Evaluating the effect of changes in temperature on Lithium Ion Battery performance.

Research Question: How do different ambient temperatures within their operating range affect the performance of LIBs?

Word Count: 3552

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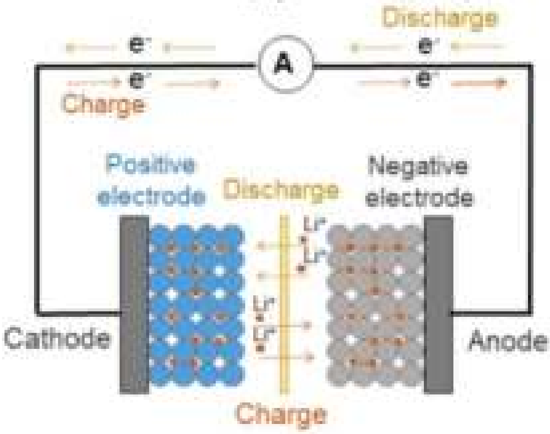
1. Introduction

Lithium-ion batteries (LIBs) are rechargeable batteries with high energy and power densities as well as low self-discharge rates and are therefore used in a variety of applications from electric vehicles to hand-held devices such as cell phones (Østby 6). Temperature significantly affects LIBs thereby playing a vital role in determining their applications. They have an operating temperature range of -20℃ to 60℃ and an optimal temperature range of 15℃ to 35℃ (Ma et al.). This essay will address the effects of ambient temperatures which are close to the boundaries of the operating temperature range on LIB performance.

1.1 Basic Functions of LIBs

An LIB cell contains an anode, a cathode (made of a lithium compound) and a porous separator soaked in electrolyte. The porous separator allows for the exchange of lithium ions between the electrodes while also acting as an insulator, creating electric potential between the anode and the cathode (Østby 9). As a result, LIBs function on an internal and external circuit. The exchange of lithium ions between the anode and the cathode (the internal circuit) and the flow of electrons generated by the resulting oxidation-reduction reactions create the external circuit (Ma et al.). During discharge, oxidation occurs at the anode and lithium ions de-intercalate and are transferred through the separator to the cathode. The resulting electrons from the oxidation reaction are forced into an external circuit since the separator acts as an electric insulator. During charge, the process is reversed and lithium ions instead flow from the cathode to the anode (Fig 1.1).

Fig 1.1 *(Schematic drawing of a typical lithium-ion battery [Researchgate])*



1.2 The Effects of Low and High Temperatures

Temperatures below 0℃ reduce the performance of LIBs. The electrolyte increases in viscosity when exposed to lower temperatures which disrupts the transfer of lithium ions between the anode and the cathode in the internal circuit. Within the electrodes, the diffusion of lithium ions is slowed as well. As the exchange of lithium ions slows, the internal resistance of the battery increases, reducing its performance (Ma et al.).

Operating under high temperatures accelerates ageing in LIBs involving loss of capacity and increased internal resistance. High temperatures cause an increase in the resistivity of the Solid Electrolyte Interface (SEI) layer (Ma et al.).The increased resistivity of the SEI- a layer on the surface of the anode made up of products of reduction of the electrodes that form after four to six charge and discharge cycles- also increases charge transfer resistance in the battery (Barcellona et al.).

In addition, high temperatures increase the degradation rate of electrodes during operation. One of the dangers of operating LIBs at high temperatures is triggering thermal runway–a series of exothermic reactions in the battery that can cause fire and explosion (Ma et al.).

2. Methodology

To evaluate the effects of different ambient temperatures on the performance of LIBs, I will discharge four batteries, cycling between low and high-temperature environments, while measuring current, voltage and surface temperature. A cycle will be defined as a discharge at low temperature, then a charge at room temperature followed by a discharge at high temperature and a charge again at room temperature.

During charge, a UC-4200 everActive battery charger will be used to monitor State of Charge (SOC), internal resistance and time taken to charge.

2.1. Diagrams of Experimental Set-up

For the low-temperature environment I will be using a household freezer at -18℃ which will provide a relatively stable low temperature.

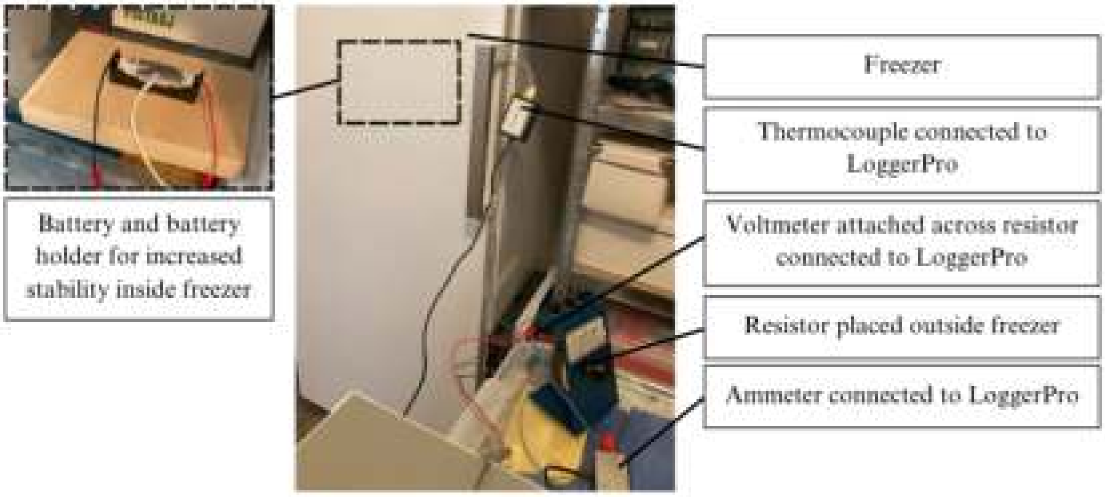


Fig 2.1 *Labelled photograph of experimental set up for discharge at -18°C*

For the elevated temperature environment, I will use a household oven out of lack of a better device. Unfortunately, the temperature inside the oven is unstable.

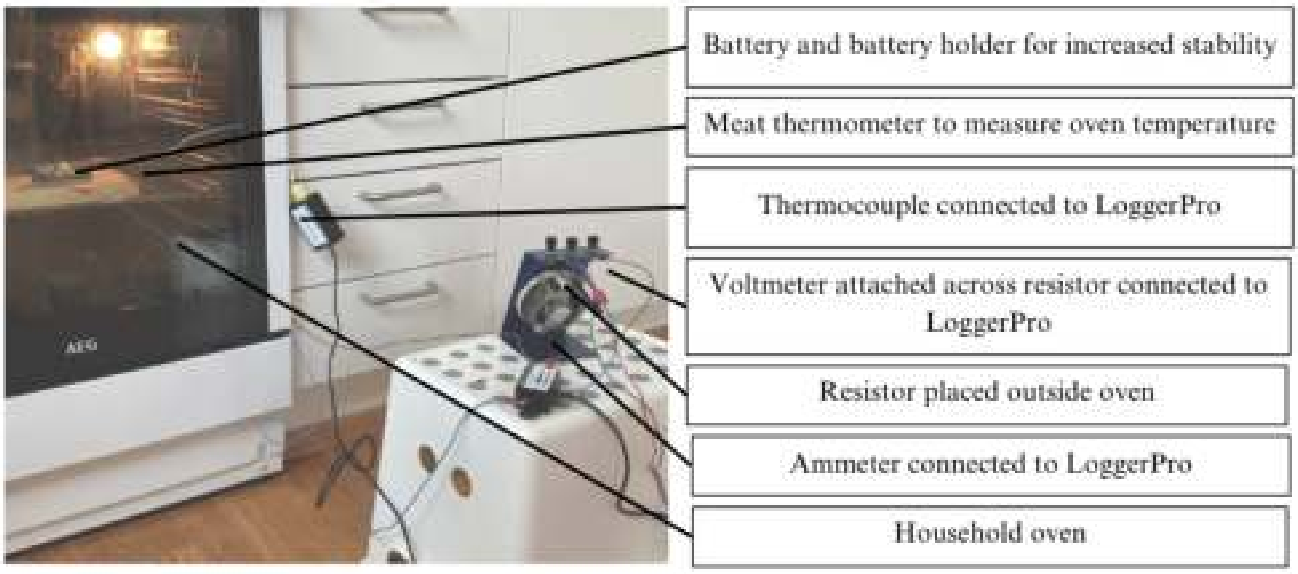


Fig 2.2 *Labelled photograph of experimental set up for discharge at 50 °C*

2.2. Measurements and Data Collection

During discharge three variables will be measured continuously with probes connected to the graphing software LoggerPro: voltage across the resistor using a voltmeter, current using an ammeter and the surface temperature using a thermocouple attached to the surface of the battery halfway between the positive and negative terminal (Fig 2.3). A measurement will be taken automatically every second and at $time\ =\ 0$ in order to track any sudden variations if they might occur. The internal resistance of the battery will be recorded twice: at the beginning and end of charge. In addition, the time taken to charge the battery and the state of charge of the battery after discharge will also be collected to determine whether the rate of discharge and charge are affected by temperature.

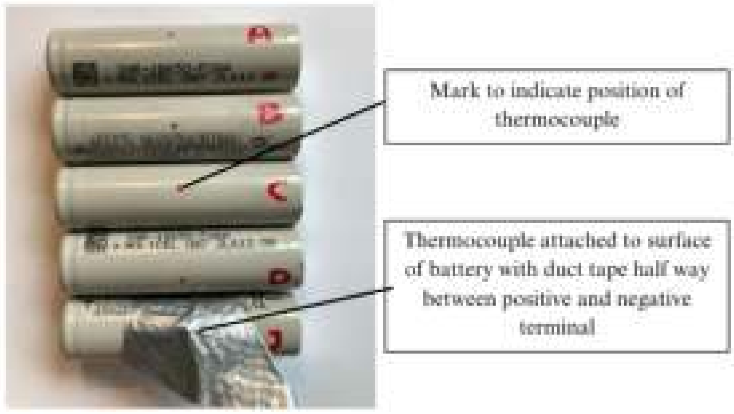


Fig 2.3 *Labelled photograph to indicate positioning of thermocouple on battery surface during discharge*

During discharge in the oven, ambient temperature will be recorded manually every five minutes using a meat thermometer. To measure the uncertainty of the meat thermometer, water was brought to a boil and the difference between the temperature displayed by the thermometer and 100℃ was recorded as the uncertainty. Although not ideal, the process allowed an estimation of the uncertainty.

2.3. Resistance

The LIB used in this experiment is an 18650 rechargeable lithium-ion battery with a capacity of 1.1 Ah and a voltage of 3.6 V. A discharge rate of 1C means that the battery is discharged from 100% to 0% in one hour. For a discharge rate of 1C, the resistor would have to be approximately 3 Ω (rounded to the nearest Ohm).

$V = 3.6,\ I = 1.1$

$R = \frac{V}{I} = \frac{3.6}{1.1} \approx 3\ \Omega$

The resulting circuit is therefore shown in Fig 2.4.

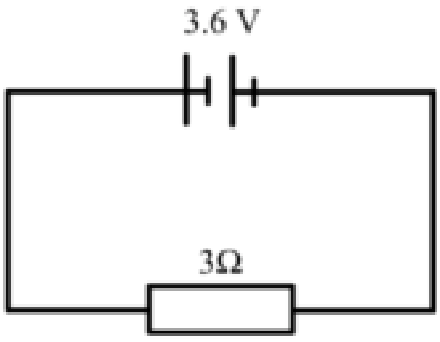


Fig 2.4 *Circuit diagram for experimental set up*

To ensure that the resistivity of the resistor is not affected by the high or low-temperature environments, it will be placed outside the oven and freezer.

The resistance of the copper wires is very low compared to the 3Ω resistor therefore it will not be taken into account in this experiment.

2.4. Temperature

To measure the effects of changing temperatures on lithium-ion battery performance, the experiment will use temperature cycling. The maximum and minimum temperature specified in ISO 12405-1:2011- an industry standard used for testing lithium-ion battery packs for road vehicles is 40℃ and -18℃ respectively. However, 50℃ will be used as a maximum temperature instead because it is the minimum temperature of the oven. Despite the 10℃ increase in temperature, it still lies within the operating range for LIBs which extends to approximately 60℃ therefore safety is not affected (Ma et al.).

During charge, the battery will be kept at approximately 23℃ to allow for more efficient charging and to mimic the environment that electric car batteries and mobile phones are exposed to since charging stations are often located indoors. Therefore as the battery is brought from 23℃ ambient temperature into the 50℃ or -18℃ environments to start discharge, it mimics the conditions electric car batteries and mobile devices are exposed to as they exit the charging stations and are moved outside into high or low outdoor temperatures.

That is also the reason why the surface temperature of the battery will not be brought down or up to -18℃ or 50℃ before discharge.

The resulting cycles are shown in Table 1.

Cycle 1	Discharge -18℃	Recharge 23℃	Discharge at 50℃	Recharge 23℃
Cycle 2	Discharge -18℃	Recharge 23℃	Discharge at 50℃	Recharge 23℃
Cycle 3	Discharge -18℃	Recharge 23℃	Discharge at 50℃	Recharge 23℃

Table 1: *Charge and discharge cycles for batteries A, B, C, D during testing.*

2.5. State of Charge

By keeping the SOC of the LIBs between 20% and 80%, battery degradation is minimized (Bal). Therefore the effects of changing temperature are isolated.

I will be discharging the battery by 60% (to keep SOC between 80% and 20%) at a 1C discharge rate.

$0.6 \times 60\, minutes = 36\, minutes$

Therefore the battery will be discharged in each environment for 36 minutes.

Due to equipment limitations, SOC can only be measured during charging. It will be monitored using data from the UC-4200 battery charger where SOC is displayed.

2.6.Control Battery

Five batteries will be tested in total: batteries A, B, C, and D will undergo temperature cycling and battery J will be kept at room temperature (approximately 23 ℃) while undergoing the same number of charges and discharges as shown in Table 1. Therefore comparison can be made to a battery that has not undergone temperature cycling.

3. Results and Discussion

3.1 Voltage over time

Figures 3.1 and 3.2 show the relationship between surface temperature and voltage during discharge for batteries A, B, C and D.

Figure 3.1 shows a strong positive correlation between surface temperature and voltage. As the graph approaches the optimum temperature for LIB performance (15℃ to 35℃), voltage increases and after approximately 15℃ there is a plateau which could suggest that optimum temperature has been reached.

Fig 3.1 *Graph to show the relationship between voltage and surface temperature of the LIBs during discharge at -18 ℃ ambient temperature. Every 60th data point plotted.*

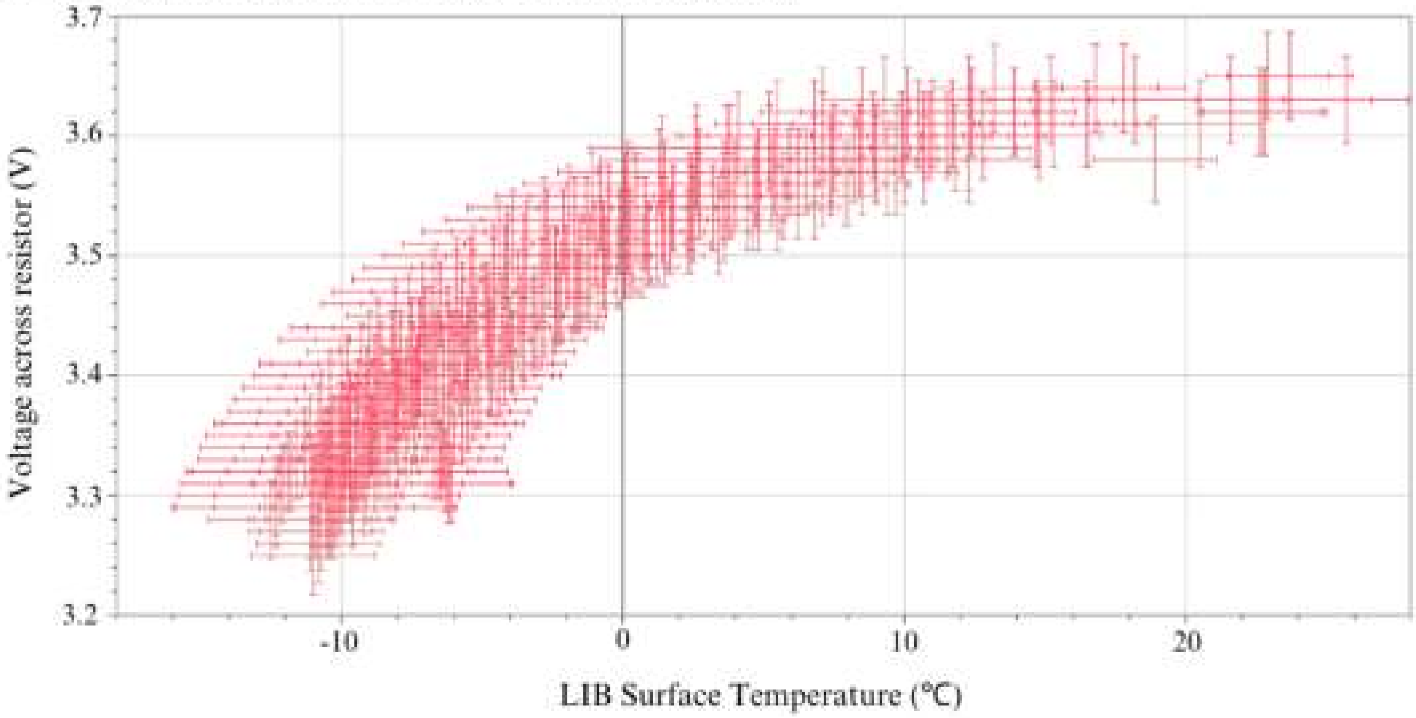


***Fig 3.2** Graph to show the relationship between voltage and surface temperature of the LIBs during discharge at 50 °C ambient temperature. Every 60th data point plotted.*

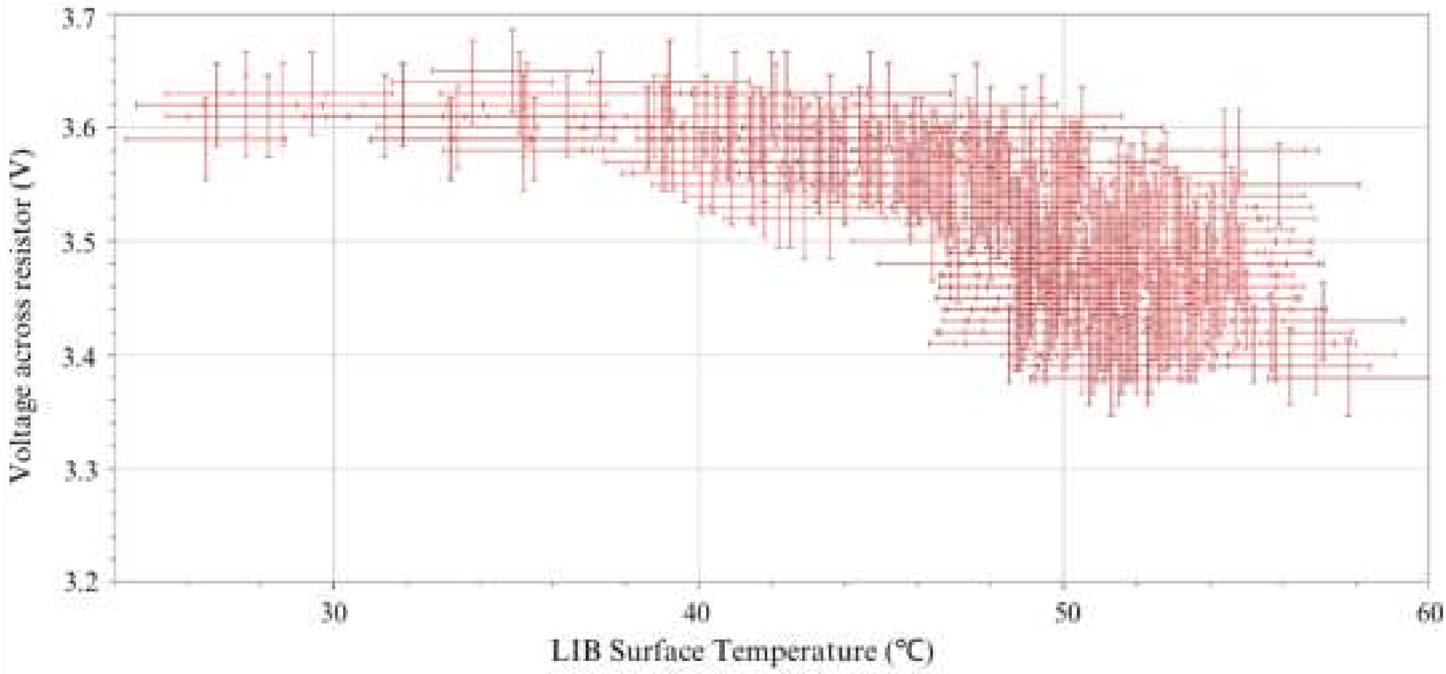
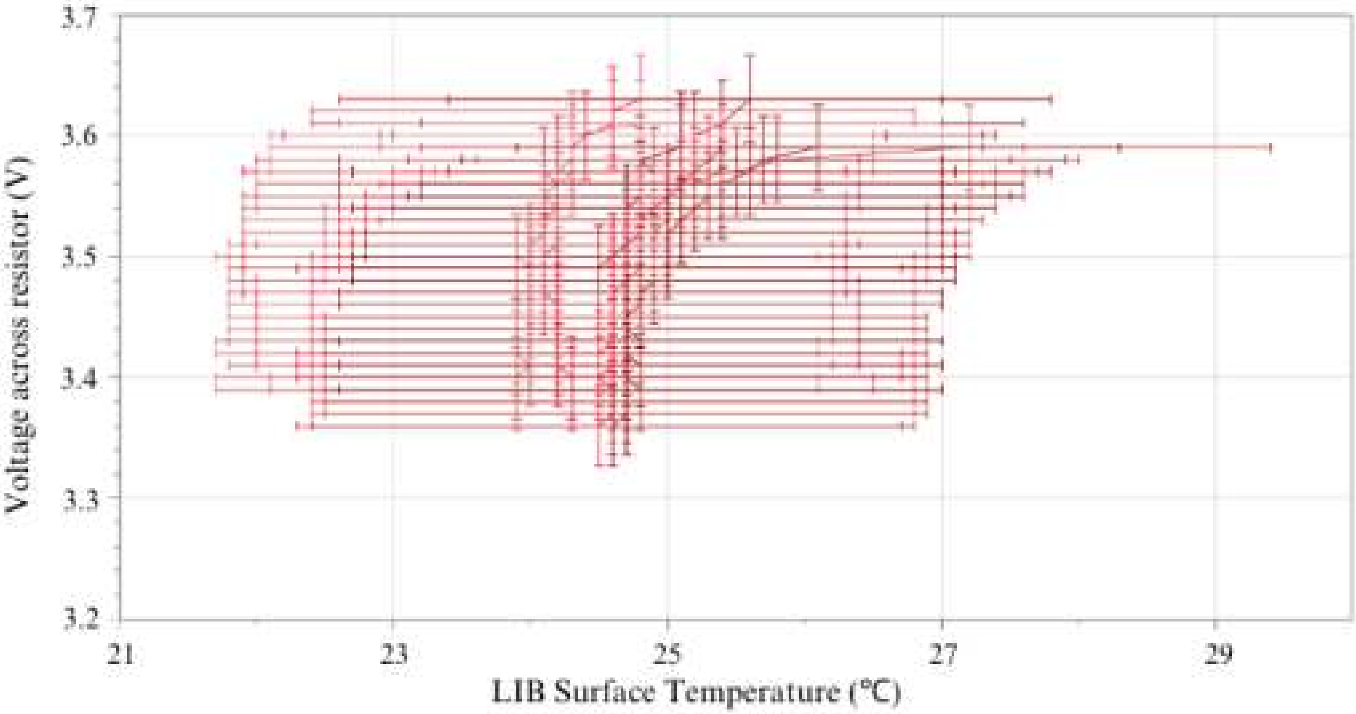


Fig 3.2 shows voltage against surface temperature for discharges at 50℃. There is a plateau until about 25℃ to 40℃ which is approximately the upper range of the optimum temperature. As temperature increases beyond that point, there is a decrease in voltage.

Based on the two graphs above, the graph of voltage at discharge at 23℃ (Fig 3.3) would be expected to be centred around the peaks of both graphs, however, this is not the case.

Fig 3.3 *Graph to show the relationship between voltage and surface temperature of the LIBs during discharge at 23 °C ambient temperature. Every 60th data point plotted.*



The range of voltages (from above 3.6V to below 3.4V) is approximately the same as the range of voltage for discharges at 50℃. This is because of the third variable problem. During discharge SOC decreases. As SOC decreases, the electromotive force of the battery decreases and so does the voltage across the resistor (Fig 3.4). As the battery is placed into the freezer from room temperature, the surface temperature of the battery decreases over time and the opposite is true for when the battery is placed into the oven.

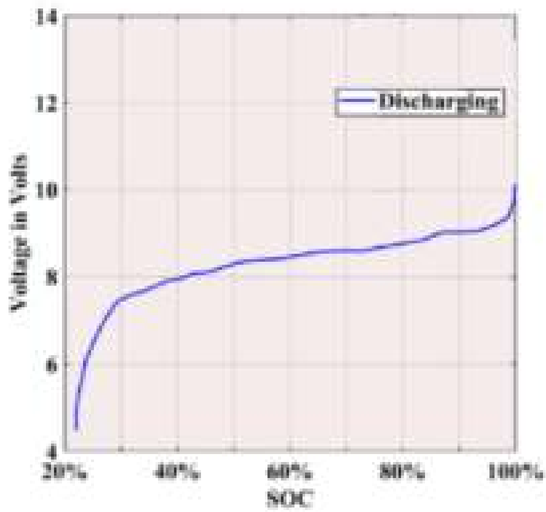


Fig 3.4 *Graph to show the relationship between voltage and SOC of an LIB during discharge at 1C (Voltage and SOC Ratio[ResearchGate]).*

However, a trend can still be observed when comparing the rate of change in voltage at the three different ambient temperatures.

Figures 3.5, 3.6 and 3.7 show the voltage decreases over time during discharge at -18℃, 50℃ and 23℃ respectively.

Fig 3.5 *Graph to show the decrease in voltage at -18℃ ambient temperature over time spent discharging. Every 60th data point plotted.*

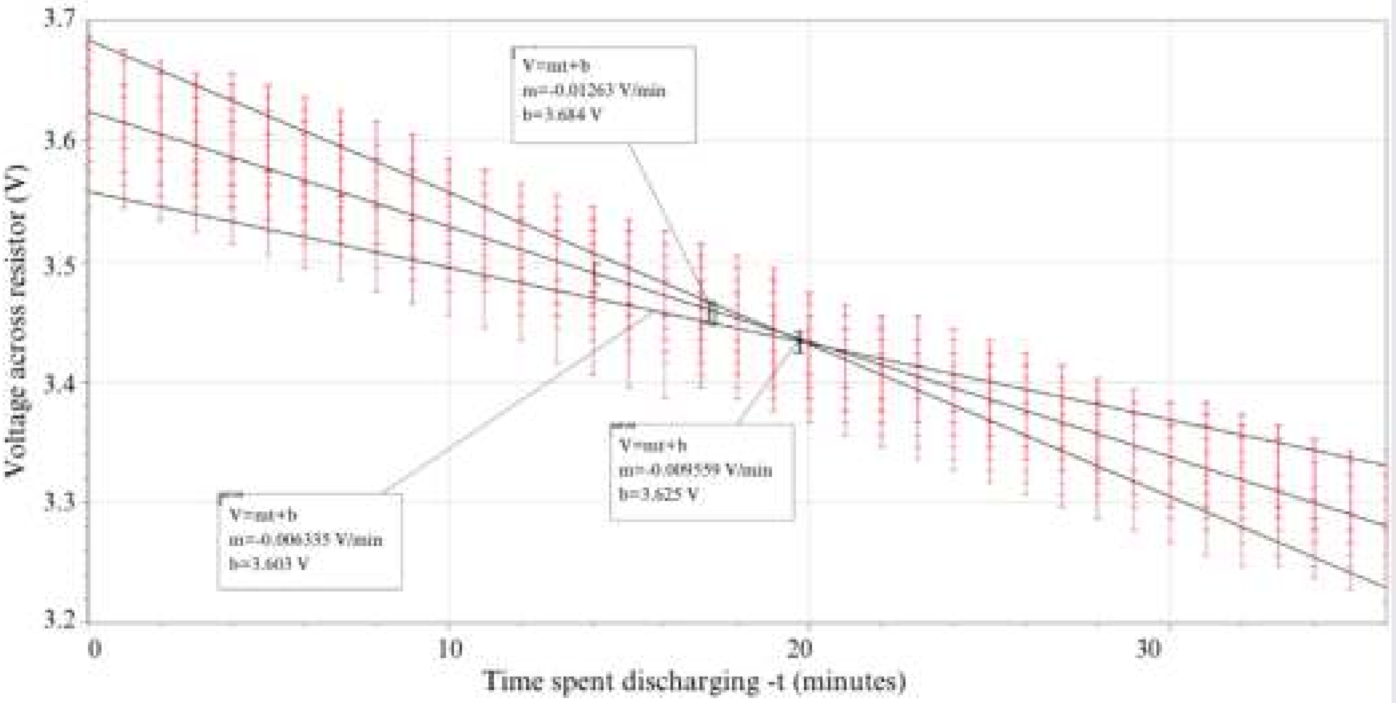


Fig 3.6 *Graph to show the decrease in voltage at 50℃ ambient temperature over time spent discharging. Every 60th data point plotted.*

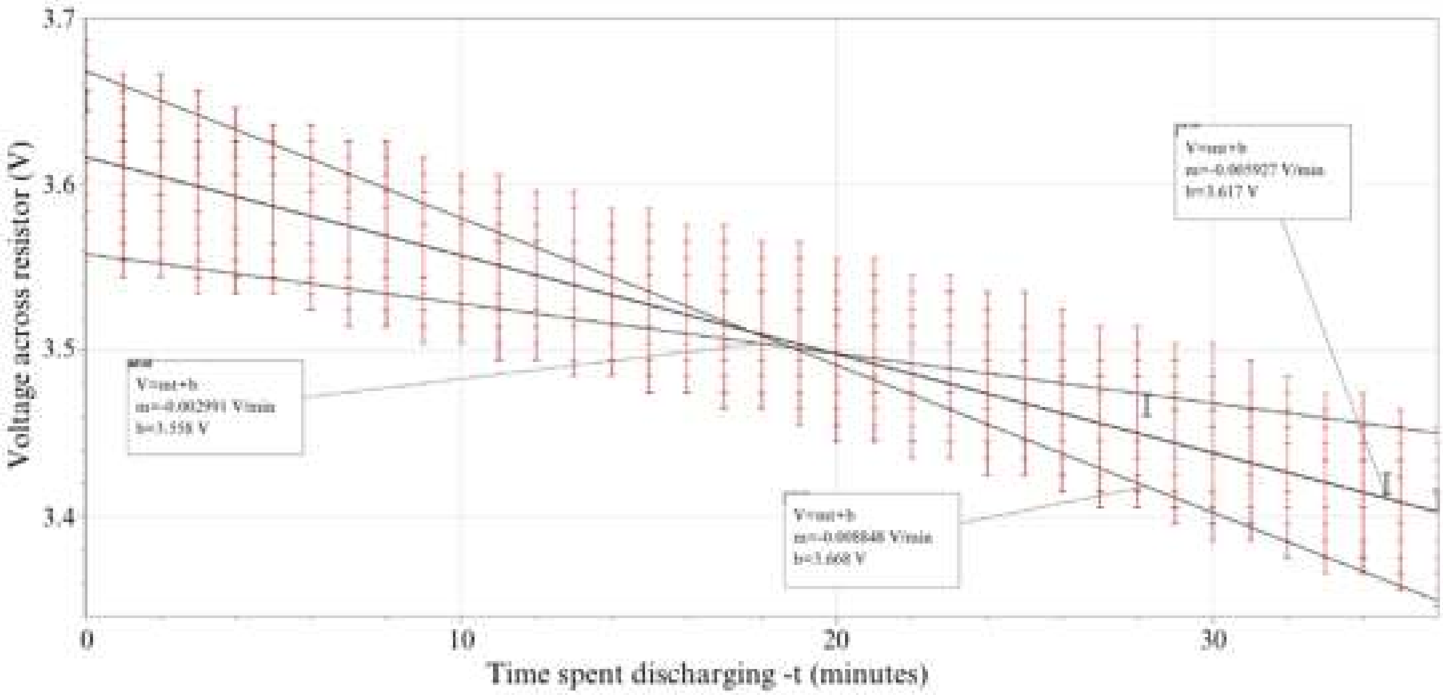
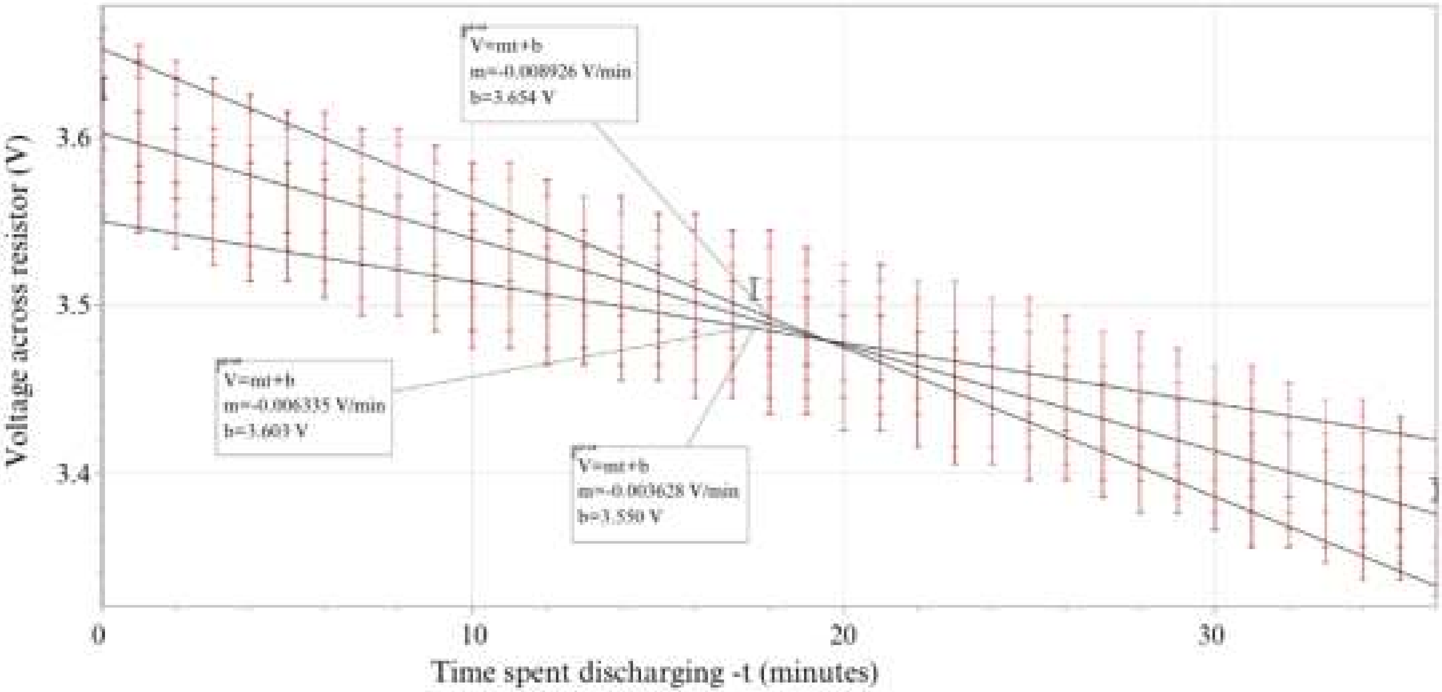


Fig 3.7 *Graph to show the decrease in voltage at 23℃ ambient temperature over time spent discharging. Every 60th data point plotted.*

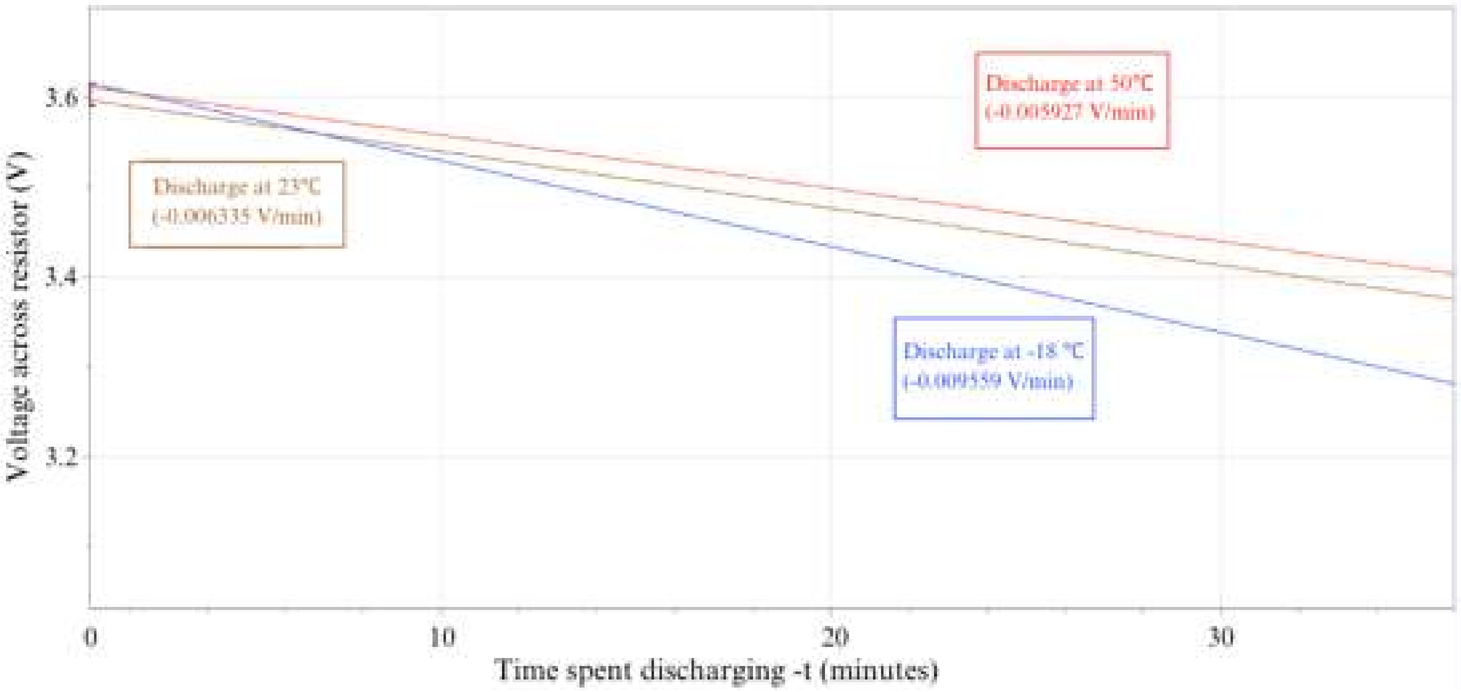


Voltage decreases linearly during discharge.

At -18℃ the rate of decrease over time is at approximately $9.559 \times 10^{-3}\ Vmin^{-1}$. At 50℃ it is 40% lower at about $5.927 \times 10^{-3}\ Vmin^{-1}$. At 23℃ the rate of voltage decrease is around $6.335 \times 10^{-3}\ Vmin^{-1}$ – slightly higher than the rate at 50℃.

Figure 3.8 illustrates the average rate of voltage decrease at all three ambient temperatures.

Fig 3.8 *Graph to show the average rate of decrease in voltage over time spent discharging at -18°C, 50°C and 23°C. Best fit lines from figures 3.5, 3.6, 3.7 are plotted.*



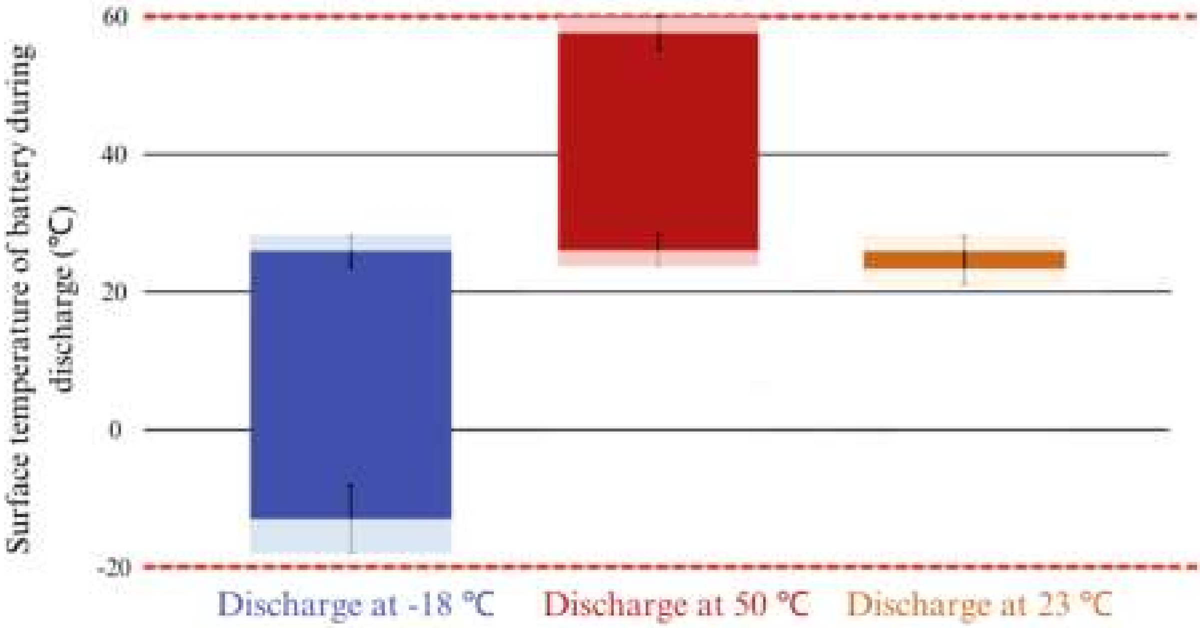
The rate of voltage decrease is significantly higher at -18℃ ambient temperature compared to discharges at 50℃ and 23℃ which suggests that the low ambient temperature caused a more rapid reduction in voltage. Since voltage is the energy in joules transferred by each coulomb, a lower voltage means that less energy can be transferred to other forms during battery use (Johnson et al. 230). Therefore a faster decrease in voltage is a faster reduction in performance suggesting that the battery performs worse at -18℃ than at 23℃ or 50℃.

The linear decrease in voltage for all three ambient temperatures is consistent with the graph in Figure 3.4 for SOCs between 40% and 80%.

3.2 Surface temperature

Figure 3.9 compares the range of surface temperatures recorded during testing to the operating range of the LIBs–between -20℃ and 60℃.

<u>Fig 3.9</u> *Chart to show the range of surface temperatures of battery during discharge at -18°C, 50°C and 23°C ambient temperature compared to its operating range (-20°C– 60°C)*



The surface temperature of the battery during discharge at 50℃ was much closer to the upper limit of the operating range than the lower limit during discharge at -18℃. Despite the lower surface temperatures being further away from the limit of the operating range, they had the greatest effect on the battery's performance. Potentially, the results could suggest that LIBs are more affected by colder temperatures.

The batteries underwent only 3 discharges in a high-temperature environment and 6 discharges total which was not sufficient for the formation of the Solid Electrolyte Interface on the anode. Since the effects of high temperatures are attributed to the increased resistivity of that layer, they may not be visible after such a low number of cycles. On the other hand, low temperatures increase the viscosity of the electrolyte and disrupt the internal circuit of the LIB which can be detected at a low number of cycles.

3.3 SOC and Internal Resistance

No trend was observed between the SOC after discharge or rate of charge (% SOC/min) over the number of cycles. This indicates that there was not an increase in internal resistance due to cycling. The lack of battery ageing is consistent with studies on LIBs such as the "Effect of Temperature on the Aging Rate of Li-Ion Battery Operating above Room Temperature" conducted by Leng et al. In this study, a total of 260 cycles were completed at a 1C rate and the lowest number of cycles chosen to investigate battery ageing was 50 (*2-3*).

Data collected from testing could indicate a temporary difference in the internal resistance of the battery after discharge at -18℃ (Table 2-see appendices). Below is a summary table of the average values of internal resistance taken at the beginning and end of charge after discharges at -18℃, 50℃ and 23℃.

Let $R_{initial}$ be the average internal resistance at the beginning of charge, R_{final} be the average internal resistance at the end of charge, both values rounded to the nearest ohm. Let $\Delta R = R_{final} - R_{initial}$.

After discharge at -18℃			After discharge at 50℃			After discharge at 23℃		
$R_{initial}$ (mΩ)	R_{final} (mΩ)	ΔR (mΩ)	$R_{initial}$ (mΩ)	R_{final} (mΩ)	ΔR (mΩ)	$R_{initial}$ (mΩ)	R_{final} (mΩ)	ΔR (mΩ)
25	7	-18	9	6	-3	5	6	1

Table 3: *Average internal resistances at the beginning and end of charge*

$R_{initial}$ values after discharge at -18℃ were on average 18mΩ higher than the R_{final} which is much higher than the 6mΩ increase after discharge at 50℃ or the 1mΩ decrease after discharge at 23℃.

There are three factors that could be attributed to this effect.

i. The SOC of the battery

SOC was on average 6% lower after discharges at -18℃ (Table 4)

	-18℃	50℃	23℃
Average SOC after discharge	39%	45%	45%

Table 4: *Average SOC after discharge*

The results are consistent with the higher voltage decrease at -18℃ and positive correlation between voltage in SOC shown in Fig 3.4.

The recorded change in internal resistance is too large to be attributed to SOC alone. According to Fig 3.10, there should be a 1mΩ decrease from 40% to 80% SOC but Table 3 shows an 18mΩ decrease between 35% and 80% SOC.

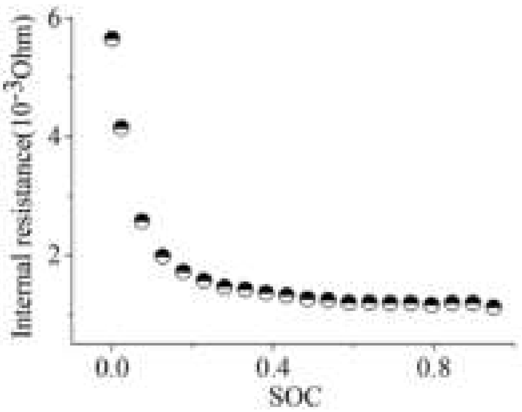


Fig 3.10 *Graph to show the variation in the internal resistance of LIBs due to changes in SOC (Internal Resistance versus SOC [ResearchGate]).*

ii. The effect of low temperature

The large ΔR could be attributed to the low surface temperature of the battery which reaches -13℃. At lower temperatures, rates of chemical reactions are reduced, increasing internal resistance (Barcellona et al.).

iii. The reliability of the measurement device

According to the user manual, users should “not attempt to charge frozen cells” (qtd. in *Professional Battery Charger User Manual UC-4200* 8). As battery surface temperatures reached sub-zero temperatures, the data could be unreliable.

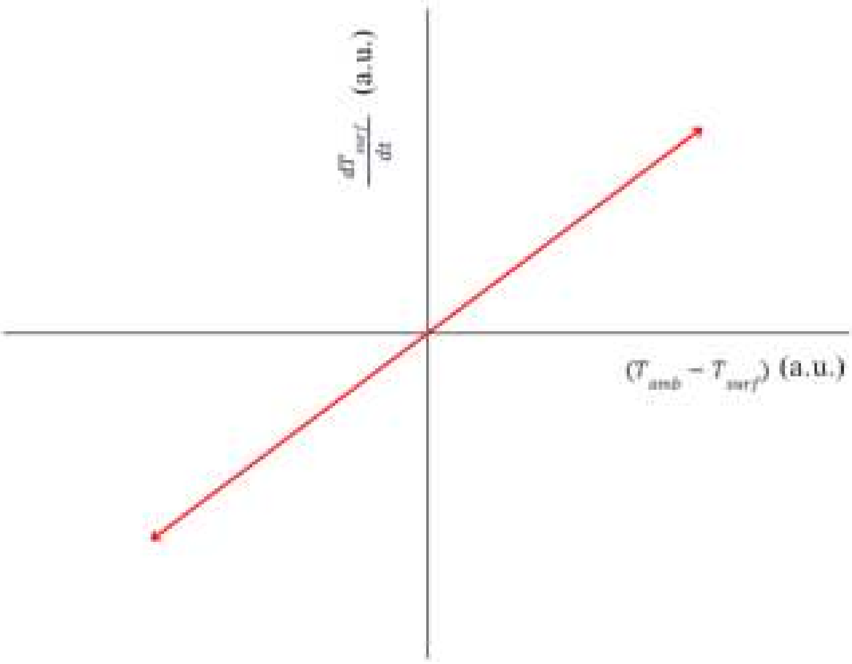
3.4 The effects of ambient temperature on surface temperature

According to Newton’s Law of Cooling, “the rate of change of temperature of an object should be proportional to the difference between the temperature of the object and the ambient temperature” (qtd. in "Newton's Law of Cooling", 00:31-00:42). Applying it to the experiment, it could be written using the following equation:

$$\frac{dT_{surf}}{dt} = k\,(T_{amb} - T_{surf}) \qquad (1)$$

Where T_{surf} is the surface temperature of the battery, T_{amb} is the ambient temperature $\frac{dT_{surf}}{dt}$ is the rate of change of T_{surf} with respect to time and k is the heat transfer coefficient.

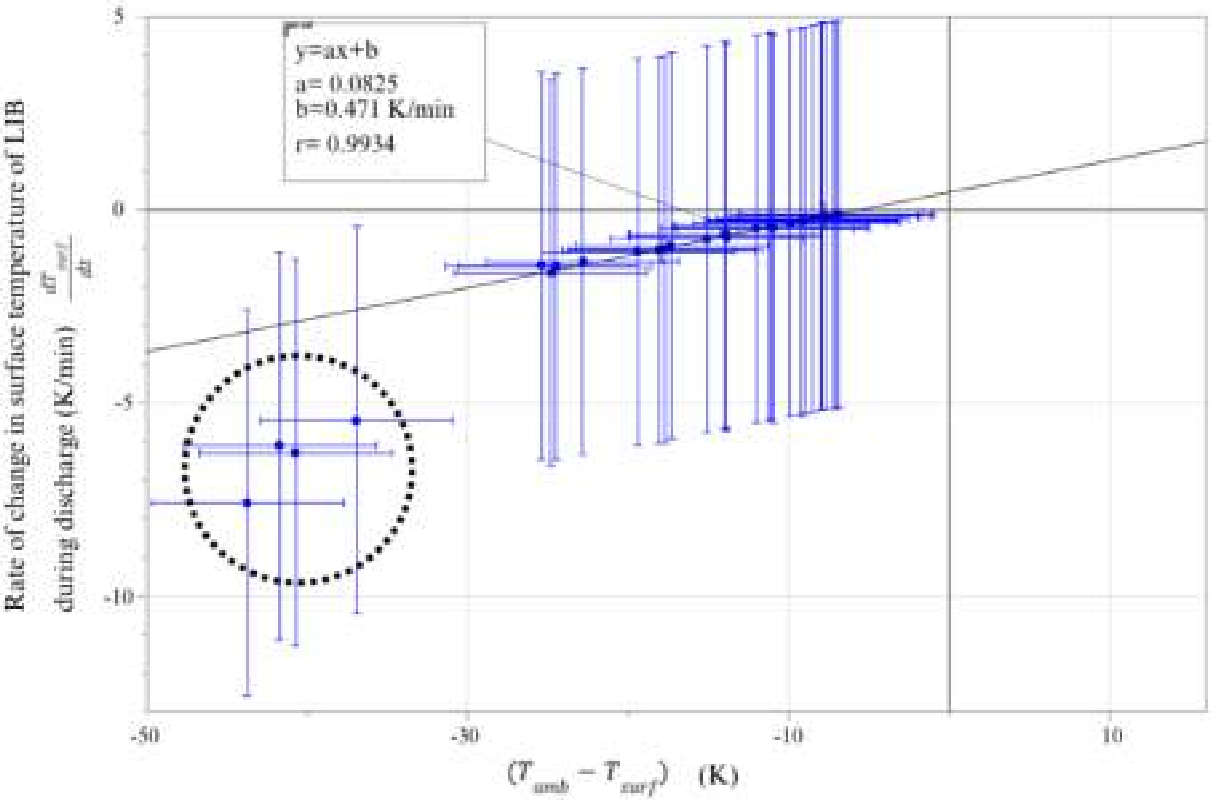
Fig 3.11 *Sketch graph to show the correlation between the rate of change of the surface temperature of the battery with respect to time (abbreviated $\frac{dT_{surf}}{dt}$) and the difference between ambient temperature and the surface temperature of the battery (abbreviated $T_{amb} - T_{surf}$) according to Newton's Law of Cooling.*



Therefore $\frac{dT_{obj}}{dt}$ the difference between the ambient and surface temperature of the battery are directly proportional and their graph should look like Fig 3.11.

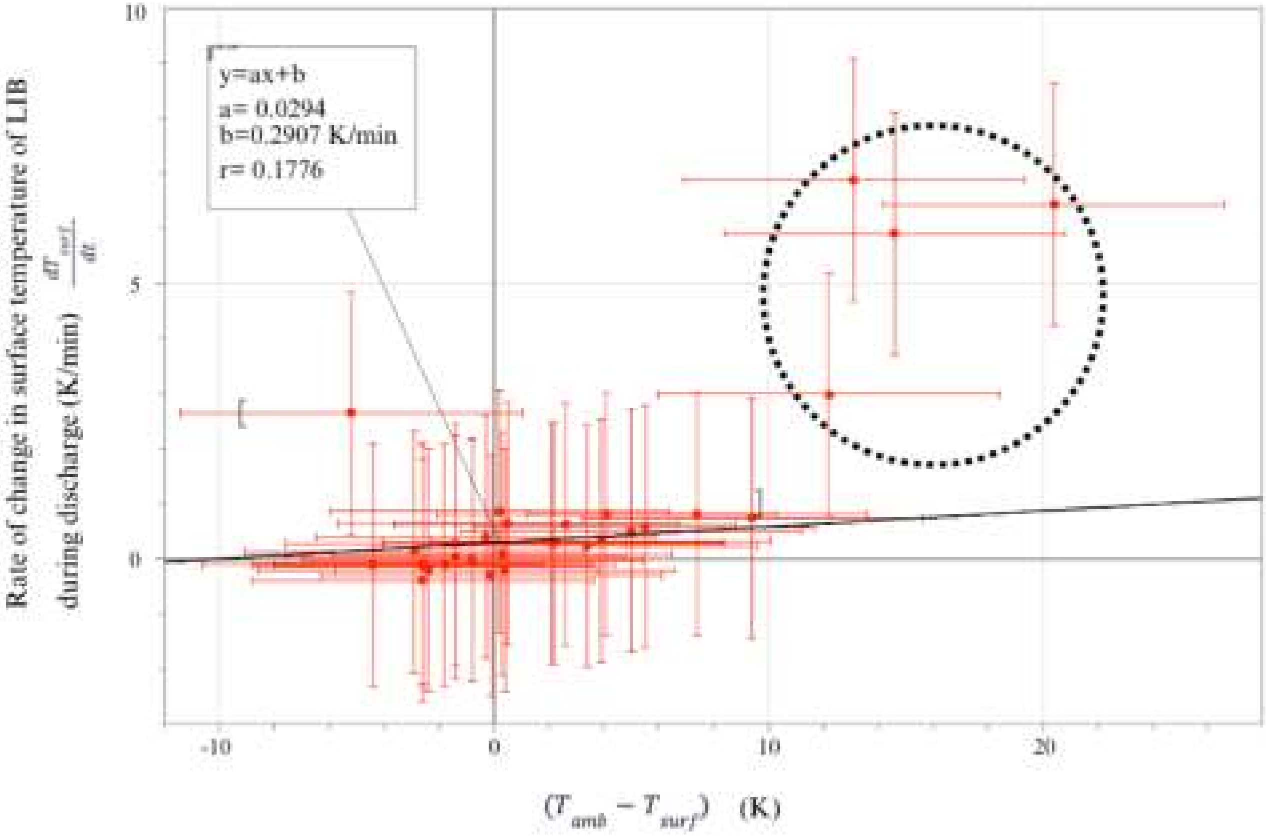
Both Figures 3.12 and 3.13 show the graph at discharges at -18℃ and 50℃ respectively. Fig 3.12 and 3.13 are plotted using the second cycle of battery A, B, C and D because it generally contained the fewest irregularities.

Fig 3.12 *Graph to show the dependency of the rate of change in surface temperature during discharge at -18°C on the difference between the ambient and surface temperature of the battery. Anomolous group of data points is circled.*



There are a group of anomalous values in Fig 3.12 circled on the graph. They occur at the lowest values of $T_{amb} - T_{surf}$. Excluding those points, there is a high linear correlation ($r = 0.9934$) between the remaining values. Unlike the prediction in Fig 3.11, the line does not go through the origin.

***Fig 3.13** Graph to show the dependency of the rate of change in surface temperature during discharge at 50°C on the difference between the ambient and surface temperature of the battery. Anomolous group of data points is circled.*



Similarly to graph 3.12, Fig 3.13 has a collection of anomalous points for high values of $T_{amb} - T_{surf}$. Its best-fit line also does not go through the origin. The correlation in the graph, excluding those four anomalous points, is much lower (Pearson's coefficient of 0.1776) than Fig 3.12.

The low correlation could be attributed to heat production within the battery amplified at high ambient temperatures. Newton's Law of Cooling does not account for internal heat production and therefore might not be accurate. Theoretically when $T_{amb} - T_{surf} < 0$, $\frac{dT_{surf}}{dt} < 0$ as the battery achieves thermal equilibrium. There are ten data points when $T_{amb} - T_{surf} < 0$ and of those data points four show that temperature continues to increase. This could indicate that heat production within the battery allows the battery's temperature to continue rising above ambient temperature. However, irregularities in oven temperature could also contribute to the observed phenomenon since in Newton's law of cooling the ambient temperature is a constant.

The anomalous points that are circled in both Figures 3.12 and 3.13 could be attributed to the deviations from Newton's Law of Cooling that occur at larger temperature differences (Vollmer).

The line of best fit in both graphs does not go through the origin. In Fig 3.12, the y-intercept is 0.4710K and in Fig 3.13 it is 0.2907K. It could be a result of a systematic error in either the thermocouple or the fridge and oven temperatures. Notably, since the the axes are calculated values and the errors are subsequently large a line through the origin is still within range.

Another notable difference in the two graphs is the gradient of the best-fit line which is (according to equation 1) the heat transfer coefficient. Neither the surface area of the battery nor its specific heat capacity has changed. However, the heat transfer coefficient during discharge at 50℃ is approximately 0.0294 and at -18℃ it is approximately 0.0825. The average rate of voltage decrease at -18℃ is also higher which suggests a possible correlation with the heat transfer coefficient. Further testing would be required to support or reject the correlation between the two variables.

3.5 Changing surface temperature and Voltage

Changes to the surface temperature of the battery over time are shown in Figures 3.14 and 3.15 for discharge at -18℃ and 50℃ respectively.

Fig 3.14 *Graph to show the change in surface temperature of the battery over time during discharge at -18°C.*

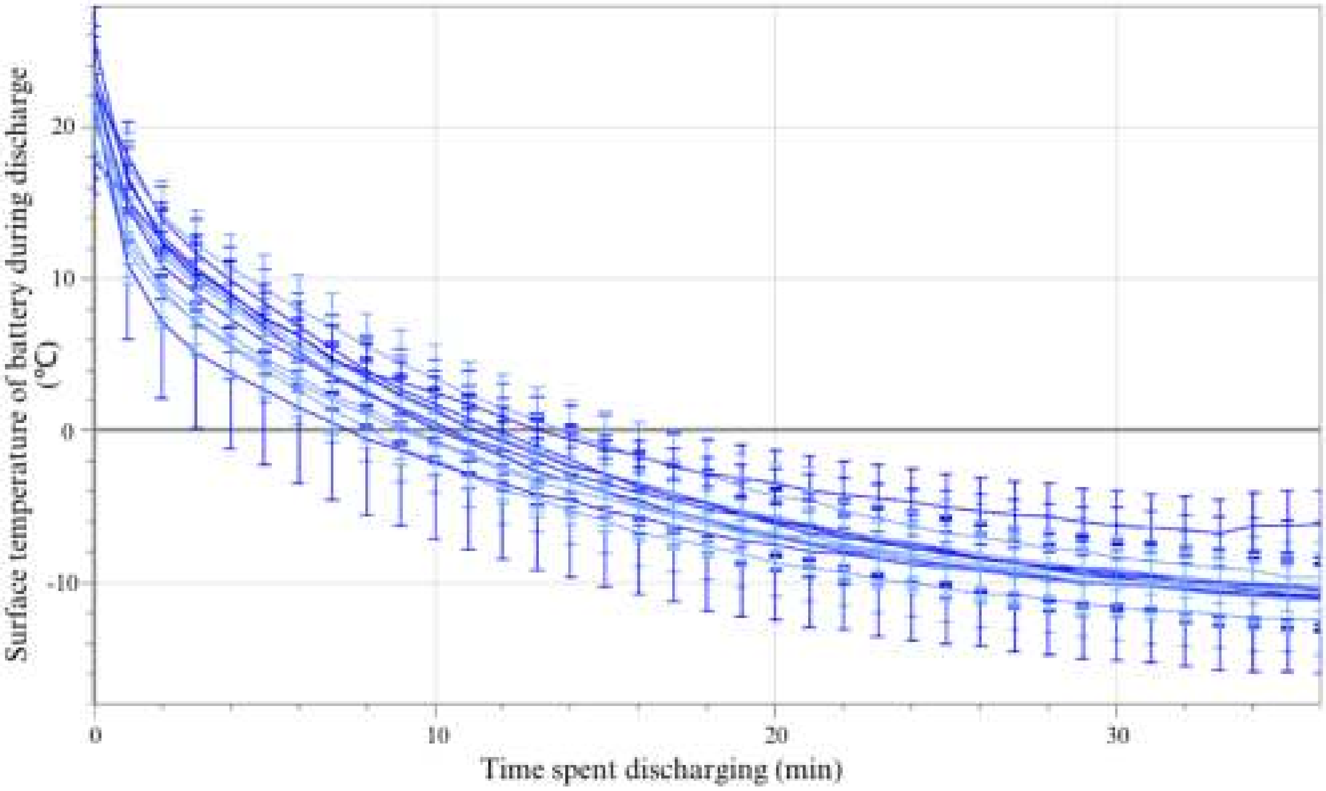
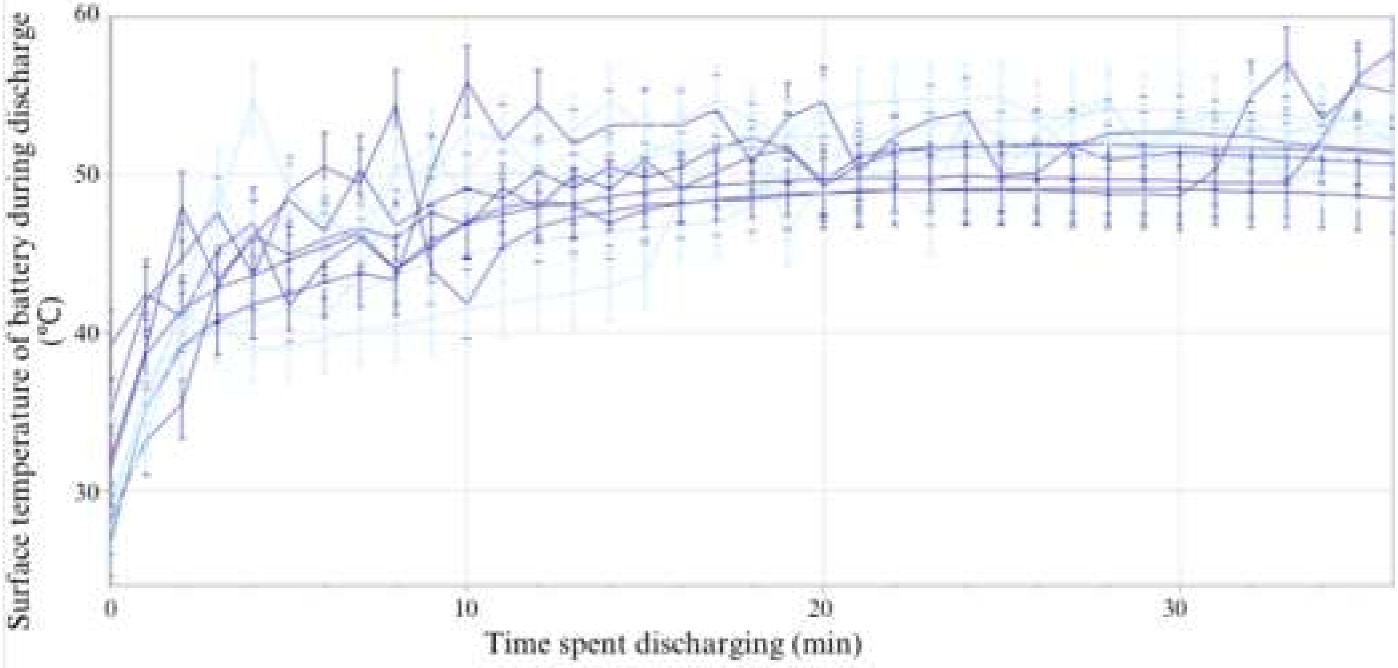


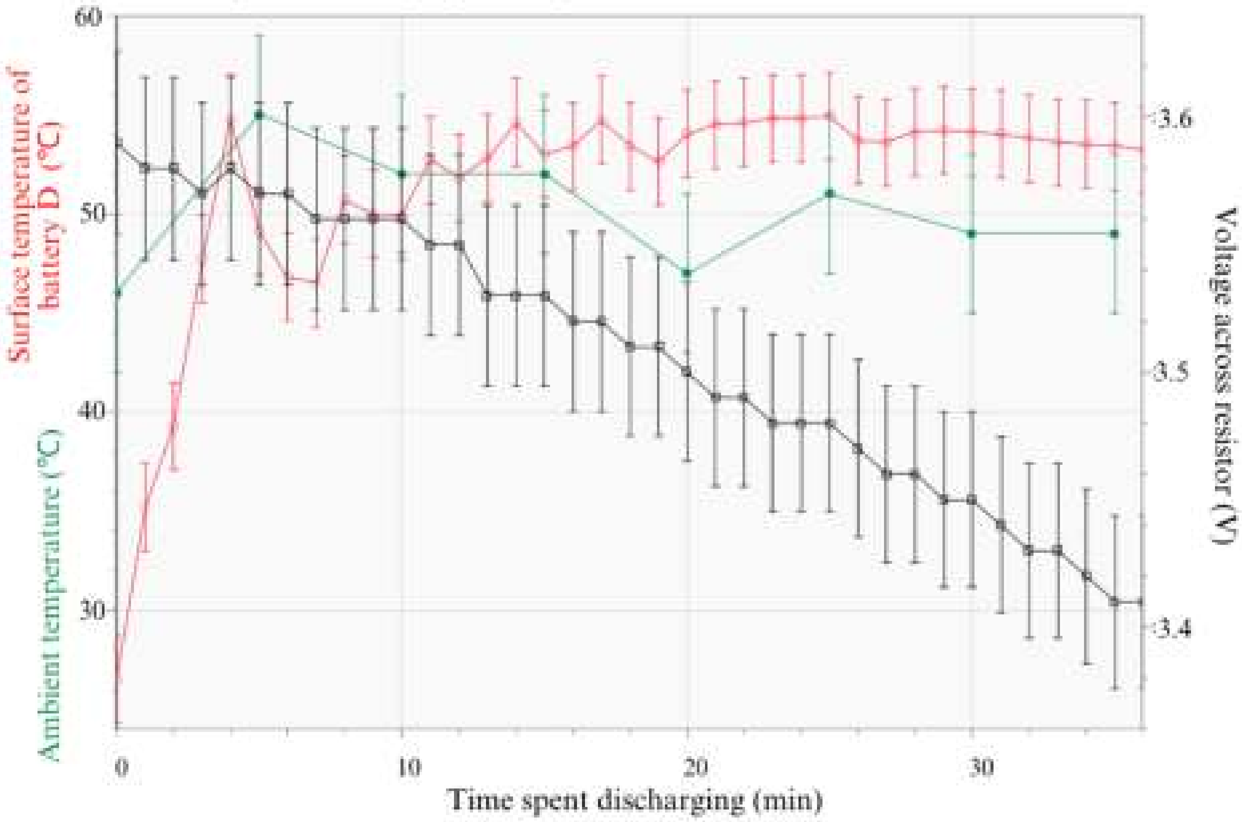
Fig 3.15 *Graph to show the change in surface temperature of the battery over time during discharge at 50°C.*



In Figure 3.15 the inconsistencies in oven temperature are prominent when compared to Figure 3.14 which follows a smooth curve. Despite these temperature inconsistencies, the rate of voltage decrease remained constant.

Fig 3.16 shows the surface temperature, ambient temperature and voltage for one of the most temperature-inconsistent discharges.

Fig 3.16 *Graph to show the relationship between the voltage across the resistor and ambient and the surface temperature of Battery D over time.*
Shows second cycle discharge of battery D at 50°C.

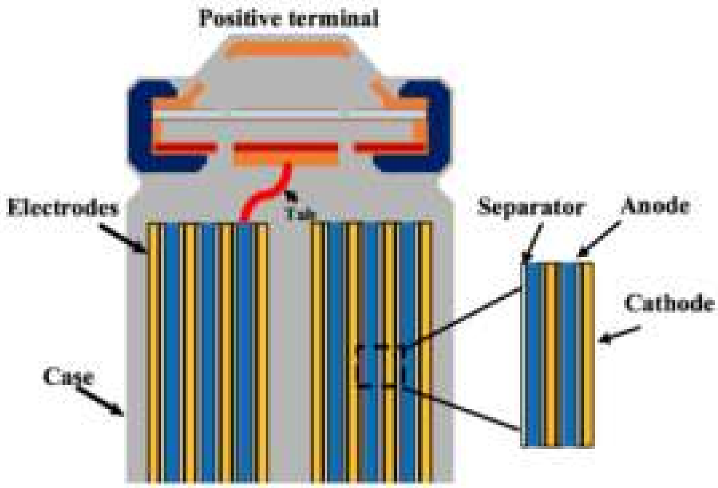


Ambient temperature varies significantly by up to 9℃ but there was no resultant change in voltage.

There are several factors that could contribute to this. Firstly, it could be that the voltage probe with an error of 1% wasn't sensitive enough to detect the changes when considering that the difference between the rate of voltage decrease at -18℃ and 50℃ was $3.632 \times 10^{-3}\ Vmin^{-1}$.

Another potential reason why the effects of quick changes in ambient and surface temperature were not evident in the voltage readings could be the delay in heat transfer between the insulative case and the electrodes (Fig 3.17). Since the changes in temperature were rapid it could be that there wasn't enough time for the heat to be transferred through the casing.

Fig 3.17 *Diagram of a cross-section of an 18650 LIB (Yao)*



4. Conclusion

The essay examined voltage, SOC and internal resistance as aspects of LIB performance to answer the research question "How do ambient temperatures within their operating range affect the performance of LIBs?". The results showed that overall the effects of low temperatures were more prevalent than the effects of high temperatures. At -18℃ the batteries experienced higher rates of voltage decrease, higher rates of SOC decrease and greater internal resistance. Therefore the performance of 18650 LIBs was reduced at low temperatures.

Voltage decreased at a higher rate at -18℃ compared to at 23℃ and 50℃. SOC decreased faster at -18℃ as well. This suggests that the low temperature environment had a greater impact on LIB performance despite the fact that the range of surface temperatures was much closer to the upper limit of 60℃ than the lower limit of -18℃. On the other hand, the effects of high temperatures are frequently attributed to the increased resistivity of the Solid Electrolyte Interface which had only just started to form towards the third cycle. The low number of cycles in the experiment therefore could have created a bias towards the effects of low temperatures.

When the batteries were first taken out of the -18℃ environment there was a large temporary increase in internal resistance. This could be attributed to multiple factors such as the SOC of the battery, the temperature of the battery and error from the charger.

The rate of change in surface temperature was much more irregular at 50℃ ambient temperature than at -18℃ when data was compared to Newton's Law of Cooling. The anomalies could be a result of increased heat production in the battery or the unstable temperature of the oven.

During discharges in the oven, voltage decreased linearly despite the large fluctuations in ambient temperature which varied by up to 9℃.

5. Evaluation

There were multiple limitations in the experiment that affected the validity of the data. For instance, some of the equipment used (such as the charger, meat thermometer, oven and freezer) was intended for household use. Therefore uncertainties were unknown. For instance, increased internal resistance after discharge at -18℃ could be attributed to error because the charger is not designed to charge batteries at negative temperatures. Ambient temperatures were also difficult to control. The temperature in the oven, which was supposed to be a controlled variable, varied by up to 9℃. The oven temperature was regulated manually by opening the oven door to reduce temperatures which caused rapid drops. The temperature in the freezer was also not constant. Depending on how much time the freezer door was open while the batteries were placed into the freezer, the temperature would increase. Furthermore, the starting temperature of the batteries was also inconsistent. As I held the batteries in my hands to insert them into the battery holder and attach the thermocouple, their surface temperature would increase as a result.

Furthermore, probes disconnected during a few of the discharges. The voltmeter was clipped onto the resistor, and the clips would occasionally slip off resulting in data anomalies. The thermocouple was attached to the battery using duct tape which was prone to detaching. As a result, the thermocouple would lose contact with the surface of the battery until reattached.

6. Practical applications and further investigation

18650 LIBs (the LIB type used in this experiment) have a wide range of applications for example in electric vehicles. 18650 cells are used in Tesla's Model S and X (Loveday). The results from the experiment could indicate that the performance of electric cars is reduced during cold winters.

However, these results cannot be extended to other LIB-powered devices that we use on a regular basis. The results alone don't determine that mobile phones function better at room temperature rather than on a cold winter day. There are multiple types of LIBs in use that have different operating temperature ranges and different chemical compositions.

Furthermore, the batteries tested were cylindrical but there are other types of cells such as prismatic cells, button cells and pouch cells (Murashko). Since they have different shapes and compositions their response to temperature would differ. Therefore it would be interesting to investigate the differences in the effects of temperature on LIBs depending on cell type and chemical composition so that conclusions could be made about the performance of other LIB-powered devices.

Due to both equipment limitations and human error, the accuracy of the data was compromised so further investigation could involve a more controlled temperature environment and higher accuracy sensors to determine whether the trends that could have been attributed to error were actually present. For example the temporary increase in internal resistance or the constant rate of voltage decrease.

7. Appendices

Table 2: Internal resistances after discharge and at the end of charge.

	Charge 1			Charge 2			Charge 3		
Battery*	Resistance Start/mΩ ±8	Resistance Final/mΩ ±8	Change in resistance/mΩ ±16	Resistance Start/mΩ ±8	Resistance Final/mΩ ±8	Change in resistance/mΩ ±16	Resistance Start/mΩ ±8	Resistance Final/mΩ ±8	Change in resistance/mΩ ±16
B	**40**	**5**	**-35**	**4**	**10**	**6**	**40**	**5**	**-35**
C	**13**	**5**	**-8**	**9**	**5**	**-4**	**13**	**5**	**-8**
D	**22**	**10**	**-12**	**9**	**10**	**1**	**22**	**10**	**-12**
J	**9**	**5**	**-4**	**4**	**4**	**0**	**4**	**10**	**6**

	Charge 4			Charge 5			Charge 6		
Battery*	Resistance Start/mΩ ±8	Resistance Final/mΩ ±8	Change in resistance/mΩ ±16	Resistance Start/mΩ ±8	Resistance Final/mΩ ±8	Change in resistance/mΩ ±16	Resistance Start/mΩ ±8	Resistance Final/mΩ ±8	Change in resistance/mΩ ±16
B	**9**	**9**	**0**	**21**	**5**	**-16**	**4**	**4**	**0**
C	**14**	**5**	**-9**	**31**	**5**	**-26**	**4**	**4**	**0**
D	**14**	**5**	**-9**	**27**	**10**	**-17**	**14**	**5**	**-9**
J	**5**	**5**	**0**	**5**	**5**	**0**	**4**	**4**	**0**

Charge after -18℃ environment
Charge after 50℃ environment
Charge after 23℃ environment
*Battery A is not included in the table because during data collection internal resistance was only recorded once because I did not realise that recording two values was necessary at the time.

Table 5: Current, discharge and surface temperature during discharge. Every 60th datapoint displayed.

	Battery A					
	A -18 1			A 50 1		
Time (s)	Current (A)	Voltage (V)	Temperature (℃)	Current	Voltage	Temperature (℃)
	±1%	±1%	±5	±1%	±1%	±2.2
0	0.62	3.64	18	0.62	3.65	34.9
60	0.62	3.63	15	0.62	3.63	42.0
120	0.62	3.62	12	0.62	3.63	44.7
180	0.62	3.61	11	0.62	3.62	47.6
240	0.62	3.60	9	0.62	3.61	43.6
300	0.62	3.59	7	0.62	3.60	48.9
360	0.62	3.57	6	0.62	3.60	50.5
420	0.62	3.56	5	0.62	3.59	49.4
480	0.62	3.55	4	0.62	3.58	54.4
540	0.62	3.54	3	0.62	3.58	44.0
600	0.62	3.53	2	0.62	3.57	41.8
660	0.62	3.52	2	0.62	3.57	45.4
720	0.62	3.51	1	0.62	3.56	46.7
780	0.62	3.50	0	0.62	3.56	47.3
840	0.62	3.49	-1	0.62	3.55	47.7
900	0.62	3.48	-1	0.62	3.55	48.1
960	0.62	3.47	-2	0.62	3.54	48.2
1020	0.62	3.46	-2	0.62	3.53	48.4
1080	0.62	3.45	-3	0.62	3.53	48.4
1140	0.62	3.44	-3	0.62	3.52	48.7
1200	0.62	3.43	-3	0.62	3.52	48.8
1260	0.62	3.42	-4	0.62	3.51	48.9
1320	0.62	3.41	-4	0.62	3.50	49.0
1380	0.62	3.40	-4	0.62	3.50	49.0
1440	0.62	3.40	-5	0.62	3.49	49.1
1500	0.62	3.39	-5	0.62	3.48	49.1
1560	0.62	3.38	-5	0.62	3.48	49.1
1620	0.62	3.37	-6	0.62	3.47	49.1
1680	0.62	3.36	-6	0.62	3.47	49.1
1740	0.62	3.36	-6	0.62	3.46	49.1
1800	0.62	3.35	-6	0.62	3.45	49.1
1860	0.62	3.34	-6	0.62	3.44	49.0
1920	0.62	3.33	-7	0.62	3.44	48.9
1980	0.62	3.33	-7	0.62	3.43	48.9
2040	0.62	3.32	-6	0.62	3.42	48.8
2100	0.62	3.31	-6	0.62	3.42	48.7
2160	0.62	3.31	-6	0.62	3.41	48.5

	Battery A					
	A -18 2			A 50 2		
Time (s)	Current (A)	Voltage (V)	Temperature (℃)	Current	Voltage	Temperature (℃)
	±1%	±1%	±5	±1%	±1%	±2.2
0	0.62	3.58	19	0.62	3.64	33.8
60	0.62	3.58	12	0.62	3.63	37.3
120	0.62	3.57	10	0.62	3.61	39.1
180	0.62	3.56	8	0.62	3.61	40.2
240	0.62	3.55	6	0.62	3.60	40.8
300	0.62	3.54	5	0.62	3.60	41.5
360	0.62	3.53	4	0.62	3.59	40.9
420	0.62	3.52	2	0.62	3.58	43.7
480	0.62	3.51	1	0.62	3.58	48.3
540	0.62	3.50	0	0.62	3.57	50.2
600	0.62	3.49	-1	0.62	3.56	52.8
660	0.62	3.48	-2	0.62	3.56	52.2
720	0.62	3.47	-2	0.62	3.55	50.1
780	0.62	3.45	-3	0.62	3.55	51.5
840	0.62	3.44	-3	0.62	3.54	49.8
900	0.62	3.43	-4	0.62	3.54	51.5
960	0.62	3.42	-5	0.62	3.53	52.1
1020	0.62	3.43	-5	0.62	3.53	51.5
1080	0.62	3.42	-6	0.62	3.52	52.5
1140	0.62	3.41	-6	0.62	3.51	52.4
1200	0.62	3.40	-7	0.62	3.51	51.1
1260	0.62	3.39	-7	0.62	3.50	52.0
1320	0.62	3.38	-8	0.62	3.50	52.8
1380	0.62	3.37	-8	0.62	3.49	53.1
1440	0.62	3.36	-8	0.62	3.49	53.3
1500	0.62	3.35	-9	0.62	3.48	53.4
1560	0.62	3.34	-9	0.62	3.47	53.5
1620	0.62	3.33	-9	0.62	3.47	51.4
1680	0.62	3.32	-10	0.62	3.46	52.4
1740	0.62	3.31	-10	0.62	3.45	52.8
1800	0.62	3.30	-10	0.62	3.45	52.9
1860	0.62	3.29	-10	0.62	3.44	53.0
1920	0.62	3.28	-10	0.62	3.43	52.9
1980	0.62	3.28	-11	0.62	3.42	52.8
2040	0.62	3.27	-11	0.62	3.42	52.7
2100	0.62	3.26	-11	0.62	3.41	52.6
2160	0.62	3.25	-11	0.62	3.40	52.4

	Battery A					
	A -18 3			A 50 3		
Time (s)	**Current (A)**	**Voltage (V)**	**Temperature (℃)**	**Current**	**Voltage**	**Temperature (℃)**
	±1%	±1%	±5	±1%	±1%	±2.2
0	0.62	3.28	23	0.62	3.64	39.2
60	0.62	3.63	18	0.62	3.63	42.4
120	0.62	3.62	14	0.62	3.63	41.0
180	0.62	3.61	12	0.62	3.62	45.2
240	0.62	3.60	10	0.62	3.61	47.0
300	0.62	3.59	8	0.62	3.60	41.7
360	0.62	3.58	7	0.62	3.60	44.4
420	0.62	3.57	5	0.62	3.59	45.9
480	0.62	3.56	4	0.62	3.59	44.0
540	0.62	3.55	3	0.62	3.58	45.4
600	0.62	3.54	2	0.62	3.57	47.0
660	0.62	3.53	1	0.62	3.57	47.9
720	0.62	3.52	0	0.62	3.56	48.3
780	0.62	3.51	-1	0.62	3.55	48.1
840	0.62	3.50	-2	0.62	3.55	46.9
900	0.62	3.49	-3	0.62	3.54	47.8
960	0.62	3.48	-3	0.62	3.54	48.2
1020	0.62	3.47	-4	0.62	3.53	48.4
1080	0.62	3.46	-5	0.62	3.52	48.6
1140	0.62	3.45	-5	0.62	3.52	48.8
1200	0.62	3.43	-6	0.62	3.51	48.8
1260	0.62	3.42	-6	0.62	3.51	49.0
1320	0.62	3.41	-7	0.62	3.50	49.0
1380	0.62	3.40	-7	0.62	3.50	49.0
1440	0.62	3.39	-8	0.62	3.49	49.0
1500	0.62	3.38	-8	0.62	3.48	49.0
1560	0.62	3.37	-8	0.62	3.48	49.0
1620	0.62	3.36	-9	0.62	3.47	48.9
1680	0.62	3.35	-9	0.62	3.47	48.8
1740	0.62	3.35	-9	0.62	3.46	48.8
1800	0.62	3.33	-10	0.62	3.45	48.7
1860	0.62	3.33	-10	0.62	3.44	50.3
1920	0.62	3.32	-10	0.62	3.44	55.0
1980	0.62	3.31	-10	0.62	3.43	57.1
2040	0.62	3.30	-10	0.62	3.42	53.5
2100	0.62	3.29	-11	0.62	3.42	55.7
2160	0.62	3.28	-11	0.62	3.41	55.2

	Battery B					
	B -18 1			B 50 1		
Time (s)	Current (A)	Voltage (V)	Temperature (℃)	Current	Voltage	Temperature (℃)
	±1%	±1%	±5	±1%	±1%	±2.2
0	0.62	3.65	23	0.62	3.63	29.4
60	0.62	3.64	13	0.62	3.63	35.1
120	0.62	3.63	9	0.62	3.62	42.1
180	0.62	3.62	7	0.62	3.61	49.4
240	0.62	3.61	6	0.62	3.60	44.7
300	0.62	3.60	4	0.62	3.59	47.4
360	0.62	3.59	3	0.62	3.58	47.5
420	0.62	3.58	1	0.62	3.57	45.6
480	0.62	3.56	0	0.62	3.57	50.0
540	0.62	3.55	-1	0.62	3.55	51.9
600	0.62	3.54	-2	0.62	3.55	48.1
660	0.62	3.53	-3	0.62	3.57	50.4
720	0.62	3.52	-4	0.62	3.56	49.8
780	0.62	3.51	-4	0.62	3.56	47.0
840	0.62	3.49	-5	0.62	3.55	49.7
900	0.62	3.48	-6	0.62	3.55	51.5
960	0.62	3.47	-7	0.62	3.54	51.7
1020	0.62	3.46	-7	0.62	3.54	47.7
1080	0.62	3.45	-8	0.62	3.53	48.4
1140	0.62	3.44	-8	0.62	3.53	50.3
1200	0.62	3.43	-9	0.62	3.52	51.0
1260	0.62	3.42	-9	0.62	3.52	51.4
1320	0.62	3.41	-9	0.62	3.51	51.5
1380	0.62	3.40	-10	0.62	3.51	51.5
1440	0.62	3.39	-10	0.62	3.50	51.5
1500	0.62	3.38	-10	0.62	3.50	51.4
1560	0.62	3.37	-11	0.62	3.49	51.3
1620	0.62	3.36	-11	0.62	3.48	51.2
1680	0.62	3.35	-11	0.62	3.48	51.1
1740	0.62	3.34	-11	0.62	3.47	51.0
1800	0.62	3.33	-12	0.62	3.47	50.8
1860	0.62	3.32	-12	0.62	3.46	50.7
1920	0.62	3.32	-12	0.62	3.45	50.4
1980	0.62	3.31	-12	0.62	3.44	50.4
2040	0.62	3.30	-12	0.62	3.44	50.1
2100	0.62	3.29	-12	0.62	3.43	50.0
2160	0.62	3.28	-13	0.62	3.42	50.0

	Battery B					
	B -18 2			B 50 2		
Time (s)	Current (A)	Voltage (V)	Temperature (℃)	Current	Voltage	Temperature (℃)
	±1%	±1%	±5	±1%	±1%	±2.2
0	0.62	3.65	24	0.62	3.62	31.9
60	0.62	3.64	17	0.62	3.60	39.0
120	0.62	3.63	12	0.62	3.60	48.0
180	0.62	3.62	10	0.62	3.59	43.3
240	0.62	3.62	8	0.62	3.59	46.1
300	0.62	3.61	7	0.62	3.58	48.4
360	0.62	3.60	5	0.62	3.58	46.4
420	0.62	3.59	4	0.62	3.57	50.3
480	0.62	3.58	3	0.62	3.56	46.8
540	0.62	3.57	1	0.62	3.56	48.2
600	0.62	3.55	0	0.62	3.55	49.1
660	0.62	3.54	-1	0.62	3.55	48.5
720	0.62	3.53	-2	0.62	3.54	50.2
780	0.62	3.52	-3	0.62	3.53	49.1
840	0.62	3.51	-3	0.62	3.53	50.5
900	0.62	3.50	-4	0.62	3.52	49.8
960	0.62	3.49	-5	0.62	3.52	50.5
1020	0.62	3.48	-5	0.62	3.51	51.7
1080	0.62	3.47	-6	0.62	3.51	52.3
1140	0.62	3.46	-6	0.62	3.50	51.7
1200	0.62	3.44	-7	0.62	3.49	49.6
1260	0.62	3.43	-7	0.62	3.48	51.1
1320	0.62	3.42	-8	0.62	3.48	51.6
1380	0.62	3.42	-8	0.62	3.47	51.7
1440	0.62	3.41	-9	0.62	3.47	51.8
1500	0.62	3.40	-9	0.62	3.46	51.8
1560	0.62	3.39	-9	0.62	3.46	51.8
1620	0.62	3.38	-9	0.62	3.45	51.8
1680	0.62	3.37	-10	0.62	3.44	50.9
1740	0.62	3.36	-10	0.62	3.44	51.2
1800	0.62	3.35	-10	0.62	3.43	51.4
1860	0.62	3.35	-10	0.62	3.43	51.3
1920	0.62	3.34	-10	0.62	3.42	51.2
1980	0.62	3.33	-11	0.62	3.41	51.1
2040	0.62	3.32	-11	0.62	3.41	50.9
2100	0.62	3.31	-11	0.62	3.40	50.8
2160	0.62	3.31	-11	0.62	3.39	50.7

	Battery B					
	B -18 3			B 50 3		
Time (s)	**Current (A)**	**Voltage (V)**	**Temperature (℃)**	**Current**	**Voltage**	**Temperature (℃)**
	±1%	±1%	±5	±1%	±1%	±2.2
0	0.62	3.62	23	0.62	3.62	28.6
60	0.62	3.23	17	0.62	3.61	36.4
120	0.62	3.23	14	0.62	3.60	40.9
180	0.62	3.59	12	0.62	3.59	40.5
240	0.62	3.58	11	0.62	3.58	39.0
300	0.62	3.57	9	0.62	3.58	39.1
360	0.62	3.56	8	0.62	3.57	39.6
420	0.62	3.55	7	0.62	3.56	40.1
480	0.62	3.54	5	0.62	3.56	40.4
540	0.62	3.54	4	0.62	3.55	40.9
600	0.62	3.52	3	0.62	3.55	41.5
660	0.62	3.52	2	0.62	3.54	41.8
720	0.62	3.51	1	0.62	3.53	42.2
780	0.62	3.50	1	0.62	3.53	42.5
840	0.62	3.49	0	0.62	3.52	42.9
900	0.62	3.48	-1	0.62	3.52	43.6
960	0.62	3.47	-2	0.62	3.51	48.6
1020	0.62	3.46	-2	0.62	3.50	51.5
1080	0.62	3.44	-3	0.62	3.50	52.8
1140	0.62	3.44	-4	0.62	3.50	48.0
1200	0.62	3.43	-4	0.62	3.49	54.6
1260	0.62	3.42	-5	0.62	3.49	50.8
1320	0.62	3.41	-5	0.62	3.48	49.4
1380	0.62	3.40	-6	0.62	3.48	47.1
1440	0.62	3.39	-6	0.62	3.47	54.1
1500	0.62	3.38	-7	0.62	3.46	49.6
1560	0.62	3.37	-7	0.62	3.46	52.7
1620	0.62	3.36	-7	0.62	3.45	54.3
1680	0.62	3.35	-8	0.62	3.44	54.7
1740	0.62	3.34	-8	0.62	3.44	51.2
1800	0.62	3.33	-8	0.62	3.43	53.1
1860	0.62	3.33	-9	0.62	3.43	53.8
1920	0.62	3.32	-9	0.62	3.42	54.1
1980	0.62	3.31	-9	0.62	3.41	49.2
2040	0.62	3.30	-9	0.62	3.40	50.5
2100	0.62	3.29	-10	0.62	3.40	52.0
2160	0.62	3.29	-10	0.62	3.39	52.3

	Battery C					
	C -18 1			C 50 1		
Time (s)	Current (A)	Voltage (V)	Temperature (℃)	Current	Voltage	Temperature (℃)
	±1%	±1%	±5	±1%	±1%	±2.2
0	0.62	3.63	22	0.62	3.61	28.2
60	0.62	3.61	11	0.62	3.59	33.2
120	0.62	3.60	7	0.62	3.59	35.5
180	0.62	3.59	5	0.62	3.58	42.9
240	0.62	3.59	4	0.62	3.57	46.2
300	0.62	3.57	3	0.62	3.57	44.9
360	0.62	3.56	2	0.62	3.56	45.9
420	0.62	3.55	0	0.62	3.55	46.6
480	0.62	3.54	-1	0.62	3.55	46.0
540	0.62	3.53	-1	0.62	3.54	47.6
600	0.62	3.52	-2	0.62	3.54	46.8
660	0.62	3.51	-3	0.62	3.53	49.2
720	0.62	3.50	-3	0.62	3.53	47.9
780	0.62	3.49	-4	0.62	3.52	50.0
840	0.62	3.48	-5	0.62	3.52	49.1
900	0.62	3.47	-5	0.62	3.51	50.9
960	0.62	3.46	-6	0.62	3.51	49.1
1020	0.62	3.44	-6	0.62	3.50	50.2
1080	0.62	3.44	-7	0.62	3.50	51.2
1140	0.62	3.43	-7	0.62	3.49	51.6
1200	0.62	3.41	-7	0.62	3.48	49.3
1260	0.62	3.41	-8	0.62	3.48	50.6
1320	0.62	3.40	-8	0.62	3.47	51.4
1380	0.62	3.39	-9	0.62	3.47	51.7
1440	0.62	3.38	-9	0.62	3.46	51.8
1500	0.62	3.37	-9	0.62	3.46	51.8
1560	0.62	3.36	-9	0.62	3.45	51.9
1620	0.62	3.36	-10	0.62	3.44	51.9
1680	0.62	3.35	-10	0.62	3.44	51.9
1740	0.62	3.34	-10	0.62	3.43	51.8
1800	0.62	3.33	-10	0.62	3.42	51.8
1860	0.62	3.32	-10	0.62	3.42	51.7
1920	0.62	3.32	-11	0.62	3.41	51.7
1980	0.62	3.31	-11	0.62	3.40	51.6
2040	0.62	3.30	-11	0.62	3.40	51.6
2100	0.62	3.29	-11	0.62	3.39	51.5
2160	0.62	3.29	-11	0.62	3.38	51.3

	Battery C					
	C -18 2			C 50 2		
Time (s)	Current (A)	Voltage (V)	Temperature (℃)	Current	Voltage	Temperature (℃)
	±1%	±1%	±5	±1%	±1%	±2.2
0	0.62	3.62	23	0.62	3.63	27.6
60	0.62	3.61	15	0.62	3.62	35.3
120	0.62	3.60	12	0.62	3.61	38.8
180	0.62	3.59	10	0.62	3.60	40.5
240	0.62	3.58	8	0.62	3.60	41.7
300	0.62	3.57	7	0.62	3.59	42.6
360	0.62	3.56	5	0.62	3.58	43.4
420	0.62	3.55	4	0.62	3.58	42.6
480	0.62	3.54	3	0.62	3.57	43.6
540	0.62	3.53	1	0.62	3.57	44.5
600	0.62	3.52	0	0.62	3.56	45.0
660	0.62	3.51	-1	0.62	3.56	45.4
720	0.62	3.50	-1	0.62	3.55	45.8
780	0.62	3.49	-3	0.62	3.55	46.1
840	0.62	3.48	-3	0.62	3.54	46.4
900	0.62	3.47	-4	0.62	3.54	46.6
960	0.62	3.46	-5	0.62	3.53	46.8
1020	0.62	3.44	-5	0.62	3.53	47.0
1080	0.62	3.44	-6	0.62	3.52	48.0
1140	0.62	3.42	-7	0.62	3.51	52.5
1200	0.62	3.41	-7	0.62	3.51	52.3
1260	0.62	3.40	-7	0.62	3.50	52.3
1320	0.62	3.39	-8	0.62	3.50	52.2
1380	0.62	3.38	-8	0.62	3.49	50.5
1440	0.62	3.37	-9	0.62	3.49	53.5
1500	0.62	3.36	-9	0.62	3.48	52.4
1560	0.62	3.35	-9	0.62	3.48	51.4
1620	0.62	3.34	-10	0.62	3.47	53.6
1680	0.62	3.34	-10	0.62	3.46	54.4
1740	0.62	3.33	-10	0.62	3.46	51.7
1800	0.62	3.32	-10	0.62	3.45	53.4
1860	0.62	3.31	-10	0.62	3.44	54.1
1920	0.62	3.30	-11	0.62	3.44	50.8
1980	0.62	3.29	-11	0.62	3.43	52.5
2040	0.62	3.28	-11	0.62	3.42	53.4
2100	0.62	3.28	-11	0.62	3.41	53.6
2160	0.62	3.27	-11	0.62	3.41	51.9

	Battery C					
	C -18 3			C 50 3		
Time (s)	**Current (A)**	**Voltage (V)**	**Temperature (℃)**	**Current**	**Voltage**	**Temperature (℃)**
	±1%	±1%	±5	±1%	±1%	±2.2
0	0.62	3.62	23	0.62	3.62	26.8
60	0.62	3.61	15	0.62	3.61	35.2
120	0.62	3.60	11	0.62	3.60	39.1
180	0.62	3.59	9	0.62	3.59	40.8
240	0.62	3.58	7	0.62	3.59	41.8
300	0.62	3.57	6	0.62	3.58	42.4
360	0.62	3.57	5	0.62	3.57	43.2
420	0.62	3.56	4	0.62	3.57	43.8
480	0.62	3.55	2	0.62	3.56	43.3
540	0.62	3.53	1	0.62	3.56	50.3
600	0.62	3.53	0	0.62	3.55	55.9
660	0.62	3.52	-1	0.62	3.55	52.2
720	0.62	3.50	-1	0.62	3.54	54.4
780	0.62	3.49	-2	0.62	3.53	51.9
840	0.62	3.48	-3	0.62	3.53	53.1
900	0.62	3.47	-3	0.62	3.52	53.2
960	0.62	3.46	-4	0.62	3.52	53.1
1020	0.62	3.45	-5	0.62	3.51	54.1
1080	0.62	3.44	-5	0.62	3.51	50.8
1140	0.62	3.43	-6	0.62	3.50	53.6
1200	0.62	3.42	-6	0.62	3.50	54.6
1260	0.62	3.41	-7	0.62	3.49	50.2
1320	0.62	3.40	-7	0.62	3.49	52.4
1380	0.62	3.39	-7	0.62	3.48	53.5
1440	0.62	3.38	-8	0.62	3.48	53.9
1500	0.62	3.38	-8	0.62	3.47	49.9
1560	0.62	3.37	-8	0.62	3.46	50.1
1620	0.62	3.36	-9	0.62	3.46	51.8
1680	0.62	3.35	-9	0.62	3.45	52.6
1740	0.62	3.34	-9	0.62	3.44	52.7
1800	0.62	3.33	-9	0.62	3.44	52.7
1860	0.62	3.33	-10	0.62	3.43	52.5
1920	0.62	3.32	-10	0.62	3.43	52.4
1980	0.62	3.31	-10	0.62	3.42	52.0
2040	0.62	3.30	-10	0.62	3.41	51.8
2100	0.62	3.29	-10	0.62	3.40	51.6
2160	0.62	3.29	-10	0.62	3.40	51.5

	Battery D					
	D -18 1			D 50 1		
Time (s)	Current (A)	Voltage (V)	Temperature (℃)	Current	Voltage	Temperature (℃)
	±1%	±1%	±5	±1%	±1%	±2.2
0	0.62	3.61	21	0.62	3.61	27.6
60	0.62	3.60	15	0.62	3.60	33.4
120	0.62	3.59	12	0.62	3.60	39.9
180	0.62	3.58	10	0.62	3.59	44.7
240	0.62	3.57	8	0.62	3.58	46.5
300	0.62	3.56	7	0.62	3.57	45.5
360	0.62	3.55	6	0.62	3.57	45.0
420	0.62	3.54	5	0.62	3.56	46.5
480	0.62	3.53	3	0.62	3.55	45.7
540	0.62	3.52	2	0.62	3.55	48.4
600	0.62	3.51	1	0.62	3.55	47.3
660	0.62	3.51	0	0.62	3.54	47.9
720	0.62	3.49	-1	0.62	3.54	49.7
780	0.62	3.48	-1	0.62	3.53	50.1
840	0.62	3.47	-2	0.62	3.53	50.0
900	0.62	3.46	-3	0.62	3.52	51.0
960	0.62	3.45	-4	0.62	3.52	51.5
1020	0.62	3.44	-4	0.62	3.51	51.8
1080	0.62	3.43	-5	0.62	3.50	51.8
1140	0.62	3.42	-5	0.62	3.50	46.4
1200	0.62	3.41	-6	0.62	3.50	49.7
1260	0.62	3.40	-6	0.62	3.49	50.8
1320	0.62	3.39	-7	0.62	3.49	50.8
1380	0.62	3.39	-7	0.62	3.48	51.0
1440	0.62	3.38	-7	0.62	3.48	51.1
1500	0.62	3.37	-8	0.62	3.47	51.2
1560	0.62	3.36	-8	0.62	3.47	51.2
1620	0.62	3.35	-8	0.62	3.46	51.2
1680	0.62	3.35	-9	0.62	3.46	51.2
1740	0.62	3.34	-9	0.62	3.45	51.2
1800	0.62	3.33	-9	0.62	3.44	51.1
1860	0.62	3.32	-9	0.62	3.44	51.1
1920	0.62	3.31	-10	0.62	3.43	51.0
1980	0.62	3.31	-10	0.62	3.42	51.0
2040	0.62	3.30	-10	0.62	3.42	51.7
2100	0.62	3.29	-10	0.62	3.41	55.8
2160	0.62	3.28	-10	0.62	3.40	56.9

	Battery D					
	D -18 2			D 50 2		
Time (s)	Current (A)	Voltage (V)	Temperature (℃)	Current	Voltage	Temperature (℃)
	±1%	±1%	±5	±1%	±1%	±2.2
0	0.62	3.63	26	0.62	3.61	31.4
60	0.62	3.61	16	0.62	3.60	38.6
120	0.62	3.60	13	0.62	3.59	41.4
180	0.62	3.60	11	0.62	3.59	42.8
240	0.62	3.58	9	0.62	3.58	43.6
300	0.62	3.57	7	0.62	3.57	44.6
360	0.62	3.57	6	0.62	3.57	45.4
420	0.62	3.56	5	0.62	3.56	46.3
480	0.62	3.55	4	0.62	3.55	44.0
540	0.62	3.54	2	0.62	3.54	45.8
600	0.62	3.53	1	0.62	3.54	46.9
660	0.62	3.52	0	0.62	3.53	47.5
720	0.62	3.51	-1	0.62	3.53	48.0
780	0.62	3.50	-1	0.62	3.52	48.2
840	0.62	3.49	-2	0.62	3.52	48.6
900	0.62	3.48	-3	0.62	3.51	48.9
960	0.62	3.47	-4	0.62	3.51	49.2
1020	0.62	3.45	-4	0.62	3.50	49.3
1080	0.62	3.44	-5	0.62	3.50	49.5
1140	0.62	3.43	-6	0.62	3.49	49.6
1200	0.62	3.42	-6	0.62	3.49	49.7
1260	0.62	3.41	-6	0.62	3.48	49.8
1320	0.62	3.41	-7	0.62	3.48	49.8
1380	0.62	3.40	-7	0.62	3.47	49.8
1440	0.62	3.39	-8	0.62	3.47	49.9
1500	0.62	3.38	-8	0.62	3.46	49.8
1560	0.62	3.37	-8	0.62	3.46	49.8
1620	0.62	3.36	-9	0.62	3.45	49.8
1680	0.62	3.35	-9	0.62	3.44	49.7
1740	0.62	3.34	-9	0.62	3.44	49.7
1800	0.62	3.33	-9	0.62	3.43	49.6
1860	0.62	3.33	-10	0.62	3.43	49.5
1920	0.62	3.33	-10	0.62	3.42	49.5
1980	0.62	3.32	-10	0.62	3.41	49.5
2040	0.62	3.31	-10	0.62	3.40	52.3
2100	0.62	3.30	-10	0.62	3.39	56.2
2160	0.62	3.29	-11	0.62	3.38	57.8

	Battery D					
	D -18 3			D -18 3		
Time (s)	Current (A)	Voltage (V)	Temperature (℃)	Current	Voltage	Temperature (℃)
	±1%	±1%	±5	±1%	±1%	±2.2
0	0.62	3.46	22	0.62	3.59	26.5
60	0.62	3.46	12	0.62	3.58	35.2
120	0.62	3.46	9	0.62	3.58	39.3
180	0.62	3.52	7	0.62	3.57	47.7
240	0.62	3.52	6	0.62	3.58	54.8
300	0.62	3.50	4	0.62	3.57	49.1
360	0.62	3.49	3	0.62	3.57	46.8
420	0.62	3.48	2	0.62	3.56	46.5
480	0.62	3.47	1	0.62	3.56	50.7
540	0.62	3.46	0	0.62	3.56	50.0
600	0.62	3.45	-1	0.62	3.56	49.9
660	0.62	3.43	-2	0.62	3.55	52.7
720	0.62	3.42	-3	0.62	3.55	51.8
780	0.62	3.41	-3	0.62	3.53	52.8
840	0.62	3.40	-4	0.62	3.53	54.6
900	0.62	3.39	-4	0.62	3.53	53.0
960	0.62	3.37	-5	0.62	3.52	53.4
1020	0.62	3.37	-6	0.62	3.52	54.7
1080	0.62	3.36	-6	0.62	3.51	53.4
1140	0.62	3.35	-7	0.62	3.51	52.6
1200	0.62	3.34	-7	0.62	3.50	54.0
1260	0.62	3.29	-7	0.62	3.49	54.5
1320	0.62	3.28	-8	0.62	3.49	54.6
1380	0.62	3.27	-8	0.62	3.48	54.8
1440	0.62	3.26	-8	0.62	3.48	54.8
1500	0.62	3.26	-8	0.62	3.48	54.9
1560	0.62	3.25	-9	0.62	3.47	53.7
1620	0.62	3.25	-9	0.62	3.46	53.6
1680	0.62	3.24	-9	0.62	3.46	54.1
1740	0.62	3.24	-10	0.62	3.45	54.2
1800	0.62	3.23	-10	0.62	3.45	54.1
1860	0.62	3.22	-10	0.62	3.44	54.0
1920	0.62	3.22	-10	0.62	3.43	53.8
1980	0.62	3.21	-10	0.62	3.43	53.6
2040	0.62	3.18	-10	0.62	3.42	53.5
2100	0.62	3.17	-10	0.62	3.41	53.4
2160	0.62	3.17	-11	0.62	3.41	53.2

	Battery J (Control)					
	J 24 1			J 24 2		
Time (s)	Current (A)	Voltage (V)	Temperature (℃)	Current	Voltage	Temperature (℃)
	±1%	±1%	±2.2	±1%	±1%	±2.2
0	0.62	3.63	24.8	0.62	3.63	25.6
60	0.62	3.62	24.6	0.62	3.61	25.4
120	0.62	3.61	24.6	0.62	3.60	25.2
180	0.62	3.60	24.4	0.62	3.60	25.1
240	0.62	3.59	24.3	0.62	3.59	25.1
300	0.62	3.58	24.3	0.62	3.58	24.8
360	0.62	3.58	24.2	0.62	3.57	24.9
420	0.62	3.57	24.2	0.62	3.57	24.8
480	0.62	3.57	24.1	0.62	3.56	24.8
540	0.62	3.56	24.2	0.62	3.56	24.8
600	0.62	3.55	24.2	0.62	3.55	24.8
660	0.62	3.55	24.2	0.62	3.54	24.7
720	0.62	3.54	24.2	0.62	3.54	24.8
780	0.62	3.53	24.1	0.62	3.53	24.8
840	0.62	3.53	24.1	0.62	3.53	24.7
900	0.62	3.52	24.1	0.62	3.52	24.7
960	0.62	3.52	24.1	0.62	3.52	24.7
1020	0.62	3.51	24.1	0.62	3.51	24.7
1080	0.62	3.51	24.2	0.62	3.50	24.6
1140	0.62	3.50	24.1	0.62	3.50	24.6
1200	0.62	3.49	24.1	0.62	3.49	24.5
1260	0.62	3.49	24.1	0.62	3.49	24.6
1320	0.62	3.48	24.1	0.62	3.48	24.6
1380	0.62	3.48	24.2	0.62	3.48	24.6
1440	0.62	3.47	24.2	0.62	3.47	24.6
1500	0.62	3.47	24.1	0.62	3.46	24.6
1560	0.62	3.46	24.2	0.62	3.46	24.6
1620	0.62	3.45	24.2	0.62	3.45	24.6
1680	0.62	3.45	24.2	0.62	3.44	24.6
1740	0.62	3.44	24.2	0.62	3.44	24.6
1800	0.62	3.43	24.2	0.62	3.43	24.6
1860	0.62	3.43	24.2	0.62	3.42	24.6
1920	0.62	3.42	24.2	0.62	3.42	24.6
1980	0.62	3.41	24.2	0.62	3.41	24.6
2040	0.62	3.41	24.2	0.62	3.40	24.6
2100	0.62	3.40	24.3	0.62	3.40	24.6
2160	0.62	3.39	24.3	0.62	3.39	24.6

	Battery J (Control)					
	J 24 3			J 24 4		
Time (s)	Current (A)	Voltage (V)	Temperature (℃)	Current	Voltage	Temperature (℃)
	±1%	±1%	±2.2	±1%	±1%	±2.2
0	0.62	3.61	24.8	0.62	3.59	27.2
60	0.62	3.60	24.3	0.62	3.58	25.8
120	0.62	3.59	24.3	0.62	3.57	25.5
180	0.62	3.59	24.3	0.62	3.57	25.4
240	0.62	3.58	24.3	0.62	3.56	25.2
300	0.62	3.57	24.2	0.62	3.55	25.2
360	0.62	3.57	24.3	0.62	3.55	25.0
420	0.62	3.56	24.2	0.62	3.54	25.0
480	0.62	3.56	24.2	0.62	3.53	25.0
540	0.62	3.55	24.1	0.62	3.53	25.0
600	0.62	3.54	24.2	0.62	3.52	24.9
660	0.62	3.54	24.1	0.62	3.52	24.9
720	0.62	3.53	24.1	0.62	3.51	24.9
780	0.62	3.53	24.1	0.62	3.51	24.8
840	0.62	3.52	24.1	0.62	3.50	24.8
900	0.62	3.51	24.0	0.62	3.50	24.7
960	0.62	3.51	24.0	0.62	3.49	24.7
1020	0.62	3.50	24.0	0.62	3.49	24.8
1080	0.62	3.50	23.9	0.62	3.48	24.7
1140	0.62	3.49	24.0	0.62	3.48	24.7
1200	0.62	3.49	24.0	0.62	3.48	24.6
1260	0.62	3.48	24.0	0.62	3.47	24.6
1320	0.62	3.48	24.1	0.62	3.47	24.6
1380	0.62	3.48	24.0	0.62	3.45	24.6
1440	0.62	3.47	24.0	0.62	3.45	24.6
1500	0.62	3.46	24.0	0.62	3.45	24.6
1560	0.62	3.45	24.0	0.62	3.44	24.6
1620	0.62	3.45	24.0	0.62	3.43	24.6
1680	0.62	3.44	24.0	0.62	3.43	24.6
1740	0.62	3.43	24.0	0.62	3.42	24.6
1800	0.62	3.43	23.9	0.62	3.41	24.6
1860	0.62	3.42	23.9	0.62	3.41	24.6
1920	0.62	3.41	24.0	0.62	3.40	24.6
1980	0.62	3.41	24.0	0.62	3.39	24.6
2040	0.62	3.40	23.9	0.62	3.39	24.6
2100	0.62	3.39	23.9	0.62	3.38	24.6
2160	0.62	3.39	23.9	0.62	3.38	24.6

	Battery J (Control)					
	J 24 5			J 24 6		
Time (s)	Current (A)	Voltage (V)	Temperature (℃)	Current	Voltage	Temperature (℃)
	±1%	±1%	±2.2	±1%	±1%	±2.2
0	0.62	3.59	25.4	0.62	3.59	26.1
60	0.62	3.58	25.3	0.62	3.58	25.7
120	0.62	3.57	25.2	0.62	3.57	25.6
180	0.62	3.56	25.1	0.62	3.56	25.4
240	0.62	3.55	25.0	0.62	3.55	25.4
300	0.62	3.55	25.0	0.62	3.55	25.3
360	0.62	3.54	24.9	0.62	3.54	25.2
420	0.62	3.53	24.8	0.62	3.53	25.1
480	0.62	3.53	24.8	0.62	3.53	25.1
540	0.62	3.52	24.8	0.62	3.52	25.0
600	0.62	3.51	24.7	0.62	3.52	25.0
660	0.62	3.51	24.8	0.62	3.51	25.0
720	0.62	3.50	24.8	0.62	3.50	25.0
780	0.62	3.50	24.7	0.62	3.50	24.9
840	0.62	3.49	24.7	0.62	3.49	24.9
900	0.62	3.49	24.6	0.62	3.49	24.9
960	0.62	3.48	24.6	0.62	3.48	24.9
1020	0.62	3.48	24.7	0.62	3.48	24.9
1080	0.62	3.47	24.6	0.62	3.47	24.8
1140	0.62	3.47	24.6	0.62	3.47	24.8
1200	0.62	3.46	24.6	0.62	3.46	24.8
1260	0.62	3.46	24.6	0.62	3.46	24.8
1320	0.62	3.45	24.6	0.62	3.45	24.7
1380	0.62	3.44	24.6	0.62	3.44	24.7
1440	0.62	3.44	24.6	0.62	3.44	24.7
1500	0.62	3.43	24.6	0.62	3.43	24.8
1560	0.62	3.43	24.6	0.62	3.43	24.7
1620	0.62	3.42	24.5	0.62	3.42	24.7
1680	0.62	3.41	24.5	0.62	3.41	24.8
1740	0.62	3.41	24.6	0.62	3.41	24.7
1800	0.62	3.40	24.5	0.62	3.40	24.7
1860	0.62	3.39	24.6	0.62	3.39	24.8
1920	0.62	3.39	24.6	0.62	3.39	24.7
1980	0.62	3.38	24.6	0.62	3.38	24.7
2040	0.62	3.37	24.6	0.62	3.37	24.7
2100	0.62	3.37	24.6	0.62	3.37	24.7
2160	0.62	3.36	24.5	0.62	3.36	24.6

Table 6: Oven temperature during discharge at 50℃

Time (mins)	Battery A: ambient temperature (℃) ±4			Battery B: ambient temperature (℃) ±4		
	A 50 1	A 50 2	A 50 3	B 50 1	B 50 2	B 50 3
0	50	46	53	47	45	50
5	53	47	51	55	51	49
10	47	53	51	51	53	49
15	50	52	50	53	52	56
20	50	51	50	50	50	52
25	50	49	50	51	51	53
30	48	50	48	51	50	51
35	47	50	53	48	49	51

Time (mins)	Battery C: ambient temperature (℃) ±4			Battery D: ambient temperature (℃) ±4		
	C 50 1	C 50 2	C 50 3	D 50 1	D 50 2	D 50 3
0	46	48	49	45	46	46
5	50	52	48	53	52	55
10	52	50	52	50	51	52
15	51	50	50	51	51	52
20	50	52	49	48	50	47
25	51	50	51	50	49	51
30	51	52	51	50	47	49
35	50	51	51	52	51	49

Table 7: SOC and charging time after discharge

	1			2		
	SOC after -18 discharge (%)	Time taken to charge to 80% (min)	Rate of charge (%/min)	SOC after 50 discharge (%)	Time taken to charge to 80% (min)	Rate of charge (%/min)
	±8	±1	±0.045	±8	±1	±0.045
A	**30**	**87**	**0.575**	**35**	**83**	**0.542**
B	**39**	**78**	**0.526**	**38**	**81**	**0.519**
C	**40**	**74**	**0.541**	**44**	**79**	**0.456**
D	**42**	**76**	**0.500**	**47**	**73**	**0.452**
J	**45**	**75**	**0.467**	**44**	**76**	**0.474**

	3			4		
	SOC after -18 discharge (%)	Time taken to charge to 80% (min)	Rate of charge (%/min)	SOC after 50 discharge (%)	Time taken to charge to 80% (min)	Rate of charge (%/min)
	±8	±1	±0.045	±8	±1	±0.045
A	**24**	**98**	**0.571**	**33**	**87**	**0.540**
B	**39**	**81**	**0.506**	**40**	**77**	**0.519**
C	**39**	**80**	**0.513**	**45**	**78**	**0.449**
D	**40**	**77**	**0.519**	**46**	**78**	**0.436**
J	**47**	**72**	**0.458**	**44**	**75**	**0.48**

	5			6		
	SOC after -18 discharge (%)	Time taken to charge to 80% (min)	Rate of charge (%/min)	SOC after 50 discharge (%)	Time taken to charge to 80% (min)	Rate of charge (%/min)
	±8	±1	±0.045	±8	±1	±0.045
A	**37**	**82**	**0.524**	**37**	**81**	**0.531**
B	**39**	**79**	**0.519**	**40**	**80**	**0.500**
C	**40**	**77**	**0.519**	**40**	**77**	**0.519**
D	**43**	**71**	**0.521**	**47**	**78**	**0.423**
J	**43**	**74**	**0.500**	**44**	**74**	**0.486**

After discharge in -18℃ environment
After discharge in 50℃ environment
After discharge in 23℃ environment

8. Works Cited

1. Barcellona, Simone, et al. "Aging Effect on the Variation of Li-ion Battery Resistance as Function of Temperature and State of Charge." *Journal of Energy Storage*, vol. 50, June 2022, p. 104658. *Science Direct*, https://doi.org/10.1016/j.est.2022.104658. Accessed 2 Aug. 2023.
2. *Internal Resistance versus SOC*. 2017. *ResearchGate*, www.researchgate.net/figure/nternal-resistance-versus-SOC_fig2_312558387/actions #reference. Accessed 2 Aug. 2023. Chart.
3. "ISO 12405-1:2011." *ISO*, Aug. 2011, www.iso.org/standard/51414.html. Accessed 6 Apr. 2023.
4. Johnson, Keith, et al. *Advanced Physics for You*. 2nd ed., Oxford, Oxford UP, 2015.
5. Leng, Feng, et al. "Effect of Temperature on the Aging Rate of Li Ion Battery Operating above Room Temperature." *Scientific Reports*, vol. 5, no. 1, 6 Aug. 2015. *ResearchGate*, https://doi.org/10.1038/srep12967. Accessed 2 Aug. 2023.
6. Loveday, Steven. "Tesla Now Has Multiple Battery Options: Which One Should You Choose?" *InsideEVs*, 22 Mar. 2022. *InsideEVs*, insideevs.com/news/575956/tesla-battery-chemistries-explained/. Accessed 14 Aug. 2023.
7. Ma, Shuai, et al. "Temperature Effect and Thermal Impact in Lithium-ion Batteries: A Review." *Progress in Natural Science: Materials International*, vol. 28, no. 6, Dec. 2018, pp. 653-66. *Science Direct*, https://doi.org/10.1016/j.pnsc.2018.11.002. Accessed 4 July 2023.
8. Murashko, Kirill. "The Most Common Lithium-ion Cell Types." *ResearchGate*, Jan. 2016,

www.researchgate.net/figure/The-most-common-lithium-ion-cell-types_fig2_304023316. Accessed 19 Sept. 2023.

9. "Newton's Law of Cooling | First Order Differential Equations | Khan Academy." *YouTube*, 24 Sept. 2014, youtu.be/IICR-w1jYcA. Accessed 12 Aug. 2023.
10. Østby, Frode. *Internal Temperature Measurement in Lithium Ion Battery with FBG Sensors*. 2021. NTNU, MS thesis. *NTNU Open*, NTNU, ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2787184/no.ntnu%3Ainspera%3A80323407%3A17912670.pdf?sequence=1. Accessed 3 July 2023.
11. *Professional Battery Charger UC-4200 User Manual*. Ever Active. *Ever Active*, everactive.pl/uploads/UC4200_manual.pdf. Accessed 2 Aug. 2023.
12. Schematic Drawing of a Typical Lithium-ion Battery. 2016. *ResearchGate*, www.researchgate.net/figure/Schematic-drawing-of-a-typical-lithium-ion-battery_fig7_297719133. Accessed 4 July 2023.
13. Bal, Arie. Videoconference interview with the author. 4 May 2023.
14. Vollmer, M. "Newton's Law of Cooling Revisited." *European Journal of Physics*, vol. 30, no. 5, 24 July 2009, pp. 1063-84. *IOP Science*, https://doi.org/10.1088/0143-0807/30/5/014. Accessed 13 Aug. 2023. Abstract.
15. *Voltage and SOC Ratio Curve for Charging, OCV and Discharging*. 2018. *ResearchGate*, www.researchgate.net/publication/325286105_Overviewing_Quality_of_Electric_Vehicle_Charging_Stations'_Service_Evaluation. Accessed 2 Aug. 2023. Chart.
16. Yao, Xingyan. *Structure of 18650 Li-ion Battery.* Apr. 2019. *ResearchGate*, www.researchgate.net/figure/Structure-of-18650-Li-ion-battery_fig1_332203420. Accessed 13 Aug. 2023.