, which is applicable for the manufacture of the battery.

Another part of this project involved the heating of the battery, heating is important for when the temperature falls below the operating temperature limits. The thermal simulations allow the user to determine and apply the specific amount of back-up power between each cell, required to stabilize the battery temperature at. This is useful as it extends the amount of time that the battery is readily available for use. It also shows the amount of power required between different thicknesses and types of insulation materials. Depending on the power required to maintain the temperature and the power of the back-up heater battery, it is possible to discover the specific time that heat can be supplied for. Within the industry, an appropriate amount of time for the car to remain at 160℃ would be the length of time that a car is typically left for overnight. For example, if the battery can remain at 160℃ for at least 12 hours, it is likely that the use of startup power and time can be minimized. It was an aim of the project to create a heating system that provides heat uniformly throughout battery packs, for a length of time that would suit consumers.

Although a sizeable part of the project involved retaining high temperatures, another important scenario to take into account involves periods that the battery runs at a high power. During this time the power between each cell will increase, causing the temperature to increase. Due to the maximum operating temperature being 300℃, it was an important aim of the project to explore whether the temperature rises too high during times of heavy usage. Therefore, ideally, a balance between keeping the temperature high for as long as possible when it is not in operation, and keeping the temperature low when it is running at high power needs to be achieved. The wide range of results aims to provide information that helps towards discovering a system that works in an efficient way, whilst taking different considerations into account.

Another aim of the project was to take individual battery packs and put them together into a system that would be suitable for an industry. For this project, the chosen industry was the electrical vehicle market, which is one of the main applications for electricity storage systems. Once useful results were gained from individual battery packs, it was important to apply these to a more advanced model with industry applications. A car requires multiple battery modules, for example, the original Nissan Leaf contains 48 modules each with four cells and the most recent model contains 28 modules each with eight cells (Lima, 2018). The aim of this part of the project was to create a battery system with a similar design to the Nissan Leaf, but with LiNa battery packs. These were thermally analyzed in order to gauge the temperature distributions throughout the model during the cooling process, which was important considering the high temperature operation.

1. **Background**
   1. **The Battery Market**

Batteries can be categorized into the following groups: primary, secondary, battery systems for grid scale energy, fuel cells and electrochemical capacitors (Linden, 2002). Primary batteries are used for small portable devices; they are usually not recharged, and are disposed of at the end of their life. This project is looking at larger battery types used for EVs and renewables, therefore primary batteries are not particularly relevant. Secondary batteries are applicable for this project; they are rechargeable cells that are used for a number of purposes such as portable electronic devices and car ignition. They are also being developed to power EVs and are becoming increasingly popular for residential power storage as people are investing in renewable technology for their homes (Dehghani-Sanij, 2019) (Hoppmann, 2014). Examples of secondary battery types and some details are listed as follows:

**Lead-acid batteries**

Lead-acid batteries are one of the oldest battery technologies having been first invented in 1859. They are still used extensively, particularly for automotive SLI (starting, lighting, ignition). This is because they are robust, tried and tested and because of their low cost (Mpoweruk, 2019). Other advantages of lead-acid batteries include a good high rate performance, wide size range, good performance in varying temperature, good charge retention, and high voltage (Hoppmann, 2014) (May, 2018). Whilst there are good features there are also some negatives that must be taken into account. Firstly, the use of lead itself presents its own environmental issues; recycling is required to reduce impacts (Davidson, 2016). Other disadvantages include: relatively low life cycle, difficulty in downscaling, occasional acid leakages due to damage, limited energy density and acid stratification (Linden, 2002). Lead-acid batteries have proved to be useful for energy storage, however, there are now alternatives available that out-perform them (Dehghani-Sanij, 2019).

The chemical reactions of the lead-acid batteries are as follows:

Negative: Pb(s) + HSO4– + H2O(l) –> 2e– + PbSO4(s) + H3O+(aq) (–> discharging, 🡨 charging)

Positive: PbO2(s) + HSO4–(aq) + 3H3O+(aq) + 2e–  –> PbSO4(s) + 5H2O(l) (–> discharging, 🡨 charging)

Lead sulfate is formed at both the electrodes. Two electrons are also transferred in the complete reaction. The lead acid battery is packed in a thick rubber or plastic case to prevent leakage of the corrosive sulfuric acid (Byju, 2016).

**Nickel-metal hydride (Ni-MH) batteries**

The Ni-MH battery consists of a metal hydride anode, a nickel hydroxyl oxide cathode, a KOH electrolyte, and a separator. They are used for power tools and hybrid vehicle applications as well as electrical vehicles (Sullivan G. L., 2010). Ni-MH batteries are known to have high energy density and specific energy, good charge retention, rapid charging, good operation temperature range, and a long cycle and shelf life. The downsides to these batteries include a decreased performance at low temperatures, and a higher cost and lower specific power when compared to Lead-acid batteries (Linden, 2002).

The nickel–metal [hydride](https://www.sciencedirect.com/topics/chemistry/hydride) battery makes use of hydrogen for the positive [electrode](https://www.sciencedirect.com/topics/chemistry/behavior-as-electrode). This hydrogen is stored in alloy (i.e., metal hydride). The reactions of the battery during charging and discharging are shown in the equations (N. Omar, 2014):

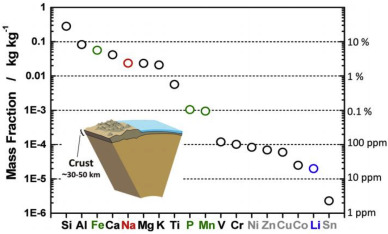
Positive electrode: 2NiOOH + 2H2O + 2e- 🡪 2Ni(OH)2 + 2OH- E=0.49V

Negative electrode: H2 + 2OH- 🡪 2H2O + 2e- E= -0.83V

Overall reaction: MH2 + 2NiOOH 🡨🡪 M + 2Ni(OH)2 E= -1.32V

**Lithium-ion (Li-ion) batteries**

Li-ion batteries are currently the type that is used most extensively for electrical/hybrid vehicles as well as for renewable energy and micro-grid systems. They are also used for most portable devices such as mobile phones and laptops because of their high energy per unit mass compared to other energy storage devices (AFDC.Energy, 2019). Advantages of Li-ion batteries include a long cycle life, wide operation temperature range, rapid charging, high charge/discharge efficiency, ample design flexibility, and sealed cells that don’t often require maintenance (Linden, 2002). Furthermore, they provide a high storage efficiency of 83% (Manuel, 2014). Rechargeable Li-ion batteries have excellent energy and power density; however, their downsides include cost, lithium resource depletion, reliability, and safety issues (Qi Li, 2016). The relative abundance of lithium compared to other elements is visualized in figure 1, showing that the presence of lithium in the earth’s crust is a low 20ppm (Yabuuchi, 2014). The battery type that this project is looking at uses sodium as its base instead of lithium. It is clear that sodium is much more abundant, which is a clear advantage for this type of energy storage.



**Fig 1:** Elemental abundance in the earth's crust. Copyright 2014 American Chemical Society.

The equations below presents the reaction for the positive and negative electrodes of a LiCoO2 battery, which is a certain type of lithium-ion battery (Kang, 2015):

Positive electrode: C + xLi+ 🡨🡪 LixC (🡨 discharging, 🡪 charging)

Negative electrode: LiCoO2 🡨🡪 Li1-xCoO2 + xLi+ (🡨 discharging, 🡪 charging)

**Lithium-Sulphur (Li-S) batteries**

Li-S batteries are perceived as a promising power storage type due to their high theoretical capacity and their low cost. They are cheap to produce due to the use of sulphur as the base material, which is relatively cheap when compared to elements (Seh, 2016). The limitations of these batteries include low volumetric density, high internal resistance, self-discharge, rapid capacity fading/ capacity loss, and low coulombic efficiency due to polysulfide shuttling (Ji, 2009) (Fang, 2017). The theoretical capacity of this battery is very high; however, it has been difficult to achieve this in actual operation making Li-S batteries less advanced than initially predicted (Ji, 2009). This battery is receiving a considerable amount of attention as many of the drawbacks can countered by the specific design of the cell.

The lithium sulphur battery has a specific capacity of about 1600 mA·h·g−1. And the discharge occurs in two stages:

S8 + 2e- + 2Li+ 🡪 Li2S8

Li2S8 🡪 Li2Sn + (8-n)S

The main technical challenges come from the high solubility of Li2Sn in the electrolyte. This results in the decrease of the active mass of the cathode and therefore a decrease in capacity. Furthermore, lithium sulphide reacts with the lithium [anode](https://www.sciencedirect.com/topics/engineering/anode) electrode and reduces the energy efficiency. The formation of Li2S results in a decrease of the cycle life. In order to reduce the [electrochemical process](https://www.sciencedirect.com/topics/engineering/electrochemical-process) in lithium sulphur batteries, carbon particles can be doped in the sulphur cathode electrodes. The carbon has a [porous structure](https://www.sciencedirect.com/topics/engineering/porous-structure) which allows it to create a large surface area, which supports the polysulphide (Justin Salminen, 2014).

**Lithium-air (Li-air) batteries**

Li-air batteries are as close as possible to the theoretical limits for energy density of a battery. This value is approximately ten times higher than the energy density of a conventional Li-ion battery, and would be a sufficient replacement to gasoline engines. The engineering of the battery proved to be a challenge due to a few issues. There were problems with electrode passivation, superoxides, degradation at high powers, and atmospheric water within the battery (Liu, 2015). Li-air batteries are promising technology that could benefit from further research.

Lithium-air batteries consist of lithium metal anodes electrochemically coupled to atmospheric oxygen through an air cathode. The oxygen that is used in the battery through the air cathode is essentially an unlimited cathode reactent source due to atmospheric air. The lithium metal reacts with oxygen gas to give electricity according to the following discharge reactions (Oi Lun Li, 2018):

4Li 🡪 4Li+ + 4e- (lithium electrode, anode)

O2 + 4e- 🡪 2O2- (gas electrode, cathode)

4Li + O2 🡪 2Li2O (cell)

2Li + O2 🡪 Li2O2 (cell)

**Sodium-Sulphur (Na-S) batteries**

Na-S batteries uses liquid sodium and sulphur and is similar to the battery that this project focuses on, in the way that it operates at high temperature (300C). The high operating temperature has held it back from being the energy source of choice for electric vehicles (Sullivan L. G., 2010). The production of this battery is relatively cheap to produce due to the high availability of the materials involved (Yabuuchi, 2014). Other advantages include high energy density, high cycle life, flexible operation and insensitivity to ambient conditions (Kumar, 2017). The main disadvantages revolve around maintaining the high operating temperature of the battery. Due to the high operating temperature and the highly corrosive nature of the sodium polysulphide discharge products, this type of battery is only suitable for large-scale, non-mobile applications such as grid energy storage (Yuan, 2012).

Sodium-sulfur battery operates on the principle of a reversible [redox reaction](https://www.sciencedirect.com/topics/engineering/redox-reaction) between sodium and sulfur. The battery is similar to the ZEBRA battery in the way that the operating temperature is high at 300℃ and it uses beta-alumina as its electrolyte. The chemical reaction of the battery is (Breeze, 2019):

2Na + xS 🡨🡪 Na2Sx

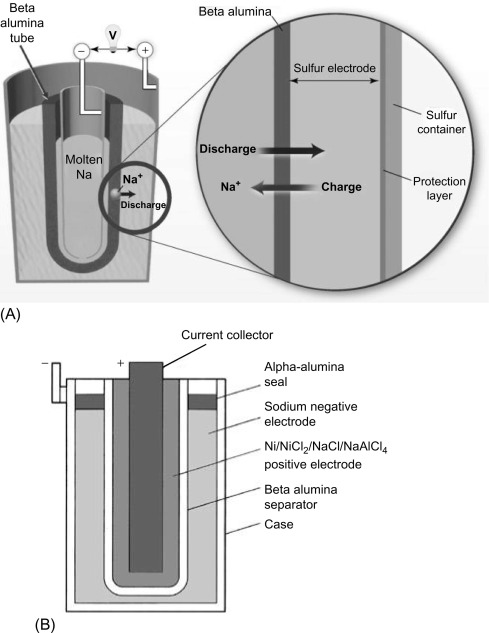
**Sodium-nickel chloride (Na-NiCl) /ZEBRA/ LiNa battery**

This type of battery is the focus for this project. Extensive research will work towards providing information about the liability of this battery as an alternative to other types for electric vehicles, renewable energy storage, and other possible applications. There are differences in design between the ZEBRA and LiNa cell; however, the fundamental chemistry is the same for both. The NaNiCl cell evolved from the Na-S cell and it is similar in the way that it consists of a liquid sodium negative electrode separated from a positive electrode by a sodium ion-conducting electrolyte (Sudworth, 2001). There are different electrolytes that are suitable for this battery, the main options being Beta-Alumina (used for the ZEBRA) and NaSICON. Both were compared in a study and it was found that there were clear advantages for the use of NaSICON at lower temperature operations, due to high ionic conductivity of sodium ions (Jeongsoo, 2015). The Na-NiCl cell differs from the Na-S because a second, liquid, electrolyte (sodium chloroaluminate) is added to allow the rapid transport of sodium ions to and from the sodium nickel chloride electrode and the ceramic electrolyte (Coetzer, 1986). This salt must be in liquid form for the cell to be in operation. The melting point of the salt is 157C, which is therefore the minimum temperature for cell operation. Optimum performance of the ZEBRA cell is achieved at 270C-350C (Sudworth, 2001). Although the high temperature operation batteries can come with disadvantages at times, it can also be an advantage for certain applications.

The high temperature operation of the ZEBRA technology means that certain parameters like insulation and cooling agents must be involved in design. The insulation is required to maintain as much heat as possible whilst the battery is not in operation, so that the battery requires less energy when it is required for operation. Cooling agents can also be important to keep the temperature within the operating temperature limits when it is in operation. One paper has specified the design of a ZEBRA battery pack. It states that ZEBRA cells can be connected in parallel and in series, they can be made with up to five parallel strings and up to 220 cells in series, with 100-500 cells in one battery pack. The standard battery type has 216 cells arranged in one (557V) or two (278V) parallel strings. Between every second cell there was a cooling plate where ambient air is circulated through, providing a cooling power of 1.6-2kW. For the thermal insulation and mechanical support, the cells are surrounded by a double walled vacuum insulation, which is usually around 25mm thick. Light plates made from silicon oxide take the atmospheric pressure load (Dustmann, 2004).

The big difference between the ZEBRA and the LiNa cell is in the design of the battery, and more specifically the electrolyte. The ZEBRA battery uses a beta-alumina electrolyte whereas the LiNa cell consists of ultra-thin layers of the NaSICON electrolyte, supported by a thin layer of metal. From the resistivity equation, it can be observed that the resistance of a material increases with the length. The thin layers of electrolyte causes the length to be shorter, which allows the resistance to become smaller. Ideally, a battery should have zero resistance. This is to allow all voltage to be supplied to the element that the battery is powering, instead of voltage being used on itself (Learningaboutelectronics, 2016). It is not possible to achieve zero resistance in practice, so therefore it is preferable to keep resistance as low as possible.

The sodium nickel-chloride cell is considered a promising storage technology due to a number of reasons. Firstly, it consists of materials with a high relative abundance, making the technology cheap to manufacture in comparison to other battery types such as lithium-ion (Yabuuchi, 2014). Previous research has led to design changes to improve various aspects of the battery. Improvements include: a high power of 150 W kg-1 for 80% depth of discharge, further optimization of chemical composition has allowed for specific energies in excess of 140 Wh kg-1 (Galloway, 1999). The Na-NiCl provides a good balance of performance in terms of costs, safety and energy density. Other positives include the cell being 100% recyclable, high efficiency in terms of charge/discharge, zero maintenance, energy availability, and the ability to work in any climate and environmental conditions (Dustmann, 2004). There are disadvantages involoved with temperature management in industry, along with the fact that extra energy is sometimes required to maintain the high operating temperatures.



NaSICON electrolyte

**Fig 2:** A diagram of the sodium-nickel chloride cell.

The sodium nickel-chloride cell as shown in figure 2 consists of a nickel chloride salt (sodium tetrachloroaluminate (NaAlCl4)) as the positive electrode and liquid sodium metal as the negative electrode. These are separated by a ceramic aluminium oxide separator. The sodium tetrachloroaluminate allows the rapid transport of sodium ions from the solid nickel chloride electrode to and from the NaSICON electrolyte. The melting point of the sodium tetrachloroaluminate is 157℃, which represents the minimum operating temperature of the battery. The chemical reaction during charge is (Johnson, 2014):

Ni + 2NaCl 🡪 NiCl2 + 2Na

The voltage range of the sodium chloroaluminate electrolyte is 1.5 V, and at the top of charge, it is decomposed in the following reaction (Sudworth, 2001):

2NaAlCl4 + Ni 🡪 NiCl2 + 2Na + 2AlCl3

Sodium nickel chloride batteries have high energy per kg metrics, which is compareable to lithium ion packs. MES-DEA produced a 21 kW-hr battery pack (Model # Z5-278-ML3P-76) for transportation applications with the following metrics (Johnson, 2014):

* Specific Power: 170W/kg
* Specific energy: 120W-hr/kg
* Power density: 250W/L
* Energy density: 175W-hr/L

**3.2 Insulation Materials**

An important part of this project involves identifying suitable insulation materials for the battery. A wide range of insulation types were tested at varying thicknesses. The insulation types, with their descriptions are listed below.

**Pyrogel XT:**

Pyrogel XT is a very effective high temperature insulation blanket of silica aerogel that is secured with a non-woven, glass fibre batting. The insulation is an environmentally safe product that is easy to use due to it being a flexible material. Silica aerogels achieve the lowest thermal conductivity of any known solid making it very effective as a high temperature insulating material. The blankets come in thicknesses of 5mm and 10mm, this could be increased with more than one layer. The material is physically robust and can be applied to any shape. It is hydrophobic and breathable as it repels liquid water but allows water vapour to pass through. It also has a high electrical resistance, which is an important property in relation to battery insulation (Thermaxx Jackets, 2019). The molecular formula of silica aerogel is C23H22N2O3S2 (U.S National Library of Medicine, 2018).

Commercial details:

Thermax Jackets- 14 Farwell Street, BLDG 2B, West Haven, CT 06516

Phone number and email: (203) 672-1021, [info@thermaxjackets.com](mailto:info@thermaxjackets.com)

**Mikroporous Aerogel:**

This insulation type, along with Pyrogel XT is an aerogel material that possesses the lowest thermal conductivity of any insulating material (Refractory and high temperature insulation materials, 2019)**.** Despite the name, the Aerogel insulation is in the form of a solid plate/board. The insulation is safe to use and can be applied to electrical equipment. This insulation material should have a very high level performance, however it may be higher in cost in comparison to other insulation types (Özkan, 2019). The molecular formula of silica aerogel is C23H22N2O3S2 (U.S National Library of Medicine, 2018).

Commercial details:

İTOSB, İstanbul Tuzla Org. San. Böl. 2. Cadde No: 13 Tepeören, 34959 Tuzla / İstanbul / Türkiye

Phone number and email: +90 216 467 31 40, [akm@akm.com.tr](mailto:akm@akm.com.tr)

**Superwool Plus Blanket:**

Although the thermal insulation of the Superwool Plus Blanket is lower than the silica aerogels, it’s insulating properties still show high performance. It has an advantage over ceramic fibres as it generally costs less and performs just as well. Superwool also has a uniquely low biopersistance, which means it comes with less health and safety requirements when handling the material. (Lynn Manufacturing Inc, 2019) The insulation is easy to use and has high resistance to tearing. It is suitable for electric equipment, which makes it an option for this project. The Superwool Plus Blanket is made from alkaline fibres. The fibres are incombustible and thanks to their compressibility the blankets provide a very good fire and smoke tightness (Odice, 2019).

Commercial details:

ODICE LLC, 1997 Newborn Road , GA 30663 Rutledge, USA

Phone number and email: +1 706 557 77 72, [info@odice.com](mailto:info@odice.com)

**Vermiculite:**

Vermiculite has good insulating properties; this makes it a good high temperature insulation. It has low thermal conductivity and a high specific heat capacity, it does however have a low density due to its form (The Vermiculite Association, 2019). The downside to this type of insulation is that vermiculite may contain asbestos, which is potentially harmful to human health (Wise Geek, 2019). This is likely to be a deciding factor against the use of this insulation, however the results gained provide as a useful comparison to other insulating materials. Vermiculite is the name given to a group of hydrated laminar minerals that are aluminum-iron-magnesium silicates. The chemical formula for vermiculite is (Mg,Ca,K,Fe+2)3(Si,Al,Fe+3)4O10(OH)2. 4H O (Mathieson, 1958).

Commercial details:

The Vermiculite Association, 2207 Forest Hills Drive, Harrisburg, PA 17112

Phone number and email: 717 238 9902, [tva@vermiculite.org](mailto:tva@vermiculite.org)

**Aluminum Silicate Blanket:**

Aluminium Silicate is a composite of around half alumina and half silicon oxide (Materials Hub, 2019). This type of insulation is in the form of a blanket, the thickness of the blanket is 50mm, however this can be reduced if necessary. The blanket is fireproof and is a strong, lightweight and durable material, which performs well as a high temperature insulation. It has a respectably low thermal conductivity and has good electrical resistance (Iking Group, 2019).Aluminium Silicate comes in three different forms: kyanite, andalusite, or sillimanite. They all have different crystal structures but the same chemical formula; Al2SiO5. Only kyanite and sillimanite are used industrially (George, 2020).

Commercial details:

Iking: +86 22 60767280, [info@iking-glasswool.com](mailto:info@iking-glasswool.com)

**Silica Sol Gel:**

This type of insulation comes in the form of a lightweight board. It has good insulating properties and its density is the highest of all the insulation types that have been tested. The gel is thermally stable and shows negligible electrical conductivity (Cheng, 2017). Although the properties of this material make it a good insulator, it is not as effective as other types of insulation and has a higher thermal conductivity of the other gels involved with the project. The chemical formula of silica gel is mSiO2 . nH2O, it appears as a slightly transparent white solid substance. This material was taken from a journal article and therefore the commercial details cannot be provided.

**Ceramic Fibre Board HP:**

This ceramic fibre board is a lightweight material processed with alumina silica fibres that is suitable for applications up to 1650℃. It has good insulating properties and it would be a suitable insulation material for electrical equipment (SIG Technical Insulation, 2019). It boasts the lowest thermal conductivity of any of the other ceramic fibre boards that this project analyses, meaning should have a high level of performance. Standard ceramic fibres are made from inorganic materials, the main types are aluminium oxide and silicon dioxide, which leads to very high thermostability. By adding small amounts of chemicals such as zirconium oxide the application temperature can be increased from 1260℃ to 1600℃ (Emre Yalamac, 2016).

Commercial details:

SIG Distribution- Adsetts House, 16 Europa View, Sheffield Business Park, Sheffield, S9 1XH

Phone number: 0330 123 0100

**Ceramic Fibre Fireproof Board:**

This ceramic fibre board is primarily used for fire protection and in the linings of furnaces. It can also be used for other applications such as for a battery. The board is manufactured with process of wet vacuum forming. It has higher strength than fibre blanket and can is suitable for high rigidity and strength requirements(Refractory Online, 2019)**.** It has a relatively high density and its thermal conductivity is quite high compared to some other insulation types. The main types of cermic fibres that are used for insulation are aluminium oxide and silicon dioxide. Ceramic fibres from different manufacturers will have some variety in their properties, as the properties are defined by the production method.

Commercial details:

Zhengzhou Rongsheng Kiln Refractory Material Co., Ltd.:

13th Floor, No. 6 Building, China Central Electronic Commerce Port, Daxue Road, Erqi District, Zhengzhou, He’nan, China, 450000

Phone number and email: +86 0371-86555658, [Sales@refractoryonline.com](mailto:Sales@refractoryonline.com)

**Ceramic Fibre Board Vitcas:**

The refractory ceramic fibre board is a vacuum formed product. It can be produced in a range of thicknesses and is a lightweight material that is suitable for electrical applications**.** It has similar properties to the ceramic fibre board HP, with low thermal conductivity a good general insulating properties. This type ceramic fibre is made from high-purity alumino-silicate materials. Ceramic fibre is produced by melting these products in a furnace, a stream is poured and cooled to form the fibre strands from which the ceramic fibre products are produced. (Vitcas, 2019)**.**

Commercial details:

Vitcas- 204-208 Broomhill Road, Brislington, Bristol, BS4 5RG, United Kingdom

Phone number: +44 (0)117 911 7895

**Calcium Silicate Board:**

The NR-1000 calcium silicate board is a hard high temperature thermal insulations material based on lightweight calcium silicate. It possesses high strength, low thermal conductivity and is suitable for electrical equipment. Typical dimensions of the thickness is 25-100mm but this can be changed to fit a consumers request. The material is suitable for applications that reach temperatures up to 1000℃ (North Refractories, 2019)**.** The chemical formula of calcium silicate is Ca2O4Si (Royal Society of Chemistry, 2020).

Commercial details:

North Refractories- Room 1108, Lucky Tower B, Dong San Huan North Road, Chaoyang District, Beijing, China. 100027.

Phone number and email: +861062151268, info@northrefractories.com

**E-Glass Fibre:**

The thermal conductivity of E-Glass Fibre is much higher than any other insulation materials on this list, and is less suitable for high temperature solutions. It was noticeable from early in the project that the performance wasn’t at a high level, this lead to the decision of disregarding it as a possible choice of insulation as the thermal models developed. The composition of the E-Glass is as follows: 54% SiO2- 15% Al2O3- 12% CaO (Azom, 2019)**.**

Commercial details:

AZO Materials- AZoNetwork UK Ltd. NEO, 4th Floor, 9 Charlotte Street, Manchester M1 4ET, UK

Phone number: +44 (0)16 1457 7150

* 1. **Thermal Modelling of Batteries**

The thermal modeling of this battery will be important to provide a deeper understanding of the physical processes, and will aim to ensure the operation of the battery is as efficient as possible. Using software to model batteries is extremely useful to predict any problems that may have otherwise surfaced during manufacture. It saves resources and materials, as the battery does not need to be physically made to be tested. There is various literature available for battery thermal modelling with examples of highly useful information achieved from a range of different approaches, using simulation software such as ANSYS and Abaqus.

One example of a thermal model of a cylindrical lithium-ion battery is by a researcher called Zhang; he developed a coupled electrochemical-thermal model considering the electrolyte transport properties as functions of temperature and lithium-ion concentration. He also considered three types of heat generation sources including the ohmic heat, the active polarization heat and the reactions heat for the battery discharge process. In conclusion, he found that increasing the thickness of the separator and the electrodes leads to an increase in temperature at the end of discharge (Zhang, 2011). Another report by Huo et al., presented a 3D thermal model of the thermal performance of a lithium-ion battery. They used FEA analysis to visualize the effect of discharge conditions on the thermal behavior. They looked at the dynamic thermal behavior by utilizing a number of drive cycles. This allowed them to reach the conclusion that, natural convection was adequate to retain the temperature at 25℃ (Huo, 2015). Furthermore, one study produced a two dimensional electrochemical coupled with thermal behavior of the commercial 18650 lithium-ion phosphate battery. They found that the reaction rate contributed around 85% of the total heat generated from both charging and discharging of the cell. They also looked at the effect of electrical contact resistance between the terminals and connectors of the cell, which led to the realization that the electrical contact resistance caused a high temperature gradient across the cell (Saw, 2013). A group of researchers studied the 18650 cylindrical lithium-ion batteries and specifically, the heat generation and heat dissipation characteristics. They used ANSYS software to carry out finite element analysis (FEA) during the charging process with natural cooling conditions. The group established that at the end of 2C and 1C discharge rate, the maximum temperature is 58.88℃ and 42.33℃ respectively. They also realized that the temperature is not the same at different parts of the battery, with the internal and surface temperatures being different. It was also reported that the maximum temperature is at the center of the battery and the minimum temperature is at the bottom edge of the surface (Meng, 2017).

A study looked at the three-dimensional (3D) thermal modelling of a single Li-ion battery cell, as well as a 50V Li-ion battery pack made up of 14 prismatic batteries. They studied the heat from electrical resistance and electrochemistry reactions to see how it would affect the battery performance. The modelling provided a highly resolved 3D insight to the thermal and battery dynamics under fast discharging and abusive conditions. They found that a low coolant velocity causes the cell temperature to easily exceed 40℃, and temperature non-uniformity exceeds the limit value of 5℃ under 5C discharging condition. They also realized that under external shorting condition, the temperature rises quickly and reaches the 80℃ point, which can trigger thermal runaway. It became noticeable, thanks to the thermal modelling, that with adequate coolant flow rate the cell temperature and temperature gradients can be effectively limited to a suitable level, under both 5C discharging and external shorting conditions (Li, 2019).

Another piece of literature presents the analysis of sodium nickel-chloride batteries in transient operation, and the author has proposed a simple but precise model to represent both the steady and transient battery behaviors. Their modelling procedure was designed to represent the electrical behavior of NaNiCl2 batteries for electrical stationary storage applications in the high voltage network, during the transient operations, to reach a good understanding of the battery performances. The gathered results demonstrated the good performance of this storage technology for power intensive applications, which indicates fast charge/discharge cycles. The reason for this is due to the battery voltage drop being independent from the depth of discharge (DoD) in transient conditions. This essential characteristic allows this technology to be fully compatible with a number of high voltage network services, and particularly with network frequency regulation. They also presented a precise modelling approach to foresee the transient battery behavior starting from a set of steady measures, without making use of electrical circuits involving several electric parameters (Sessa, 2017).

A study looked at hybrid energy storage system (HESS) management strategies for urban road electric vehicle applications. They were aiming to extend battery pack durability by reducing charging/discharging current peaks with the use of supercapacitors. The HESS consisted of a high power unit and a high energy unit, they used a supercapacitor and a battery pack based on ZEBRA technology. The work looks at analysis methods based on non-linear programming and calculus of variations theory, in order to evaluate management strategies to aim to have high effectiveness in reducing battery current transients. They used Matlab-Simulink simulation environment to build a model, this was for the identification and optimization of these strategies. The simulation software helped to validate results found in various experimental work. It was proved that the methodology proposed in the paper definitely reduces the negative consequences of power peaks on the HESS (Capasso, 2018).

The thermal modelling of the LiNa battery is different to lithium-based cells due to the high temperature operation. The aims for the modelling of the LiNa cell will partly relate to providing the battery with heat, as well as retaining the high temperatures for as long as possible. Lithium-ion cells can experience thermal runaway at high temperatures, so the aims of the thermal simulations for this type of battery is to keep the temperature relatively low for operation (Li, 2019). Thermal models of other batteries like the lithium-ion are still relevant as a comparison, and there are aspects where the methods of analysis will be similar to this project. For example, some literature looked at the thermal distributions of a lithium ion battery to gain information about its design and performance; this will also be a key part to this project (Meng, 2017).

1. **Methodology**

The design of the battery took place on the CAD platform on Abaqus software, this software was ideal to use, as it was highly accurate; it made the design element relatively easy and all of the materials required were included in the design. Abaqus can also run various simulations including in depth thermal analysis, finite element analysis (FEA) and computational fluid dynamics (CFD). The focus for this project involved the thermal analysis, results gained from this provided valuable information that will work towards creating a sodium nickel-chloride battery that performs at its full capacity. Since the Lina battery performs at a high temperature, there are certain parameters involved with the design that need to be taken into consideration when creating a thermal battery model. For example, a big part of the project involved finding suitable insulation types to maintain high temperatures, and another part involved the inclusion of heaters. This makes the design of a sodium-nickel chloride based battery different to other battery types, which would not usually require high temperature conditions to operate.

This project makes use of uncoupled transient heat transfer analysis. Time integration in transient simulations uses the backward Euler method in the pure conduction elements. In transient heat transfer analysis with second order elements there is a relationship, as shown below, between the element size and the minimum usable time increment. Where Δt is the time increment, Δℓ is a typical element dimension, ρ is the density, c is the specific heat, k is the thermal conductivity (Abaqus Help Handbook, 2017).

Δt > Δℓ2 ρc / 6k

The software solves heat transfer equations that allow simulations to be run. The first is presented below, where, Q is power, k is thermal conductivity, ΔT is difference in temperature, A is area of thermal conductivity, and L is thickness of material.

Q = kΔTA / L

The software also makes use an equation that relates to energy conservation. This equation is below, where the accumilation is the heat energy leading to temperature rise, when considering the simulations carried out in this project.

Wout = Win + Accumulation

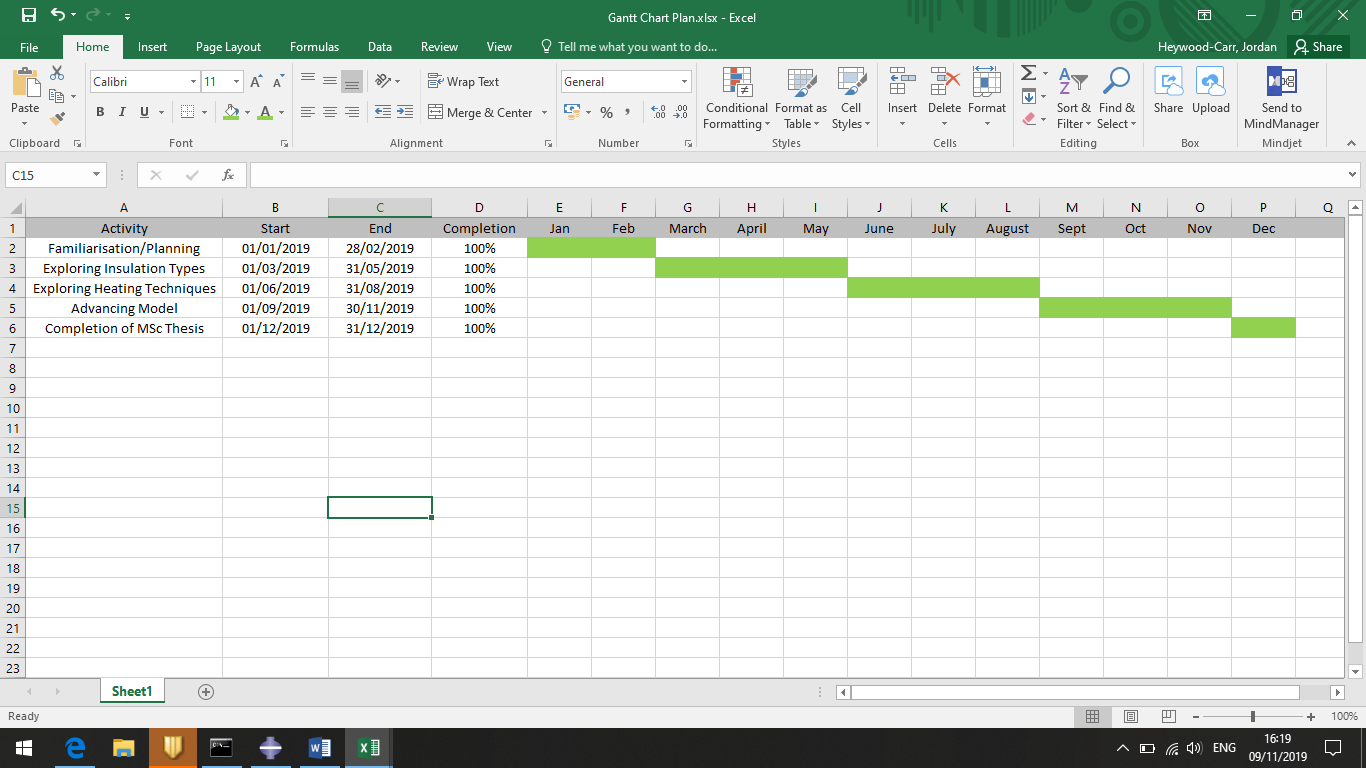
Whilst researching possible insulation types, it was important to discover certain properties of the materials, including the thermal conductivity, specific heat capacity and density. These properties thermally define a material and allow thermal simulations to run on Abaqus software. Firstly, a simple model of a steel block surrounded by different types of insulation was created. The steel block represented the core of battery and although this model was a simple design, it was important to become acquainted with the software and it provided a good insight into the best performing insulation types. The models were designed to test the length of time it takes for the battery to cool from the maximum operating temperature (300℃), to the minimum operating temperature (160℃), and then to room temperature (25℃). They were left to cool for 100,000 seconds from 300℃ with a sink temperature of 25℃. Due to the high temperature, it was necessary to apply heat transfer coefficients to the surface of the model, as the relationship between the surface and surrounding air changes as the temperature increases/decreases. The heat transfer coefficient table can be found in the appendix (figure 21) (Richardson C. a., 2001). The mesh size used for this project was 1mm. This size of mesh proved to be suitable for providing accurate results. Figure 16 shows a comparison of the results from the mesh size used and smaller mesh sizes, showing that the change made little difference. Various design aspects such as insulation types and thicknesses were differed with the aim being to maximize the amount of time that the battery takes to cool. It is favorable for the battery core temperature to remain within the operating temperature limits so that it is ready for ignition for an extended amount of time.

The model design then developed from a steel block to a block of individual cells. The individual cells are 4.8mm thick and consist of layers of steel (0.2mm), porous nickel (3mm), steel (0.2mm), sodium (1.2mm), and steel (0.2mm), in that respective order. In a pack of batteries, there are 28 individual cells and the dimensions of a battery pack are 92mm x 92mm x 138mm. This updated model was left to cool with the same conditions and parameters as the original, and this allowed for a more accurate representation of the cooling of the battery packs. Numerous types of insulation were applied to both the original and updated models at thickness of 10mm, 15mm, 20mm, 25mm, 30mm, 35mm, 40mm, 45mm and 50mm. This provided a large amount of results, and delivered useful information regarding the insulating properties of materials.

As the project progressed, the objectives involved including heaters within the battery design. The heaters were applied on the surface between each individual cell. This meant that the heat was distributed evenly throughout the core of the battery, which allowed the temperature distribution to be consistent. The heaters were set to turn on at the specific time that the temperature of the battery core fell to 160℃. They were given enough power to stabilize the temperature of the battery core at 160℃, so that it is within the operating temperature limits and is ready for ignition. Once this power was recorded, it was possible to discover the amount of time that a 1kWh back-up battery could supply heat to the battery packs. The amount of power required varied with the different thicknesses of the insulation materials being applied. This meant that the back-up battery could provide heat for various lengths of time depending on the model.

In order to simulate periods that the battery runs at high power, the next part of the project involved increasing the power between each cell to see the effect it had on the temperature. When the battery pack running at a high power of 500W, 10% of this power is lost as heat energy. Therefore, 50W was applied to the battery pack to simulate the effect that the extra heat would have. It was important that the temperature of the battery core remained below 300℃ with this added power, in the case that the temperature becomes too high the battery would cut out. This methodology aims to find a balance between keeping the battery hot for a suitable length of time, and ensuring that the battery temperature does not rise by too much. The models were heated by the extra power for 50,000 seconds to gain knowledge of the temperature distributions after this length of time. It was necessary to take data from these simulations to visualize the models being heated for a shorter amount of time of around 5000 seconds, as it is a more regular occurrence for a battery to run at high power for this length of time.

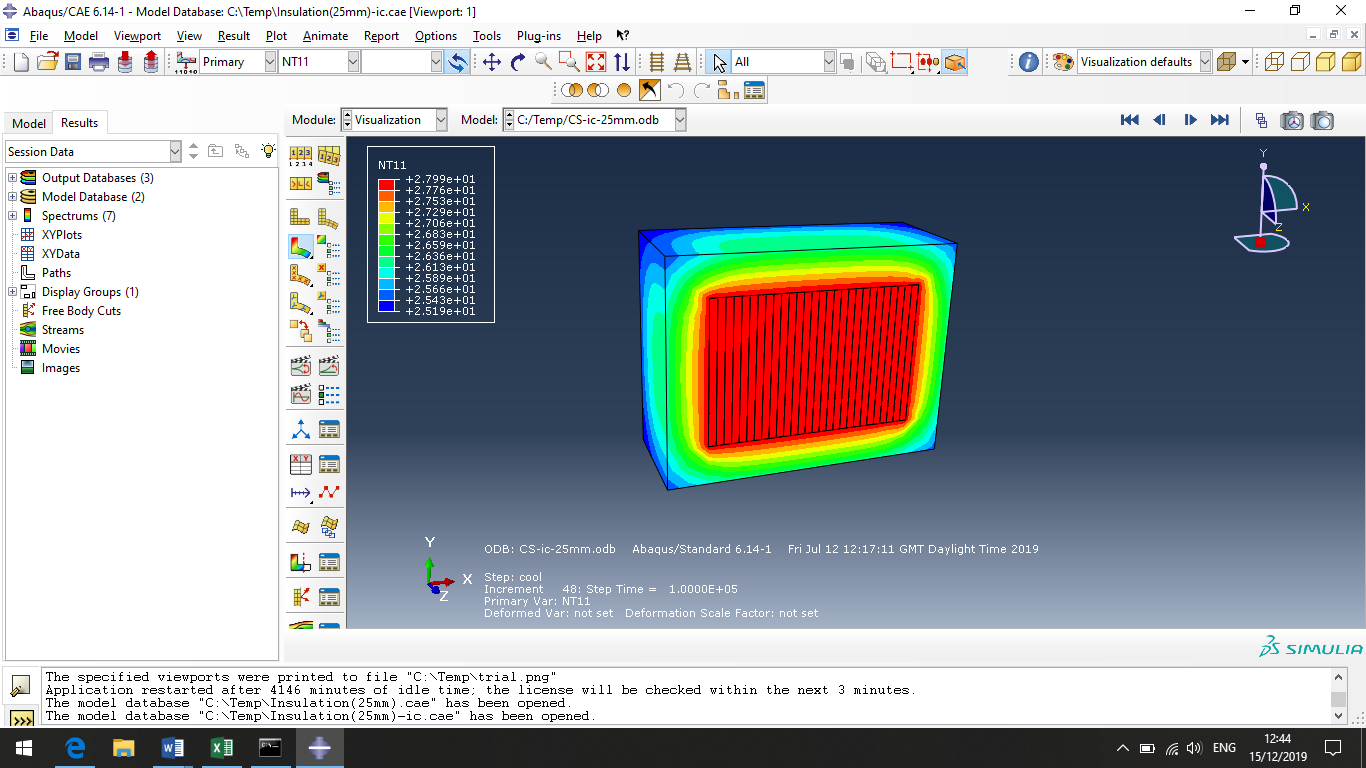
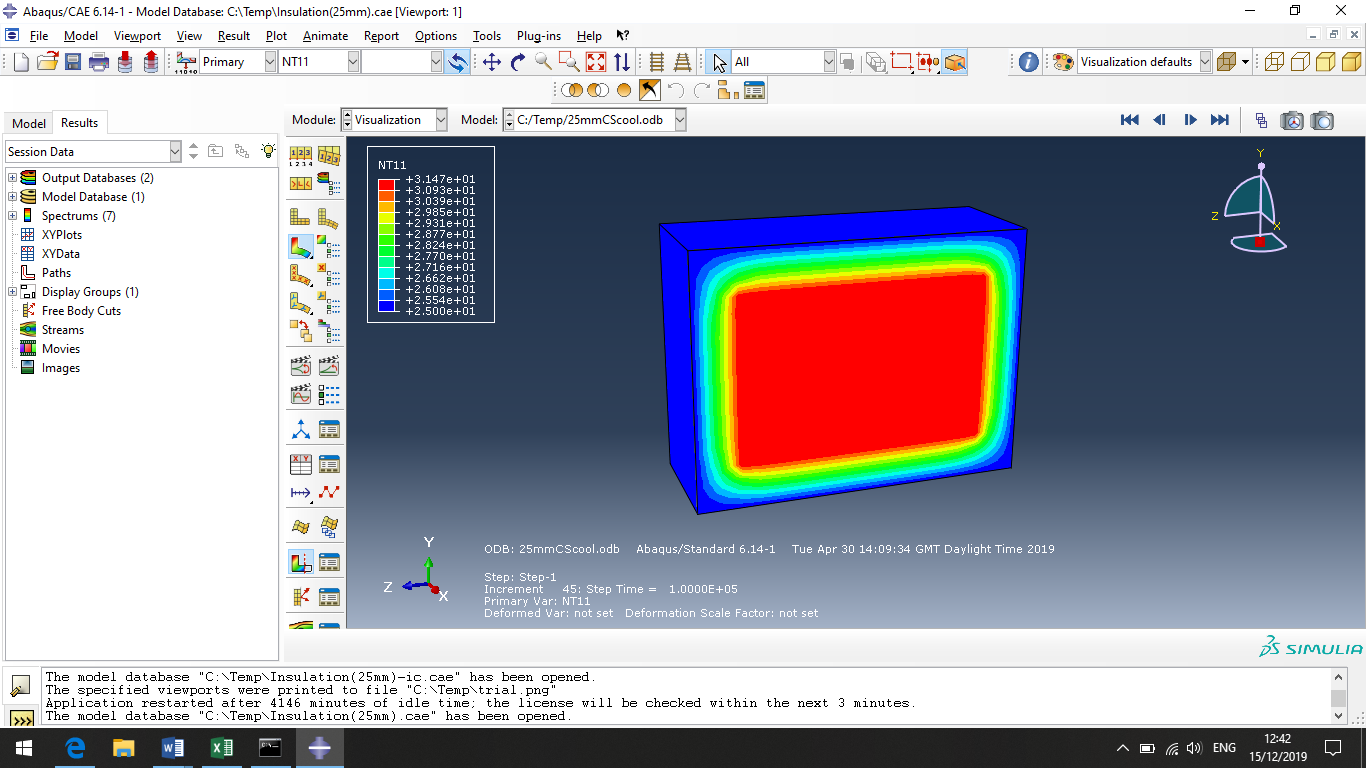
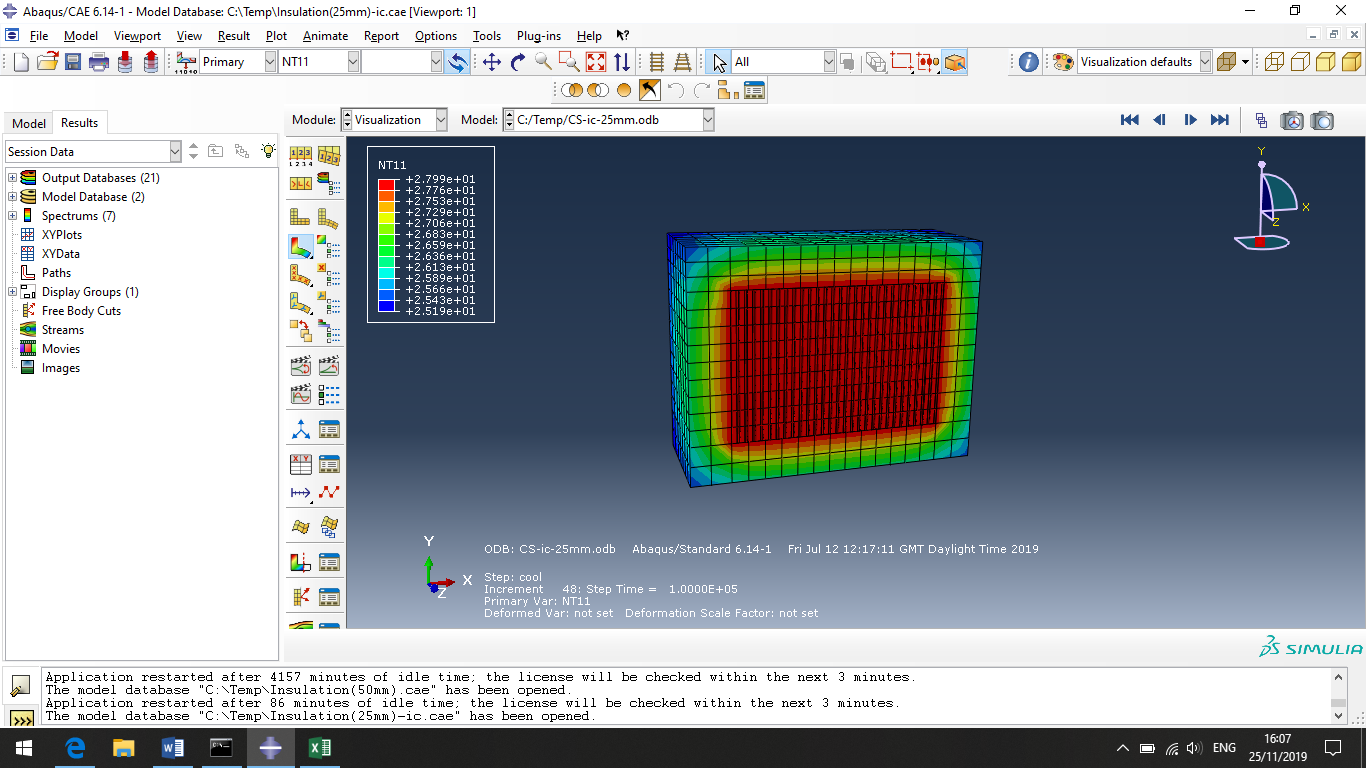
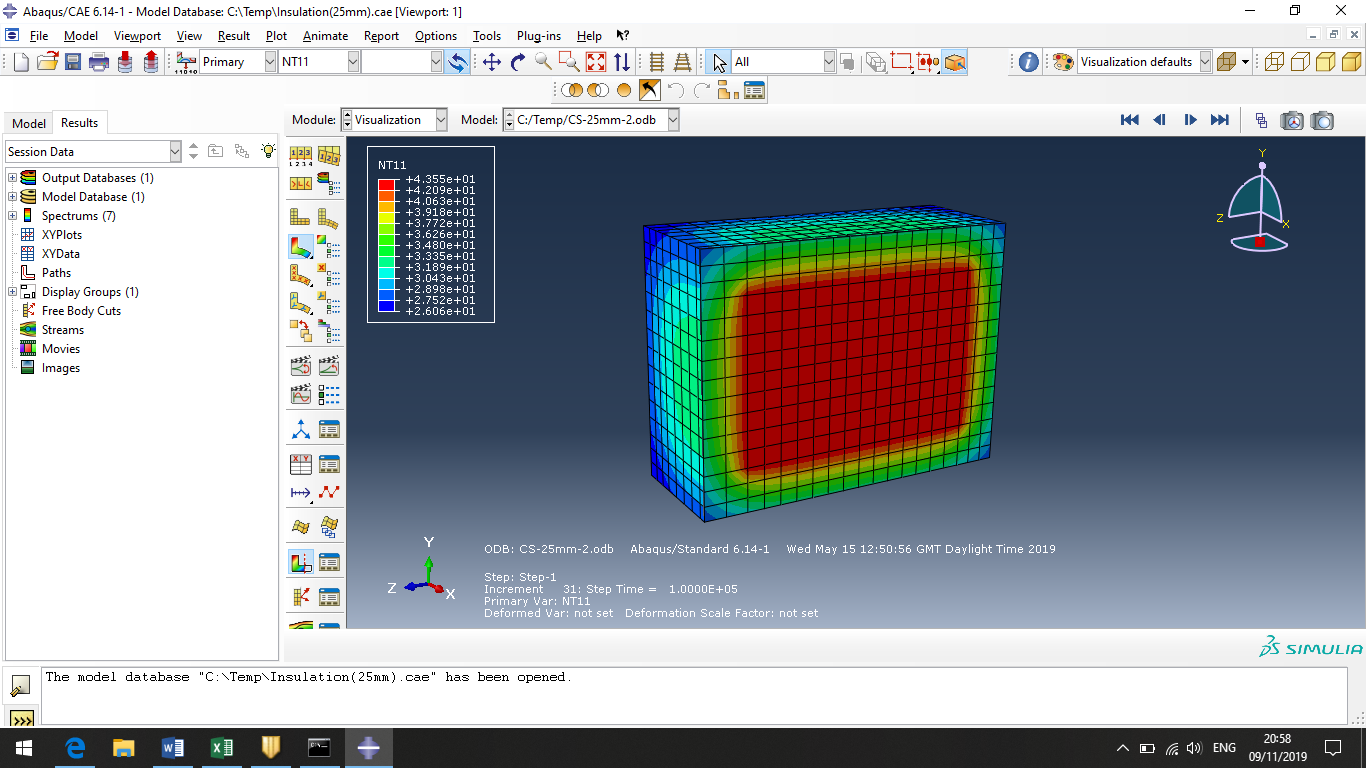
The final part of the project involved creating a design that brought individual battery packs together into a system that is applicable for an electric vehicle. The final design brings together 84 individual packs, each with 28 individual cells, which would provide more than enough electrical storage space to power an electric vehicle. Each of these packs are surrounded by a thin layer (3mm) of the Pyrogel XT, and then the model is surrounded with a second casing of Pyrogel XT insulation at 10mm thickness. The Pyrogel insulation proved to be one of the best performing insulation materials, making it a good choice for the final model design. This insulation set-up came from studying previous results to create a system that works effectively by utilising the impressive insulating properties of the Pyrogel XT, to create a system that contains the high temperature that is required. The layout of the battery system was based on the Nissan Leaf, it was designed so that the system fits below the passengers along the bottom of a vehicle (Hearn, 2019). The battery system is presented in figure 17, it visualizes that the shape of system would fit well into the bottom of a car, with extra battery packs beneath the seats of the vehicle and space in between for passenger leg room. The dimensions of the model can be viewed in figure 18. The system was left to cool for 100,000 seconds from 300℃ to view the temperature distributions. It had the same interaction properties and mesh size as the previous models involved in the project.

**Project Plan Gantt Chart:**

**Fig 3:** Gantt chart showing the project fulfillment over a specified time period.

1. **Results and Discussion**

At the start of the project it was important to become familiar with the Abaqus software, this was done by creating a simple model that provided an idea of the best performing insulation types. The model consisted of a steel block surrounded by insulation, they were left to cool from 300℃ for 100,000 seconds, with a sink temperature of 25℃. A view of the simple model with 25mm thick calcium silicate board insulation is presented in figure 4. It shows the model split in half so that a rainbow plot can be seen, which visualises the temperature throughout. Figure 3 also presents a more developed model that replaces the steel block with individual cells. The model with the individual cells represents a battery pack. This model has been utilised to show the varying cooling times with different insulation materials and thicknesses applied, it is also the model that heaters were applied to as the project developed. This was beneficial as it was important to gain information about individual battery packs before bringing the packs together into any sort of system.



**Fig 4:** An example of the rainbow plot of the simple model (left) and the more developed model with individual cells (right), both with 25mm thick calcium silicate insulation and each of their temperature distributions (℃) after 100,000 seconds of cooling from 300℃.

Due to the high temperature operation of the LiNa battery, an important aspect of this project involved discovering suitable insulation types. Table 1 presents a list of a wide range of insulation materials that were considered for the duration of the project. The list details the necessary thermal properties, these being the thermal conductivity, specific heat capacity and the density (Help.Solidworks, 2017). The thermal conductivity measures the ease with which heat can travel through a material by conduction (Greenspec, 2019). Therefore, generally, the lower the thermal conductivity, the better a material can insulate. The thermal conductivity can often change with temperature, however, some of the companies that provide the insulation material properties provided one standard value. This means that some of the values taken could be slightly inaccurate as it is likely that the thermal conductivity value would change marginally, especially with the large operating temperature range of the Lina battery (Safa Kasap, 2017). The specific heat capacity of a material is the amount of energy required to increase the temperature of a material of a certain mass by 1℃, in the unit of J/kg.K. Therefore, usually materials with a higher specific heat will be better insulators. However, the effect of this is less than some other properties (Wu, 2018). The density of materials can also have an effect on its insulating properties, it would be expected that the higher the density the better the insulation material, however, this is not always the case. Often pockets of air within insulation can improve the insulating properties, which would cause the density to be lower. For example, one source compares a low density ultimate wool insulation with a high density stonewool. It concludes that the thermal conductivity is lower for the low density insulation (Isover Saint-Gobain, 2018). This shows that the density of a material does not always determine whether the material would be a good insulator, and it can often depend on the consistency and design of materials. However, the density must be known in order to simulate using Abaqus. Before considering thermal simulations, the thermal properties from table 1 provided an idea of the insulation types which would be the most effective. The materials with the lowest thermal conductivities were Mikroporous Aerogel (0.03W/m.K) and Pyrogel XT (0.028W/m.K at 200℃, 0.035W/m.K at 300℃) therefore they were expected to perform better than others. Whereas insulation types such as ceramic fibre boards and fibre glass had lower thermal conductivities and therefore were not expected to perform as well. The table included below in table 1 shows the required thermal properties of all the materials in order to complete the thermal simulations. The stainless steel, porous nickel and sodium are materials that make up the battery cells. The rest of the materials are the various insulation types that have been considered for the project.

|  |  |  |  |
| --- | --- | --- | --- |
| **Material** | **Density (kg/m^3)** | **Specific Heat (J/kg.K)** | **Thermal Conductivity (W/m.K)** |
| Stainless Steel 430 | 7750 | 460 | 26.3 |
| Porous Nickel (50%) | 8912 | 220 | 43 |
| Sodium | 970 | 1230 | 80 |
| E-Glass Fibre | 2.55x10^3 | 800-805 | 1.2-1.35 |
| Calcium Silicate Board | 250 | 840 | 0.058 |
| Mikroporous Aerogel | 300 | 810 | 0.03 |
| Ceramic Fibre Board- Vitcas | 300 | 1070 | 0.08 at 400℃ |
| Ceramic Fibre Fireproof Board | 320 | 1050 | 0.125 at 400℃ |
| Ceramic Fibre Board - HP | 300 | 1070 | 0.055 at 200 0.073 at 400℃ |
| Siica based sol gel | 387 | 820 | 0.076 |
| Aluminium Silicate Fibre Blanket | 128 | 840 | 0.09 at 400℃ |
| Vermiculite | 90 | 840 | 0.064 |
| Superwool plus blanket | 160 | 830 | 0.07 |
| Pyrogel XT | 200 | 820 | 0.028 at 200. 0.035 at 300 |

**Table 1:** A table that presents the thermal properties of the materials used for the project.

The initial simulations involved a simple model of insulation applied to a steel block, which was left to cool for 100,000 seconds from the maximum operating temperature of 300℃. This was done early in the project to gain experience and knowledge about the Abaqus software, whilst also providing useful information regarding the insulation materials. Figure 5 presents a graph that shows the cooling times of the various insulation applied at 50mm thickness to the initial model. Firstly, it confirms that the two best performing insulation types are Pyrogel XT and the Mikroporous Aerogel, with the battery core temperature falling to 110.4℃ after 100,000 seconds for both. Other insulation materials that performed well are the Ceramic Fibre Board- HP and the Calcium Silicate Board which fell to 60.6℃ and 59.3℃, respectively. The Silica Sol Gel, Superwool, and Vermiculite insulation all had a medium performance level in comparsion to the other insulation types, the temperature that the battery core fell to was 48.8℃, 47.7℃ and 50.5℃, respectively. After this was the lesser performing insualtion materials that included the Ceramic Fibre Fireproof Board the Aluminium Silicate and finally the E-Glass Fibre. The E-Glass fibre in particular had a much lower performance level to the other insulation types, with the battery core falling to 29.3℃. This lead to an early decision not to consider E-Glass Fibre any further for the duration of the project, as it was logical to conclude that it would not be suitable for this application. Although the initial model of the project was simple, it provided beneficial information especially in regards to the insulation, which is an important aspect of the project. It was not necessary to include the simple model graphs of all of the insulation thicknesses in this thesis, as they show very similar trends in regards to the best performing insulation types. Furthermore, the model with individual cells included in the design provided more accurate results, therefore making the results more viable to discuss. The figures also show the cooling times of the model without any insulation applied, it can be visualised that it cools much more quickly taking only 285.8 seconds to fall to 25℃.

**Fig 5:** A graph showing the simple model cooling with various types of 50mm thick insulation.

The next part of the project involved advancing the model by replacing the metal block with individual cells to respresent a battery pack. Figures 5 and 6 show the cooling of the original simple model and the more advanced individual cell model, both with the same insulation thickness. The first noticeable difference is that the battery core temperature was lower for the individual cell model. For example, the 50mm thick Mikroporous Aerogel and Pyrogel XT fell to 64.5℃ and 62.8℃ after 100,000 seconds, which is around 45℃ cooler than the simple model. Also, the 50mm thick Ceramic Fibre Board- HP and Calcium Silicate fell to 36.5℃ and 34.8℃, which is around 25℃ cooler than that of the simple model. The temperature drop was a common trend for all the insulation materials when comparing the simple and more advanced model, which shows the importance of a more accurate model design. This larger drop in temperature was expected, as the steel block would have had a lower overall thermal conductivity than the block of individual cells, therefore allowing less heat energy to be dissipated. The results from the cooling of the block of individual cells backed up the original conclusions as to the best performing insulation types. The Pyrogel XT and the Mikroporous Aerogel performed at the highest level, with the Ceramic Fibre Board- HP and the Calcium Silicate Board also performing well.

**Fig 6:** A graph showing the cooling times of various insulation types applied at 50mm thickness to a block of individual cells.

A wide range of insulation thicknesses were applied to the models in order to provide a large set of results that would be of importance as the project developed. Figure 7 presents an example of a model with 25mm thick insulation, which is thinner in comparison to the models shown in figure 5 and 6. There is also graphs with a wider range of insulation thicknesses applied included within the appendix section (figure 19-22) . As expected, the models cooled at a quicker rate with thinner insulation applied. The Mikroporous Aerogel and Pyrogel XT fell to 39.3℃ and 40℃, and the other insulation materials at 25mm thickness fell close to the sink temperature of 25℃ after the 100,000 seconds. The final temperature that the models fell to after 100,000 seconds provided useful information regarding the best performing insulation materials. However, it is more beneficial to be aware of the time each model takes to cool to the minimum operating temperature of 160℃. If this time can be maximised, it helps to prevent the use of heaters or a start-up battery for a longer length of time, which means less energy is required. It also provides the time that it would be necessary for heaters to be applied to maintain the opperating temperature, which leads on to the next part of the project. This time was lengthened with the better performing insulation materials and thicker insulation being applied. For example, the 50mm thick Pyrogel XT insulation took 36,679 seconds to cool to 160℃, whereas the 20mm thick Pyrogel XT insulation took 19,822 seconds. The 50mm thick Calcium Silicate Board insulation had a much shorter cooling time to 160℃, of 20,500 seconds, and the 20mm thick Calcium Silicate Board insulation took 11,900 seconds. This shows the importance of suitable insulation materials/thicknesses, as the LiNa battery is required to maintain the operating temperature for a considerable amount of time. The appendix shows results from the four best performing insulation materials, at a range of thicknessess. This can be viewed to gain further knowledge on the effect of the insulation thicknesses on the cooling times of the battery packs.

**Fig 7:** A graph that shows the cooling times of various insulation types applied at 25mm thickness to a block of individual cells.

The results from figures 8-11 show the length of time that the battery core temperature of certain models, firstly, cools to 160℃. This temperature is then maintained by heaters, of which power is supplied from a 1kWh back-up battery. The length of time that this can maintain the temperature for is also revealed by the figures. Once the back-up battery runs out of power the models slowly cool towards room temperature (25℃). The amount of power required to maintain the temperature varies between each model, if the model has a better performing insulation it would require less power, and therefore the back-up 1kWh battery could last for an increased amount of time. Included in figure 8-11 are the results from the best performing insulation materials, which was the Pyrogel XT and the Mikroporous Aerogel, at different thicknesses of 25mm and 50mm. Further graphs with a wider range of insulation thicknesses are also included in the appendix (25-32). For example, the 50mm thick pyrogel insulation battery pack shown in figure 8 required a power of 8.22W, which equated to 32 W/m2/cell. This means that the back-up battery could provide heat for 121.7 hours, it may not be necessary for it to last this long when taking other considerations into account as it is a very large amount of time. Figure 9 shows the heating of the 50mm thick Mikroporous Aerogel battery pack, it shows similar results to the Pyrogel XT with the power required being 7.97W, which is 31W/m2/cell. This means that for this model the back-up battery could last for 125.5 hours, which is marginally better than the same thickness of Pyrogel XT insulation. Figure 10 and 11 presents the Pyrogel XT and the Mikroporous Aerogel at 25mm thickness. There was more power required for these models, the Pyrogel XT required 11.8W and the Mikroporous Aerogel required 12.08W. This means that the back-up battery would last for 84.7 hours and 82.8 hours repectively. This shows that the Pyrogel XT was the better performing insulation at this thickness, whereas it didn’t perform as well at 50mm thickness. However, the results from both are reasonably similar as the insulation materials have similar thermal properties. The results also visualises that the amount of time that the back-up battery can provide heat is still very high for the thinner insulation. This means that although it is favourable for an increased length of time, a thinner insulation could be still be suitable. This is important as another part of the project involves the battery running at high power, which could cause the temperature to become too high. Therefore, a balance needs to be found between keeping the battery hot for a long time when out of operation, and ensuring the temperature does not rise too high during operation. By viewing the appendix (figures 23 and 27) it can be seen that even with the thinnest insulation thickess of 10mm applied, the 1kWh battery can provide heat to the battery pack with Pyrogel XT insulation for 51.8 hours. This is still a considerable amount of time which would suit consumers, by reducing the reliance on start-up power.

From viewing the results taken from the simulation that is shown in figure 8, the average heat flux was found to be 32W/m2 on the outer surface when the core of the battery was at 160℃. The power required to maintain 160℃ temperature can be found by multiplying the heat flux and the area of the pack with 50mm thick insulation applied:

(192 x 192 x 2) + (192 x 238 x 4) = 256,152mm2 = 0.257m2

32 x 0.257 = 8.22W

(For reference the area of the pack without insulation applied is:

(92 x 92 x 2) + (92 x 138 x 4) = 67, 712mm2 = 0.0677m2)

From this the value the power required to be applied between each individual cell can be found. This can be done by dividing the value, firstly, by the number of cells (28) and then by the area of one cell face (0.00864m2). This methodology of discovering the power required between each cell from the overall power of the pack is the same for all of the models, as they all have 28 cells and the area of each cell is the same for all of the models.

**Fig 8:** The cooling time of 50mm thick pyrogel insulation with heaters applied to maintain the 160℃ temperature for 438120s.

The area of the pack shown on figure 9 is the same as the pack used for figure 8, which is 0.257m2.

The average heat flux for this model was taken as 31W/m2. Therefore the power of the pack can be found:

31 x 0.257 = 7.97W

**Fig 9: T**he cooling time of 50mm thick microporous aerogel insulation with heaters applied to maintain the 160℃ temperature for 451694s.

The area of the model in figure 10 is:

(142 x 142 x 2) + (142 x 188 x 4) = 147,112mm2 = 0.147m2

The average heat flux taken for this model was 80W/m2. Therefore the power of the pack can be found:

80 x 0.147 = 11.8W

**Fig 10:** The cooling time of 25mm thick Pyrogel XT insulation with heaters applied to keep the temperature at 160℃ for 30,4517s.

The area of the model in figure 11 is the same as the model shown in figure 10, which is 0.147m2.

The average heat flux for this model was taken as 82.3W/m2.

Therefore the power of the pack can be found:

82.3 x 0.147 = 12.1W

**Fig 11:** The cooling time of 25mm thick Mikroporous Aerogel insulation with heaters applied to maintain the 160℃ temperature for 298037s.

50W was applied across the battery pack to gain an idea of the temperature distributions during periods of high power usage. Table 2 shows the final temperature of all the models after 50,000 seconds with the increased power supplied. It shows that the temperature rose significantly, with the majority of the models rising above the maximum operating temperature of 300℃. For example, the Mikroporous Aerogel and the Pyrogel XT at 10mm thickness rose to 356.6℃ and 348.1℃, respectively. Other types remained below the operating temperature limits with a thinner insulation being applied, with the majority being below 300℃ at 15mm thickness. The results from table 2 provided useful information regarding the temperature distributions of models running at high power. However, this would usually occur for less time than 50,000 seconds. Therefore, results were extracted from the simulations to show the battery running at high power for around 5000 seconds, which is a more common amount of time for this to happen. These results are presented in figure 12 and 13, and they show the heating of the four best performing insulation types at 50mm and 25mm thickness. Figure 12 shows that the 50mm thick insulation models heated up quickly, but they all remained below the 300℃ mark, which is the aim for this part of the project. The Pyrogel XT rose to 246℃ after 4989 seconds and the Mikroporous Aerogel rose to 243.8℃ after 5090 seconds, this shows that the two insulation types at the same thickness performed similarly when heating due to increased power. The Ceramic Fibre Board – HP and the Calcium Silicate Board also performed in a similar way, with the final temperature being 225.2℃ and 226.1℃ after the 5000 seconds. Figure 13 shows results from the same type of model but with the insulation thicknesses at 25mm. It shows a similar trend in results with the Pyrogel XT and Mikroporous Aerogel temperature being 238℃ and 236.2℃ after 5000 seconds of heating with the added power. The Ceramic Fibre Board and the Calcium Silicate Board had risen to 212.1℃ and 214.3℃ after 5000 seconds. The results for the battery running at high power show that it could be more suitable to use a thinner layer of insulation, as it is not favourable to risk the battery temperature rising too high. Although the battery would not usually run at high power for an extended period of time, it is possible that these periods could last for longer than 5000 seconds. Therefore, as a precaution it is important to ensure that the temperature does not rise too quickly, by making sure the insulation material of choice are applied at a suitable thickness.

**Table 2:** Shows the final temperature after 50W are applied between each cell of every model for 50,000s, with varying insulation types and thicknesses.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  | **Insulation Thickness (mm)** | |  |  |  |  |
| **Insulation Type** | 50 | 40 | 35 | | 30 | 25 | 20 | 15 | 10 |
| **Aluminium Silicate** | 352.8 | 321 | 308.9 | | 292.8 | 276.3 | 259.6 | 237.3 | 216.8 |
| **CFB-V** | 375.7 | 342.7 | 330.1 | | 312.3 | 294.4 | 275.5 | 249.8 | 225.9 |
| **CFB-HP** | 451.7 | 410.6 | 394 | | 371.3 | 348 | 322.4 | 287.1 | 253 |
| **CFFB** | 280.6 | 259.8 | 252.6 | | 242.1 | 231.7 | 222 | 207.9 | 195.8 |
| **Calcium Silicate** | 467.4 | 423.8 | 405.4 | | 381.1 | 356.5 | 329.5 | 292.7 | 257.1 |
| **Microporous** | 667.6 | 614.7 | 591 | | 562.6 | 524.3 | 484.2 | 422.4 | 356.6 |
| **Pyrogel XT** | 655.9 | 602.1 | 578.8 | | 546.6 | 509.7 | 469.3 | 412.7 | 348.1 |
| **Silica Sol Gel** | 388.9 | 354.1 | 340.7 | | 322.4 | 303.1 | 283 | 255.8 | 230.3 |
| **Superwool** | 417.3 | 377.2 | 361.7 | | 340.4 | 319.3 | 296.7 | 266.3 | 237.8 |
| **Vermiculite** | 445 | 400.9 | 383.8 | | 361 | 337.2 | 312.1 | 278.2 | 246.6 |
|  |  |  | **Battery Core Temperature (℃)** | | | |  |  |  |

**Fig 12:** A graph that shows the model heating up with 50W applied between each cell of the 50mm thick insulation model to simulate the battery running hard.

**Fig 13:** A graph that shows the models heating up with 50W applied between each cell of the 25mm thick insulation model.

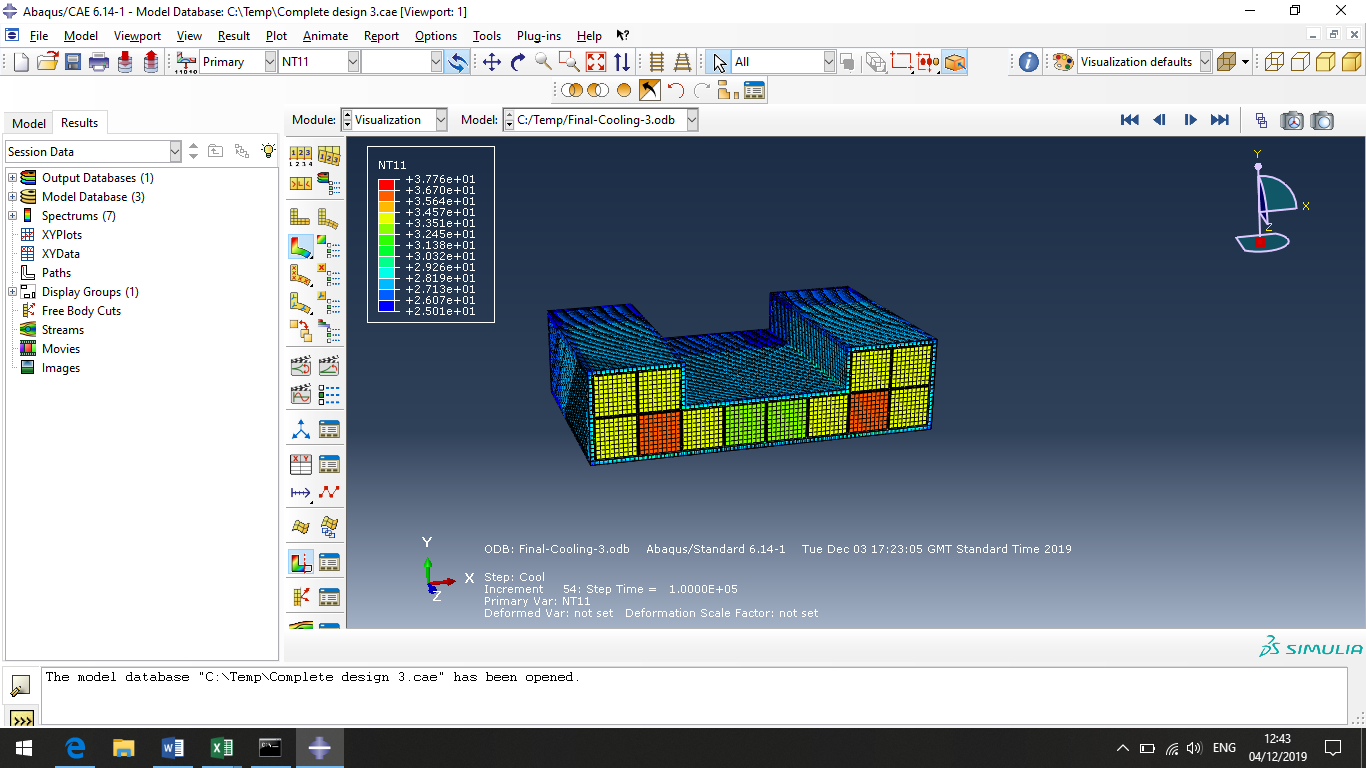
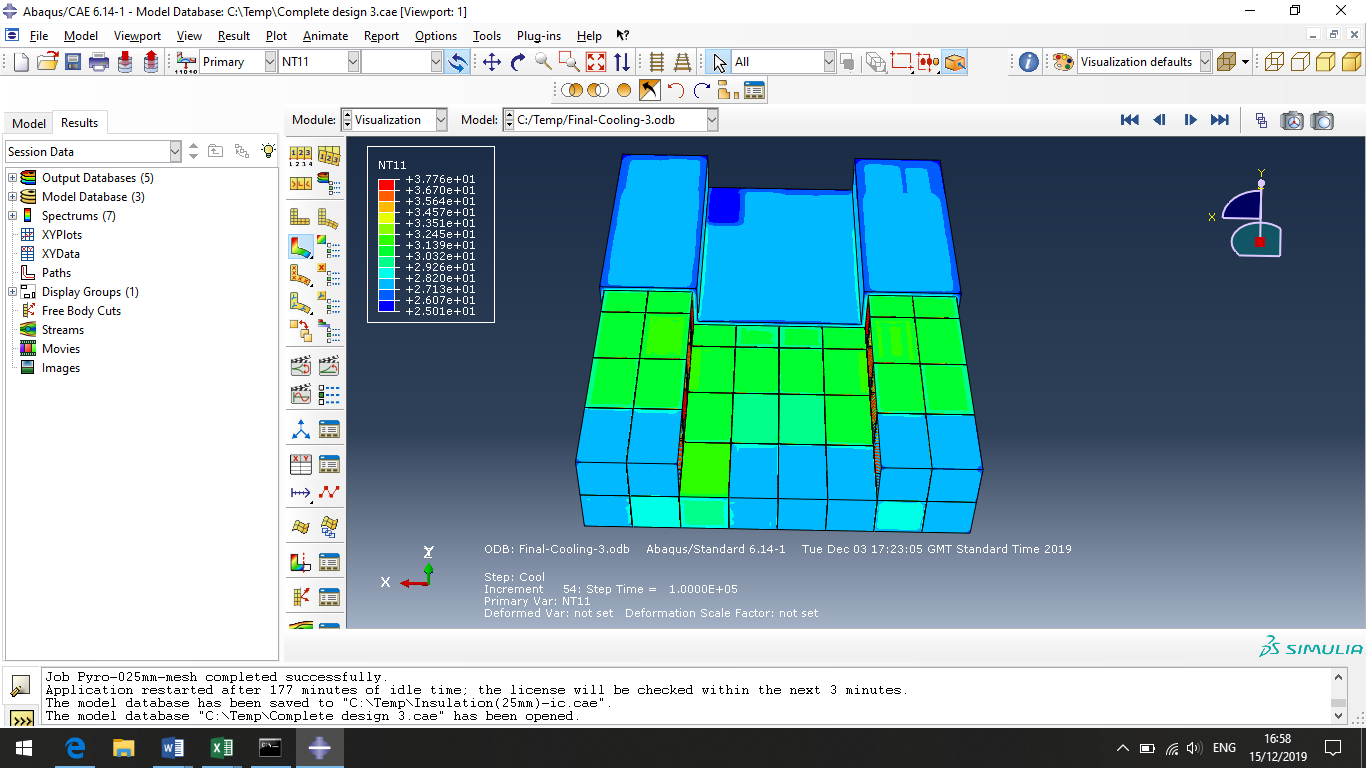
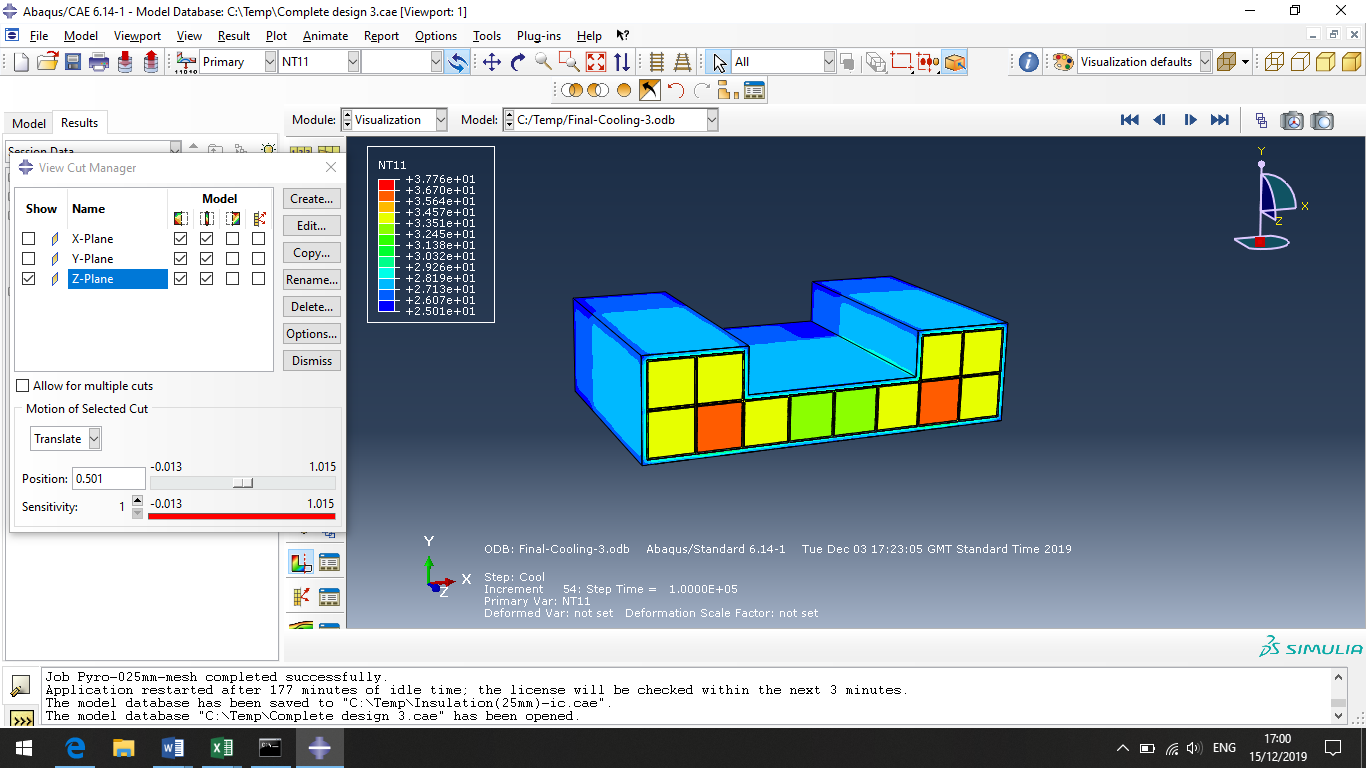
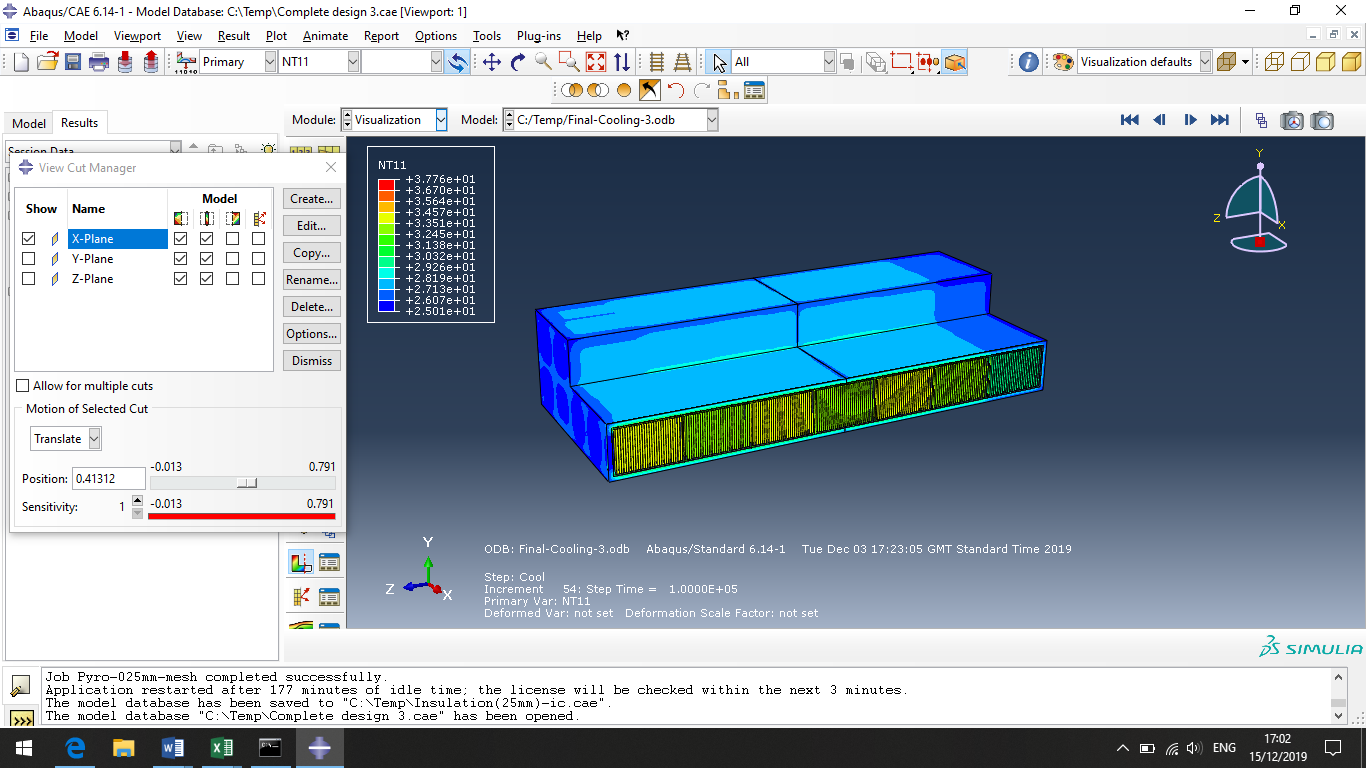
Figure 14 shows a comparison between the cooling of the 25mm thick Pyrogel XT insulation individual cell model, with the changing factor being the mesh size. This shows that there was little difference between the temperature of the models as the mesh size was changed. This varifies the choice of mesh size for this project, which was 1mm. Various insulation was applied to the models shown in figure 4. They were applied at thicknesses ranging from 10mm to 50mm, increasing by 5mm with each step. The mesh size applied to the models was set at 1mm, which proved to be suitable. Figure 14 shows a graph that represents the cooling times of the battery pack with 25mm thick Pyrogel XT insulation, with the difference between the results being the changing mesh size. It shows that the smaller mesh sizes of 0.5mm and 0.25mm provided very similar results to the 1mm mesh. Having a smaller mesh size means that the accuracy of the results are increased, therefore figure 14 was put together to validate the choice of mesh for the project (Yucheng, 2013). Having a decreased mesh size also causes the length of time for simulations to be completed to increase. Therefore, since the 1mm mesh provided accurate results, it was necessary to save time by avoiding the use of a smaller mesh.

**Fig 14:** This shows the cooling of 25mm thick Pyrogel XT insulation models with different mesh sizes, at 1mm and 0.5mm and 0.25mm.

As the project developed, it was an aim to combine individual battery packs into a system that could be suitable for an industry. The industry chosen for this was the electrical vehicle market, which is one of the main big industries that benefits from the improvement of battery storage technology. The design and dimensions of the system are shown in figure 15 and 16. The design is based on the Nissan Leaf, where the system fits beneath a vehicle with extra battery packs below the passenger seats, and also space in the middle for passenger leg room. The layout of the Nissan Leaf electricity storage system is shown on figure 18 (Hearn, 2019). This design allows the system to contain a large amount of battery packs, the system design in this project brought together 84 packs, which allows for a considerable amount of electricity storage. As well as this, it doesn’t take up too much space in the vehicle, which is an important feature. It was thought that the layers of thin insulation around individual battery packs, all surrounded by another thin layer of insulation would perform well in insulating the system. It was important to maintain the temperature of the individual battery packs so that the whole system was within the operating temperature limits, and therefore the system was in full operation. Figure 17 shows the battery system cooling for 100,000 seconds. It shows that the insulation performed reasonably well, with the average temperature taking around 18,000 seconds (5 hours) to fall to 160℃. This is similar to the amount of time that the individual battery pack with 15mm Pyrogel XT insulation took to cool to this temperature. This specific model required 15.4W of energy to maintain the 160℃ temperature of the battery pack, which means a 1kWh back-up battery could provide heat for 64.8 hours. It is likely that each battery pack in the electric vehicle system would require a similar amount of power, therefore, with heaters applied the battery system would remain at a high temperature for a large amount of time. Figure 17 does however use an average temperature of the system to create the graph, as the temperature varies between different parts as can be seen in figure 14. This temperature variation means that the power required to maintain 160℃ would change between various battery packs. It would be beneficial for heaters to be set to begin heating individual battery packs when the temperature of each has fallen to 160℃, this would help to ensure that the temperature distribution is even throughout the system. The power required for each pack to keep the temperature at 160℃ will change marginally, it would be ideal if the system could automatically provide the required heat to each pack at the point of time that it is needed.

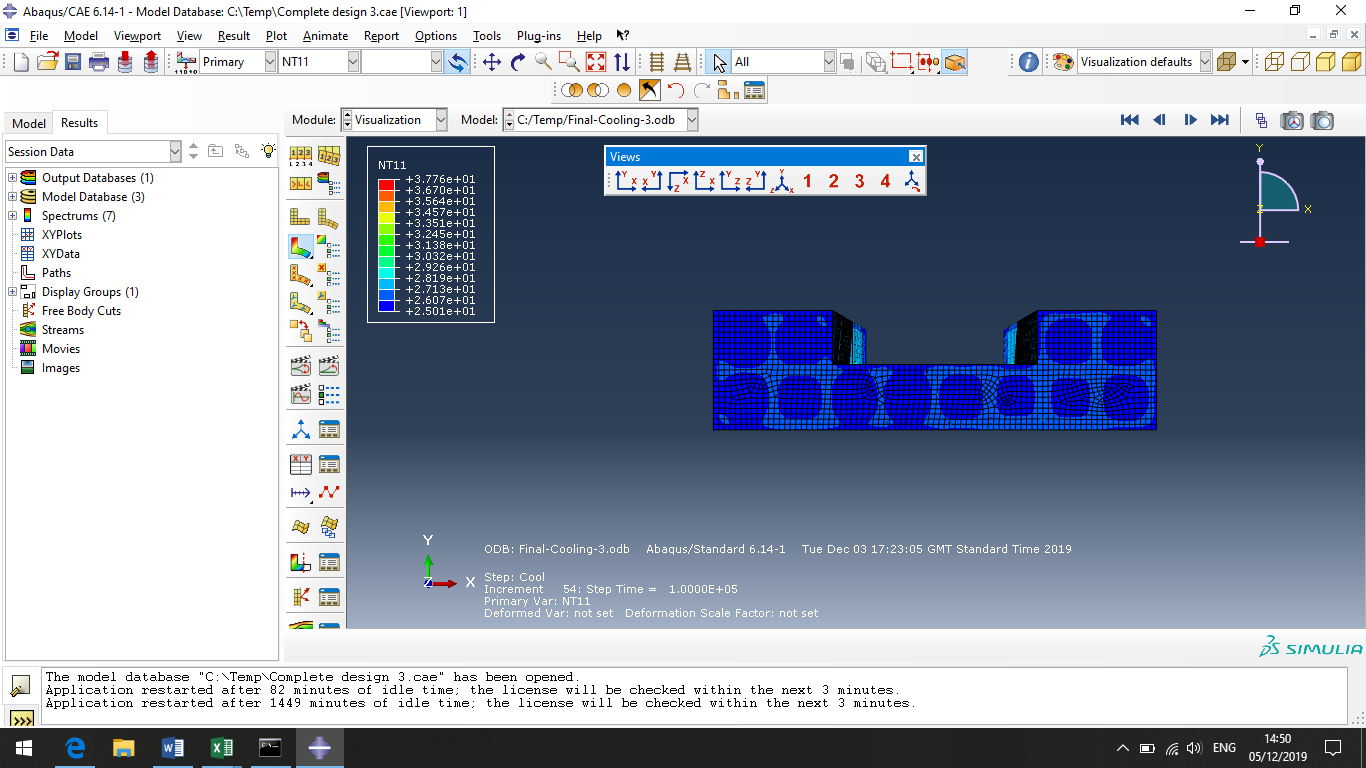
**(a)**

**(b)**



**(c)**

**Fig 15:** (a) The temperatue rainbow plot of the battery system with half of the outer layer of insulation removed. (b) The temperature rainbow plot of the battery system split in the x-axis direction. (c) The temperature rainbow plot of the battery system split in the z-axis direction. The temperature values of the rainbow plot is also presented in ℃ (right).



**804**

**216**

**372**

**216**

**98**

**Fig 16:** The 2D dimensions of the battery system (mm), with a volume of 1038mm.

**Fig 17:** The average cooling time of the battery system with Pyrogel XT insulation applied.



**Fig 18**: The Nissan Leaf battery arrangement.

1. **Conclusion**

The first set of results from the project allowed conclusions to be made regarding the insulation of the battery. From early on in the project, it became clear which insulation materials performed at the best level. It was visualised from the results, as shown in figures 5 – 7, that the best performing insulation materials were the Pyrogel XT and the Mikroporous Aerogel. This was expected due to the gel materials having the lowest thermal conductivity of any known solid (Thermaxx Jackets, 2019). Other insulation materials with a good performance, as shown in figures 5 -7, included the Ceramic Fire Board – HP and the Calcium Silicate Board. The results from early in the project helped to decide which insulation materials would be the best for applying to the LiNa battery system. Although all of the simulations were run with a wide range of insulation materials, as the project developed it was necessary to include results for the few materials with the best performance. For example, figure 5 shows that the E-Glass Fibre was not as good of an insulator compared to other materials. This lead to the conclusion that it would not be suitable for the project, so the results from the E-Glass simulations were not included in the following figures. Instead, the figures concentrate on the better performing insulation types that are likely to be involved in the design of the LiNa battery. The results from this project show that the four most suitable insulation materials for the LiNa battery are the Pyrogel XT, Mikroporous Aerogel, Ceramic Fibre Board- HP, and the Calcium Silicate Board.

It is favourable for the insulation to be thinner in a battery system, so that it doesn’t take up a large amount of space in a vehicle or in any other applications that the LiNa battery could be used for. Therefore, it is important that the choice of insulation for the project performs as well as possible, so that a thinner layer could be used, whilst still maintaining a good amount of heat. The preferred insulation material that was applied to the the final battery system design was the Pyrogel XT. It had a very good performance, and also the company that produces the insulation provided the thermal conductivity at different temperatures. This meant for more accurate results in comparison to the Mikroporous Aerogel, which also performed very well. Pyrogel XT is also a robust material that has high electrical resistance, which makes it a good choice of insulation for this application (Thermaxx Jackets, 2019).

The results shown in figures 8-11 show the graphs of the cooling of the battery packs; heaters were applied once the temperature fell to 160℃ in order to maintain this temperature for as long as a 1kWh back-up heater battery can provide the heat for. The results show that the heater battery lasts a considerable amout of time even with the thinner insulation applied. For example, figure 10 shows that the Pyrogel XT insulation at 25mm thickness could be heated for 304,517 seconds (84.6 hours) by the 1kWh battery. Furthermore, within the appendix (figure 22) are the results for the 10mm thick Pyrogel insulation, the 1kWh battery could provide heat for 186,528 seconds (51.8 hours). This is much more than the minimum amount of time required, and means that the battery could be left for days whilst being readily available for ignition. The back-up heater battery would be recharged whilst the main battery system is in operation, which means it doesn’t require extra electricity for heating. This is an important feature when considering the environmental impact this type of battery has in comparison to others. Since the back-up battery can provide heat for such a large amount of time, it shows that it may not be necessary to apply a thick layer of insulation to the battery packs, especially when taking into account scenarios such as the battery running at high power. The results gained from the simulations with heaters involved in the design are for individual battery packs. This provides a good understanding of the amount of power required for each pack, this can be scaled up into a group of packs to gain an idea of the amount of power required to heat a battery system.

Figure 13 shows the final temperature of models that have been running at a high power of 50W for 50,000 seconds. Judging by this figure, the majority of insulation materials and thicknesses woud have caused the temperature of the models to rise by too much. However, a battery would not usually run hard for this length of time. Therefore, the figures 12 and 13 presents some of the models heating due to running hard for a more regular time of 5000 seconds. Figure 12 shows the results with the most thick insulation of 50mm, the temperature of the core of the battery remained comfortably below 300℃ after 5000 seconds of running at high power. This revealed that the battery system should remain functional in periods of power fluctuations, especially with a thinner insulation being applied. It is however important that the system does not run at high power for an extended period of time, because there is a risk of the temperature rising above the maximum operating temperature. By studying the results, it can be concluded that a thinner layer of insulation would be favourable for the final system. As the heaters could maintain the 160℃ temperature for a good amount of time even with a thinner insulation applied, so it was not of upmost importance for the insulation to maintain heat for too long. Furthermore, the risk of the battery temperature rising too high during periods of the battery running at high power was less with thinner insulation applied. It was also favourable that the system would take up less space with less insulation. The design of the insulation of the final system had a thin 3mm layer of insulation around each individual battery pack, with another thin 10mm layer of insulation surrounding the whole system. The rationale behind this was to ensure that the temperature distribution was fairly even across the battery system. The results from figure 17 show that the insulation system worked well, by preventing the temperature from falling by too much for a good length of time. It was, however, hard to avoid some temperature variation between different parts of the system. This issue could be resolved by the use of heaters, which would heat individual battery packs in the system once the temperature falls to 160℃, when the battery is not in operation. This would ensure that the risk of battery packs falling below 160℃ would be very low, meaning the whole system can be in operation.

This project focuses on the thermal analysis of the LiNa battery. Although the high operating temperature of the LiNa and Zebra batteries can be seen as a disadvantage, the results go towards showing that it could be suitable in replacing other rival batteries in the industry such as lithium-ion (Zyl, 1996). The LiNa battery requires little additional energy to allow the system to run. The primary occasion for which it would require additional energy is when the battery is being heated to reach 160℃, as shown from the results this would only be necessary when the battery had been out of operation for numerous days. The majority of electric vehicles would be in operation for the majority of days, depending on the owner. Therefore, it is not often that the LiNa battery would require additional energy, which is an important feature in regards to the battery being eco-friendly. The LiNa battery has energy density and efficiency that is compareable to lithium-ion batteries and can be manufactured with relative ease. The materials involved in the production of the Lina battery are relatively cheap and abundant and the battery can be recycled. Along with the results from this project, this shows that it would be viable competition in the battery market, and there is no reason why the Lina battery couldn’t be implemented into a wide range of industries.

1. **Further Work**

Although the project provides a wide range of results that are useful for the production of the LiNa battery, there is some further work that could have been completed with more time and resources. For example, it would have been an aim to reduce the risk of the battery overheating when it is in operation. A cooling system may have helped to reduce this risk, as it could be used to balance the temperature once it becomes too high. There is an example of a cooling system on a ZEBRA battery pack found in literature, this may be suitable for the LiNa cell, however, alternatives could have been explored (Dustmann, 2004). A cooling system could be introduced by implementing a fan that provides cooler air throughout the system, causing the temperature to be reduced. The air from the fan could be blown through a mesh, this would help to ensure that the battery temperature does not reduce by too much and means that the temperature of the system could be regulated efficiently.

The simulations with heaters on battery packs provided a good idea of the power required to maintain 160℃, however, it could have been useful to add heaters to the design of the final battery system. It might have been beneficial to check whether the power required for each battery pack remained the same, when put together into a system. Due to the temperature variation throughout the system, it is likely that different battery packs would need to be supplied different amounts of power, and would require the power at different times depending on the temperature of each pack. With more time and resources, the heaters could be set to begin heating individual battery packs at the point that they each cool to 160℃. This allows the system to remain within the operating temperature margins, meaning it would be readily available for ignition, which is important to consumers. It could have also been beneficial to figure out the amount of time that the battery takes to heat up to the operating temperature, when it has been out of operation for an extended period of time.

There is a wide range of designs of battery systems in the electric vehicle market and there are positives and negatives attributed to each of them (Erriquez, 2017). Therefore, further work could go towards implementing the Lina battery into other designs, as well as the design based upon the Nissan Leaf. Exploring other options may lead to a final electricity storage system for a vehicle that works more efficiently in maintaining the temperature of the core of the battery packs. The Lina battery is also suitable for more than just the electrical vehicle industry. Similarly to lithium-ion batteries the Lina battery could be used for storing electricity from renewable energy, portable electronics and many more applications. Therefore, the project could have explored battery systems that have applications to other industries.

1. **Appendix**

**Table 3:** Heat transfer coefficients of air at different temperatures. (Richardson C. , 1999)

|  |  |
| --- | --- |
| **Temperature (℃)** | **Heat Transfer Coefficient (W/m2K)** |
| 27 | 3.2 |
| 77 | 3.9 |
| 127 | 4.7 |
| 177 | 5.6 |
| 227 | 6.5 |
| 277 | 7.8 |
| 327 | 9.1 |

**Fig 19:** A graph showing the cooling times of the four best performing insulation materials applied to the battery pack at 10mm thickness.

**Fig 20:** A graph showing the cooling times of the four best performing insulation materials applied to the battery pack at 20mm thickness.

**Fig 21:** A graph showing the cooling times of the four best performing insulation materials applied to the battery pack at 30mm thickness.

**Fig 22:** A graph showing the cooling times of the four best performing insulation materials applied to the battery pack at 40mm thickness.

**Fig 23:** A graph showing the cooling time of the battery pack, with a 1kWh heater battery applied to stabilize the temperature at 160℃. This battery pack has 10mm thick Pyrogel XT insulation applied.

**Fig 24:** A graph showing the cooling time of the battery pack, with a 1kWh heater battery applied to stabilize the temperature at 160℃. This battery pack has 20mm thick Pyrogel XT insulation applied.

**Fig 25:** A graph showing the cooling time of the battery pack, with a 1kWh heater battery applied to stabilize the temperature at 160℃. This battery pack has 30mm thick Pyrogel XT insulation applied.

**Fig 26:** A graph showing the cooling time of the battery pack, with a 1kWh heater battery applied to stabilize the temperature at 160℃. This battery pack has 40mm thick Pyrogel XT insulation applied.

**Fig 27:** A graph showing the cooling time of the battery pack, with a 1kWh heater battery applied to stabilize the temperature at 160℃. This battery pack has 10mm thick Mikroporous Aerogel insulation applied.

**Fig 28:** A graph showing the cooling time of the battery pack, with a 1kWh heater battery applied to stabilize the temperature at 160℃. This battery pack has 20mm thick Mikroporous Aerogel insulation applied.

**Fig 29:** A graph showing the cooling time of the battery pack, with a 1kWh heater battery applied to stabilize the temperature at 160℃. This battery pack has 30mm thick Mikroporous Aerogel insulation applied.

**Fig 30:** A graph showing the cooling time of the battery pack, with a 1kWh heater battery applied to stabilize the temperature at 160℃. This battery pack has 40mm thick Mikroporous Aerogel insulation applied.

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