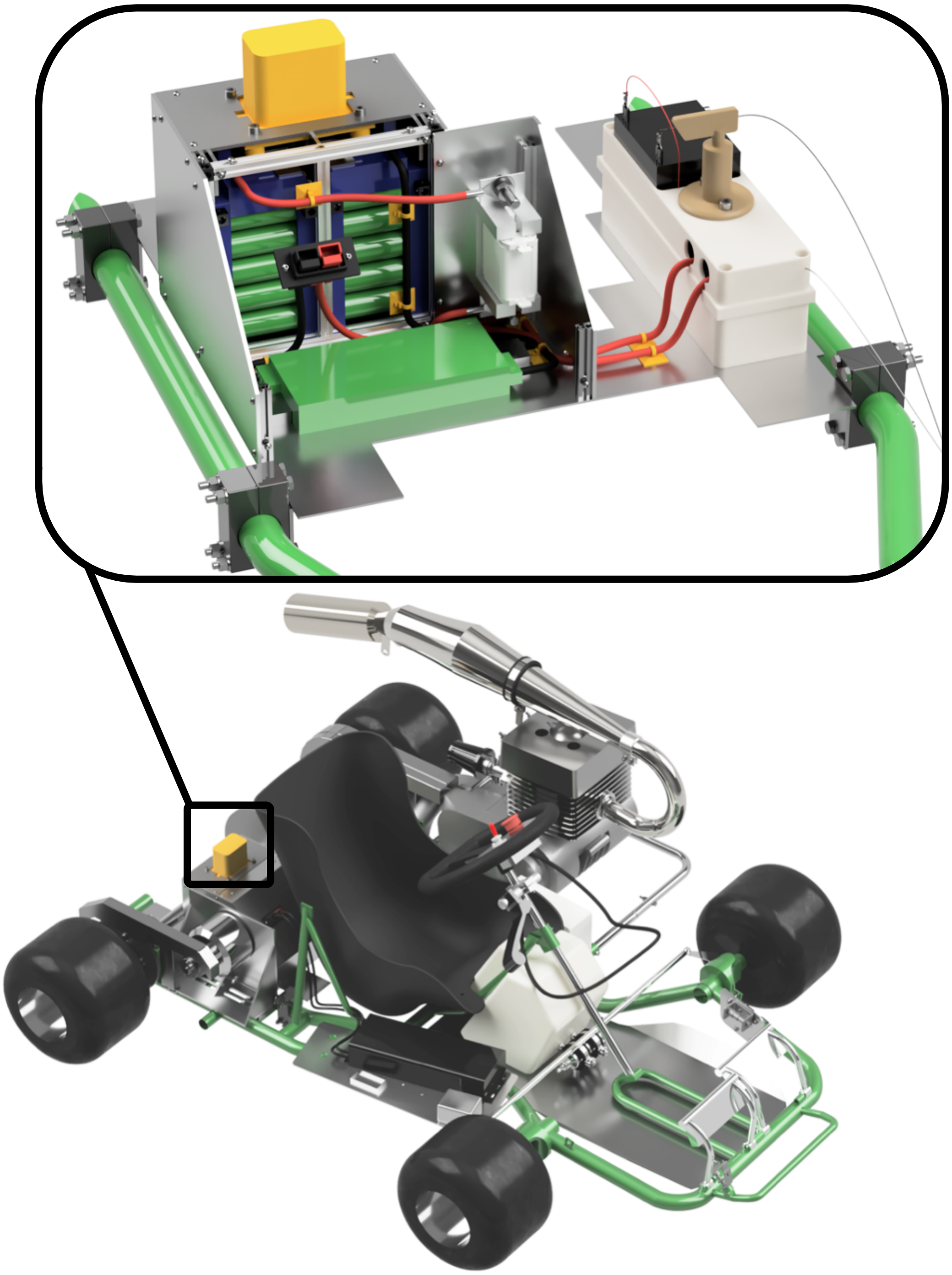
Department of Mechanical Engineering

ME3 Design, Make and Test

Imperial College London

DMT 8A - Hybrid Go-Kart Battery

Product Presentation and Test Report



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Acknowledgements

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Executive Summary

As a part of the hybrid go-kart superproject, the battery team has been tasked with designing, manufacturing, and testing a lightweight battery pack. The battery team successfully produced a 20S 2P battery pack with nominal voltage of 72V, consisting of two 10S 2P modules. It is capable of intermittently supplying 4kW to the electric motor during a 30-minute race with regenerative braking. Additionally, the team designed a 12V battery system to power the safety components of the high voltage battery pack and the components of the Fuel injection team. During the testing phase, the team conducted two critical tests. Firstly, a single cell discharge test was performed to assess the need for fan cooling. The results demonstrated that at 35A intermittent discharge, the cell temperature remained below the maximum temperature of 60°C, eliminating the need for additional fan cooling. Secondly, a 1C continuous discharge test was conducted on each module separately to verify the manufacturing quality and to identify any imbalances. The results have confirmed the consistency between the two modules, ensuring a safe series connection to form the battery pack. Subsequently, the battery pack was subjected to testing on the go-kart to evaluate its performance against requirements specified in the PDS. However, unforeseen strikes led to difficulties for other teams in delivering their subassemblies on time, resulting in multiple postponements of the road test on the go-kart. The road test will now be conducted after the submission deadline of this report, thus precluding the inclusion of the test results.

Future developments should concentrate on refining the casing design. Given the limited space available, designing a lightweight battery pack without compromising safety features poses a significant challenge. Additionally, conducting studies on battery pack degradation and the impact of vibrations would be beneficial in improving the reliability of the battery pack.

Overview of the Superproject

This superproject aims to utilise a combination of pre-existing and bespoke-designed components to create a competitive racing vehicle. Specifically, the approach involves repurposing a conventional combustion engine go-kart and retrofitting it with a parallel-hybrid drivetrain. This includes the replacement of two 4-stroke Honda GX160 engines with a single 2-stroke ETZ-250 engine, in parallel with a battery-powered, 18kW brushless DC (BLDC) electric motor. The go-kart is designed to be competitive with common 100cc and 125cc karts and achieve a drive time of 30 minutes with regenerative braking capabilities. All subassemblies required to realise the parallel-hybrid design were to be integrated onto the original kart, without any irreversible modifications to the chassis itself.

This project has been divided into four subassemblies, shown in Figure 1, each with a clear set of interfaces required for implementing the parallel-hybrid transmission design. The battery team is responsible for designing a battery pack, which accommodates regenerative braking and provides power to the BLDC electric motor and controller, when the engine runs below a pre-determined speed. This power is used when required, to accelerate the kart to the optimal speed range of the 2-stroke engine. The battery team is also tasked with designing a low voltage battery pack for the safety components and to provide power for the Fuel Injection team's subassembly. The E-motor & Drivetrain team is responsible for designing part of the parallel hybrid transmission, which incorporates the electric motor drivetrain, and chassis mounts for the motor and motor controller. This team is also to implement pedal position sensors for motor control and regenerative braking. The objectives of the Fuel Injection team include converting the carburetted ETZ250 engine into fuel injected and designing a new intake manifold. Finally, the Engine & Drivetrain team is responsible for designing the part of the parallel hybrid transmission which incorporates the 2-stroke engine drivetrain and a chassis mount for the engine, exhaust, and clutch system.

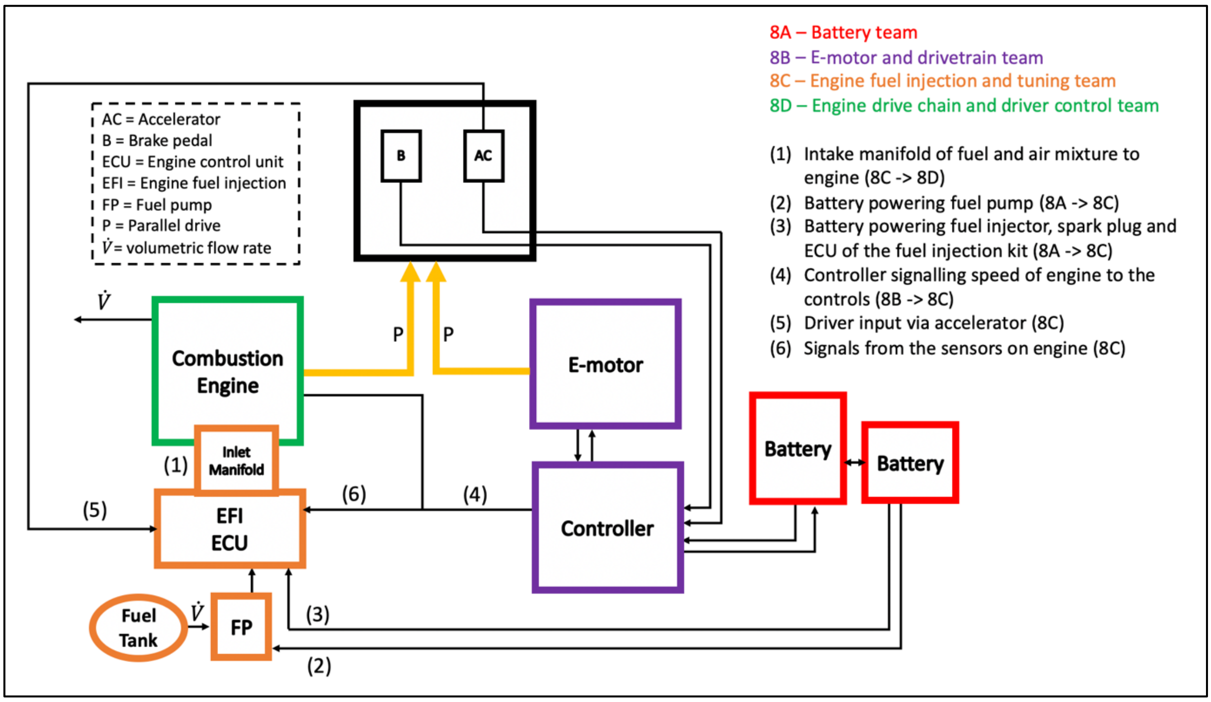

Figure 1 - Schematic diagram of the project interfaces

Project Description

Objectives and Priorities

The Product Design Specification (PDS) jointly developed with our client focused on four crucial aspects that largely steered the Lithium-Ion battery pack project. Firstly, the requirement for power delivery and capacity underscored the need for a battery pack capable of providing sufficient energy levels for a standard race distance. Equally as important, safety was a non-negotiable attribute, from electrical, thermal, and mechanical perspectives. Thirdly, tight space constraints were strictly defined, along with a crucial requirement that prohibited any modifications to the existing kart chassis. Finally, the weight of the battery pack was to be minimised within the bounds of other specifications.

Ultimately the client's objective was to have the kart operational and safe. This warranted a pragmatic approach, placing an emphasis on function over aesthetics. Given the paramount importance of delivering the functioning product, project risk management was a key concern, taking priority over performance optimisations.

To ensure adherence to these targets, in addition to analytical calculations, two key tests were performed. One in the design phase and one on the finished product. Prior to manufacturing, a single cell discharge experiment was set up to guide design decisions on thermal management. Once the battery pack was complete, each module was individually tested on a cycler to ensure their performance and quality.

Design Phase and Single Cell Test

Several requirements could be satisfied without the need for tests. Capacity and power delivery needs were met through a rigorous analytical cell selection procedure, accounting for the potential benefits of regenerative braking. While the nuances of this process were covered in the design review, the outcome achieved a balance between performance, cost, and weight (Appendix A). For electrical safety, the design incorporated three distinct shut-off mechanisms, alongside thorough insulation to prevent electrical faults, thus safeguarding both the equipment and users. Mechanically, the battery pack was protected by a casing based on safety guidelines suggested in the Formula Student rules (IMechE, 2023), which provided substantial protection against physical impacts or accidents.

Given the complexity of modelling thermal behaviour, the number variables proved difficult to quantify through purely theoretical modelling. Thus, a single-cell discharge test was conducted, providing crucial empirical evidence to guide choices on thermal management. A detailed description of the test will follow in the dedicated section. Based on its results and ergonomic considerations a strategic decision was made to reduce the output power of the battery pack by about 30%. This decision was based on two key reasons: firstly, it allowed to reduce the pack size, reducing potential issues arising from tight tolerances and lowering overall project execution risk. Secondly, capping the output power helped manage the heat dissipation effectively, ensuring operational temperatures to stay below the safety threshold of 60°C. Given the priorities laid out by the client, this trade-off between performance, safety and execution risk was considered worthwhile. All details were presented and discussed in the manufacturing review, so it will only be concisely summarised in Appendix B.

Module Assembly and Quality Control

Once all test-driven design compromises were finalized, the manufacturing phase commenced, spanning a period of approximately 10 weeks. Assembly and quality control of the casing and the battery modules were handled separately, with this section focusing on the latter. The modules were responsible for two key features from the PDS: safety and power delivery. In terms of safety two aspects were considered: Firstly, care was taken to thoroughly insulate all live surfaces and an acrylic insulation plate was secured between module connections. Secondly when working with the modules only one connection was exposed at a time, and PPE (lab coat, safety specs and rubber gloves) was worn. Consistency between manufacturing quality, discharge characteristics, and thermal behaviour was demonstrated with a discharge test which is detailed in a subsequent section. Figure 2 shows the completed modules with all key safety features next to the CAD design. Please note that the shape of the copper strips differs, this was only a minor change to make the welding process safer. As can be seen in the right side of Figure 2, the slits on the copper busbars originally aligned with the TIG weld locations and hence the shift from square to H-shaped busbars allowed for realignment of these slits thereby making the welds stronger and safer.

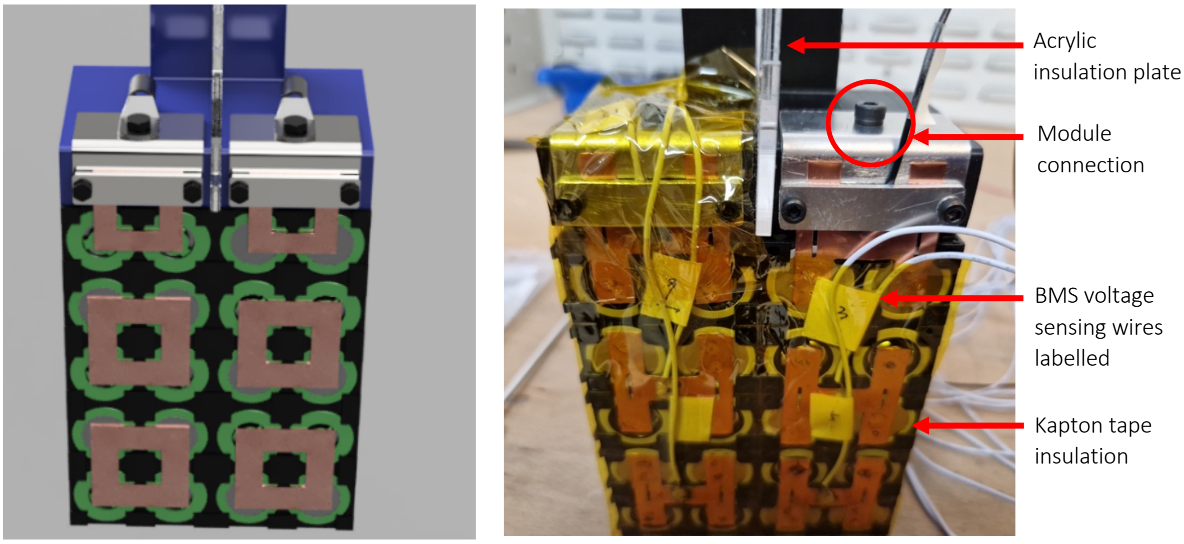

Figure 2 - Module assembly

Once the modules were inspected and tested on a battery cycler, they were placed into the casing.

Compliance with PDS

In this section, the completed product will be showcased from various angles to present key design features that fulfil the main points from the PDS.

Figure 3 shows the assembled battery pack without the protective lid to highlight all electrical safety features. In addition to the fuse, three independent shut-off mechanisms are available: a high voltage switch ensures a safe series connection between the two modules, a master switch disconnects the terminals, and a safety switch provides the driver with quick access to disconnecting the battery.

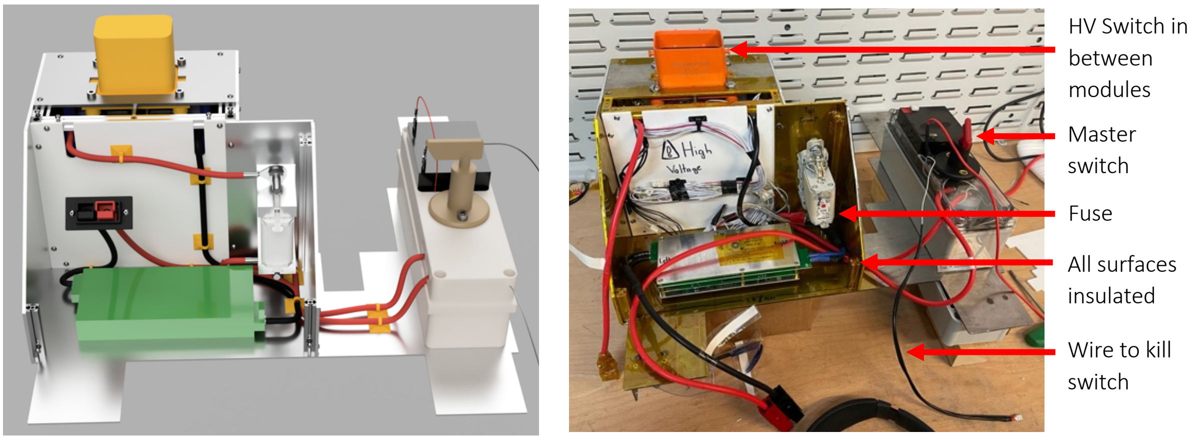

Figure 3 - Open casing safety features

With all electrical connections insulated and protected within their casings, the battery pack was mounted on the kart chassis. Figure 4 shows how four removable mounts attach the battery casing to the kart, without the need for any modifications to the chassis, satisfying this key requirement. When not operational, the module connections were taped to insulate any accidental shorts, master switch turned off and HV switch disengaged.

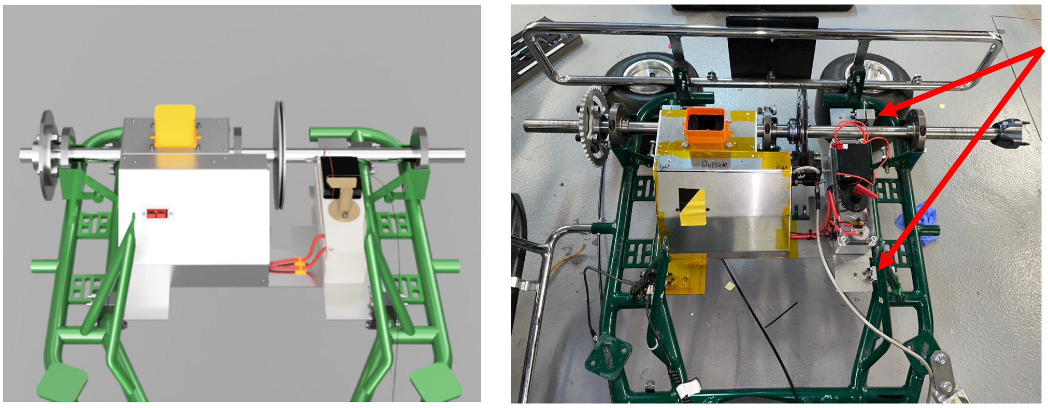

Figure 4 - Mounting mechanism

As discussed with the other teams in the superproject, the battery pack was mounted as the first component. As a result, the interfaces between teams were added after the battery installation. Referring to Figure 1, two responsibilities were to be fulfilled. Firstly, the main battery pack was to power the e-motor, with an Anderson connector going to the motor controller. Secondly, the 12V battery was to power the electronics of the fuel injection team. Figure 5 shows how these connections were made.

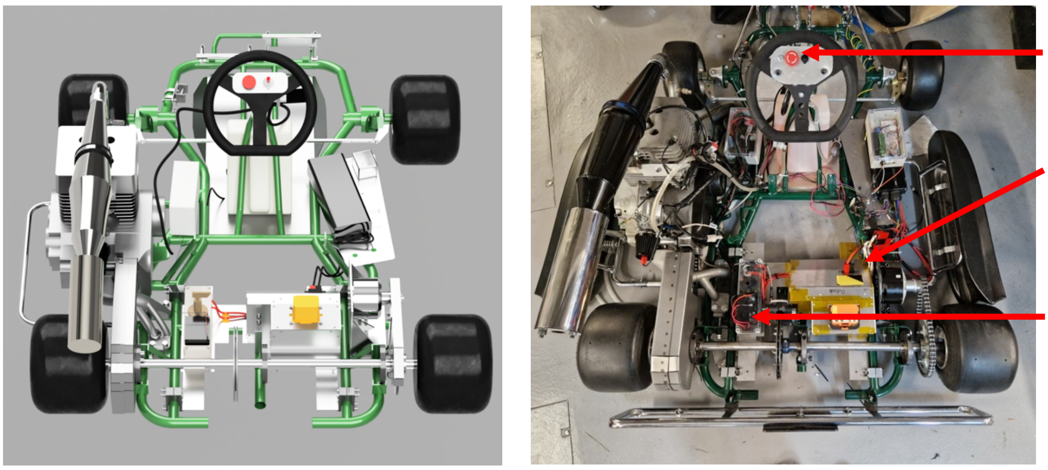

Figure 5 – Interfaces between subassemblies

The final requirement to address was ensuring ergonomic integration within the kart's space envelope. This proved challenging due to the complex geometry of the kart seat and the absence of an accurate CAD model. To compensate for potential seat flex under the driver's weight - another difficult factor to model - additional clearance was incorporated, accommodating these uncertainties, and enabling a satisfactory fit of the battery pack. Figure 6 demonstrates the absence of any interference between subassemblies, including the connections, and the seat while Dr. Alexis was seated in the kart.

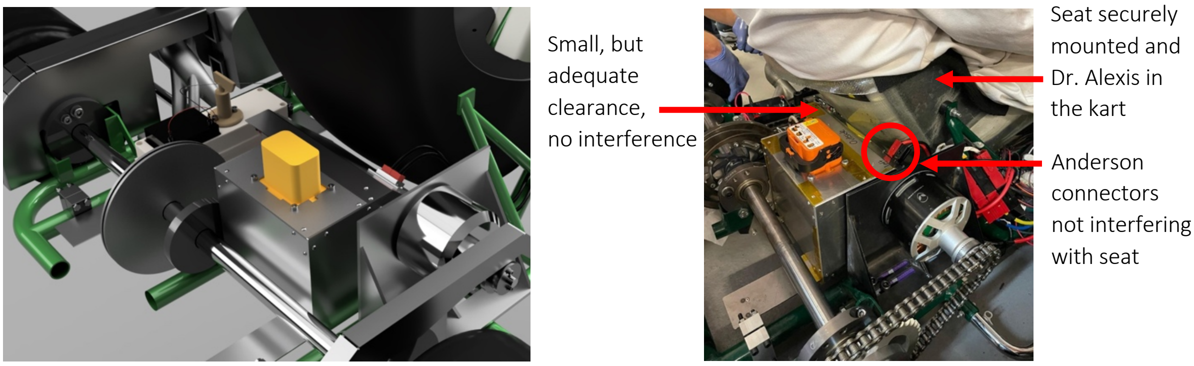

Figure 6 - Final ergonomics

Road test

In addition to the aforementioned tests, a comprehensive track test at Rye House karting was scheduled for 31st June to evaluate the collective performance of all subassemblies by operating the kart under real driving conditions. Unfortunately, unforeseen STW strikes had a significant impact on timelines of other teams' progress leading to the entire group ultimately missing the deadline, the track test was changed to a simple road test on campus for the 1st of June. Although the battery pack was ready and mounted to chassis by the 31st of May as planned in the Gantt chart (Appendix C), the whole superproject could not meet the deadline. It must be reiterated that other teams allowed the battery to be mounted first, potentially causing a slight delay in their schedules. Subsequently a new date has been set to after the submission deadline of this report, hence no results could be cited here.

Budget

The total budget for the battery subassembly was set at £1000. Initial estimates of costs after the Manufacturing gateway were set just under £1300. Electrical components were to make up about 70% of expenses, mechanical components about 27% with a few small purchases making up the rest. At the review, both the client and the supervisor suggested that the budget should not be a concern for safety expenditures and an 84V Battery Pack is over the College set safety limit of 60V.

Subsequently, there were a few more expenses on electrical and mechanical connections that were needed to appropriately insulate and secure the pack, but costs were saved on certain expensive components. By changing suppliers, the contactor price was halved, and significant savings were achieved on outsourced manufacturing. Overall, the final expenditure amounted to £1307 which is in line with the predicted budget but still over the initial allocated project budget. However, this includes a £345 safety spend to create multiple failsafe mechanisms to protect the user. If this over specified safety expenditure can be excluded, the net spend is £962 which is within the initial budget.

A detailed breakdown of the cashflow can be found in Appendix D and is divided into sub-sections to better illustrate how the budget was utilised.

Test 1 – Single Cell Discharge Test

Introduction

The single cell drive cycle testing was conducted on the Molicel INR-21700-P42A (Molicel, 2023) battery model (datasheet in Appendix A), under the guidance and supervision of Dr. Mohammed Samieian. This involved a two-pronged approach, both aiming to create an increasingly realistic worst-case scenario for the final operation. The first test was a continuous discharge at 45 at the maximum rated current of 45A while the second test aimed to simulate the drive cycle using available track data from telemetry. The main objective of these tests was to verify that the cell would be able to perform to the power delivery requirements set out in the PDS and understand how the cell behaves in contingency situations of high current draw.

Test Description

Both the tests were conducted in thermal chamber Binder KB23 with current load from cycler MACCOR. The test chamber of the battery cycler is thermally insulated and could actively adjust temperature to manually set the ambient conditions to 35°C. Additionally, all the fans in the test chamber were turned off to ensure no airflow or passive cooling effects on the cell.

The connection between the cell terminals and cycler terminals was established through the TIG welded copper strips which was securely clamped by copper blocks. The cycler terminals, comprising of load cables and voltage sensing wires, were bolted to the copper blocks, which were mounted on an acrylic sheet for insulation. The copper clamps, wire terminals, and bolts were further insulated by Kapton tapes to prevent short circuit during the test. A temperature sensor was also attached to the surface of the cell using Kapton tape. The entire test setup can be seen in Figure 7.

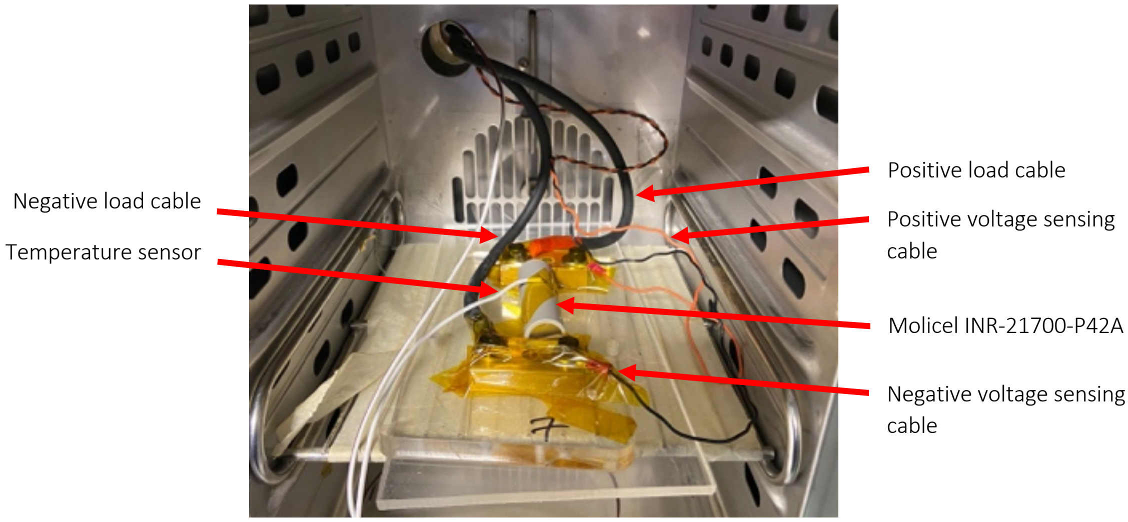

Figure 7 - Single cell discharge test setup

Firstly, the continuous discharge current load is illustrated below (Figure 8). To conduct the maximum current discharge test at 45A, various steps were coded into the cell cycler. First, the cell was charged to its maximum voltage of 4.2V, followed by a voltage hold to prevent voltage drops immediately after charging. Then, the cell was discharged at 45A until the voltage of the cell reached 2.5V or the surface temperature crossed 60°C. The detailed steps for this are as follows:

1. Rest for 1 min.
2. Constant Current (CC) Charge at 1C (4.2A) to 4.2V.
3. Constant voltage holds for 10 min.
4. Constant Current (CC) Discharge at 45A till temperature above 60 °C or voltage below 2.5V

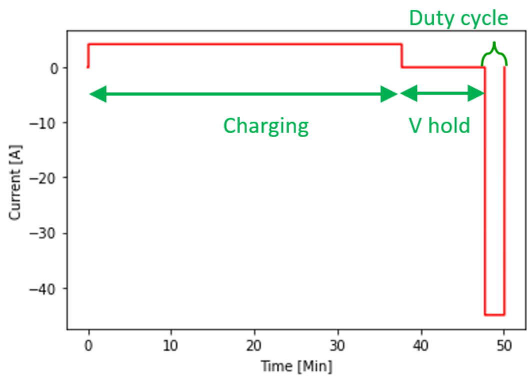

Figure 8 – Single cell 45A continuous discharge load

Secondly, to simulate the drive cycle discharge of the cell, an intermittent duty cycle was required. The initial steps remained the same in that the cell was first charged to 4.2V and then subsequently held at that voltage. The duty cycle was then configured into the cell cycler which comprised of 40 cycles of 10s of 35A discharge and 35s rest. The continuous discharge current load is illustrated below and shown in Figure 9.

1. Rest for 1 min.
2. Constant Current (CC) Charge at 1C (4.2A) to 4.2V.
3. Constant voltage holds for 10 min.
4. Stop when following steps repeated 40 times, voltage below 2.5A, or temperature above 60°C
    a. Constant Current (CC) Discharge at 35A for 10 seconds
    b. Rest for 35 seconds

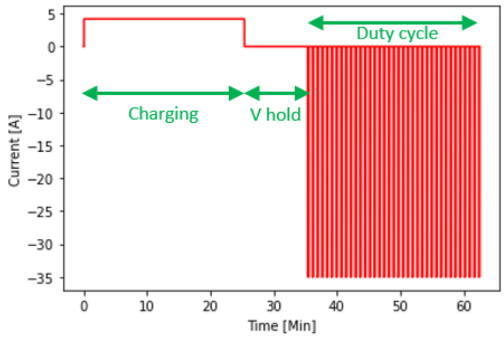

Figure 9 - Single cell 35A intermittent discharge load

Justification

The rationale behind discharging the cell at 45A was to understand the thermal behaviour of the cell at highest loading conditions under the advice of our supervisor for added safety. A similar philosophy of contingency management governed the decision to use an ambient temperature of 35°C which is higher than the expected temperatures for the testing conditions outlined in the PDS and by the client.

As outlined in the specification: the hybrid kart needed to compete in a 30-minute race at the Rye House karting track and the electric motor needs to be used when the engine shaft rotation speed is below 4000 rpm. The drive cycle simulation was derived from track telemetry data which indicated that the electric motor would be engaged for 10 seconds per lap over 40 laps where each lap was roughly 45s. The current draw of 35A from the cell was also calculated using the data and simulations from the motor and controller power specifications. The prevention of passive convection cooling results in reduced heat convection rate which increases the maximum temperature at the cell surface, thereby giving an upper estimate on cell temperature.

Test Results – Predicted

The 45A discharge is exceedingly high for a 21700 cell with a nominal capacity of 4.2Ah as it corresponds to a >10C discharge which would completely deplete the cell in under 6 minutes. Under continuous heavy current draw, it is expected that the temperature threshold will be the bottleneck step and that the test will stop due to overheating of the cell as opposed to the cell reaching 2.5V. However, the cell overheating is not a concern for the final design as the fuse is rated for 90A which implies that each cell will never stay under these loading cycles.

The drive cycle test result has a much stronger impact on design considerations. Calculations based off cell datasheets that were done during the cell selection process suggest that the cell will be able to provide current for the entire test without falling below the lower voltage limit and staying within the acceptable temperature bounds. This test served the purpose of verifying the capacity of the battery pack and obtaining more accurate temperature measurements of the cell under the intended load.

The battery cycler is configured to simulate a worst-case heating scenario to improve the validity of the conclusions drawn. However, a disadvantage of this is that should the cell fail the simulated drive cycle, it not indicative of PDS unfulfillment. Furthermore, there may be manufacturing defects between various cells and hence testing multiple samples would add statistical significance to the final data. However, given the quality of the supplier, it is a reasonable to assume uniformity across cells and since it is not possible to accurately predict drive cycle requirements, an upper bound is still beneficial.

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Test Results – Actual

All results of the continuous discharge test conducted on the single cell are illustrated in Figure 10. To focus on the voltage and temperature fluctuations during discharge, only the data from the final 5 minutes of the test were plotted.

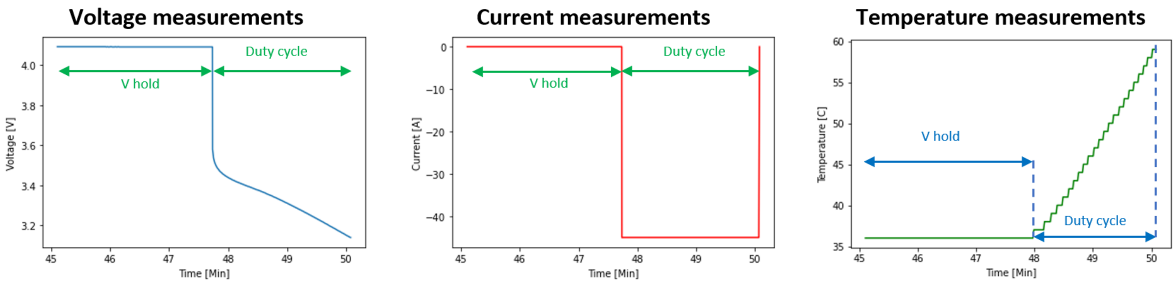


Figure 10 - Voltage and temperature result on single cell 45A continuous discharge

The surface temperature of the cell reached threshold of 60 °C within 2 minutes (120 seconds), which is significantly shorter than the total discharge time of 400 seconds from the real drive cycle. Therefore, in consideration with the downsized pack capacity, the discharge current of the intermittent drive cycle was lowered to 35A. The continuous discharge temperature plot changes linear with respect to time, due to the short period of testing, (Figure 10), and has discrete steps, which is caused by the quantization error of the temperature sensor (1°C). The result of intermittent discharge cycle of the single cell is shown in Figure 11: At the end of the 40 intermittent discharge cycles, the cell temperature remained under 60 °C and cell voltage was kept above 2.5V.

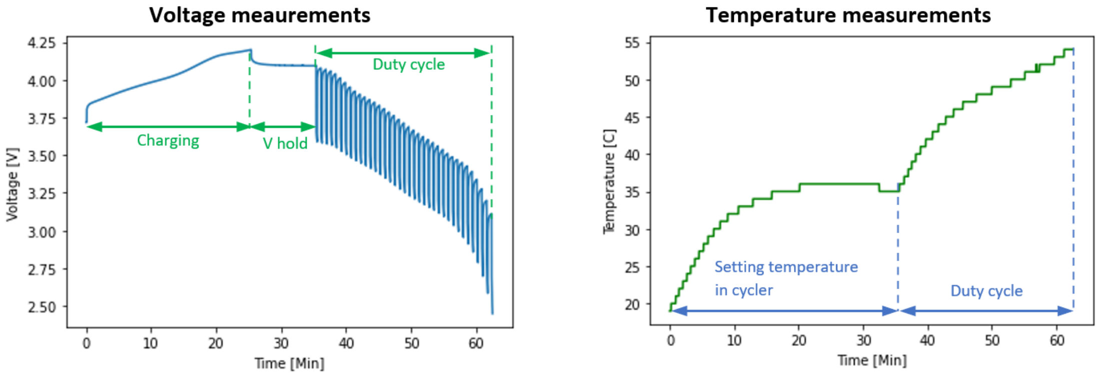
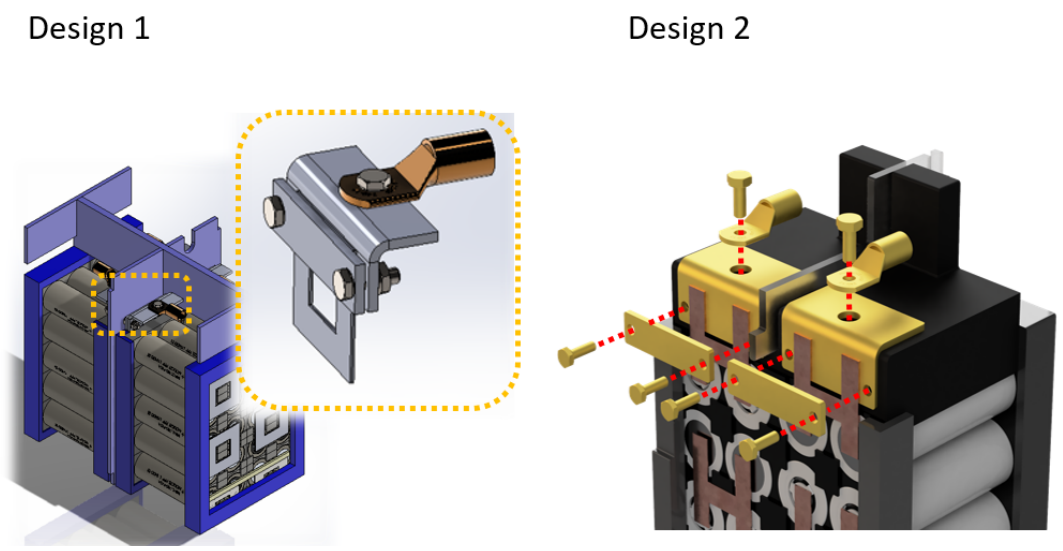


Figure 11-Voltage and temperature result on single cell 35A intermittent discharge

The temperature and time plot of the intermittent discharge graph shows the discrete step, which are due to the quantization error of temperature sensor. The duty cycle section of the temperature against time plot shows that the gradient of temperature variation is the steepest at the start of intermittent discharge cycle, then gradually decreases, and slightly increases at the end.

Discussion and Conclusion

This result substantiated the selected cell's capacity to fulfil the entire drive cycle in terms



of energy storage and its competence to operate under a 35A load without the need for active cooling components during racing conditions.

The shape of the temperature curve can be attributed to the following factors. The initial decrease in the gradient can be explained by the higher rate of convection heat dissipation as the temperature difference between the cell surface and the ambient air in the chamber increases. When a significant portion of the generated heat is dissipated from the cell, less energy is available to raise the cell's temperature, causing a slowdown in the rate of temperature increase. Additionally, the temperature gradient is influenced by the electrical properties of cylindrical cells. During discharge from 100% to 0% state of charge, the internal resistance of a cylindrical cell initially decreases and then rises. This change in internal resistance affects the heat generation, as represented by the equation $P = I^2R$, which varies with the state of charge. Consequently, there is a higher heat output at the beginning and end of the charge cycle, resulting in a more pronounced temperature gradient during intermittent discharge of a single cell. Therefore, the observed outcomes of single cell discharges align with principles of electronics theory.

However, the single cell discharge test encountered limitations when attempting to accurately replicate the genuine ambient conditions encountered by an individual cell within a battery pack. Despite the utilization of various measures such as deactivating the fans and establishing a controlled chamber temperature of 35°C, the boundary conditions surrounding single cells within the battery pack diverge due to the inherent inability of the test chamber to fully simulate the heat generation from neighbouring cells in the actual pack. This proximity consequently gives rise to an elevated ambient temperature, thereby impeding effective heat dissipation. Nevertheless, considering that the intermittent discharge test was simulated under an overestimate of the ambient temperature and operating power, it is reasonable to assume that the temperature within the actual pack would remain below the maximum threshold of 60°C.

Test 2 – Module Comparative Discharge Test

Introduction

The second meaningful test was conducted on both the modules of the pack to ascertain their performance in terms of power delivery and thermal characteristics. The objective is to validate the uniformity of the modules, the PDS requirements and to ensure balanced performance. This test was conducted with the help of Dr. Carlos Garcia from the battery lab as the primary advisor.

Test Description

Each module has 20 cells of Molicel INR-21700-P42A in a 10S 2P configuration resulting in a voltage that ranges between 25V and 42V at a 36V nominal rating. Each module therefore has a nominal capacity of 8.4Ah and a maximum continuous discharge current of 90A. To compare the modules, each was discharged to 30V at a rate of 1C discharge as advised by the project supervisor. The overall module setup and test apparatus is shown in Figure 12 and uses the Neware 2-channel 60V/150A Pack Cycler.

Module in test chamber | Voltage and Temperature Wires | Cycler and Data Acquisition

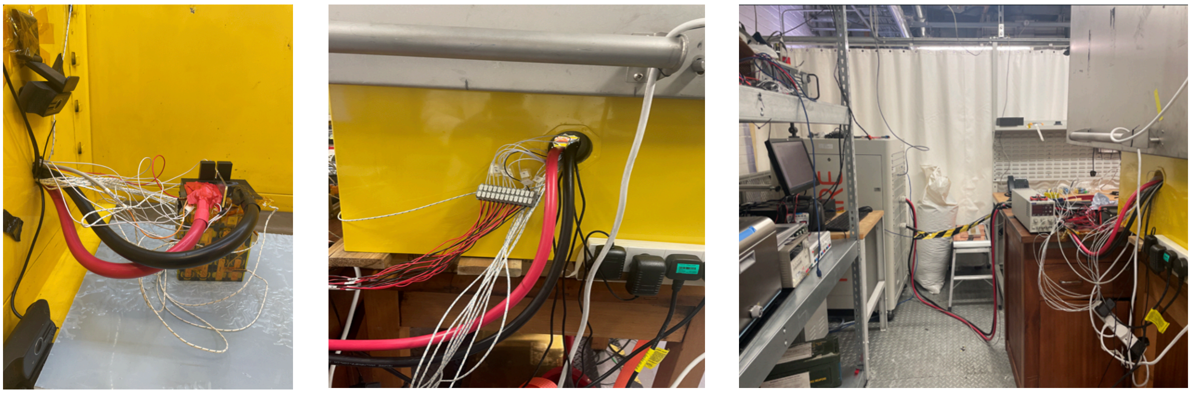


Figure 12 - Module test setup

After setting up the module to the module cycler, the following instructions were programmed:

1. Rest for 1 min.
2. Constant Current (CC) Discharge at 0.5C (4.2A) to 30V.
3. Rest for 30 min.
4. Constant Current/Constant Voltage (CCCV) Charge at 1C (8.4A) to 42V and subsequent voltage hold till current reduces to 0.168A.
5. Rest for 30 min
6. Constant Current (CC) Discharge at 1C (8.4A) from 42V to 30V.
7. Rest for 30 min.
8. Constant Current (CC) Charge at 1C (8.4A) to 36V.

The module cycler measured each various discharge characteristics including the overall and individual cell voltage, current, capacity, and energy with a time step of 1s. A Pico logger with 8 thermistors was used to monitor the temperature of the pack and it measured the average temperature every 1 second. Thermistors were strategically positioned for the test, with one placed on each module connection terminal and the remaining four distributed across the copper busbar

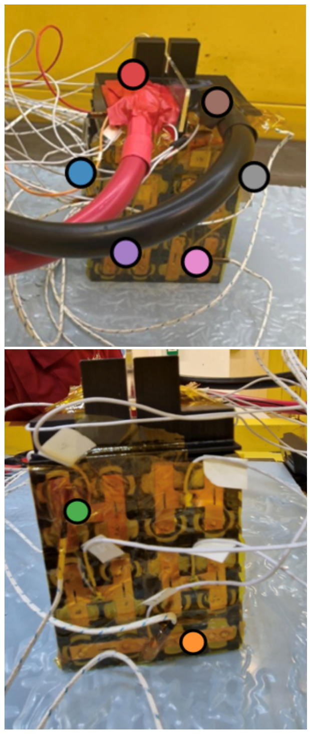


Figure 13 - Thermistor locations on the front (top) and back (bottom)

connections at both the front and back ends. These thermistors were kept in identical locations when testing the two modules. Figure 13 illustrates the locations of these sensors.

Justification

Each module was tested individually, not connected in series to get a better understanding of individual cell discharges to identify and prevent voltage imbalances. Testing and comparing the modules individually would also help in the identification of faulty electrical and mechanical connections such as the welds as those would heat up disproportionately. Considering the pack cycler has a maximum voltage of 60V it was not feasible to test the entire pack (which has a maximum voltage of 84V). Lastly, the Pico logger has only 8 channels for temperature monitoring and by testing modules separately, the thermal characteristics on each module can be measured more accurately. Given that module comparison was the aim of the test, a 1C discharge was chosen as opposed to the actual drive cycle to set a consistent and representative baseline for comparative analysis. It was also decided to only discharge the module to 30V as opposed to 25V as it would minimise battery degradation thereby preserving the cell life. The battery capacity towards the lower end of its voltage range (between 25V and 30V) only accounts for a small portion of the overall capacity and hence this decision does not result in significant performance losses.

Each step coded into the cycler was done with the help of Dr. Carlos with the aim of creating a standard operating procedure to enable accurate comparisons of the 2 modules. The voltage hold (Step 4) was conducted until 0.168A as it is the capacity of the module divided by 50 which is standard procedure. The location choices for the temperature sensors were made such that every key aspect of the module is monitored such as the module connections, busbar connections, and cells themselves. This was then used to decide where the four-temperature sensor could be attached to the pack when it is assembled. The test is both relevant and functional to the overall project as it can be used as evidence of design and manufacturing quality and, should the modules perform similarly, it is also evident that the entire pack will deliver power in a manner similar to the single cell discharge.

Limitations

While the test is an accurate and well-designed method to verify the performance of the overall design, there are still potential improvements and extensions that can be made. It would be beneficial to discharge the pack at various C rates to see how its performance and temperature parameters change with varying load. However, this is not necessary to demonstrate PDS fulfilment and would only result in cell degradation since the final design does not need to consider loading under multiple cycles. Furthermore, the limited cycler availability and voltage limit of 60V resulted in the entire drive cycle not being tested on the module and the entire pack not being tested. A superior cycler that could perform the drive cycle on the entire pack would be an insightful extension. The final limitation is the limited number of temperature inputs for a Pico logger. It would be better to have a sensor on every busbar to monitor the temperature, but since 8 sensors were available, they had to be spread out over various locations. However, this limitation is inconsequential as the BMS for the final design has only four temperature sensors and hence the module testing is already more specified. Overall, since there are a few limitations and possible extensions, the test remains highly relevant and insightful.

Test Results – Predicted Performance

Data from the Molicel P42A battery cell datasheet suggests that the cells can provide the current requirements of a 1C discharge at 8.4A with ease, as the specified maximum continuous discharge current is 45A. Similarly, considering that the welds and connections were made with extreme care and under supervision, it was also assumed that they would not result in remarkably high temperatures as the contact resistances are minimal. The operating conditions of the module as mentioned in the PDS, and datasheet can be defined as:

I. Voltage of each cell > 2.5V
II. Temperature < 60°C throughout.

It is predicted that the module performance will be well within these characteristics. Since a 1C discharge rate is high, there is expected to be a small amount of capacity loss but since the overall design is meant for a one-time use, this loss is insignificant.

Test Results – Actual Performance

The thermistor data can for both the modules is graphed in Figure 14 and Figure 15 to show the heat generated as the modules charge and discharge, the colour in the legend (Figure 16) corresponds to the labels in Figure 13.

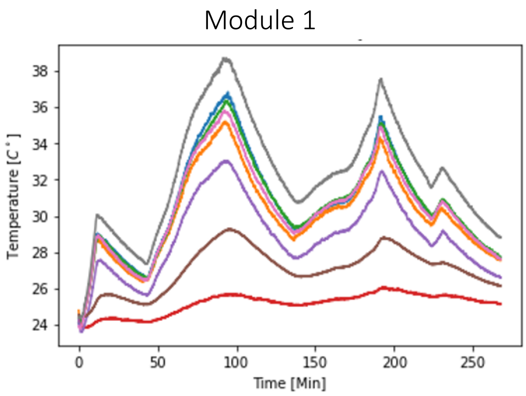


Figure 14 - Module 1 Thermistor Data

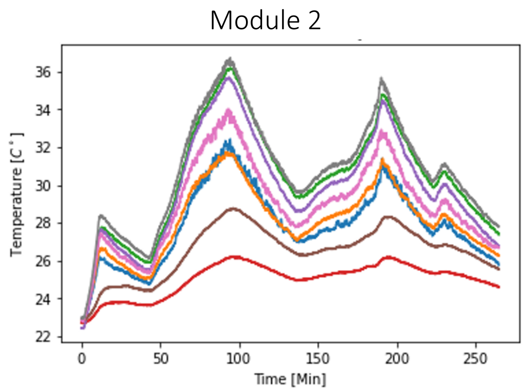


Figure 15 - Module 2 Thermistor Data

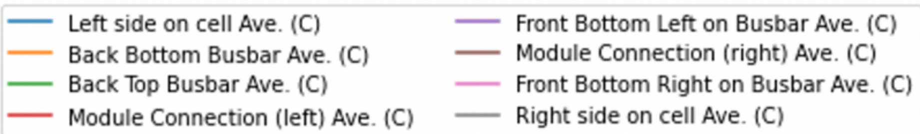


Figure 16 - Legend for the thermistor data

Finally, the performance parameters of the modules were also examined in addition to the thermal characteristics to create a holistic picture for design validity for current, voltage, capacity, and energy. These results are compared on the same graph for each parameter in Figures 17, 18, 19, and 20 respectively. Individual graphs for each have been included in Appendix E.

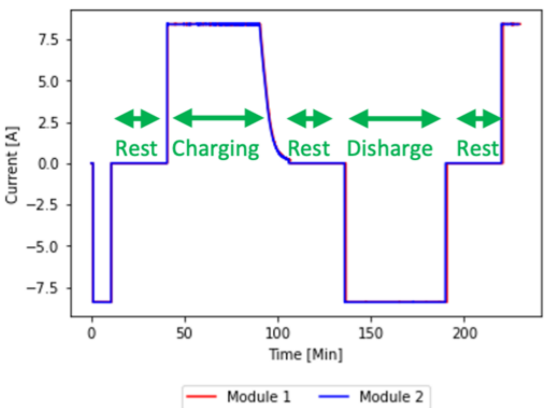


Figure 17 - Current Characteristics Comparison

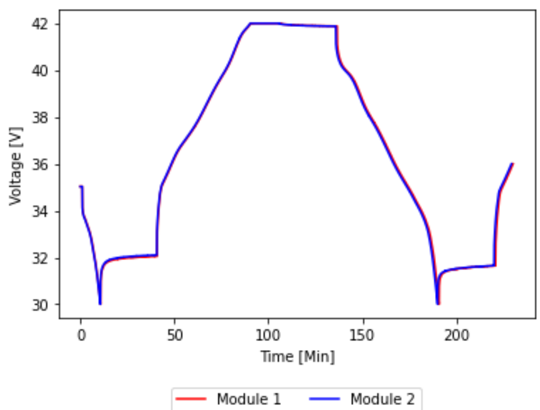


Figure 18 - Voltage Characteristics Comparison

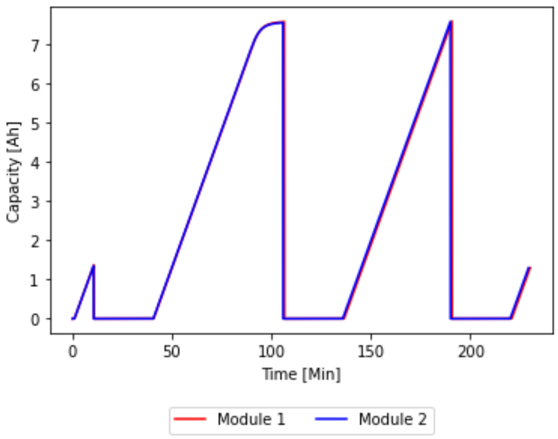


Figure 19 - Capacity Characteristics Comparison

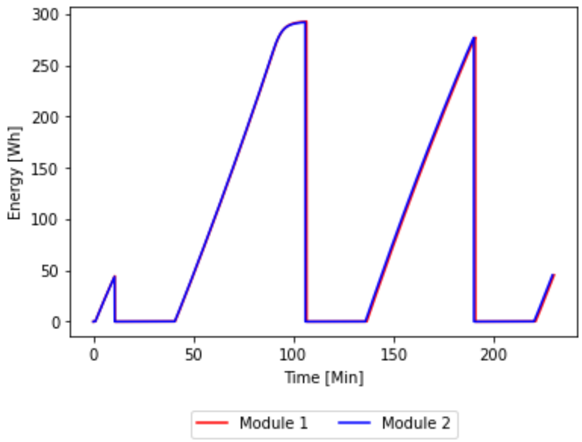


Figure 20 - Energy Characteristics Comparison

Discussion and Conclusion

Overall, the test showed promising results as both the modules perform in an exceptionally similar manner while being considerably under the temperature limit.

The highest temperature of both modules is measured to be approximately 40°C with module 1 having a slightly higher average temperature in comparison to module 2 as shown in Appendix E. It must be noted that ambient temperature effects the temperature data as the starting temperature of module 1 was higher than that of module 2 at the start of the test. Hence, the temperature changes are more relevant that the actual value of the temperature. The two modules perform almost identically showing deltas of similar magnitudes with a maximum temperature rise of 16°C. Another important aspect to consider when reading the temperature data is the effect of rest times. Out of all the steps performed, the 1C discharge was the key aspect that wanted to be analysed and a 30 minute rest period does not bring back the cell temperature back to ambient. Hence, the actual maximum temperature would be lower than the measured one given that the pack will start from ambient temperature when used for its intended purpose. Thus, it can be said with certainty that the thermal characteristics of the module and by extension of the pack are more than adequate to meet the PDS and safety requirements.

The performance parameters are also positive in that there is minimal capacity loss and a maximum voltage imbalance of 0.0334V across all the cells. Additional performance characteristics of the pack are nearly identical and overlap almost perfectly as evidenced in Figures 17, 18, 19, and 20. This points to satisfactory manufacturing quality and suggests that, should the pack be connected, it would perform as specified in the PDS. It is important to note here that voltage balancing between modules is a positive result but not a necessity as the modules is connected in series and hence a voltage difference is not as consequential as it the modules were in parallel. Nonetheless, the quality of all connections has been verified and performance characteristics have been deemed to be more than adequate.

The module testing allows for confirmation of the quality of connections and manufacturing as well as performance and thermal characteristics of the design. Thus, the reduction in size and decision to not have an active cooling system are justified. Furthermore, aside from confirming existing design and manufacturing decisions, the test allows for appropriate choice of placement for the thermal sensors for the final design. Since it was the cells themselves that saw the highest temperature rise, the BMS temperature sensors would be mounted along the cells of both the modules.

Conclusions and Recommendations for Further Work

Following the Manufacturing Readiness Gateway, the group has successfully manufactured and tested the 20S 2P battery pack with minor changes based on the feedbacks from the gateway. The battery pack is composed of two 10S 2P modules with Molicel INR-21700-P42A lithium ion cells, delivering 4kW to the electric motor to provide additional driving force. In terms of safety, the inclusion of an emergency kill switch, a contactor and a master switch ensure quick and reliable shut down capabilities in case of emergencies. The high voltage switch, fuse and battery management system protects the battery pack and the overall system, preventing any potential hazards.

The chosen tests, the single cell intermittent discharge test and the 1C continuous discharge test on the individual modules. The single cell test confirmed that additional fan cooling was unnecessary, while the modules tests verified manufacturing quality with minimal imbalances. To achieve the primary objective of making the go-kart operational, the battery pack was intended to test on the go-kart at the racetrack. Unfortunately, due to unforeseen strikes impacting the progress of other teams and their subsequent inability to deliver the required subassemblies on time, the test of the battery pack on the go-kart has been changed to a road test on campus, which has been postponed multiple times. Consequently, the test will now take place after the deadline for this report, rendering it unfeasible to include the corresponding results within this document.

For future development, a set of key lessons learned are to be noted. For weight reductions, it is recommended to explore alternative materials, or optimised shapes for the battery pack casing. In this project the lightweight requirement was compromised by safety features implemented, such as the 2mm steel base plate and the 3mm aluminium side plates to protect the battery pack from debris. To decrease manufacturing project risk, future teams are advised to be mindful of their choice of busbars and their current carrying capacity. Using copper strips as in this project increases the capacity four-fold, however it also introduces the need for TIG welding, a much more complex and risky process as compared to spot welding nickel strips. To enhance reliability, safety, and sustainability of the battery pack, studying battery pack degradation would be beneficial. This investigation can contribute to insights into improving long-term performances. Furthermore, conducting vibration tests to assess the impact of vibrations on the battery pack could prove valuable. This was unavailable to this project due to the lack of staff, who is component in supervising such tests. By implementing these recommendations, future projects can continue to refine the battery pack design enhance its reliability and ensure the highest standards of safety are met.

References

IMechE (2023) *Formula Student 2023 Rules*. Available at: https://www.imeche.org/docs/default-source/1-oscar/formula-student/2023/rules/fsuk-2023-rules---v1-2-(released-version---mar-23).pdf?sfvrsn=2.

Molicel (2023) *INR-21700-P42A Datasheet*. Available at: https://www.molicel.com/wp-content/uploads/INR21700P42A-V4-80092.pdf.

Appendices

Appendix A – Cell data sheet

To meet the power delivery and capacity requirements while minimising cost and weight, Figure 21 shows the iterative and methodology established and Figure 22 shows the result.

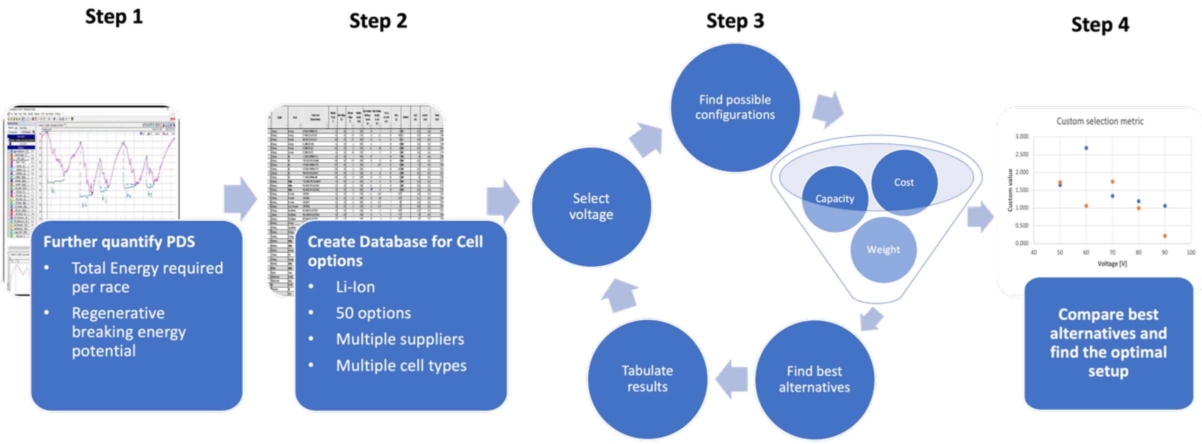


Figure 21 - Cell selection Methodology

MOLICEL®

LITHIUM-ION RECHARGEABLE BATTERY

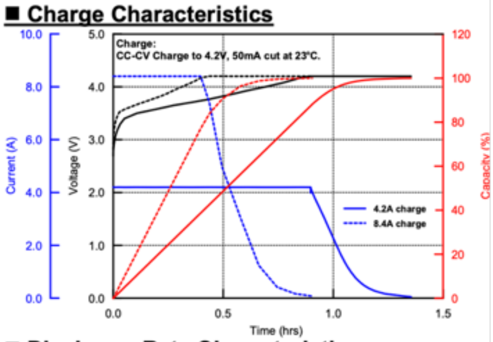
PRODUCT DATA SHEET

MODEL INR-21700-P42A

■ CELL CHARACTERISTICS

Capacity	Typical	4200 mAh 15.5 Wh
	Minimum	4000 mAh 14.7 Wh
Cell Voltage	Nominal	3.6 V
	Charge	4.2 V
	Discharge	2.5 V
Charge Current	Standard	4.2 A
Charge Time	Standard	1.5 hr
Discharge Current	Continuous	45 A
Typical Impedance	AC (1 KHz)	10 mΩ
	DC (10A/1s)	16 mΩ
Temperature	Charge	0°C to 45°C
	Discharge	-40°C to 60°C
Energy Density	Volumetric	615 Wh/l
	Gravimetric	230 Wh/kg

■ Charge Characteristics



■ Discharge Rate Characteristics

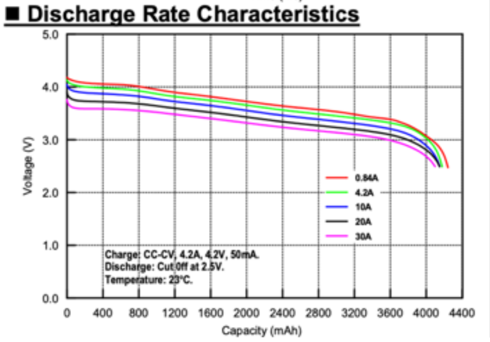


Figure 22 - Section of the Molicel INR-21700-P42A datasheet

Appendix B – Power downsizing

Originally the battery pack was designed with the power requirement of delivering 6kW of power continuously at all states of charge. This was based on the 6kW power limit on the motor controller, so essentially making the battery pack overpowered. Given the results of the single cell discharge test, without an active cooling system a maximum of 35A could be drawn continuously. This reduces the power output of the battery by 22%. A reduction in power means that less capacity is required, which in turn allowed an essential downsizing of the modules to ensure the required ergonomics. The original 28S 2P pack was reduced to a 20S 2P configuration. This lowered the output power further to about 30% of the original. Figure 23 shows the operating windows of the battery pack before and after downsizing. (More rigorous calculations were presented in the manufacturing review.)

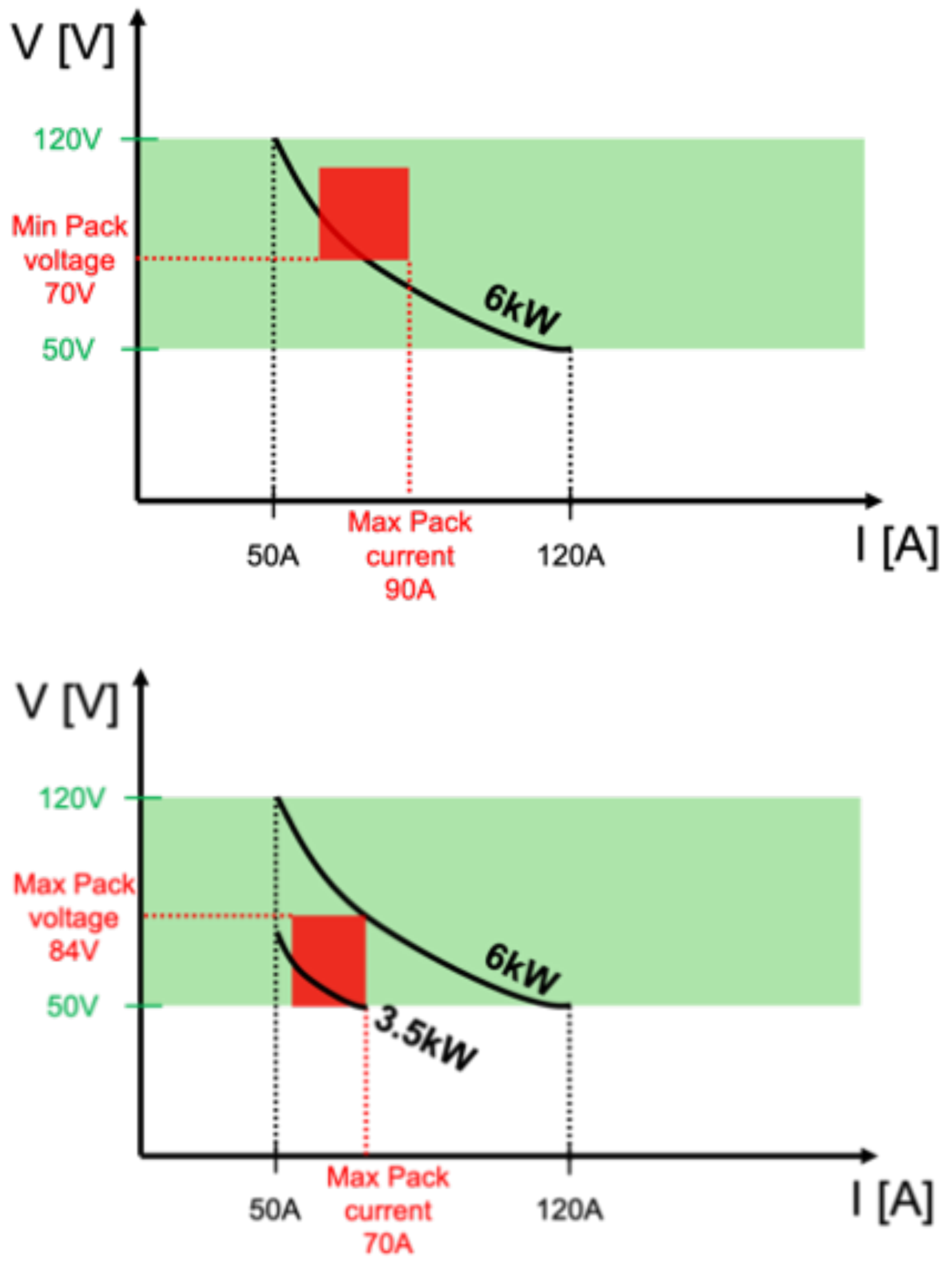


Figure 23 - Power output before (top) and after (bottom) downsizing

Appendix C – Gantt Chart

The Gantt chart in Figure 24 gives an overview of key stages during the manufacturing and testing phase after the manufacturing readiness gateway.

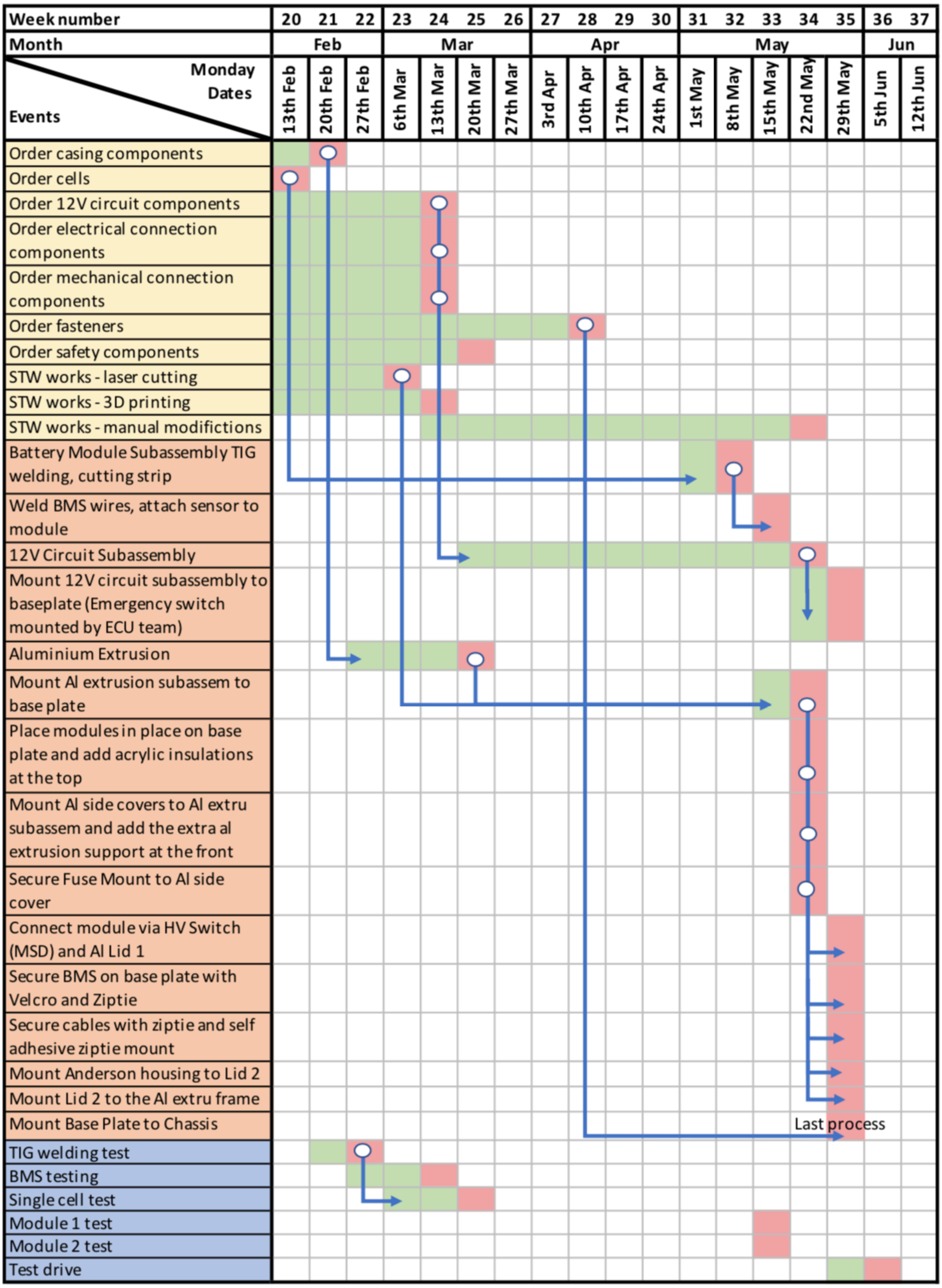


Figure 24 - Gantt Chart for manufacturing and testing phase

Appendix D – Expenses

DMT 08A EXPENSES BREAKDOWN				
Category	Item	Supplier	Quantity	Total Price
12 V	12V Lead Acid Battery Pack	RS Components	1	£ 31.63
			TOTAL	£ 31.63
HV Battery Pack	21700 Molicel P42A Cells	Cell Supply	70	£ 329.40
TOTAL				£ 329.40
Casing	12V Custom Box	Tao Bao	2	£ 5.00
	Steel Base Plate	ME Stores	1	£ 50.00
	Chassis Mounting Clamps	Tao Bao (Outsourced)	8	£ 95.00
	Al Extrusions	Technobots MarkerBeam	6	£ 68.16
	Corner Cubes for Extrusion	Technobots MarkerBeam	4	£ 61.44
	T Slots for Extrusions	Technobots MarkerBeam	6	£ 72.70
	Al Housing Plates	ME Stores	6	£ 40.00
			TOTAL	£ 392.30
Electrical Connections	Nickel Strips	Amazon	1	£ 9.00
	Copper Square Busbar	Fruugo	1	£ 61.62
	M4 8AWG Crimp Connector	Mouser	1	£ 23.22
	M6 8AWG Crimp Connector	Amazon	1	£ 8.09
	M8 AWG Crimp Connector	Amazon	1	£ 6.99
	Anderson Connectors	12 Volt Factory	2	£ 14.90
	8 AWG wires	Amazon	2	£ 21.23
	BMS cables	Tao Bao	30	£ 4.00
			TOTAL	£ 149.05
Mechanical Connections	Cell Brackets	Cell Supply	69	£ 12.32
	Threadlock	Amazon	1	£ 4.85
	Velcro	Amazon	2	£ 17.98
	Zipties	Amazon	1	£ 7.99
	Long Zipties	Amazon	1	£ 7.44
			TOTAL	£ 50.58
Fasteners	M4 Nuts	ME Stores	10	£ 0.30
	M6 Nuts	ME Stores	4	£ 0.12
	M4 Washer	ME Stores	4	£ 0.16
	M8 Nyloc Nuts	ME Stores	4	£ 0.20
	M4 Countersunk 30mm	ME Stores	8	£ 2.88
	M3x16 Socket Cap	ME Stores	10	£ 1.00
	M3x20 Socket Cap	ME Stores	10	£ 1.00
	M4x8 Socket Cap	ME Stores	14	£ 1.40
	M3x8 Socket Cap	ME Stores	4	£ 0.40
	M4x10 Socket Cap	ME Stores	4	£ 0.40
	M4x16 Socket Cap	ME Stores	4	£ 0.40
	M4x40 Socket Cap	ME Stores	4	£ 0.60
	M6x20 Socket Cap	ME Stores	4	£ 0.40
			TOTAL	£ 9.26
Safety	Fuse Subassembly	RS Components	3	£ 26.00
	Contactor	RS Components	1	£ 111.34
	Emergency Stop Switch	Tao Bao	1	£ 1.00
	HV Switch	RS Components	1	£ 176.93
	Voltage Isolator Switch	Amazon	1	£ 10.99
	High Voltage Stickers	Amazon	6	£ 3.49
	Orange HV Electrical Tape	Amazon	1	£ 4.99
	Kapton Tape	Amazon	1	£ 9.99
			TOTAL	£ 344.73
TOTAL EXPENDITURE				**£ 1,306.95**
TOTAL EXPENDITURE (EXCL. SAFETY)				£ 962.22

Figure 25 – Project expense breakdown

Appendix E – Module Testing Data

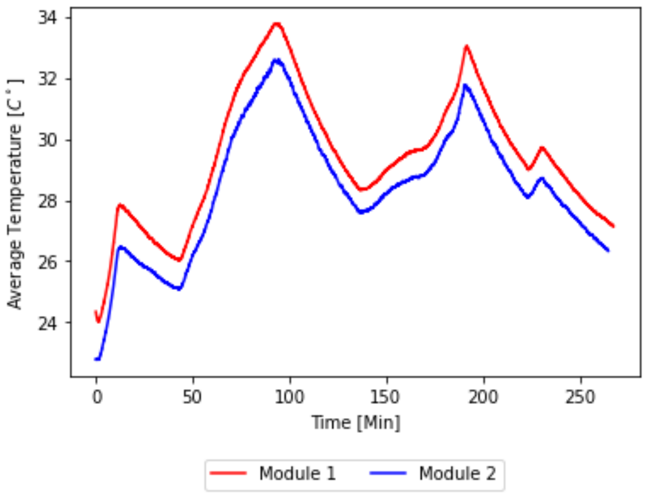


Figure 26 - Average Module Temperatures

Module 1

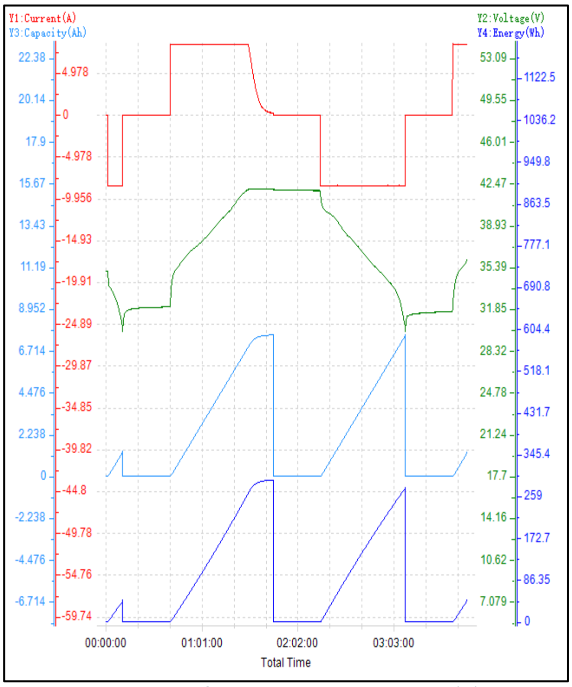


Figure 27 - Performance Parameters Module 1

Module 2

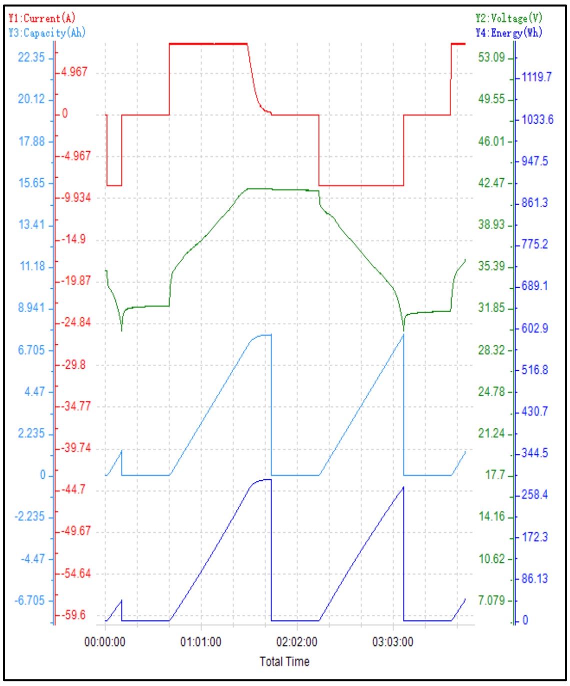


Figure 28 - Performance Parameters Module 2