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Bachelor thesis
Bachelor of Science in Engineering Technology:
Electronics-ICT

ACCUMULATOR DESIGN FOR A FORMULA STUDENT RACE CAR

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ENGINEERING SCIENCES

T 2.1.1

The vehicle must be designed and fabricated
in accordance with good engineering practices.

Abstract

This thesis tackles a common challenge in Formula Student teams: developing a reliable accumulator. Drawing from previous VUB Racing experience, the objective is to create a foundational accumulator design to serve as a blueprint for subsequent years.

Within this thesis, one phase of the multiyear project is undertaken: the design, manufacturing and testing of an accumulator segment. The segment is designed for a new accumulator that is reasonably dimensioned for VUB Racing's existing powertrain.

Considerable effort was invested in manufacturing a Formula Student rule-compliant accumulator segment. Utilizing 3D-printing for rapid prototyping, a design-for-manufacturing philosophy was implemented to optimize for the competition demands.

The finished segment underwent continuous discharge testing in a battery lab, where electrical and thermal characteristics were monitored to evaluate design decisions. Given the absence of active cooling, the hypothesis was that it might not withstand the tests.

The segment's testing demonstrated that its design is sufficient for short race lap durations, confirming its potential for integration within an electric race car. This finalized segment lays the essential groundwork for future researchers, enabling them to focus on its integration within the accumulator.

VUB Racing's electric powertrain has a promising road ahead. While the electrical puzzle of the accumulator has been solved, challenges remain in finalization of the complete accumulator and its vehicle integration.

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Nomenclature

AC	Air Cooled
AIR	Accumulator Isolation Relay
AMS	Accumulator Management System
AWD	All Wheel Drive
BMS	Battery Management System
BOTS	Brake Over Travel Switch
BSPD	Brake System Plausibility Device
CC	Constant Current
CV	Constant Voltage
EV	Electric Vehicle
FFF	Fused Filament Fabrication
FR	Fire Retardant
FS	Formula Student
FSG	Formula Student Germany
GLV	Ground Low Voltage
IC	Integrated Circuit
ICE	Internal Combustion Engine
IMD	Insulation Monitoring Device
IR	Infrared Radiation
LVS	Low Voltage System
MV	Medium Voltage
NC	Normally Closed
NO	Normally Open
NTC	Negative Thermal Coefficient
PC	Polycarbonate
PCB	Printed Circuit Board
RPM	Rotations Per Minute
RWD	Rear Wheel Drive
SAE	Society of Automotive Engineers
SDC	Shutdown Circuit
TIG	Tungsten Inert Gas
TS	Tractive System
TSAC	Tractive System Accumulator Container

1 Introduction

1.1 Context

1.1.1 Formula Student

Formula Student (FS) is an international design competition with 279 teams [1] partaking in 20 official events [2]. As can be read in Table 1-1 university students operate a team creating a smaller formula style race car.

Table 1-1: Formula Student Rules: Administrative Regulations [3]

A 1.1.1	The competition challenges teams of university students to conceive, design, fabricate, develop and compete with small, formula style, race cars.
A 1.2.1	The competition is split into the following classes: - Internal Combustion Engine Vehicle (CV) - Electric Vehicle (EV)
A 1.2.3	The competition starts with a series of technical inspections described in chapter IN to check the vehicle for safety and compliance with the rules.

The international competition sees most European Union teams following Formula Student Germany rules. FSG is the leading organisation that is responsible for updating these rules on a yearly basis. The German event at the Hockenheim ring is the largest Formula Student event (Table 1-2).

Table 1-2: 2022 European Formula Students competitions [4]

Competition country	Start date	No. of EVs	No. of ICEVs
Netherlands	July 9	22	16
Italy	July 13	26	25
Switzerland	July 13	15	EV only event
Czechia	July 18	22	19
Austria	July 24	30	24
Hungary	August 8	33	21
Germany	August 15	70	26
Croatia	August 23	31	14
Spain	August 29	38	15

Outside the EU, teams partake in Formula SAE events. SAE International is the organization providing the rulebook and organization of the non-EU events.

1.1.2 VUB Racing: a personal perspective

This document is conducted for the Formula Student team VUB Racing. During this academic year our 36-person team was focussed on building our 2023 car, EOS (Figure 1-1).

Figure 1-1: Eos on the Assen TT-Circuit during Formula Student Netherlands 2023

As a deputy manager, I co-led the team alongside team manager Alexis Salmon. While he oversaw the mechanical projects, I concentrated on the electrical architecture of the vehicle. Throughout our team leadership, our primary focus was on reorganizing the team to span over multiple faculties, aiming to enhance professionalism, and the team's cohesion.

Considerable time was dedicated to leading the electronics and autonomous department. The highlights include:

- Completely redesigning the electric vehicle architecture and delegating production of the newly developed sub systems to the members of our department.
- Writing a 65 page Electrical Systems Form documenting the electric vehicle architecture.
- Setting up 2 successful master theses within the autonomous department.
- Closely guiding 1 bachelor thesis about embedded design and manufacturing.

Competition wise, the newly reorganised team is too young and inexperienced to build a vehicle able to pass the rigorous technical inspections. This year, gathering scrutineering feedback was of the utmost importance. By building this foundation of knowledge and prioritizing easy sharing of information with the next year's team, we planned on increasing the team's future competitiveness.

This thesis exemplifies this way of thinking. By offering a tested and well-documented prototype it paves the way for future team members to continue research on the subject.

As we step into the roles of team leaders for the 2023-2024 season, Alexis and I have a clear vision: to dedicate our final year in Formula Student towards creating a robust, roadworthy, and well documented vehicle that will continue to benefit the future of VUB Racing.

1.2 Literature

1.2.1 Tractive system of a Formula Student race car

The tractive system (TS) powers the motors of the electric FS vehicle. It consists of: a shutdowncircuit safeguarding an accumulator that powers a motor through an inverter. Multiple motors and controllers (inverters) may be used.

Table 1-3: Formula Student Rules: TS Regulations [3]

EV 1.1.1	Tractive System (TS) – every part that is electrically connected to the motor(s) and TS accumulators.
EV 2.2.1	The TS power at the outlet of the TSAC must not exceed 80 kW.
EV 2.2.2	Regenerating energy is allowed and unrestricted.
EV 4.1.1	The maximum permitted voltage that may occur between any two electrical connections is 600 VDC.

FS-teams produce various powertrains, Table 1-4 shows a typical team's progression.

Table 1-4: Typical progression of a formula student powertrain [5]

2 motors		2 motors		2 motors		4 motors
RWD belt or chain transmission	▶	RWD in chassis planetary gearbox	▶	RWD in wheel planetary gearbox	▶	AWD in wheel planetary gearbox

VUB Racing is currently at the first stage.

1.2.2 Accumulator

There is no typical accumulator progression. FS-Accumulators designs are more flexible than the motors they power. The voltage of the accumulator is specifically dimensioned to align with the chosen motor configuration.

The capacity of the accumulator is dimensioned to meet the requirements for the dynamic FS events. Among these events, The lengthiest dynamic event is the Endurance Event (Table 1-5).

Table 1-5: Formula Student Rules: Endurance Regulations [3]

D 7.1.2	The length of one lap of the endurance track is approximately 1 km.
D 7.1.3	The length of the complete endurance is approximately 22 km

The use of regenerative braking is allowed. By allowing the vehicle to recover some energy during braking, it is possible to utilize a smaller accumulator capacity without sacrificing performance. This not only reduces the weight of the vehicle but also enhances its overall efficiency.

Completing a full endurance is not within the current capabilities of VUB Racing 2023 vehicle design. The lengthiest event would be 2 1.5 km laps during an autocross event [3].

The FSG magazine summarizes the design concepts of the participating teams. Figure 1-2 shows that most of the teams design a 6 kWh or larger accumulator.

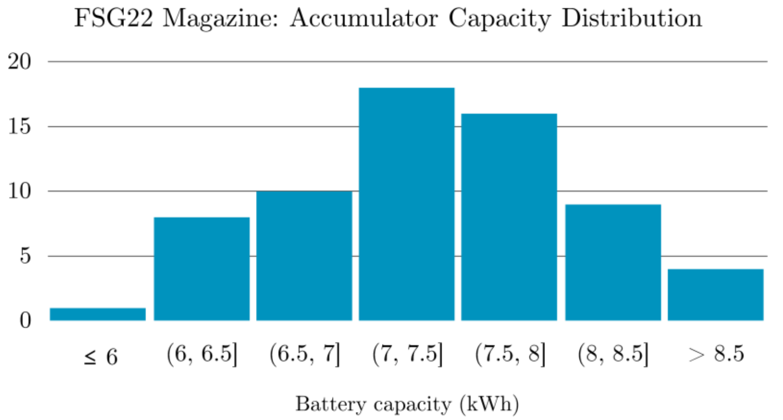


Figure 1-2: Histogram of accumulator capacity for FSG22 participants

Figure 1-3 shows the distribution between pouch and cylindrical cells used within the competition.

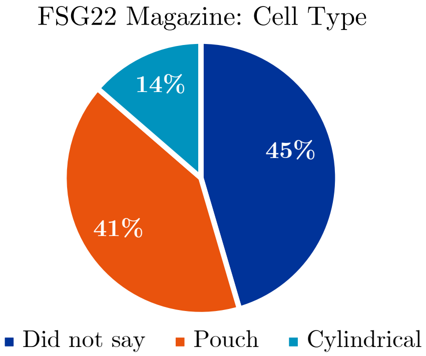


Figure 1-3: Pie chart of used accumulator cell type for FSG22 participants

The accumulator is enclosed in the Tractive System Accumulator Container or TSAC. This is a large metal or composite box usually housed behind or under the driver, dividing both using a firewall.

The TSAC houses:

- Accumulator segments containing the accumulator cells
- Accumulator management system (AMS or BMS)
- 2 accumulator isolation relays (AIR)
- Additional safety circuitry interacting with the shutdown circuit

1.2.3 Shutdown circuit

The shutdown circuit (SDC) controls the AIRs. This circuit is combined with different safety circuitry intended to protect the driver.

The SDC is considered open when the TS is intended to be disconnected from the vehicle side (e.g., a fault is detected).
The SDC is considered closed when the TS is intended to be connected to the vehicle side (i.e., the AIRs are closed).

The SDC can be simplified to a long series of normally closed (NC) and normally open (NO) switches, buttons, or relays. This is done in Figure 1-4.

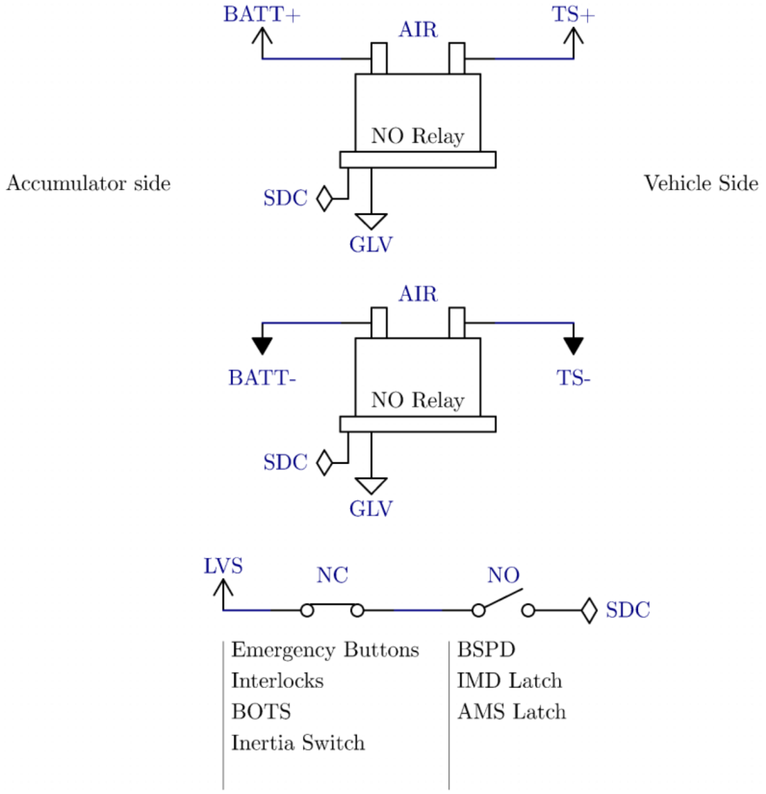


Figure 1-4: Simplified Formula Student shutdown circuitry

The safety systems that are of importance to this document are: the IMD latch and the AMS latch. The accumulator management system latch is responsible for opening the SDC when the AMS (i.e., BMS) detects a fault. When the insulation monitoring device (IMD) detects a fault the IMD latch opens the SDC. Both of these systems are often installed in the accumulator.

The negative pole of the accumulator must be isolated from the negative side of the low voltage system (LVS). The chassis is connected to the ground low voltage (LVS). This means that the metal accumulator container which is fastened to the chassis is considered LVS while the insides are considered TS. Galvanic isolation between the TS and the LVS is highly important within the design of an accumulator.

1.2.4 Competition accumulator designs

Formula Student is a design competition that allows teams to get inspired and replicate designs from their competitors. During the competition teams are judged by the designer's knowledge on their design integration. However, design choices are contingent on contextual factors, encompassing the team's experience, finances, and available workforce. A team must be vigilant of these factors while looking at other competition designs.

Segment design: Integrated BMS segment using PCB-welded cell tabs.
Team: Formula Electric Belgium - Koninklijke Universiteit Leuven

When visiting VUB Racing's neighbouring team Formula Electric Belgium, the experienced rivals showcased a previously used segment design (Figure 1-5). The team is still using this original design concept to this day. Within the competition, this is considered to be the peak of pouch cell segment design. By using a custom master/slave BMS implementing precisely fitted slave modules for the segments. A custom BMS mounted on the segment can save a lot of space when designing an accumulator.
The current of the segment flows through thick PCB traces. The enclosure is fire-retardant and professionally 3D-printed by Materialise. The cell tabs are laser welded to the PCB using professional machinery from Absolem. This omits the use of fasteners to build the cell stack. This is a massive plus during technical inspections as it is seen as a very reliable and safe design choice.

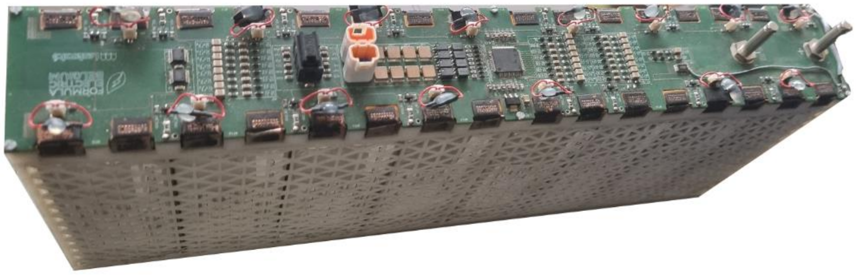


Figure 1-5: Formula Electric Belgium 2017 segment

Segment design: Integrated BMS module using bolted cell tab connections.
Team: Race UP Team - Università degli Studi di Padova

This integrated BMS design uses bolted connections for the cell tab (Figure 1-6). No specialized welding machinery is needed. Similar to Formula Electric Belgium, this design incorporates pouch cells manufactured by Shenzhen Melasta Battery Corporation [6].

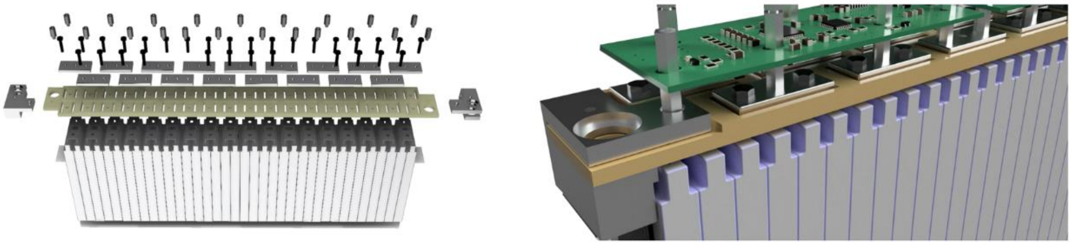


Figure 1-6: Race UP Team 2022 segment design [6]

Accumulator design: First year team cylindrical cell battery
Team: UGent Racing – Universiteit Gent

UGent Racing is a newly founded Belgian Formula Student team. VUB Racing visited their workshop and got a look at their 2022 accumulator design used for their first competition. The team did not pass the accumulator scrutineering that season. Cylindrical 18650 cells are arranged into 5 segments integrated inside an aluminium container. As can be seen in Figure 1-7; the design has clear separation of the segments and the other battery electronics. Kapton tape and isolating sheeting is used to isolate the conductive wall material. This is not an integrated BMS design as can be seen by the large wire loom going to a centralized cable conduit.

Figure 1-7: UGent Racing 2022 segments and accumulator container

1.2.5 VUB Racing accumulator designs

2017-2018

Designer: Robin Verbruggen

Figure 1-8: Accumulator design 2017-2018 (R. Verbruggen, 2018)

Besides the picture and some anecdotes. The documentation for this design is unavailable.

2018-2019
Designer: Jeroen Schelkens

Figure 1-9: Accumulator Build 2018-2019 [7]

Table 1-6: Specifications Accumulator 2018-2019

	Value	**Unit**
Maximum voltage	436.8	V
Nominal voltage	374.4	V
Capacity	8.4	kWh
Cell type	Cylindrical 18650	-
Cell capacity	2.5	Ah
Segment maximum voltage	109.2	V
Segment configuration	13s9p	-
Cooling Strategy	No cooling	-
Estimated total weight	80	kg

Notable:

- Spot welded 18650 segment design
- Self-developed integrated BMS
- Track tested at FS-Andorra in 2019

2019-2021

Designers: Noham Behe, Jeroen Schelkens and Yannick Vandervelden

Figure 1-10: Segment & 18650-module 2019-2021 [8]

Table 1-7: Specifications Accumulator 2019-2021

	Value	**Unit**
Maximum voltage	470.4	V
Nominal voltage	403.2	V
Capacity	8.4	kWh
Cell type	Li-ion 18650-modules	-
Cell capacity	2.600	Ah
Configuration	112s8p	-
Segment maximum voltage	67.2	V
Segment configuration	16s8p	-
Cooling Strategy	Air	-
Total cell weight	48	kg

Notable:

- First design using Energus Li2x4p25RT battery modules
- 2nd iteration on self-developed BMS
- Never completed

2021-2022

Designers: Iwan De Valckenaere, Alexis Salmon and Max Raes

Figure 1-11: Accumulator 2021-2022 [9], [10]

Table 1-8: Specifications Accumulator 2021-2022

	Value	**Unit**
Maximum voltage	151.2	V
Nominal voltage	129.6	V
Capacity	1.3	kWh
Cell type	Li-ion 18650-modules	-
Cell capacity	2.6	Ah
Configuration		-
Segment maximum voltage	67.2	V
Segment configuration	18s8p	-
Cooling Strategy	Liquid	-
Estimated total weight	100+	kg

Notable:

- 2nd iteration on 18650-module segment design
- 3rd iteration on self-developed BMS
- Water cooling using custom machined heat sinks
- 10 mm Aluminium for walls
- Container and 2 segments were built

Conclusions
The 2018-2019 accumulator was the only design that was finished and tested by the team. The thesis connected to this project found that spot welding cells negatively affected the manufacturability of the accumulator.

To tackle this problem in 2019, Energus battery modules were chosen. These modules consisted of 8-parallel 18650 lithium-ion cells, they were used in the team's next two accumulator designs. An accumulator project would never be completed using these specific cell modules.

A conclusion from the research included interest in assessing the feasibility of transitioning to the widely used Melasta LiPo pouch cells [10]. Unlike cylindrical cells, which have poles on opposite sides, the rectangular shape of these batteries places both poles on the same side. This simplifies the process of fastening them inside an accumulator segment, making them more straightforward to work with.

1.3 Scope of the project

As mentioned above, VUB Racing never succeeded in building a rule compliant accumulator. To address this difficult challenge, the team has decided to embark on a complete design overhaul. The new approach will focus on:

- **Ease of manufacturing:**
  Simplifying the design to facilitate production.

- **Reliability:**
  Ensuring that the accumulator will function consistently and dependably.

- **Realistic timeline:**
  Dimensioning the project to ensure it can be completed within a few seasons.

By concentrating on these pillars, VUB Racing aims to create a rule-compliant accumulator that is both effective and achievable.

October 2022
The 1 year thesis, Accumulator design for a Formula Student race car, would entail the design and build of a complete battery pack.

March 2023
After designing a first draft of the accumulator it was realised that finishing a rule compliant FS accumulator would take more than one year. A complete accumulator would not be part of the scope of this project. The goal would be to only do design work on the accumulator, while focussing on the build and testing of the segments.

June 2023
Finally, it was decided to manufacture and test 1 segment. Together with the finalized designs of the accumulator, future students would pick-up were this document ends and manufacture the final accumulator.

2 Tractive system accumulator container

2.1 Existing components

Before the design was started certain TS components were already chosen by the team. The accumulator powers 2 Emrax 208 motors controlled by 2 UniTek Bamocar inverters.

Table 2-1: Motor maximum values [11]

Motor	Emrax 208 MV AC	Unit
Maximum voltage	350	VDC
Continuous power	35	kW

Table 2-2: Inverter maximum values [12]

Inverter	Bamocar D3 700 160	Unit
Supply voltage	12 to 700	VDC
Continuous current	160	A
Continuous power	50	kW

Another fixed component is the BMS. The 96-cell version of the Orion 2 by Ewert Energy Systems inc. is a centralized BMS bought for this year's accumulator design. The BMS was bought last year because of a recommendation from another FS team. The BMS choice mainly restricts the segment design as it required to group cells in groups of 12.

Figure 2-1: Orion BMS 2 96-cell version (rear)

It is important to mention that the team started off with the 180-cell version. This product was exchanged for the smaller version for easier accumulator integration. The 180-cell model can be seen in some of the early TSAC designs represented in Appendix A: Accumulator Design iterations TSAC V1 – V.

2.2 Vehicle integration

The accumulator is located behind the firewall that sits between the driver and the TS components. To mount the accumulator our mechanical department designed the accumulator attachments (i.e., brackets).

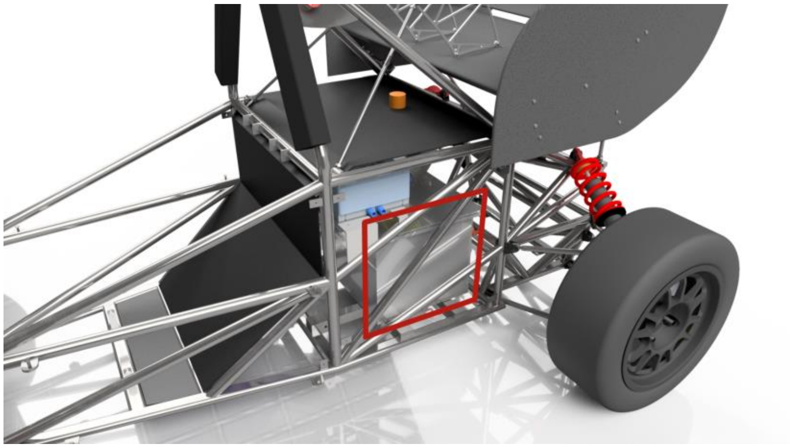


Figure 2-2: Accumulator location inside VUB Racing's 2023 race car

2.3 Voltage and capacity

Because of Section 2.1: Existing components, restrictions on the electrical design are put:

- **350 VDC max** dictated by motor choice (Table 2-1)
- **12S groups** dictated by BMS choice
- **Lithium-ion cells** max cell voltage ±4.2 V, nominal cell voltage ±3.6 V.

2.3.1 Option 1: 84s | 350 VDC max

This would result in the highest allowed TS voltage. Dividing the cell count by 12 gives us an uneven amount of 7 cell groups. This configuration was deemed unsuitable after designing a first draft of the accumulator. Due to its inefficient use of space (Figure 2-3).

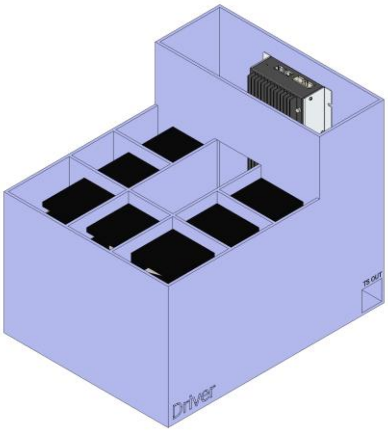


Figure 2-3: 7-segment TSAC design concept

2.3.2 Option 2: 72s | 300 VDC max (chosen configuration)

Six 12s cell groups are mechanically organized into three segments. The three battery segments consist of 24 cells, organized into two groups of 12 cells each. These groups are placed next to each other, with one group flipped in an alternating orientation. This configuration allows for a compact arrangement, reducing the overall size of the accumulator.

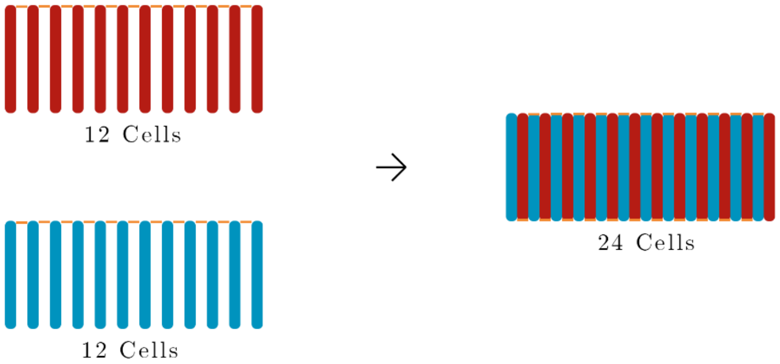


Figure 2-4: 24s segment cell grouping concept

In this arrangement, every cell is situated directly next to another, forming a closely packed configuration. This design was chosen because it represents the most compact grouping possible.

By choosing the 72s configuration the specifications of the accumulator can be represented in Table 2-3.

Table 2-3: Accumulator specifications

	Value	Unit
Maximum voltage	302.4	V
Nominal voltage	266.4	V
Capacity	2.4	kWh
Cell type	LiPo pouch cell	-
Cell capacity	8	Ah
Configuration	72s	-
Segment maximum voltage	100.8	V
Segment configuration	24s	-
Cooling Strategy	No cooling	-
Estimated total weight	37.4	kg

As clarified in Figure 1-2 the total capacity is low for a Formula Student vehicle. Completing a complete 22 km endurance run is not within the current goals of the team it was decided to build a 2.4 kWh accumulator that is smaller, cheaper, and easier to build.

2.3.3 Range estimate calculation

The team's competition goal is to complete 2 1.5 km autocross laps. Completing a 22 km endurance was not considered when dimensioning the battery.

Figure 2-5: TU Dortmund (GET Racing) driving the FSG 2023 autocross event (FSG, 2023)

Assuming a continuous speed of 70 km/h the 2.4 kWh battery would run the 2-motor vehicle for 4 minutes or 4.2 km (Appendix B. Calculations).

This is more than 2 laps. Leaving margin for mechanical losses.

2.4 Container

2.4.1 Design

The container of the accumulator, the TSAC, is heavily constricted by the FS rules.

Table 2-4: Formula Student Rules: Mechanical TSAC regulations [3]

EV 5.5.4	The TSAC(s) must be constructed of steel or aluminium. With the following requirements: - The bottom of the TSAC must be at least 1.25 mm thick if made from steel or 3.2 mm if made from aluminium. - The internal and external vertical walls, covers, and lids must be at least 0.9 mm thick if made from steel or 2.3 mm if made from aluminium. Alternative materials are allowed with proof of equivalency per T 3.3 or for composite materials per EV 5.5.5. This must be documented in the SES. When alternative materials are used, test samples must be presented at technical inspection
EV 5.5.6	The floor and walls of the TSAC must be joined by welds, bonding, and/or fasteners.
EV 5.5.8	The accumulator segments, see EV 5.3.2, must be separated by a rigid, electrically insulating and fire retardant barrier, see T 1.2.1.
EV 5.5.3	All TSAC materials as well as all structural parts must be fire retardant, see T 1.2.1.
T 1.2.1	Fire Retardant – A material meeting one of the following standards: - UL94 V-0 for the minimum used material thickness - FAR 25.853(a)(1)(i) Equivalent standards are only accepted, if the team shows equivalence and this is approved by the officials prior to the event.

As can be read in Table 2-4 TSACs are typically made out of aluminium or steel. A composite TSAC is allowed but at technical inspections equivalency has to be shown. With the team's experience in aluminium TIG welding aluminium 7075 was chosen as the container material. 4 mm inner walls and 6 mm outer walls.

For isolating the conductive walls from the insides of the container nonconductive sheathing (Mica insulator sheets) is glued to the walls.

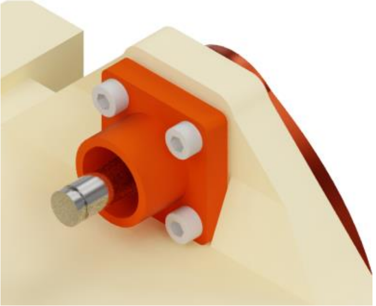


Figure 2-6: Maintenance plugs (Amphenol SurLok EV Connectors)

50 mm^2 EV-cabling is used to carry the current from one segment to another. Maintenance plugs (Figure 2-6) are used to disconnect the segments. With an ampacity of 200 A, the current limiting factor will either the segment busbars (calculated in Section 3.1.4) or the 35 mm 2 cabling used outside of the accumulator.

In Figure 2-7 the latest version of the complete accumulator design is shown. The 3 segments are separated by the inner walls leaving a section open for the electronics (green) and the OEM BMS. The AIRs and the main fuse are mounted on the left side of the accumulator separating the high voltage part from the electronics section.

In the CAD model, the blue parts represent covers that are bolted to the top portion of the segment to hide any potential open contacts. The segment core, which houses the cells, is highlighted in magenta to make them more easily identifiable.

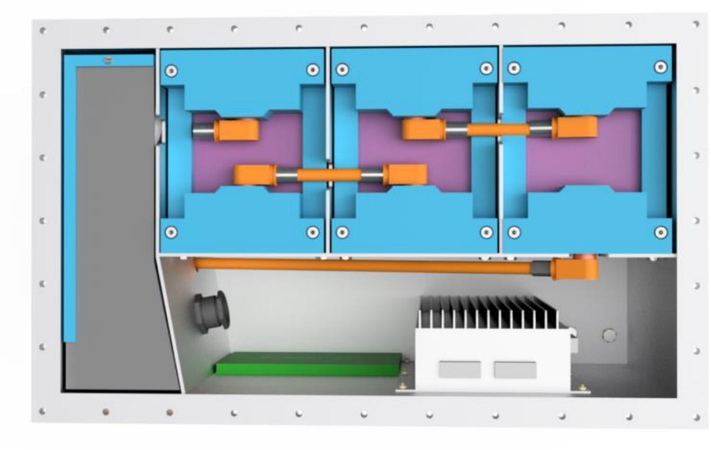


Figure 2-7: Accumulator container top view

A 3 pole connector is used to carry an extra ground conductor to the 2nd inverter. This can be seen in Figure 2-8.

Figure 2-8: Accumulator container perspective view with lid

2.4.2 Future plans

As discussed in the project scope in Section 1.3 the realization of the complete accumulator would be postponed to a future project.

Constructing a rule-compliant accumulator presents significant challenges. By emphasizing the completion and validation of the segment design, the team can strategically position itself to complete the entire accumulator within the next academic year.

To accomplish this task, a larger and more specialized team is required to focus solely on the accumulator. By bringing together the skills of both electronics and electromechanics students, it would be possible to finalize the accumulator within a year.

These students would have the following specific goals:

- Final iteration of the segment design and production of three copies
- Redesign of this document's accumulator container
- Manufacturing of the accumulator container
- Structural Equivalency Spreadsheet calculations and simulations [3]
- BMS integration
- Accumulator lab testing
- If possible, charger integration

Essentially, the accumulator team would have the intricate electrical work laid out, allowing them to concentrate on the structural challenges dictated by the FS-rulebook.

3 Accumulator segment

3.1 Design

3.1.1 Cell choice

VUB Racing has five years of accumulator experience. The team has encountered integration issues while using cylindrical cells. Last year A. Salmon recommended switching over to lithium polymer pouch cells made by Melasta [10].

Shenzhen Melasta Battery Corporation is a Chinese manufacturer offering a wide variety of LiPo pouch cells. They have seen large adoption within the competition and give a Formula Student discount to teams ordering their products.

An 8 Ah cell capacity chosen because it gave a good balance between cost and the physical size of the cell. While long rectangular pouch cells are commonly used for our specific application, we have instead opted for a more compact, square-like shape

After discussing this with Melasta's sales representative the exact cell model was chosen.

Table 3-1: Melasta SLPB9095100 specifications [13]

SLPB9095100	Value	Unit
Maximum voltage	4.2	V
Nominal voltage	3.7	V
Capacity	8.0	Ah
Continuous discharge	240	A
Continuous charge	8	A
Length	99.5±1.0	mm
Width	94.5±1.0	mm
Thickness	8.4±0.3	mm
Weight	169.0±3.0	g

Figure 3-1 Melasta SLPB9095100 pouch cell

3.1.2 Mechanical characteristics and cell mounting

As seen in Section 1.2.4 there are different ways to fasten pouch cells. A bolted connection was chosen for simplicity. Additionally, a bolted cell mounting mechanism makes it easier to remove a faulty cell.

These fasteners must comply with T 10:

Table 3-2: Formula Student Rules: Fastener Regulations [3]

T 10.1	All threaded critical fasteners must be at least 4 mm metric grade 8.8, equivalent size or of that specified in the referencing rule, whichever is larger.

Because of rule T 10.1 it was decided to mount the cell using a 4 mm (M4) bolted connection with a heat threaded insert. The threaded insert is heat pressed in the thermoplastic enclosure. This would be the most compact solution (Figure 3-2).

1	Temperature PCB
2	Pouch-tab
3	Strain relief tab
4	M4 Bolt
5	Heat threaded insert

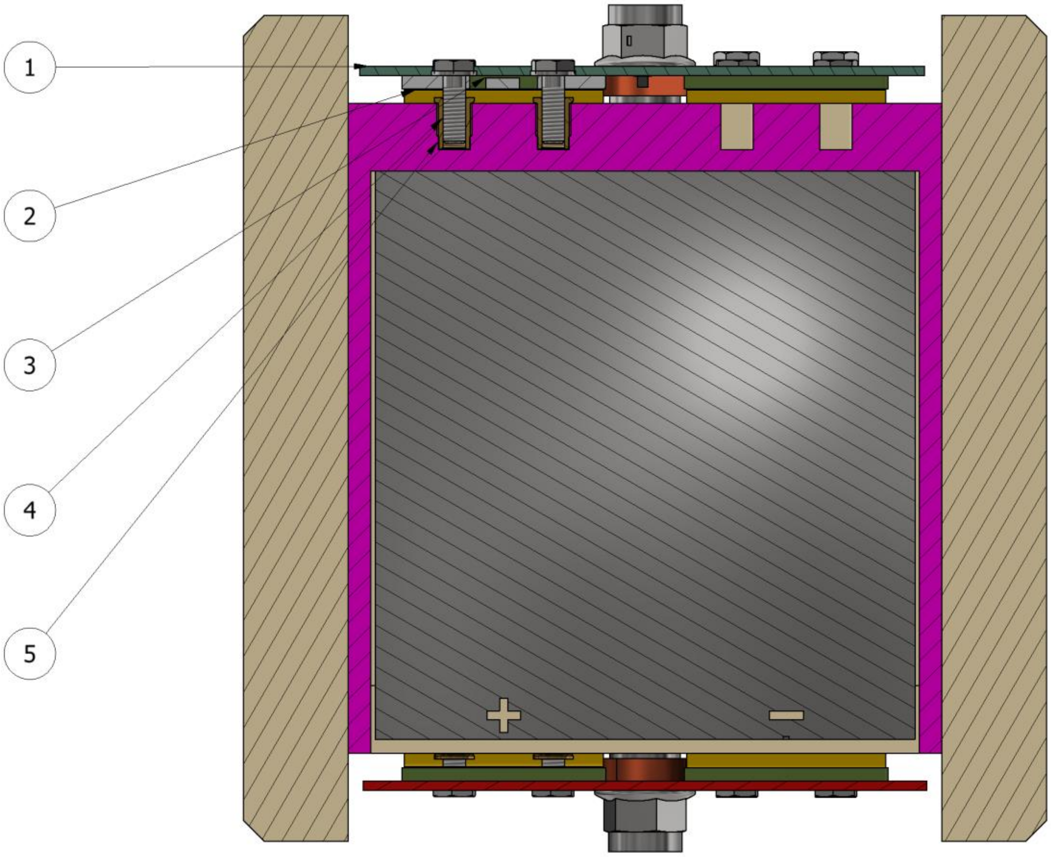


Figure 3-2: Segment section view and parts list showing the cell stack method

Fastener testing

To prove that the inserts can be used for a T 10.1 compliant bolted connection a torsion test was conducted on 20 inserts. Half of them were bought on RSComponents the other half were bought from Tinytronics. The tests were conducted using a VDE Torque wrench with a resolution of 0.1 Nm.

Inserts were fitted in a test 3D-print designed to mimic a cell fixture. Held in place by a vise, the connection was torqued till failure.

The procedure is illustrated in Figure 3-3.

Figure 3-3: Heat threaded insert torque testing

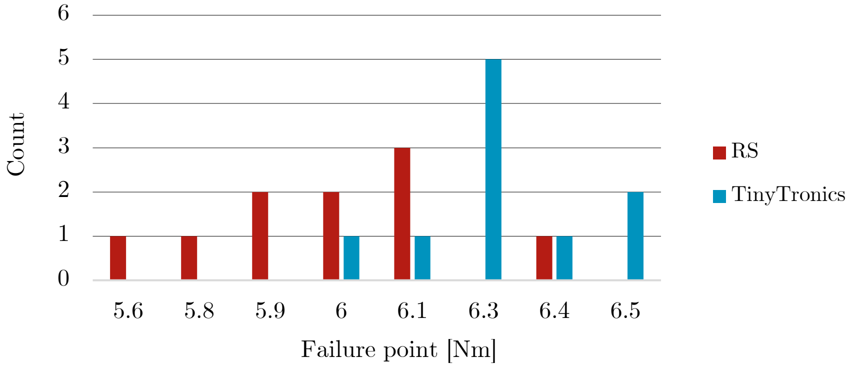


Figure 3-4: M4 Heat threaded inserts, failure point due to torsion

Both inserts outperform the required 3.1 Nm for an M4 grade 8.8 connection.
The failure always resulted with the insert coming loose from the 3D-print.

The TinyTronics inserts were used for the segments because of their better performance.

CAD model

On the next page the finalized CAD model is presented. The individual parts are explained in their respective sections.

1	3D-printed polycarbonate enclosure
2	Amphenol SurLok EV connector (Maintenance Plug)
3	Segment busbar
4	Melasta pouch cell
5	M4 heat threaded insert
6	Thermal pad
7	Strain relief plate
8	Temperature PCB

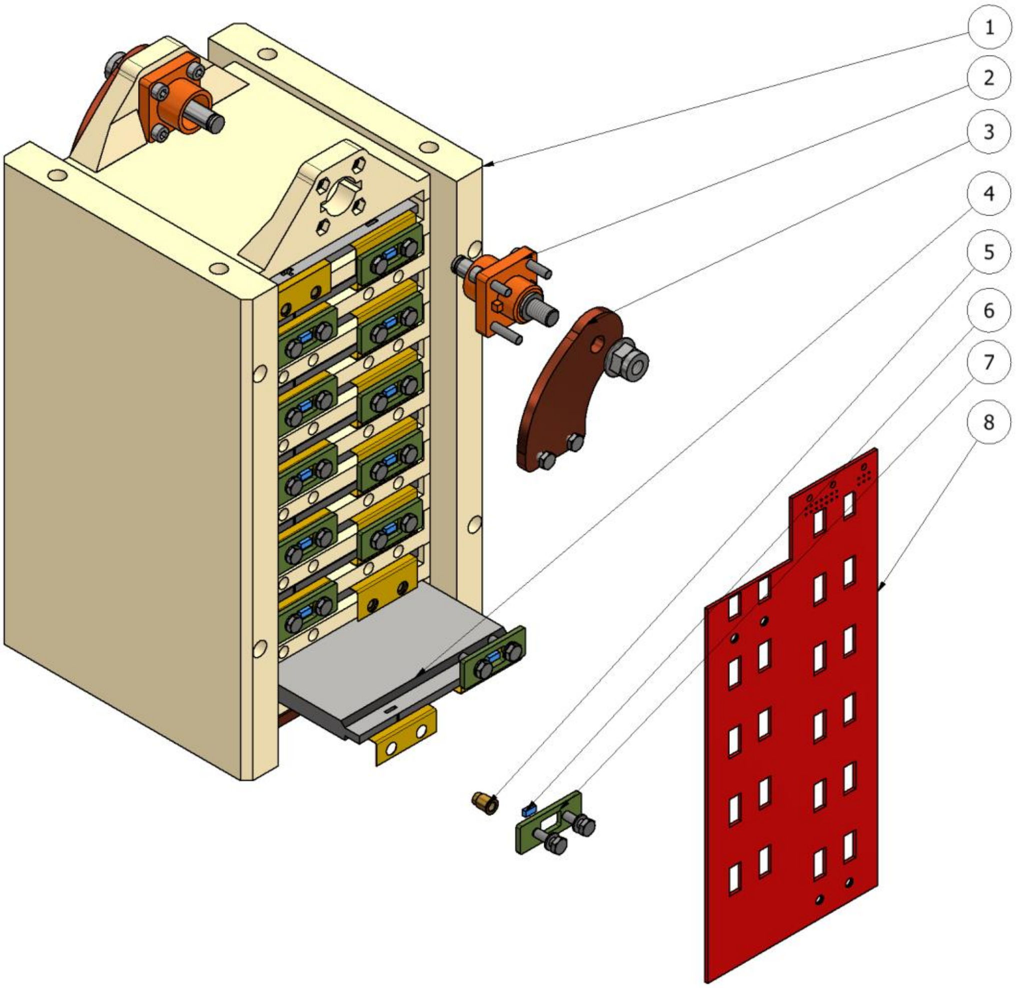


Figure 3-5: Segment exploded view model and parts list

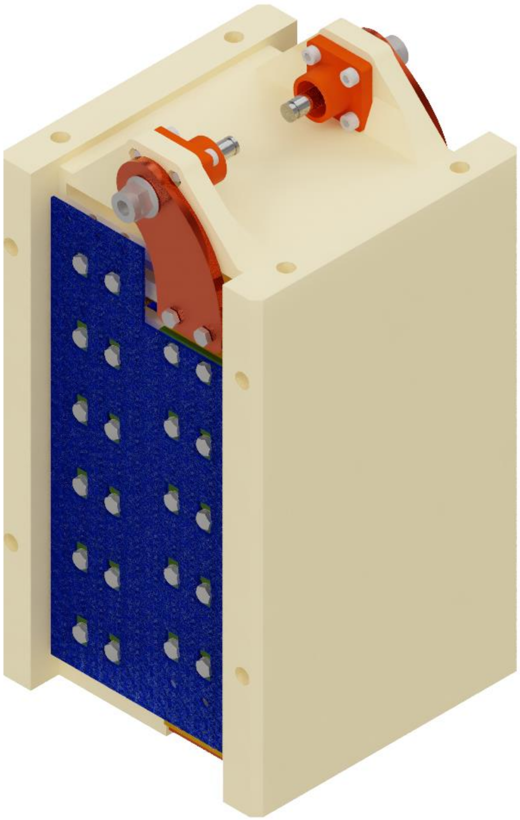


Figure 3-6: Segment CAD model

3.1.3 Electrical characteristics

The 100.8 V segment can theoretically deliver 240 A continuously (Table 3-1). In practice, this is limited by the copper busbars used in its design.

Smallest busbar section: 30 mm
Thickness: 5 mm

$$\text{Cross sectional area: } A = 5 \text{ mm} \cdot 30 \text{ mm} = 150 \text{ mm}^2$$
$$\text{Ampacity: } 150 \text{ mm}^2 \cdot 1 \, {}^{\text{A}}\!/_{\text{mm}^2} = 150 \text{ A}$$

One A per square millimetre was chosen as a general guideline value [14].
The maximum continuous current of the segment would be 150 A. As of now, these high currents are untested.

3.1.4 Electronical characteristic

The competition requires the measurement of the pouch-tab temperature.
This is clarified in table Table 3-3.

Table 3-3: Formula Student Rules: Accumulator cell temperature regulations

EV 5.8.4	Cell temperature must be measured at the negative terminal of the respective cell and the sensor used must be in direct contact with the negative terminal or less than 10 mm along the high current path away from the terminal in direct contact with the respective busbar. It is acceptable to monitor multiple cells with one sensor if this requirement is met for all cells sensed by the sensor.
EV 5.8.5	The maximum cell temperature is 60 °C or the limit stated in the cell data sheet, whichever is lower.

Within the accumulator 30% of alle the cells temperature must be measured. The original BMS only allows for 8 analogue NTC thermistors sensors.

Therefore, a complete custom temperature sensing system, named Mintaka, is integrated within the segment design.

The Orion BMS has a thermistor expansion package available. It is a costly upgrade that adds additional analogue measurements to the system. A better solution is to integrate digital sensors. As the “analogue to digital” conversion happens at the place of measurement, there is less room for interference.

Mintaka is built up of 11 OneWire sensors that use 1 IO pin to transfer their sensor data. This bus protocol reduces the number of wires needed. This mean that for a 12s group of cells only 1 cable with 3 wires is needed.

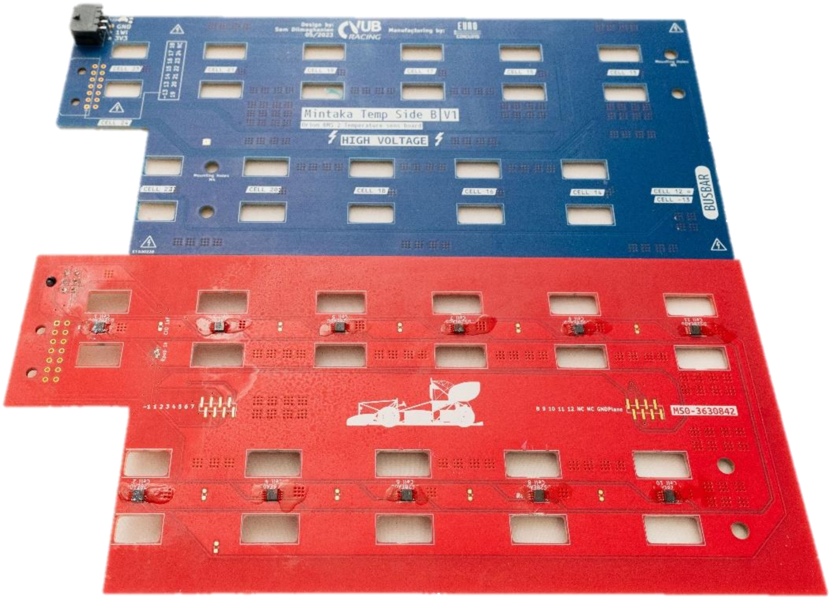


Figure 3-7: Mintaka Temperature Side A (red) & Side B (blue)

PCB Design

The PCB is serves as barrier between the outside world and the cell tabs. Therefore, thermal via's were added to use the copper of the PCB as a heatsink. If future research would be done on air cooling the segment design, the PCB would interfere less.

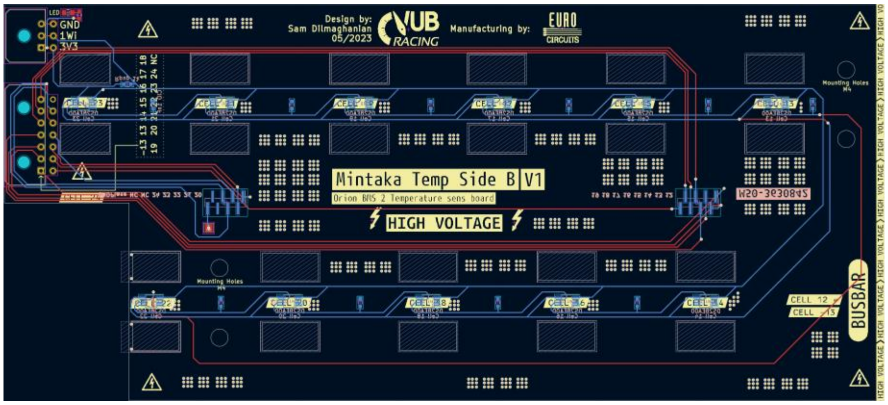


Figure 3-8: Mintaka Temperature Side B inside the KiCad 7 PCB Editor

Thermal pads (Arctic TP-3) are used as a nonconductive filling layer between the cell tab and the temperature sensor. In Figure 3-7 the use of red clear-coat is visible. This nonconductive lacquer is applied to the conductive parts of the temperature IC.

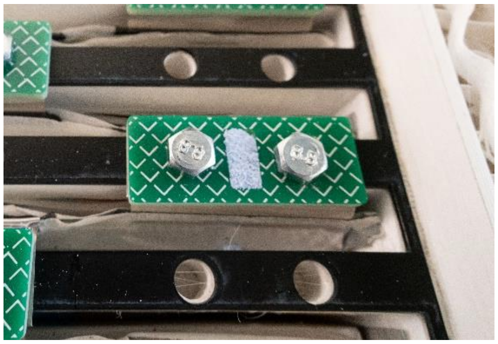


Figure 3-9: Blue thermal pads applied after fastening the strain relief plates

To interface with the electronics, Molex Microfit 3.0 connectors are used. On Mintaka, these can be seen in the top left of the PCB. The 6 position connector implements the temperature data while the 14 position connector could be used for BMS integration as it carries the individual cell voltages.

Reading out the temperature data

A Python program was used to log and display the temperature data. Using the serial input, any compatible computer can be used to interact with the measurement system.

For future vehicle integration an embedded solution must be designed to gather the temperature data interacting with the BMS and the other parts of the vehicle. The easiest solution would be to design some kind of datalogging device. A more complete integration would be to disregard the Orion 2 BMS and build a custom BMS that immediately takes in the data from the used temperature expansion board.

3.2 Manufacturing

3.2.1 3D-printing

Why 3D-printing?

Additive manufacturing is a useful tool for complex custom sized prototypes. An FS vehicle is engineered for performance and reliability, rather than for mass production.

Consumer grade fused filament fabrication (FFF) is slow and often unreliable for large projects. It is highly important to leave margin for printing failures and redesigns of the prototypes.

In total, for the final enclosure, 8 full scale prototypes were printed allowing for design iterations and printer tuning (Table 3-4).

Table 3-4: 3D-printing statistics

Printed enclosures	8 (including 2 failed jobs)
Material weight estimate	8.2 kg (over 10 spools)
Print time estimate	500 hours over 4 weeks

Figure 3-10 shows a printing failure that occurred 2 days into a 4-day print, caused by an overheated printer toolhead clogging the filament path. This older design used a different printing orientation allowing for easy to remove supports. The downside of this orientation is the relatively long printing duration. The used printing orientation for the final enclosure can be seen in Figure 3-12.

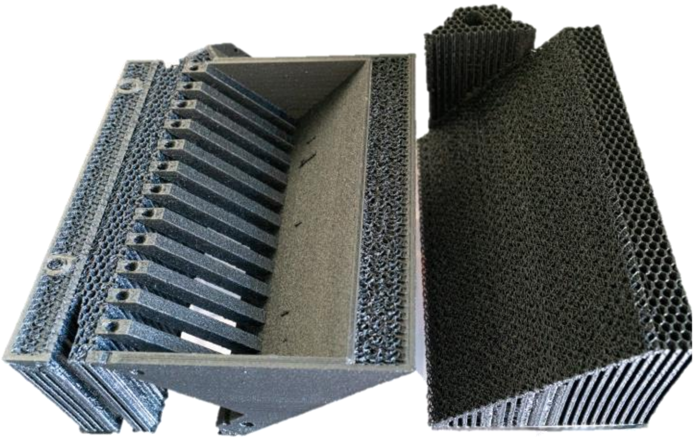


Figure 3-10: Printing failure, 3rd design iteration using different print orientation

In-house 3D-printing was preferred to allow for a more flexible timeline, as designs are only accepted after a review of the Electrical Systems Form (June 2023, Section: 1.1.2). Professional 3D-printer services, like Materialise, would be a possible future solution for the production of the complete accumulator.

Material choice and printer

As mentioned in the mechanical restrictions (Table 2-4), a rule compliant accumulator uses UL 94 V-0 fire retardant components. Very few filaments carry this rating. The chosen PolyMax PC-FR is a fire retardant polycarbonate-based filament. This thermoplastic is widely regarded as some of the strongest and stiffest 3D-printing materials that can be printed on consumer grade FFF machinery. The high temperatures and proneness to warping during printing require an enclosed 3D-printer.

Table 3-5: UL 94 V-0 Rating (paraphrased) [14]

UL 94 V-0	Material stops burning within 10 seconds after being ignited and doesn't drip flaming particles that could ignite a cotton indicator located beneath it.

The Qidi X-Max II (Figure 3-11) is used to print the enclosure. The enclosed printer has a 300x250x300 mm printing volume and is specifically designed to print large parts using high temperature filaments. A Creality Ender 3-pro is used for any smaller objects.

Figure 3-11: 3D-printing setup, using a Qidi X-Max II and an enclosed Creality Ender 3-pro

Slicing settings

Orca Slicer is used to generate the G-code. This open-source slicer is a fork of the Bambu Slicer project, which is a fork of the widely used Prusa Slicer, itself originally forked from Slic3r [15]. Orca Slicer implements the latest Arachne generator as well as powerful custom supports.

A high wall count is used to create a strong and rigid enclosure, with other settings optimized for printing time and to remain under the 1 kg mark. This allows each print to be completed using only one 1 kg spool of filament.

The exact slicing settings used for the final enclosure are visible below.

Table 3-6: Detailed Slicer settings

Material	PolyMax PC-FR White (275 °C no cooling)
Walls	5
Infill	8% gyroid pattern
Layer Height	0.32 mm
Line Width	0.5 mm
Supports	Custom hand drawn
Build plate adhesion	Magigoo-PC bed adhesive, 10 mm wide brim
Weight	942 g
Print time	47h 49 minutes

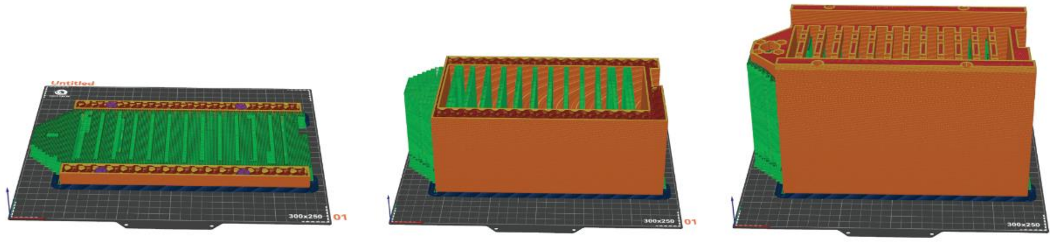


Figure 3-12: Slicer preview: green = support, red = infill, orange = walls

Figure 3-13: Enclosure close up, wall count, and infill pattern are visible

Post processing

After the printing the support material is removed, and the heat threaded inserts are installed using a soldering iron.

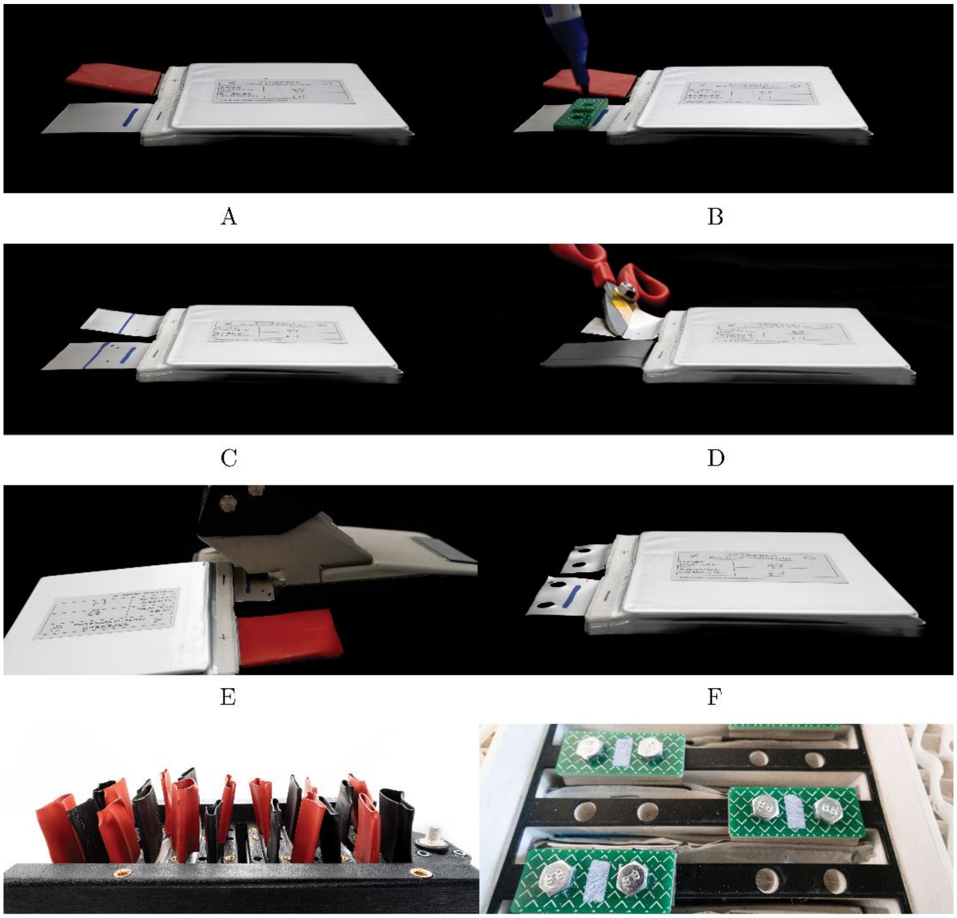
Figure 3-14: Finalized enclosure

3.2.2 Cutting pouch-tabs

Figure 3-15 shows the step-by-step process of cutting and installing the pouch-tabs in the segment:

A. Stock pouch cell, negative pole has been labelled on both sides.
B. Using the segment's strain distribution plate as a template, the cut-outs are drawn using a permanent marker.
C. Marked cells.
D. The pouch-tabs are cut to size using metal shears, with blades only large enough to cut through one cell tab to prevent shorts.
E. The pouch-tabs are perforated using a standard office hole punch (5 mm hole size).
F. Finalized cell.
G. Cells are press fit on one side of the segment.
H. Pouch-tabs are fastened using a VDE 7 mm hexagonal socket wrench.

This process is repeated for the other side. The finalized segment is shown in Figure 3-16.



A B

C D

E F

G H

Figure 3-15: Cutting and installing pouch cells

The cells come pre-labelled from the manufacturer. The cell-id order was respected when manufacturing the accumulator segments. This is clarified in Table 3-7.

Table 3-7: Individual cell allocation

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100
1	102	103	104	105	106	107	108	109	110

🟦 Used in first segment
🟧 Saved for 3 future segments
🟨 Cell tabs are cut to the wrong size

Figure 3-16: Finalized segment prototype

3.3 Testing

3.3.1 Goals

During the design process, the team brought up concerns about possible thermal issues, leading to the hypothesis that the segment may be inoperable for the vehicle without any active cooling.

The primary objective of the testing was to figure out whether active cooling would be a necessary component in the future design of the accumulator.

3.3.2 Setup

Testing was done at VUB's MOBI Battery Lab, located in Building Z (Figure 3-17).
In this temperature-regulated room, active air conditioning was directed near the top side of the segment, creating a noticeable temperature difference between the top and bottom sides. Another testing limitation was that the segment was not positioned inside the accumulator container. However, the insulation of the segment's bottom part was fairly effective, as it was situated on a wooden table.

The next sections will discuss the testing results. It is important to keep in mind that the single 24s segment is connected in 2 12s halves (Figure 3-18). The halves are always electrically loaded in the same way at the same time, thus effectively acting as a 24s segment. This was done because the testing channels have a maximum voltage of 80 V.

The voltage measurements seen in the graphs are summed from the 2 individual 12s halves measurements. The temperature measurements correspond to the highest value from the 22 individual pouch-tab temperatures, as this is how the competition measures the value.

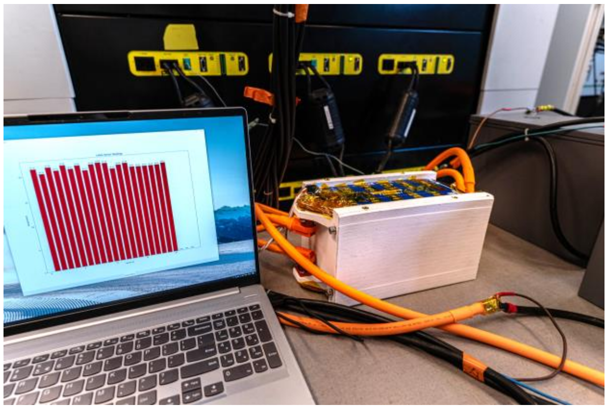


Figure 3-17: Battery lab testing setup

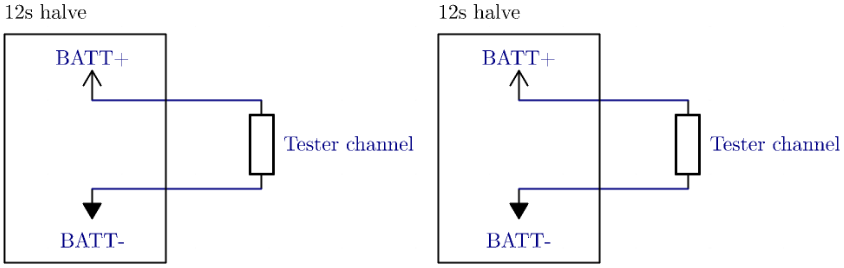


Figure 3-18: Testing setup schematic

3.3.3 Test 1

To begin, the segments are charged (Table 3-8). The cells were supplied by the manufacturers at a voltage of 3.8 V (in 24s segment 91.2 V). The segment is charged up to the corresponding max cell voltage of 4.2 V (in 24s segment 100.8 V) and then discharged to 72 V corresponding with the 3.0 V cut-off voltage of an individual cell.

Table 3-8: Test 1 charge details

Charge current	1.6 A
C-rate	0.2 C
Method	Constant Current (CC) Constant Voltage (CV) CC until 12s halve reached 50.4 V CV at 50.4 V until I $<$ 0.4 A
Highest measured temperature delta	0.7 °C

Table 3-9: Test 1 discharge details

Discharge current	10 A
C-rate	1.25 C
Equivalent vehicle speed at 300 V	11.75 km/h (Appendix B. Calculations).
Highest measured temperature delta	14.27 °C

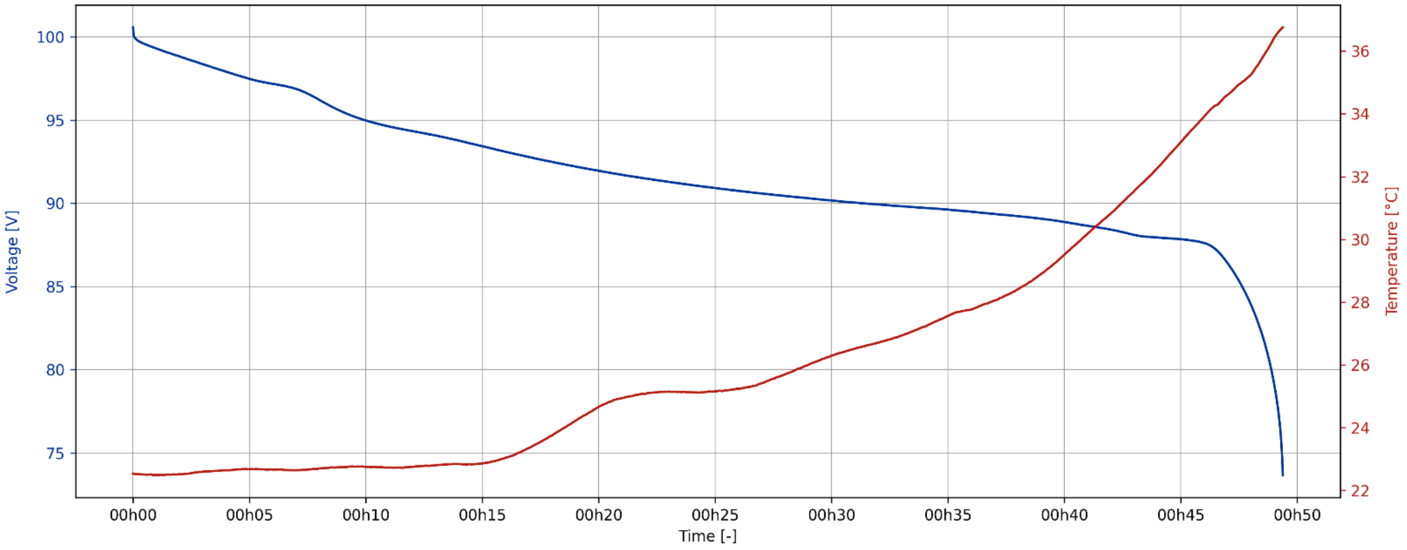


Figure 3-19: Voltage and temperature evolution during a 1.25 C continuous discharge test

3.3.4 Test 2

The 2nd tests were dimensioned after successfully completing the first 10 A discharge test. As the first test went so smoothly the plan would be to increase the electrical strain on the cells.

In Test 1 we only saw a moderate temperature delta. The goal would be to get reasonably close to the 60 °C temperature limit set by the competition (Table 3-3). Giving the Aerodynamics department information whether to include accumulator cooling in a future vehicle iteration.

Table 3-10: Test 2 discharge details

Discharge current	25 A
C-rate	3.125 C
Equivalent vehicle speed at 300 V	~ 30 km/h (Appendix B. Calculations).
Highest measured temperature delta	18.82 °C

After these tests, the segment was charged to a cell voltage of 3.75 V in the 24s segment this would equate to 90 V.

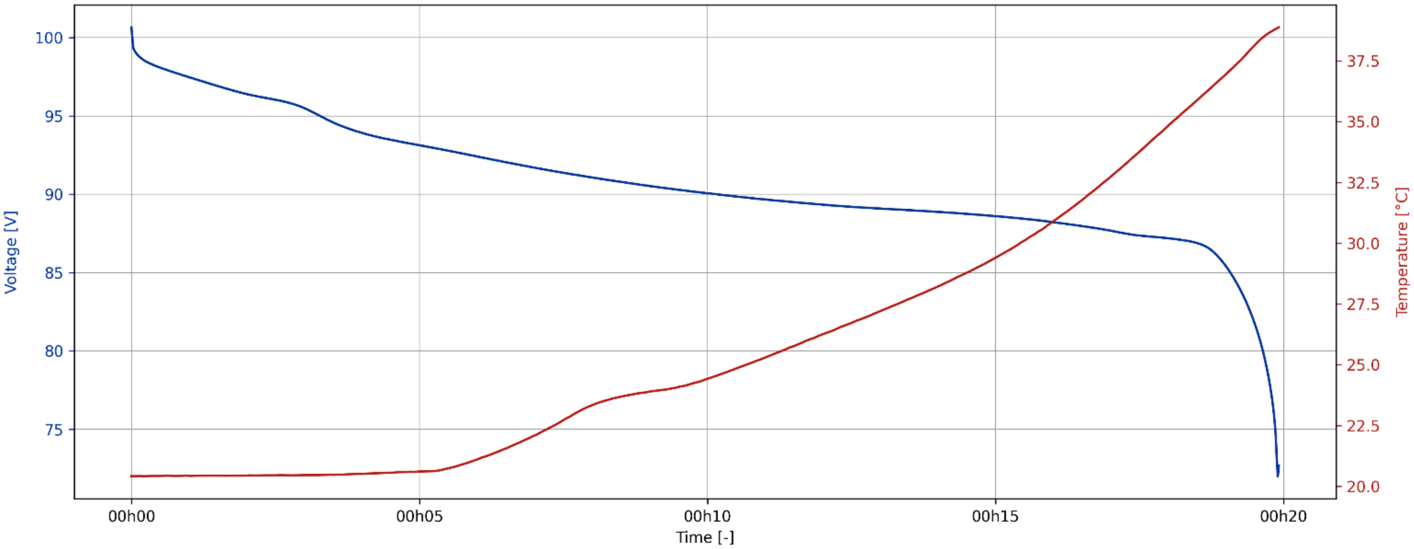


Figure 3-20: Voltage and temperature evolution during a 3.125 C continuous discharge test

While increasing the C-rate by a factor of 2.5, a 4.55 °C temperature delta increase is noticed. This nonlinear relationship could be related to the non-ideal testing conditions mentioned in Section 3.3.2. Another hypothesis would be the fact that the short test does not allow for the segment to reach its peak temperature. This is possible because the temperature curve has not yet plateaued during the discharging.

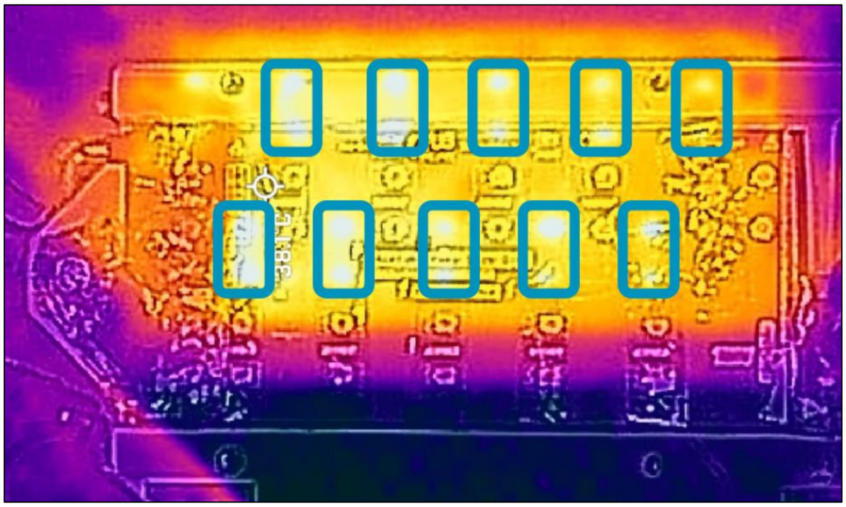


Figure 3-21: Test 2, thermal image during last minute of the test

In Figure 3-21 hot spots are visible on the bolted connections (marked in blue), confirming that the use of thermally conductive material around the pouch-tabs helps to bring out the heat. There is a vertical image shift causing the IR-image to not line up with the image of the accompanying camera sensor

3.3.5 Testing conclusions

The design is suitable to complete a 30 km/h test run.

Assuming a summer competition on a 35 °C day. This still leaves a lot of headroom for the cells to heat up to their maximum temperature of 60 °C. A higher discharge rate should be tested to reach temperature delta of, for example, 25 °C.

The competition mandates that temperature measurements are taken near the pouch-tabs (Table 3-3), the testing was primarily focused on recording the highest temperature at these locations. It is important to note that the internal resistance of the cells might lead to a temperature increase within the pack itself. Additional testing could be conducted to assess whether cooling the cell tabs or cooling the largest surface of the pouches would be effective.

The small capacity is the most likely reason why cooling is not deemed necessary. Although the cell temperature does rise, it does not plateau during the continuous discharge. The capacity is inadequate to support the required heating duration for reaching the 60°C mark.

In short, if a Formula Student team is not intending to participate in a full endurance event, a common strategy for beginner teams, accumulator cooling may not be required.

Capacity Check:
After doing these tests we can verify the 8 Ah segment capacity. By charging up to the maximum cell voltage and then discharging to the cell cut-off voltage we can compare the real life results to the manufacturers datasheet.

From Section 3.3.3 Test 1:

- Discharge time: 49 minutes
- Discharge current: 10 A

$$\text{Capacity} = \text{discharge current} \cdot \text{discharge time} = 10\ \text{A} \cdot 0.8167\ \text{h} = 8.167\ \text{Ah}$$

This exceeds the datasheet value seen in Table 3-1. The cell capacity can be used for comparison as the segment does not use any parallel cells.

3.4 Next version

In Figure 3-16 the finalized segment is presented. The design includes BMS integration, as there is a connector present precisely fitted for the Orion 2 BMS. However, this feature was never tested and will probably have to be iterated on when a BMS is programmed for the current segment design.

It is advisable to move away from the OEM BMS and develop a custom-fitted system. Since the segment formfactor has been established and the temperature logging system is working well, building a BMS would essentially be the adding of a previously used LTC6813 BMS-IC and a microcontroller [8]. As there is already a PCB present within the segment's construction, adding these components would be a reasonable design modification.

As mentioned in Section 2.4.2, a mechanical perspective is needed to bring the complete accumulator to life. In the future, calculations and simulations have to be done to ensure the safe integration of the electrical parts presented in this document.
This is crucial to pass the FS technical inspections.

Further testing on the segments is required. It would be useful to know the precise load that is needed to reach the maximum allowed temperature limit.

The manufacturing process of the segment is already good, but there is room for improvement. Now that the enclosure design is finalized, it would be beneficial to have them professionally printed.

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5 Appendix

A. Accumulator Design iterations TSAC V1 – V7

V1 and V3 were early attempts at integrating 2 major design challenges: integrating the 180-cell version of the chosen BMS and the use of the 7 12s segments.

On the other hand, V2, V4, and V5 were experimental design concepts. Although they were never fully drawn out, these explorations played a crucial role in the development of V6. This new iteration introduced a smaller BMS and employed three 24s segments.
For the final version of VUB Racing's 2023 Electrical Systems Form V7 was designed. This is a more refined and rule compliant design iteration on V6.

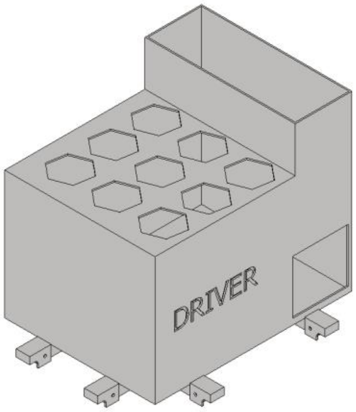

Figure 5-1: TSAC V1 (November 2022)

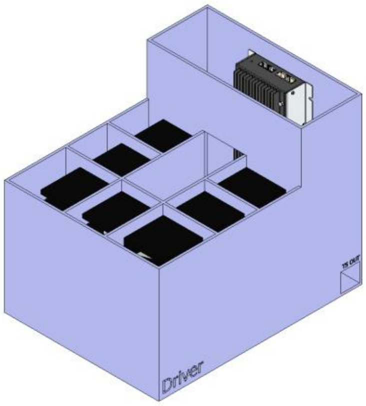

Figure 5-2: TSAC V3 (December 2023)

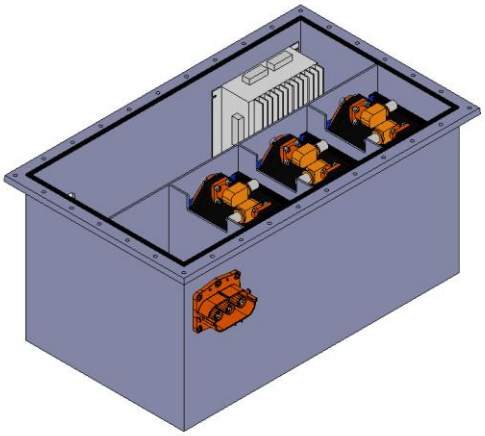

Figure 5-3: TSAC V6 (March 2023)

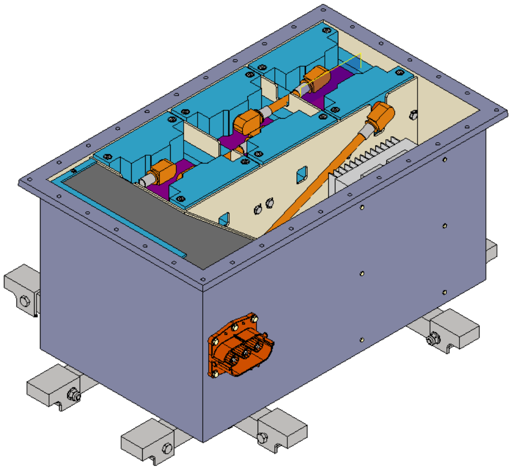

Figure 5-4: TSAC V7 (May 2023)

B. Calculations

Testing: Dimensioning current

Desired vehicle speed = 30 km/h = 500 m/min
Gear ratio = 3.35:1
Wheel diameter = 52 cm (Hoosier 13 inch)

$$\text{Wheel circumference: } C = \pi \cdot 0.52\text{ m} = 1.633\text{ m}$$

RPM Calculations:

$$\text{Wheel RPM} = \frac{v}{C} = \frac{500\,\frac{\text{m}}{\text{min}}}{1.633\text{ m}} = 306.16\text{ RPM}$$

$$\text{Motor RPM} = \text{Wheel RPM} \cdot \text{Gear Ratio} = 306.16 \;\cdot 3.35 = 1025.63\text{ RPM}$$
$$\approx 1000\text{ RPM}$$

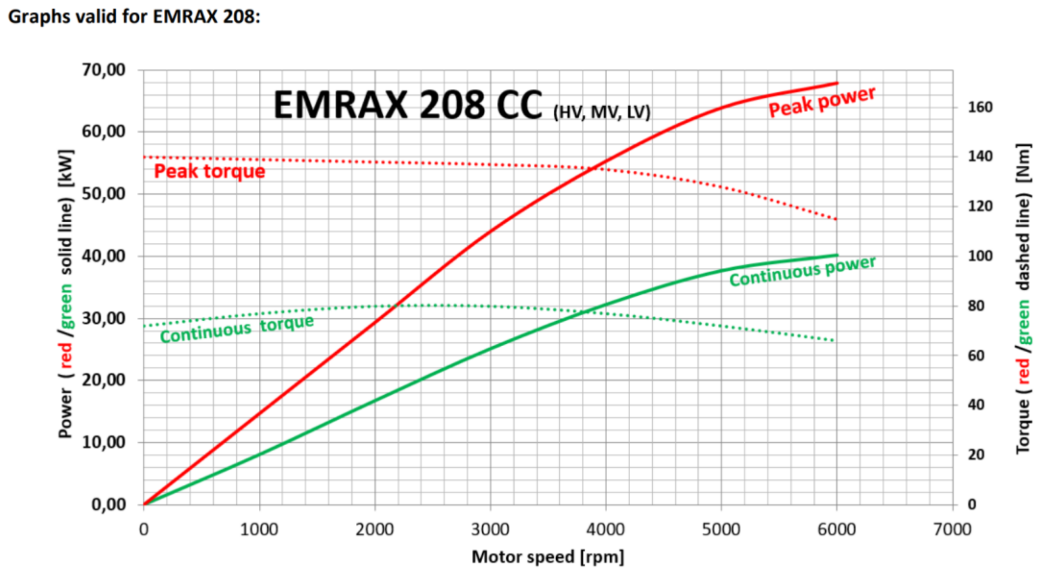

Figure B-1: Emrax 208 performance graph

At 1000 rpm we find 8 kW continuous power, with the full 300 VDC accumulator:

$$I_{\text{Discharge}} = 8000\text{ W}/\ 302.4\text{ V} = 26.45\text{ A}$$

For the 2nd test 25 A was used.

Note: These calculations are for a single motor vehicle. The current would have to be doubled when actuating Eos' 2 motors. This 2nd motor does not increase the vehicle's top speed but would greatly improve its acceleration time.

Our first discharge test was a 10 A discharge (3 kW, motor RPM = 400)
Using the same method as above a single motor vehicle speed of 11.71 km/h can be calculated

Vehicle range estimate
Using the method above for to run 70 km/h 20 kW (2400 motor RPM) is needed per motor.

Using 2 motors;
Total power: 40 kW
Battery capacity: 2.4 kWh
Vehicle speed: 70 km/h

$$\text{Runtime} = \frac{\text{Capacity}}{\text{Power}} = \frac{2.4\ \text{kWh}}{40\ \text{kW}} = 0.06\ \text{h} = 3.6\ \text{min}$$

$$\text{Range} = 70\ {}^{\text{km}}\!/_{\text{h}} \cdot 0.06\ \text{h} = 4.2\ \text{km}$$


3V3
1Wi
GND
LED
CELL -1
CELL 1
-1 1 2 3 4 5 6
7 8 9 10 11 12 NC
EVERGi RESEARCH GROUP
CELL 2
CELL 3
CELL 4
Design by:
Sam Dilmaghanian
05/2023
VUB RACING
orion BMS2
ELECTROMOBILITY RESEARCH CENTRE
CELL 5
Mintaka Temp Side A|V1
Orion BMS 2 Temperature sens board
HIGH VOLTAGE
CELL 6
Manufacturing by:
EURO CIRCUITS
CELL 7
CELL 8
This project's realization was made possible thanks to the invaluable support of MOBI VUB & Evergi Research Group
CELL 9
CELL 10
CELL 11
CELL 12
BUSBAR
HIGH VOLTAGE