Design Report v.1 - Accumulator Container
Lund Formula Student: Electric 2019

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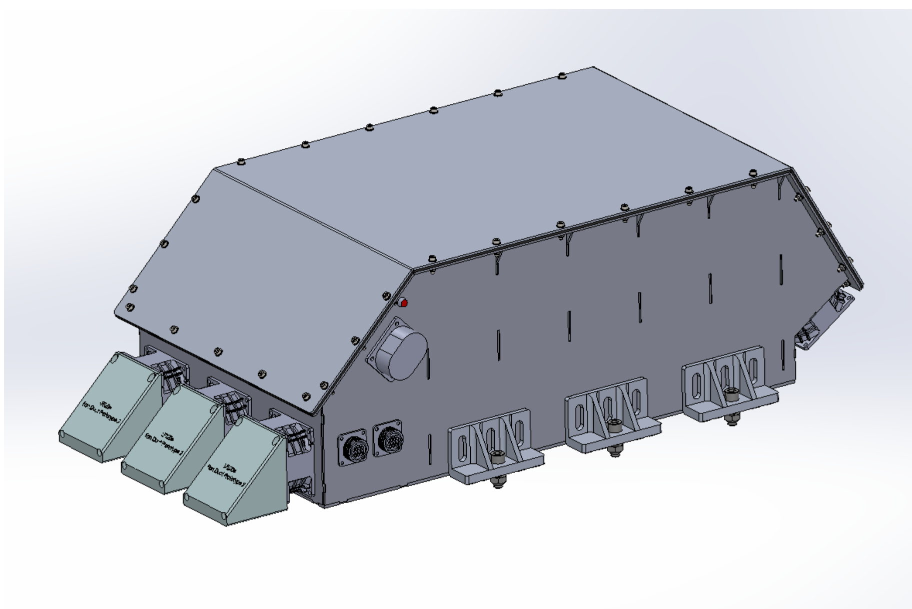

Contents

Abbreviations

AIR Accumulator Isolation Relay. 4, 25, 29

BMS Battery Management System. 4, 25

CAD Computer Aided Design. 4

CFD Computational fluid dynamics. 4, 44, 47

CGH Center of Gravity Height. 4, 9

CTMD Cell Temperature Monitoring Device. 4, 29, 49

EV Electric Vehicle. 4–6, 8

FEA Finite Element Analysis. 4, 24, 28

FS Formula Student. 4, 30

FSG Formula Student Germany. 4, 29, 49, 51

HV High Voltage. 4, 27

LFS Lund Formula Student. 4, 5, 7, 9, 50

LTH Lunds Tekniska Högskola. 4, 6

LV Low Voltage. 4, 9

LVS Low Voltage System. 4, 25

NTE Nordic Test Event. 4, 7, 14, 25

PCB Printed Circuit Board. 4, 10

1 Introduction

1.1 Report

This report is written as part of the course *MVKN80* at Lunds Tekniska Högskola and is the Design Report of the Accumulator Container of Lund Formula Student's first fully electric vehicle.

The goal of this report is to document the research performed by the High-Voltage team and what is learned during this first one and a half year of development. This to facilitate overcoming the steep learning curve of building an EV for future teams.

The report is written in the spring 2020, in which the manufacturing phase usually starts at LFS. Because of this, some sections of the design might not be complete, and therefore not fully explained in this report. Also, since the report is submitted as a part of the course *MVKN80* and therefore finished, before the project is fully evaluated, further versions of this report are possible.

1.2 Formula Student

Formula Student is a term used for a number of competitions for students world wide, in which a common rule book is shared. The competition is an engineering competition, in which students from all faculties compete by designing, manufacturing a small formula-type race car. Scoring is based not only on race-performance, but also of engineering knowledge, cost reports, presentation skills and other skills that are useful in industry. The purpose of the competition is to produce better engineering graduates, suitable for a future in the automotive industry.

1.3 Lund Formula Student

Lund Formula Student, LFS, has for a few years built combustion vehicles. In recent years, these combustion cars have shown to perform quite well during competitions and the team has improved greatly both in management and in engineering competence. As Formula Student is a competition meant to be a foundation on which to grow skilled student-engineers, well prepared for a future in the automotive industry, it makes sense to learn how to build the cars of the future. This is the reason why we at LFS decided to develop our first fully electric vehicle and have it competition-ready during the summer of 2020.

2 Background

2.1 Two - cars 2020

During the year of 2020. It was decided to build two cars. One combustion vehicle, and one fully electric vehicle. A decision was made by the team to take the frame from the old 2019 combustion vehicle and rebuild it into our first EV. It was decided by the team that the focus of this year was to build a final combustion vehicle of top class, and try as best at possible to manufacture a first EV with the main goal of making a car that is allowed to compete. Not focusing as much on performance. This was probably, in hindsight not the best decision for some subsystems. With further discussions with the team, where the decision was made to keep the vehicle dynamics and frame relatively intact, which resulted in large compromises in the packaging of the EV. It is not clear whether this decision actually saved development time as a result of spending a lot of time to find solutions to the compromises. As a final note on this matter. The space that was allowed for the accumulator container was not sufficient and many design-compromises have been made. It is highly recommended that the allowed space for accumulator containers following years is increased and regarded as sacred space for the HV-team.

2.2 Prestudy

To build Lund Formula Students first EV, a prestudy was performed by a number of Formula Student Alumni as part of a course at LTH in the year of 2019. The prestudy resulted in a general architecture of a drive-line for an electric Formula Student car with the following defined by the report:

- Motor
- Inverter
- Cell Type
- Cell Lay-Out

Along this prestudy, William Hellingwerf (The author of this report) also worked a few months on a design of the Accumulator Systems. A design for the Accumulators was finished and manufacturing began. This design is further described in section 5, *First Design*.

2.3 NTE Findings

During the summer event NTE 2019, as hosted by LFS, it was decided to scrap the design and manufactured parts of the already started accumulator container and segments. This partly as a result of new findings and better understanding of the rules after discussions with Alumni from Chalmers University's Formula Student team.

The main reasons for the change were:

- New interpretation of the fire retardancy rule. We had previously interpreted that the materials used for the Accumulators were not regarded as Accumulator Container materials, and therefore not subject to the fire retardancy rule, EV 5.5.3. The Accumulators in manufacturing were designed with non- flame retardant ABS plastic.
- The previously designed Accumulators had plastic in the stack up, which is in direct violation of rule EV 4.5.12.
- In the previously designed Accumulators, each cell was spaced 3 mm apart from each other to maximize surface area in cooling. The Chalmers alumni however, suggested that such amount of cooling should not be necessary and it would be more space efficient and easier to build a container with the cells stacked as tight as possible. They also mentioned that the cells lifespan actually increased with a small amount of compression. This information has not yet been confirmed.

2.4 Goals: LFS20e

The goal of this years EV project, is simply to build a car that is allowed to compete, that is: Passing Scrutineering, and a car that is safe to drive, and that is reliable enough to finish an endurance.

We do this by designing and building our first ever fully electric vehicle, and by researching and documenting the choices that were made and the issues that arise.

These goals are set in order to be able to create a solid foundation of knowledge and experience for following years, where cars can be optimized further and further. The great majority of time spent in this project has been researching very basic things, things that are hoped to be obvious until next years, such as what materials are available and rules compliant to use. Another example is rules understanding. In a project of this scale, it is very important to have the competence and know-how to construct the most basic solution first before any type of optimization is relevant. This is even more important when it comes to those types of optimizations that would compromise the safety factor on which the solution complies with the rules. Any over-optimization that could result in rules infringement could result in not passing scrutineering. Not passing scrutineering results in not being allowed to compete.

3 System Definition

3.1 LFS design reports & system definitions

At LFS, all subsystems write design reports similar to this one. In those reports, the system definitions are stated along with system specific targets, such as target mass or other specific targets where the performance is easily measured in numbers. This is done to be able to quantify where improvements are made in regards to previous years. These targets are also usually set by referencing old designs. As a result of this being the first report of its kind at LFS, and of the goals for this year, the system targets are not set in classical LFS fashion.

3.2 Definitions

The Accumulator Container is defined by the rules to be: EV5.1.4 *"TS Accumulator Container – the container itself, which contains the TS accumulator."* EV5.1.3 *"TS Accumulator – all cells that store the electrical energy to be used by the TS as a whole."* and EV5.1.5 *"TS Accumulator Segments – sub-divisions of the TS accumulator."*[1] These definitions have been discussed extensively internally. Further in the rule book, there seems to be some inconsistencies within these definitions.

3.3 System Targets

The system requirements can and should mainly be a result of the rules [1]. Because of the high number of rules, all requirements are not listed in this report, but a summary of our interpretation of the rules follow below.

- Movable from car to cart in <20 minutes.
- Mass Target: None, no focus on optimizing. Only focus on building a robust foundation
- The CGH is largely defined by the cell- layout and orientation. Since the layout was predefined by the prestudy, no special attention has been given to this.[2]
- The mounting of the cells to the accumulator, the mounting of the accumulator to the accumulator container, and the mounting of the accumulator container should all be able to withstand the following load cases:
  - 40 g laterally.
  - 20 g vertically.
- The Accumulator Container should house all accumulators and should house the necessary LV systems.

- All structural fasteners inside the accumulator container should be considered a critical fastener and therefore fulfill the T.10 rules. Except if they are made out of a Fire Retardant - Non conductive material and are used to mount non - structural parts, such as PCB's.
- All materials used in the container should be fire retardant, preferably according to UL94 V-0, rather than FAR25.853(a)(1)(i).

4 Cells

4.1 Cells & Configuration

The beforementioned prestudy for the electric car resulted in a choice of cells and their configuration. As for the cells, the Melasta's SLPBA875175 were chosen, in a (140s1p) configuration, divided up into 5 compartments for the LFS20e Car. See fig 1. [2] All though, it was in a later stage realized that the intended (140s1p) would not be rules compliant in a 5 segment layout, and a compromising late-stage solution would have to be a (130s1p) configuration in 5 segments. This is explained further in section 6.3, *Accumulator / Segment*

Figure 1: Four Melasta SLPBA875175 cells

The choice of the layout during the pre-study was based on the data as provided by Melasta, and simulations / calculations as performed in the prestudy. The following table, table 1 is taken from the prestudy and shows the data as provided by Melasta. [2]

SLPBA875175			
Size	15 Ah	Type	Li polymer ($LiCO_2$)
Nominal Voltage	3.7 V	Size	Prismatic
Max Continuous Charge Current	15 A (1C)	Peak Charge Current	30 A (2C)
Max Continuous Discharge Current:	150 A (10C)	Peak Discharge Current	225 A (15C)
Discharge End Voltage	2.75 V	Energy Density	180 Wh/kg
Size	10.8 x 75.5 x 175mm	Power Density	1800 W/kg

Table 1: Specifications of chosen cell type provided by Melasta

4.2 Cell Testing

As the cells were purchased prior to the start of the LFS20e team and more research on the cells in question was needed, a small team of two students from the faculty of Electrical Engineering was tasked with performing additional research and testing on the cells. This was done partly with the intention to justify some design choices for the current year, but mostly in line with the general goal of this year: Creating a solid foundation of knowledge for following years.

5 First Design

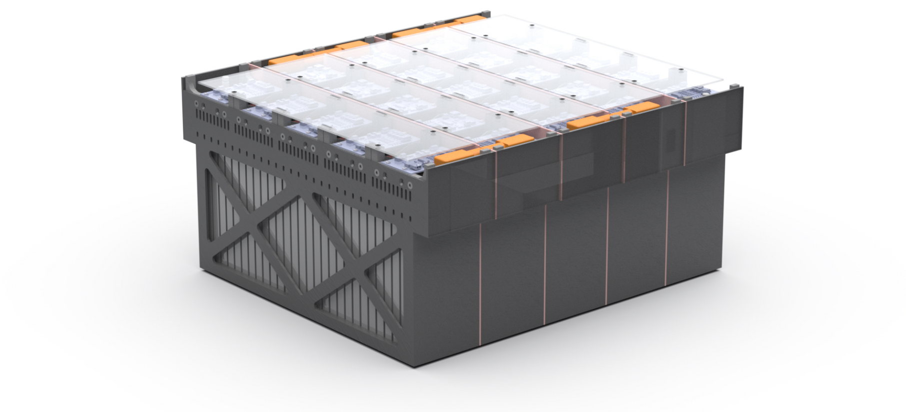

Figure 2: Five of the first design of the Accumulator Segments in series.

5.1 Cooling

The design of the first Accumulator Segments was inspired by the approach of the dutch teams at TU-Delft and TU-Eindhoven. In this design, the cells in each accumulator are spaced 3 mm apart, to allow airflow in between the cells, maximising the surface area of the forced convection cooling. The spaces in between the cells are lined up through the entire Accumulator Container to minimize the path resistance of the airflow.

5.2 Reasons for the switch

The first design used materials that arguably violated rule EV 5.5.3 that states that all materials need to be fire retardant. It also violated rules about grounding of metal parts and using a compressible material in the stack-up, which is not allowed.

The design barely fit inside the frame, and a team decision was made that it is not worth remaking the back of the frame, thus constraining space significantly. Utilizing $3mm$ air gaps in between all cells made the container $3 \times 29mm = 87mm$ wider *(With 28 cells in a segment as defined by the pre-study, and an air gap on either side of every cell)*. A design with no air gaps in between the cells would fit in the old frame with just minor modifications.

Another reason for the re-design was an idea that it would be easier to prove the structural rigidity of the container if designing parts to be in pure compression. This is however today realized not to be the case. A design that utilizes air gaps could just as easily be proven to withstand the load cases that are presented in rule EV5.5.9.

Also in favour of the switch of design approach was the information from NTE, see section 2.3

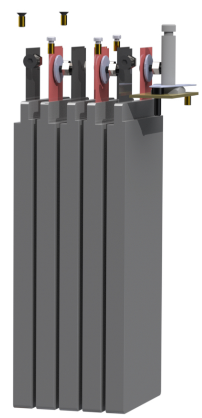

Figure 3: Cells spaced 3 mm apart for to allow for swelling, and forced convection air cooling.

6 Design of Accumulator Container

6.1 Materials

There are specific rules stating the materials that are used in the Accumulator. Some of these rules have been interpreted differently during the year and is one of the reasons why the entire Accumulator Container and the Accumulators were redesigned. The Accumulator Container is mainly manufactured out of $ENAW6082-T6$ aluminium, which has an acceptable weld-ability. $FR-4$ is used both as insulating material, and as a structural material in the accumulators. $AdamantS1$ from $add:north$ is used to print parts in house, because of its flame retardancy rating. $AdamantS1$ is the name of the filament that is provided and is consists from 100 % $polyvinylidenefluoride$. Some parts are also printed in $Ultem9085$ at $TetraPak$. The used glue is $DP100FR$ from $3M$ and is also flame retardant in compliance with the rules. ABS+ FR from 3D Prima was also purchased in a late stage to print some minor parts with.

- FR-4
- Aluminium EN AW 6082-t6
- Adamant S1 - Plyvinyledinefluoride
- Ultem 9085
- Neoprene
- ABS+ FR

6.2 configuration

6.2.1 Cell & Segment Layout

The layout of the cells as defined from the prestudy [2] is ($140s1p$). In which the cells are divided up into five accumulators / segments of 28 cells each. However, in a late stage during the project it was discovered that we didn't comply with rule EV5.3.2, since we defined cell energy as the nominal cell voltage times the nominal capacity of the cell, whereas rule EV5.1.2 clearly states that cell energy is defined as *maximum* cell voltage times the nominal capacity of the cell. This was in a very late stage of the project, in which the only possible solution was to manufacture the design, which utilized the layout as described in the prestudy, and removing two cells from each segment ($130s1p$), with 26 cells in each segment.

6.3 Accumulator / Segment

6.3.1 Introduction

The segments in the Accumulator Container, also referred to as the accumulators are the the sub divisions/identical subsystem inside the container that houses the cells. As the container is designed, inside out, the segments were the first things to be designed, and also where the most time and effort was spent. The segments primary task is to separate the cells into separate compartments and to safely hold all the cells in place. The segments should be easily connected with the help of maintenance plugs. See EV 5.4.5.

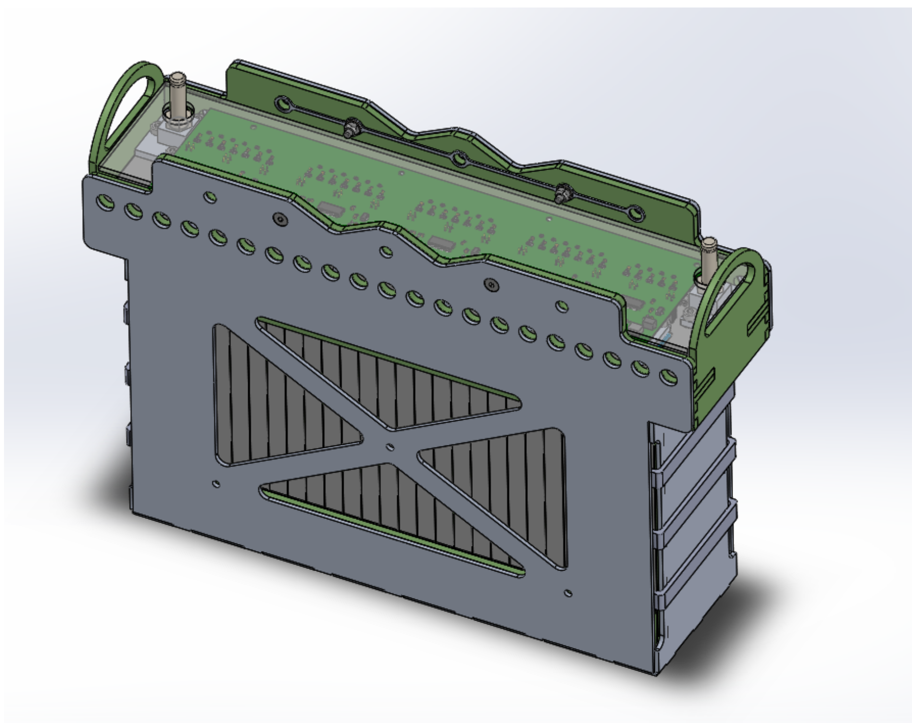

Figure 4: ISO-View of the LFS20e Accumulator / Segment

6.3.2 Segment Energy Storage

The energy storage in each segment is required to follow rule EV 5.3.2, which limits the maximum voltage *(120 VDC)*, maximum energy *(6 MJ)* and the maximum mass *(12 kg)* which is allowed per segment. As stated in 6.2.1, *Cell & Segment Layout*, the initial layout of a segment was (28s1p). Which would have been rules compliant, if it wasn't for rule EV 5.1.2, which clearly describes the energy of a cell as the *maximum* cell voltage times the *nominal* capacity of the used cell. During the pre-study, it was assumed that cell energy was defined as *nominal* cell voltage times the *nominal* capacity of the cell. With a (26s1p) segment layout, the energy of the segment can be calculated as in equation number 1. The maximum segment voltage is calculated as in equation number 2.
Nominal cell voltage 3.7 V. Maximum cell voltage 4.2 V.

$$J = C \times V_{max} \times 26 = 15000 \times 3.6 \times 4.2 \times 26 = 5896800J \approx 5.9MJ < 6MJ \quad (1)$$

$$4.2V \times 26 = 109.2V < 120V \quad (2)$$

The segment mass is calculated to be $10.8kg < 12kg$ according to CAD mass properties. All Materials defined with density, including fasteners.

6.3.3 Cell mounting

The cells are mounted in the segment by being fully restricted of movement in all directions and is not mounted with any fasteners or bonding. To constrain the cells from movement in the positive vertical direction, 3D printed spacers out of Ultem 9085 are used, pressing on top of the body of the cell. The spacers can be seen in yellow in figure 7 and in figure 10. Between each cell, there is a FR-4 spacer with a thickness of $0.4mm$ to allow for some swelling of the cells. The research on the cells as performed by *Isabella Hansen* and *Johanna Wikström* has shown that the middle of the cells swell an approximate $0.25mm$ depending on state of charge. The sides of the cell swell less but we have no data so far to tell how much. The spacer is shown in figure 6. An assembly of cells can be seen in figure 5.

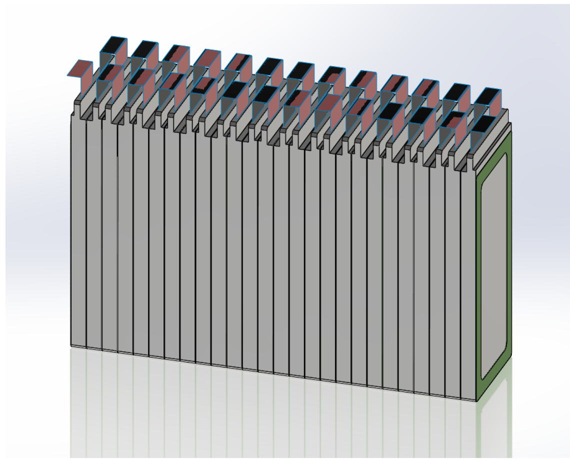

Figure 5: Stack of 26 cells with spacers in between.

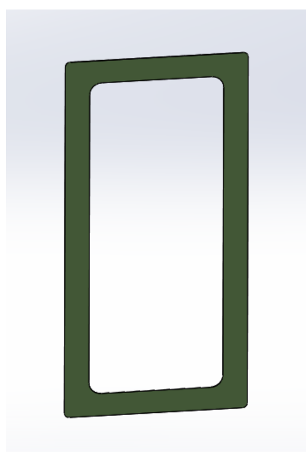

Figure 6: 0.4 mm spacer that goes in between the cells

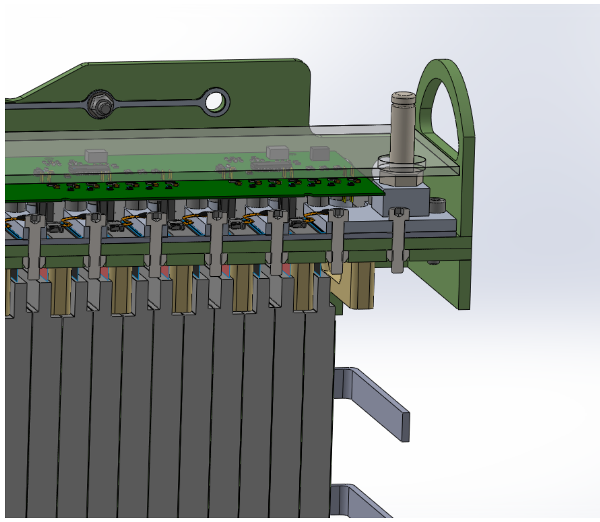

Figure 7: Detailed Cross-section view of the segment

6.3.4 Stack-up

The top of the segment consists of an assembly of $4mm$ water jet cut FR-4 sheets. There are two stacked horizontal sheets in order to achieve a $2.5D$ design with $2D$ manufacturing methods. The idea from the prestudy had been to 3D-Print the entire assembly. It was however realised that it would be possible, but hard to comply with some rules with a 3D-Printed solution, such as EV4.5.12. In addition, a rules compliant 3D-Printed solution would most likely increase the cost with an order of magnitude.

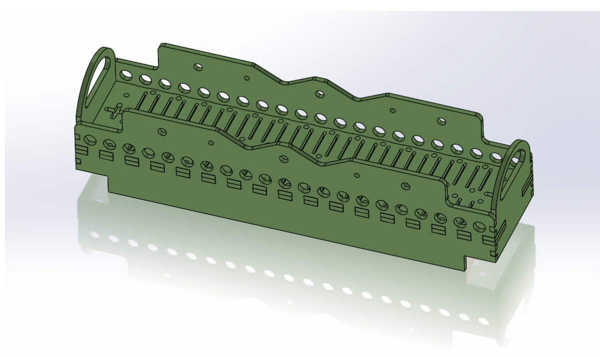

Figure 8: CAD view of assembled water jet cut FR4 assembly

In order to be able to reuse the cells following years, joining the cell tabs cannot be done by welding the tabs together, which would be a very reliable and efficient solution in regards to bonding and electrical resistance. The solution is instead to clamp the tabs together with as much surface as possible. This is done with small pieces of cut $4mm$ aluminium brackets with a hole on either side for an $M4$ bolt. See figure 9.

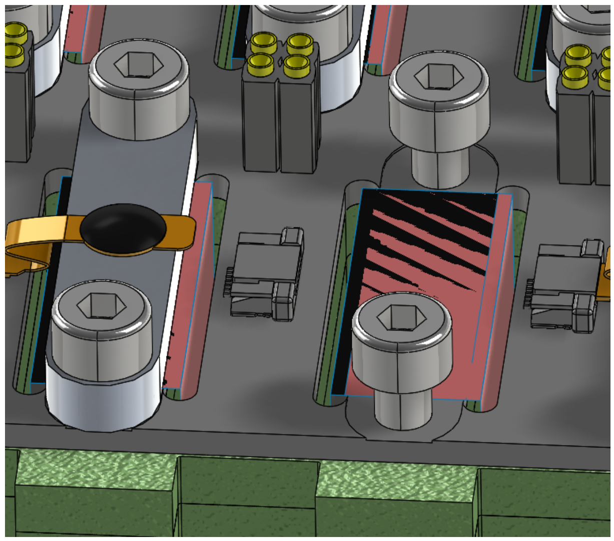

Figure 9: CAD view of clamped cell tabs to the left with aluminium bracket. Removed aluminium bracket to the right.

A receiving DIN 980 $M4$ nut is placed in a fitting slot in the bottom horizontal FR-4 sheet to comply with rule EV4.5.13. This is clearly visible in figure 7 and figure 10. The solution avoids drilling holes in the cell tabs, but does require the tabs to be shortened a bit by cutting the top.

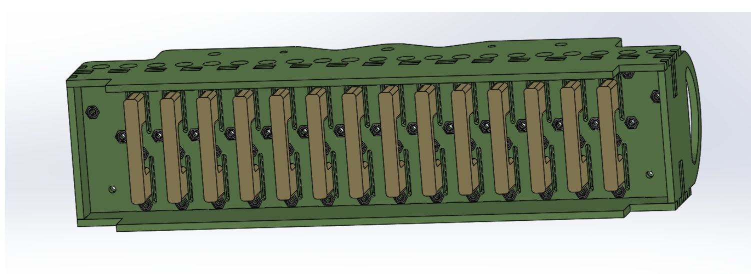

Figure 10: CAD bottom view of assembled water jet cut FR4 assembly

Instead of a a large amount of wires going from the BMS-Slave to each cell, a PCB which houses all the sensors is used in the stack-up. This PCB has been referred to as the sensor-board and houses the temperature and voltage sensors.

The BMS slaves are mounted to the sensor board with the use of board-to-board connectors, further minimizing the use of wires. See figure 11.

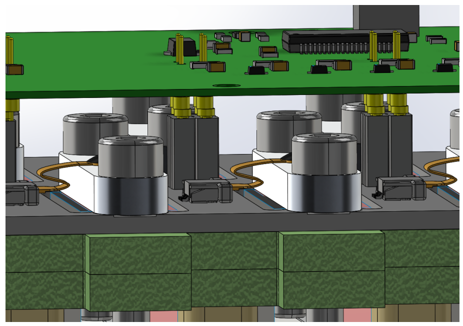

Figure 11: CAD view of the board to board connections between the sensor board and the BMS slave.

An additional covering sheet *(transparent part in figure 7)* is placed on top of the entire assembly, to protect against possible tools falling into the high current path. Sticking up as the negative and positive terminal is a threaded *Radlok 8mm* pin (see section 6.5.3), threaded into a milled block of aluminium and then spot welded into place to comply with EV4.5.13.

6.3.5 Mounting of Segment

The segment is mounted to the internal vertical walls of the container with six $M6$ bolts, three on either side. The bolts being used to mount both segments on either side of the internal vertical walls. Therefore, to calculate the loads in the fasteners and mounting points, it is approximated that a segment is mounted with only three bolts. This is seen in figure 12 and somewhat in figure 14. The bolts and slots of the containers internal vertical walls can be seen in figure 13. *Calculations on all attachment points and their loads can be found in either the LFS20e accumulator documentation folder or on the LFS20e High Voltage drive.*

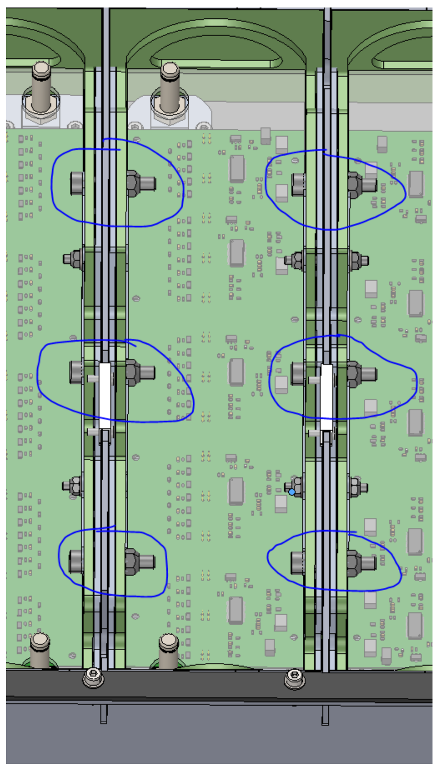

Figure 12: Figure showing the 6 M6 bolts used to fasten a segment.

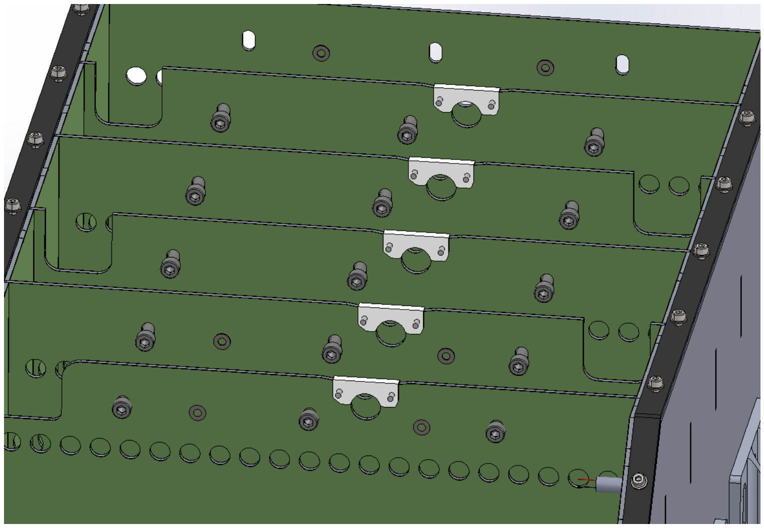

Figure 13: Figure showing the fastening slots in the containers internal vertical walls

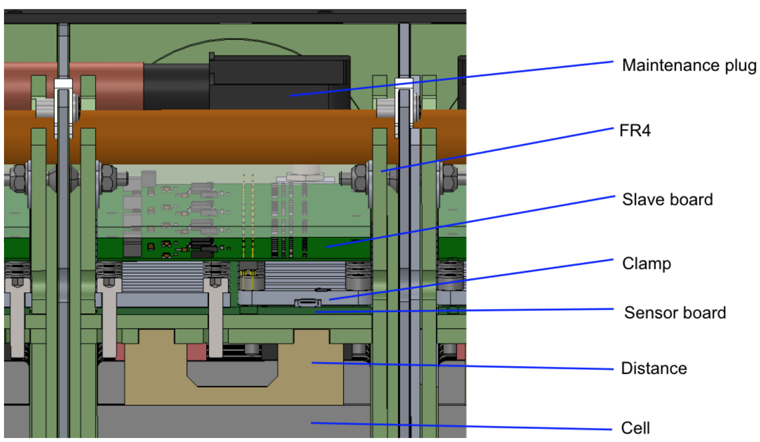

Figure 14: Cross-Section, side-view of a Segment

6.3.6 Segment FEA

In addition to hand calculations on attachment points, FEA was used as a validation method. All load cases as described in EV5.5.9 were analyzed, with the worst case being a lateral load of $40g$ as seen in figure 15.

- Segment mass: 12kg
- Lateral acceleration, Left to right. : 40 g
- Max stress: 179 MPa
- Cells are approximated by a block.
- Constrained to the casing using only frictional results.

Fixing constraints:

- Fixed supports in all 6 M6-Bolt mounting holes.
- Frictionless support on bottom of segment.

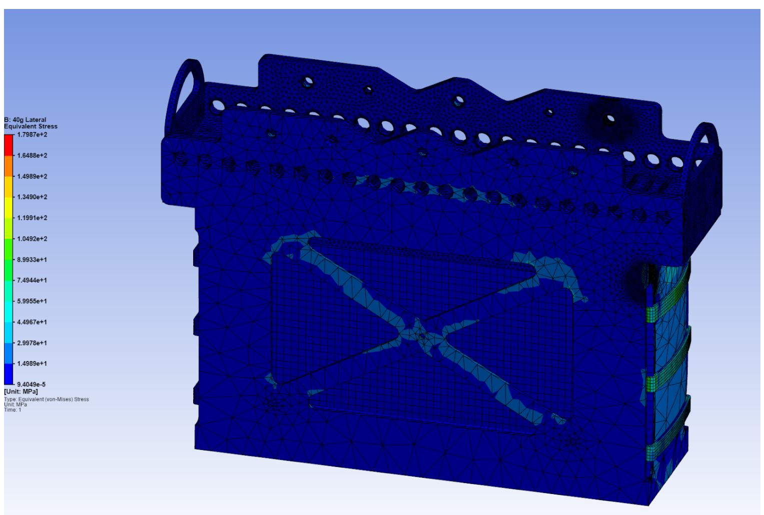

Figure 15: FEA of a Segment. Lateral 40 g

The highest loads was achieved in the welds on the side of the aluminium sheet on which the load of all the cells, accelerated laterally with $40g$ is reacted in. The addition of a few supporting ribs was necessary to reduce the stresses in the welds to below that of the yielding parameters of the filler-material.
(OK Tigrod 4043, $\sigma_s = 55MPa$, $\sigma_b = 124MPa$*)*

6.4 Accumulator Container

6.4.1 Container Layout and construction

The *Accumulator Container's* primary task is housing the segments and the necessary LVS according to rule EV5.4.3. The Designed Accumulator container consists of six separated compartments. Five identical compartments for the *Segments* and one for the AIRs, Fuse and required LVS such as the BMS master. See figure 16.

The container is constructed from water jet-cut aluminium, EN AW 6082-t6 in thickness of 2.5 mm with the exception of the bottom that has a material thickness of 4 mm. See rule EV5.5.4.

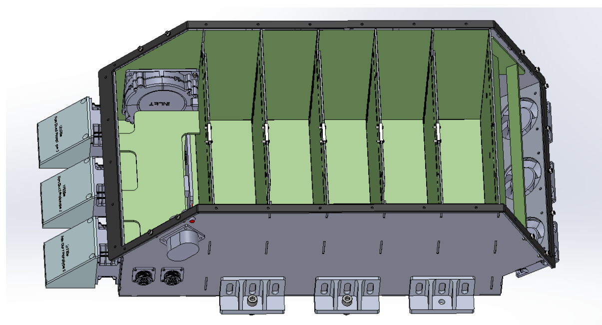

Figure 16: Side view of the accumulator container. Electronics compartment to the left and five segment compartments following to the right. FR-4 isolation in green.

6.4.2 Isolation

The insides of the container is isolated with the use of 0.4 mm thick sheets of FR-4 cut with the same geometry as the aluminium walls and floor. See figure 16. Isolation between the segments is required mostly to prevent arc flashes, but is also required to be flame retardant. *Nomex* was first considered as a suitable isolation material, but was at an early stage discarded as a result of the findings from NTE where it was mentioned that the Chalmers team have had problems with moist *Nomex* not isolating properly. This is however not investigated and should be re-evaluated.

FR-4 from *Nordbergs Tekniska* has a dielectric strength of $15kV/mm$.[13] The isolation with use of $0.4mm$ sheets should therefore be valid for voltages up to $6kV$. See equation 3.

$$13\frac{kV}{mm} \times 0.4mm = 6kV \tag{3}$$

6.4.3 Lid and Gasket

The lid is screwed in place with M4 nuts, washers and bolts. On the container side, a lip with a neoprene gasket, seals the container from eventual water from entering. The neoprene gasket material is purchased from *par-group.co.uk* and is flame retardant with certification for the required standards. The lid can be seen in figure 17, and the gasket is visible in figure 16.

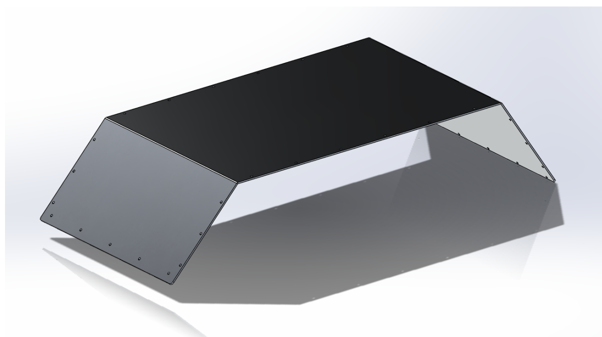

Figure 17: CAD view of the accumulator container lid

The lid and the gasket creating a seal around the accumulator container can be seen in figure 18.

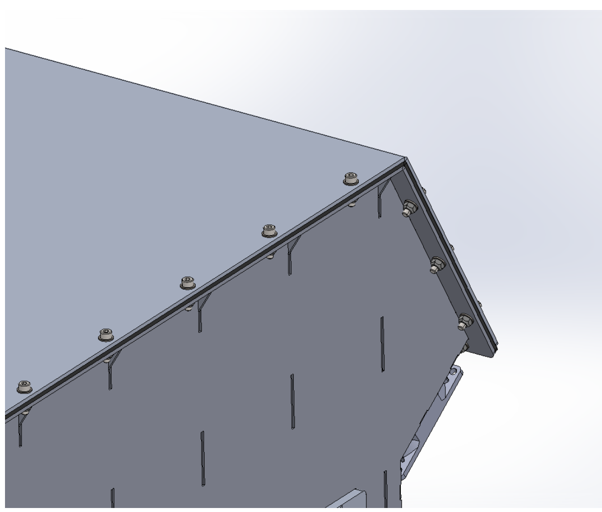

Figure 18: CAD view of the lid and gasket sealing the accumulator container with nuts and bolts.

6.4.4 High Current Path

The segments are connected internally in series with maintenance plugs. The first pole close to the electronics compartment being the negative pole *(upper left corner in fig 19)* and the last pole being the positive pole *(lower right corner in fig 19)*. The HV path is snaking between the segments with alternating polarity by being rotated 180°. In order to connect the poles to close the path between the segments, a combination of custom connectors and purchased connectors are used. See section 6.5 *HV - Connectors*.

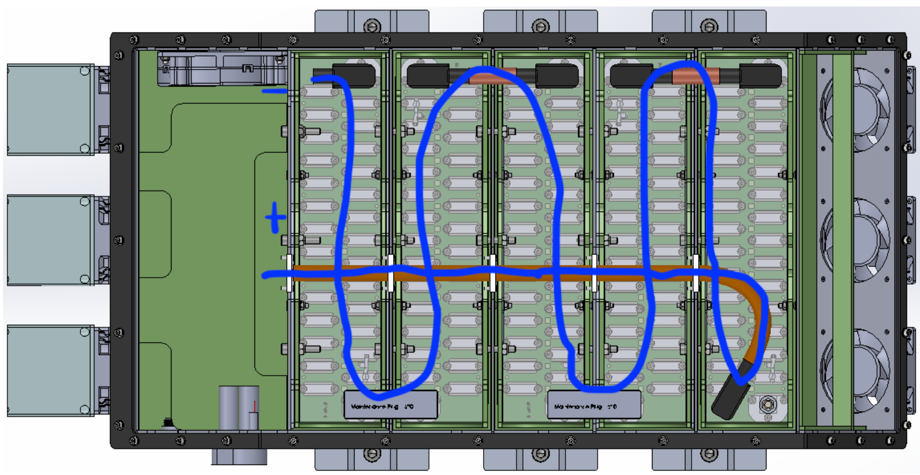

Figure 19: Snaking of the high current path inside the container

6.4.5 Container FEA

In addition to hand calculations on all attachment points in the container, FEA was used as a validation method. All load cases as described in EV5.5.9 were analyzed, with the worst case being a negative vertical acceleration of $20g$ as seen in figure 20. All hand calculations can be found in the documentation in the drive or in the physical *LFS20e High Voltage Documentation folder*.

- Container mass: 72kg
- Vertical acceleration, downwards : 20 g, Applied on the vehicle side of the mounts.
- Max stress: 181 MPa.
- Segments are approximated by 12 kg blocks with accurate fastener geometry.
- Constrained to the casing using only frictional results.

Fixing constraints:

- Mounts are bonded to the container.
- Mounts on accumulator side connected to mounts on vehicle side with nuts and bolts.

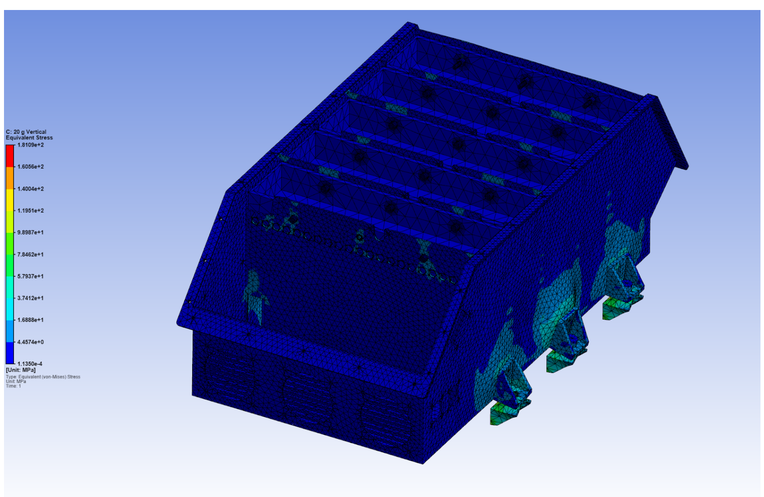

Figure 20: FEA of the Accumulator Container. Negative vertical acceleration (downwards) 20 g

6.4.6 Electronics Compartment

The electronics compartment houses the AIRs, the main fuse, the BMS master and all other necessary electronics components that are necessary on the accumulator side of the vehicle. As of the writing moment of this report, this area is not yet fully developed and is therefore largely missing in this report.

Important to note is that FSG requires the installation of a so called CTMD, or *Cell Temperature Monitoring Device*, and other competitions might implement this requirement as well for future competitions. In that case, a dedicated space must be supplied inside the accumulator container with proper mounting options. In the current accumulator container, there is no dedicated space for a CTMD.

6.5 HV - Connectors

6.5.1 Connectors

According to rule EV5.4.4, all poles of the segments needs to be connected with the use of so called maintenance plugs. That is, with easily removable connectors, that can separate the segments without the use of any tools. Maintenance plugs should ensure that it is impossible to connect the segments in any other way than intended and should be electrically insulated on all points which does not provide any electrical connection. Maintenance plugs should be positively locked and clearly show when the segments are disconnected or connected. To solve all the above criteria, two solutions have been implemented with use of purchased connectors that work together.

The chosen type of connectors for the high current path has been *Amphenol's Radlok* $8mm$ connectors and pins, which are rated for $1000V$, $200A$ and are $UL94V-0$ fire retardant. Most important is that they are widely used in FS and known by scrutineering officials and is therefore a safe choice for this type of connections. These are used in combination with the *Amphenol Radsert 0-737504-001* as seen in figure 26.[12]

6.5.2 Radlok Connector

The connecter from *Amphenol* is the *RadLok RL00801-50-1831*. This connector has a built in spring-mechanism that latches on to the cutout on the *Radlok Pin*. See figure 23. This spring mechanism allows the connector to be easily mounted and removed without the help of any tools, which is required bu rule EV 5.4.5. To release the locking mechanism, the red plastic piece is compressed by hand into the connector housing. See figure 21.

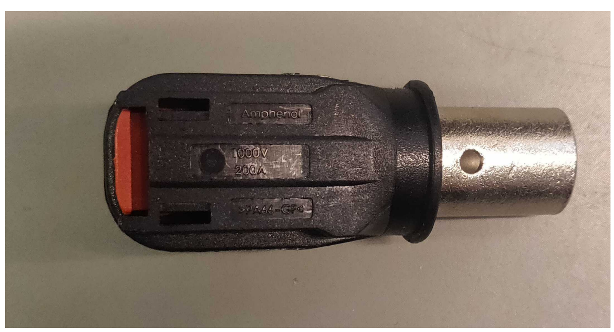

Figure 21: Top view of the Amphenol RadLok RL00801-50-1831 connector.

Figure 22: Side view of the Amphenol RadLok RL00801-50-1831 connector.

6.5.3 Radlok Pin

The pin from *Amphenol* is the *RL9080-103*. This pin is screwed into a machined aluminium block, and spot welded as to ensure positive locking. The machined aluminium block is in turn clamped on to the negative and positive terminal of each segment with the use of nuts and bolts. See figure 24.

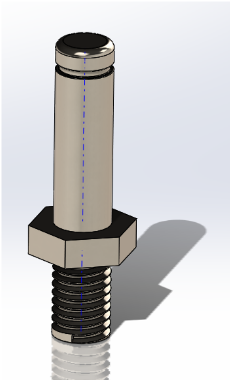

Figure 23: CAD model of the Amphenol Radlok RL9080-103 pin.

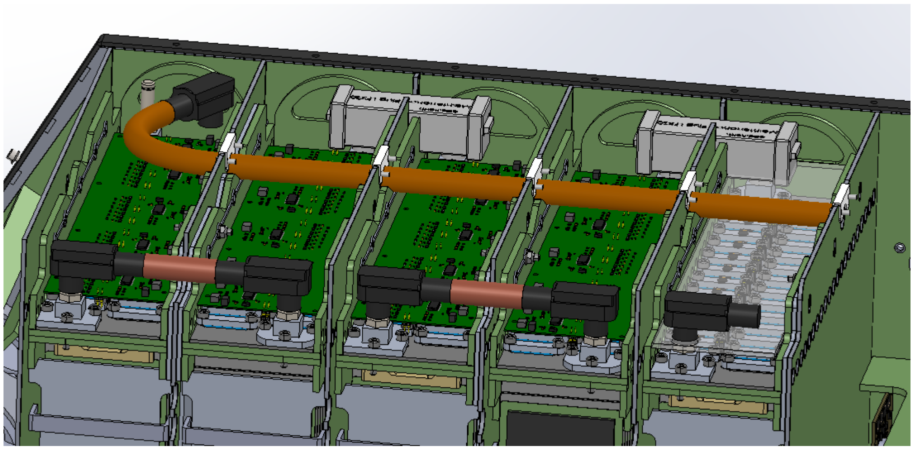

Figure 24: CAD screenshot showing the Maintenance Plugs in place.

6.5.4 Custom Maintenance Plugs

Rule EV 5.4.5 that states that maintenance plugs must be designed in such a way that it is impossible to connect them in any other way than intended. This to make it impossible to accidentally short circuit the accumulator, which would be devastating. The importance of complying with this rule cannot be stressed enough. This along with the space constraints of the container has forced the development of custom maintenance plugs. See Table 11.2 Rules.

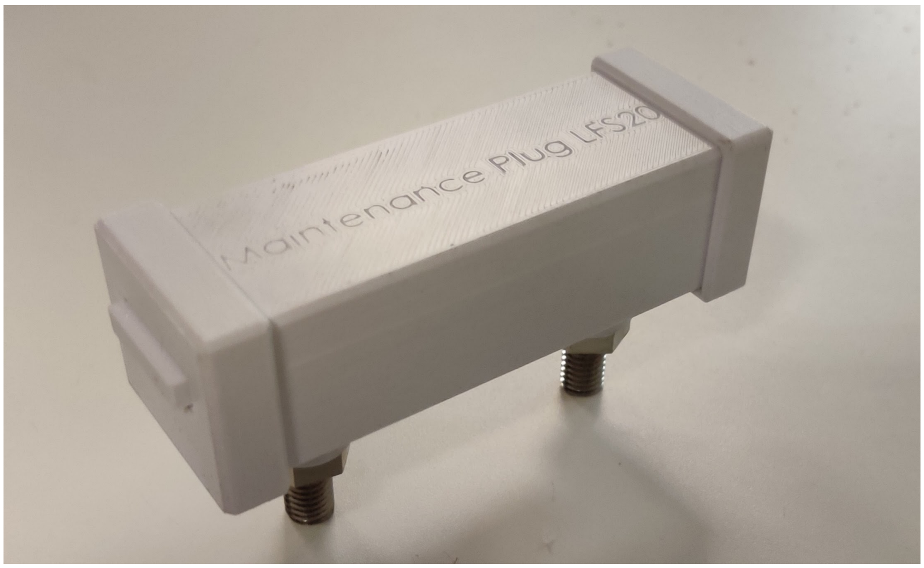

Figure 25: Prototype of the LFS20 custom Maintenance Plug

The custom maintenance plugs are constructed of a copper bus-bar with press-fitted inserts from *Amphenol* that fits the same male pin connectors as the *RadLoks*. The casing of the maintenance plug is made from 3D printed polyvinylidenefluoride from *add:north* called *Adamant S1* and is printed in-house on our own 3D-Printers. The polyvinylidenefluoride provided by *add:north* is suitable mainly because of its flame-retardancy, rated $UL94V - 0$ for thicknesses from $1.5mm$.

The bus-bars are made from $20x10x80mm$ *CW004A, Cu-ETP* from *Alumeco* which has an electrical conductivity of $100\%IACS$ which is equivalent to $17.241n\Omega$.[10] The amperage rating of a copper bus bar can be approximated to $525A$ in still air according to the *Bus Bar Rating Table* as provided by *AustralWright.com* [11]. With currents at only a fifth of this rating, the bus-bar is over-dimensioned. Dimensions of the bus bar is instead ruled by the mechanical requirements of the inserts and contact resistance. To clarify, the copper bar should accrding to above mentioned, in no way be a limiting factor.

The used contacts, or bus bar inserts, are the Amphenol Radsert 10-737504-001, which is a knurled, press in 8mm female cylindrical contact rated at $200A$. See Fig 26.

Figure 26: The Amphenol Radsert 10-737504-001

Polyvinylidenefluoride has a dielectric strength of $13kV/mm$. [9] with which it is possible to calculate the insulation rating of the maintenance plug if the material-thickness is known. As the thickness of the polyvinylidenefluoride is greater than $2mm$ the insulation of the maintenance plug is greater than $26kV$ as shown by eq. 4

$$13\frac{kV}{mm} \times 2mm = 26kV \tag{4}$$

As the maintenance plugs are required to be positively locked, which is achieved by a printed spring mechanism inside the casing, which latches on to the slot on the positive and negative poles. See fig 27 This is inspired by *Amphenols* own solution on the *radloks* which does the same. See section 6.5.2. Compressing the spring by pressing/compressing the sides of the maintenance plug releases the poles.

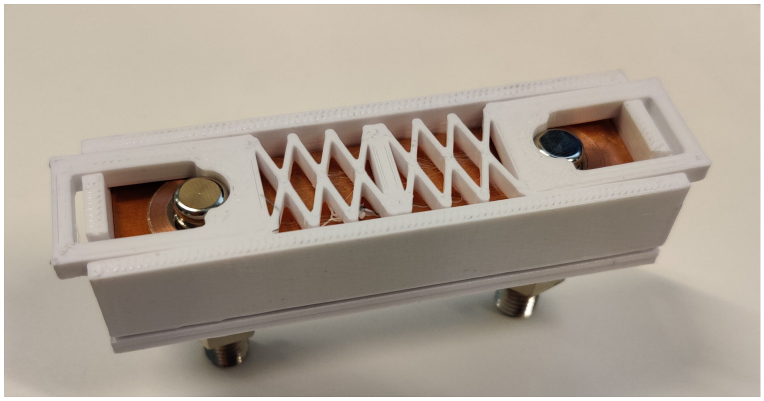

Figure 27: Spring mechanism inside the custom LFS20 Maintenance Plugs

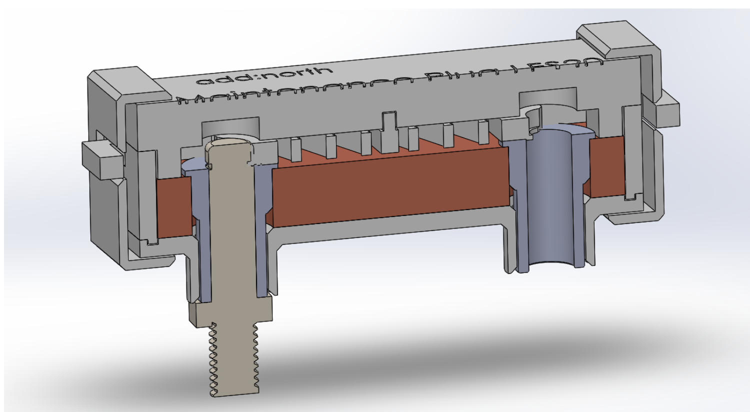

Figure 28: Section View of the custom LFS20 Maintenance Plugs

6.5.5 Mounts

There are six identical mounts on the accumulator container to the primary structure. The structure of the frame that the container is mounted to is in itself possible to dismount from the rest of the primary structure. This should be found in the design report of the Frame & Safety subsystem.

The first design of the container looked like in figure 29. However, hand calculations showed that the bearing stresses was a little bit high and that the load on the welds would yield at loads of $20kN$. The stresses in mount and welds were calculated to be below tensile stresses. However, it was decided to interpret EV5.5.13, ...*"must be able to withstand 20 kN in any direction"* and using a definition of *withstand* as being *unaffected by*. Therefore the new mounts would have to be designed in such a way that no part was subject to stresses above its yield limit.

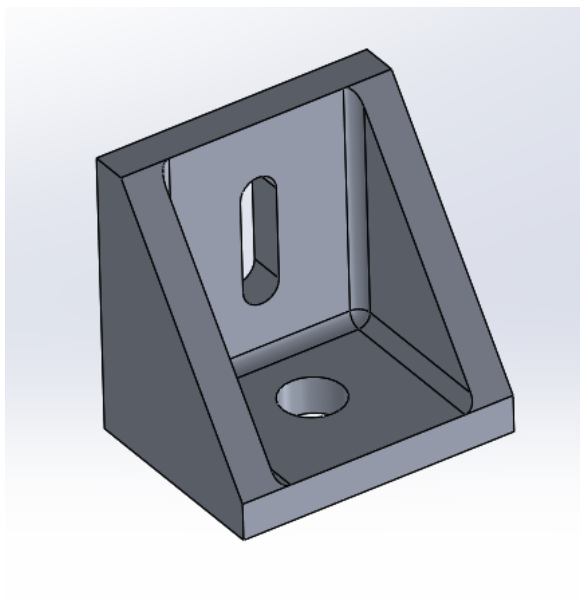

Figure 29: First design of the accumulator container mounts.

The mounts were then redesigned to allow for even greater weld-surfaces and increased material thickness on the bottom of the mount. See Fig 30. As a result of the welds being calculated to fail on the previous mount, vertical slots were added and increased in size to allow for a greater weld surface.

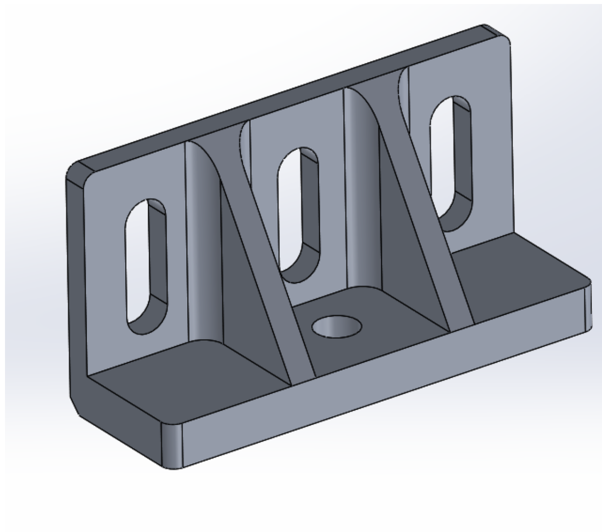

Figure 30: Second design of the accumulator container mounts.

Hand calculations on this mount and the welds showed it to hold for load cases of $20kN$ in all directions when welded to the frame with welded ribs going underneath (Fig 31) to support the lateral load case, when the mount is pulled straight out.

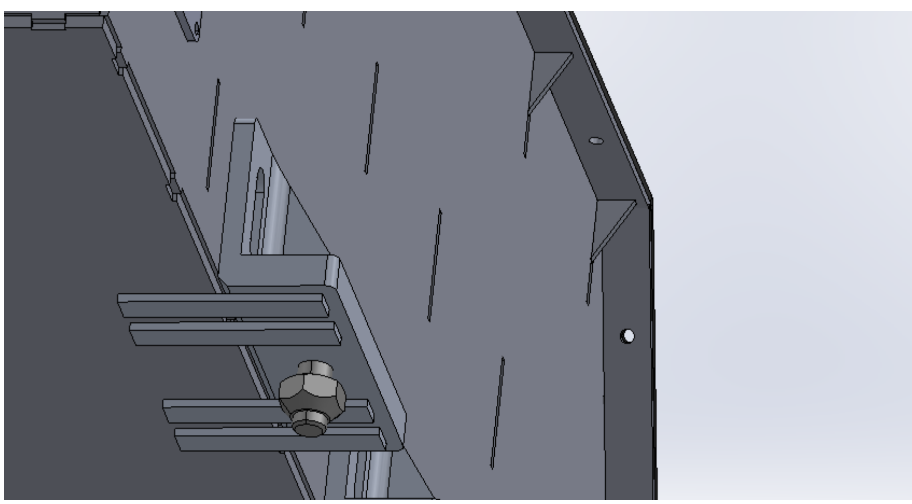

Figure 31: Mount with extra ribs to support lateral loading.

Figure 32 shows one of the five FEA loads that were analyzed on the mount.

The maximum stresses occur in the nut and bolt. The weld stays right around its yielding point and the mount as-well. Since this is only a complement to the hand-calculations the mounts are regarded to fulfil rule EV 5.5.13.

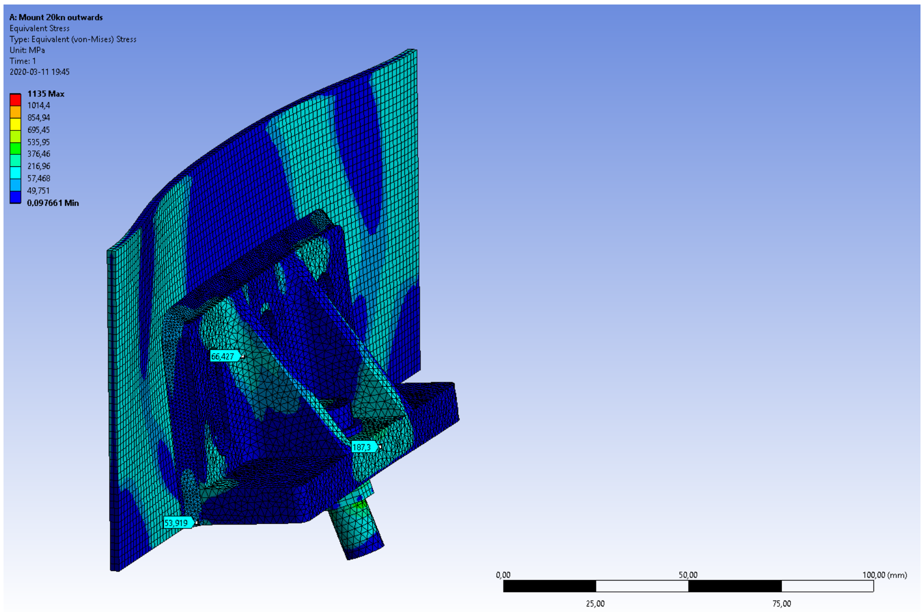

Figure 32: FEA Analysis of the mount loaded with 20 kN laterally (outwards).

7 Cooling

7.1 Forced Convection

7.1.1 Design

As a result of space constraints and of the new design approach, the cells are stacked closely together as seen in figure 33.

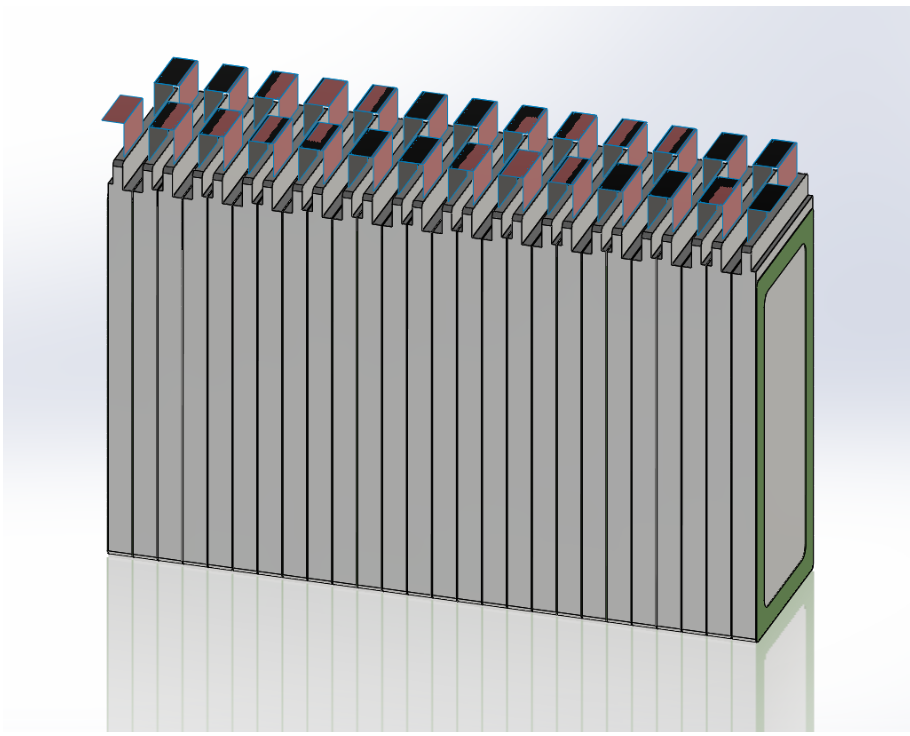

Figure 33: Cells stacked tight with small spacers between to allow for swelling. No airflow between the cells

This greatly reduces the surface area for heat transfer in forced convection air cooling. Instead of going in between the cells, the air is forced by a radial fan in the front, to go along the sides of the cell stacks and through the Accumulator as shown in fig 34. With three inlet fans and three exhaust fans, air is also directed over the accumulators to cool the BMS-Slaves and the cell tab connections in the stack-up. See figure 35.

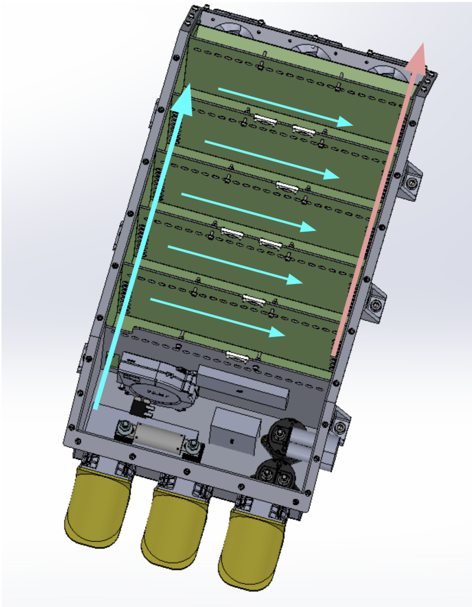

Figure 34: Airflow forced front to back, side to side in the container. Equidistant paths should result in similar pressure drops and equal cooling.

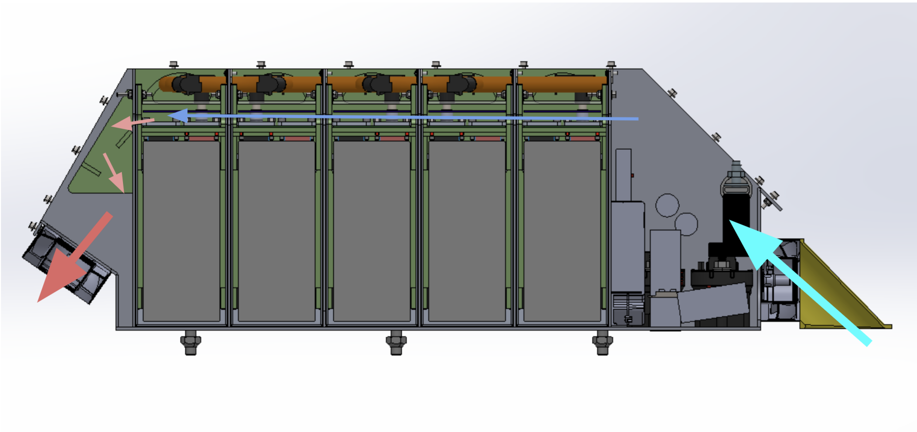

Figure 35: Airflow along the top of the accumulators, cooling the BMS-slaves and the connections in the stack-up

7.1.2 Heat transfer calculations

To make a rough steady-state estimation of the cooling and behaviour of the container, a simplified forced convection cooling calculation was made.

$$P_{HeatLoss} = I^2 R_{internal} \times n \tag{5}$$

Where $R_{internal}$ is the total internal resistance of the cell and the connections at the relevant load and temperature. n is the number of cells.

$$Q_{Cooling} = hA(T_s - T_{air}) \tag{6}$$

Where h is a convective heat transfer coefficient. A is the total heat transfer surface area, and T_s and T_{air} is the temperature of the cells and the air respectively. Ideally, the cooling is greater that the heating, which gives us together with equation (5) and (6) that:

$$h > \frac{I^2 R_{internal} n}{A(T_s - T_{air})} \tag{7}$$

With the internal resistance as supplied by Melasta [4]. This calculation takes no regard for any eventual chemical sources of heat generation, a heat transfer coefficient of at least 35 is needed. Values are shown below in table 2. In this calculation, a steady-state condition is assumed, where the temperature in the cells is assumed to be homogeneous and 55°C, close to the maximum allowed 60°C.

A	0.5	m^2
n	130	$numberofcells$
T_s	55	°C
T_{air}	25	°C
$R_{internal}$	1.5	mΩ
I	50	A
h	32.5	W/m^2°K

Table 2: Values used to calculate the heat transfer coefficient h

Physically determining h for our design is complicated. Initially a comparison is made according to the values on the website *nuclear-power.net*, which states that a value of h between 0 and 25 are generally applicable on free convection in gases, and 25 to 300 are applicable for forced convection cooling by gases.[6] This shows that forced convection air cooling is required of the system and should be investigated further.

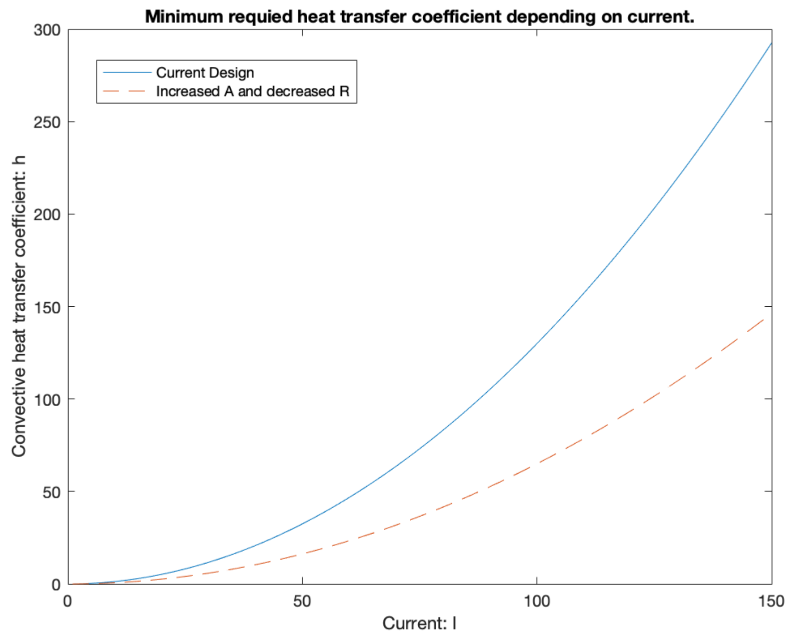

Figure 36: Graph showing the minimum required heat convection coefficient h and how it depends on the current. Dashed line has an increased surface area A = 150 % and a lower internal resistance R = 75 % compared to the solid line

Figure 36 shows a graph where the current I is increasing and how the minimum required value of the heat convection coefficient increases exponentially. This graph in accordance with equation 5 shows that using a higher number of cells in a (XXs2p) configuration as mentioned in section 8.1 which might reduce the internal resistance and increase the surface area would result in a much more easily cooled system.

7.1.3 Steady state vs Dynamic

Above calculations rely on a steady-state condition in which the maximum wanted temperature already achieved. However, since the races are typically quite short, with the longest race *Endurance* is not expected to be any longer than about 20-30 minutes, it should also be taken in to account that in some events, the cells in the container might not even reach a maximum temperature. The tests as performed by *Isabella Hansen* and *Johanna Wikström* at *Sigma Connectivity*[3], a bank of 3 cells drawing a current of $50A$ took more than 16 minutes to reach a temperature of $60°C$ between the cells, and the temperature of the cell tabs not even reaching a temperature of $40°C$. See figure 37. This points towards that it is not necessary to assume a steady state condition and that the dampening effect of the thermal capacity of the cells plays a significant role. In this report this in only speculations, but this should be investigated further. Preferably with a better understanding of heat generation in the cells, convection coefficients and the specific heat capacity of the cells.

7.1.4 Further Cooling Cell Research Recommendations

It has not been possible to perform all research this year and some questions arose during development and are still not clearly answered.

- Further research the internal resistance of the cells - heat generation
- Specific heat capacity of the cells

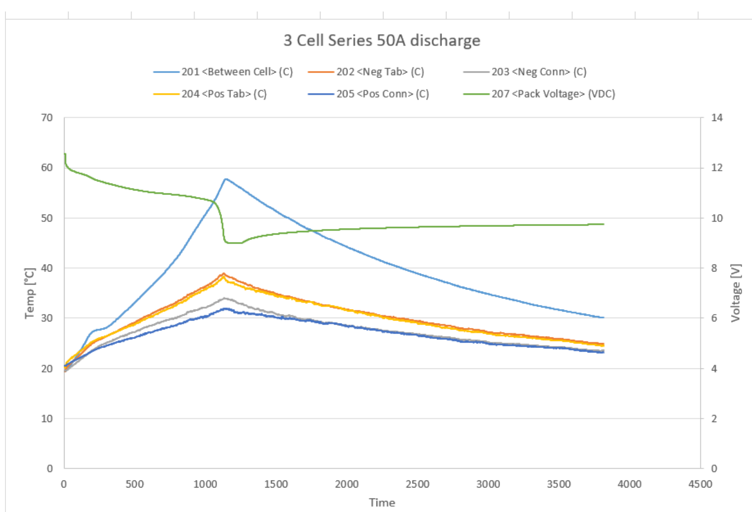

Figure 37: Graph taken from the cell research by Isabella Hansen and Johanna Wikström showing the temperature of a stack of three cells in a load of 50 A without additional cooling

7.2 Cooling Fans

7.2.1 Background

Since CFD analysis had been unsuccessful the dimensioning and choice of fans was done without sufficient understanding about the airflow through the Accumulator Container. The Accumulator Container has three inlet axial fans and three exhaust axial fans. Inside the container one axial fan is used to force flow in between the segments. Since a large pressure drop is expected for cooling with fans through the accumulator container, fans are chosen with a focus on high power output and high static pressure.

7.2.2 Radial Fan

The used radial fan is Delta's $BFB1212VH$. This fan has a maximum pressure of 33 mmH_2O which is around 320 Pa. It can be mounted on the right wall of the accumulator container, requiring a relatively small footprint inside the container to redirect airflow in between the segments as compared to axial fans.[7]

Voltage	12 V
Power	15 W (max 22.6 W)
Air Flow	max 39.55 CFM (min 31.5 CFM)
Air Pressure	max 33 mmH_2O (min 25 mmH_2O)

Table 3: Key Characteristics of the Delta BFB1212VH Radial Fan

7.2.3 Axial Fans

The used axial fans are Delta's $PFB0812UHE{-}EP$. This fan in IP56 protected which means that it is well protected against dust and water jets. Since this fan is to be mounted on the outside of the Accumulator Container, it is required to withstand the elements during race.[8]

Voltage	12 V
Power	11.88 W (max 22.32 W)
Air Flow	max 91.87 CFM (min 80.82 CFM)
Air Pressure	max 24.74 mmH_2O (min 20.51 mmH_2O)

Table 4: Key Characteristics of the Delta PFB0812UHE-EP axial fan

7.3 Further Cooling Analysis

After fan design and cooling choices, during manufacturing phase, further analysis of the cooling was wanted. Both for competition design and for documentation. A very simplified model of the container and its cooling fans was run in *STAR-CCM* with help from *Oskar Lundström* from the Aerodynamics team. The analysis included only the three inlet and three exhaust fans. Figure 39 shows that the airflow alongside the first and second segment is significantly lower than that of the airflow alongside the last segment. *(Bottom-Up)* A possible solution to this could be by using different sized holes in the paths of the airflow, restricting the airflow alongside the last segment *(from the bottom)*, forcing more air to pass along the first and second segment.

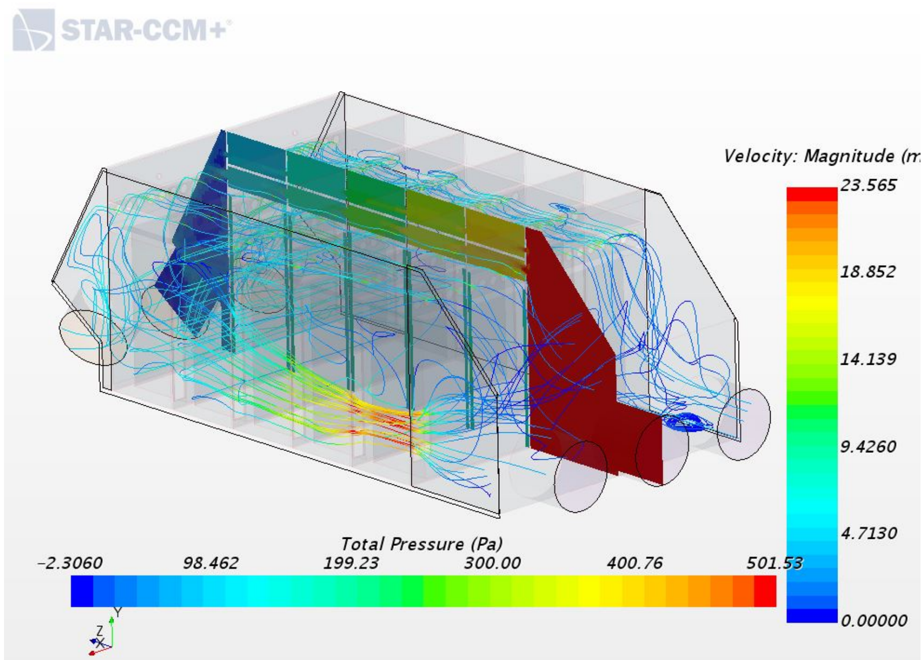

Figure 38: ISO-view, Cooling of the Accumulator Container, pressure and velocity.

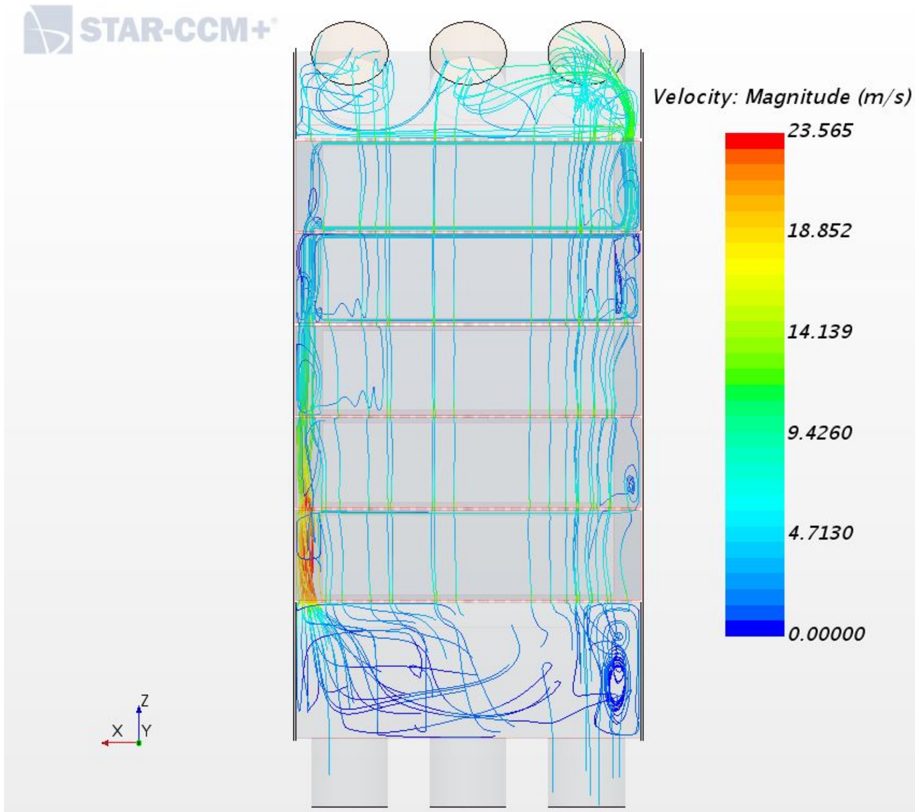

Figure 39: TOP-view, Cooling of the Accumulator Container, velocity.

7.4 Air Ducts

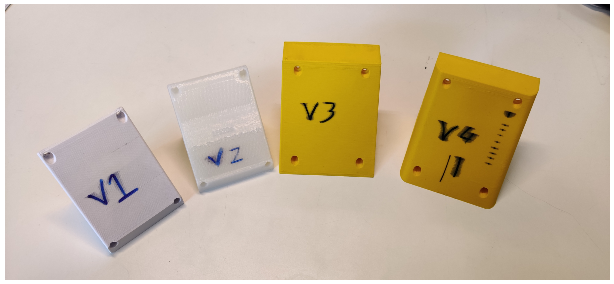

Figure 40: Four prototype versions of the inlet air-ducts

The car needs to be able to to drive safely in wet conditions, and needs to be protected from moisture and water droplets from entering the accumulator container. This can be problematic with free-flowing air through the container. The problem with trying to filter out water is a restricted airflow. There are different approaches that can be taken to this problem. For example; in a monocoque, one might place the accumulator container and it's inlet in a space inside the car where no moisture or water droplets are expected as a result of driving in wet conditions. One might also depend on filtering the air with filter-materials. The design of this accumulator container however, as a result of the vehicle it is contained in, utilizes small air-ducts on the inlets to prevent a high pressure stream of water entering the accumulator container from the inlet and exhaust. The triangular shape of the air-ducts is a result of the rule regarding distance from the firewall.

Testing, evaluating and designing the air-ducts can be done with help of CFD analysis, but can also be done by prototyping and testing. The air-duct designs were prototyped by 3D printing them in-house out of PLA-plastic and then building a small test rig, with the fan and a DC-Power supply. This is very labour efficient and easily proves the relative absolute performance in comparison. However, some CFD analysis is also performed to identify the reasons for bad/excellent performance. Prototyping the parts also gives the advantage of testing the main purpose of the ducts, protecting any water streams from passing through.

The first designed Air-Ducts depends on a water-lock inspired design and can be seen in figure 41. This design proved to generate very high resistance in the airflow. It was iterated with large internal radii on the walls, but still resulted in a very high resistance.

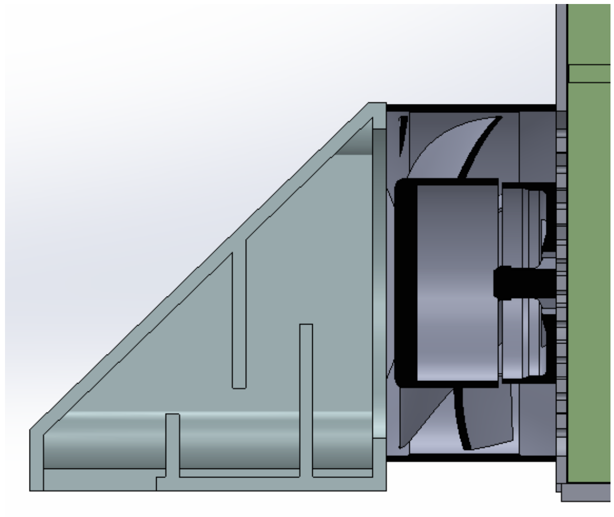

Figure 41: Cross section view; First air-duct design

A different design approach was to let the fan draw air from the sides, increasing the cross-sectional inlet area. The air is drawn in from the front wall of the accumulator container on the sides of the fan and then drawn forward to the inlet. This design proved to perform much more efficient. See figure 42.

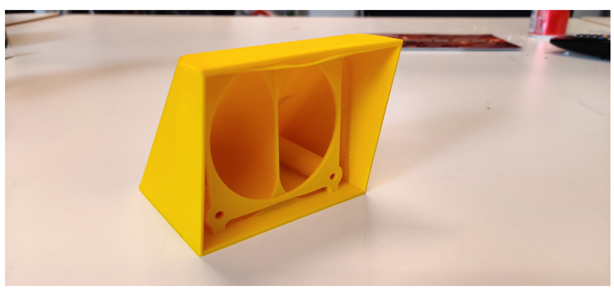

Figure 42: Prototype Nr. 4 of the air-ducts, drawing air from the sides of the fan close to the accumulator front wall.

8 Things to Consider & Recommendations

8.1 Cell Configuration

There is a mechanical simplicity to the (130s1p) configuration, but some things might benefit from some consideration.

The internal resistance generally decreases with more cells in parallel, as a result of a larger contact area, within and outside of the cell. A (XXs2p) configuration should be investigated using smaller cells, most likely increasing the number of used cells. With a larger number of smaller cells, the possible surface area for cooling is also increased. However, the mechanical complexity might increase.

9 Design Approach

It is recommended to investigate a layout that consists of six segments instead of five. This for two reasons. Firstly, it could provide the opportunity of leaving an air gap in between the cells to provide a greater surface area of cooling, and less resistance for the air in passing through the accumulator container. See section 5.1. Secondly, the maximum capacity of the container could be increased with another segment. Both of these reasons need to be evaluated after more experience with this current design of the accumulator container. Doing this should result in a slightly longer accumulator container, and possibly even a bit wider. Extra space in the electronics compartment as described in section 6.4.6 could be required in order to fit a CTMD which also is recommended in section 9.1.

9.1 Cell Temperature Monitoring Device (CTMD)

In order to compete at FSG and possibly more competitions in the future, a CTMD must be installed. See section 6.4.6. This is not implemented in the design of the current accumulator container.

9.2 Accumulator Mounts

Investigation of bolted mounts, with the use of backing plates should be investigated since it has not been evaluated sufficiently this year. The welded mounts have proven to be a bit tricky to design and calculate to withstand the required load-cases. See section 6.5.5. A bolted on solution might also be easier to manufacture.

10 Personal / Finishing Thoughts and Comments

The design and manufacturing of this accumulator container has been an incredible experience. During the one and a half years I have spent working on this project, I can definitely say that I have learned a lot. The workload has been very high in combination with full time studies. I am very grateful for my colleague *Stefan Lopar* for the design of this system. We have complemented each other very well with different approaches to problems, always discussing and arguing in order to eventually come to a conclusion together. Not to forget, without his moral support, the burden of this project would not have been possible.

Even though I think two people is one too few for the design of the Accumulator Container, I would say we have performed really well. This year we have been challenged to make a lot of compromises. But still, with very little space, sub-optimal cooling opportunities, a very low budget and no experience, we have managed to design a system that as of the writing moment, looks promising. I also want to thank the faculty of Energy Science for letting me write this report as part of the course *MVKN80*. This has allowed me more time to be thorough and essentially, leave a better foundation of experiences behind for following years.

There are many things that i feel are left out of this report, but it is also not suitable to write down everything in a report like this. If you are a new recruit of LFS and are about to design the next Accumulator Container. I wish you all the best.

Don't forget to read the rules!

11 Rules

11.1 Rulebook

The rules that are referred to are taken from the 2020 V1.0 Rule book from the FSG website. [1]

11.2 Rules

The refered to rules are stated below

1. T.1.2.1 UL94V-0 for the minimum used material thickness

2. EV4.3.3 Where both TS and LVS are present within an enclosure, they must be separated by insulating barriers made of moisture resistant, UL recognized or equivalent insulating materials, rated for 150°C or higher (e.g. Nomex based electrical insulation), or maintain the following spacing through air, or over a surface (similar to those defined in UL1741):

Voltage	Spacing
U < 100 VDC	10 mm
100 VDC < U < 200 VDC	20 mm
U > 200 VDC	30 mm

3. EV4.5.12 All TS connections must not include compressible material such as plastic in the stack-up or as a fastener. FR-4 is allowed.

4. EV4.5.13 All electrical connections, including bolts, nuts and other fasteners, in the high current path of the TS must be secured from unintentional loosening by the use of positive locking mechanisms that are suitable for high temperatures, see T10.2.

5. EV5.1.2 Cell Energy – the maximum cell voltage times the nominal capacity of the used cell.

6. EV5.3.2 Each TS accumulator segment must not exceed a maximum static voltage of $120VDC$, a maximum energy of $6MJ$, see EV5.1.2, and a maximum mass of $12kg$.

7. EV5.4.1 If the TS accumulator container is made from an electrically conductive material, the insulation barrier must be adequately protected against conductive penetrations.

8. EV5.4.3 LVS must not be included in the TS accumulator container except where inherently required. Exceptions include the AIRs, TS DC/DC converters, the Accumulator Management System (AMS), the Insulation Monitoring Device (IMD), parts of the TSAL and cooling fans.

9. EV 5.4.5 Maintenance plugs must
   • not require tools to separate the TS accumulator segments.
   • be non-conductive on surfaces that do not provide any electrical connection.
   • be designed in a way, that it is physically impossible to electrically connect them in any way other than the design intent configuration.
   • be designed such that it is clearly visible whether the connection is open or closed. Electrically controlled switches must not be used.

10. EV 5.4.6 Each TS accumulator segment must be electrically insulated by the use of suitable rigid and fire retardant, see T1.2.1, material between the segments and on top of the segment to prevent arc flashes caused by inter segment contact or by parts/tools accidentally falling into the TS accumulator container during maintenance.

11. EV 5.5.3 All TS accumulator container materials must be fire retardant, see T1.2.1.

12. EV5.5.4 TS accumulator containers must be constructed of steel or aluminium. With the following requirements:

    • The bottom of the accumulator container must be at least 1:25mm thick if made from steel or 3:2mm if made from aluminium.

    • The internal and external vertical walls, covers and lids must be at least 0:9mm thick if made from steel or 2:3mm if made from aluminium. Alternative materials are allowed with proof of equivalency per T3.3 or for composite materials per EV5.5.5. This must be documented in the SES. When alternative materials are used, test samples must be presented at technical inspection.

13. EV5.5.6 The floor and walls of the TS accumulator container must be joined by welds, bonding and/or fasteners.

14. EV5.5.7 The TS accumulator container must consist of electrically insulating internal vertical walls with a minimum of 75% of the height of the external vertical walls, that divide the accumulator container into section of a maximum of 12 kg .

15. EV5.5.8 The accumulator segments, see EV5.3.2, must be separated by a rigid, electrically insulating and fire retardant barrier, see T1.2.1.

16. EV5.5.9 The TS accumulator container itself, the mounting of the TS accumulator container to the chassis and the mounting of each cell to the container must be designed to withstand the following accelerations:
    - 40 g in the longitudinal direction (forward/aft)
    - 40 g in the lateral direction (left/right)

- 20 g in the vertical direction (up/down)

Calculations and/or tests must be documented in the SES. All considered TS accumulator container attachment points must follow EV 5.5.13. TS accumulator containers made of materials as stated in EV 5.5.4 or EV 5.5.5 may need further reinforcement in order to comply with this rule.

17. EV 5.5.13 Any brackets used to mount the TS accumulator container must be made of steel 1:6mm thick or aluminium 4mm thick and must have gussets to carry bending loads. Each attachment point including brackets, backing plates and inserts, must be able to withstand 20 kN in any direction.

18. EV5.5.14 Holes, both internal and external, in the TS accumulator container are only allowed for the wiring-harness, ventilation, cooling or fasteners. The TS accumulator container must still be compliant with all other rules, especially the ones concerning its structural requirements. External holes must be sealed according to EV4.5.

List of Figures

References

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Appendices