Accumulator

The team

Name	Sub-team Role
@ Owen Brake	Technical and Tractive System Lead

Projects

Unable to render {children}. Page not found: Accumulator Projects.

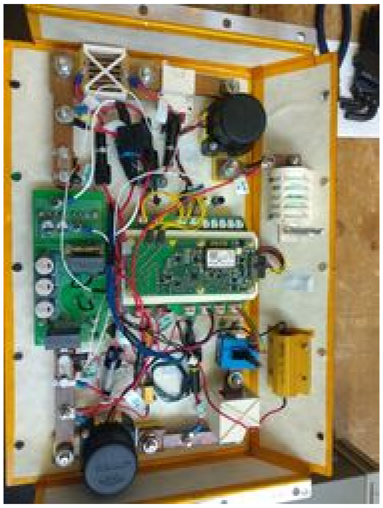
Space Links

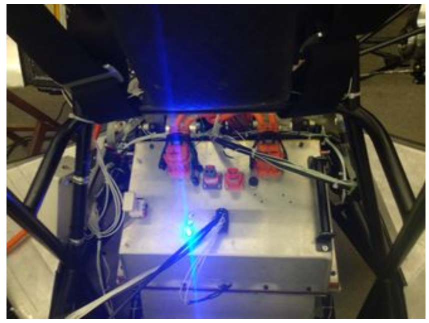
Meetings

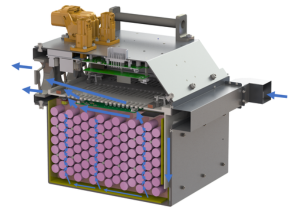
Meeting minutes should be recorded for all meetings, without exception, and be recorded in the Accumulator Task Report. Once a meeting item is documented, overwrite it. Please contact your team leads for questions related to meeting minute procedures.

Recently Updated

- Precharge Overview
  Jun 19, 2022 • contributed by Owen Brake
- Accumulator Overview
  May 29, 2022 • contributed by Owen Brake
- Accumulator Lessons
  May 29, 2022 • contributed by Owen Brake
- Accumulator
  May 29, 2022 • contributed by Owen Brake
- High Voltage Current Path 2021-2022
  Mar 18, 2022 • contributed by Chris Tseng
- Accumulator Current Sense
  Feb 06, 2022 • contributed by Jacky Lim
- Cell Packaging 2021
  Jun 25, 2021 • contributed by Calvin Ryan DeKoter
- HV MCO 2021
  Jun 09, 2021 • contributed by adestefa@uwaterloo.ca
- High Voltage and Cell Safety
  Jun 02, 2021 • contributed by Chris Xie
- Accumulator Cell Selection
  May 30, 2021 • contributed by Chris Xie
- Cooling 2021
  May 27, 2021 • contributed by a2school@uwaterloo.ca
- Cell testing 2020-2021
  May 26, 2021 • contributed by Former user (Deleted)
- Tractive System Task Report-Accumulator
  May 26, 2021 • contributed by Calvin Ryan DeKoter
- Task Template Spring 2022
  May 26, 2021 • contributed by Calvin Ryan DeKoter
- Task Template Spring 2022
  May 26, 2021 • commented by Calvin Ryan DeKoter







Deliverables

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

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Tractive System FAQ

Questions

Accumulator Documentation

2016 Car's Accumulator Cooling Design:

WFE-AM-Design.pptx Group29_Project2B.pdf

Factors to weight in decision making

- Cooling complexity
- Cable management
- Waterproofing
- Cost
- Total mass
- Room for future development
- Design points

High Level Goals

- Air cooling if possible
- High voltage
- Minimize Wires (and fires)

Voltage

A voltage range of 285 to 300 was selected.

Emrax 188 has a max voltage of 270v, Bamocar D3 has a max voltage of 400v. From the battery constrains page, the battery packs voltage does not have any hard limits.

To limit the amount of field weakening, a larger voltage is preferred. A larger voltage will also mean that less current is drawn through the pack resulting in less heat generation and smaller tractive system wiring.

Capacity

A capacity of 6.5KWh was selected.

Lap time sim analysis was performed to understand power requirements for the car. What was discovered is that a small sacrifice in lap times during endurance will conserve a large amount of power. Simply limiting the max power below 80KW through endurance is how this is achieved.

It was also found that though some rough comparison of past lincoln even times, the increase of mass from a larger battery pack does not outweigh the speed benefits from endurance.

6.5 KWh is a very average pack size that leaves room for pushing speed in endurance without sacrificing too much mass.

Box Architecture

Panel mounting connectors on the top of the box pose a problem when you want to open the box. You would have to manage all the connections to the electronics mounted below. To solve this, we are proposing to mount all electronics upside down on the lid of the box (including relays, busbars etc). As you remove the lid, you pull out the positive and negative high current bullet connectors along with the AMS board connector. Segment disconnects will be on top of the AMS boards and lexan fire sheet forcing you to pull them before you can access the modules.

To make the lid disconnect process easier and to be super cool, we could use LTs SmartMesh chip to link either all AMS boards together and to the BMS, or only populate one of the AMS boards with the chip to the BMS and wire all AMS boards together. Leave the foot print on them all so there is only one AMS layout. Now an easier way to do this that is much more practical would be to align a connector in between the power bullets for the AMS board, that way the power pins keep the connectors all aligned. We would then make a jumper cable that has 3D printed ends to hold those three connections in place. We would use this jumper when doing debugging to maintain all connections while the electronics are exposed.

Bullet connectors that can handle the current exist and are fairly sleek. They also make press fit bullets that almost look like a PEM nut and would press into the busbars. Segment connections would be made by a busbar that has pins on the end and is covered in a 3d printed shroud.

Battery Cells

Electric Power's 6.3Ah cell was selected for the 2018 battery pack.

Datasheet:

? Unknown Attachment

The cell selection detailed overview page outlines a lot of the criteria there were evaluated when going through the process of selecting this cell. The main points that lead to the final decision were as follows.

- Met desired capacity and voltage
- Layout of cells was favourable for busbar layout (many cells in parallel)
- External pack dimensions packaged well given our studies
- Cell tabs are made of nickel plated copper instead of aluminum
- Low battery impedance (<1.5mOhms)
- Very high charge rate (almost abnormally high) which is good for regen

Battery Tips from Jeff G

Jeff is a lab technician in the UW Mechatronics Vehicle Lab. He has been working with EV's for a very long time and is very knowledgeable. Reach out to @ Former user (Deleted) to get into contact with Jeff.

Accumulator Design

- Design the pack such that the cells or cell modules can be easily swapped out in a short amount of time without risking damage. The reason for this is that we will inevitable kill a lot of cells well discharging quickly. The swap process must be easy enough that we can do it a competition without a significant amount of work.
- Take very special care to ensure consistently low impedance between cells that are in parallel. This will make cell balancing during charging infinitely easier.

Cell Purchasing and Cell Storage

- Purchase a MINIMUM of 20% more cells than you actually need. More if we intend on doing a lot of driving. This reason is that we must expect to lose a lot of cells.
- Someone should be assigned to checkup on all of the cells at a regular interval, both while they are in storage and when the car is sitting
  - All cells should be stored at about 50% charge
  - DO NOT let the cells go under voltage

In-vehicle Cell Monitoring

- The most important thing to keep an eye on while driving around is minimum cell voltage. As in you should me monitoring each of the individual cells, and watching for which one is the lowest voltage.
  - If a cell drops below your minimum specified voltage, shut the car down immediately.
  - SOC monitoring is secondary to minimum cell voltage monitoring
- Cells should be balanced such that there is a less than 2% voltage difference between each of the cells.

SOC Calculation

- For LiFePO battery cells, the amount of work required is almost not worth developing an SOC algorithm, as the accuracy is usually quite low. This is due to the strong "S" curve voltage characteristics where the voltage seen between for example 70% and 30% charge may be near constant. You are usually required to 'teach' your algorithm for the pack. If someone accidentally overcharges the pack, this taught algorithm must then be redone from scratch.
- Other types of Lithium-ion battery cells exhibit more-linear voltage characteristics, in which case SOC algorithms can be justified as they are a lot less work.

Formula SAE Design Reports

- 864601926-MIT.pdf : Read and summarize this paper as it relates to the team's design @ Joseph Anthony Borromeo 10 Jun 2020
- IJRET20160515006.pdf : Read and summarize this paper as it relates to the team's design @ jlmorabi@uwaterloo.ca 10 Jun 2020
- YIN-THESIS-2016.pdf : Read and summarize this paper as it relates to the team's design @ Calvin Ryan DeKoter 10 Jun 2020

Design and Analysis of a Battery for a Formula Electric Car - By Samuel Reineman, 864601926-MIT

- Their Accumulator uses A123 20Ah pouch cells inside a Kevlar composite battery box in a 84S1P configuration
- The accumulator was designed based on the most strenuous dynamic events for the battery: Endurance and Acceleration
  - For acceleration high current output is required
  - For Endurance you need enough capacity to last the whole race
- Main Pack Fuse must be sized such that it is the first element to blow in the event of a pack short
- To ensure team member competency when working with high voltage, team members must pass the same HV safety course as Tesla powertrain engineers do.
- Power Density vs Energy Density
  - Must find the correct power/energy density trade-off to ensure the car is as light as possible and still achieves the proper power and energy densities
    - A pack composed of the ideal cell chemistry for any specific application reaches its desired power output at the same weight it reaches its desired energy storage
- To properly design the pack and characterize the power and energy demands, a track simulation was created.
  - This outputs the max current needed and the total energy needed for the 20 lap endurance race.
- Using the simulated data and the voltage and power limits from the rules, the basis of the pack specs were created.
- Chose LiFePo4 cells by A123 as they were the lightest due to their high power density, have low internal resistance and are generally a safe chemistry – Also got sponsored
- Packs with large parallel blocks need to be carefully designed with fusing in place in the event of a single cell failure.
- **They chose to add 2 more cells in series and not charging the cells all the way as the capacity increase in the last 0.1v in charge only gave a 0.5% capacity increase.**

- Final pack was 3x 28S1P segments for an overall 84S1P
- Cells were connected using mechanical clamping to allow non-destructive disassembly
- Used Kevlar reinforced nylon as the clamping plate
- Continually used FEA to iterate on the design and achieve a high strength to weight ratio
- Neoprene and an aluminum plate were sandwiched between the cells to absorb small imperfections in cell flatness and help spread heat from the center of the cell, respectively
- They also use spring loaded contacts between cell measurement boards and cells
- All cell's were characterized through testing (Internal Resistance, Capacity)
- Extensive thermal analysis was done to ensure a pack temperature of 55C was never exceeded

Summary: Provides a good overview of what is required in designing an accumulator for an FSAE Electric car. Topics include lap simulations, cell selection, cell packaging, mechanical/ electrical design and thermal analysis.

Design and Fabrication of an Accumulator Container/Battery Pack for a Formula Student Vehicle - By: Ujjwal Ashish, Bishav Raj, and Abhishek Kumar

- lithium ion chemistries widely used for their power density, performance, and efficiency
- discharge rate, cell voltages and cell temperatures are constantly monitored by the Battery Management system as this affects cell lifespan
- temperature extremes are a result of high current loading such as fast charging or acceleration transients
- Kilovac 200 series AIRS (contactors) were used
- Uses dual Agni 95R motors coupled in series, which have a 93% efficiency meaning longer run time and less frequent battery replacement
  - Max peak power of 30 kW for 5s and continuous power of 16kW
- Single Kelly's programmable PMDC motor controller to drive both motors, which has an efficiency of 97%
- Criterion for cell selection:
  - High energy density (Wh/kg)
  - High specific energy density (Wh/l)
  - High power density (kW/kg)
  - Fast charging and discharging capability
  - longer life cycles
  - eco-friendly
- Great tables that summarizes the different properties for each cell chemistry on page 3
- Energy and power requirements for transmission determined by simulations in Optimum Lap
- Accumulator container is made up of 40 Kokam Lipo cells
  - Capacity: 63Ah
  - Voltage Range per cell: 2.7 V to 4.2 V
  - Energy/cell: 233.1Wh nominal
  - Pack Energy: 10.58 kW
  - 7.5 C discharge rate (meaning maximum discharge current of 480A and maximum peak current of 720A)
  - Continuous Power: 168*480 = 80.64 kW
- 40s1p cell configuration (max voltage of 168 V)
- Air cooled by 6 fans placed at the height of the cell terminals (4 inlet fans at 20CFM and 2 outlet fans at 40CFM
- Cell segment design consists of 6061 Aluminum racks that allow 2mm of separation between each cell. Silicon sheet is placed between cells for further isolation
- Simulation conducted in ANSYS on page 7 to prove the structural integrity of the pack

Summary: Great start for how to design a pack from start to finish.

Cooling and Packaging of Accumulators for Formula SAE Electric Car - By Hang Yin, YIN-THESIS-2016

- E-16, the car produced by UTA racing, has 4 in-hub motors and a total power of 75 kW.
- LiFEPO4 Cells from A123 systems are used to store energy for the vehicle. This type of cell is preferred because of its low self-discharge and lack of memory affect.
- To conduct heat away from the battery pack, corrugated aluminum is placed in contact with one face of each cell. This corrugated aluminum conducts heat away from the cells as air is drawn through with a fan.
  - Each accumulator box holds 30 cells and one cooling fan.
- There are 60 cells total across 6 segments in a 2P30S configuration.
- An energy balance is used to find the required mass flow rate of air through the corrugated aluminum required to cool the battery.
  - The heat removal rate was not explained in the body text.
  - The trapezoidal channels in the corrugated aluminum, 264 of them, are considered to find the static pressure drop and select a fan.
    - First, the Reynolds number for the fluid flow is calculated at 2700, meaning that the air flow is becoming turbulent. For this case, the pipes are smooth enough that flow will likely be laminar.
    - At the required flow rate of 130 CFM, the calculated static pressure drop correlated well to the experimental result from a wind tunnel. This value was approximately 50 Pa.
    - For three battery packs in series, the pressure drop was approximately 200 Pa at 130 CFM.
  - A comparison of the static pressure drop vs. flow rate curve and an electric fan performance curve is used to select an appropriate fan.
  - Ansys Icepak was used to model the battery cells and cooling fan to calculate the system performance.
  - Ideally, cell segments should be arranged in parallel, so that air heated by one segment is not used to cool another segment. The cell stacks are arranged in series here.

    - **Peak** temperature of the pack, not the average calculated by mass flow, must be used as a final criteria.
- This paper was a good introduction to the air cooled accumulators, but is not as in-depth as other papers. No physical testing was completed.
- **Conclusions:**
    - If designed to be air cooled, accumulator heat rejection calculations should start with basic mass flow - energy balances.
    - Cell segments should always be arranged in parallel instead of series. This causes a higher temperature difference, aiding heat transfer, and lessens the temperature variance in the pack.
    - There should be an emphasis on physically testing the thermal performance of the battery pack, but this is tough without a very large electrical load.

2016 Accumulator Module Design - By Tathagata Chatterjee

- Packing efficiency was the priority for the accumulator, therefore pouch type cells were used.
    - Lithium based chemistry was chosen for its excellent power and energy density, combined with a relatively low cost.
    - Initially, a General Electric cells were going to be used, but they could not arrive on time, so second choice A123 AMP20M1HD-A cells were used.
    - The final configuration consisted of 5 segments in series with 10 cells in series and 10 in parallel each for a total of 180V.
- For fusing, the cell tabs had holes punched into them, limiting the amount of current they could carry.
    - Regulations forbid this practice now.
- Silicone-based foam found inside the bay was used as an insulate filler. It itself does not limit the maximum expansion of the cells, but will prevent it once pressured against expansion limiters.
- Many aspects of the accumulator design should be improved on due to limited design time.
- **Summary:**
    - The paper is a good general overview on the research and design process of an accumulator module, but does not go in depth into anything specific.
    - It is recommended to finalize an overall electrical and mechanical design early in the project.
    - Significant changes during the build process can negatively affect deadlines and rules compliance.

- [x] Rishi 2016 Accumulator Module Design.pdf : Read and summarize this paper as it relates to the team's design @ a2ivanch@uwaterloo.ca 10 Jun 2020
- [ ] Thesis on the A123 LiFEPO4 Chemistry - https://uwspace.uwaterloo.ca/bitstream/handle/10012/8378/Mathewson_Scott.pdf?sequence=1

2020 Static Event Presentation: Tractive System Design Report

- [x] @ Calvin Ryan DeKoter Final Drive System and Accumulator Cooling 03 May 2020
- [x] @ Rohan Peri Motor and Inverter Selection 03 May 2020
- [x] @ jlmorabi@uwaterloo.ca AMS and Cell Packaging and Cell Chemistry 03 May 2020
- [x] @ Joseph Anthony Borromeo Lid Electronics and BMS Systems 03 May 2020
- [x] @– Powertrain Motor and Inverter Cooling 03 May 2020

Each Section Must Answer:

Why did you choose this part/material?

What are the advantages and disadvantages of this part?

How did you verify the adequacy of this solution?

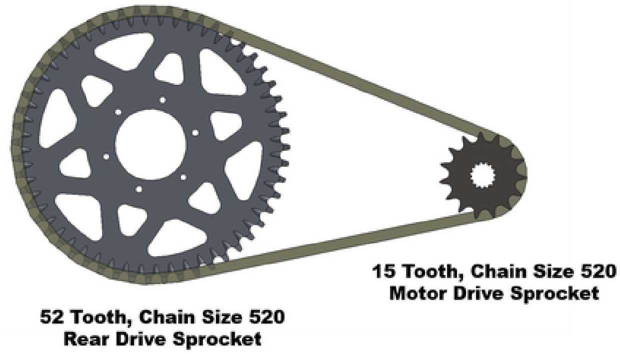
How did you implement the solution?

What will you do differently in the next competition season?

Final Driveline: Chain Drive and Tripod Half Shafts

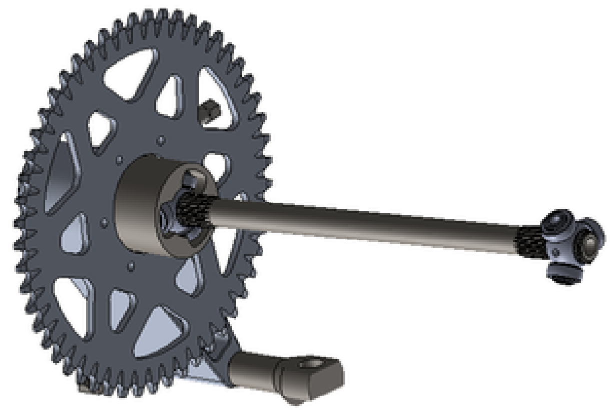
Waterloo Formula Electric's 2020 entry transmits power to the wheels through a chain reduction mechanism using with a 52 tooth rear sprocket and a 15 tooth motor drive sprocket. providing a drive ratio of 3.47 to 1. The chain is a size 520 ERT2 from DID.

At the motor. the front sprocket is attached with a splined shaft bolted to the six M8 mounting holes on the front of the Emrax 208 motor.



Gear Ratio Selection:

Dynamic Event Simulation found that a final drive ratio between 3.25 and 4 minimized the completion time of each event. Dynamic event simulations were carried out using a tire longitudinal coefficient of friction of 1.4. *Based on the other parameters used, this means that available drive torque at the wheel is higher than the grip provided by the tire, allowing acceleration at the maximum rate.* The maximum drive torque available from the motor, based on the data sheet, is 520 Nm at the tripod bearing cup.



Component Selection:

List of Components:

Component	Designed Load	Failure Load	Factor of Safety
Tripod Bearing			
Half Shaft for FSAE			

pictures of system- motor side pinion, drive side pinion and half shaft

List of torque capabilities of each component, chain tensioner calcs

Gear ratio selection

Revisions:

In the CAD Model, the snap ring grooves on the half-shaft are cut deeper than the root of the spline, which may cause early failure- verify and identity maximum torque

Add the Taylor Race Engineering Plunger System, or manufacture one

Design rear sprocket to be suspended in double shear

Motor and Inverter Selection:

The selection of the Emrax 208 motors and Sevcon Gen5 - S9 motor controllers was determined by availability of resources and satisfying team goals.

Motor - Emrax 208:

Why did you choose this part/material?

Pros:

- Cost is comparatively low ($4500 is on the lower end for name brand motors) https://wiki.uwaterloo.ca/display/FEPT/Motors
- Amazing Power to weight ratio (8.510638298 Power (peak) to Weight (kW/kg), this is the 2nd best, right behind the emrax 188)
- Setup is very popular, thus great reliability and good documentation since it is heavily used.
- Rated at IP65, a necessary requirement which this motor matched.

Cons:

- Emraxs are inboard motors, they must be used in an in-board design and not in-hub design.
- The packaging is more difficult, requires additional thought when designing mounts and gearbox setups
- Must design scatter shield and cant mount from outside of motor case

What are the advantages and disadvantages of this part?

How did you verify the adequacy of this solution?

- these motors were chosen because they have enough torque and speed to achieve a solid finish in the autocross event (numbers TBD)
- An upper limit on power is set by the competition rules- each Emrax motor is capable of 35 kW continuously, which is close to the rules limit of 80 kW

How did you implement the solution?

- Two motors with two motor controllers were used.
- Specifically, We implemented the solution with a chain drive and rigid mounting from both sides of the motor

What will you do differently in the next competition season?

- The difference for next season would be making the build process easier- i.e. not having to disconnect the cabling to remove the motors

(NOTE: We could possibly move the pros and con to answer the second question and move some of the stuff in the adequacy question to answer the first question)

Motor Controllers (Inverters) - Sevcon Gen5 -S9

Why did you choose this part/material?

- Two Sevcon Gen5-Size9 controllers mainly because Sevcon agreed to sponsor us with three controllers (two for the car plus one spare)
- Technical Support was also offered by the manufacturer, Sevcon
- Sevcon Is local and well supported and developed
- Rinehart is reliable but expensive, and Bamocar is sketchy

What are the advantages and disadvantages of this part?

Pros:

- CAN (Controller Area Network)
- Dynamic Battery current limit
- Mass is 6kg (3kg is saved off the car)

Cons:

- This package is slightly larger (Lose 50-80mm in terms surface area in comparison to the Rinehart) and has higher output than necessary since the motors will have less output

How did you verify the adequacy of this solution?

- Have not yet verified

How did you implement the solution?

- IXXAT usb-to-can interface tools were used to program the Sevcon Gen5 controllers.

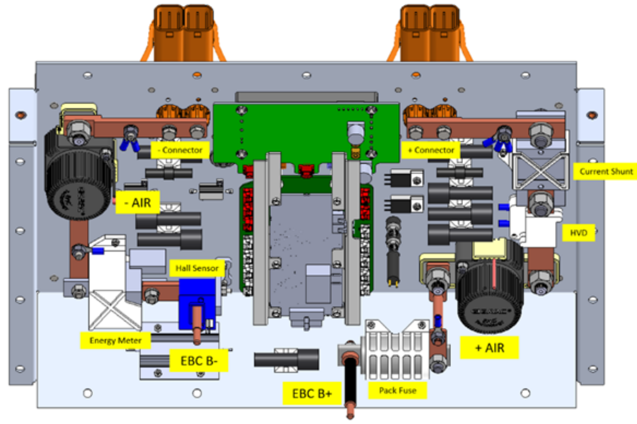
- Once connected, you can talk to the controller using Sevcon's Gen5MC software.
- This software allowed us to read values, change parameters, and update firmware
- The Software also contains most of the motor controller's documentation.

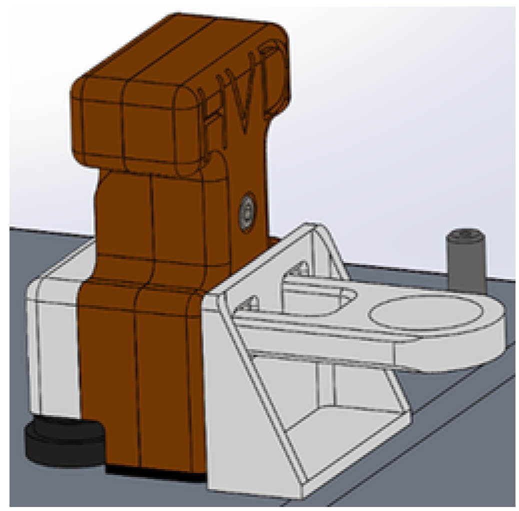
What will you do differently in the next competition season?

Lid Electronics and BMS

Accumulator Lid

The Accumulator lid houses the necessary HV electronics including the AIRs, IMD, Main Pack Fuse, Pre-charge/Discharge Resistors as well as the car's DC-DC Converter and Battery Management Unit (BMU) PCB. The top of the Accumulator lid contains our team designed High Voltage Disconnect which will break the car's High Voltage Interlock Loop when it's locking pin is removed to ensure the car begins to discharge before the current path is broken to eliminate arcing when breaking the HV current path. Two TE HVP800 connectors protrude from the top of the lid allowing us to connect the accumulator with the rest of the tractive system.





DC-DC Converter

The team designed DC-DC converter is based upon a TDK-Lambda PAF600F280-12 featuring an input voltage range of 200-400V, 90% efficiency, and a maximum continuous output power of 600W at 12V. This DC-DC was chosen since it offered a voltage input range of 200-400 VDC, allowing it to function with a fully charged or fully discharged battery. Based on an estimated current draw of 30A for the GLV system, the 50A maximum output of the DC-DC gives us extra power in case we have to add over components to the GLV system.

The GLV from the DC-DC exits the Accumulator lid through a TE AM P+ HVA 280 connector in order to power the car's GLV system.

Battery Management Unit (BMU)

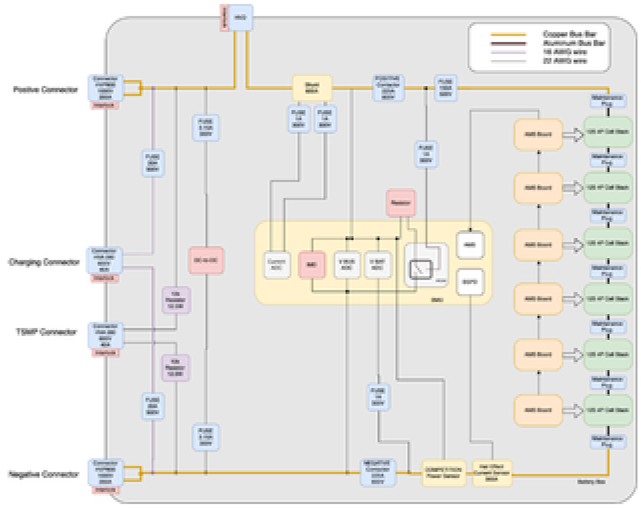
The team designed BMU monitors the individual state of each element in the HVIL and checks for faults such that it can be reported and further used for debugging. Additionally, the BMU sources and monitors a 10ma MCIL that is required by the motor controllers. The monitoring of the cell voltages and temperatures is done through the 6 AMS boards which connect to the BMU via a daisy chained isoSPI bus. Each AMS board interfaces with one of six accumulator segments to get cell temperature and voltage data.

BMS Faults

1. Under voltage - Cell Voltage below 3.0 V (100% of cells monitored)
2. Over voltage - Cell Voltage above 4.2V (100% of cells monitored)
3. Over temperature – Cell Temperature Above 58°C (100% of cells monitored)
4. Timeout – A cell temperature or voltage reading has not updated in 500ms
5. Cell Fuse Failure

In addition to the faults mentioned above, the BMU contains a watchdog timer that ensures constant operation of the board and in the event of a firmware failure the timer will trip and open the AIRs.

A BMS fault will cause the system to enter a faulted state and open the AIRs. The only way to exit this state is to cycle the GLVMS, which cannot be done by the driver.



Cell Selection

Why did you choose this part/material?

For the 2019-2020 battery, we have selected Lithium Ion Polymer cells from Electric Power. Based on the following reasons:

- Met desired capacity and voltage
- Layout of cells was favourable for busbar layout (many cells in parallel)
- External pack dimensions packaged well given our studies
- Cell tabs are made of nickel plated copper instead of aluminum
- Low battery impedance (<1.5mOhms)
- Very high charge rate (almost abnormally high) which is good for regen

What are the advantages and disadvantages of this part?

The lithium ion polymer package is condense, which improved the ease of mechanical design of the car in terms of tractive system layout and weight distribution.

The low impedance of each cell was important for battery cooling and allowed for a simpler air-cooled method.

The cell tabs being made of nickel plated copper is ideal since corrosion is negligible and they are stiffer, which is better for clamping.

The cell chemistry is lithium cobalt oxide, which in particular is known for high specific energy, short life span, low thermal stability, and limited load capabilities.

The disadvantage is that these cells are cheaper and as a result, greater risk is taken in terms of manufacturing quality, which could affect consistent cell performance across a pack if proper testing is not carried out.

How did you verify the adequacy of this solution?

Each cell underwent impedance spectroscopy to determine cell impedance and from there, optimal cell matching for thermal management.

Cell voltages were also measured twice with a 6 month interval in between measurements to determine cells that could not hold a charge.

How did you implement the solution?

Cell layout is a 72s4p configuration, resulting in a 302.4V 25.2Ah pack. Further info on cell packaging below.

What will you do differently in the next competition season?

In terms of cell selection, it is likely that we will switch over to a reliable manufacturer to improve confidence in cell performance. Real lap analysis must be carried out to determine pack constraints for optimal performance in next race season.

Cell Packaging

Why did you choose this part/material?

Cells are packaged into 12s4p segments with 6 segments in total. Each cell segment is made of 1.25 mm steel walls that are outlined in DuPont Nomex 410 and Lexan to ensure fire retardant and electrical isolation. Each cell is physically restrained both top and bottom with a Lexan cell trays that are bolted to the cell walls. From there, an expansion limiter foam is placed in between every other cell to meet EV11.1.2 (allows for a cell volumetric expansion of 8% to 12% before reaching 10 psi.

What are the advantages and disadvantages of this part?

Advantages: compact design, relatively simple and cheap, minimal wiring

Disadvantages: time-consuming assembly, safety concerns regarding shorting two cell segments

How did you verify the adequacy of this solution?

For proper isolation, all datasheets were reviewed and continuity testing was carried out with a multimeter.

What will you do differently in the next competition season?

Will likely switch over to cells with a cylindrical casing such as an 18650 for easier cell fusing, cell cooling, and modular design.

AMS

Why did you choose this part/material?

The main chip is an LTC6811 which is a next gen equivalent to the LTC6804; a trusted chip that we have used in the past.

Follows the reference design from Analog Devices - This means we know it works and is a trusted design

What are the advantages and disadvantages of this part?

This chip can measure 12 voltages which is perfect and has all the infrastructure for the other requirements. Layout of boards allows for air-cooling of discharge resistors.

How did you verify the adequacy of this solution?

Bloomy battery simulator was used to test passive charging /discharging algorithm before boards were connected to actual cell segments.

How did you implement the solution?

Pogo pins from busbars boards are spring loaded and contact pads on each AMS board which is used for cell SOC and temp readings.

All 6 AMS boards are daisy-chained and communicate using isoSPI protocol, which connects to master MCU on BMS board.

What will you do differently in the next competition season?

Accumulator Box

Mechanical Loading

All accumulator containers must be rigidly mounted to the chassis to prevent the containers from loosening during the dynamic events or possible accidents (Rule EV2.5.2)

The mounting system for the accumulator container must be designed to withstand forces from a 40g deceleration in the horizontal plane and 20 g deceleration in the vertical plane. The calculations/tests proving this must be part of the SES (EV 2.5.3)

For **tube frame** cars, each accumulator container must be attached to the Frame by a minimum of four (4) 8 mm Metric Grade 8.8 or 5/16 inch Grade 5 bolts. (EV 2.5.4)

A certain number of bolts are necessary to handle the weight of the accumulator mount a battery.

- By rules, It has to hold a 10G force acting on it from different directions

Waterproofing

- Waterproofing is a huge factor in design of the accumulator
- Waterproofing is key in order to pass the rain test where they pour water on the car

Rain Test

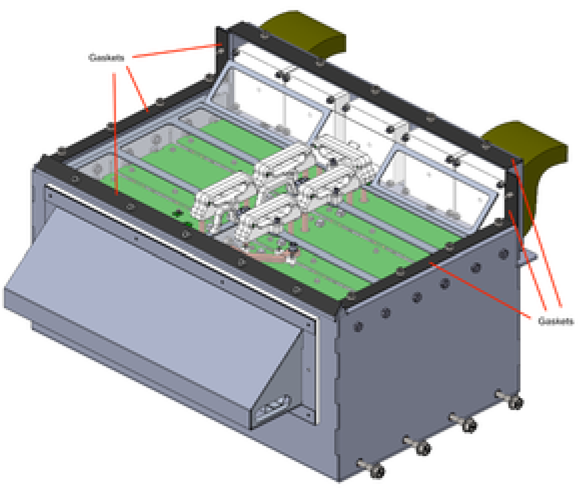
Water will be sprayed at the car from any possible direction for 120 seconds. The water spray will be rain-like. There will be no high-pressure water jet directed at the car. (EV10.5.3)

We pass the test if the IMD (Insulation Monitoring Device) doesn't trip during the rain test and for 120 seconds after the spray has stopped. (Total time of test is 240 seconds)

We must ensure that water can not accumulate anywhere in the Chassis

Example of Waterproofing for the Accumulator:

https://wiki.uwaterloo.ca/x/fQSmCQ

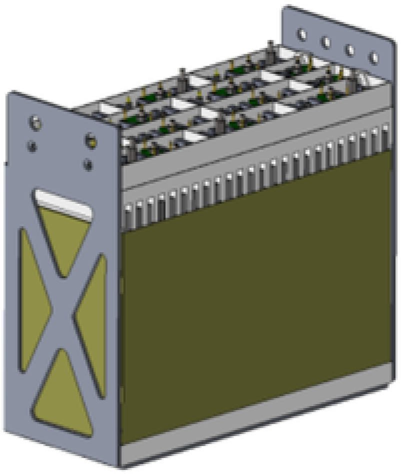


We use a 1mm thick gaskets to the seams of the battery box, for water ingress protection.

Also, in W20 Accumulator Toolbox and PPE, Another Example:

The Nomex Segment Assembly Guards must be waterproof and non-conductive - These guards act as a stopper from letting dropped parts or tools from contacting the nodes on the segment cover

Proposed new design for the Nomex guards which must also be waterproof:



Electrical Isolation

- For the physical isolation of the accumulator box, it is important to ensure that there is no electrical connection between our tractive system voltage (HV) with the metal of the box or bolts.

<u>Example:</u>

- We lined the entire electronics section of the accumulator

<u>From the As Built Documentation: High-Voltage Disconnect (HVD):</u>

- HVD is a device meant to physically break the high-current path

- Provides awesome isolation when needed

The Accumulator is lined with the paper to act as a insulator from the bus bars

A rule with the power splitter is to seperate high voltage from low voltage

Box Form Factor

- Changes depending on year
- Our cell selection and cell packaging will drive our section size, which concurrently drives our box size so that enough room for cooling, electronics, and the actual cells.

Battery Cell Style that referenced form factor:

<u>Packaged 18650s:</u>

These solutions come with the 18650 cylindrical batteries as well as housing for the cells to go inside. This results in a form factor that is easy to design around. (typically cube and rectangular prism shaped)

Accumulator Box 2018-2020

Accumulator Characteristics

Characteristic	Value	Unit	Tool Used	Date Measured	Measured By:	Comments	Equivalent CAD Measurement
Accumulator Weight	55	kg	Bathroom Scale	Winter 2019	Calvin DeKoter	Should be re-measured after design revisions	59.06914 kg using 110 g cell mass
Accumulator Length		mm	1 m scale	Winter 2019			
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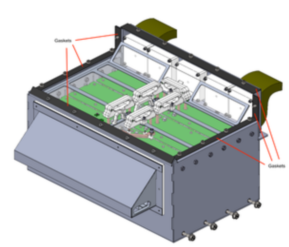
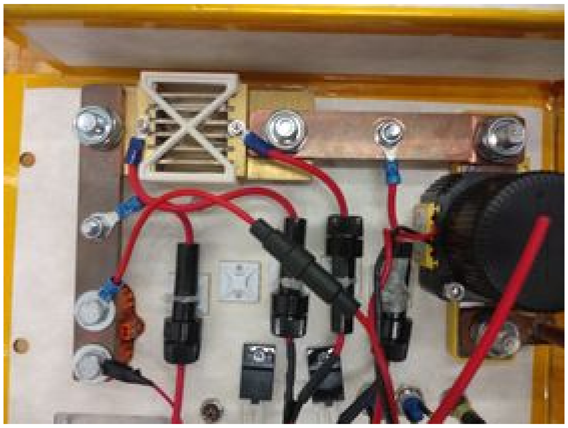
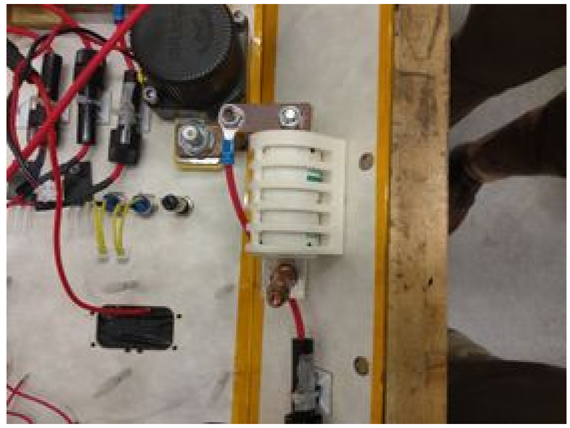
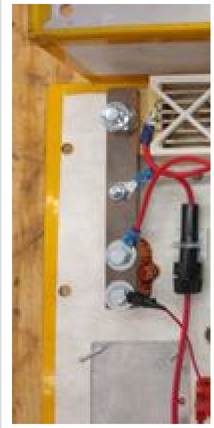


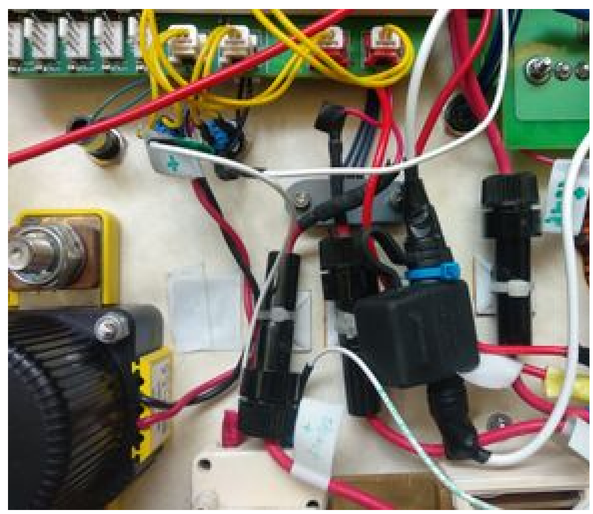
Accumulator Progress, March 17th, 2019

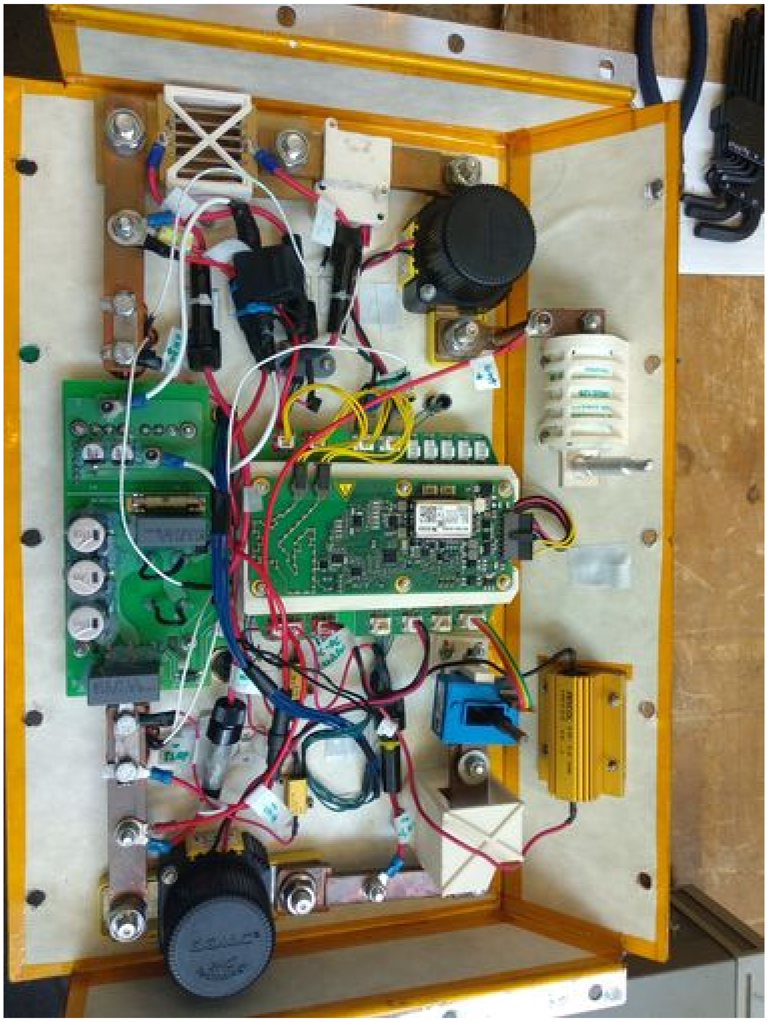
Cell Fusing Incomplete, No HVD

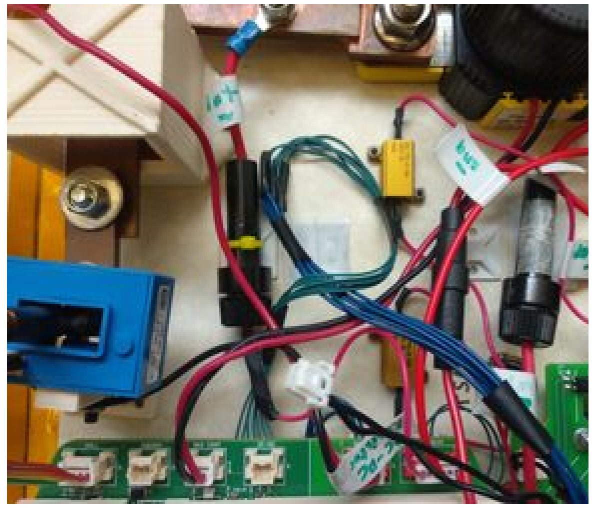
Accumulator Shunt / HVD Area	Accumulator Main Pack Fuse- L50QS150	Accumulator Lid Posi
		

Accumulator Progress, September 16th, 2019

Cell Fusing Complete and Documented, Team-Fabricated HVD Installed

Accumulator Lid: Functionally Complete	Accumulator Fuse Network
	





*As **Built** Documentation: High-Voltage Disconnect*

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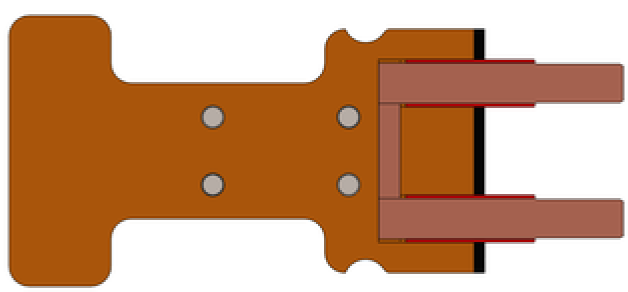
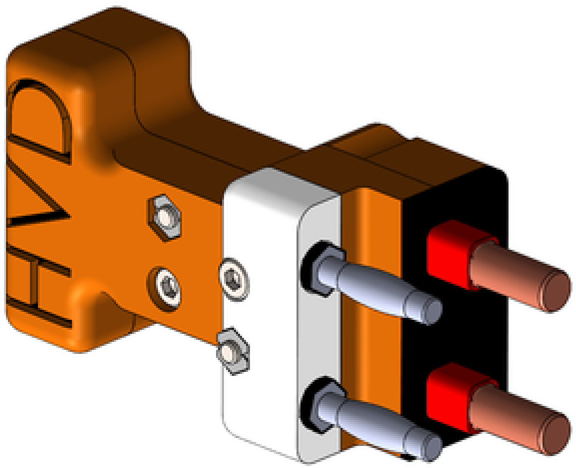
HVD Solid Model Picture	**HVD Cutaway showing tractive system path**	**H V D a s b u il**
		



Segment and Bus Bar Assembly- Build Guide

As written by @ Former user (Deleted), notes below provided by @ Calvin Ryan DeKoter

Assembly-Guide.pdf

Edits and Notes:

Page 4:

> Figure: Exploded View of Main Bus Bar Stackup
>
> All nuts that are the top most fastener **MUST** be positive locking nuts- M3 x 0.5 Fujilock nuts in this case, not a regular M3 x 0.5 nut as shown in the figure.

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As Built Documentation: M3 x 0.5 PEM Studs Clamp Load Issues

During the Spring 2018 and Winter 2019 term, there were many issues with the M3 x 0.5 PEM studs used to hold down the bus bars. While a study confirmed that they applied sufficient clamp load to the segments, the studs were prone to spinning in the aluminum cell tab tray if they were overtorqued or torqued from an angle. This was before the team had access to the Wera Torque tool, which limits the torque applied to the studs to 0.9 Nm.

In order to remove the spun studs, a variety of methods were used, including pliers, a dremel with a cutoff wheel, and simple luck. Pictures are below. *(If you found this page from the 'Fall 2019 New Members Projects' page, the Nomex guarding should look like the rightmost pictures with the blue towel and orange tape, but constructed with Nomex card and not requiring tape. The intent is that only a single bus bar is exposed at a time. The Nomex doesn't have to seal, it should just protect against dropped tools and fasteners.)*

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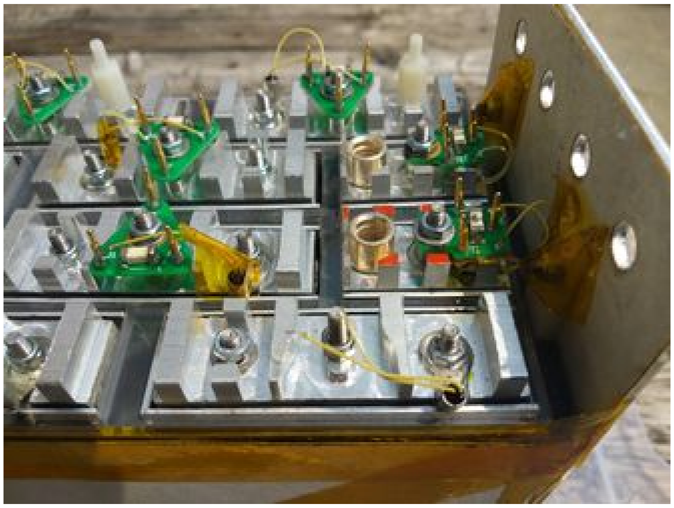	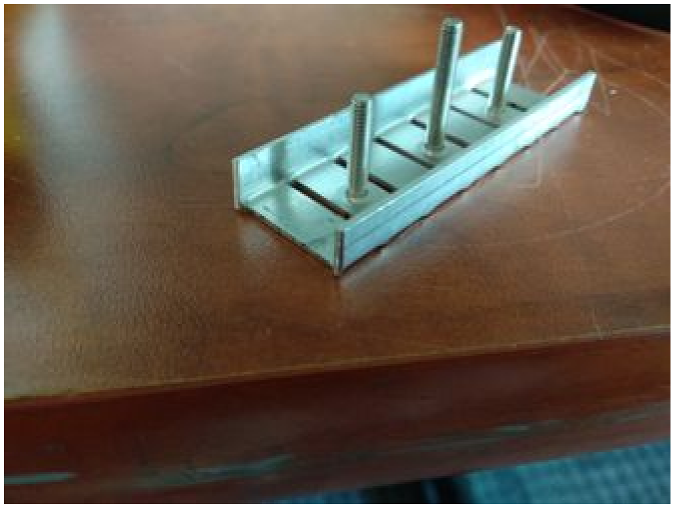

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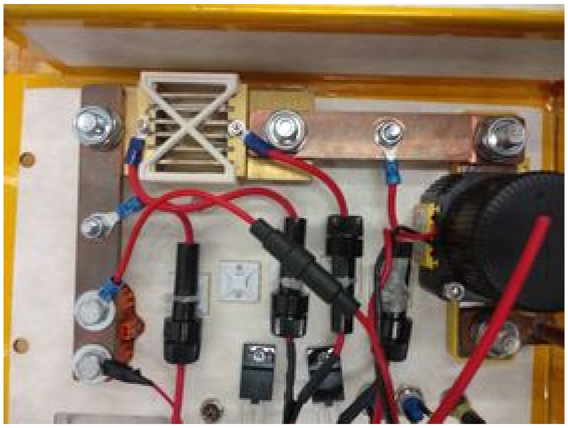
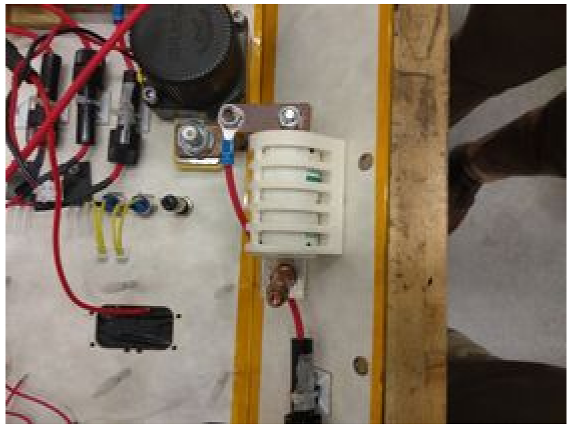
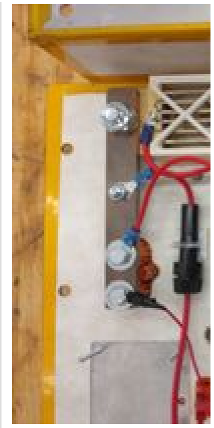
Accumulator Progress, March 17th, 2019

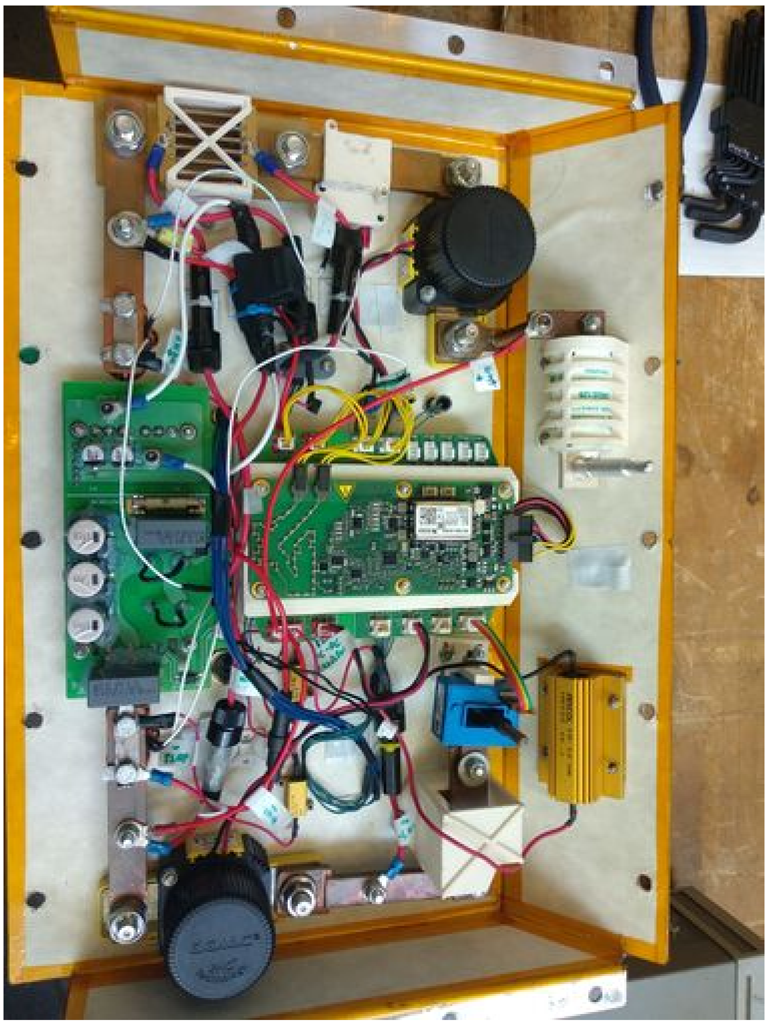
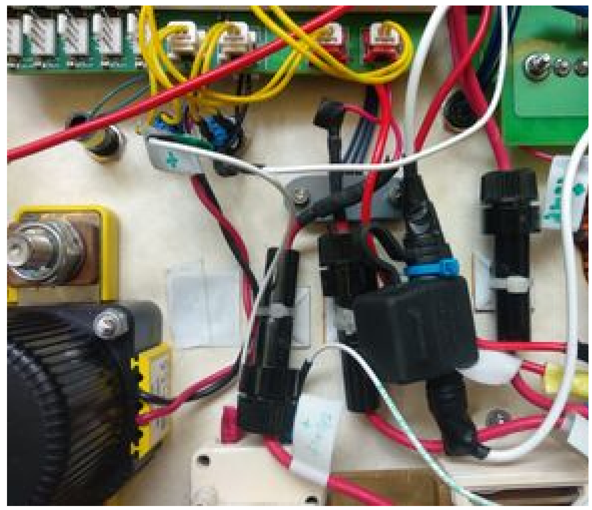
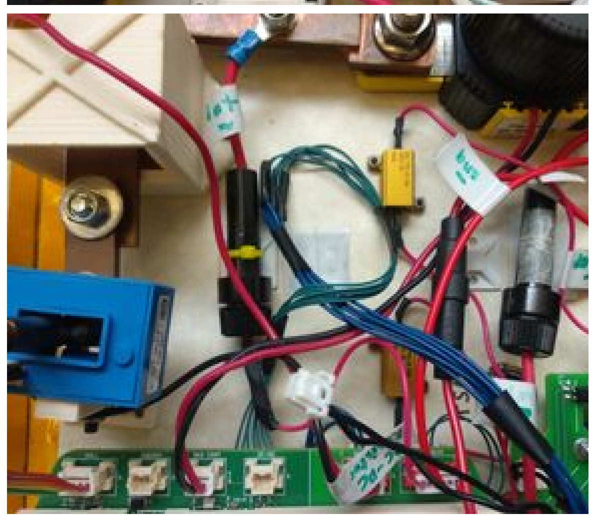
Cell Fusing Incomplete, No HVD

Accumulator Shunt / HVD Area	**Accumulator Main Pack Fuse- L50QS150**	**Accumulator Lid Posi**

Accumulator Progress, September 16th, 2019

Cell Fusing Complete and Documented, Team-Fabricated HVD Installed

Accumulator Lid: Functionally Complete	Accumulator Fuse Network
	 

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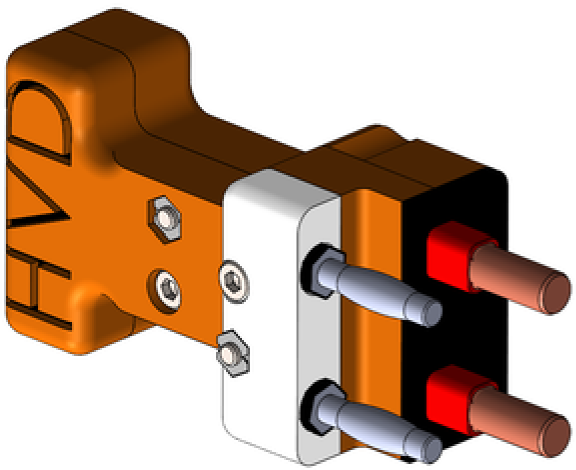	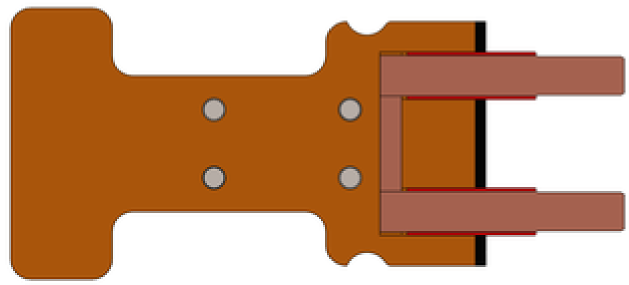	

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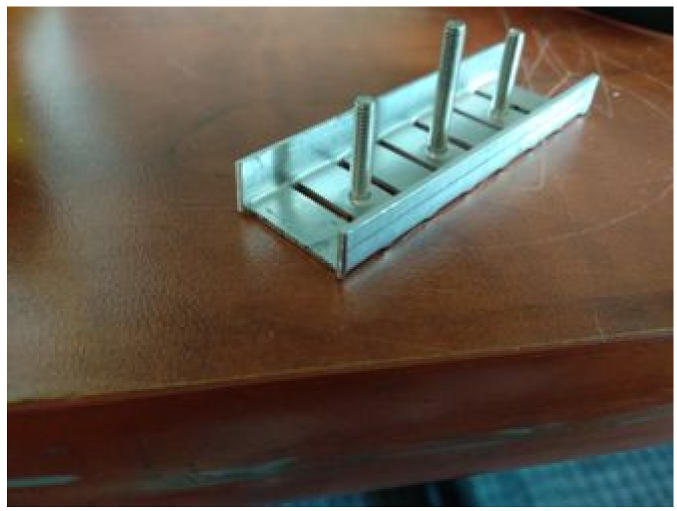
	

Accumulator Charge Cart

Project: Hand Cart

The accumulator needs to be removed from the car to be charged. A hand cart needs to be designed and manufactured to transport the accumulator, and it will be present during the Electrical Tech Inspection.

Criteria:

- The brakes must always be on, and can only be released using a dead man's switch (for example: pushing a handle to release the switch when moving the cart).
- Can carry the load of the Accumulator
- The brake should be able to stop the Cart with the Accumulator.

Waterproofing

Accumulator Box 2020

Error rendering macro 'jira' : Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Summary

The Accumulator box acts as the housing which needs to hold the actual accumulator. It is our job to design a box which can comply to the rules of the competition by considering factors such as mechanical loading, waterproofing, electrical isolation, and the form factor.

CAD Information

- CAD Design Organization: *Describe how the solid models for the project are organized.*

Design Philosophy

- "*This part improves over last year's component by ____"*
- *"Do not repeat ____ mistake"*
- *"This design fixes ____"*

Explain each feature of the part and how it accomplishes the part's function.

Problem Definition

Rules Compliance

Rule	Status	Notes	Proof of Compliance
A 1.2	Unknown macro: 'status-handy'	**Paraphrase:** For an electric vehicle, the accumulator may have a maximum usable energy of 5.40 kWh, or nominally 6.75 kWh. (Discharge measured at 2C).	The accumulator will be designed to comply and be tested.

Constraints and Criteria

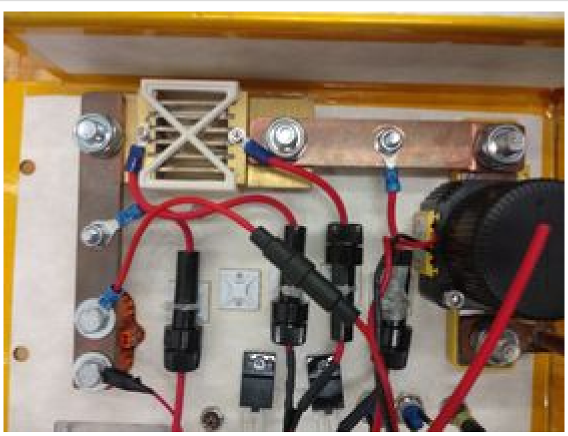
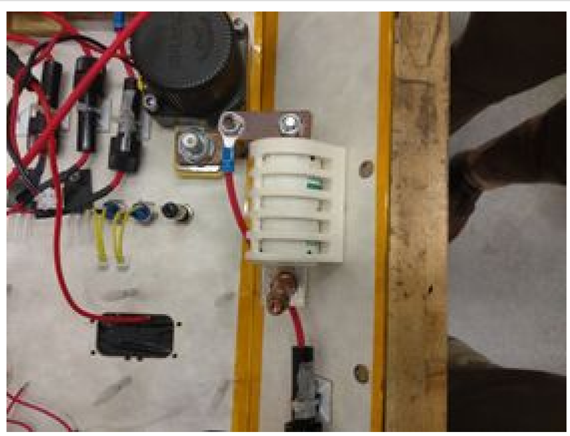
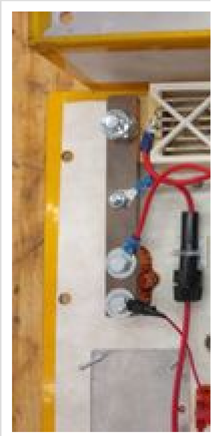
Constraint	Priority	Description	Value	Unit	Validation Method
Current Capability	Unknown macro: 'status-handy'	Each segment must be able to deliver the full rated current of the Tractive System because the segments are in series. By design, this is 135 A RMS. The pack fuse will be 40 A.	135	A	HTHC

Technical Progress

Design Process

Accumulator Progress, March 17th, 2019

Cell Fusing Incomplete, No HVD

Accumulator Shunt / HVD Area	Accumulator Main Pack Fuse- L50QS150	Accumulator Lid Posi
		

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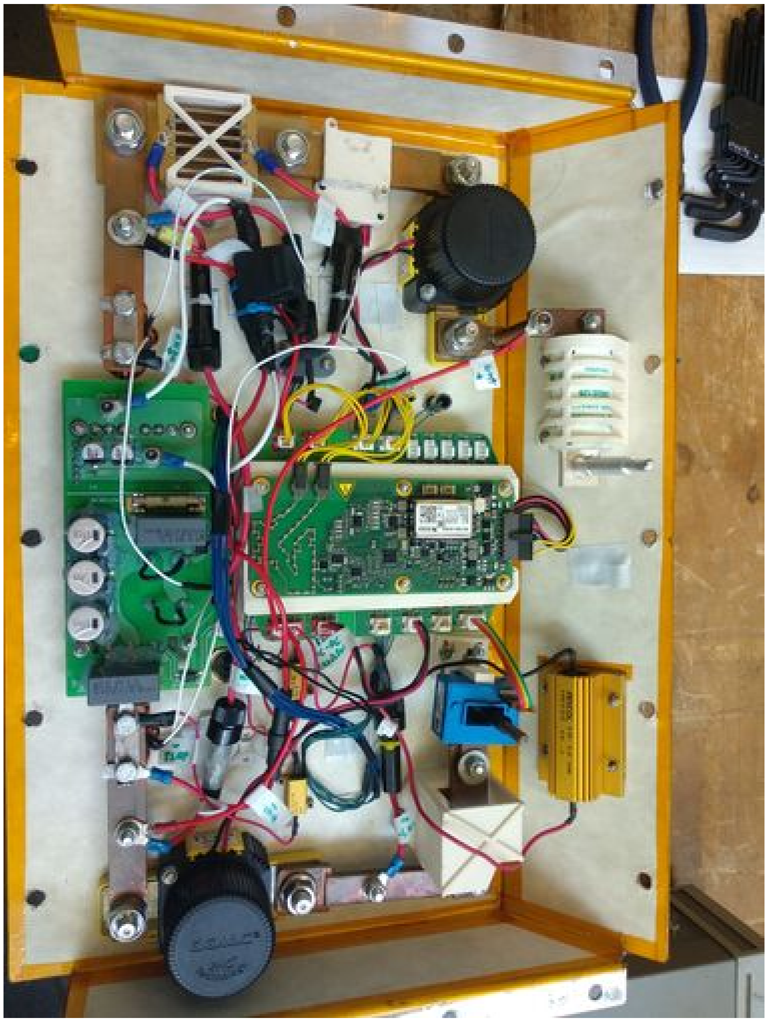
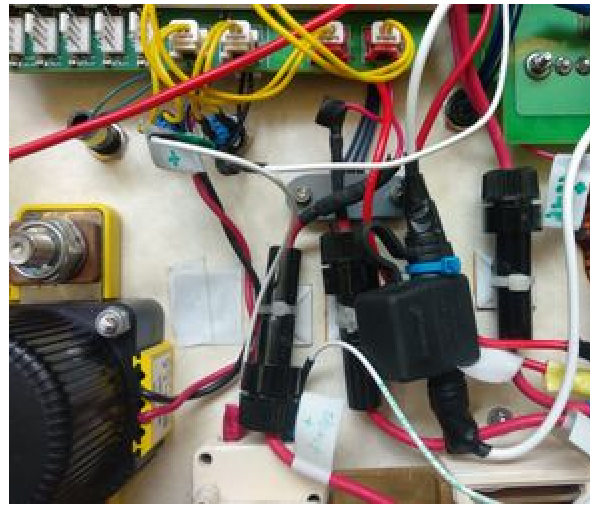
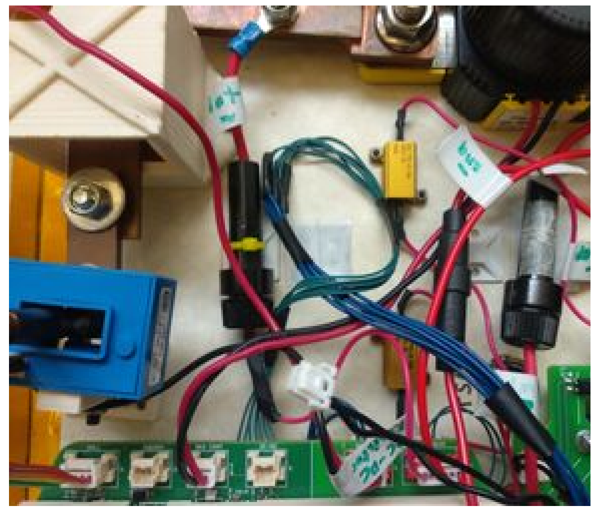
	 

Design Analysis and Manufacturing Design

Analysis Validation

Manufacturing and Implementation

Conclusions

Project Procurement:

Follow the procurement procedure as described in the Operations page Purchase and Reimbursement Procedure and then upload the purchase order spreadsheet to the table below. Consolidate as many purchases into one procurement request to simplify the process.

Generate a Jira task in the appropriate Operations Epic. Label it with *proc_ts* and an (*label specific to this page)* so that it shows up in the table below.

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Team Member Name	Purchase Order Spreadsheet	Quote / Invoice	Order Description	Company Name	Total Cost [CAD]	Status	Storage Location
						NOT YET PROCESSED	

W20 Accumulator Module Waterproofing

Project Timeline:

WBS Project Title: Accumulator Waterproofing

WBS Project Number: 1.2.1.1.1

Describe tasks and use the correct tags to show the state of the project.

Status	Unknown macro: 'status-handy'
Estimated Completion	22 Mar 2020
Project Deadline	29 Mar 2020
Required to Run	No
Priority	Unknown macro: 'status-handy'

Responsibility Cascade:

- *Project Lead:* @ Former user (Deleted)
  - *Sub-team Lead*
  - *Sub-team core member*
- *Operations sub-team support- Finances, Procurement*
- *Project Advisers:*

List the people with ultimate responsibility (sub-team leads), project champions, and people who will aid during the 'sprint' phase of the project.

The cascade should also describe the flow of ownership if the original project champion is unable to finish the task.

Design Philosophy:

- "*This part improves over last year's component by ____"*
- *"Do not repeat ____ mistake"*
- *"This design fixes ____"*

Explain each feature of the part and how it accomplishes the part's function.

Task list:

- [ ] JB Weld vents over fan exterior
- [x] Purchase gasket maker
- [x] Add Silicon/gasket sealant to corners of battery box

Description

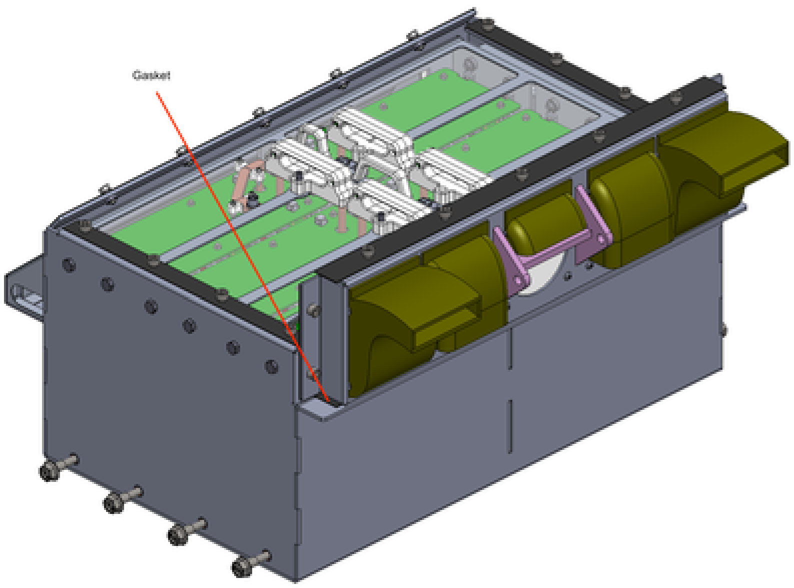
General description including *purpose*.

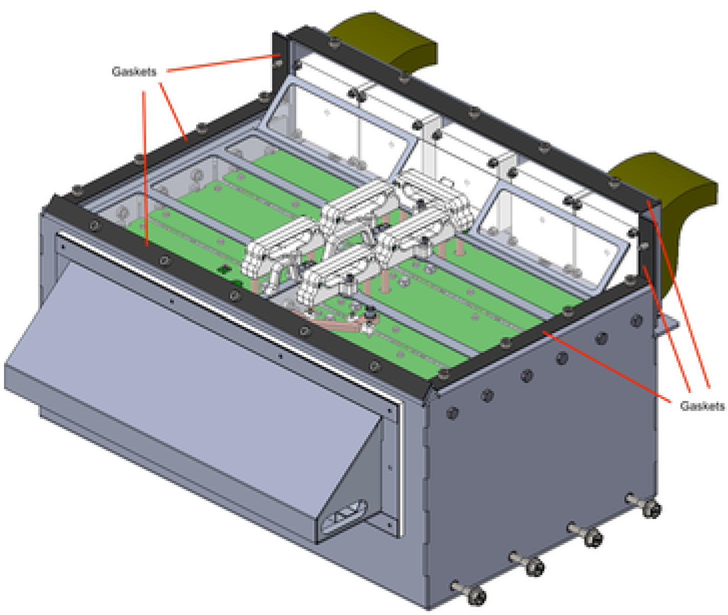
Relevant Documentation:

- Confluence page
- Pdf file
- Technical Datasheets.pdf

Rules Compliance

Section	Status	Notes	Documentation
EV2.2.6	Unknown macro: 'status-handy'	- Something something, fails this, questions that.	Pictures? Logs?





- Create and glue ~1mm thick gaskets to the seams of the battery box, for water ingress protection

Expenditures:

Items	Vendor	Payment	Cost (CAD/USD)	Form Link	

		Method			

Project Bring-up

Winter 2020 Progress	Details + pictures

Accumulator Box 2021

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Summary

Briefly describe the project purpose and current state.

CAD Information

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Accumulator Cell Packaging

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

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Cell Packaging Requirements

Requirements for Lithium Ion Polymer Pouch Cells

The rectangular format of pouch cells and lack of a metallic case mean that they have excellent power and energy density, as shown in the page Accumulator Cell Selection. These characteristics mean that much more care must be taken when designing the cell packaging, as pouch cells can be damaged by something as small as laying them down on a dirty surface or excessively stressing the copper tab of the cell.

Although professional manufacturing standards must be applied to all parts of the vehicle, they are especially important when assembling pouch cell accumulator segments. All parts must be deburred, have no sharp corners, and must be cleaned before installation. Assembly must be performed on a dedicated workbench without any unnecessary conductive items on it. Remove rings and other metallic jewelry, wash hands of all metallic particles, and remove loose fitting clothing.

The Formula Hybrid rulebook lays out strict requirements for the design of accumulators with pouch cells- see section EV.11. The table below lists the most important design aspects of pouch cell packaging, as recommended by the Formula Hybrid Rulebook, the A123 design guide and the EP8545148HP datasheet.

Design Aspect			
Pouch Support			
Cell Tab Support			
Pouch Face Pressure			
Expansion Requirements			
Vibration			
Thermal Limit			
Minimum Insulation			

These requirements can be met by careful design and anaylsis- Pouch Support, Tab Support, Pouch Face Pressure, Vibration, and Thermal Limit requirements can be taken from the Formula Hybrid rules and the manufacturer's datasheet. The insulation requirement is driven by team goals for the IMD system and the team's ability to measure the insulation using a hi-pot tester.

Several other accumulator subsystem design requirements can be made easier by smart packaging and segment design. Accumulator cooling requirements can be met by using a cold plate on the face of the cell, providing a path for heat to leave the cell pouch. Such a cold plate would be solid aluminum or stamped aluminum with internal coolant channels. The requirements for pouch face pressure and room for cell expansion can be met with a very soft foam, as long as it is electrically insulating and fire retardant.

Requirements for Lithium Ion Cylindrical Cells

Requirements for Lithium Ion Prismatic Cells

Maintenance Requirements for Cell Packaging

Design for Maintenance is a key part of safe battery design. It is critical that the accumulator segments are designed to be worked on using insulated tools, which typically require more clearance than ordinary mechanic's tools.

Cell Segment Design

After the cell packaging design is finalized, the cells and their support structures can be packaged into segments, which, per Formula Hybrid rules, are a removable section of the battery with a voltage less than 120 V and energy less than 6 MJ (V * Ah * 3600).

The segments are much safer to work on than the full accumulator, as they are lower voltage and do not contain as much energy. They also are much easier to move around safely. Typically, segments are constructed from welded steel or aluminum and insulated with G10-FR4 sheet. It is critical that the aluminum pouch of the battery is not in contact with the metal frame of the segment, as this could lead to insulation breakdown and pouch corrosion.

The segment is responsible for maintaining pressure on the cell face or relieving stress from the cylindrical cell trays, as well as mounting the tractive system connections at the top of the segment.

Cell Segment Bus Bar Layout

To operate motors and motor controllers at their rated voltages and currents, multiple battery cells must be connected in series and parallel. In the case of the 2018-2020 accumulator, each segment has four cells in parallel and twelve in series. This layout is detailed below.

Project Description

- Design, manufacture and assemble the cell modules that hold the battery cells in the accumulator module
- Develop the connections between modules
- Develop sealing off the airflow between modules
- Design the busbars and make sure we can manufacture them. The might have heat sinks cut into them, possibly channels for PCM material

Supporting Information, Project Details

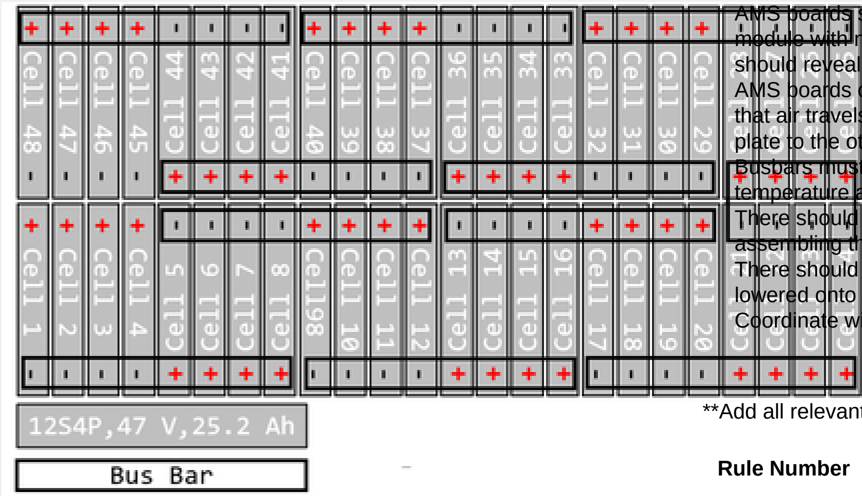
Main structure

There is a 95% chance that we use Electric Power 6.3Ah cells arranged in a 4p72s configuration. The only other likely cell option has a very similar size and would be laid out the same way.

Cells are arranged in groups of 4 forming cell blocks. The accumulator will be divided into 6 segments each holding 48 cells and 12 blocks. One module would like like this.

Requirements and Considerations

- The airflow channel for cooling should be relatively sealed so that condensation is not going to form on the surface of the batteries or of any sensitive electronics. This could be achieved though conformal coating on PCBs but a better solution would be preferred. This means that both the top and bottom of the air flow channel should be sealed.
- Per Formula Hybrid Rules, each segment should be entirely isolated from the other segments by a 1/8" fibreglass barrier. The current design of six segments with two segments side by side and three segments in-line does not allow this, leading to problems with rules compliance and cooling.
- The discharge resistors should be mounted in such a way that they are in the direct flow of air. This allows them to spec'ed larger allowing us to discharge the cells faster. The cells should be able to discharge at something like 0.1C or better.
- Bus bars should be designed in accordance to cooling requirements.
- Battery modules should be self contained units and should all be identical, not even mirrors of each other. This especially includes the +- current path.
- There should be the minimum number of mechanical fasteners needed to hold the modules in place. Mechanical stack ups are preferred for holding the modules in place.

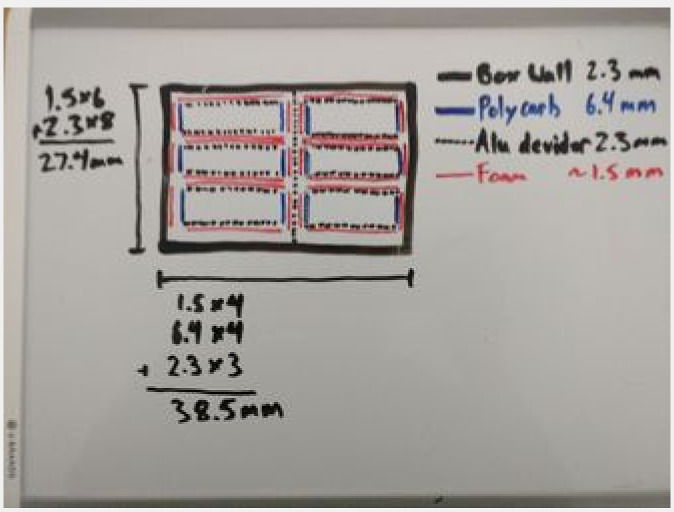


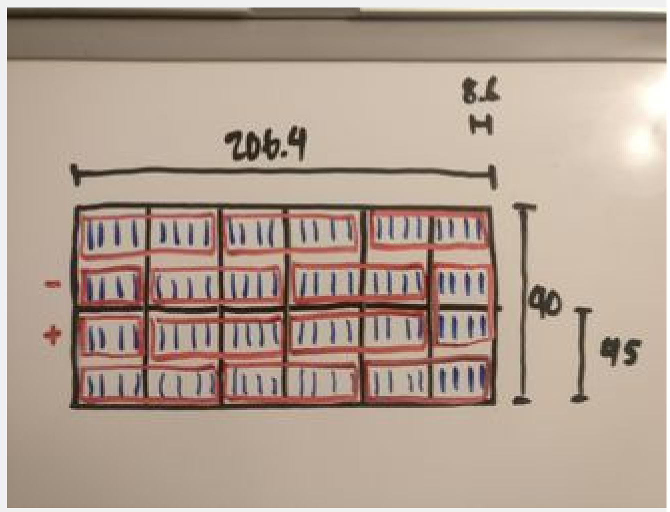
AMS boards should be disconnected from the top surface of the module with no more than 4 individual connections. Doing so should reveal the bus bars underneath. To facilitate sealing, the AMS boards can be mounted to a plate that forms the surface that air travels through. Connections could be made through the plate to the other side for voltage and temperature measurement. Busbars must interface with the AMS boards to provide temperature and voltage information
There should be very little to no risk of shorting cells when assembling the bus bars.
There should be no risk of shorting things as the AMS boards are lowered onto the busbars.
Coordinate with S2018 AMS

Add all relevant rules

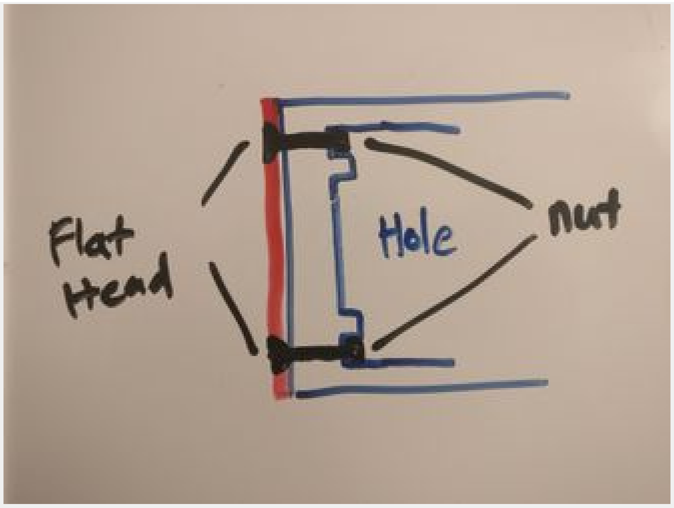
Rule Number	Rule Description

The cells have a thickness of 8.6mm and a width of 45mm this makes the stackup of cells have a width here of 206.4mm and a depth of 90mm. I use width and depth because of how the module are arranged relative to the car. The total box arrangement would look like this from the top down where the box has a larger width than depth. The width will span the width of the car and the outside dimensions of the box will form the width of the rear end of the chassis with minimal gap between the frame tubing and the external face of the box. From this image and given the size of the modules from above, the box ends up having external dimensions of 451.3 mm in width and 297.4mm in depth.





The tractive system path can be seen in the image above. All modules would be identical with no mirrored modules. This conforms to the requirements listed to the right. From the second picture above, you can see the internal structure. of the modules and pack. The modules should have sheet metal main faces that have been lightened (look into the ruling for this, ive seen other teams do it). Fire resistant 1/4 inch polycarb can be used the for the rest of the design for the top, bottom and two sides. The polycarb allows us to drill holes into the cross section to put screws through. To increase the strength of the screw connections, you can do this, adding a nut in the polycarb. An M3 would be small enough to be flush on the sides.



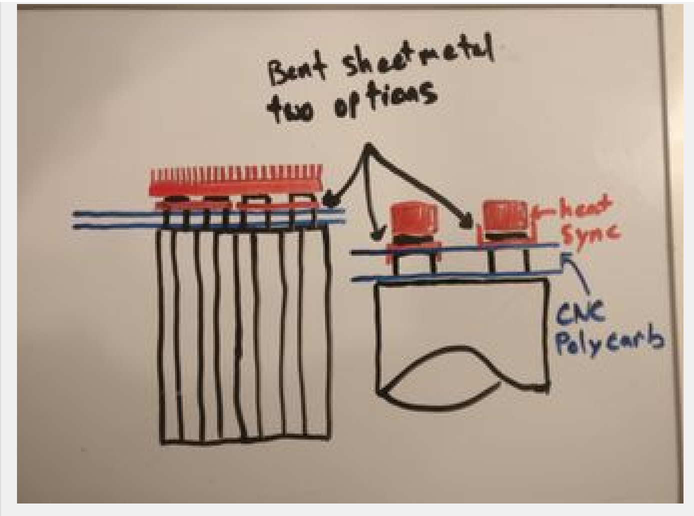
My vision is to use the CNC router to cut all the polycarb and route out most of the mass keeping enough to contain the cells. One other suggestion is to route pockets rather than full holes through the polycarb which will contain the cells. Careful consideration could then be made about how to vent potential fires/explosions. (#designpoints).

Additionally, a lot of the architecture is based around how to minimize the amount of water that we ingest. We want to isolate the air stream from the batteries and from sensitive electronics. For this reason, polyurethane foam or some other gasketing material is drawn in between all segments, this hopefully will seal the air passageway between the tops of the cell modules and the bottom of the AMS board (or have the AMS boards above a thin polycarb layer to isolate the air from the electronics)

Bus Bars

Busbars are the primary means for cooling, they will likely have heat sync fins cut into them (validation needed for this) and could have holes drilled to be filled with phase change material (PCM) to handle spikes of heat. Keep this in mind in the design. The cell tabs will stick up through slots in the cnc'ed polycarb top and then through some form of aluminum. In the rules, your tractive system cell clamping must not include plastics, has to be metal. My idea was to try and laser cut the bottom metal part with thin slots for the cell tabs with a desire to tolerance the slots tightly keeping humid air contained in the air passageway. This part will bend if only a single bolt is used in the centre of the piece. Need to figure out the best arrangement for how to do this, below are two suggestions.

You need to also consider how to assemble the segments, one option is to leave the heat shrink that comes with the batteries on and CNC the polycarb such that the heat shrink can pass through. All cells would be added to the module casing and it would all be closed up. Then, each group of four cell tabs would have the heat shrink removed and the aluminum piece threaded on, cell tabs bent and then bolt the aluminum piece down to the polycarb to prevent it from moving around. Ill leave this up to you. A single bolt/stud can be used to connect the top and bottom parts of the clamp, need to think about how to prevent the bolt from rotating while tightening.



Each busbar is going to need a BB (busbar board) attached to it. This PCB needs to interface with the busbar electrically to send a galvanic link to the busbar back to the AMS boards and also send a thermistor reading back to the AMS board. My thought is to have a thermistor potted into the busbar like this past year with a thermally conductive electrically insulative epoxy. This thermistor would have leads that solder directly to through hole pads on the BB. Alternatively, a surface mount arrangement would simplify the assembly but care needs to be taken in preventing shorts and ensuring a strong thermal contact. Maybe some thermal squishy tape?

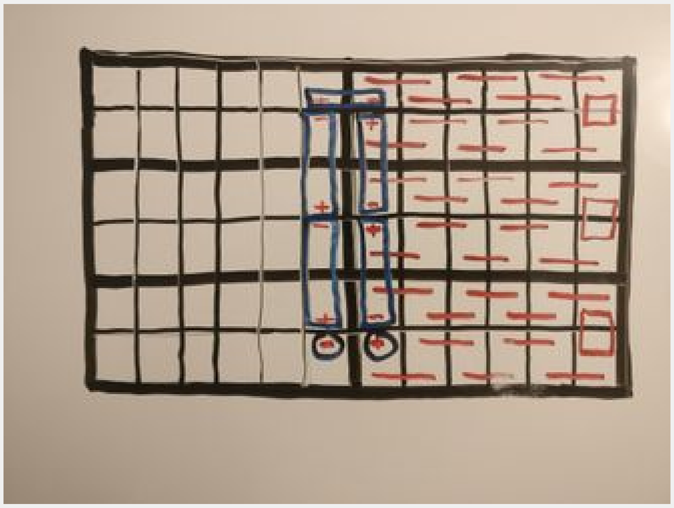
The idea is to use pogo pins on the AMS board to contact round pads on the busbar board. 3 pins per busbar would send the thermistor and bus bar voltage. There might be a tricksy way to make this only two connections sharing one thermistor pin with the bus bar voltage, this could be overly complicated though. One other thought was regarding the balancing resistors. We need a way to short each cell across the terminals through a resistor for a discharge balance, is there any way to have this resistor be on the bus bar PCB and have it be in series with the voltage measurement lead? This would allow this resistor to be in the air stream without needing to expose the PCB to humid air. Alternatively, cutouts in a top polycarb sheet could expose the resistors to the air stream and then use a sealing material to seal off the electronics, or just have a form fit.

Also think about how to seal the edges of the AMS boards to each other to limit the amount of air passing over the AMS boards. In general, think about how to manage the air stream and how to make condensation a non issue.

Segment disconnect

Above the AMS boards should be an isolation plate in polycarb or aluminum that the electronics above would be mounted to. Segment disconnects can be done with bullet connectors, my thought is to have bullet connectors sticking up through the AMS boards and isolation plate to the electronics enclosure. Up here, we would have busbars with a 3D printed surround/handle act as the links between each of the segments. This would allow us to easily pull the segments apart and it would be required before lifting the isolation plate which gives us access to the internals of the battery. #safety. The drawing below shows the segment connection bars.

Mechanical locking can be achieved by passing a stud through the centre of the disconnect bar (electrically isolate the passage through the hole) and then put a spring cotter pin through a hole in the top of the stud. A nice string back to the handle of the disconnect will prevent this cotter pin from getting lost.

Accumulator Segment Design - 2020

Summary

As per Formula Hybrid and Formula Electric rules, the accumulator must be divided up into equally sized segments, based on energy and weight limits.

This makes the whole accumulator safer- the segments are lower voltage. can be carried by one person, and the energy released is lower in the case of a thermal event.

48 cells in a 4p12s configuration make up the accumulator. They are put face to face, with foam in contact with one of the faces. The cell tabs are folded over onto cell tab trays and clamped by aluminum bus bars with heat dissipation fins. These bus bars have a thermistor clamped to them and a nylon stud to allow mounting the Bus Bar Board with voltage and temperature sense. The bus bar is mounted with M3 PEM studs and Fujilock nuts.

The bus bar boards have pogo pins which make contact with the AMS board contacts. The AMS measures the resistance of the thermistor and the voltage of the cell relative to the previous segment and reports it to the BMS over an isoSPI connection. A purpose-built LT chip with multiplexed inputs from the thermistors is used to measure the signals.

CAD Information

CAD Design Organization- See Accumulator File

The segment packaging is now stored in final designs, but the bulk of the CAD revision history and Solidworks simulations are stored in the conceptual designs folder.

Design Philosophy:

- This design fixes several issues with last year's LiPo cell packaging including proper cell constraint and applied face pressure under thermal expansion
- This design also quantifies the expansion limiting capability of the segment container and accumulator through FEA with an applied temperature condition.

Attribute	Value	Unit	Comments
Segment Voltage Maximum	50.4	V	By Design
Segment Voltage Minimum	33	V	By Design
Segment Capacity	25.2	Ah	By Design
Segment Ampacity	756	A	Limited by cell fusing
Segment Energy	3900.096	J	Evaluated at 2C rate as in ESF
Segment Temperature Maximum	57	°C	As measured by AMS
Segment Weight	tbd	kg	Measured with Electronic Scale

Rule Clarifications

Inquiry about Formula Hybrid Cell-Level Fuse Rules

> Waterloo Formula Electric would like to ask about the differences between the Formula SAE Electric and Formula Hybrid cell fusing rules. Our accumulator has team-designed and tested fuses on each cell, cut into the tab of our pouch cells. We designed the cell fuse to always clear before the battery cell sustains thermal damage, but not clear before our main pack fuse blows. This is shown in the attached photo. Upon reading the Formula Hybrid Rules, it seems that we do not meet the particular design requirements, based on our pack fuse continuous current and cell fuse continuous current. Is our current situation adequate? If not, we will resize the main pack fuse to meet these requirements. (Raising the continuous current of the pack fuse will not exceed the limits we have specified for the rest of the electrical / Tractive System)

Project Design Process

Problem Definition

The Formula Hybrid rules mandate that teams that construct their own Accumulator out of pouch cells (which WFE has historically done) must meet a series of extra requirements to improve the safety of the accumulator.

Article **EV11** lays out these requirements.

In short, they require that WFE adds mechanical restraint for all cells, add a soft, compliant separator for one in two cell faces, and otherwise improve the fixturing of the cells.

Each segment will have a frame fixture the bottom of the cell and contain the separator.

Rules Compliance

Complete the table below with rules relevant to the project. Please familiarize yourself with the entire rulebook before beginning design.

Rule	Status	Notes	Proof of Compliance
EV1.2	Unknown macro: 'status-handy'	**Paraphrase:** Table 9 lists the maximum segment voltage as 120 V and energy as 6 MJ.	The accumulator cell configuration meets the requirements.
EV2.2.1	Unknown macro: 'status-handy'	The accumulator segments must be separated so that the segment limits in Table 9 are met by an electrically insulating barrier meeting the TS/GLV requirements in EV5.4. For all lithium based cell chemistries, these barriers must also be fire resistant (according to UL94-V0, FAR25 or equivalent).	In progress.
EV2.2.2	Unknown macro: 'status-handy'	The barrier must be non-conducting, fire retardant (UL94V0) and provide a complete barrier to the spread of arc or fire. It must have a fire resistance equal to 1/8" FR4 fiberglass, such as Garolite G-911.	

Constraints and Criteria

Design considerations based on testing and analysis of past designs, as well as feedback from competition judges and professionals.

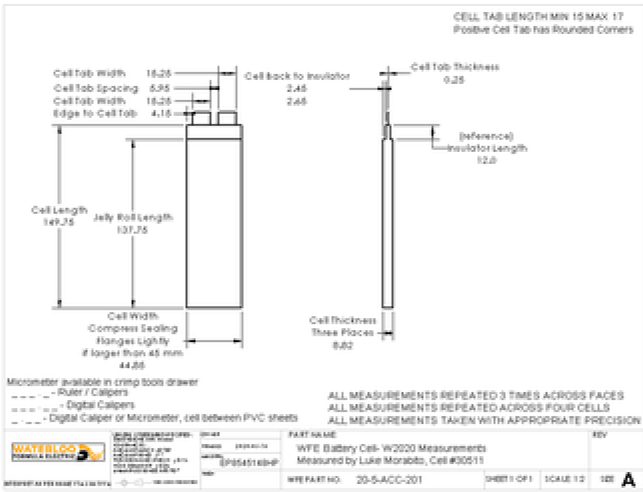
Constraint	Priority	Description	Value	Unit	Verification Method
Current Capability	Unknown macro: 'status-handy'	Each segment must be able to deliver the full rated current of the Tractive System because the segments are in series. By design, this is 135 A RMS. The pack fuse will be 40 A.	135	A	HCTC
Voltage	Unknown macro: 'status-handy'	Each segment must be designed to hold a 4P12S block of cells to give the correct OCV.	48 (Nominal)	V	Multimeter
Heat Rejection	Unknown macro: 'status-handy'	Each segment must be able to dissipate the heat generated by the cells and cell fuses under load.	TBD	W	Analysis
Voltage Sense	Unknown macro: 'status-handy'	Each segment must be able to accurately measure the voltage of each parallel group to avoid cell damage, within 0.01 V.	Accuracy ±0.01	V	Design
Temperature Sense	Unknown macro: 'status-handy'	Each segment must be able to accurately measure the temperature of the negative cell tab and bus bar to within a few degrees Celsius to prevent damage.	Accuracy ± 3	C°	Design
Weight	Unknown macro: 'status-handy'	Lower component weight means lower stress on the mounting locations and lower overall car mass. Weight was given a low priority compared to component functionality.	7.5	kg	Electronic Scale

Design of Cell Support Structure and Compliant Material Selection

Description

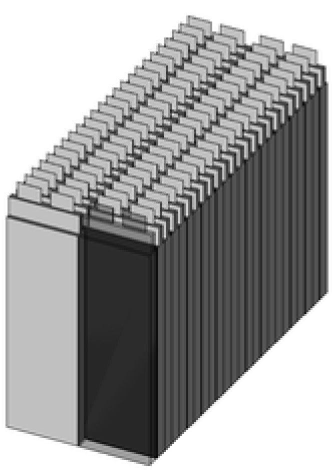
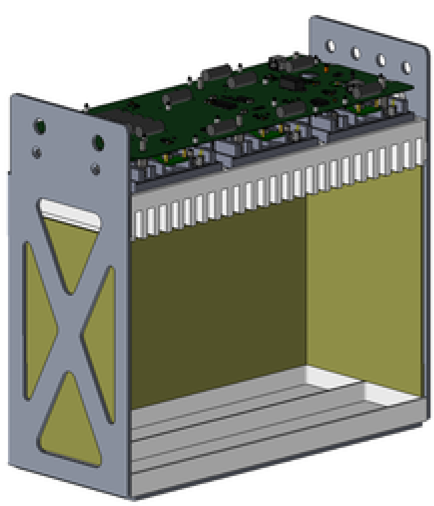
The cell segment is a section of the battery defined by the Formula Hybrid rulebook, containing a maximum of 6 MJ of energy and having a voltage less than 120 V. See Table 9 - Voltage and Energy Limits in the Formula Hybrid Rulebook. As described by the page Accumulator Cell Selection, lithium-ion pouch cells need to be supported when installed into an accumulator with appropriate structures to restrain the pouch, cell tabs, and prevent the expansion of the pouch.

The 2020 accumulator segment design is an adaption of the 2018 accumulator segment, which used 48 EP8514548HP Electric Power LiCoO2 cells, which are more energy dense than the LiFePO4 cells used previously. A drawing of these cells with nominal dimensions and dimensions measured by WFE is included below.



48 of these cells are packaged in each segment in a 4P12S configuration, meeting the team's voltage and ampacity requirements, while staying within the Formula Hybrid rules requirements.

The 48 cells are packaged side by side and face to face with a piece of 0.8 mm foam touching one of the two faces. This foam applies an even pressure to the face of the cell, maintaining a consistent internal resistance of the cell.

Cell Stack	Accumulator Segment Frame
	

On revision that must be applied is adding a sheet of Nomex paper between the cells. Right now, the pouch of each cell is in contact with the pouches beside them. If the insulation on the outside and inside of the aluminum pouch failed, there could be a short circuit that would result in a thermal event.

One key feature of the accumulator segment frame, pictured above, is that it must be able to maintain its strength even at elevated temperatures up to 90 °C. Currently, the parts are designed to be machined from PVC and Delrin, but these plastics have lower softening and melting points. Better plastics that retain their strength at elevated temperatures are listed in the table below.

Thermally Resistant Plastics	Softening Point [C°]	Strength	Machinability	Relative Cost
https://www.craftechind.com/dont-sweat-4-high-temp-plastics-can-take-heat/				
https://www.curbellplastics.com/Research-Solutions/Materials/G10-FR-4-Glass-Epoxy				
https://www.curbellplastics.com/Research-Solutions/Materials/PAI				
https://www.curbellplastics.com/Research-Solutions/Materials/PEEK				

Selected Design and Design Values

- Alternate Designs

Design Analysis - Cell Restraint Simulation and Cell Expansion Testing

Project Bring-up

Winter 2020 Progress

Cell Expansion Testing:

Test Set-up:

Uses the high current test fixture (See High Current Test Circuit for more info) to discharge the cell as well as two dial indicators to measure

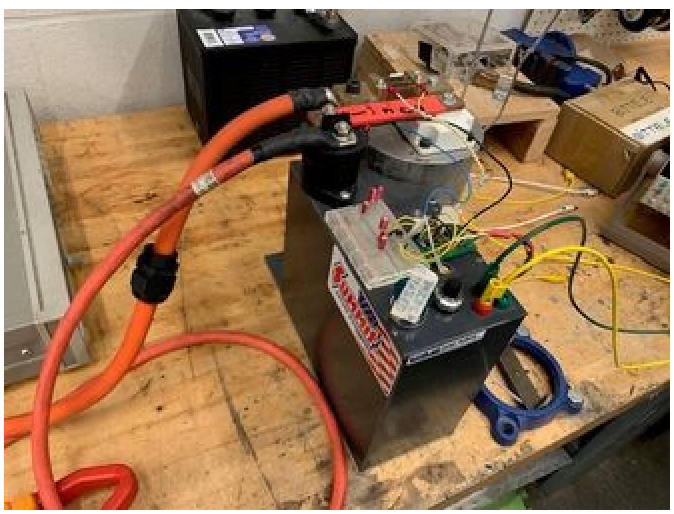
The locations were obtain by the dividing the length of the cell by 4 and selecting the 1st and 3rd point. A piece of acrylic laser cut to the fac

Discharge current was monitored using an AC current clamp and temperature was monitored using a thermocouple connected to the negati

Live data was gathered for current and temperature using the Keysight Handheld Meter Logger software.

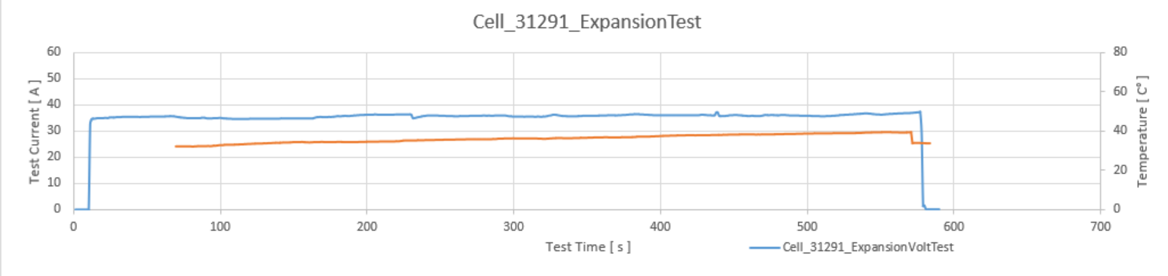
Live data for expansion was gathered using a video recording from an iPhone XR.

The a timer was used to determine the 10 min 45 sec end time, however, the test ended early at roughly 10 min as the cell voltage dropped

High Current Test Circuit	Cell Expansion Measuring Setup
	

6C Discharge Cycle for Cell 31291 (approx time is 10 min):

Test Current and Temperature vs. Time Plot



Starting Cell Voltage: 4.156 V

Current Data

NOTE: 1mv = 1A

Cell_31291_ExpansionVoltageTest (Good).xlsx

Temperature Data
Cell_31291_ExpansionTempTest (Good).xlsx

Expansion video accessible on Luke's onedrive - contact @ jlmorabi@uwaterloo.ca for access

Results: Maximum cell expansion was 0.15 mm in location 1 and 0.1 mm in location 2

15C Discharge Cycle for Cell 31291 (approx time is 15 sec burst):

Final Temp: ~60°C

Max Expansion: 0.02 mm for both locations

Expansion Limiter CAE Verification

One of the rule requirements for the accumulator segments is that it is able to maintain 10 psi of face pressure on each cell, at 90 °C. The aluminum segment frame does not have enough strength to restrain the expansion of the cell, so the battery box and PVC filler panels were also considered. The solid model of the accumulator was saved to a folder to prepare the model. The faces of the accumulator segment frame were split so that the pressure generated by the expanding cells could be appropriately applied.

- Cell Expansion Test Plan
- Cell Fuse Heating Test Plan

- Segment Analysis Results
  - Simulation Error
  - Physical Testing Uncertainty

Project Implementation

This section is to track issues with the cell segments and their respective bus bars.

Date	Issue

17 Dec 2019	Thermistor Validation:
	• Segment 6:
	  ◦ Thermistor 0, 1, 11, and 12 have readings of approximately 5.68 kohms. These bus bar boards needs to be investigated to determine what the appropriate action is.
	• Segment 2:
	  ◦ Pogo pins for thermistor 6 are not making contact with their contact points. This will need to be addressed (new pogo pins)
	• Segment 3:
	  ◦ To be reassembled with new bus bar boards (already brought-up). Thermistor validation must be completed after.

	• Segment 3:

18 Dec 2019	• Fully assembled

Conclusions

- Lessons Learned
  - Description of design improvements
  - Description of design disadvantages
- Estimation of project cost and engineering hours

Project Procurement:

Follow the procurement procedure as described in the Operations page Purchase and Reimbursement Procedure and then upload the purchase order spreadsheet to the table below. Consolidate as many purchases into one procurement request to simplify the process.

The Jira table below shows the outstanding purchase orders.

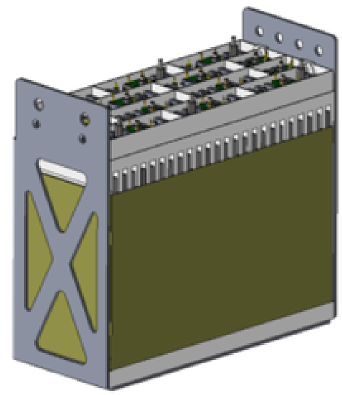
Team Member Name	Purchase Order Spreadsheet	Order Description	Company Name	Total Cost [$]	Status	Storage Location
Calvin DeKoter	N/A	EMS Materials	EMS	TBD	Unknown macro: 'status-handy'	
Calvin DeKoter	TBD	4701-30 Poron Foam 0.03125"	Rogers Corp	TBD	Unknown macro: 'status-handy'	
Calvin DeKoter	TBD	McMaster-Carr Materials - G10-FR4	McMaster-Carr	TBD	Unknown macro: 'status-handy'	

Bill of Materials

Item Description	Purpose	Vendor Link	Quantity Required	Quantity to be Purchased	Projected Cost	Model Link (GrabCAD)	Drawing Link	Status
1/2" Grey PVC	Bottom Cell Support Tray	To be purchased at the EMS	24" x 9" Piece	No extra required	To be Determined	20-5-ACC-214-R01		Unknown macro: 'status-handy'
1" Grey PVC	Cell Support Top Tray	To be purchased at the EMS	24" x 9" Piece	No extra required	To be Determined	20-5-ACC-217-R02		Unknown macro: 'status-handy'
1" Grey PVC	Cell Expansion Limiter	To be purchased at the EMS	24" x 12"	No extra required	To be Determined	20-5-ACC-182		Unknown macro: 'status-handy'
0.03125" Poron 4701-30 Foam	Battery Foam Pad	Rogers Corp Itape Store	8 square feet	10 square feet	To be determined	20-5-ACC-218		Unknown macro: 'status-handy'
1/16" G10 FR4	G10 Front /Rear Insulator	G10 FR4-McMaster-Carr Eplastics	24" x 36"	24" x 36" or bundle with below. 12 parts	~$38 + Shipping	20-5-ACC-213-R01		Unknown macro: 'status-handy'
1/16" G10 FR4	G10 Insulator, Sidewall	G10 FR4-McMaster-Carr	12" x 24"	12" x 24", 12 parts	~ $15 + Shipping	20-5-ACC-215-R01		Unknown macro: 'status-handy'
3/4" Round Delrin	Cell Top Support Clamp Tab	To be purchased at the EMS	6" bar	12" bar, or found in the bay	To be Determined	20-5-ACC-215C		Unknown macro: 'status-handy'

Cell Packaging 2018-2020

- Summary
- CAD Information
- Design Philosophy
- Problem Definition



Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Summary

Briefly describe the project purpose and current state.

CAD Information

- CAD Design Organization: *Describe how the solid models for the project are organized.*

Design Philosophy

- *"This part improves over last year's component by ____"*
- *"Do not repeat ____ mistake"*
- *"This design fixes ____"*

Explain each feature of the part and how it accomplishes the part's function.

Problem Definition

Rules Compliance

Rule	Status	Notes	Proof of Compliance
A 1.2	Unknown macro: 'status-handy'	**Paraphrase:** For an electric vehicle, the accumulator may have a maximum usable energy of 5.40 kWh, or nominally 6.75 kWh. (Discharge measured at 2C).	The accumulator will be designed to comply and be tested.

Constraints and Criteria

Constraint	Priority	Description	Value	Unit	Validation Method
Current	Unknown macro: 'status-handy'	Each segment must be able to deliver the full rated current of the Tractive System because the segments are in series. By design, this is 135 A RMS. The pack fuse will be 40 A.	135	A	HTHC

Cap ability					

Technical Progress

Design Process

Design Analysis and Manufacturing Design

Analysis Validation

Manufacturing and Implementation

Conclusions

Project Procurement:

Follow the procurement procedure as described in the Operations page Purchase and Reimbursement Procedure and then upload the purchase order spreadsheet to the table below. Consolidate as many purchases into one procurement request to simplify the process.

Generate a Jira task in the appropriate Operations Epic. Label it with *proc_ts* and an (*label specific to this page)* so that it shows up in the table below.

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Team Member Name	Purchase Order Spreadsheet	Quote / Invoice	Order Description	Company Name	Total Cost [CAD]	Status	Storage Location
						NOT YET PROCESSED	

Low Voltage Accumulator Cell Fusing

Project Timeline: April 25th, 2019- Completion

Updated- Cell Fusing was completed immediately before the accumulator. Documentation was finished over the summer of 2019

Sim Code: WFE_T_19_6- Waterloo Formula Electric, Thermal Simulations, 2019, 'Accumulator' project

- [x] Assemble equivalent Formula Hybrid Test Fixture @ Former user (Deleted) 25 Jan 2020
- [ ] Acquire current readout for high current test fixture @ Former user (Deleted) **25 Jan 2020**
- [x] Test cell fuses according to Formula Hybrid Requirements @ Former user (Deleted) 25 Jan 2020

Work Term Report by Calvin DeKoter, Fall 2019: LV Cell Fusing

Responsibility Cascade:

- Calvin DeKoter
  - No support- need a team for critical projects like this
- Alex Bondarenko- Electrical/Mechanical Design Advisor
- Aaron Grenke- Preliminary Simulation and Design Work

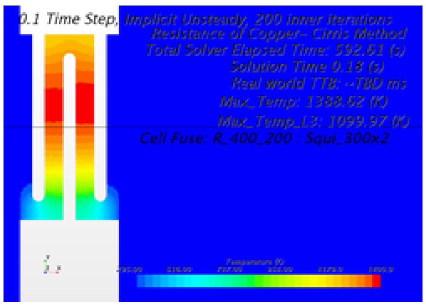
Design Philosophy:

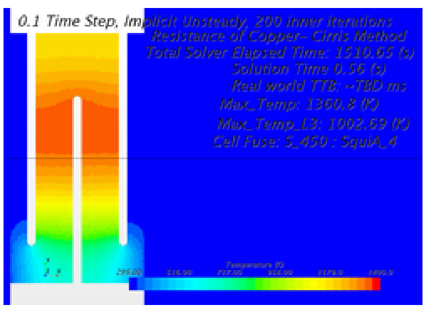
- This cell fuse protects the accumulator and battery cells from abuse and internal shorts.
- This is a rules-mandated device- all current-carrying parallel elements must be fused- See Rule EV.8.1.5.
- This cell fuse time to blow curve (ttbc) is fit between the main pack fuse- LS50Q125 and the energy/temperature boundary of the cell.

Cell fusing is a critical part of safe battery design- for a brief introduction to battery pack design, read this design document by A123, written with FSAE accumulators in mind. After the voltage, power, and energy requirements have been met by the battery architecture, module design and protection must be considered. Typically, the high current path is protected by an accumulator level fuse, designed to protect the cells and current path from overcurrent conditions. This would be the lowest rated fuse in the pack, because there is only one fuse which can be easily replaced. A soft limit would be set in the battery management system firmware to prevent this fuse from ever blowing, except in rare cases of software or hardware failure.

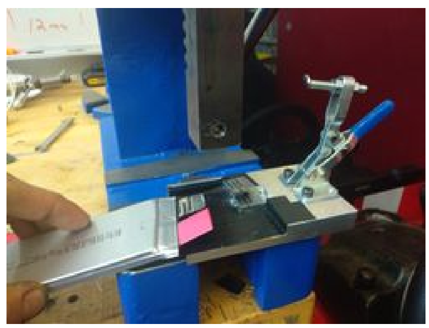
Cell fuses are required to protect the battery against overcurrent events not prevented by the pack level fuse- this includes internal short circuits caused by cell failure, module-level short circuits in the event of a dropped bolt or tool, or assembly error resulting in a cell being inserted backwards. Since cell fuses are so difficult to fabricate, are integral to the cell they protect, and usually do not have sufficient guarding to prevent damage to the battery, it is imperative that no cell fuse ever clears.

Final Cell Fuse Design: Long Current Path, Wide Current Trace





Cell Fuse Manufacturing: Copper Sheet cut with a Punch and Die



Example of Finished Cell Fuse- Cut on Negative Tab (the Wrong One)

Lessons Learned:

Having a cell fuse cut into the battery cell tab is an excellent production-level solution, where professionals can design and fabricate a consistent, safe, and efficient fuse. It is the best solution for packaging a fuse on a battery pack with pouch cell architecture.

For student teams, it is more important to have a design that is well constrained- wire type fuses have two parameters which control the TTBC that are easily varied. However, this requires a two stage bus bar design- one bus bar clamp for each cell tab which connects the fuse wire to the cell tab, then one main bus bar which collects all the parallel cells fuses together.

Component Attribute	**Manufacturable?**	**Works as Intended?**	**Serviceability**	**Notes**
Cell Fuse cut in Cell Tab	No- very difficult and risky	Barely- packaging the fuse and manufacturing is very difficult	No- entire cell must be replaced, as well as possible damage to other cells	Don't cut a cell fuse into the cell tab- you have one chance to cut the fuse, and the geometric size of the cell tab severely limits the design of the fuse.
Copper Cell Tab	Yes- Easy to Cut	Okay- blows at a high temperature	N/A	Copper is a good material, even when cut by plain mild steel tooling.
Cell Fusing by the current collector	No- very difficult and risky	Barely- manufacturing is very difficult	No- entire cell must be replaced, as well as possible damage to other cells	Cell fuses are protected by PVC guard, which would limit damage to other cells or fuses. Packaging of the fuse itself is excellent and allows compact bus bar designs.

Citations, Documentation, and

- Primer on RC LiPo Batteries- Very applicable to our car- read the sections about charging, discharging, and cell damage.
- Definition of Terms-
  - Short- a very high current event, many times the rated current of the battery- 300A and beyond for these particular batteries, corresponding to a 50C burst. This event causes the fuse to blow suddenly as the fuse is heated exponentially by the current. See simulation plots.
  - Overcurrent Event- a condition where the maximum output of the cell is exceeded- more than 15C (95A) for these batteries, up to the 'short' regime. The when designed properly, the fuse will blow, but only after a period of slow temperature increase. See simulation plots.

Mechanical/Thermal/Electrical Design Process Flow

- Definition of thermal and electrical performance limits
  - Using the datasheet values from the manufacturer, Electric Power Co., and the internal resistance of the cell, an upper limit of the cell output was found. Each cell could output 15C continous, 30C for 10 seconds, and theoretically, 1000A for 0.001 s, without damage. The last value was found using the thermal mass of the cell and the internal resistance. At that short circuit condition, the cell would experience ~1500 W of heating power (citation needed), and so could only be sustained for a very short time.
  - After this, a time-delay fuse from LittelFuse was specified that would create a region for the cell fuse to protect. From the A123 design guide, this main pack fuse must be the first element of protection to clear under all conditions. The manufacturer provided fuse curve was graphed along with the cell electrical performance limits.
- Research of cut-cell fuse designs
  - Using prior work by Nick Qu, Aaron Grenke, and Rob Rowland, the fusing lead (Calvin) set up multiphysics simulations of the copper fuse material in Star CCM+, a CFD program (for both the mesh and solving). Detailed here.
  - After some initial experimentation and learning, it was decided that a cell fuse with a thin, long section would not be robust enough to survive the vibration and shock of competion. (Picture required)
  - The cell fuse would have to have radiused corners, multiple current paths, and remain simple to fabricate with a punch and die.
  - Below are some of the cell fuses considered. (picture of notch fuse, picture of holey fuse, picture of fuse with many holes, picture of deformed fuse)
    - These fuses all have one thing in common- they have a relatively short path from the area of minimum cross section (maximum heat generation) to the bulk material of the cell fuse and the bus bar. This means that they will blow in a short condition, but almost never blow in an overcurrent condition. See the Waterloo Hybrid Fuses below for an extreme example of this. The deformed fuse also shares this condition. There is simply too much material for the small crushed region to heat.
  - After the design and assembly of the High Current Test Circuit (HCTC) was completed in late March, testing and correlation could begin in earnest with the simulation. It was found that the above designs readily blew at high currents (~350A), but would not blow at low currents because they were too effective at removing heat from the area of minimum cross section.
  - Simulations in Star CCM+ were again used to validate the design of cell fuses designed to blow at the correct time, even at low currents. This was done by lengthening and thinning the current path. These two degrees of freedom were the way in which the offset and slope of the TTBC curve was controlled.
    - During correlation, it was noted that while the TTB value predicted by Star CCM was relatively accurate for the 'short' condition fuses (±10%), it overestimated the TTB for the 'overcurrent' condition, up to %100 error.
    - This was attributed to the lack of testing put into the values of contact thermal conductivity, electrical contact resistance, and the interface between the cell fuse and the air.
      - Because of this, simulation was stopped and physical testing was used to design the fuse by improving on each iteration.
  - In order to package the longer and thinner current path in the cell tab area, a number of cuts would be made such that the current would flow back and forth across the width of the tab. (See picture below).
    - In the prototyping phase, these cuts were made with a knife and an aluminum jig. The cell fuse would be stuck down to the jig with double sided tape and the knife would be pushed through. (See picture / rendering below)
    - After this, a 1/32" slitting saw was used to make a punch and die jig.
      - Two pieces of mild steel were flattened, brought to thickness, and polished on one face.
      - Then, the slitting saw was used to cut 3 slots into the pieces.
      - Two 4 mm dowels were used to hold the parts together.
      - A piece of HSS with the same width as the slitting saw was ground into a punch shape with positive tip relief in order to minimize the force on the copper during punching.
      - Initially, the punch was hammered through, but an arbor press was acquired in order to greatly speed up the process.
  - It was found that the length and thickness of the trace controlled two aspects of the time to blow curve.
    - The length of the trace would control both the offset of the curve along the **I** (current) axis, but also the slope of the curve. This is because the length of the trace strongly affects heat rejection over long time scales, but under 'short' conditions, has little effect on whether or not the minimum cross-section region will blow.
    - The width of the trace would change only the offset- more cross-sectional area means that less heat is generated, so the fuse takes longer to heat up under all conditions.
    - These characteristics were used to define a theoretical fuse that meets the rules.

Excel spreadsheets **must** have colour coding on results cells, units on all numbers, and be set up in such a way that anyone could repeat your calculations. Use standard colours for the input cells, call out assumptions, and briefly explain the workflow for using the sheet.

Testing must be photographed, documented, and performed in a repeatable way.

Planned Hybrid Testing

Set up the High Current Test Circuit with the 6V battery as described here: High Current Test Circuit. Set Keysight DMM to measure the current flowing through the shunt, either with the current clamp or directly by the shunt voltage. Multiply the shunt voltage by 250 A / 0.06 V to convert it.

Set the other Keysight DMM to measure the temperature of the cell fuse- it must not rise about the measurement threshold, about 60° C. The Formula Hybrid Rule EV2.6.6 states that the temperature rise must be less than 50 C°, but in our case the absolute temperature must be less than 60 C°.

Set up the cell fuse fixture with a conductor that can handle more than the test current and fine tune the test current to 30 A. Replace the conductor with a cell fuse, found in the green cabinet, in the wooden organizer. Measure the cell temperature rise and log all the data. Take video of the test in such a way that the current and temperature measurements are visible. The test current at which the cell fuse temperature to 55° C will be the continuous working current for the cell fuse. After this, set the test current to 3 times the continuous current and run the test until the cell fuse opens. If the continuous current * 3 is greater than 105 A, set up the oscilloscope and make a capture of the cell fuse opening.

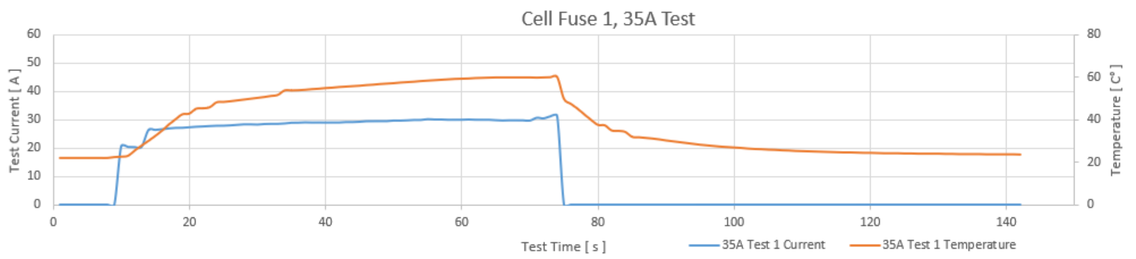
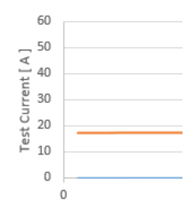
Requirements

- Take video of the test showing the current and temperature measurements
- Make sure to test every setpoint current with a conductor

Test Results:

Using the High Current Test Circuit, a cell fuse was subjected to approximately 25 A for 10 minutes and had an operating temperature of 41° C at 23 °C ambient temperature. The next test will increase the test current until the operating temperature is 55 °C, the maximum safe operating temperature of the battery cells.

Plot of temperature vs. time for 35A, Cell Fuse 1.

Test Time 63 s, Test Current 30 A, Temperature Rise 60 C°	Test Time 8 s, Tes
	

Further testing was not possible due to COVID 19 restrictions. The continuous current was assumed to be 30 A, but further testing is required with longer test times and better data collection.

Alternate Designs

Alternate Designs were considered before @ Calvin Ryan DeKoter joined the project. Other teams have used integral fuses, built into the cells, or using cylindrical cells with wire type fusing.

Waterloo Hybrid Fuses- Okay	A123 20Ah NPh Fuse- Good	A123 20Ah NPh Fuse- Inconsis

		
Note the thick cross-section and large area for dissipating heat. This fuse would not adequately protect the cell in the event of a ~50C short (See LiPo Terms, top of mechanical design area)	The current collector is thin nickel coated sheet copper, 0.2 mm thick **(verify).** Note the high quality of the fuse- regular hole spacing and equal distance at edges. **This fuse cut by WFE**	This is a fuse from the same lot c cell fuse is different. The author c comments that this process was fuse was cut by a hole punch, an **This fuse cut by WFE**

Cell Fuse - Formula Electric and Formula Hybrid Documentation Requirements

Project Properties

Project ID	EM-16
Status	WORKING
Upcoming Deadline	01 Sep 2017
Project Deadline	01 Sep 2017
Manager	@ cztsengt@uwaterloo.ca
Project Lead	@ Former user (Deleted)
Support	@ ba2nguye@uwaterloo.ca

Project Description

Given that the battery design uses sets of 4 cells in parallel, a fuse is needed between each individual cell. To accomplish this, testing on the cell tabs will be conducted to validate that the tab itself will burn away, opening the contact when the fusing conditions are met. To begin the engineering, a fuse specification is determined through finding the region on a current vs time log-log plot where the fuse must blow within.

The energy limit of the cell is determined and plotted as a theoretical upper time boundary on the plot. This can be seen as a line through points (1,22680) and (1000,22.7) determined by taking the capacity of the battery (6.3Ah) and converting to amp-seconds. Next, the current output capabilities of the cell is found based on the maximum DCR of the cell. From the cell's datasheet , the ACR at 1KHz of the battery is spec'd to be no more than 1.5 mOhms. The DCR of the battery has not been characterized, however the supplier confirmed that the DCR is roughly equivalent to their measured ACR. Without characterizing the DCR properly, it is difficult to spec a maximum current output capability of the battery, but to close the plot, a minimum DCR of 1.5 mOhms is used giving a maximum current output of 2800A. The first region of interest is the continuous current draw region (green). This represents the normal operating state of the battery while driving in autocross. The 43.8A bound is obtained by running lap time simulations from a custom lap simulator developed in Matlab and compared to existing programs for sanity checks. The lap simulator gives an RMS current assuming worst case driving conditions and with safety factor of 175A. Per single cell, this is 43.75A. The cooling system of the battery is designed to allow driving in this region. Next the peak discharge region (blue) is defined. The maximum power draw by rules is 80KW, assuming a discharged battery pack is at 230V minimum, a peak current of about 350A total or 87.5A per cell is found. From the Matlab simulator, this peak current is maintained for less than 5 seconds at a time giving the region an upper time bound of desired operating conditions. With the desired operating region defined, the unsafe battery region is now defined. From the datasheet, the cells can operate at 189A peak (30C) for an assumed 10 seconds and can operate continuously below 95A (15C). The (grey) region is an unknown grey area between peak and continuous rating, it is optimal to not let the fuse curve pass through this area however doing so may be permitted given validation of battery safety. Similarly, at some point, very short but still high current spikes will not bring the battery into an unsafe region due to the thermal mass of the system. This is represented by the (orange) region. This leaves us with all keep out regions of the plot and therefore defines the bounds of the fuse curve needed for usable, safe operation. .

Supporting Information, Project Details

- The pack needs fuses for each of the cells to limit the effects of a cell short circuiting.
-
- Example: The A123 Zipper fuse:
-

A123 battery design guide:

Requirements and Considerations

-

Relevant Rules

Rule Number	Rule Description

Fuse Design Specifications:

The fuse needs to clear within the boundaries described above. On the right side of the graph, the fuse must clear before the thermal safety limit of the battery is reached, defined by the short circuit current and energy capacity. On the left side of the graph, the cell fuse must **not** clear before the pack fuse blows, at any time, for any reason. This occurrence would almost certainly result in a 'Did Not Run' for any remaining dynamic events. Changing a cell fuse takes upwards of three hours and must be done in accordance with competition safety requirements mandating PPE and a designated area for HV work.

After the fuse clears, the Battery Management System must be able to detect an open cell fuse and shutdown the Tractive System. This is critical to the function of the cell fuse- if the fuses in parallel with it also open, those four fuses could be subjected to a potential difference of 300V. (Or the maximum operating voltage of the car.) No testing has been done to validate the capability of the fuses to withstand this condition. Depending on the overcurrent event which caused the failure, the fuse may or may not prevent arcing. To do this, the BMS will measure the voltage rise across each bank of parallel cells. This voltage rise is the OCV of the cell at its current state of charge, minus the voltage drop due to the internal resistance of the cell. If one cell fuse clears, the same TS current is flowing through three cells (in the case of the 2019 battery). This means that the internal resistance of the parallel bank changes from four parallel 1.5 m resistances (0.375 m) to three 1.5 m resistances in parallel(0.500 m).

The BMS will detect the change in voltage drop in the parallel cell and shut down the Tractive System. This feature is waiting to be implemented (August 2019).

Cell Fuse Designs:

Three main designs are currently being considered for the cell fuse: using punched holes to reduce the cross-sectional area, lessening the cross sectional area by deforming the cell tab, and cutting slots in the cell tab to lengthen the current path while decreasing the current carrying capacity of the cell tab.

Modification of the Intercepts of the Fuse Curve:

For the cell fuse to function, it needs to clear at the correct times. This is done by changing the shape, current path length, and the cross sectional area of the cell fuse.

Discrete Fuse Curve Points	**Minimum Time To Blow with LS50Q125**	**Minimum Time To Blow with LS50Q150**	**Maximum Time to Blow: Cell Thermal Limit**
75	50	125 seconds	
95 A (Currents listed for single cell output)		14 seconds	215 seconds (energy limit of battery)
100 A	10 seconds	30 seconds	200 seconds
125 A	2.4 seconds	8 seconds	62 seconds
145		3 seconds	
150 A	0.1	2.1 seconds	24 seconds
151.25		2 seconds	
155	0.04	1 second	
157.5		0.9 seconds	
162.5		0.6 seconds	
172.5		0.2 seconds	
175	0.02	0.1 seconds	
189 A			
200 A	0.0105	0.03	
205 A		0.02	
247.5		0.01	
250 A	0.0053		
287.5		0.005	
400 A	0.0024	0.003	
600 A (Peak output of fuse tester)			
1150 A (Not achievable)	0.00086	0.001	

Modification of the Slope of the Fuse Curve:

For the fuse to meet all of the intercepts, the slope of the fuse curve must be altered. This is done by changing the way the cell fuse rejects heat. For example, a single line of holes across the fuse produces a very steep curve: real world testing showed that the fuse could hold ~350 A for 2-5 seconds (likely almost indefinitely) because the heat flow away from the fuse grew more quickly than the increased heat generation due to the change in resistivity of the copper. Two lines of holes would mean that heat is no longer being extracted from both sides of the fuse region, meaning that the fuse may enter thermal runaway at a lower current level. Simulations are currently being run to characterize the effects of the number of holes and slot lengths.

Fuse testing:

a battery analogue and fuses will be tested in a jig designed to draw a pre-tuned maximum current from the cell. An IGBT with a tuned input will calibrate the current rating and a shunt in series with the IGBT will plot the current draw throughout the test. The batteries cell tabs will be clamped in an identical configuration to that of the installed cell providing a ~4mm gap between the edge of the cell pouch and the bus bar clamping the cell tab. This ~4mm area is the fusible link. To run the test, a large contactor will close the short circuit loop around the battery cell, shunt and IGBT until either the fuse blows, or an elapsed time passes. Tests at various currents will be performed to ensure that the current time plot is within spec. If the testing reveals that the fuse is out of spec, the width of the cell tab on the positive side will be reduced effectively reducing the cross-sectional area of the tab. Tests will be repeated until 3 consecutive tests reveal fuses that are within tolerance and reasonably similar to one and other.

The IGBT:

(found on the cell fuse tester stand) (datasheet here: APTGT600U170D4G-Rev3.pdf)

(old igbt) (datasheet https://www.mitsubishielectric-mesh.com/products/pdf/CM600DU-24NFH_n.pdf) (obsolete)

Fuse tester electrical requirements

Characteristic	Requirement	Achieved?
Rise time	100 [µs]	Yes
Test Current	800 [A]	No- 600 A for 0.3 s absolute maximum, one time before cooldown

Circuit:

High Current Test Circuit

Cell_Fuse_Tester_R.asc

Identify Battery Tab Material

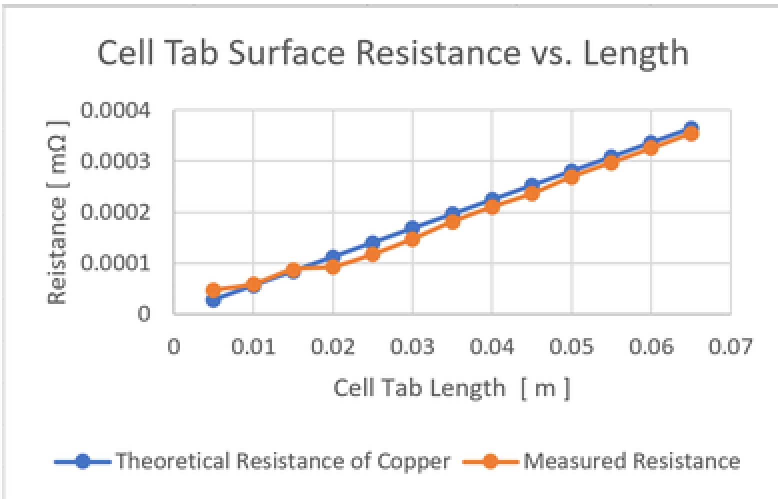
Skip to end of metadata

- Created by Unknown User (abondare), last modified by Calvin Ryan DeKoter on Jun 14, 2020

Go to start of metadata

Project	EM-16
Deadline	22 Jan 2018
Responsible	@ Former user (Deleted)
Status	COMPLETE
Type	BLOCKING
Priority	HIGH

The battery tab material is very likely to be a nickel coated copper. Resistance measurements show that the resistance of the cell tab is nearly identical to copper.



Cell Dimensions
Length (cm) Width (cm) Thickness (cm) Tab Length (cm) Tab Width (cm) Tab Location (mm)
1 14.91 4.45 0.89 1.58 1.41 4.08
2 14.96 4.48 0.87 1.62 1.49 4.38
3 15.02 4.44 0.86 1.39 1.51 5.3
4 14.89 4.46 0.87 1.52 1.49 5.38
5 15.01 4.42 0.88 1.53 1.5 5.15
6 14.93 4.47 0.85 1.62 1.5 4.41
7 14.9 4.5 0.89 1.61 1.5 4.59
8 14.81 4.44 0.89 1.69 1.51 4.93
9 14.91 4.4 0.9 1.7 1.5 4.67
10 14.93 4.46 0.88 1.62 1.49 4.6
Min 14.81 4.4 0.85 1.39 1.41 4.08
Avg 14.927 4.452 0.878 1.588 1.49 4.749
Max 15.02 4.5 0.9 1.7 1.51 5.38

Set Up Fuse Testing Rig

Skip to end of metadata

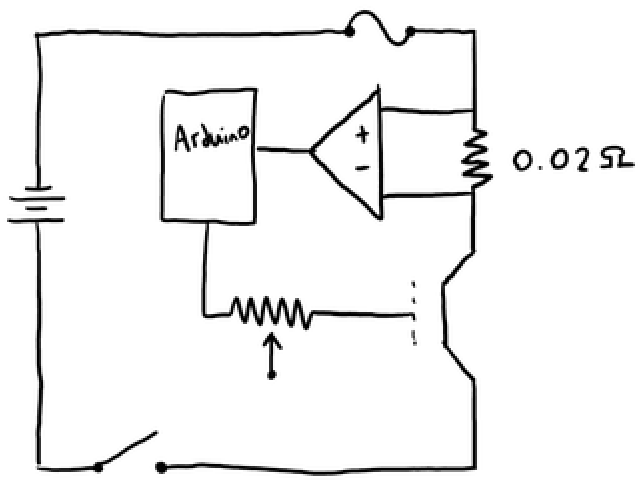
- Created by Unknown User (abondare), last modified by Calvin Ryan DeKoter on Oct 07, 2019

Go to start of metadata

Project	EM-16

Deadline	29 Jan 2018
Responsible	@ Former user (Deleted) @ Calvin Ryan DeKoter
Status	COMPLETE
Type	CHECKPOINT
Priority	HIGH

Here is a basic drawing of the proposed fuse-testing circuit:



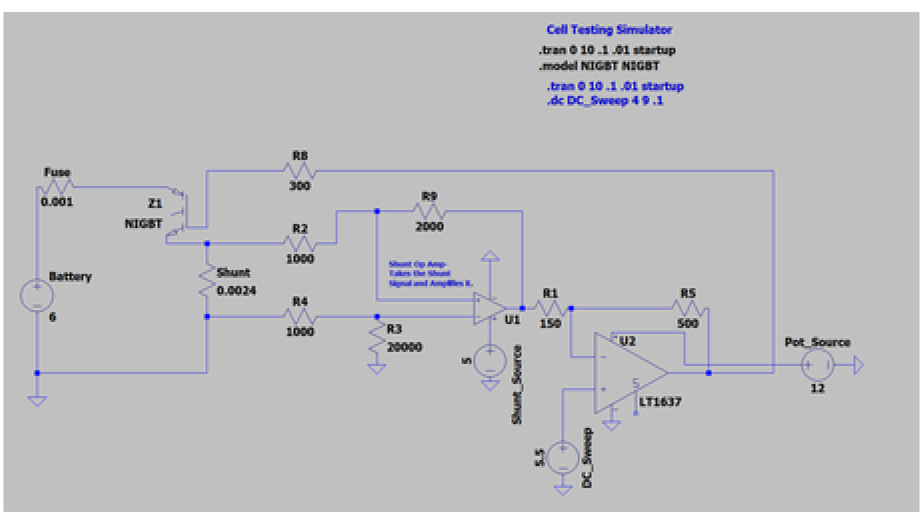
We are using the arduino to output values of the amperage across the shunt resistor.

A potentiometer will be used to modulate the current.

LT Spice Simulation with NIGBT Model

A rough analog of the circuit (two op-amps, shunt, cell fuse, 6 volt car battery source, 12 volt and 5 volt rails for op-amps) was modeled in LT Spice using the NIGBT model. This doesn't represent the 1700V Trench IGBT we have, as it seems to have a high internal resistance.

The circuit nicely models the behavior of the IGBT to modulate fuse current based on gate voltage, but doesn't replicate the resonance of the circuit.



Next steps: reduce the circuit to the bare minimum- the battery, NIGBT model, fuse, shunt, and the two op-amps.

W20 Cell Segment Re-Design

Project Timeline:

WBS Project Title: Cell Packaging

WBS Project Number: 1.2.1.2.1

Describe tasks and use the correct tags to show the state of the project.

Status	Unknown macro: 'status-handy'
Estimated Completion	08 Mar 2020
Project Deadline	10 Mar 2020
Required to Run	No
Priority	Unknown macro: 'status-handy'

Responsibility Cascade:

- *Project Lead: @ Calvin Ryan DeKoter*
  - *Cell Expansion Testing Conducted by: @ jlmorabi@uwaterloo.ca*

Design Philosophy:

- This design fixes several issues with last year's LiPo cell packaging including proper cell constraint and applied face pressure under thermal expansion
- This design also quantifies the expansion limiting capability of the segment container and accumulator through FEA with an applied temperature condition.

Attribute	Value	Unit	Comments
Segment Voltage Maximum	50.4	V	
Segment Voltage Minimum	33	V	
Segment Capacity	25.2	Ah	
Segment Ampacity	756	A	Limited by cell fusing
Segment Energy	3900.096	J	Evaluated at 2C rate as in ESF
Segment Temperature Maximum	57	°C	As measured by AMS
Segment Weight	tbd	kg	Measured with Electronic Scale

Task list:

- @ jlmorabi@uwaterloo.ca to complete cell expansion testing at 6C and 15C
- @ Calvin Ryan DeKoter to finalize packaging re-design

@ Jack Dai to review CNC capabilities

Description

The cell segment is a section of the battery defined by the Formula Hybrid rulebook, containing a maximum of 6 MJ of energy and having a voltage less than 120 V. See Table 9 - Voltage and Energy Limits in the Formula Hybrid Rulebook. As described by the page Accumulator Cell Selection, lithium-ion pouch cells need to be supported when installed into an accumulator with appropriate structures to restrain the pouch, cell tabs, and prevent the expansion of the pouch.

The 2020 accumulator segment design is an adaption of the 2018 accumulator segment, which used 48 EP8514548HP Electric Power $LiCoO_2$ cells, which are more energy dense than the $LiFePO_4$ cells used previously. A drawing of these cells with nominal dimensions and dimensions measured by WFE is included below.

48 of these cells are packaged in each segment in a 4P12S configuration, meeting the team's voltage and ampacity requirements, while staying within the Formula Hybrid rules requirements.

The 48 cells are packaged side by side and face to face with a piece of 0.8 mm foam touching one of the two faces. This foam applies an even pressure to the face of the cell, keeping the cell from entering over-heating in a specific area.

Relevant Documentation:

- Confluence page
- Pdf file
- Technical Datasheets.pdf

Rules Compliance - Nomex Fire Resistance

In order to meet the new rules for Formula Hybrid, cell segments must be properly isolated. Previous design used 0.35mm Nomex in between cell segments, this material selection must be validated for Formula Hybrid rules.

Section	Status	Notes	Documentation
EV2.2.1	Unknown macro: 'status-handy'	The accumulator segments must be separated so that the segment limits in Table 9 are met by an electrically insulating barrier meeting the TS/GLV requirements in EV5.4. For all lithium based cell chemistries, these barriers must also be fire resistant (according to UL94-V0, FAR25 or equivalent).	DPT16_21668_Nomex_410_Tech_Data_Sheet_me03_REFERENCE.pdf
EV2.2.2	Unknown macro: 'status-handy'	The barrier must be non-conducting, fire retardant (UL94V0) and provide a complete barrier to the spread of arc or fire. It must have a fire resistance equal to 1/8" FR4 fiberglass, such as Garolite G-9.	
EV5.4	Unknown macro: 'status-handy'	All electrical insulating material must be appropriate and adequately robust for the application in which it is used. Insulating materials used for TS/TS insulation or TS/GLV segregation must: (a) Be UL recognized (i.e., have an Underwriters Laboratories24 or equivalent rating and certification). (b) Must be rated for the maximum expected operating temperatures at the location of use, or the temperatures listed in Table 14 (whichever is greater). (c) Must meet the minimum thickness requirements listed in Table 14 Insulating materials must extend far enough at the edges to meet spacing and creepage requirements between conductors. Thermoplastic materials such as vinyl insulation tape may not be used. Thermoset materials such as heat-shrink and self-fusing tapes (typically silicone) are acceptable.	

Bill of Materials

Item Description	Purpose	Vendor Link	Quantity Required	Quantity to be Purchased	Projected Cost	Model Link (GrabCAD)	Drawing Link	Status
1/2" Grey PVC	Bottom Cell Support Tray	To be purchased at the EMS	24" x 9" Piece	No extra required	To be Determined	20-5-ACC-214-R01		Unknown macro: 'status-handy'
1" Grey PVC	Cell Support Top Tray	To be purchased at the EMS	24" x 9" Piece	No extra required	To be Determined	20-5-ACC-217-R02		Unknown macro: 'status-handy'
1" Grey PVC	Cell Expansion Limiter	To be purchased at the EMS	24" x 12"	No extra required	To be Determined	20-5-ACC-182		Unknown macro: 'status-handy'
0.03125" Poron 4701-30 Foam	Battery Foam Pad	Rogers Corp Itape Store	8 square feet	10 square feet	To be determined	20-5-ACC-218		Unknown macro: 'status-handy'
1/16" G10 FR4	G10 Front /Rear Insulator	G10 FR4-McMaster-Carr Eplastics	24" x 36"	24" x 36" or bundle with below. 12 parts	~$38 + Shipping	20-5-ACC-213-R01		Unknown macro: 'status-handy'
1/16" G10 FR4	G10 Insulator, Sidewall	G10 FR4-McMaster-Carr	12" x 24"	12" x 24", 12 parts	~ $15 + Shipping	20-5-ACC-215-R01		Unknown macro: 'status-handy'
3/4" Round Delrin	Cell Top Support Clamp Tab	To be purchased at the EMS	6" bar	12" bar, or found in the bay	To be Determined	20-5-ACC-215C		Unknown macro: 'status-handy'

Expenditures:

Items	Vendor	Payment Method	Cost (CAD/USD)	Form Link	

Project Bring-up

Winter 2020 Progress

Cell Expansion Testing:

<u>Test Set-up:</u>

Uses the high current test fixture (See High Current Test Circuit for more info) to discharge the cell as well as two dial indicators to measure expansion at two locations along the cell face.

The locations were obtain by the dividing the length of the cell by 4 and selecting the 1st and 3rd point. A piece of acrylic laser cut to the face dimensions of the cell is placed between the dial indicator probes and the cell's polymer case.

Discharge current was monitored using an AC current clamp and temperature was monitored using a thermocouple connected to the negative terminal of the cell. In addition, cell voltage was monitored using the "meter" function on the Agilent power supply.

Live data was gathered for current and temperature using the Keysight Handheld Meter Logger software.

Live data for expansion was gathered using a video recording from an iPhone XR.

The a timer was used to determine the 10 min 45 sec end time, however, the test ended early at roughly 10 min as the cell voltage dropped below the minimum voltage rating of 2.7 V.

6C Discharge Cycle for Cell 31291 (approx time is 10 min):

Starting Cell Voltage: 4.156 V

Current Data

NOTE: 1mv = 1A

Temperature Data

Cell_31291_Expa...est (Good).xlsx

Expansion video accessible on Luke's onedrive - contact @ jlmorabi@uwaterloo.ca for access

Results: Maximum cell expansion was 0.15 mm in location 1 and 0.1 mm in location 2

<u>15C Discharge Cycle for Cell 31291 (approx time is 15 sec burst):</u>

Final Temp: ~60°C

Max Expansion: 0.02 mm for both locations

Thermally Resistant Plastics

https://www.craftechind.com/dont-sweat-4-high-temp-plastics-can-take-heat/

https://www.curbellplastics.com/Research-Solutions/Materials/G10-FR-4-Glass-Epoxy

https://www.curbellplastics.com/Research-Solutions/Materials/PAI

https://www.curbellplastics.com/Research-Solutions/Materials/PEEK

Cell Packaging 2021

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Summary

@ **Calvin Ryan DeKoter**

The battery cells that power the vehicle must be safely held in the accumulator

CAD Information

- CAD for the battery box is currently stored in the conceptual designs folder on GrabCAD - \GrabCAD\2021 Vehicle\2 - Conceptual Designs\05-ACC-000\Packaging_Concepts

Design Philosophy

- Using cylindrical 18650 cells will simplifying packaging and improve the safety and reliability of the battery pack.
- This segment design will be fully rules compliant which will simplify the submission process.

container. The cells must also be monitored by the AMS to make sure that their voltage and temperature stay within limits.

- The segment CAD is completed as a single part to simplify the size relationships between the different parts of the packaging solution.

- Temperature monitoring will be greatly improved with this design because the thermistor will be in direct contact with 1/3rd of all cells in the battery pack.

Problem Definition

It is necessary to package the cells so that they stay in the accumulator container and operate within their voltage and temperature limits. The cells must also be packaged to minimize the risk to the driver and vehicle in the event of a cell venting incident. According to the vehicle architecture and cell selection process, 490 18650 30Q cells will be held in 5 segments inside the 2020 accumulator box.

Rules Compliance

Please see the 2021 Formula Hybrid Rules Compliance page: Rules Compliance. The segment design is driven by sections EV2 and EV3.

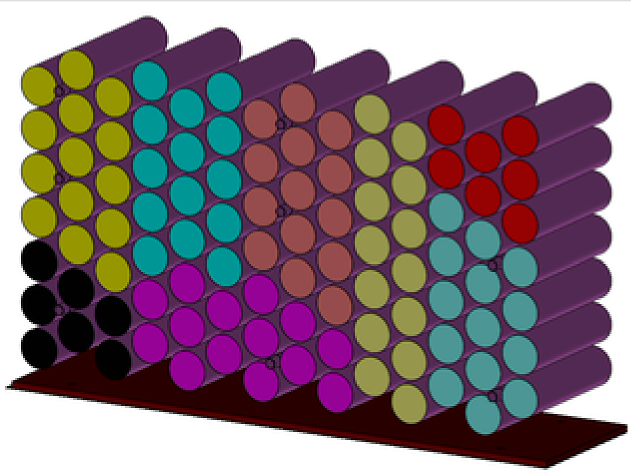
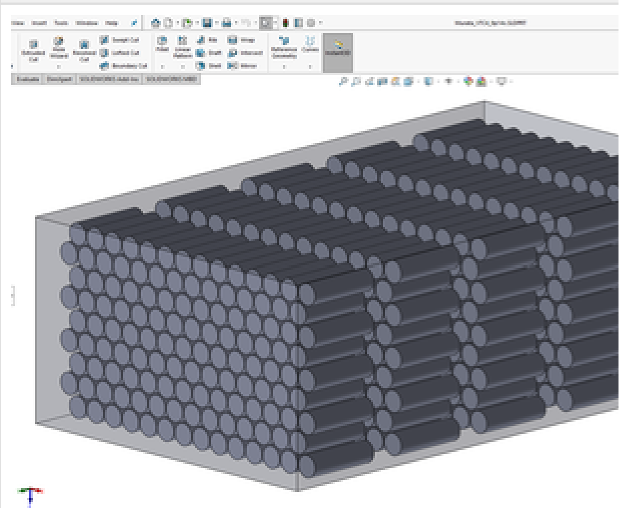
Constraints and Criteria

Constraint	Priority	Description	Value	Unit	Validation Method
Current Capability	Unknown macro: 'status-handy'	Each segment must be able to deliver the full rated current of the Tractive System because the segments are in series. Based on lap time simulations, this current is 139A during autocross (for 3 minutes), roughly 200A during acceleration (for 5 seconds), and 40A during endurance (for 50 minutes). Design should be conducted with a maximum current of 250 A in mind and a continuous current of 150 A.	150	A	HTHC - Load Bank
Mounting	Unknown macro: 'status-handy'	The segments should be mounted with M6 fasteners for the FSAE ruleset, but M4 fasteners with appropriate calculated strength were selected for FH	M6	Size	By Design

Technical Progress

Design Process

Using the selected number of cells and segments, various packaging configurations inside the 2020 accumulator chassis were tested:

	
Conceptual 7p14s package with groups	Preliminary packaging study with 9p14s in accumulator volume

Design Analysis and Manufacturing Design

Load Calculations - each segment should withstand a load of 20g vertical (upwards) and 40 g lateral / longitudinal. The segment will be supported by 8 M4x0.7 fasteners per segment.

Conductor Design:

From lap time simulations, the segment projected average current (absolute maximum based on cell voltage sag and heating) during autocross is 216 A (HV Harness 2021). All conductors should be able to carry this current for at least 3 minutes and with minimal voltage drop. If Nickel 201 sheet is used, which has a resistivity of 8.5 x 10E-8 * m. Based on the new segment design, the bus bars will carry a current that varies between the current from one cell, ~30A, and the sum of the current from all cells in a parallel group, ~216 A, must be carried across the middle of the bus bar. It should be noted that these are the highest expected currents from the battery pack and continuous currents during endurance will be much lower.

SigmaClad 60, which has an equivalent conductivity of 60% of copper, has been offered to the team to use as the bus bar material. In 0.5 mm thickness, it has a maximum current density equal to 10.5 A / mm^2 in still, cool air. These conditions will not be respected inside the segment, so derating will be necessary. Luckily, this is a continuous rating, and during endurance, the average current is projected to be equal to or less than 42A (Assuming 2C discharge). The worst-case bus bars were moved into Star-CCM to simulate the rise in temperature with various currents. An 8 mm circle was used to represent the current inflow and outflow points. This likely underestimates the actual temperature, as the fuse heating is not taken into effect**.**

Cell Connection and Fuse Design

Based on the Formula Hybrid fuse rules requirement, the fuse should open at less than the 50% of the short circuit current. For the 30Q Samsung cells, which have an internal resistance of roughly 0.031 , implying a short circuit current of 116 A. (I_sc = Vnom / DCIR). Since the fuses will not be rated for the full tractive system voltage, they must also meet the requirements outlined in **EV2.6.5.** For example, if the cell fuse is rated at 40A and there are 7 cells in parallel, the pack fuse must have a rating of 140A or less. The cell fuse must open at 120 A and deliver the rated current with a temperature rise of less than 50 °C. The small amount of experiments showed that a cross sectional area of roughly 0.8 mm^2 or less would be appropriate.

Cell Mounting

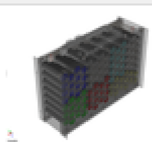
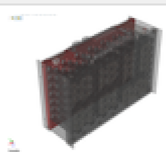
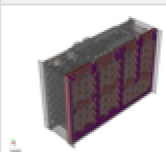
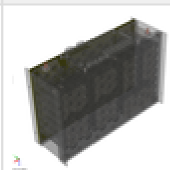
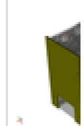
Cells will be held in GPO-3 industrial laminate plastic, with

Manufacturing and Implementation

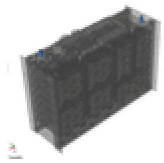
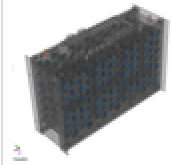
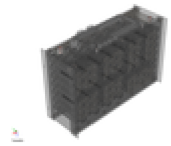
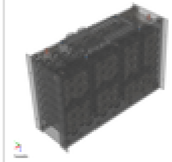
Conclusions

CAD Photos and Assembly Structure

The segment was designed as a single part in SolidWorks and then split apart into it's constituent parts, each with a set material. Photos of the different parts in CAD are shown below along with the friendly name.

Part Number	21-5-ACC-200	21-5-ACC-250	21-5-ACC-201	21-5-ACC-211	21-5-ACC-212	21-5-ACC-213	21-5-ACC-214	21-5-AC
Photo from CAD								
Friendly Name	Segment A	Segment B	Samsung 30Q Cells	GPO-3 SI YP	GPO-3 SI YM	G-7 Panel YP	G-7 Panel YM	G-7 Pan
Description				GPO-3 SI YP	GPO-3 SI YM	G-7 Panel YP	G-7 Panel YM	G-7 Pan
Drawing	N/A	N/A	N/A	21-5-ACC-211-R01	21-5-ACC-212-R01	21-5-ACC-213-R01	Same as 213	21-5-AC
Drawing PDF				21-5-ACC-211-R01.pdf	21-5-ACC-212-R01.pdf	21-5-ACC-213-R01.pdf	Same as 213	21-5-AC pdf

Part Number	21-5-ACC-222B	21-5-ACC-223	21-5-ACC-224	21-5-ACC-225	21-5-ACC-232	21-5-ACC-233	92095A471

Photo from CAD							
Friendly Name	EBC 3.6 mm	EBC Pressfit Ring	EBC Isolator	Nickel Cell Fuse	USP 10982 Thermistor	AMS Mount Spacer	BH M3x0.5 4 mm
Description	EBC 3.6 mm	EBC Pressfit Ring	EBC Isolator	Nickel Cell Fuse	USP 10982 Thermistor	AMS Mount Spacer	BH M3x0.5 4 mm
Drawing	As Bought	21-5-ACC-223-R01	21-5-ACC-224-R01	N/A - Waterjet	N/A - As assembled	**TBD**	As Bought
Drawing PDF	As Bought	21-5-ACC-223-R02.pdf	21-5-ACC-224-R02.pdf				

Project Procurement:

To build the accumulator segments, several purchases are required. First, the required amount of GPO-3 laminate and G-7 laminate, which meet the temperature and flame retardance specifications in the rules, were ordered.

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Accumulator Cell Selection

Overview

The pack options for 2021 are based on a number of constraints, tradeoffs and sets of analysis. Various architecture decisions to consider can be found in the Accumulator Documentation Page These factors were all considered when feeding into the options for the accumulator module design.

Generally speaking, the problem of determining which battery cell to use is a very under constrained problem yielding a large list of potential options. There are a number of factors that should be considered when narrowing the list down which require an understanding and vision for what the goals and desires are for many aspects of the pack. Some of these options are listed below followed by a short explanation of what to think about for each.

Factor	What and Why to consider
Shape and Form Factor	Cells come in a number of shapes and sizes. The three main options are round cells, pre-packaged round cells and pouch /rectangular cells. These options have a range of costs, range of implementation complexity and range of layout flexibility.
Company	Some companies have better or worse credibility than others. Look at what other teams use and why. Look at what others say about companies and why. Make sure that you don't commit to sketchy cells without testing them prior to committing.
Battery Unloading	Think about how you are going to remove the battery from the car. There are a number of options and they all have implications on the design of other subsystems.

Capacity	This is super fundamental to battery design, see below for more.
Voltage	This defines the number of cells in series which in turn defines capacity. You also have to consider the implications on conductor sizing, and motor / controller requirements, see below for more.
Current Draw	This defines the C rating of cells as well as the capacity per cell and number of cells in parallel, see below for more.
Module Size	The accumulator has to be divided into sections as per the rules, consider how these sections are shaped and other constraints that go along with them.
Box Dimensions	Look at the size of the cells and how they can be arranged into a pack, typically each cell will only have a couple possible arrangements that conform to a loose size constraint. See below for more.
Energy Density	This is a measure of Wh per unit mass. The larger this number, the lighter the pack will be for a given capacity. We make race cars, keep the mass down.
Fusing	If there are cells in parallel, a fuse must be in line with each cell and bust blow if one cell shorts. Pouch cells can use the tab as a fuse if it is narrow enough. A test must be performed to validate this.
+- Terminals	Cells have a number of options for terminals and how to connect to them. Connections can be made with spot welding, clamping or bolting depending on the cell and each have their own implications. See below for more.
Impedance	The cells internal impedance (resistance r) will define the amount of heat generated by the cell while current is being drawn, heat_energy = r*i^2. The lower the impedance the better

Styles

Style	Comments
Pouch Cells	• This solution comes as a pouch with tabs that can be used as connections. (2015-2016 and 2016-2017 used this type of cell) • Pouch cells will require us to design temperature sensing, fusing, and packaging for protection. • Cooling is likely to be air cooled using Washington's accumulator as reference
Packaged 18650s	• These solutions come with the 18650 cylindrical batteries as well as housing for the cells to go inside. This results in a form factor that is easy to design around. (typically cube and rectangular prism shaped) • Cell packaging is much simpler to design as housing comes with cells. • Connections need to be made between housings; the connections within the housings are taken care of as part of the package. • Both companies (Tyva and Energus) allow for simple solutions for temperature sensing. (area on each housing for temperature sensors)

Electrical Constraints

Lookup Spreadsheet

A cell selection spreadsheet was made to help calculate the viable cells for a given pack design. The sheet takes an input set of constraints and uses these to look through all inputed cell options to fine which could be made into a pack of the desired electrical configuration. The lookup is performed from a database of cells. Not all cells are added to it, just the ones that have been looked at and compared before. Adding additional sheets to the lookup is difficult. In the future, if you want to add more cells to the lookup, add them to the "additional cells" tab/sheet.

Capacity

The capacity is something that is established from a number of factors. In order to compete endurance, unless you have a very large battery or a very light car, you need to limit your power to conserve energy. This obviously means that your car will drive slower, leading to lower lap times. Lap Simulation Analysis should be performed to understand the implications of the size of the battery. In general, a larger pack increases mass at the benefit of faster endurance times. This tradeoff should be made based on an understanding of who your competitors are and what their event times are as your score is entirely relative to the other teams.

Mechanical Constraints

Fusing

If using pouch cells, you can use the thinness of the cell tab to your advantage as a fuse. Other teams have done this without a need to modify the cell tab in any way (we have done this by punching hole in the tab to increase the electrical resistance). A thinner cell tab will blow faster. Keep this in mind when selecting a cell.

Terminal Material

This is important for a couple reasons. Spot welding works better on some materials, look into this if this is an option. Some materials will oxidize forming a high resistance layer (aluminum, copper), make sure the implications of this are understood. Some materials are more malleable than others which can be good or bad.

For pouch cells, if you are clamping, use nickel plated copper, dont have to worry about corrosion and they are stiffer.

Cell Layout

Initial experimentation was performed to determine the viability of different layout options. This analysis also fed into discussion about

Comparing to other teams also gives a good ballpark estimate. typically batteries are between 6 and 7 KWh. You may also have to lower your capacity for physical size limitations. Keep this in mind.

Voltage Requirements

The voltage requirements of the pack are commonly misunderstood. Motors have a max voltage, and a motors output speed is proportional to input voltage, but there are ways around both of these facts.

If the motors max voltage is above the max battery voltage, than normally, the motor would not be able to spin at its max speed. Even if it is much larger, many motors and controllers support automatic field weakening which allow the motor to spin faster even though the voltage is low. Field weakening changes the motor constant such that the motor can spin at a higher RPM than what the voltage would normally produce (and it also changes the current to torque constant). There is a small amount of efficiency loss, but it can be as low as ~5% for 75% field weakening. Production EVs go up to 400% field weakening.

If the motors voltage is below the battery voltage, this is also not actually an issue as long as the motor controllers max voltage is above the battery voltage. The motor controller is the interface between battery power and motor power. All the motor controller does is control the current fed into the motor by pulsing input voltage to produce a lower average voltage. The motor controller will limit the max average voltage and current that it outputs to the motor.

Current Requirements

Look at your minimum voltage of the pack, for Lipo cells, this is usually when each cell has a voltage of around 2.6v - 3v. Take your maximum power draw of 80KW and find your max current draw at this voltage and power (80000 / (2.6*#series)). Then consider the amount of current flowing through each cell, if there are cells in parallel, the current is shared equally.

Assuming 72s4p, (80000/(72*2.6))/4 = 106.8A

The max current capability of the cell is based on its C rating. This is a rating of the multiple of a cells capacity that can be drawn from the cell. You simply take the Ah capacity, multiply by the C rating and that is the current draw limits. Typically, there is a continuous C and peak C, make sure the implications of using a cell that has a continuous current rating lower than the max current draw is understood.

Assuming 6.3Ah and 15C continuous, 6.3*15 = 94.5A

Although the continuous C yields a lower continuous current than expected max current, keep in mind that the peak current draw does not represent the average current draw. Lap time sims can then be performed to understand what the average current draw throughout a race is. This helps to understand the cell constraints as well as wiring requirements.

how to remove the battery given the expected rough dimensions of the battery. This analysis early on will help understand packaging constraints.

From here, a more narrowed down box layout sheet was made to evaluate and compare the remaining cell options to each other while considering the amount of room in the rear of the chassis for the powertrain. This packaging is discussion in the chassis page for the r ear end packaging (Link no longer functions).

Companies

This section is to keep track of the companies that make battery cells and for providing notes about those companies. In addition, it is for organizing spreadsheets of information pertaining to cell options on an ongoing basis

Company	Cell	Notes
Electric Power		Must email for further information
Melasta	Link to their website with cell options Spreadsheet of cells fro m an inquiry	Lots of different pouch cell options. The website doesn't have all of the options though, the excel spreadsheet contains many more. Many teams have used these cells due to their flexibility and high energy density. There are quality and consistency issues that can be avoided if each cell is tested individually prior to use. One nice thing about their cells is that they are thick, so they become much easier to package.

Energus	Pre packaged 18650 cells in a number of sizes	These guys make cell modules specifically for use in FSAE. They have air cooling passageways to make cooling easy and in general allow you to make a pack with minimal work.
EiG	Lithium ion pouch cells (This website is gone)	This company only has a couple of options for cells, teams have reported very high quality and minimal issues. The chemistry for their cells are different. Some allow very high charge rate at the sacrifice of energy density, not something we want. At the time of writing this, the only option in a workable chemistry has a capacity of 20Ah which makes it hard to package as there will be little room for bus bars. The cells are also very thin which again, makes packaging hard.
EEMB	Lithium Polymer pouch cells	These actually seem good. Seem like a good company, maybe they will turn something out.
Lipol	Lithium ploymer pouch cells	Don't know too much about this company, they have a lot of cell options though.
Envia	Pouch Cells (This company doesn't appear to have a website anymore)	Ultra-high energy density (350Wh/Kg) pouch cells. Multiple sizes available. Specifically targeted at electric vehicles and other applications where low mass is a priority.
Kokam	Lithium polymer pouch cells	These seem well made and have lots of good characteristics. They also just seem to have good marketing. Large range of energy densities.
Tyva Energie	Pre Packaged 18650 cells	These seem to be a good option if you know nothing about building batteries. Very simple to use, simple connections between modules and they mechanically link together. They are lower energy density and very bulky. Not meant for an SAE car.
Gaia	Round li-po with lugs (This website no longer has a link to specific cells)	This German company makes round cells with lugs on either end to make it easier to attach to. The smallest are 7.4Ah. They could actually be put in groups of 3 and have it form a hexagonal pattern of bus bars. Energy to mass is fairly low though, but they do have lugs built in.

2021 Selected Cells

5 Cells were selected for further testing. These cells can be found in the attached spreadsheet highlighted in green. Cell_Masterlist.xlsx

Cell data acquired from individual testing of each cell can be found on GrabCad: 2021 Vehicle\8 - Documentation\2021-Accumulator\Cell Testing

Samsung 30Q 18650 26J Cells were selected for the 2021 and 2022 Accumulator.

630 Cells will be used in a 70s9p configuration. Cells were selected for several reasons including

- A good aspect ratio for cooling, allowing cell pack cooling to be easier and more effective
- Less risk of critical damage if cells go bad or get damaged; lower risk than pouch cells and less negative impact

A summary of the cell data referenced above showed that the Samsung 30Q's boasted both a slightly higher voltage and a lower internal resistance than their competitors the Sony Murata VTC4's.

Cell Selection 2021

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Summary

@ Chris Xie

CAD Information

CAD Design Organization- See Accumulator File

Design Philosophy:

The battery cells store energy required for the tractive system. It is critical that appropriate and safe cells are chosen. If possible, the cells should be selected to fit in the old accumulator box.

Cell Selection Worksheet: Prepared by Joseph Borromeo, cells in green are shortlisted.

- The selected cells for 2021 must be of high quality, providing good performance and safety
- The selected cells must balance cost and performance, according to team goals.
- The selected cells must fit into the 2018 accumulator box without modification.

Cell Selection Process

Problem Definition

The battery cells store energy required by the tractive system to make the vehicle move. Rule requirements set out voltage and energy limits. In the Formula Hybrid competition, there is no power limit, but the energy limits are low enough that the vehicle will not run at full power during the endurance event.

Formula Hybrid Rules Compliance

Complete the table below with rules relevant to the project. Please familiarize yourself with the entire rulebook before beginning design.

Rule	Status	Notes	Proof of Compliance
A1.2	Unknown macro: 'status-handy'	**Paraphrase:** For an electric vehicle, the accumulator may have a maximum usable energy of 5.40 kWh, or nominally 6.75 kWh. (Discharge measured at 2C).	The accumulator will be designed to comply and be tested.

Constraints and Criteria

Design considerations based on testing and analysis of past designs, as well as feedback from competition judges and professionals.

Constraint	Priority	Description	Value	Unit	Verification Method
Total Energy	Unknown macro: 'status-handy'	The accumulator must not have a capacity greater than 6.75 kWh, but should have enough energy to complete endurance at a reasonable speed.	<6.75	kWh	By Design
Cell Thermals	Unknown macro: 'status-handy'	The accumulator cells must output power without overheating. For the acceleration event, the thermal mass can be considered. Lap time simulations will provide profiles for the other events.			
Power Output	Unknown macro: 'status-handy'	The accumulator must be able to deliver power at the limit of tire traction during acceleration and enough to complete the autocross and endurance events.	TBD (~50 kW)	kW	By Design, Testing
Cells Total Volume	Unknown macro: 'status-handy'	The new accumulator must fit inside the volume allotted for the old accumulator.	290 * 497 * 167 xyz	mm	By Design
Cell Total Mass	Unknown macro: 'status-handy'	The total mass of the accumulator cells should be minimized to make the vehicle more efficient and faster.	50	kg	By Design

Technical Progress

For the first round of cell selection, it was assumed that the largest possible accumulator would yield the best competition scores because the team's powertrain is very powerful. If the accumulator is not matched to the large powertrain, that weight is wasted. Since the two Emrax 208 motors and Sevcon Gen5S9 motor controllers can easily deliver 70 kW continuously, Alternatively, if the average power outputs are closer to 40 kW, running only one motor should be considered.

Lap Time Simulation

A Matlab script called OpenLap was used to simulate the path of the car around a track similar to the theoretical track outlined in the Formula Hybrid rulebook. This script has many of the same limitations as the OptimumLap software- it considers the car as a point mass, with no change in handling characteristics due to the change in attitude or weight transfer of the car. The script first calculates the speed at each corner apex where the vehicle becomes grip limited. After this, it works backwards to find the point on the previous straight where the driver must begin braking. The simulation also works forward from the corner apex to find the maximum speed attained on the straight. The intersection of the acceleration and braking plots marks the maximum speed on the straight.

Specific Outputs:

The script was designed to work with a traditional combustion vehicle, and logs fuel consumption data to a vector for every time step. For the purposes of electric vehicle analysis, the instantaneous motor power, under both acceleration and braking must be considered. This power is multiplied by the time step and summed to a vector logging the energy used.

Cell Selection Matrix

Cell Name	Cell Format	Cell Chemistry	Cell Nominal Voltage [V]	Cell Capacity [Ah]	Cell Ampacity [C]	Cell Cost [CAD]	Cells Required		Total Cell Weight [kg]	Total Cell Cost [CAD]
Samsung 30Q	Cylindrical									
Kokam SLPB60216216	Pouch		3.7	25	125					
Kokam SLPB98188216P	Pouch		3.7	30	600					

Cell Selection

Pouch Cell Option

We can simplify the design of battery by running a 72s pack. Under Formula Hybrid Rule EV 2.6.3, no cell fuses are required, which greatly reduces total assembly time and engineering hours for fuse design validation.

Kokam offers a wide range of cells including SLPB60216216 (2021 Battery Cell Datasheet).pdf which has many great characteristics, including a voltage range of 2.7 V - 4.2 V (nominal: 3.7 V) as well as a capacity of 25 Ah.

Under Formula Hybrid 2020 Rules, the maximum pack voltage is 300 Vdc and the maximum segment voltage is 120 Vdc. In addition, maximum segment energy is limited to 6 MJ. As a result, the accumulator consisting of 72 cells in series would have to be separated into 6 segments of 50.4 V and 1260 Wh (4.54 MJ).

- Design Solutions
  - Selected Design and Design Values
  - Alternate Designs
- Solution Test Plan: Setup and Procedure
  - Simulation Test Plan (FEA, CFD)
  - Physical Subsystem Test Plan (HITL, Load Bank, Static Vehicle Testing)
  - Vehicle Testing
- Test Plan Results and Analysis
  - Table of Measured Design Values
  - Description of Analysis Process
  - Discuss Measurement Error and Uncertainty

Cylindrical Cell Options

Conclusions

- Lessons Learned
  - Description of design improvements
  - Description of design disadvantages
- Estimation of project cost and engineering hours

Project Procurement:

Follow the procurement procedure as described in the Operations page Purchase and Reimbursement Procedure and then upload the purchase order spreadsheet to the table below. Consolidate as many purchases into one procurement request to simplify the process.

Generate a Jira task in the appropriate Operations Epic. Label it with *proc_ts* and an (*label specific to this page)* so that it shows up in the table below.

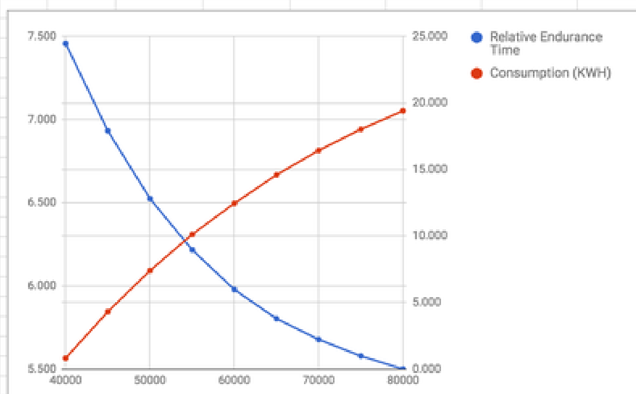
Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Team Member Name	Purchase Order Spreadsheet	Quote / Invoice	Order Description	Company Name	Total Cost [CAD]	Status	Storage Location
						Unknown macro: 'status-handy'	

Cell Selection 2018-2020

Power Limit	Endurance Time	Relative Endurance Time	Consumption (KWH)
40000	1266.6	24.465	5.565
45000	1260.1	17.910	5.844
50000	1254.9	12.805	6.092
55000	1251.1	8.960	6.309
60000	1248.1	5.974	6.496
65000	1245.9	3.784	6.667
70000	1244.4	2.220	6.814
75000	1243.1	0.979	6.942
80000	1242.1	0.000	7.053



Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Briefly describe the project purpose and current state.

- CAD Design Organization: *Describe how the solid models for the project are organized.*

- "*This part improves over last year's component by ____*"
- *"Do not repeat ____ mistake"*
- *"This design fixes ____"*

Explain each feature of the part and how it accomplishes the part's function.

Problem Definition

Rules Compliance

Rule	Status	Notes	Proof of Compliance
A 1.2	Unknown macro: 'status-handy'	**Paraphrase:** For an electric vehicle, the accumulator may have a maximum usable energy of 5.40 kWh, or nominally 6.75 kWh. (Discharge measured at 2C).	The accumulator will be designed to comply and be tested.

Constraints and Criteria

Constraint	Priority	Description	Value	Unit	Validation Method
Current Capability	Unknown macro: 'status-handy'	Each segment must be able to deliver the full rated current of the Tractive System because the segments are in series. By design, this is 135 A RMS. The pack fuse will be 40 A.	135	A	HTHC

Technical Progress

Analysis Validation

Lap Time Simulations

Lap time simulations were conducted and documented using our Matlab simulator and the results of a number of tests were documented in a google sheet. These simulations were conducted to help define different characteristics about the battery pack such as the energy capacity.

Motor Currents

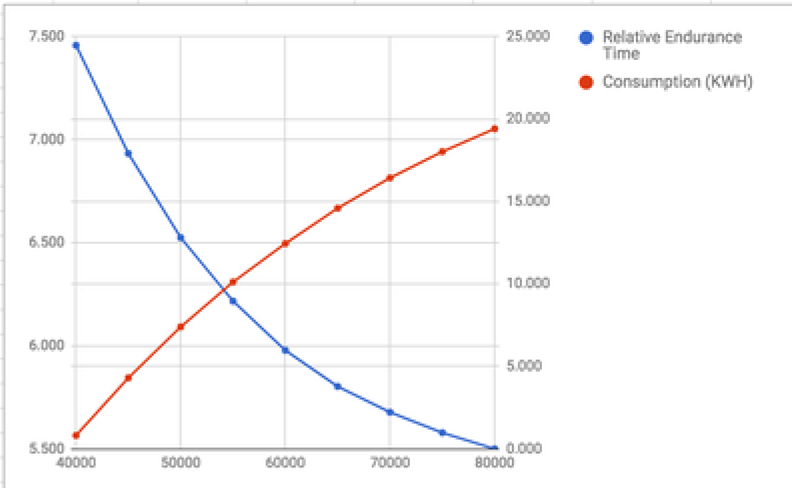
Endurance Inverter RMS Current = 75.6A per inverter 151A total (this value seems unreasonably high)

Endurance Phase Current = 200.26A

Capacity Drop From Power Limit

We ran lap time simulations to determine the effect of changing the power limit to energy capacity requirements of the battery.

Power Limit	Endurance Time	Relative Endurance Time	Consumption (KWH)
40000	1266.6	24.465	5.565
45000	1260.1	17.910	5.844
50000	1254.9	12.805	6.092
55000	1251.1	8.960	6.309
60000	1248.1	5.974	6.496
65000	1245.9	3.784	6.667
70000	1244.4	2.220	6.814
75000	1243.1	0.979	6.942
80000	1242.1	0.000	7.053



From the image you can see that by sacrificing 13 seconds over a 1250 second endurance race (1%), you reduce the energy consumed by 1KWh (14%). This is done by reducing the power limit from 80KW to 50KW throughout endurance

Capacity Mass Drawback

We ran simulations to examine the effect of changing mass as a result of increased energy capacities. Two simulations were run with a sweep of power limit for endurance in order to pick the power limit that used the full capacity of the battery. The first was run with a mass of 320kg and the other with a mass of 330kg. The 10kg difference represents a very conservative estimate for the accumulator mass increase from 6 to 7 KWh.

Mass of 320Kg (6KWh)				
Power Limit	Accel Time	Autocross Time	Endurance Time	Power Drain
40000	3.854	66.956	1266.605	5.565071198
42500	3.854	66.956	1262.994	5.708381626
45000	3.854	66.956	1260.05	5.844396746
47500	3.854	66.956	1257.354	5.972084336
50000	3.854	66.956	1254.945	6.091700303
52500	3.854	66.956	1252.841	6.204537209
55000	3.854	66.956	1251.1	6.309370359
57500	3.854	66.956	1249.549	6.405403031
60000	3.854	66.956	1248.114	6.49575141
62500	3.854	66.956	1246.924	6.583232441
65000	3.854	66.956	1245.924	6.667440891
67500	3.854	66.956	1245.076	6.743496376
70000	3.854	66.956	1244.36	6.814266004
72500	3.854	66.956	1243.682	6.879443762
75000	3.854	66.956	1243.119	6.941647896
77500	3.854	66.956	1242.61	6.999612917
80000	3.854	66.956	1242.14	7.052725278

Mass of 330Kg (7KWh conservative mass increase)				
Power Limit	Accel Time	Autocross Time	Endurance Time	Power Drain
40000	3.902	67.055	1269.608	5.622538821
42500	3.902	67.055	1265.995	5.770105013
45000	3.902	67.055	1262.841	5.909311739
47500	3.902	67.055	1260.05	6.039490048
50000	3.902	67.055	1257.641	6.163990173
52500	3.902	67.055	1255.44	6.282427445
55000	3.902	67.055	1253.527	6.388292578
57500	3.902	67.055	1251.939	6.488298898
60000	3.902	67.055	1250.464	6.582318158
62500	3.902	67.055	1249.198	6.671386963
65000	3.902	67.055	1248.141	6.760153024
67500	3.902	67.055	1247.199	6.839786172
70000	3.902	67.055	1246.426	6.914244376
72500	3.902	67.055	1245.729	6.982556083
75000	3.902	67.055	1245.127	7.047523619
77500	3.902	67.055	1244.581	7.10788906
80000	3.902	67.055	1244.111	7.164965448

From the image, you can extract a time sensitivity result for the 1KWh increase.

Power Limit	Acceleration Time	Autocross Time	Endurance Time	Power Consumed
+35KW	-0.05s	-0.1s	+12s	+1KWh
	0.964	29.882	43.225	

This time sensitivity study can then be compared to some benchmark average sensitivity studies from competition to determine what the expected point deferential is for the tradeoff. This was done using this calculator which has its methodology described here (link no longer in service).

Event	Time Sensitivity	Delta	Predicted Point Shift
Acceleration	0.964	-0.05	-4.95
Autocross	29.882	-0.1	-0.40
Endurance	43.225	+12	69.40
Total			64.05

One thing to consider is that efficiency is based on the amount of energy consumed. With a larger pack, this goes up. There is also a very likely chance that the point sensitivity on efficiency is very large leading to a desired for a smaller pack that results in less energy consumed. Need to investigate this further.

Current Draw

RMS current is found through logging the current draw throughout a lap and taking the root mean square. Simple data from a number of test surrounding current draw in different power limits and re-gen settings are documented in the google sheet liked above.

Re-gen is not done perfectly in the simulation. Rather than characterize weight transfer and what not, we simply assume that a fixed percentage of the braking force is produced by re-gen braking and calculate what the power generation and current generation is that results.

From some studies that @ Former user (Deleted) did in June 2017 (data unfortunately lost) he found that about 15-20% braking could be accomplished from re-gen.

The data contains single endurance laps that start at a speed of 0 at the start line (19 would be performed to complete 22km). Re-gen braking percentages of 0, 5, 10, 15 and 20% are tested at max power to simulate the worst case without consideration of battery capacity.

The data follows the given key:

Acceleration (m/s^2)	data =>, dt = 1ms
Velocity (m/s)	data =>, dt = 1ms
Local Displacement (m)	data =>, dt = 1ms
Global Displacement (m)	data =>, dt = 1ms
Power Draw (W)	data =>, dt = 1ms
Current Draw (A)	data =>, dt = 1ms

Conclusions

The 2017 car uses A123's Lithium Iron Phosphate Prismatic Cells arranged in a 1 parallel 50 series configuration.A123 20 Ah Cells

Parameter	Value	Design Guide	Datasheet
Ampacity	19.6 Ah	See Accumulator Documentation	
Nominal Voltage	3.3 V		
Max Voltage	3.65		
Min Voltage	2.6		
Mass	0.496 kg		
Size	7.25 x 160 x 227 mm		
Energy	65 Wh		

The 2018 - 2019 - 2020 Accumulator uses Electric Power cells- P / N

Electric Power 6.3 Ah Cells, EP8545148HP

Parameter	Value	Datasheet	Invoice	Cell SDS	Cell Safety Infomation
Ampacity / Hour	6.3 Ah				
Nominal Voltage	3.7 V				
Max Voltage	4.2 V				
Mininum Voltage	2.75 V				
Mass	126 g				
Size	148 x 45 x 8.6 mm				
Energy					

Project Procurement

Follow the procurement procedure as described in the Operations page Purchase and Reimbursement Procedure and then upload the purchase order spreadsheet to the table below. Consolidate as many purchases into one procurement request to simplify the process.

Generate a Jira task in the appropriate Operations Epic. Label it with *proc_ts* and an (*label specific to this page)* so that it shows up in the table below.

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Team Member Name	Purchase Order Spreadsheet	Quote / Invoice	Order Description	Company Name	Total Cost [CAD]	Status	Storage Location
						NOT YET PROCESSED	

Accumulator Cell Testing

Project Description

In the past, we have assembled battery packs in a haste and let bad cells get put in the assembly. Battery packs are typically very difficult to work with given the live voltages and so it is best to only have to assemble the pack once. If a pack is built with a bad cell, there is a good chance that under load, the bad cell will have an impedance spike that causes a significant amount of heat buildup. This will likely cause the cell to overheat and catch fire which has a good chance of destroying the whole pack

The purpose of this project is to develop a testing procedure for our cells. By testing every cell, we can ensure that bad cells are discarded prior to assembly. This project includes:

- Designing a test procedure for cycling the cells and establishing thresholds for good and bad cells
  - Intake Voltage Measurement
  - Initial Charge - Discharge Cycle
  - Bounceback Testing ??
  - Cell Spectroscopy and Internal Resistance
  - Thermal Characterization
  - Developing the code to run the test
- Testing all 320 cells

Supporting Information, Project Details

Validation Testing Process

This process was taken from a reddit page talking about why a lot of battery packs were catching fire. It offers a very comprehensive test for validating a battery cell. It seems like it would take a long time to test all 320 cells at the pace suggested in this excerpt. I think we need a better solution, but this can be a start. Detail the process and its justification below.

- Log all the cell serial numbers in a spreadsheet and the supplied voltage
- Take note if they are sequential or not and also look for any marks on the cell tabs like dents from multimeter probes or scratches crocodile clips, this gives an indication if they bothered to try and weed out defective cells.
- For each cell, charge them to maximum voltage, record the voltage, let the cell rest for a few hours then record the voltage again
- Discharge at a lowish C rate like 1-3C taking them to 2.7V, let the cells rest for a few hours, then charge back to 4.2V then log the voltage immediately after taking off the charger then after an hour or so.
- Keep a close watch on cells while charging, this is when a ~~fire~~ thermal event is most likely to occur because the charger current fuels the ~~fire~~ th ermal event .
- The worst cells which are most likely to go up will struggle to come back to 4.2v or will fall back to 4.1V or lower after the charger is disconnected.
- After that check the cells every day or two logging the voltage, any that are loosing charge faster will also be a risk.
- I wouldn't expect to see too many bad cells and the good news is the cells that hold the charge will not spontaneously combust at a later date. Lastly be really gentle with the pouches, avoid directly handling the cells as much as possible the grip of a hand can compess the cell.

Small Scale Cell Tester

Old Shunt - ?? W, 0.120 - Value pack of three resistors

Shunt - 50W, 0.02002

Current [A]	Voltage [mV]	Resistance []
0.500	10.001	0.02002
2.000	40.006	0.02003
4.000	80.15	0.020375
6.000	120.28	0.02047
Overall		0.0204

Op-Amp Inverting Input changed to 3.9 k - combo of 20k and 5.1k

Capacity Measurement

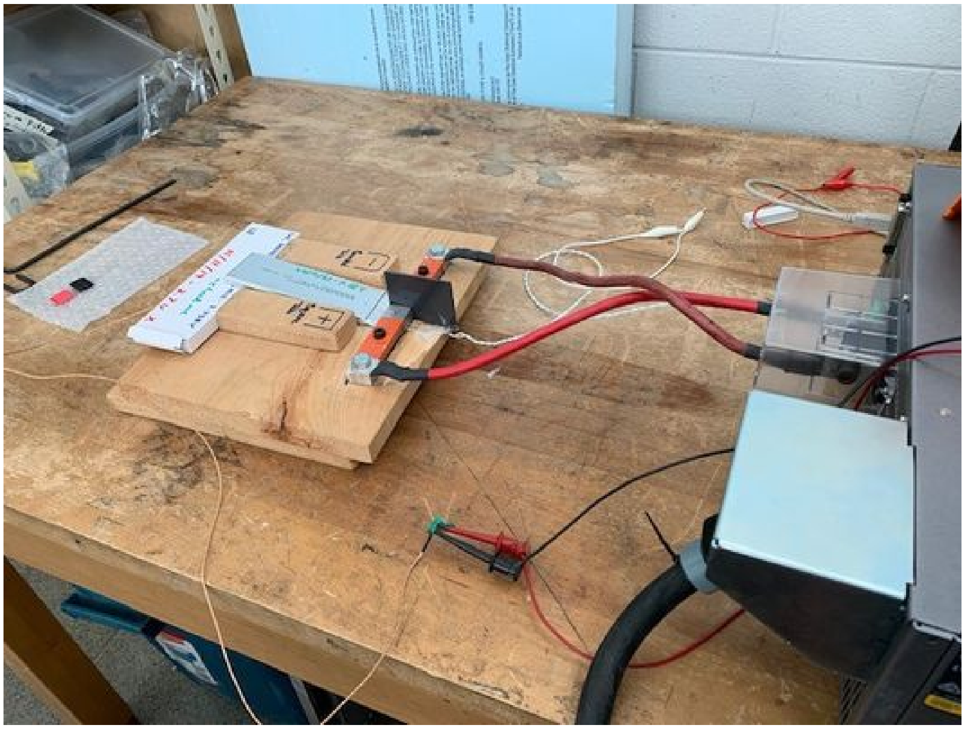
DC Internal Resistance Test

Cell Testing and Lifetime Characteristics

2012 NASA Presentation on OCV and Pouch Corrosion: NasaPouchCorrosion.pdf

Pouch corrosion caused the failure of several cells in the 2019 accumulator

Cell Testing 2018-2020



Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Summary

The purpose of this project is to develop a testing procedure for our cells. By testing every cell, we can ensure that bad cells are discarded prior to assembly.

CAD Information

- CAD Design Organization: *Describe how the solid models for the project are organized.*

Design Philosophy

- Testing carried out on the 2018 Electric Power Cells was much more rigorous than testing in previous years, involving cell testing and matching.
- Matlab scripts and test equipment connected over VISA greatly improve the speed and reliability of testing by automating the bulk of data collection.
- Testing and matching cells improves the reliability of the accumulator, making it safer and higher performing. Matching cells inside their parallel groups also extends the life of the battery pack so that some cells are not excessively worn.

Problem Definition

Rules Compliance

Rule	Status	Notes	Proof of Compliance
A 1.2	Unknown macro: 'status-handy'	**Paraphrase:** For an electric vehicle, the accumulator may have a maximum usable energy of 5.40 kWh, or nominally 6.75 kWh. (Discharge measured at 2C).	The accumulator will be designed to comply and be tested.

Constraints and Criteria

Constraint	Priority	Description	Value	Unit	Validation Method
Current		Each segment must be able to deliver the full rated current of the Tractive System because the segments are in series. By	135	A	HTHC

Capability	Unknown macro: 'status-handy'	design, this is 135 A RMS. The pack fuse will be 40 A.			

Technical Progress

Cell Testing Requirements

- Test Circuit must clamp onto the positive and negative battery tab
- Clamps must connect to a wire that can handle the current requirement of the tests. Use 8 gauge wire, make sure you consider the hole size of a lug that would be crimped to the end of the wire. This lug would be bolted to the clamping assembly
- Hold the cell in a repeatable position
- Don't damage the cell tab or the cell- must have guarding to protect the cell against dropped tools or mis-clamping
- The fixture should be designed for cleaning- it must be easy to make sure the fixture is completely free of swarf or debris.
- Easy to operate

Design Analysis and Manufacturing Design

Electric Power 6.3 Ah Cell Testing

Testing carried out by Nerissa Wong

Cell Testing: First Batch

10 cells received at beginning of November

All 10 cells received at 3.80 V

Testing Plan:

1. Charge cells
2. (1 cell) Cell Testing Procedure
3. Thermal validation (4 cells in parallel)
4. Fuse test (maybe not)

Cell Testing: Full Pack Test, Inventory, and Match

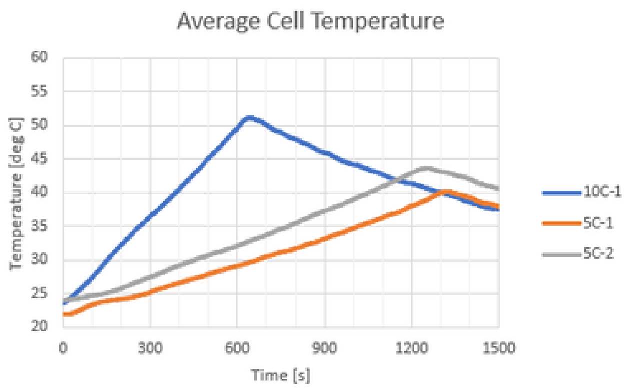
Here are the results from testing several different cells. As well as the voltage measurements from all five boxes.

Box 1				Box 4			Comments
	Cell Number	Voltage (V)			Cell Number	Voltage (V)	
1	Cell_30649	3.8		1	Cell_31001	3.8	
2	Cell_30184	3.8		2	Cell_31026	3.8	
3	Cell_30802	3.8		3	Cell_30808	3.8	
4	Cell_30532	3.8		4	Cell_30735	3.8	
5	Cell_30359	3.8		5	Cell_30456	3.79	
6	Cell_30435	3.8		6	Cell_30676	3.79	
7	Cell_30996	3.8		7	Cell_30967	3.8	
8	Cell_30506	3.81		8	Cell_31256	3.8	
9	Cell_30960	3.8		9	Cell_30870	3.8	
10	Cell_30127	3.8		10	Cell_30214	3.8	
Box 2				Box 5			
	Cell Number	Voltage (V)			Cell Number	Voltage (V)	Comments
1	Cell_30726	3.8		1	Cell_30941	3.8	
2	Cell_30324	3.8		2	Cell_30911	3.7	* Has two square tabs
3	Cell_30711	3.8		3	Cell_31092	3.8	
4	Cell_30143	3.8		4	Cell_30018	3.8	
5	Cell_30074	3.79		5	Cell_31212	3.8	
6	Cell_30906	3.8		6	Cell_31136	3.8	

7	Cell_30096	3.8		7	Cell_30823	3.8	
8	Cell_30674	3.8		8	Cell_31312	3.8	
9	Cell_30714	3.8		9	Cell_31158	3.8	
10	Cell_30376	3.8		10	Cell_31200	3.79	
Box 3							
	Cell Number	Voltage (V)					
1	Cell_30582	3.8					
2	Cell_31247	3.8					
3	Cell_31037	3.8					
4	Cell_30329	3.8					
5	Cell_31010	3.8					
6	Cell_30724	3.8					
7	Cell_30392	3.8					
8	Cell_31105	3.79					
9	Cell_31087	3.8					
10	Cell_30147	3.8					

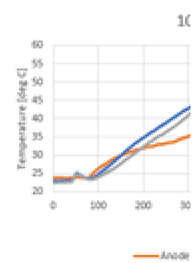
A load bank with a constant current mode controlled by a connected power supply was used to load the EP8545148HP cells at the 10C and 5C rates. The data was logged to Matlab and inserted into Excel for analysis. The results are shown below, and the raw data is available here: Cell testing 2017-12-05.xlsx. Raw voltage and current vs. time data is available here: TenC_1_data.txt, FiveC_2_data.txt, FiveC_1_data.txt

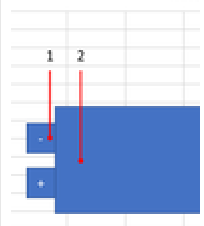
Testing Summary



	T_start	T_end	ΔT	Δt
Trial	deg C	deg C	deg C	s
10C-1	24	51	28	630
5C-1	22	40	18	1300
5C-2	24	44	20	1250

Discharge Test: 10C





This testing showed that the cells could be discharged in free air at the 10C rate, but further investigation is needed to find if the cells can discharge at the 15C rate, as stated on the datasheet.

Manufacturing and Implementation

Lithium Ion Polymer Cell Grading and Testing: Naming Convention

Each white box containing a cell from Electric Power must bear the following information:

- The cell ID number
- The date of testing
- The measured OCV after testing
- A letter / number grade
- General Notes

Cell Matching

- Impedance Spectroscopy was conducted to measure cell impedance: https://wiki.uwaterloo.ca/display/FEAM/Cell+Testing+Procedure
- From there, cells were matched into groups of 4 based on this impedance, since internal resistance is proportional to thermal energy produced by the cell
- Cells were assembled into a segment by taking the highest impedance groups and the lowest impedance groups. For instance, segment 1 has groups 2, 73, 3, 72, 4, 71, 5, 70, 6, 69, 7, 68.
- The idea is that the cells are matched to minimize thermal energy generated by distributing it across the entire segment. For example, the low thermal energy of segment 2 will offset the higher thermal energy of segment 73
- After, matching by impedance, all cell voltages were measured. Before combining cells in parallel, the voltage levels must be within a 10 mV range of each other to prevent high current running through the cells. The current can be calculated using Ohm's Law, where the resistance is the combined total resistance of the cells in parallel.
- If cells were out of the 10 mV range, the cells with the lower voltage were charged using a power supply to the required voltage level.
- See this spreadsheet from Summer 2018 for all cell groupings and measurements: Cell-Voltage-Testing.xlsx

Bulk testing was planned using these fixtures:

Conclusions

Lessons Learned:

The test fixture was not professionally manufactured- wood test fixtures have the possibility to splinter and damage cells and collect metallic swarf, risking damage to the sensitive pouch cells. The test fixture also did not properly support the cell- it didn't have a "shelf" for the cell tabs, so the cell had to be propped up with a marker. In addition to this, it would be helpful to have a polycarbonate shield to avoid accidental damage to the cell from a flying tool or part.

Component Attribute	Manufacturable?	Works as Intended?	Notes
Wooden Test Fixture	Yes	Somewhat, but room for improvement	Test Fixture should support cell more, should be made from plastic to avoid splinters.
Test Fixture Current Path	Yes	Yes, needs an inline fuse	Test fixture should also have fusing on sense wires, which are typically 24 ga stranded wire.
Instrumentation	Available	Yes, VISA + Matlab is a great combination	The team should maintain a repository of Matlab scripts and best practices.
Test Source and Sink	Available	Cell testing in volume is difficult without higher power sources and sinks - 1.5 kW or more, ideally	It's tough to buy a high power unit, but Keysight is very happy to work with SDC teams.

Project Procurement:

Follow the procurement procedure as described in the Operations page Purchase and Reimbursement Procedure and then upload the purchase order spreadsheet to the table below. Consolidate as many purchases into one procurement request to simplify the process.

Generate a Jira task in the appropriate Operations Epic. Label it with *proc_ts* and an (*label specific to this page)* so that it shows up in the table below.

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Team Member Name	Purchase Order Spreadsheet	Quote / Invoice	Order Description	Company Name	Total Cost [CAD]	Status	Storage Location
						NOT YET PROCESSED	

Accumulator Cell: State of Health Testing:

20-5-ACC-CellSOH

WBS Title: Cell Testing

WBS Number: 1.2.1.2.2

Project Timeline:

Describe tasks and use the correct tags to show the state of the project.

Unknown macro: 'status-handy'

- Cell Leakage (Long-term Charge Retention)
- Cell Capacity
- DC Internal Resistance Testing

Responsibility Cascade:

- @ Calvin Ryan DeKoter
  - *@ jlmorabi@uwaterloo.ca*

Design Philosophy:

- To determine the state of health of the spare cells Electric Power cells we currently have. If determined healthy, the cells will be assembled back into the damaged cell segments.

Test 1: Cell Leakage (Long-term Charge Retention)

Description: This test simulates a cell's ability to retain its charge over long periods of time

Test Method: Measure open circuit voltage (OCV) of cell with a precise multimeter (provided by Keysight). Compare this to previous OCV measured from last term.

Evaluation: Acceptable decline is less than 0.1 V

Test 2: Cell Capacity

Description: This test measures the amount of energy stored in the cell.

Test Method: DC Power Supply + DC Electronic Load Bank + Data Acquisition Unit

1. Charge the cell to its maximum voltage: Using DC power supply, set a constant current of 1C (current that the cell can flow for one hour), set the maximum voltage (4.2 V for EP8545148HP), connect the cell's positive terminal to positive supply lead and the cell's negative terminal to the negative supply lead, then, turn on output on the supply.

2. Discharge to its cut-off voltage: Connect the cell to a DC electronic load bank and a precise current measurement device that logs current vs time. On the load bank, set the minimum voltage (2.75V for EP8545148HP) and set a constant current discharge. **Critical! Do NOT let the cell drop below cut-off voltage (2.75V)!**

3. Log the constant current discharge vs time and integrate to find the capacity in Ampere-Seconds (As). Divide this number by 3600 to get the SI unit of Ampere-hours (Ah). Sample the current every three seconds or less to maintain accuracy.

4. Charge the cell to its nominal voltage (3.8 V for EP8545148HP) for safe storage.

Evaluation: Compare measured capacity to minimum capacity rating on datasheet: EP8545148HP Cell Datasheet.pdf. Lower capacities below the minimum rating indicate that the cell is chemically faulty and will not perform as expected.

Test 3: DC Internal Resistance

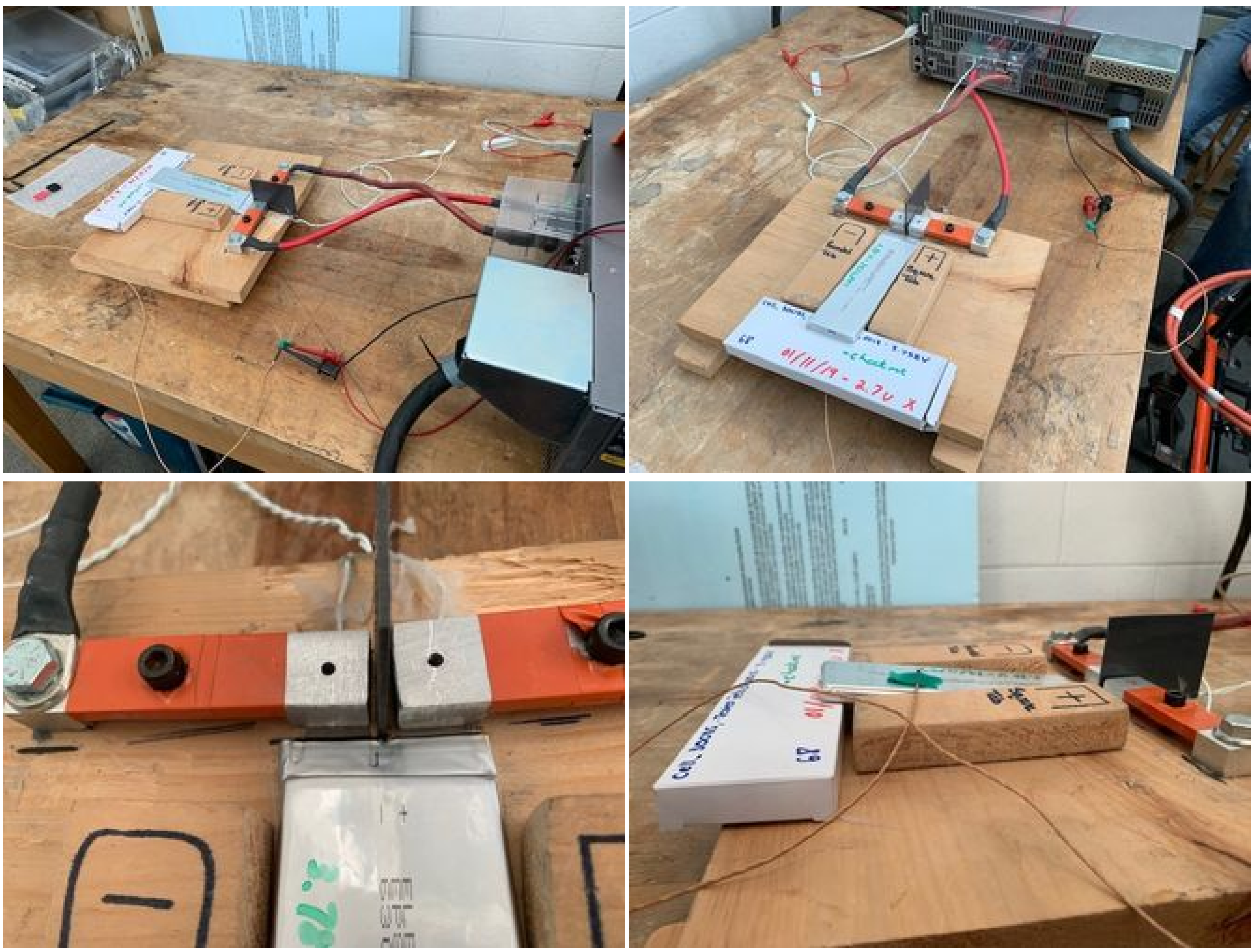
Description: This test measures DC internal resistance (NOTE: This is not the same as impedance spectroscopy). Internal resistance is a measure of the inherent DC resistance of a cell which is flowing current.

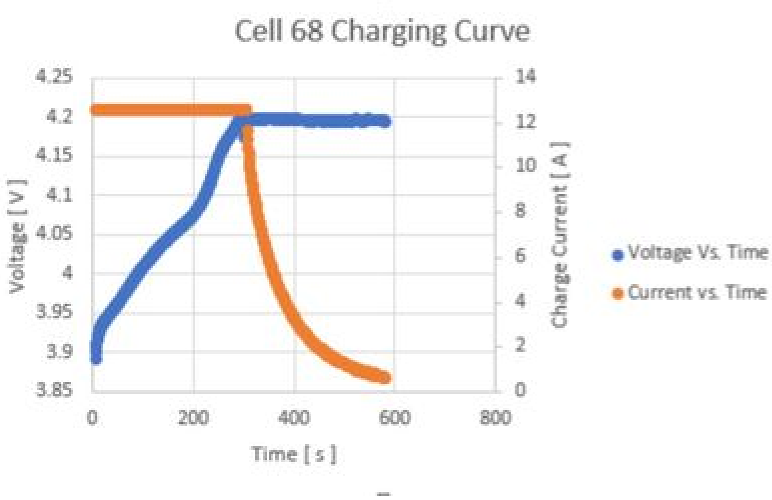
Test Method: Connect the cell to a high precision multimeter and a DC electronic load that can quickly ramp up and down the current flowing from the battery. Draw a current from the battery, and compare the closed circuit voltage to the open circuit voltage. This change in voltage is due to the internal resistance of the cell, By applying Ohm's Law, we can calculate the simple DC Internal Resistance of the cell. For the EP8545148HP cells, a suitable value is less than 6 ms.

EP85_DCIR.m - obsolete (as we don't have the rp7952a anymore) DCIR test script. A bit of a dumpster fire of coding practices, but works great for simple DCIR. Note that the average shouldn't ever include the first few points taken during the test. Message @ Calvin Ryan DeKoter for help with Matlab scripting

EP85_DCIR.m.txt - text version, hopefully is viewable in the browser

Pictures of Test Set-up 2





Lessons Learned:

To effectively program the BenchVue software, don't output the "CH1 Voltage Measurement". This will get written into a different column in the Excel sheet. Instead, write to a common variable called "Current" or "Time". Use the "Set" command to achieve this.

The cells must be allowed to "rest" between charging and discharging, Diffusion occurs after charging and after discharging, which will have a massive effect on the cell OCV and capacity. The cell datasheet requires 30 minutes rest between charging to 4.2V, 315 mA cutoff and discharge.

Test Scripting- Automate your Battery Testing!

Benchview script to run Test 2 and Test 3: Cell Capacity- EP85_Capacity_DCIR.bvseq. This BenchVue script discharges a fully charged cell while integrating the current over time to solve for the overall cell capacity. The file linked in this page is non-functional.

So far, the "delay" command is not at all accurate. If your computer 'hangs' at all during the script, that delay will be added into the loop period. Using TDelta = T2 - T1 allows accurate current integration over time. To achieve higher accuracy, TDelta should encompass all steps in the loop, as each step takes some time (up to half a second in a worse case). The first measurement of cell capacity understated the capacity because of this.

BenchVue is a fine program for small, simple, non-time-critical scripts, but is not fast enough for integration of current for capacity testing.

A better way to interface with the supply is to use MatLab's instrument control panel, in the Apps folder. This tool has both a command line interface, where the user can set up direct connections to the supply and send individual commands, and a toolbox full of commands to run a script of SCPI commands. Matlab is relatively easy to use and understand, so it is a good fit for our situation. PYVISA uses the same protocols in a Python environment to complete the same tasks.

Since the Keysight RP7952a is a high voltage supply, it has a relatively high internal resistance of 0.2 . This means that the maximum current that can be drawn from a single cell over a full charge-discharge cycle is about 12 A.

Cell Test Step	Charge:		
Program Name			
Notes			

Test Results: EP8545148HP Cell Testing and Grading

All Cell Data and Results stored in this folder: Tractive System Members Added: Message Calvin DeKoter for access

After all testing was completed, the testing results were compiled in the table below. Pay special attention to the "Notes" column.

Data from the DC IR test is an average of the resistances from the later half of the test. Check out some of the plots to see why this is.

*****This table will be re-sorted in Excel after all testing is complete*****

Cell	Cell	Cell	OCV [V]	Charg	Discharge	Capac	Internal	Notes

Type	Num ber	Name	(25/11/28)	e Finish	Start	ity [Ah]	Resistance [m]	
EP85451 48HP	30085	Cell 68	3.788					This cell was discharged to 2.66V, but holds charge well. More testing done on this cell than others.
EP85451 48HP	30717		3.790					This cell has been shorted (see marks on tabs).
EP85451 48HP	30248		3.795	4:25	4:55	6.4135	0.0042573	
	31748		3.851			6.0654	0.0054	
	30200		3.7072	2:50	3:50	6.4573	0.0039589	Cell charged to 4.20 V, settled to 4.25V over about an hour- cell left to sit for 60 minutes before test
	30511		4.0368			6.0844	0.0051749	
	30141		3.723					Cell discharged to 2.66 V during tests
	30276		3.9767			6.1065	0.0045	Cell held at 4.0 V for a long time, several tries taken at the DCIR Test due to code issues
	31291		3.77					
	30332		3.7928					
	30846		3.781					
	30978	Group 1	3.7407	2:45	3:15	6.4234	0.003963	
	31219		3.7955	3:50	4:30	6.4537	0.0040154	
	31263		3.784					
	31138		3.7836					
	30675		3.784					
	31215		3.747					
	30562		3.7486					
	30104		3.7472					
	30359		3.7489					
	30735		3.7387					
	30039		3.7380					

2020-02-15- Cell Bulge Testing

The point of this test is to determine cell temperature rise and expansion when placed under the nominal competition load.

The high current test circuit is used to flow 5C from the cell for 12 minutes (by definition) and 16C from the cell for 10 seconds- peak load.

Cell Thickness- 10s 16C Pulse Test- subract the fixture thickness- Cell # 30511

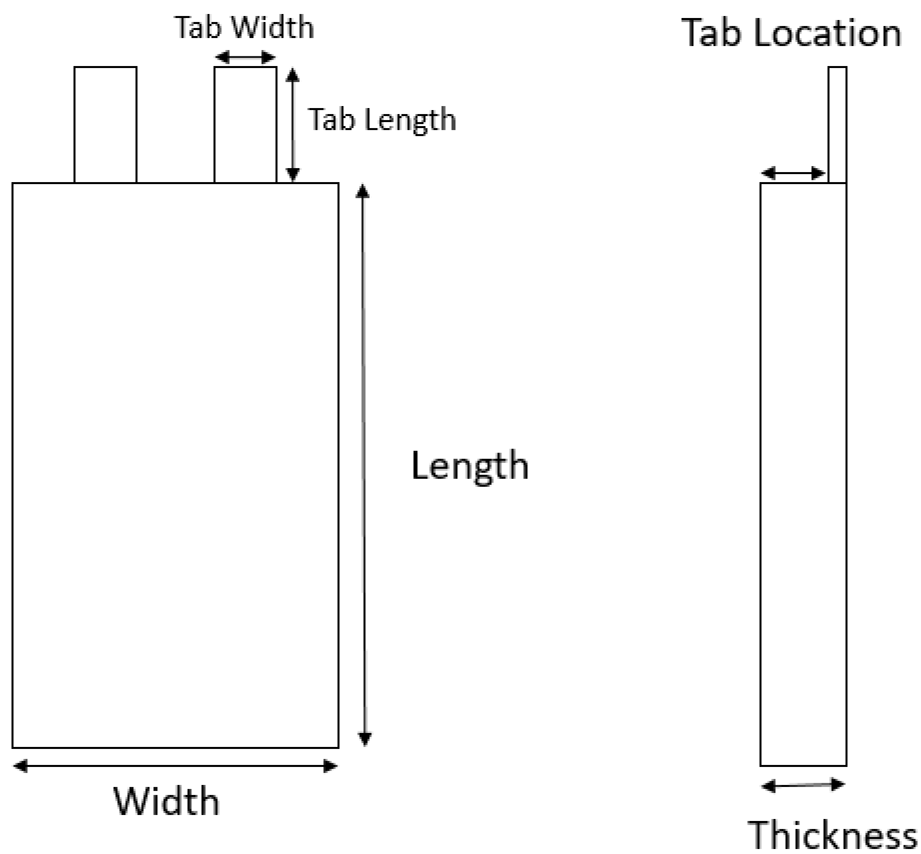
Cell Start Voltage: 3.7815, Cell End Voltage: - screwup, currently recharging

Position	Initial	Final
Tab End Point 3	6.78	
Middle Point 2	6.63	
Pouch End Point 1	6.55	

Electric Power Cell Dimensions:

Cell Dimensions						
	Length(cm)	Width(cm)	Thickness(cm)	Tab Length(cm)	Tab Width(cm)	Tab Location(mm)
1	14.91	4.45	0.89	1.58	1.41	4.08
2	14.96	4.48	0.87	1.62	1.49	4.38
3	15.02	4.44	0.86	1.39	1.51	5.30

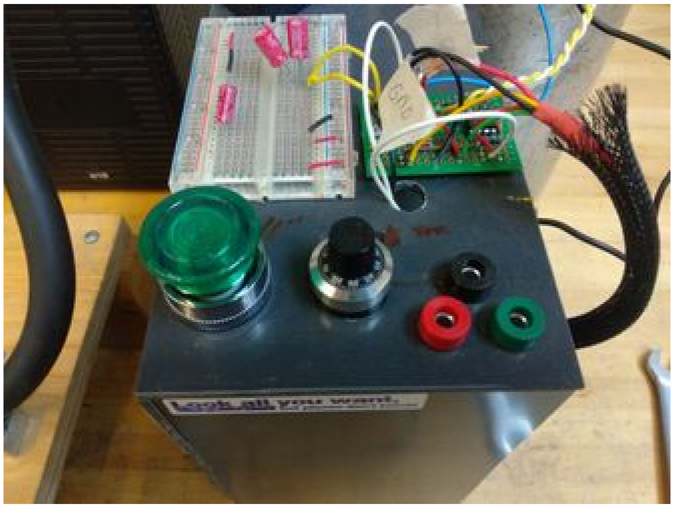
4	14.89	4.46	0.87	1.52	1.49	5.38
5	15.01	4.42	0.88	1.53	1.50	5.15
6	14.93	4.47	0.85	1.62	1.50	4.41
7	14.90	4.50	0.89	1.61	1.50	4.59
8	14.81	4.44	0.89	1.69	1.51	4.93
9	14.91	4.40	0.90	1.70	1.50	4.67
10	14.93	4.46	0.88	1.62	1.49	4.60
Mean	14.93 ± 0.1cm	4.45 ± 0.05cm	0.88 ± 0.03cm	1.59 ± 0.2cm	1.49 ± 0.08cm	4.75 ± 0.7mm

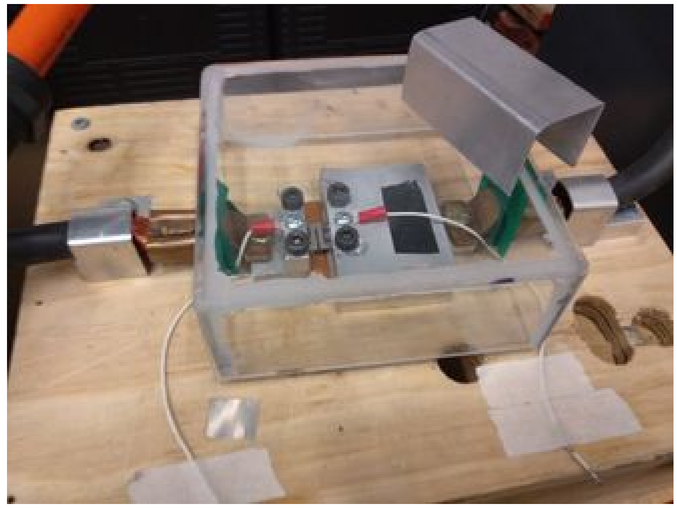


High Current Test Circuit:

Test setup:

HCTC Control Panel	HCTC Fuse Testing Fixture





Specs:

Config	**6V**	**12V**
max current	500A	• 600A Burst (<50ms) • 200A for 10s • 50A continuous (monitor temps using thermocouple in heatsink cylinder - Stop around 50 Celsius)
Battery Ampacity	280 Ah ?	85 Ah ?

Instructions:

Connect the HCTC according to the instructions below. It doesn't matter which cables you use, as long as you fundamentally understand cable ratings, heat rejection, and safe working practices for high current applications.

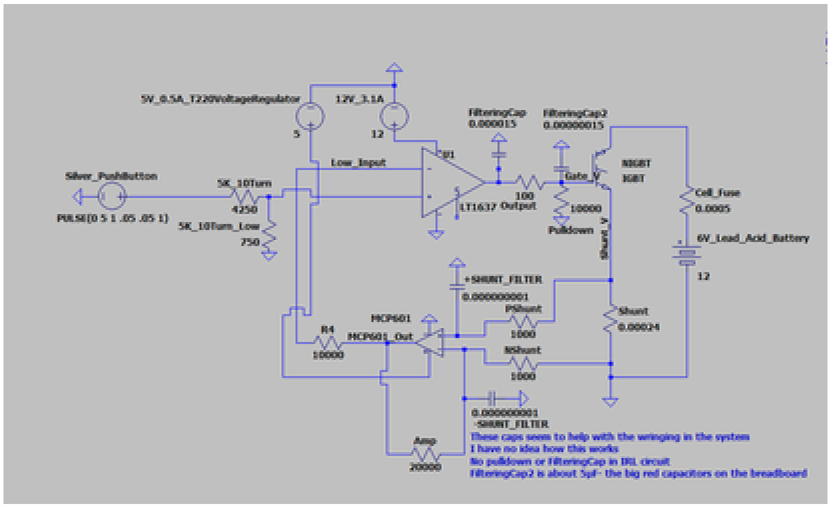
Remove all rings, jewelry, chains, and conductive items from yourself and the table near the HCTC. Work from Negative (Earth Ground Referenced by the Oscilloscope)

- Identify the most positive terminal of the power source- a lead acid battery or a LiPo battery.
- Identify the most negative terminal of the power source and connect it to the brass shunt with a wire of size 4 AWG or lower. **Be very careful to not move the shunt relative to the IGBT- it is very fragile.**
- Confirm that the shunt is connected to the IGBT Emitter. (This will be in the correct configuration, don't change it.)
- Confirm that the copper busbar is connected to the IGBT Collector (This will be in the correct configuration, don't change it.)
- Confirm that the copper busbar is connected to the low side (marked with a "2") of the Gigavac contactor. (@ jlmorabi@uwaterloo.ca please confirm)
- Connect the positive high current cable to the high side of the Gigavac contactor.
- Carefully connect the positive high current cable to the positive pole of the battery. The circuit is now live- confirm that all conductive items are away from the circuit.

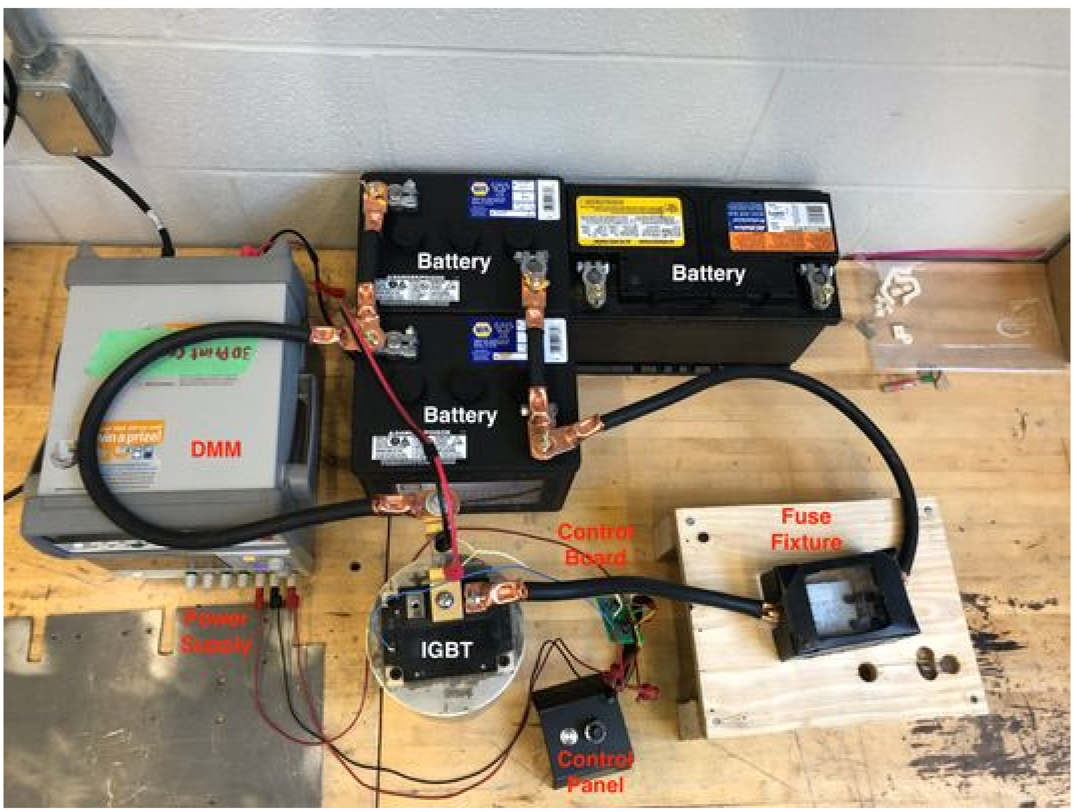
Circuit Functionality Tests

- Connect the power supply to the red banana jack with 12V, 3.1A supply voltage. Connect the power supply ground to the black banana jack. Leave the green banana jack empty.
- Measure the continuity across the contactor. It should be open. Push the green button and confirm that the contactor closes.
- Measure the voltage between the circuit ground (shunt negative side) and the blue gate wire on the IGBT. It should be zero.
- Confirm that the contactor is open, then push the silver button to run the IGBT. No current is flowing, so the IGBT is driven closed. The gate voltage should be 12V.
- Confirm the position of the potentiometer at 0 - 50
- If required, connect an oscilloscope probe across the shunt and make a current trace- 20 mV / div, 50 ms / div timescale, 20 mV rising edge trigger, 1 div time trigger from the left edge.
- Confirm that the circuit functions as expected- it should only flow current when both the contactor button and the silver button is pushed. **Never** make or break current flow with the contactor- it's not rated for that.

Cell_Fuse_Tester_R.asc



Test setup:

Specs:

Config	**6V**	**12V**

max current	500A	TBD 1000A?
Battery Ampacity	280 Ah ?	85 Ah ?

Instructions:

Connect the HCTC according to the instructions below. It doesn't matter which cables you use, as long as you fundamentally understand cable ratings, heat rejection, and safe working practices for high current applications.

Remove all rings, jewelry, chains, and conductive items from yourself and the table near the HCTC. Work from Negative (Earth Ground Referenced by the Oscilloscope)

- Identify the most positive terminal of the power source- a lead acid battery or a LiPo battery.
- Identify the most negative terminal of the power source and connect it to the brass shunt with a wire of size 4 AWG or lower. **Be very careful to not move the shunt relative to the IGBT- it is very fragile.**
- Confirm that the shunt is connected to the IGBT Emitter. (This will be in the correct configuration, don't change it.)
- Confirm that the copper busbar is connected to the IGBT Collector (This will be in the correct configuration, don't change it.)
- Confirm that the copper busbar is connected to the low side (marked with a "2") of the Gigavac contactor. (@ jlmorabi@uwaterloo.ca please confirm)
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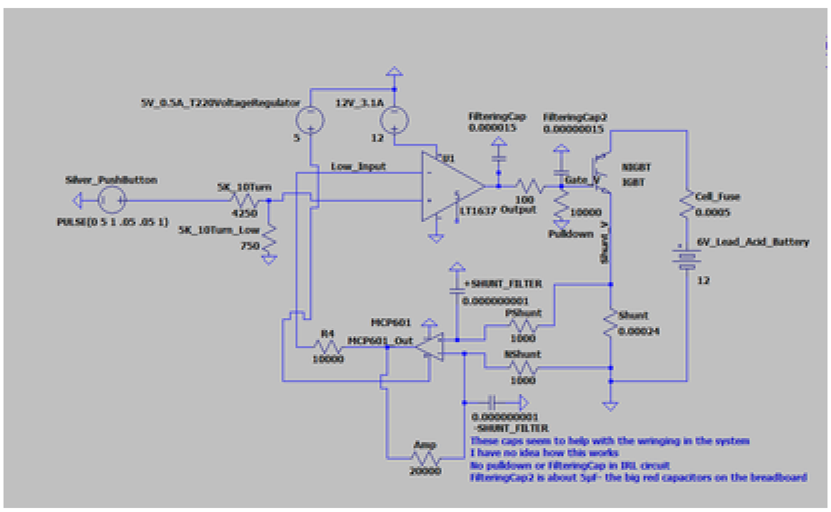
- If required, connect an oscilloscope probe across the shunt and make a current trace- 20 mV / div, 50 ms / div timescale, 20 mV rising edge trigger, 1 div time trigger from the left edge.
- Confirm that the circuit functions as expected- it should only flow current when both the contactor button and the silver button is pushed. **Never** make or break current flow with the contactor- it's not rated for that.

Cell_Fuse_Tester_R.asc



Cell Testing Procedure:

Requirements:

- Laptop with at least 3 USB ports
- MATLAB installed with NI-VISA
- Latest Script made by @ Former user (Deleted)
- All files related to cell testing located in a folder.
- Two people must be working on Cell testing at all times.

Setup Procedure:

- Proper safety precautions (Sand buckets and fire extinguisher)
- Record data collected to excel table shared on google docs.

Safe Cell Handling:

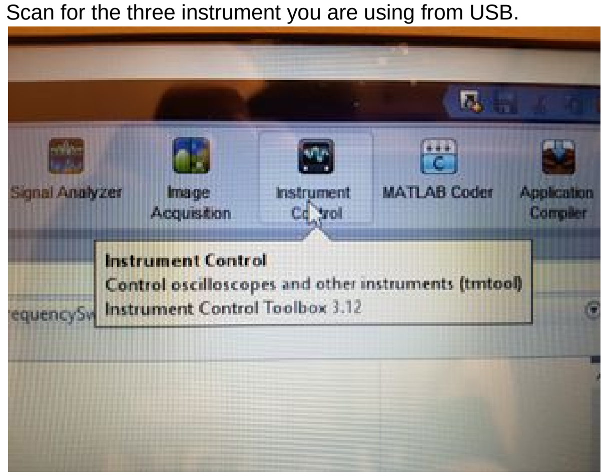
- Avoid placing cells on any rough surfaces where there is a risk of puncturing the cell.
- Do not connect the cell tabs together under any circumstance.
- If the cell catches on fire, place it on one bucket of sand, and bury it with the other,
- Do not bend or distort the cell tabs.
- Only items relevant to cell testing should be on the table.
- Make sure nothing on the table can short the cell.

Before Leaving:

- Make sure no cells are left outside.
- Turn off all devices and unplug them.
- Clean up table of any extraneous items.
- Take key with you when you leave.

1. Plug in all devices, turn them on manually, and connect each device to your laptop using their USB cables.

2. On MATLAB click "Instrument Control" located under APPS. Scan for the three instrument you are using from USB.

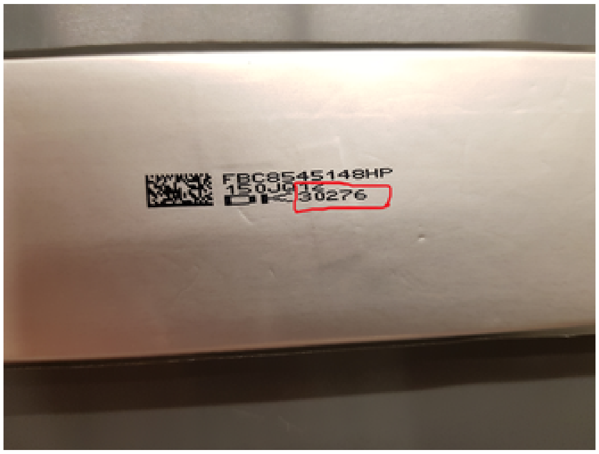


3. Name the batteryPartNumber as "Cell_Test", and run a script. You should get an error message saying voltage is too low. This is to check if the script is able to run. Do not have a battery in the testing bed for this check!

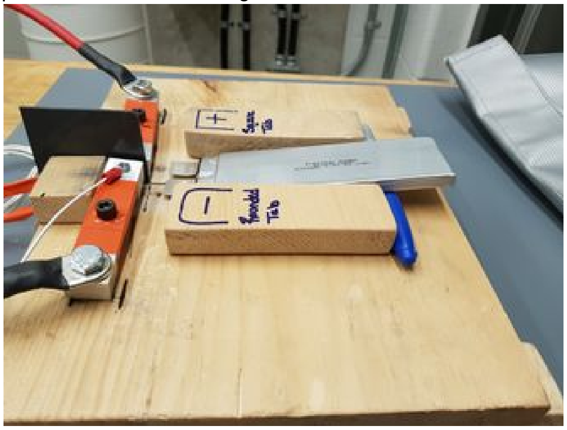
Cell Testing Procedure:

1. Grab a cell that has not yet been tested, remove it from its packaging.

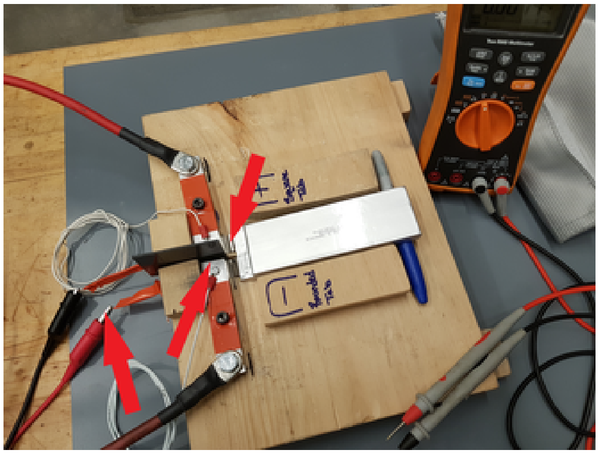
2. Change batteryPartNumber to "Cell_#####", the numbers will correspond to the 5 digit code written on the back face of the cell as shown.



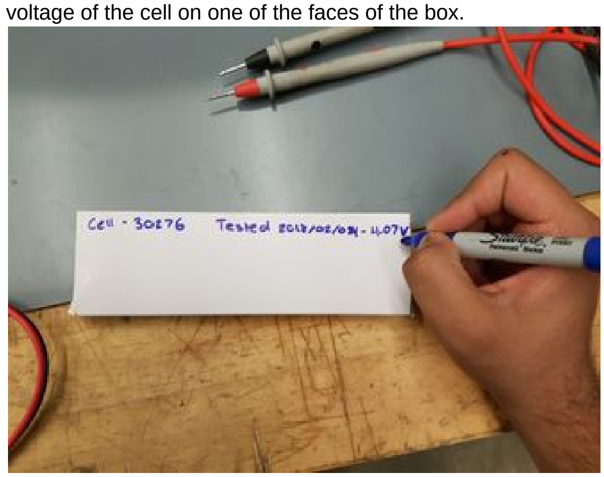
3. Place the cell on the table setup, use the visual aid on the blocks to help make sure that the cell is facing the right way.
   a. Warning 1: placing a cell in backwards (cell tabs reversed) can result in damage to the cell and the equipment. Be very careful to install in the right orientation.
   b. Warning 2: Avoid deforming the cell tabs or cell pouch. Deformation to any part of the cell can result in permanent internal damage.



4. Loosen the metal bars of the table such that the cell tabs can fit under them, if necessary, use a sharpie on the back end of the cell tab to angle the cell tabs for a better fit.
5. Tighten the bars, avoid deforming the tabs, but make sure there is a stable connection between the tabs and the copper wires underneath.



6. Check the voltage of the cells using a multi-meter on the tabs, on top of the metal bars, and by the alligator clips connected to the copper wires (they should all be roughly the same). Record the voltage you read from the cell tabs.
7. Begin running the test, check the power supply and make sure the current is around 10 Amps. When the test is finished, make sure the data is saved in the same file as other cell testing related files.
8. Find the voltage of the cell after the test and record it. If the cell voltage has dropped below 3 volts, it should be recharged before storage to prevent degradation. An SOC of approximately 40% is recommended for storage.
9. Loosen the bars and remove the cell, place it back into it's pack with the black rubber tab and bubble wrap.

10. Write down the cell number, "Tested", date tested, and final voltage of the cell on one of the faces of the box.


11. Place the cell on a shelf and repeat each step for a new cell.

Cell Testing Resources

A technique for measuring internal resistance:

https://www.tek.com/blog/measuring-battery-internal-resistance-easy

The following notes are from the page "Accumulator Meeting 2018-10-10"

- Ciara
  - 12 cells in series - not a great idea (Alex) because you have to monitor when you are charging it, discharging it, and how it recovers from a spike
    - If it takes a while to recover compared to the others, it’s probably a bad cells

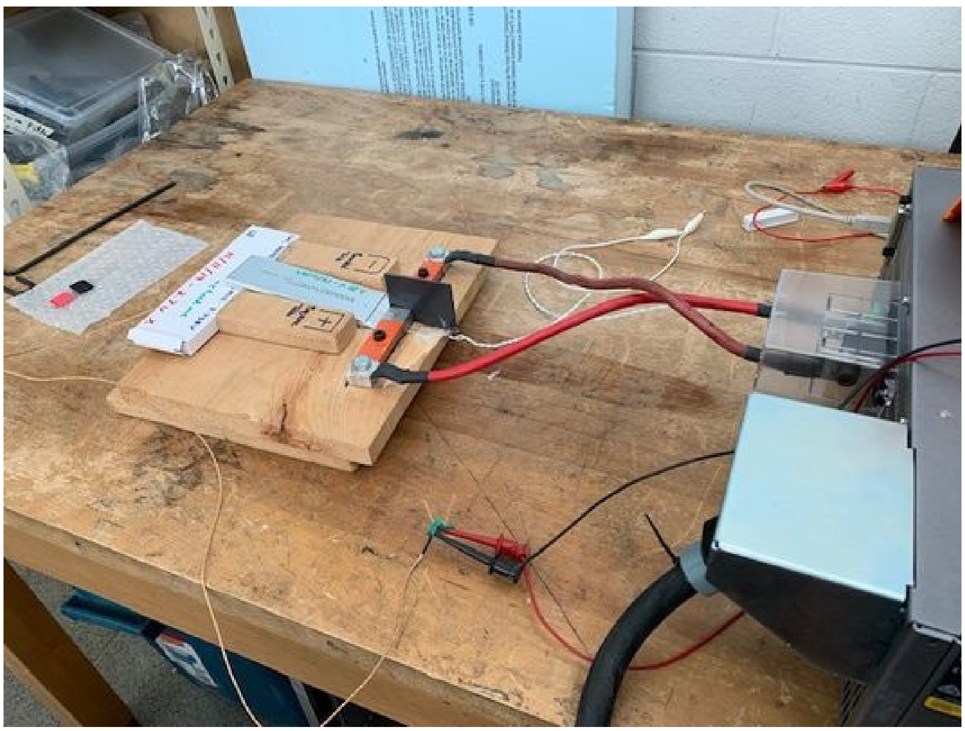
    - We can discharge and monitor 12, but then how do we charge them?
    - 12 cells in series is more voltage than what we have - we don't have a HV supply
  - We can cut down time by doing 5C charge, 5C discharge - 30 minutes per cell
  - 6.3 Ah
  - We need to find power supplies!!
  - Keep working on making this plan solidified - we get cells in 10 calendar days!

The following notes are from the page "Accumulator Meeting 2018-10-18"

- Testing - immediate - 10 cells next week (Ciara)
- Fuse test - Ciara work with Bondo + Rishab
  - Ciara check voltage and current of the power supply
  - 1 kW load - verify the load is this
  - blow one up to see if the cell tabs can act as fuse
- Thermal characterization - Ciara work with Nerissa
  - Nerissa can get thermal camera for next week, the week after if not
- Cooling validation- Ciara work with Nerissa
  - Tab bus bar cooling

2016-2017 Cell Testing

Please see this powerpoint- cellcoolingresults.pdf



  - Summary
  - CAD Information
  - Design Philosophy
  - Problem Definition
  - Rules Compliance
  - Constraints and Criteria
  - Technical Progress
  - Cell Testing Requirements
  - Design Analysis and Manufacturing Design
  - Electric Power 6.3 Ah Cell Testing

Cell Testing: First Batch
Cell Testing: Full Pack Test, Inventory, and Match

- Manufacturing and Implementation
- Lithium Ion Polymer Cell Grading and Testing: Naming Convention
- Cell Matching
  - Lessons Learned:
- Project Procurement:
- Accumulator Cell: State of Health Testing:
- Project Timeline:
- Responsibility Cascade:
- Design Philosophy:
  - Pictures of Test Set-up 2
  - Lessons Learned:
  - Test Scripting- Automate your Battery Testing!
- Test Results: EP8545148HP Cell Testing and Grading
- 2020-02-15- Cell Bulge Testing
- Electric Power Cell Dimensions:
- High Current Test Circuit:
- Instructions:
- Instructions:
- Cell Testing Procedure:

Cell Testing Resources

- 2016-2017 Cell Testing
- Summary
- CAD Information
- Design Philosophy
- Problem Definition

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Summary

The purpose of this project is to develop a testing procedure for our cells. By testing every cell, we can ensure that bad cells are discarded prior to assembly.

CAD Information

- CAD Design Organization: *Describe how the solid models for the project are organized.*

Design Philosophy

- Testing carried out on the 2018 Electric Power Cells was much more rigorous than testing in previous years, involving cell testing and matching.
- Matlab scripts and test equipment connected over VISA greatly improve the speed and reliability of testing by automating the bulk of data collection.
- Testing and matching cells improves the reliability of the accumulator, making it safer and higher performing. Matching cells inside their parallel groups also extends the life of the battery pack so that some cells are not excessively worn.

Problem Definition

Rules Compliance

R	Status	Notes	Proof of Compliance

ule			
A 1.2	Unknown macro: 'status-handy'	**Paraphrase:** For an electric vehicle, the accumulator may have a maximum usable energy of 5.40 kWh, or nominally 6.75 kWh. (Discharge measured at 2C).	The accumulator will be designed to comply and be tested.

Constraints and Criteria

Constraint	Priority	Description	Value	Unit	Validation Method
Current Capability	Unknown macro: 'status-handy'	Each segment must be able to deliver the full rated current of the Tractive System because the segments are in series. By design, this is 135 A RMS. The pack fuse will be 40 A.	135	A	HTHC

Technical Progress

Cell Testing Requirements

- Test Circuit must clamp onto the positive and negative battery tab
- Clamps must connect to a wire that can handle the current requirement of the tests. Use 8 gauge wire, make sure you consider the hole size of a lug that would be crimped to the end of the wire. This lug would be bolted to the clamping assembly
- Hold the cell in a repeatable position
- Don't damage the cell tab or the cell- must have guarding to protect the cell against dropped tools or mis-clamping
- The fixture should be designed for cleaning- it must be easy to make sure the fixture is completely free of swarf or debris.
- Easy to operate

Design Analysis and Manufacturing Design

Electric Power 6.3 Ah Cell Testing

Testing carried out by Nerissa Wong

Cell Testing: First Batch

10 cells received at beginning of November

All 10 cells received at 3.80 V

Testing Plan:

1. Charge cells
2. (1 cell) Cell Testing Procedure
3. Thermal validation (4 cells in parallel)
4. Fuse test (maybe not)

Cell Testing: Full Pack Test, Inventory, and Match

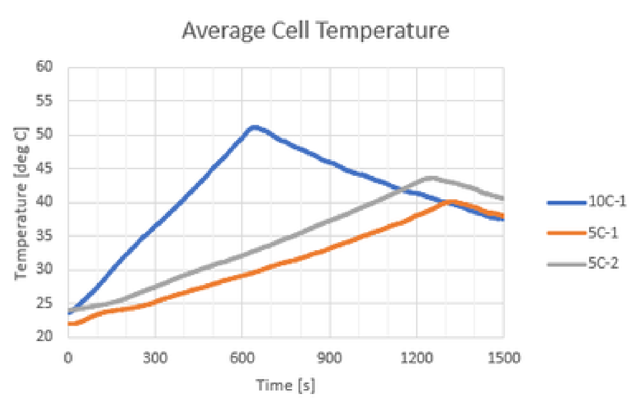
Here are the results from testing several different cells. As well as the voltage measurements from all five boxes.

Box 1				Box 4			Comments
	Cell Number	Voltage (V)			Cell Number	Voltage (V)	
1	Cell_30649	3.8		1	Cell_31001	3.8	
2	Cell_30184	3.8		2	Cell_31026	3.8	
3	Cell_30802	3.8		3	Cell_30808	3.8	
4	Cell_30532	3.8		4	Cell_30735	3.8	
5	Cell_30359	3.8		5	Cell_30456	3.79	
6	Cell_30435	3.8		6	Cell_30676	3.79	
7	Cell_30996	3.8		7	Cell_30967	3.8	
8	Cell_30506	3.81		8	Cell_31256	3.8	
9	Cell_30960	3.8		9	Cell_30870	3.8	

10	Cell_30127	3.8		10	Cell_30214	3.8	
Box 2				Box 5			
	Cell Number	Voltage (V)			Cell Number	Voltage (V)	Comments
1	Cell_30726	3.8		1	Cell_30941	3.8	
2	Cell_30324	3.8		2	Cell_30911	3.7	* Has two square tabs
3	Cell_30711	3.8		3	Cell_31092	3.8	
4	Cell_30143	3.8		4	Cell_30018	3.8	
5	Cell_30074	3.79		5	Cell_31212	3.8	
6	Cell_30906	3.8		6	Cell_31136	3.8	
7	Cell_30096	3.8		7	Cell_30823	3.8	
8	Cell_30674	3.8		8	Cell_31312	3.8	
9	Cell_30714	3.8		9	Cell_31158	3.8	
10	Cell_30376	3.8		10	Cell_31200	3.79	
Box 3							
	Cell Number	Voltage (V)					
1	Cell_30582	3.8					
2	Cell_31247	3.8					
3	Cell_31037	3.8					
4	Cell_30329	3.8					
5	Cell_31010	3.8					
6	Cell_30724	3.8					
7	Cell_30392	3.8					
8	Cell_31105	3.79					
9	Cell_31087	3.8					
10	Cell_30147	3.8					

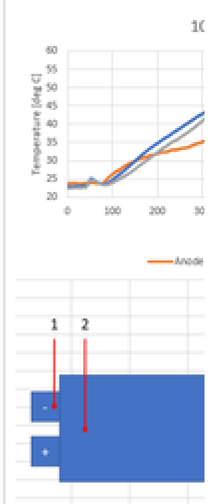
A load bank with a constant current mode controlled by a connected power supply was used to load the EP8545148HP cells at the 10C and 5C rates. The data was logged to Matlab and inserted into Excel for analysis. The results are shown below, and the raw data is available here: Cell testing 2017-12-05.xlsx. Raw voltage and current vs. time data is available here: TenC_1_data.txt, FiveC_2_data.txt, FiveC_1_data.txt

Testing Summary



	T_start	T_end	ΔT	Δt
Trial	deg C	deg C	deg C	s
10C-1	24	51	28	630
5C-1	22	40	18	1300
5C-2	24	44	20	1250

Discharge Test: 10C



This testing showed that the cells could be discharged in free air at the 10C rate, but further investigation is needed to find if the cells can discharge at the 15C rate, as stated on the datasheet.

Lithium Ion Polymer Cell Grading and Testing: Naming Convention

Each white box containing a cell from Electric Power must bear the following information:

The cell ID number

The date of testing

The measured OCV after testing

A letter / number grade

General Notes

Cell Matching

- Impedance Spectroscopy was conducted to measure cell impedance: https://wiki.uwaterloo.ca/display/FEAM/Cell+Testing+Procedure
- From there, cells were matched into groups of 4 based on this impedance, since internal resistance is proportional to thermal energy produced by the cell
- Cells were assembled into a segment by taking the highest impedance groups and the lowest impedance groups. For instance, segment 1 has groups 2, 73, 3, 72, 4, 71, 5, 70, 6, 69, 7, 68.
- The idea is that the cells are matched to minimize thermal energy generated by distributing it across the entire segment. For example, the low thermal energy of segment 2 will offset the higher thermal energy of segment 73
- After, matching by impedance, all cell voltages were measured. Before combining cells in parallel, the voltage levels must be within a 10 mV range of each other to prevent high current running through the cells. The current can be calculated using Ohm's Law, where the resistance is the combined total resistance of the cells in parallel.
- If cells were out of the 10 mV range, the cells with the lower voltage were charged using a power supply to the required voltage level.
- See this spreadsheet from Summer 2018 for all cell groupings and measurements: Cell-Voltage-Testing.xlsx

Bulk testing was planned using these fixtures:

Conclusions

Lessons Learned:

The test fixture was not professionally manufactured- wood test fixtures have the possibility to splinter and damage cells and collect metallic swarf, risking damage to the sensitive pouch cells. The test fixture also did not properly support the cell- it didn't have a "shelf" for the cell tabs, so the cell had to be propped up with a marker. In addition to this, it would be helpful to have a polycarbonate shield to avoid accidental damage to the cell from a flying tool or part.

Component Attribute	Manufact urable?	Works as Intended?	Notes
Wooden Test Fixture	Yes	Somewhat, but room for improvement	Test Fixture should support cell more, should be made from plastic to avoid splinters.
Test Fixture Current Path	Yes	Yes, needs an inline fuse	Test fixture should also have fusing on sense wires, which are typically 24 ga stranded wire.
Instrumentation	Available	Yes, VISA + Matlab is a great combination	The team should maintain a repository of Matlab scripts and best practices.
Test Source and Sink	Available	Cell testing in volume is difficult without higher power sources and sinks - 1.5 kW or more, ideally	It's tough to buy a high power unit, but Keysight is very happy to work with SDC teams.

Project Procurement:

Follow the procurement procedure as described in the Operations page Purchase and Reimbursement Procedure and then upload the purchase order spreadsheet to the table below. Consolidate as many purchases into one procurement request to simplify the process.

Generate a Jira task in the appropriate Operations Epic. Label it with *proc_ts* and an (*label specific to this page)* so that it shows up in the table below.

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Team Member Name	Purchase Order Spreadsheet	Quote / Invoice	Order Description	Company Name	Total Cost [CAD]	Status	Storage Location
						NOT YET PROCESSED	

Accumulator Cell: State of Health Testing:

20-5-ACC-CellSOH

WBS Title: Cell Testing

WBS Number: 1.2.1.2.2

Project Timeline:

Describe tasks and use the correct tags to show the state of the project.

Unknown macro: 'status-handy'

- Cell Leakage (Long-term Charge Retention)
- Cell Capacity
- DC Internal Resistance Testing

Responsibility Cascade:

- @ Calvin Ryan DeKoter
  - @ *jlmorabi@uwaterloo.ca*

Design Philosophy:

- To determine the state of health of the spare cells Electric Power cells we currently have. If determined healthy, the cells will be assembled back into the damaged cell segments.

Test 1: Cell Leakage (Long-term Charge Retention)

Description: This test simulates a cell's ability to retain its charge over long periods of time

Test Method: Measure open circuit voltage (OCV) of cell with a precise multimeter (provided by Keysight). Compare this to previous OCV measured from last term.

Evaluation: Acceptable decline is less than 0.1 V

Test 2: Cell Capacity

Description: This test measures the amount of energy stored in the cell.

Test Method: DC Power Supply + DC Electronic Load Bank + Data Acquisition Unit

1. Charge the cell to its maximum voltage: Using DC power supply, set a constant current of 1C (current that the cell can flow for one hour), set the maximum voltage (4.2 V for EP8545148HP), connect the cell's positive terminal to positive supply lead and the cell's negative terminal to the negative supply lead, then, turn on output on the supply.

2. Discharge to its cut-off voltage: Connect the cell to a DC electronic load bank and a precise current measurement device that logs current vs time. On the load bank, set the minimum voltage (2.75V for EP8545148HP) and set a constant current discharge. **Critical! Do NOT let the cell drop below cut-off voltage (2.75V)!**

3. Log the constant current discharge vs time and integrate to find the capacity in Ampere-Seconds (As). Divide this number by 3600 to get the SI unit of Ampere-hours (Ah). Sample the current every three seconds or less to maintain accuracy.

4. Charge the cell to its nominal voltage (3.8 V for EP8545148HP) for safe storage.

Evaluation: Compare measured capacity to minimum capacity rating on datasheet: EP8545148HP Cell Datasheet.pdf. Lower capacities below the minimum rating indicate that the cell is chemically faulty and will not perform as expected.

Test 3: DC Internal Resistance

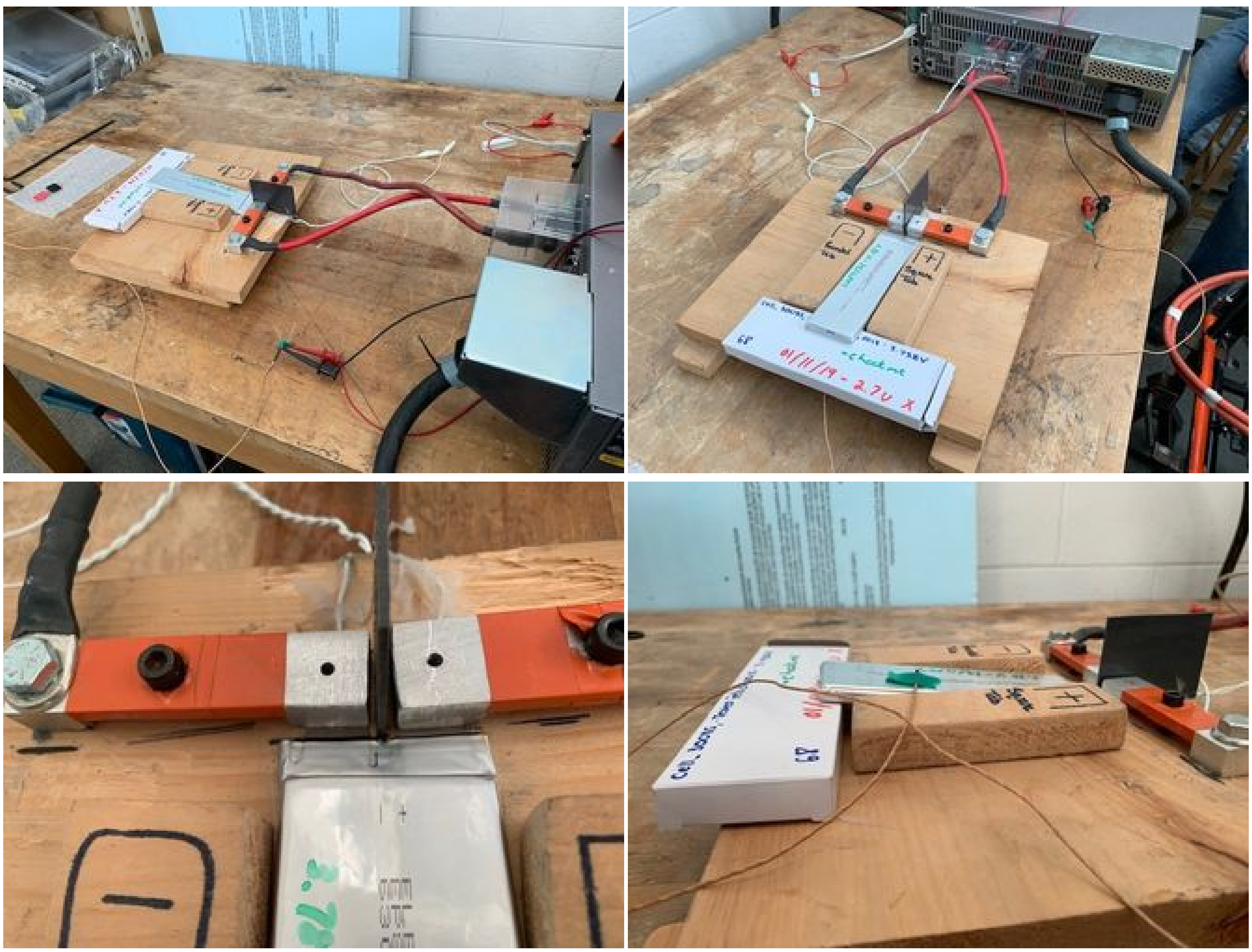
Description: This test measures DC internal resistance (NOTE: This is not the same as impedance spectroscopy). Internal resistance is a measure of the inherent DC resistance of a cell which is flowing current.

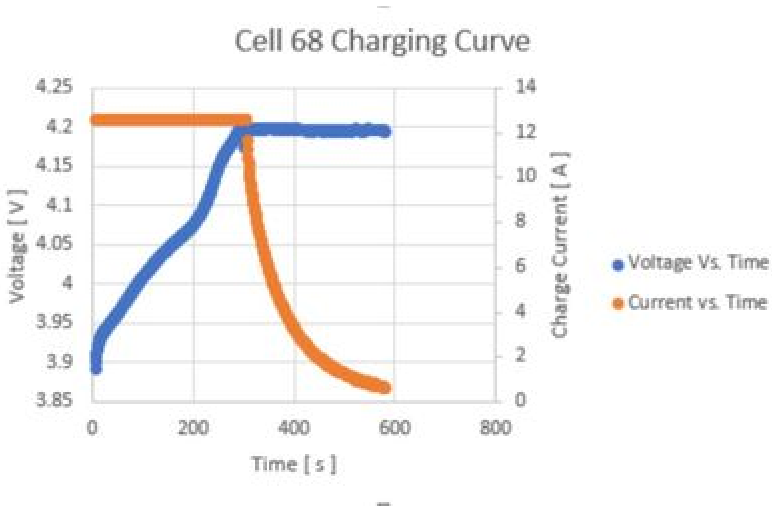
Test Method: Connect the cell to a high precision multimeter and a DC electronic load that can quickly ramp up and down the current flowing from the battery. Draw a current from the battery, and compare the closed circuit voltage to the open circuit voltage. This change in voltage is due to the internal resistance of the cell, By applying Ohm's Law, we can calculate the simple DC Internal Resistance of the cell. For the EP8545148HP cells, a suitable value is less than 6 ms.

EP85_DCIR.m - obsolete (as we don't have the rp7952a anymore) DCIR test script. A bit of a dumpster fire of coding practices, but works great for simple DCIR. Note that the average shouldn't ever include the first few points taken during the test. Message @ Calvin Ryan DeKoter for help with Matlab scripting

EP85_DCIR.m.txt - text version, hopefully is viewable in the browser

Pictures of Test Set-up 2





Lessons Learned:

To effectively program the BenchVue software, don't output the "CH1 Voltage Measurement". This will get written into a different column in the Excel sheet. Instead, write to a common variable called "Current" or "Time". Use the "Set" command to achieve this.

The cells must be allowed to "rest" between charging and discharging, Diffusion occurs after charging and after discharging, which will have a massive effect on the cell OCV and capacity. The cell datasheet requires 30 minutes rest between charging to 4.2V, 315 mA cutoff and discharge.

Test Scripting- Automate your Battery Testing!

Benchview script to run Test 2 and Test 3: Cell Capacity- EP85_Capacity_DCIR.bvseq. This BenchVue script discharges a fully charged cell while integrating the current over time to solve for the overall cell capacity. The file linked in this page is non-functional.

So far, the "delay" command is not at all accurate. If your computer 'hangs' at all during the script, that delay will be added into the loop period. Using TDelta = T2 - T1 allows accurate current integration over time. To achieve higher accuracy, TDelta should encompass all steps in the loop, as each step takes some time (up to half a second in a worse case). The first measurement of cell capacity understated the capacity because of this.

BenchVue is a fine program for small, simple, non-time-critical scripts, but is not fast enough for integration of current for capacity testing.

A better way to interface with the supply is to use MatLab's instrument control panel, in the Apps folder. This tool has both a command line interface, where the user can set up direct connections to the supply and send individual commands, and a toolbox full of commands to run a script of SCPI commands. Matlab is relatively easy to use and understand, so it is a good fit for our situation. PYVISA uses the same protocols in a Python environment to complete the same tasks.

Since the Keysight RP7952a is a high voltage supply, it has a relatively high internal resistance of 0.2 . This means that the maximum current that can be drawn from a single cell over a full charge-discharge cycle is about 12 A.

Cell Test Step	Charge:		
Program Name			
Notes			

Test Results: EP8545148HP Cell Testing and Grading

All Cell Data and Results stored in this folder: Tractive System Members Added: Message Calvin DeKoter for access

After all testing was completed, the testing results were compiled in the table below. Pay special attention to the "Notes" column.

Data from the DC IR test is an average of the resistances from the later half of the test. Check out some of the plots to see why this is.

*****This table will be re-sorted in Excel after all testing is complete*****

Cell	Cell	Cell	OCV [V]	Charg	Discharge	Capac	Internal	Notes

Type	Num ber	Name	(25/11/28)	e Finish	Start	ity [Ah]	Resistance [m]	
EP85451 48HP	30085	Cell 68	3.788					This cell was discharged to 2.66V, but holds charge well. More testing done on this cell than others.
EP85451 48HP	30717		3.790					This cell has been shorted (see marks on tabs).
EP85451 48HP	30248		3.795	4:25	4:55	6.4135	0.0042573	
	31748		3.851			6.0654	0.0054	
	30200		3.7072	2:50	3:50	6.4573	0.0039589	Cell charged to 4.20 V, settled to 4.25V over about an hour- cell left to sit for 60 minutes before test
	30511		4.0368			6.0844	0.0051749	
	30141		3.723					Cell discharged to 2.66 V during tests
	30276		3.9767			6.1065	0.0045	Cell held at 4.0 V for a long time, several tries taken at the DCIR Test due to code issues
	31291		3.77					
	30332		3.7928					
	30846		3.781					
	30978	Group 1	3.7407	2:45	3:15	6.4234	0.003963	
	31219		3.7955	3:50	4:30	6.4537	0.0040154	
	31263		3.784					
	31138		3.7836					
	30675		3.784					
	31215		3.747					
	30562		3.7486					
	30104		3.7472					
	30359		3.7489					
	30735		3.7387					
	30039		3.7380					

2020-02-15- Cell Bulge Testing

The point of this test is to determine cell temperature rise and expansion when placed under the nominal competition load.

The high current test circuit is used to flow 5C from the cell for 12 minutes (by definition) and 16C from the cell for 10 seconds- peak load.

Cell Thickness- 10s 16C Pulse Test- subract the fixture thickness- Cell # 30511

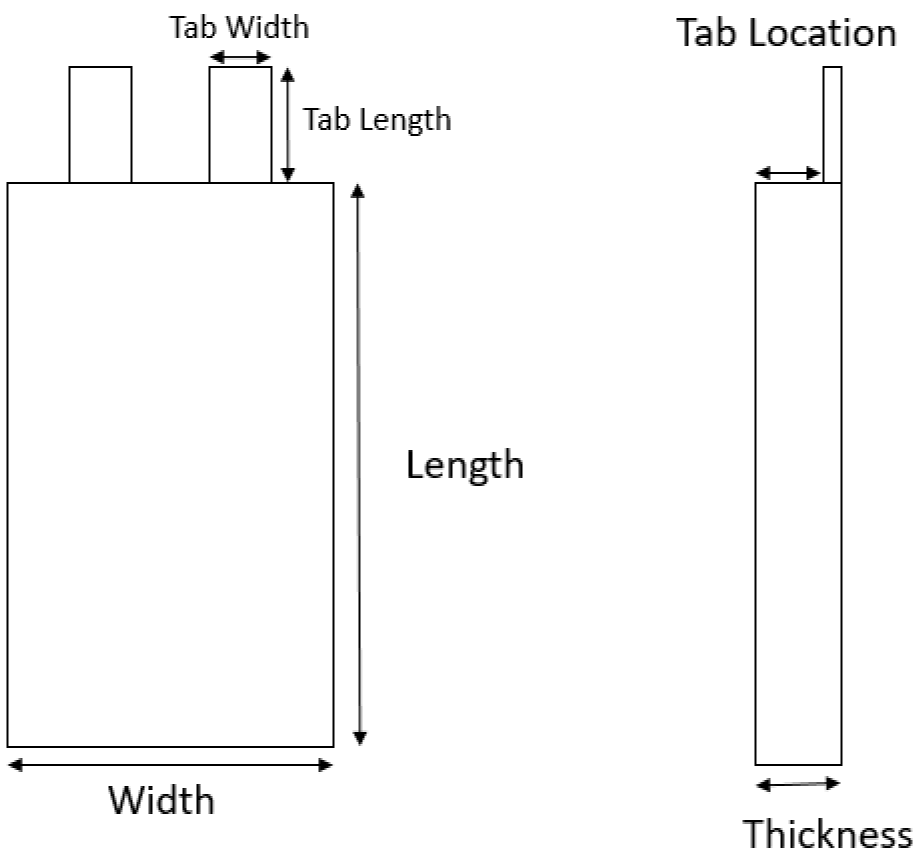
Cell Start Voltage: 3.7815, Cell End Voltage: - screwup, currently recharging

Position	Initial	Final
Tab End Point 3	6.78	
Middle Point 2	6.63	
Pouch End Point 1	6.55	

Electric Power Cell Dimensions:

Cell Dimensions						
	Length(cm)	Width(cm)	Thickness(cm)	Tab Length(cm)	Tab Width(cm)	Tab Location(mm)
1	14.91	4.45	0.89	1.58	1.41	4.08
2	14.96	4.48	0.87	1.62	1.49	4.38
3	15.02	4.44	0.86	1.39	1.51	5.30

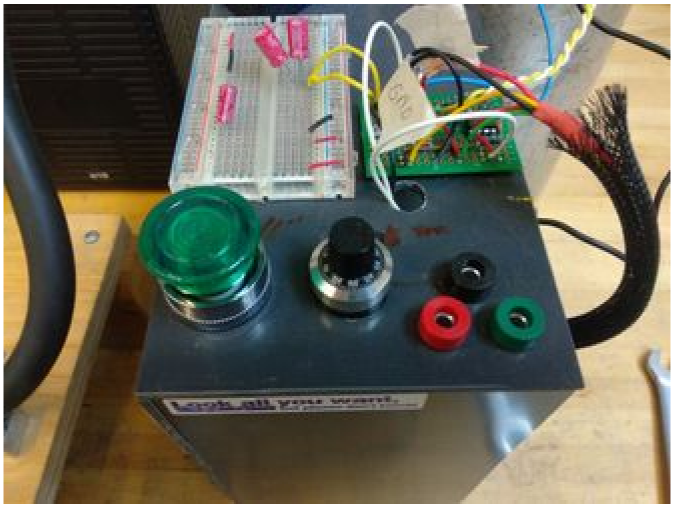
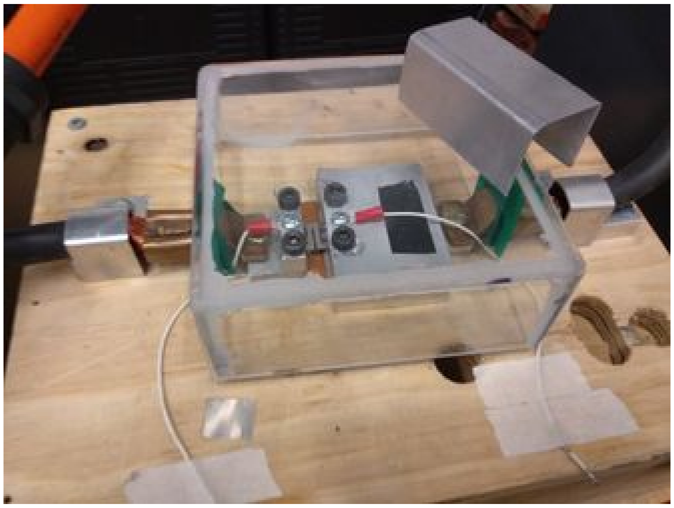
4	14.89	4.46	0.87	1.52	1.49	5.38
5	15.01	4.42	0.88	1.53	1.50	5.15
6	14.93	4.47	0.85	1.62	1.50	4.41
7	14.90	4.50	0.89	1.61	1.50	4.59
8	14.81	4.44	0.89	1.69	1.51	4.93
9	14.91	4.40	0.90	1.70	1.50	4.67
10	14.93	4.46	0.88	1.62	1.49	4.60
Mean	14.93 ± 0.1cm	4.45 ± 0.05cm	0.88 ± 0.03cm	1.59 ± 0.2cm	1.49 ± 0.08cm	4.75 ± 0.7mm



High Current Test Circuit:

Test setup:

HCTC Control Panel	HCTC Fuse Testing Fixture

Specs:

Config	**6V**	**12V**
max current	500A	TBD 1000A?
Battery Ampacity	280 Ah ?	85 Ah ?

Instructions:

Connect the HCTC according to the instructions below. It doesn't matter which cables you use, as long as you fundamentally understand cable ratings, heat rejection, and safe working practices for high current applications.

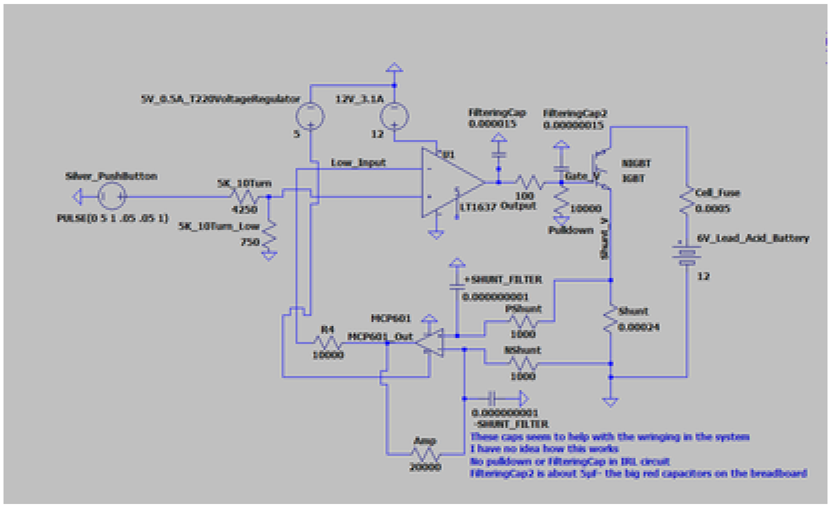
Remove all rings, jewelry, chains, and conductive items from yourself and the table near the HCTC. Work from Negative (Earth Ground Referenced by the Oscilloscope)

- Identify the most positive terminal of the power source- a lead acid battery or a LiPo battery.
- Identify the most negative terminal of the power source and connect it to the brass shunt with a wire of size 4 AWG or lower. **Be very careful to not move the shunt relative to the IGBT- it is very fragile.**
- Confirm that the shunt is connected to the IGBT Emitter. (This will be in the correct configuration, don't change it.)
- Confirm that the copper busbar is connected to the IGBT Collector (This will be in the correct configuration, don't change it.)
- Confirm that the copper busbar is connected to the low side (marked with a "2") of the Gigavac contactor. (@ jlmorabi@uwaterloo.ca please confirm)
- Connect the positive high current cable to the high side of the Gigavac contactor.
- Carefully connect the positive high current cable to the positive pole of the battery. The circuit is now live- confirm that all conductive items are away from the circuit.

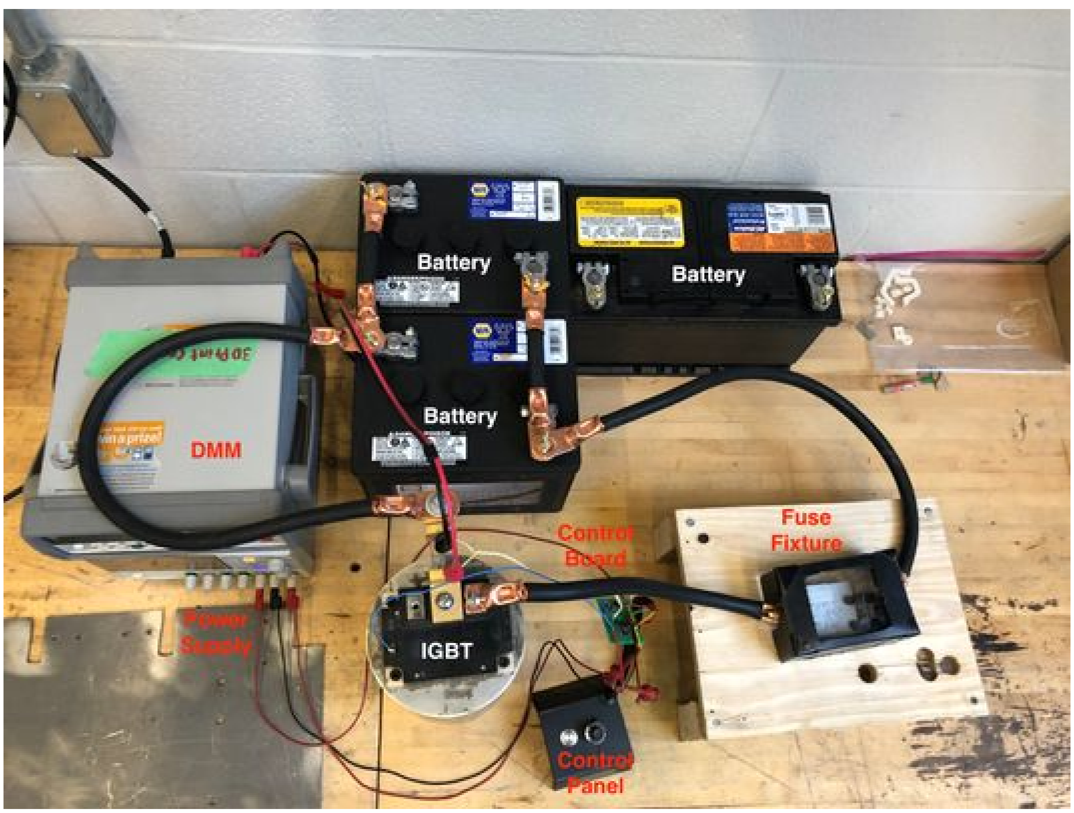
Circuit Functionality Tests

- Connect the power supply to the red banana jack with 12V, 3.1A supply voltage. Connect the power supply ground to the black banana jack. Leave the green banana jack empty.
- Measure the continuity across the contactor. It should be open. Push the green button and confirm that the contactor closes.
- Measure the voltage between the circuit ground (shunt negative side) and the blue gate wire on the IGBT. It should be zero.
- Confirm that the contactor is open, then push the silver button to run the IGBT. No current is flowing, so the IGBT is driven closed. The gate voltage should be 12V.
- Confirm the position of the potentiometer at 0 - 50
- If required, connect an oscilloscope probe across the shunt and make a current trace- 20 mV / div, 50 ms / div timescale, 20 mV rising edge trigger, 1 div time trigger from the left edge.
- Confirm that the circuit functions as expected- it should only flow current when both the contactor button and the silver button is pushed. **Never** make or break current flow with the contactor- it's not rated for that.

Cell_Fuse_Tester_R.asc



Test setup:

Specs:

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max current	500A	TBD 1000A?
Battery Ampacity	280 Ah ?	85 Ah ?

Instructions:

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- Identify the most positive terminal of the power source- a lead acid battery or a LiPo battery.
- Identify the most negative terminal of the power source and connect it to the brass shunt with a wire of size 4 AWG or lower. **Be very careful to not move the shunt relative to the IGBT- it is very fragile.**
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- If required, connect an oscilloscope probe across the shunt and make a current trace- 20 mV / div, 50 ms / div timescale, 20 mV rising edge trigger, 1 div time trigger from the left edge.
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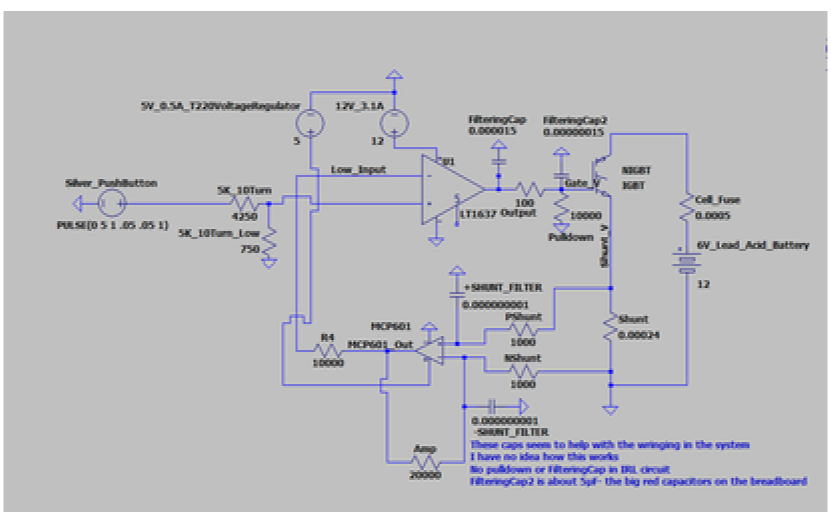
Cell_Fuse_Tester_R.asc



Cell Testing Procedure:

Requirements:

- Laptop with at least 3 USB ports
- MATLAB installed with NI-VISA
- Latest Script made by @ Former user (Deleted)
- All files related to cell testing located in a folder.
- Two people must be working on Cell testing at all times.

Setup Procedure:

- Proper safety precautions (Sand buckets and fire extinguisher)
- Record data collected to excel table shared on google docs.

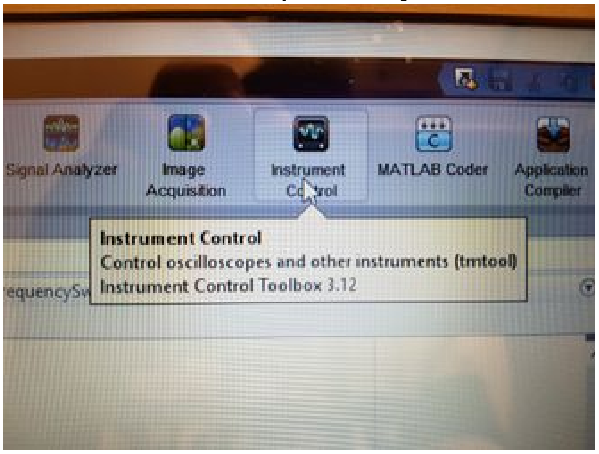
Safe Cell Handling:

- Avoid placing cells on any rough surfaces where there is a risk of puncturing the cell.
- Do not connect the cell tabs together under any circumstance.
- If the cell catches on fire, place it on one bucket of sand, and bury it with the other,
- Do not bend or distort the cell tabs.
- Only items relevant to cell testing should be on the table.
- Make sure nothing on the table can short the cell.

Before Leaving:

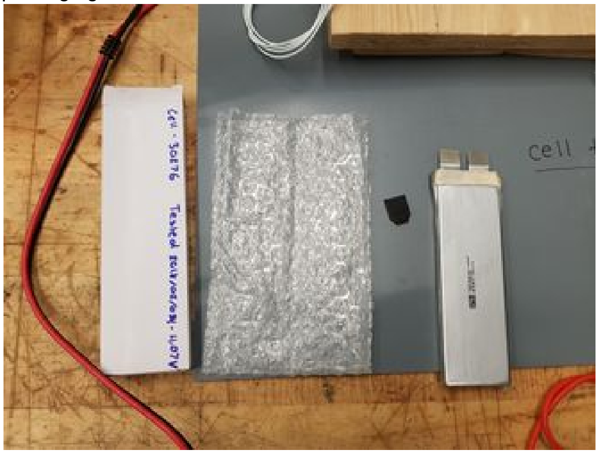
- Make sure no cells are left outside.
- Turn off all devices and unplug them.
- Clean up table of any extraneous items.
- Take key with you when you leave.

1. Plug in all devices, turn them on manually, and connect each device to your laptop using their USB cables.

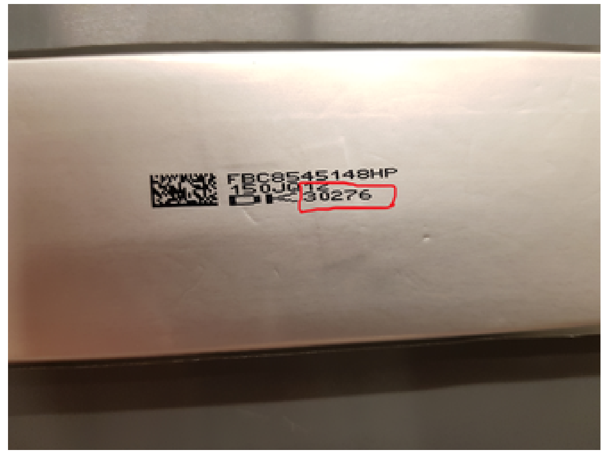
2. On MATLAB click "Instrument Control" located under APPS. Scan for the three instrument you are using from USB.


3. Name the batteryPartNumber as "Cell_Test", and run a script. You should get an error message saying voltage is too low. This is to check if the script is able to run.   Do not have a battery in the testing bed for this check!

Cell Testing Procedure:

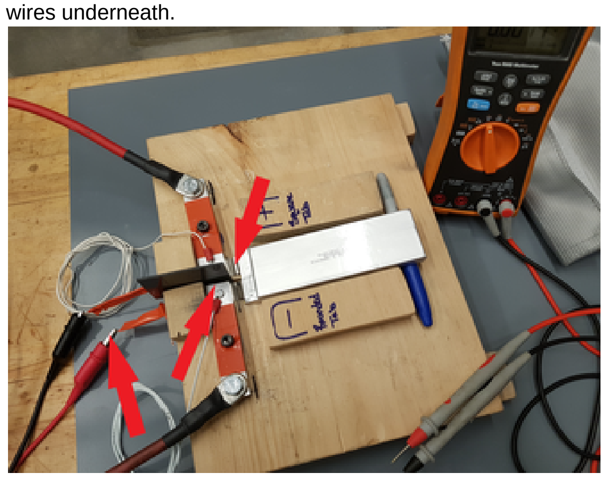
1. Grab a cell that has not yet been tested, remove it from its packaging.


2. Change batteryPartNumber to "Cell_#####", the numbers will correspond to the 5 digit code written on the back face of the cell as shown.

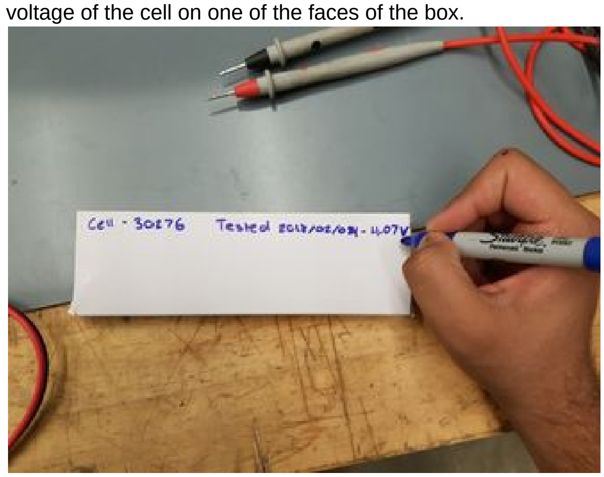


3. Place the cell on the table setup, use the visual aid on the blocks to help make sure that the cell is facing the right way.
   a. Warning 1: placing a cell in backwards (cell tabs reversed) can result in damage to the cell and the equipment. Be very careful to install in the right orientation.
   b. Warning 2: Avoid deforming the cell tabs or cell pouch. Deformation to any part of the cell can result in permanent internal damage.

4. Loosen the metal bars of the table such that the cell tabs can fit under them, if necessary, use a sharpie on the back end of the cell tab to angle the cell tabs for a better fit.
5. Tighten the bars, avoid deforming the tabs, but make sure there is a stable connection between the tabs and the copper wires underneath.



6. Check the voltage of the cells using a multi-meter on the tabs, on top of the metal bars, and by the alligator clips connected to the copper wires (they should all be roughly the same). Record the voltage you read from the cell tabs.
7. Begin running the test, check the power supply and make sure the current is around 10 Amps. When the test is finished, make sure the data is saved in the same file as other cell testing related files.
8. Find the voltage of the cell after the test and record it.   If the cell voltage has dropped below 3 volts, it should be recharged before storage to prevent degradation.   An SOC of approximately 40% is recommended for storage.
9. Loosen the bars and remove the cell, place it back into it's pack with the black rubber tab and bubble wrap.

10. Write down the cell number, "Tested", date tested, and final voltage of the cell on one of the faces of the box.


11. Place the cell on a shelf and repeat each step for a new cell.

Cell Testing Resources

A technique for measuring internal resistance:

https://www.tek.com/blog/measuring-battery-internal-resistance-easy

The following notes are from the page "Accumulator Meeting 2018-10-10"

- Ciara
  - 12 cells in series - not a great idea (Alex) because you have to monitor when you are charging it, discharging it, and how it recovers from a spike
    - If it takes a while to recover compared to the others, it’s probably a bad cells

    - We can discharge and monitor 12, but then how do we charge them?
    - 12 cells in series is more voltage than what we have - we don't have a HV supply
  - We can cut down time by doing 5C charge, 5C discharge - 30 minutes per cell
  - 6.3 Ah
  - We need to find power supplies!!
  - Keep working on making this plan solidified - we get cells in 10 calendar days!

The following notes are from the page "Accumulator Meeting 2018-10-18"

- Testing - immediate - 10 cells next week (Ciara)
- Fuse test - Ciara work with Bondo + Rishab
  - Ciara check voltage and current of the power supply
  - 1 kW load - verify the load is this
  - blow one up to see if the cell tabs can act as fuse
- Thermal characterization - Ciara work with Nerissa
  - Nerissa can get thermal camera for next week, the week after if not
- Cooling validation- Ciara work with Nerissa
  - Tab bus bar cooling

2016-2017 Cell Testing

Please see this powerpoint- cellcoolingresults.pdf

Cell testing 2020-2021

- Summary
- CAD Information
- Design Philosophy
- Problem Definition
- Rules Compliance
- Constraints and Criteria
- Technical Progress
- Project Procurement:

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Summary

The purchased accumulator cells must be tested to validate their features and performance, in order to ensure accumulator functionality and safety. This process involves creating a test setup to test all cells and designing tests to measure state of charge. Currently the firmware sub-team is working on updating the scripts to test the cells.

@ Former user (Deleted)

CAD Information

- There is current no CAD for this project at the moment.

Design Philosophy

- Testing and matching cells improves the reliability of the accumulator, making it safer and higher performing. Matching cells inside their parallel groups also extends the life of the battery pack so that some cells are not excessively worn.

Problem Definition

Rules Compliance

Rule Number	Rule Description	Status As Built	Compliant?	Verification	Picture
EV 2.3.1	Manufacturer's data sheets showing the rated specification of the accumulator cell(s) which are used must be provided				

	in the ESF along with their number and configurations.				

Constraints and Criteria

Constraint	Priority	Description	Value	Unit	Validation Method

Technical Progress

The current test scripts can be found here (https://github.com/josephborromeo/CellTester/tree/main/Python). The software is being redesigned to be more reliable and able to test all cells at the same time.

Design Process

The team built a custom Li-Ion cell tester to compare different 18650 cells. This allowed an informed, data driven decision to be made of which cell to use for the new 2021 Accumulator.

The following work term report details the design of the cell tester: Joseph Borromeo 2B Work Term Report.pdf

Design Analysis and Manufacturing Design

Analysis Validation

DC IR Full Sweep Plan

Sweep the cell from full SOC to zero SOC using the DC IR test. To measure the DC IR at different temperatures, vary the current drawn during the test. This test should be done at closer to 50% duty cycle so that the higher current tests increase the temperature of the cell.

Bulk Cell Testing - 36 Capacity Measurements from 660 cells

- Charge to 4.2V at 1C
- Let the cell rest for 30 minutes
- 2C Discharge Current - 6 A
- Charge to 3.6V at 1C
- Let the cell rest for 30 minutes
- Perform medium IR measurement (5% duty cycle - 0.5 seconds on, 20 seconds off)

Conclusions

Project Procurement:

Follow the procurement procedure as described in the Operations page Purchase and Reimbursement Procedure and then upload the purchase order spreadsheet to the table below. Consolidate as many purchases into one procurement request to simplify the process.

Generate a Jira task in the appropriate Operations Epic. Label it with *proc_ts* and an (*label specific to this page)* so that it shows up in the table below.

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Team Member Name	Purchase Order Spreadsheet	Quote / Invoice	Order Description	Company Name	Total Cost [CAD]	Status	Storage Location
						NOT YET PROCESSED	

Accumulator Cooling

Cooling System Requirements:

The following note is from the page "Accumulator Meeting 2018-10-10"

- Find heatsink stock- similar to this. This material is already in the bay.

- Aaron
  - Used 380W heat generation to run some CFD models - fins allows final bus bar temp to be 57 C, no fins and flat plate with 35 mm channel height 97 C
  - Need to consider the heat generation in the bus bar using resistance of aluminum
  - 380W is only from the cells, but did not take into account I2R of aluminum bus bars, and R is dependent on Ax for bus bars -> what's the lowest possible Ax?
  - Aaron keep working on air flow sims for channel - figure out if we really really need fins
  - *Heat generation can be calculated using the internal resistance of the cell, which is about 5 m. Note added by Calvin*
- PCM Material- Ciara
  - Sealing PCM material
    - Silicon for aluminum sealing
    - 3 mm
    - 1.3 kg of PCM keeps everything at 40C, but how much PCM material are we going to use?
    - We need to figure out the minimum we need..
    - Feasibility of drilling along y axis vs z axis - this is feasible - 3 mm
    - /facepalm

The following note is from the page "Accumulator Meeting 2018-10-18"

- PCM (Ciara)
  - we can only fit 50 g into the bus bars
  - it seems not feasible to only have flat bus bars, but if we should use fins if possible because it will be simpler than machining them - need to design for enough HT via forced convection
- Bus bars (Rishab)
  - 25 mm heat sinks with 6.3" base thickness
    - Don't need to have separate bus bars
  - More heat generation - higher RMS current (due to 208s + super conservatism)
- Cells (Michael)
  - nickel bus bars don't tarnish, like the aluminum coated ones
  - need to use anticorrosion paste... conductivity??
- Segments (Rishab)
  - Make mounting tabs higher than the rest of the bus bar stack up
  - Make outboard blind mounts for mounting the segments
  - Use polycarb for mickey mouse ear mounting holes
- Inlet duct (Kevin)
  - Cut off top of the inlet - lower pressure region
  - Nerissa added a flange to the front of the box for bolting to
  - Kevin needs to add flow directors in the inlet duct to even out the air flow distribution going into the box - currently there is more air through the center
  - Michael to give Aaron and Kevin the average velocity to consider ram air
      - Make a "full" air flow model from side scoops to outlet of battery box
- Air flow simulations (Aaron)
  - Simulation does not
  - Constant heat source of 380W on bottom of cells
  - The lateral member behind the box can be removed since the suspension points have changed
    - We can then direct the fans facing backwards so the last cells are not being air limited
  - Move the fan and add fins to the simulation is the next step

Cooling systems in vehicles are important to ensure that the battery runs smoothly and without bursting into flames. Fire can be dangerous to both the driver and observers which can result in serious injury or even death. In addition to this, the act of a battery bursting into flames can cause damage to the car itself and set back months of gruelling work and lose the team thousands of dollars.

It is for these reasons that cooling the battery pack is of utmost importance. In order to make a conscious decision on the basis of cooling, one must explore all available options and ensure that the method chosen is the best option given the constraints of the car.

Cooling Strategies

Air cooling

Air cooling is a common method for cooling a system. It uses a fan to circulate cool air over the object which is to be cooled. Through the process of convection, the batteries are able to maintain a cool temperature as the warm air is blown away. The fan generally changes speed as the battery uses more energy. The rate of the fan speed is generally proportional to the acceleration of the car and this is the most power intensive operation of the battery.

Moisture and Condensation

Condensation occurs when the temperature is below the dew point. The dew point is the point at which the rate of condensation exceeds the rate of evaporation, allowing droplets to form. In the case of a battery pack, the battery is the warmest component. Thus, it is unlikely that the battery itself will be below the dew point. It is much more likely that condensation will form on the exterior walls of the battery pack. The walls of the battery pack is made of aluminum and thus has a relatively high thermal conductivity.

Some of the advantages of an air cooling system are that they are inexpensive, lightweight, simple to install and easy to use. Some of their drawbacks include the fact that air convection is a relatively poor way of keeping systems cool and that moisture buildup within the system is inevitable due to the large quantity of air passing through the system

Water Cooling

Water cooling uses conduction to transfer heat from the heat sinks in the battery to a water system. The water is pumped through lines. As the water passes over the battery, it collects the batteries heat and disperses it as it leaves the battery system.

Some advantages of this system are that it is relatively easy to implement and it is fairly cheap to do so. In addition, this method does cool better than the air counterpart. Some drawbacks include the fact that it is heavier than the air cooling option and that the risk of a leak could result in the shorting of a battery.

Liquid Gas Cooling

There exist gaseous cooling systems such as liquid helium of liquid nitrogen cooling systems which work in the same manner as a water cooling system, however a liquid gas is used to cool.

Some advantages of this method are that it is extremely efficient. Some drawbacks include the fact that this method is volatile, difficult to implement, costly and dangerous in general.

Phase Changing Materials

Phase changing materials (PCM's) use the premise that during a change of state, a large amount of thermal energy can be absorbed. Thus, if a battery operates at say 40 degrees celsius, you place a PCM with a melting point of ~45 degrees celsius next to the battery. The PCM will absorb the energy released by the battery and will become a liquid. As the battery is not used (when the car is no longer accelerating), the PCM will release the energy stored and will solidify once again.

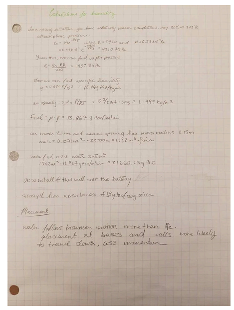
Some advantages of this method are that these materials are fairly easy to fabricate and relatively cheap. In addition, they are quite safe and pose no risk of shorting circuits. Some drawbacks are that they take up space within the battery pack and they may still require an air cooling system to aid them in solidifying again.

2018-2020 Accumulator Cooling

An option to avoid condensation would be to coat the interior of the aluminum casing with a polymer. This should not be attempted as polymers tend to be insulating and would thus prevent additional heat diffusion. This option could be considered if a PEDOT:PSS polymer was considered as a coating, however this polymer is quite toxic and expensive.

Instead of avoiding moisture, one could attempt to coat the batteries in polymer such that they will not short when placed in contact with water. This option would once again prevent heat transfer especially since the areas that would require polymer coatings are the heat sinks for the battery. This option is perhaps viable as an extra precaution and should be used in small doses.

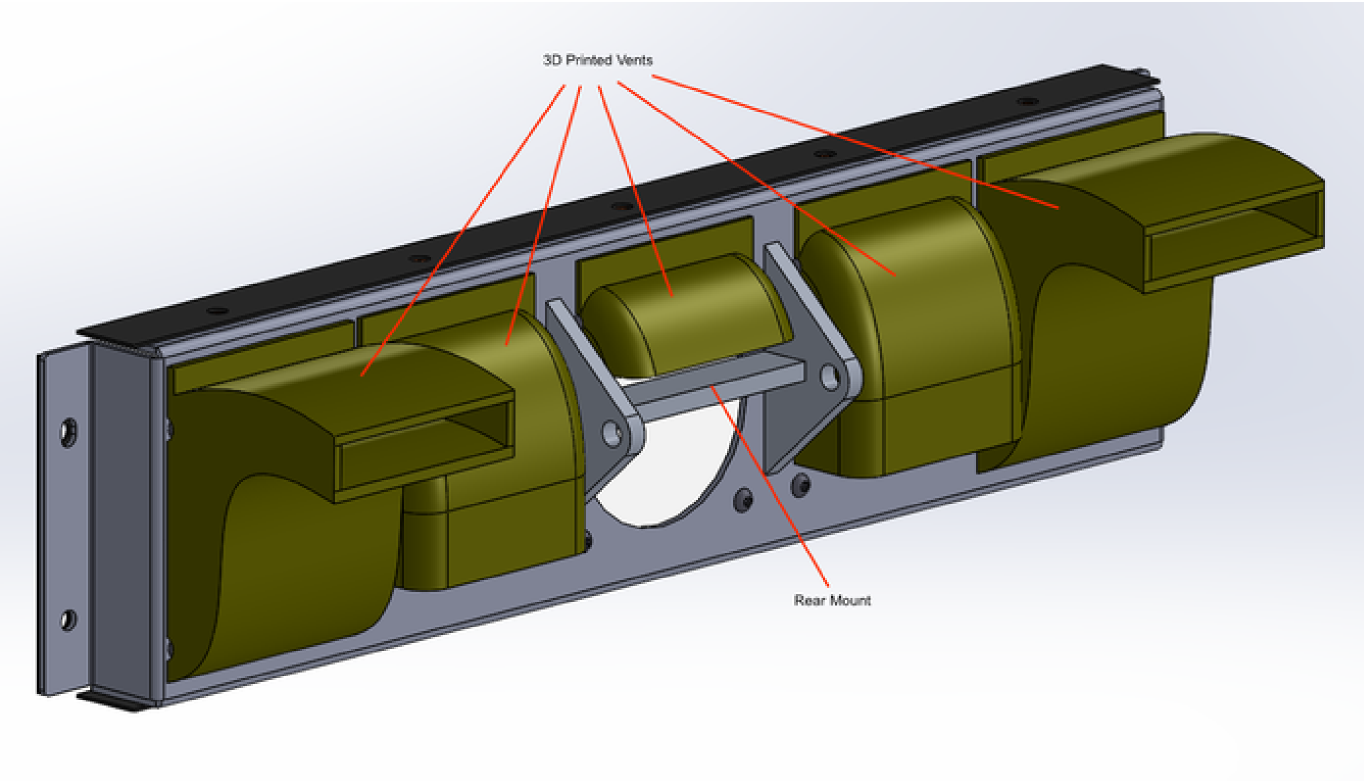
A last option would be the use of a desiccator. In this case, silica gel would be preferable to a molecular sieve, as they are shown to be more effective at humidities greater than 40%. Figure 3.1 depicts the mass of water that would pass through the battery in a 22km race.



It also demonstrates that a large amount of silica would be required, which adds weight to the car. In addition to this, once the silica absorbs water from the air, it will be even heavier. Thus, it is believed that this is not a viable option.

Particle size and its effect on trajectory

The size of a particle has been seen to affect its trajectory. This is due to the fact that after going through a fan, all particles are travelling at roughly the same velocity. Due to their differences in mass, larger particles take a direct path and follow the direction that the fan pushes them in. Lighter particles tend to adhere more to brownian motion and tend to travel more easily through turns. Research has been done on this subject in humans and mice with and particulates travelling through their respiratory tract.



- Machine down mount so that mount fits onto battery. Make sure **gaskets are on** when test fitting
  - mount to be JB welded onto fan assembly.
- 3D print vents and JB weld to rear box (low priority, wait until we get fans working)

Cooling Design Resources

39978385.pdf - THERMAL MODELLING OF COMMERCIAL LITHIUM-ION BATTERIES

Skip to the conclusions section at the bottom, then read this. The summary needs a summary, otherwise it's tough to see the big picture.

- This study evaluates AltairNano batteries, which are a LTO/NMC (anode/cathode) chemistry. They have good safety characteristics, can be briefly discharged/charged at up to 10C, and have long cycle life.
- Battery heating is caused by two distinct processes. One is Joule heating, or resistive heating, that is non-reversible. The second is reversible heating, caused by the electro-chemical reactions in the cell.
  - Batteries can be modeled using a electrochemical model, which tends to be more analytic. It uses physical data to calculate the processes happening inside the battery accurately, but is intensive to run.
  - EIS, or Electrochemical Impedance Spectroscopy can be used to create an equivalent circuit model. It passes a sinusoidal signal through the battery at a variety of frequencies and plots the response.
    - The equivalent circuit model tends to have lower accuracy than an electrochemical model.
- Experimental determination of the battery parameters can be done as follows:
  - Determination of heat capacity of a single cell:
    - A calorimeter is used to calculate the heat capacity of a substance or component by measuring the temperature of an insulated vessel of liquid containing the component before and after a known amount of energy is added.
    - For most battery cells, the specific heat capacity, or heat capacity per unit mass is calculated.
    - For a cylindrical cell, a heating band that is well insulated on the outside is used to raise the temperature of the battery cell. Once a known amount of energy is added, the change in temperature of the cell is used to calculate the heat capacity.
  - Determination of the thermal conductivity of a cell and cell materials:
    - A hot plate with known heat flux applies a thermal load to the component, and the temperature is measured at known part thicknesses.
    - A similar approach measures the temperature at points of the substance while it is contained in a long tube with heat applied from the midpoint of the tube.
    - Several transient approaches can also be used. A hot wire represents an ideal heat source with infinite length and no thickness. As heat spreads from the wire, the temperature change of the part can be measured in real time.
    - Thermal Impedance Spectroscopy has several analogues to the EIS method mentioned above and is used to calculate the specific heat capacity and thermal conductivity of the cell.

- Lithium Ion pouch cells can be optimized for power delivery or energy storage depending on the internal structure. The AltairNano pouch cells in this report, with LTO chemistry, have a structure typical of other cells with LTO chemistry.
- Modeling heating due to resistance losses requires an accurate map of where current is moving in the cell structure. The cell potential difference and the resistance of the electrodes, including the electrochemical resistance, is used to define a plot of heat generation in the cell. The electrochemical resistance, the sum of all effects, varies with charging / discharging frequency, temperature, and SOC. Polynomial curves can be used to represent the resistance of the cell as the SOC or temperature is varied.
- When testing, the electrochemical resistance is the difference between the OCV and the CCV, measured under both charging and discharging conditions. Be careful to maintain the temperature of the cell.
- *I still have lots of stuff to learn about equivalent circuits and filters- at medium to low frequencies, the cell behaves as a capacitor and resistor in parallel. More circuit elements are needed to model all frequencies form 4 mHz to 2 kHz.*
  - The final equivalent circuit chosen for this paper is a voltage source, a resistor, and a resistor in parallel with a constant phase element. These elements in parallel describe the charge transfer and mass transfer effects on the cell.
- After an equivalent model was designed, the cell was tested. The entire SOC range and a wide range of temperatures were swept. Relevant parameters, such as current, temperature, and terminal voltage were also recorded.
  - Note that the effects of charge and mass transfer are clearly seen- the total cell resistance decreases as the cell "relaxes" after discharge.
  - The ohmic resistance of the cell also increases significantly during discharge, as does the direct current resistance. This means much more heat generation occurs in a cell with less energy left in it. An increase in temperature lowers the resistance of the cell.

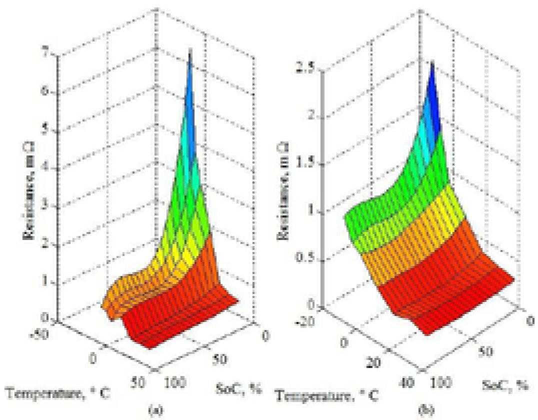


Fig. 2.17: Measured total resistance of the LTO pouch cell as a function of SoC and temperature for discharging (a) and charging (b).

  - As would be expected, the ohmic resistance of the cell does not depend on operating current, but the DC resistance, the element in parallel to the CPE, decreases in resistance until about 3.4 C.
- After this modelling, the researchers were rewarded with excellent correlation of the measured data with their models.
- Heat loss and current density occur in similar regions in the cell- near the cell tabs. This causes a very strong thermal and electrical gradient along the cell, with some parts of the current collector dissipating almost twice as much heat as another region.
  - If the cell tabs are placed on the cell centreline, but on opposite ends, this gradient is mitigated.
- To determine the thermal parameters of the cell, they are first assumed to be an infinite plate.
  - Heat flux across and along the plate is calculated using a number of measured an assumed paramaters.
- After calculating the thermal characteristics, they are measured using an incandescent light bulb heating a stack with the cell sandwiched between materials with known thermal conductivity. The edges of the stack are insulated. Temperature and heat flux sensors are used to measure the characteristics of the outer layers.
  - Interestingly, the thermal parameters of the cell change by about 5% as the SOC is varied.
    - The through-plane thermal conductivity rises as the cell is charged, while the heat capacity drops.
    - This change was within the uncertainty of the measurements, so it is not conclusive.
    - This change was negligible in regions away from the current collectors.
- As described in the paper below and in the section on cell terminal placement above, the cell temperature is highest near the terminals and lowest at the bottom of the cell.
  - This gradient is as much as 6 K, and so would cause the cell to lose performance compared to operating at a higher temperature.
  - To design a cooling strategy, this temperature distribution was used to inform a heat generation map in a simulation.
  - These virtual batteries were then placed into various configurations with passive and active cooling.
- One simple solution is to apply a thin aluminum plate to the face of each cell to make the heat distribution more uniform
  - The cell would have an aluminum plate on one side and a compliant foam pad on the other.
  - This approach maintained a temperature gradient of about 10 K for reasonable thicknesses of aluminum
  - An approach with heat pipes, placed according to an optimization strategy in MatLAB / COMSOL, lowered this difference to 5 K. The maximum temperature was also much lower.
- A commercial battery module was also analyzed, consisting of 10 cells in series, encased in plastic with PCM material beside the cells.
  - Thermal Impedance Spectroscopy was used to analyze the module without disassembling it.
  - The test frequency was low, on the order of 1 mHz to 0.1 mHz.
  - As a whole, the module was modelled as a network of heat sources, transfers, and reservoirs, similar to an electrical network of current sources, resistors, and capacitors.
- **Conclusion**
  - This paper describes in depth some simple methods for experimentally determining the electrical and thermal parameters of a battery cell.

- For a student team, the list below is a good start on making a complete model of the cell.
    - EIS and TIS should be used to generate a model of the battery that can be used to inform laptime simulations.
    - The battery thermal capacity should be measured by insulating the cell while it is under load and measuring the electrical energy dissipated in it.
    - A thermal camera or infrared thermometer should be used to make a measurement of temperature distribution in the cell to inform cooling design decisions.
    - As soon as a segment is assembled, it should undergo the thermal impedance spectroscopy test to generate a model of a whole segment. The segment test setup should be representative of the final installation, including the battery case material or insulation representing another segment.

@ Calvin Ryan DeKoter 27 May 2020 Summarize this paper, make recommendations for our cells

J. Electrochem. Soc.-2015-Wu-A181-91.pdf - Thermal Design for the Pouch-Type Large-Format Lithium-Ion Batteries

Summarize this paper, make recommendations for our cells

batteries-03-00003 (1).pdf - Test Method for Thermal Characterization of Li-Ion Cells and Verification of Cooling Concepts

- This testing is conducted on prismatic cells because the fragile plastic and aluminum skin of a pouch cell cannot withstand the pressure of the sensors.
- Thermal management is vital to extending the lifetime of cells in a battery- cells that are operated outside of their temperature range will be degraded.
    - If cells in parallel have a difference in temperature, the change in internal resistance will drain one of the cells before the others in the cell group, leading to a reduction in the cell's lifetime.
    - Measuring cell temperature during individual testing can be useful to determine how much heat is produced while cycling, but does not accurately represent cell thermal performance in a pack.
    - To better measure the thermal characteristics of a cell as typically packaged, a heat sink with liquid cooling and temperature/heat flux sensors are placed on the cell faces.
        - Each of the 87 sensors sends a temperature feedback signal and a heat flux signal, allowing precise closed loop control over the cell temperature.
        - Each Temperature Heat Flux Sensor also contains a thermo-electric cooler and generator, allowing control over the heat flux through the unit.
- Batteries are characterized by applying a constant current load across the cell. In the case of the cell tested, a 60 Ah LMO cell, is is charged at 2C by one third of its nominal capacity, and then discharged when it reaches the CV phase of charging. This process is repeated for a few cycles because heat generation in Li-Ion battery is not constant.
    - Heat generation is caused by Joule, or Ohmic, heating, as well as reaction heating. The heat generated varies with SOC.
    - Charging and discharging a cell also generates different amounts of heat because the chemical reaction is happening in a different direction.
- The internal structure of these particular prismatic cells means that heat can flow upwards toward the electrical connectors, but is blocked by the plastic insulators that mount the cell tabs inside the battery.
- If the cells are placed face to face, as is preferable the mechanical design aspects, it is advantageous to draw heat outwards through the connectors. This is because of their strong thermal connection to the cell structure compared to the bottom of the cell.

- In future years, batteries should be characterized by placing sandwiching them in between aluminum plates or back to back with another cell under load.
    - Thermocouples embedded in the aluminum plate should be used measure the temperature rise of the cell based on various cooling strategies.
    - Battery thermal characteristics should be one of the first things tested upon receiving the cells- perform a load test with materials that have a known thermal resistance surrounding the cell.

@ Calvin Ryan DeKoter 27 May 2020 Summarize this paper, make recommendations for our cells

Cooling 2018-2020

- Summary
- CAD Information
- Design Philosophy
- Problem Definition
- Rules Compliance
- Constraints and Criteria
- Technical Progress

Accumulator Cooling 2018

- Project Description
- Supporting Information, Project Details
    - Water and Humidity

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Summary

Accumulator cells can produce a lot of heat under load. In order for the them to operate safely and efficiently, they need to stay within a specific temperature range. The accumulator cooling system ensures the cells do not get too hot during use.

CAD Information

- CAD Design Organization - See Accumulator File

Design Philosophy

- "*This part improves over last year's component by ____*"
- *"Do not repeat ____ mistake"*
- *"This design fixes ____"*

Explain each feature of the part and how it accomplishes the part's function.

Problem Definition

Rules Compliance

Rule	Status	Notes	Proof of Compliance
A 1.2	Unknown macro: 'status-handy'	**Paraphrase:** For an electric vehicle, the accumulator may have a maximum usable energy of 5.40 kWh, or nominally 6.75 kWh. (Discharge measured at 2C).	The accumulator will be designed to comply and be tested.

Constraints and Criteria

Constraint	Priority	Description	Value	Unit	Validation Method
Current Capability	Unknown macro: 'status-handy'	Each segment must be able to deliver the full rated current of the Tractive System because the segments are in series. By design, this is 135 A RMS. The pack fuse will be 40 A.	135	A	HTHC

Technical Progress

Accumulator Cooling 2018

Project Description

Develop the cooling system for the battery pack. This includes many parts.

- Thermal characterization
- Airflow simulation
- PCM justification
- Cooling simulation
- Mechanical design
- Cooling sensors
- Cooling testing
- Humidity testing?

Supporting Information, Project Details

Water and Humidity

Moving to air cooling means that we have to consider all the implications of the new system. At Lincoln, we noticed other teams having issues with both water injection into their battery back during the spray down test as well as what seemed to be condensation from the humid air causing problems.

To mitigate these issues a few things have been considered.

- Ducting/baffles that the air has to flow through and uses gravity to restrict water from entering the battery pack. See below for design ideas.
- Using a membrane on the entrance to the cooling system to restrict water from entering and allow air to enter (probably highly restrictive).
- Descant for absorbing humidity and moisture. (this wont work)
- Sealing the airflow passages from the airflow to restrict where condensation is likely to form (implementing this)
- PCM material to average the required heat dissipation through fan cooling leading to lower airflow rates
- Moisture sensors in the bottom of the box to provide information
- Humidity sensors for data collection
- Pressure sensors in the pack for airflow understanding and limiting necessary airflow

PCM Material

Cooling design could include PCM material. This is a wax

Accumulator Cooling

Ducting Design

Can draw air from under the car, but you will have poor airflow due to the low pressure region. Can draw air from sides but then the ducts have to be detachable. Need to have a system to prevent water from coming in.

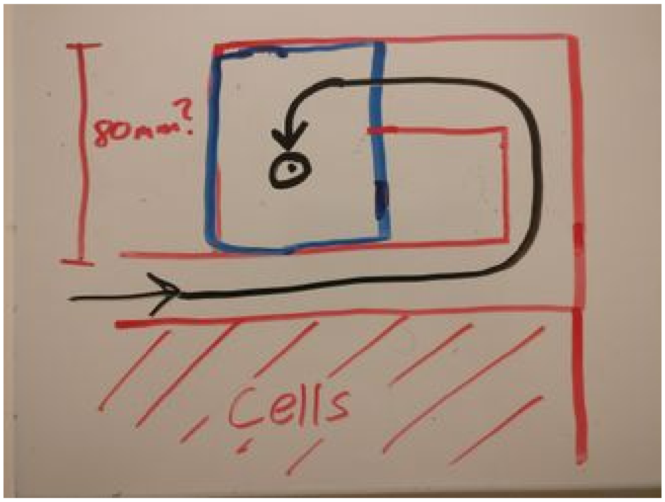
See picture below, the first is a side view, second is a top down view.

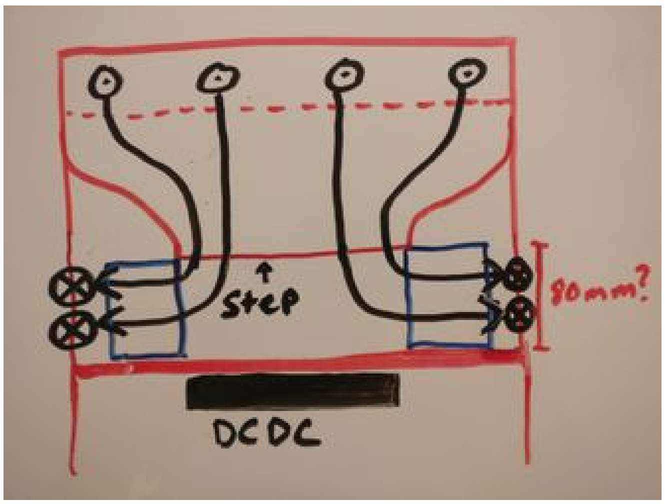
Requirements and Considerations

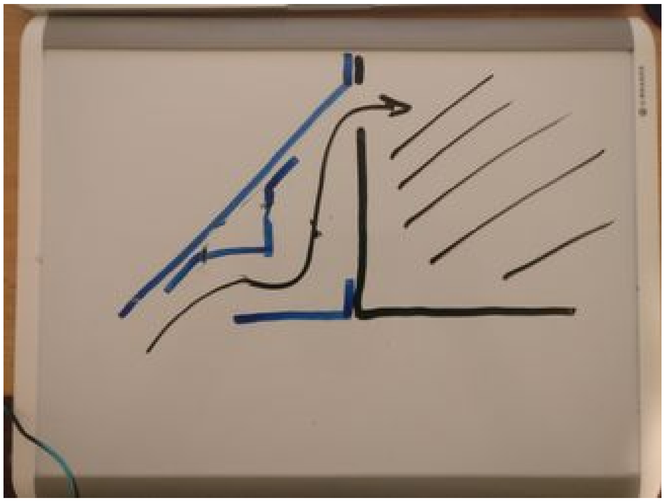
- Protect against water splashing into and through the air cooling system
- Cool the battery bus bars (and ultimately the battery) as well as a DC to DC converter
- Isolate airflow from batteries and sensitive electronics
- Monitor the airflow and temperature with sensors to develop a cooling controller in the future

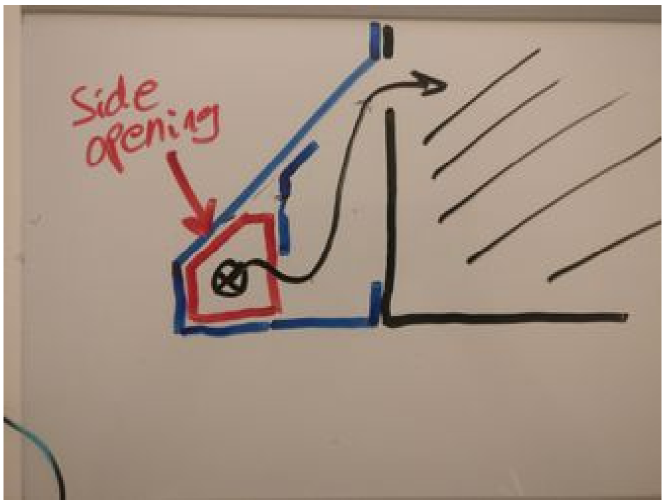
Relevant Rules

Rule Number	Rule Description


80mm?
Cells


step
80mm?
DCDC

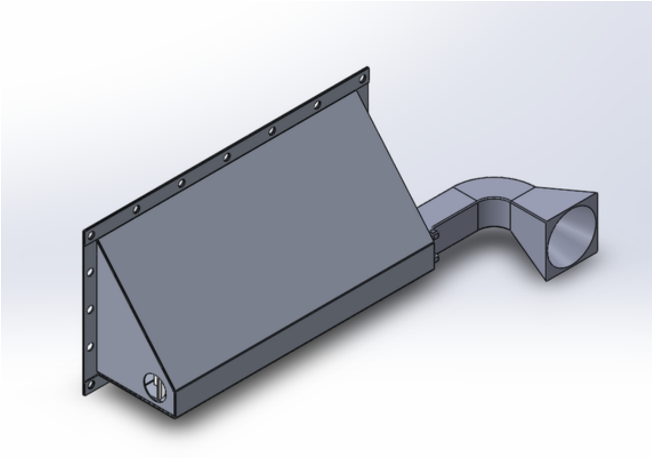


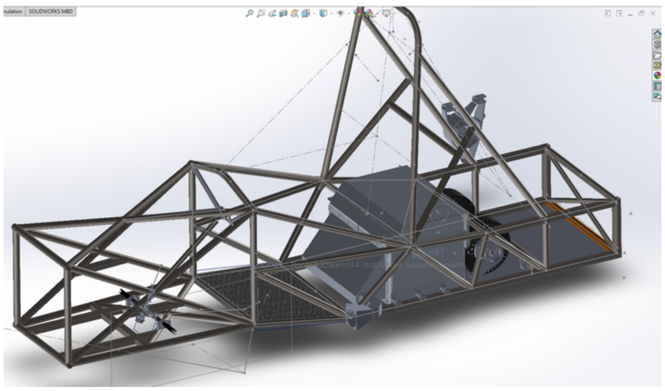


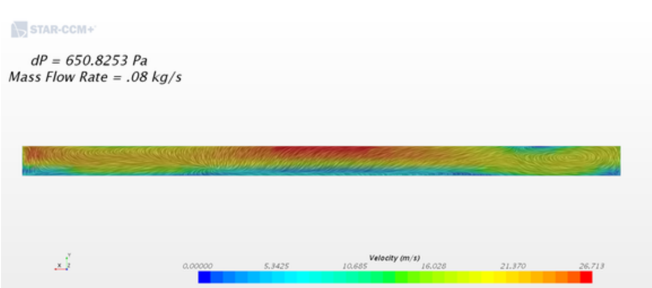
The duct was decided to be made from sheet metal aluminum; this was decided because the duct is not designed to take significant amounts of load, the price of sheet metal aluminum is reasonable and this solution is relatively light. The duct is being sealed using a soft foam single-sided tape around the opening into the battery box.

Arms were designed to be attached to the sides of the duct to collect air flowing along the sides of the car as it's running. The air is evenly distributed across the width of the outlet directed by the fins.The arms will be attached to the duct with a pin through tabs attached to the duct and the arm; this pin will also provide the force to compress foam to keep the design leak resistant. It was decided to use the pin instead of bolts for the speed of assembly.

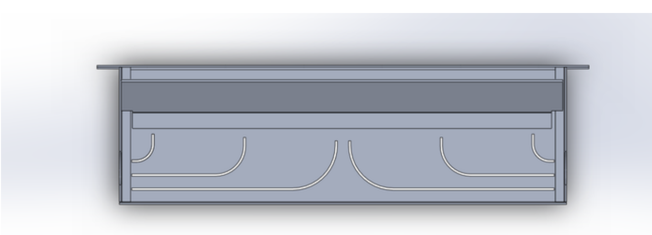
See pictures below, the first picture is a CAD of the duct with the side arm attached on the far side, the second picture is of the duct and arm in position in the most recent MAIN assembly (Nov 5th) the third picture is the flow across the outlet before introduction of fins.

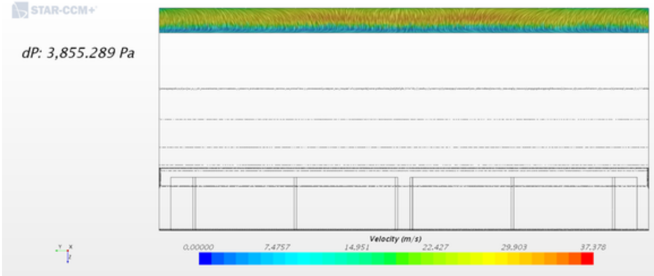






The next set of pictures below are as follows: the first picture below showcases the fins to be 3D printed for distribution of airflow, the second picture is the airflow across the outlet after the introduction of said fins.





Below is a picture of the quick release pin and a link to the one-sided soft foam.

https://electronics.stackexchange.com/questions/255731/copper-or-aluminum-heatsink#

PCM Simulations

Setup

As we do not currently know the exact layout of the battery yet, it is hard to calculate the minimum PCM material needed to see a difference in the lap time simulations. Therefore, a reasonable layout was designed and used for calculations.

@ Calvin Ryan DeKoter Make a task 21 Nov 2019

In our current design, there are 72 positive terminals and 72 negative terminals on cells that are connected in parallel. This gives us 144 sections of aluminum that can be drilled into. I propose drilling 15 cylinders per section for a total of 2160 cylinders. The cylinders will be 0.2cm in diameter and 3.4cm long. They will be arranged in the following configuration

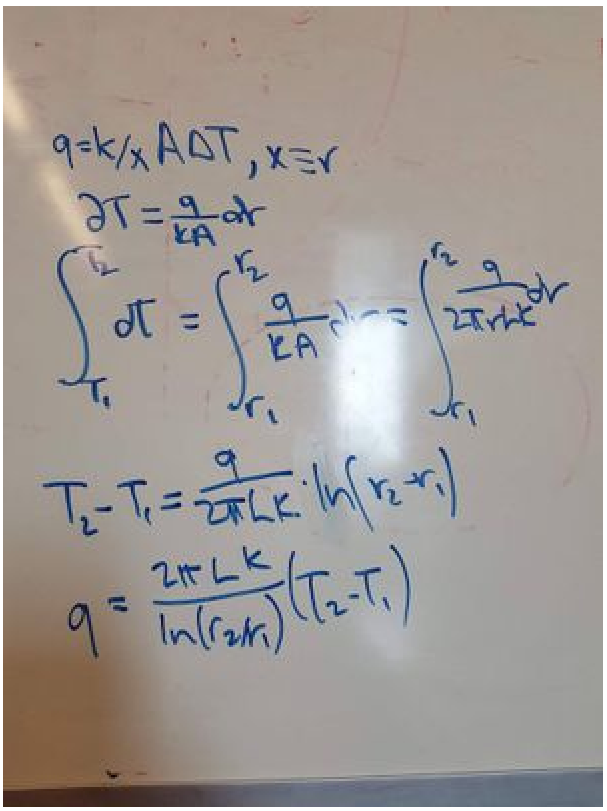
These cylinders will have a total volume of 1447.3cm^3 and will actually help to remove mass from the car as they are less dense than aluminum.

Assumptions

In this simulation, for simplicity's sake, we are assuming that all the heat that enters the aluminum/PCM material stays within it. In other words, no heat is being lost to ventilation. Since this simulation is simply to demonstrate the difference in the chemical behaviors of the aluminum and the PCM, it does not matter that we do not consider air cooling, as long as the same assumptions apply to both materials.

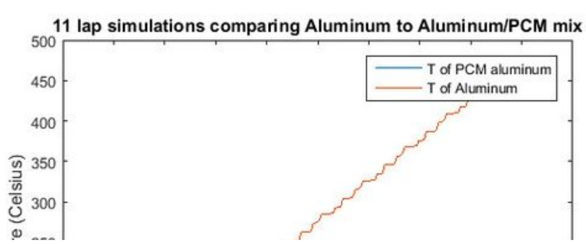
Another assumption that is being made is that there is approximately 11kg of aluminum present to act as a heat sink.

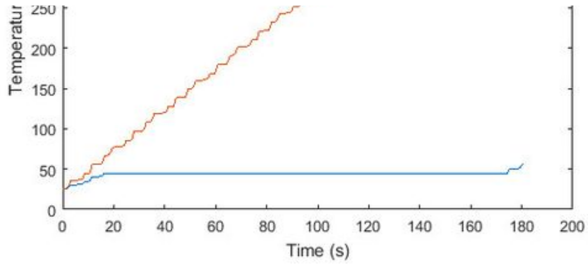
Lastly, we are assuming that for each millisecond of simulation, the heat transfer from aluminum to PCM follows the following derivation:

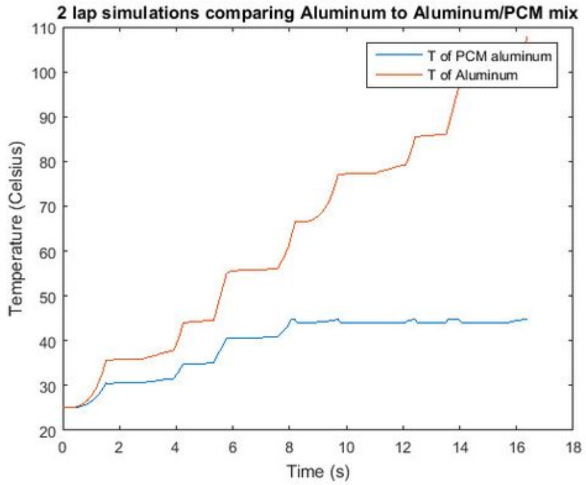


Results

The following graph shows the difference in heat for the battery pack with PCM material and the pack without it.







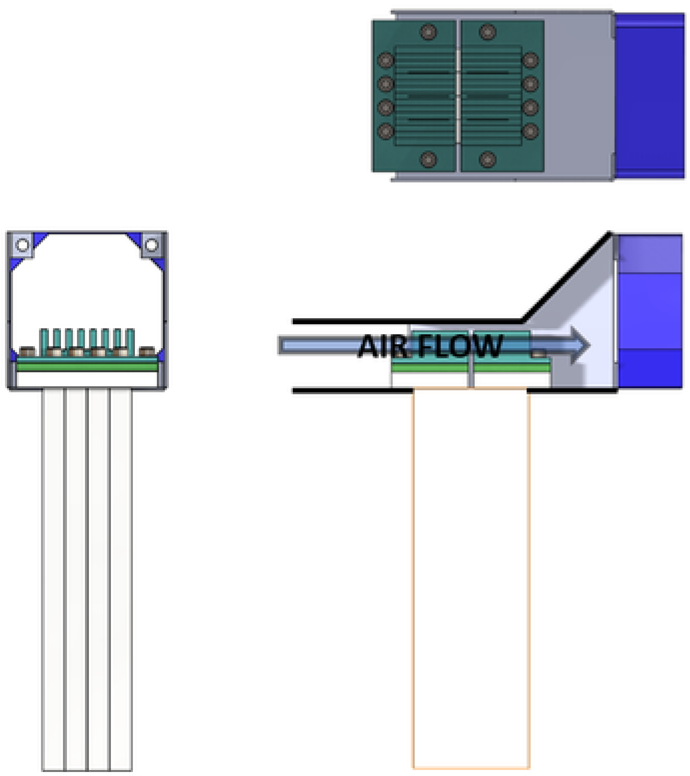
Cooling System Validation

Project Description

- Designing a rig to replicate our cooling system design on a small scale and determine if any changes need to be made
- 4 cells in parallel
- Thermistors to monitor cell and bus bar temperature
- Using fans and wind tunnel to test effect of finned bus bars vs flat
- 6 tests

- Discharge at 1C - any higher we will need larger wiring which will be impractical.

Bus bar	Fan speed
No fins	0%
Fins	50%
	100%

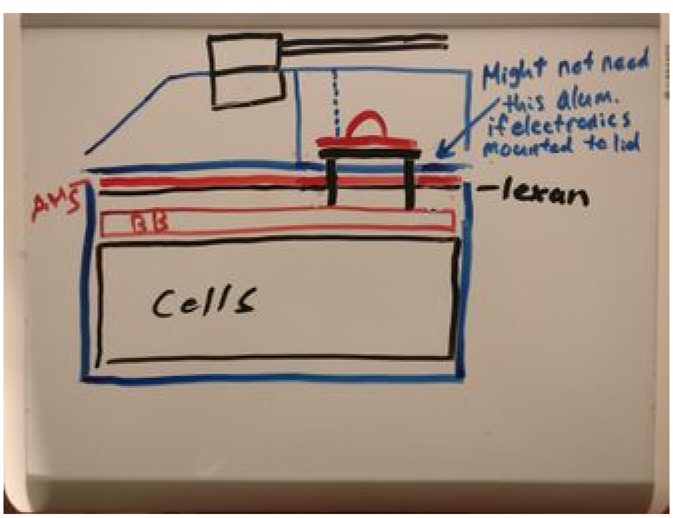


This test is not 100% representative of the actual performance and design in the accumulator module, but it will show the relative effect of changing the above parameters. We will use the data and scale up to actual accumulator size.

Accumulator Box

Supporting Information, Project Details

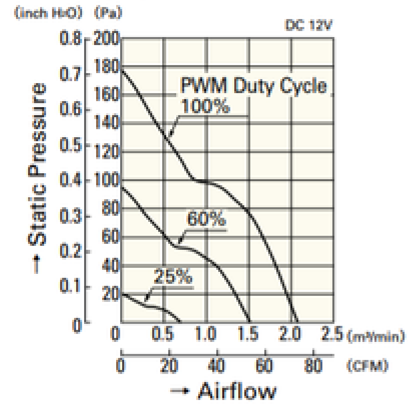
- Electronics can mount to lid, three connections are Main +, Main -, AMS 4 pin
- DC-DC mounting on vertical face, this face is bent to accommodate segment disconnects



Fans Used

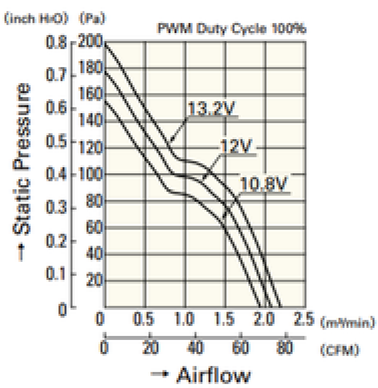
5x 9GA0812P4J001

PWM Duty Cycle



9GA0812P4J001

Operating Voltage Range



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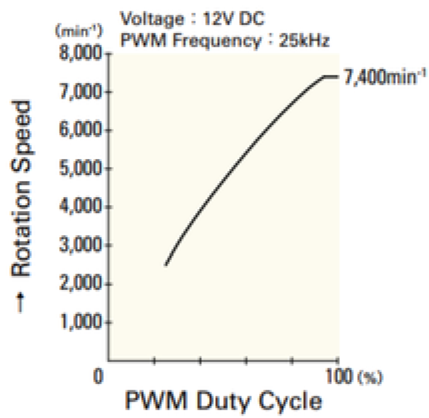
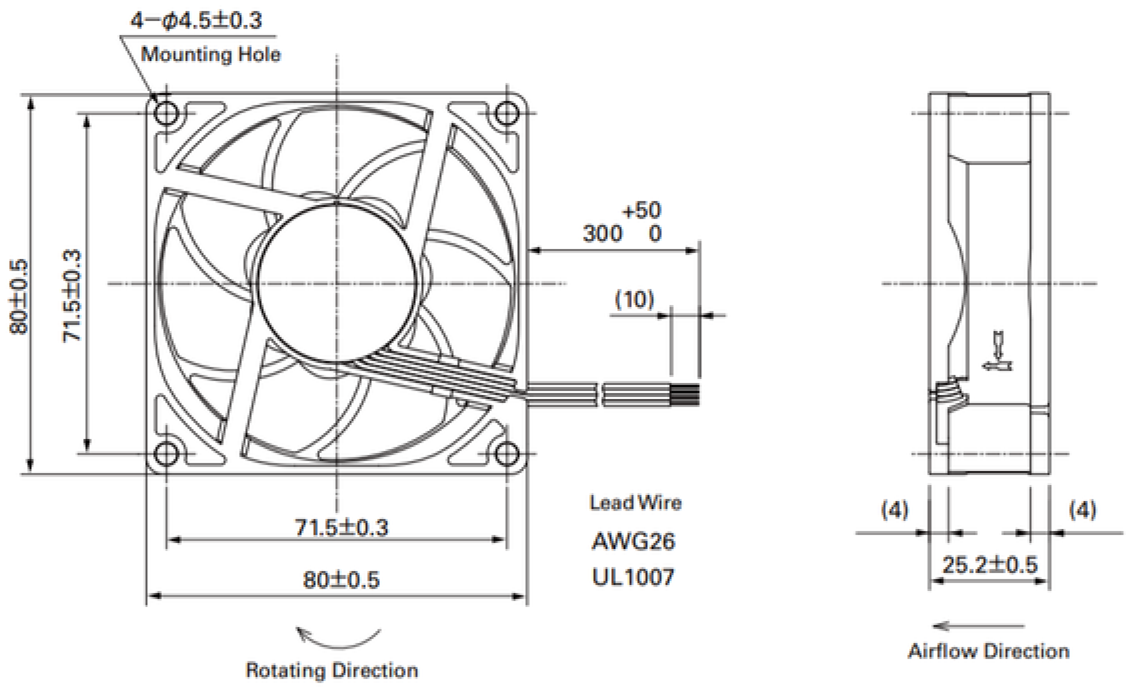
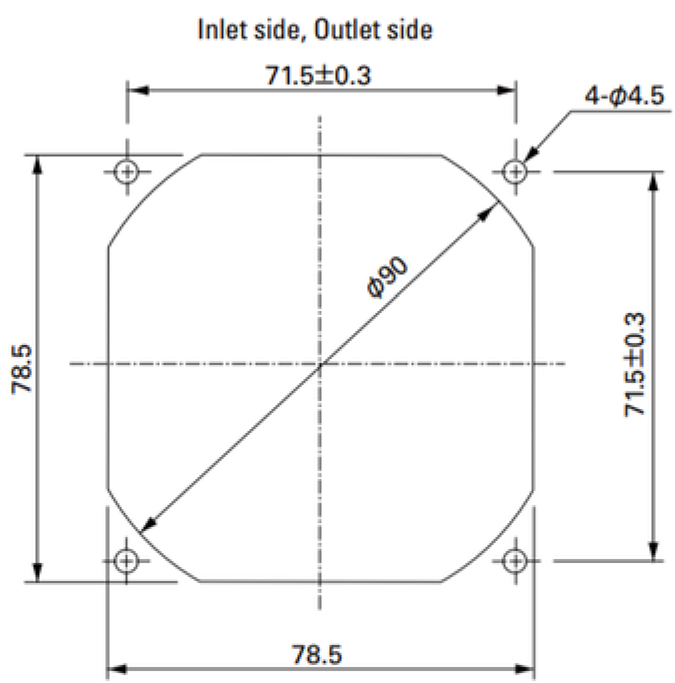


9GA0812P4J001

Dimensions (unit: mm) (With ribs)



Reference Dimensions of Mounting Holes and Vent Opening (unit: mm)

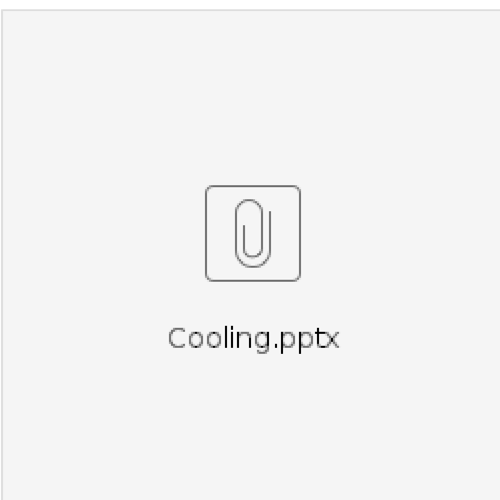


https://www.digikey.ca/product-detail/en/sanyo-denki-america-inc/9GA0812P4J001/1688-1589-ND/6192305

Manufacturer	Sanyo Denki America Inc.
Manufacturer Part Number	9GA0812P4J001

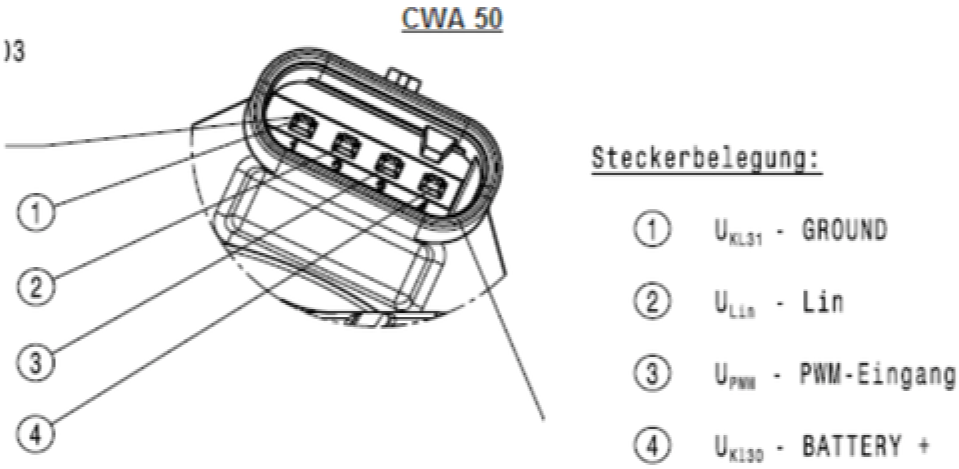
Moisture Sensitivity Level (MSL)	1 (Unlimited time)
Voltage - Rated	12VDC
Size / Dimension	Square - 80mm L x 80mm H
Width	25.00mm
Air Flow	73.0 CFM (2.04m³/min)
Static Pressure	0.700 in H2O (174.4 Pa)
Features	PWM Control, Speed Sensor (Tach)
Noise	48.0 dB(A)
Power (Watts)	7.20W
RPM	7400 RPM
Termination	4 Wire Leads
Operating Temperature	14 ~ 158°F (-10 ~ 70°C)
Weight	0.243 lb (110.22g)
Current Rating	0.600A
Voltage Range	10.2 ~ 12.6VDC
Material - Frame	Plastic
Material - Blade	Plastic
Lifetime @ Temp.	40000 Hrs @ 60°C

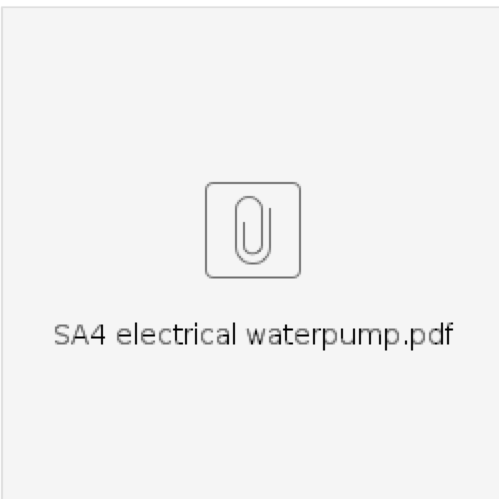
Accumulator Cooling 2016



Pump:

Pierburg CWA50





Cooling 2021

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Summary

@ **a2school@uwaterloo.ca**

During operation, the battery cells generate heat during operation due to the internal resistance and chemical processes happening in the cell. To use the cells to their full potential, it is a must to cool the cells, maintaining their temperature at around 40 °C, potentially more under worst case conditions.

CAD Information

- CAD Design Organization: *Describe how the solid models for the project are organized.*
- CAD for the battery box is currently stored in the conceptual designs folder on GrabCAD - \GrabCAD\2021 Vehicle\2 - Conceptual Designs\05-ACC-000\Packaging_Concepts
- CAD for the cooling ducts is currently stored in the conceptual designs folder on GrabCAD - \GrabCAD\2021 Vehicle\2 - Conceptual Designs\05-ACC-000\21-5-ACC-000

Design Philosophy

- Instead of cooling cell tab of the pouch cell, the 2021 accumulator will cool the entire cylindrical cell.
- EIS and TIS should be used to generate a model of the battery that can be used to inform laptime simulations.
- The battery thermal capacity should be measured by insulating the cell while it is under load and measuring the electrical energy dissipated in it.
- A thermal camera or infrared thermometer should be used to make a measurement of temperature distribution in the cell to inform cooling design decisions.

▪

- As soon as a segment is assembled, it should undergo the thermal impedance spectroscopy test to generate a model of a whole segment. The segment test setup should be representative of the final installation, including the battery case material or insulation representing another segment.
- The battery must protect against splashing into and through air cooling system as battery is no longer sealed; other teams had trouble with the water injection into battery pack during spray down test. In order to mitigate this, some solutions include:
  - Ducting/baffles that the air has to flow through and uses gravity to restrict water from entering the battery pack.
  - using membrane to restrict water
  - pcm material to average the required heat dissipation through fan cooling leading to lower airflow rates
  - Pressure sensors in the pack for airflow understanding and limiting necessary airflow
- batteries and other sensitive electronics should be ISOLATED from airflow

Explain each feature of the part and how it accomplishes the part's function.

Problem Definition

It is necessary for the battery cells in the accumulator to be cooled when under load during vehicle operation. Temperatures of the battery cells must be monitored and managed to protect them from damage and overheating.

Rules Compliance

Rule	Status	Notes	Proof of Compliance
A 1.2	Unknown macro: 'status-handy'	**Paraphrase:** For an electric vehicle, the accumulator may have a maximum usable energy of 5.40 kWh, or nominally 6.75 kWh. (Discharge measured at 2C).	The accumulator will be designed to comply and be tested.

Constraints and Criteria

Constraint	Priority	Description	Value	Unit	Validation Method
Current Capability	Unknown macro: 'status-handy'	Each segment must be able to deliver the full rated current of the Tractive System because the segments are in series. By design, this is 135 A RMS. The pack fuse will be 40 A.	135	A	HTHC

Technical Progress

Design Process

Design Analysis and Manufacturing Design

System Design Goals and Analysis:

Need to design cooling system to have static pressure drop less than 80 Pa based on 16.7 L / s flow rate from fans.

Projected heat generation at autocross current (23 A) is 17 W

Total heat dissipation in accumulator is 8330 W

Without cooling, temperature rise in cells is 87 - 25 = 62 °C

With cooling, temperature rise is roughly 25 °C when the average accumulator current is 130 A.

System design goals were set by finding the overall pack heat generation (parallel cell group resistance * autocross rms current squared * series cell groups, described in "Cell_Heat_Generation_Calculator on GrabCAD) and using a constant Cp mass / heat balance. T_out is the maximum outlet temperature of the accumulator, which was set at 50 °C. T_in is the maximum inlet heat, equal to the air temperature, set at 30 °C.

~50 L / s - **Minimum Flow Rate**

~125 L / s - **Maximum Flow Rate**

**This assumes adequate heat transfer between the cells and the airflow.

Cell Thermal Sim:

****INCOMPLETE****

Analysis Validation

Test Segment Thermal Characteristics:

After the first segment is assembled, use a load bank to draw current from the cells while logging the temperature and current draw, and fan cooling. Will compare thermal model to physical test once segment is built. ****INCOMPLETE****

Test Cell Characteristics:

Once sample cells have been procured, carefully measure the heat capacity, thermal conductivity, and estimate the convective heat loss of each cell.

This could be done by standing the cell on a hot plate, like a 3D printer build plate, and comparing the temperature at either end of the cell. Empirical methods and simulation will be used to find the coefficients of loss and conductivity.

Manufacturing and Implementation

Conclusions

Project Procurement:

Follow the procurement procedure as described in the Operations page Purchase and Reimbursement Procedure and then upload the purchase order spreadsheet to the table below. Consolidate as many purchases into one procurement request to simplify the process.

Generate a Jira task in the appropriate Operations Epic. Label it with *proc_ts* and an (*label specific to this page)* so that it shows up in the table below.

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Team Member Name	Purchase Order Spreadsheet	Quote / Invoice	Order Description	Company Name	Total Cost [CAD]	Status	Storage Location
						NOT YET PROCESSED	

Battery Management System

Cell Voltage Monitoring

Cell Temperature Monitoring

Cell Balancing

State of Charge Measurement

To provide the driver with accurate feedback about the state of charge of the battery, the BMS system needs to understand how the electrical and thermal characteristics of the battery relate to the amount of charge remaining. Two methods are typically used together to ensure an accurate model: Voltage Measurement, where the state of charge is estimated by the relationship of voltage to charge remaining, given by an S-shaped graph, and Coloumb Counting, where an ammeter is used to measure the total amount of charge being removed from the battery and subtract that from the known capacity of each cell.

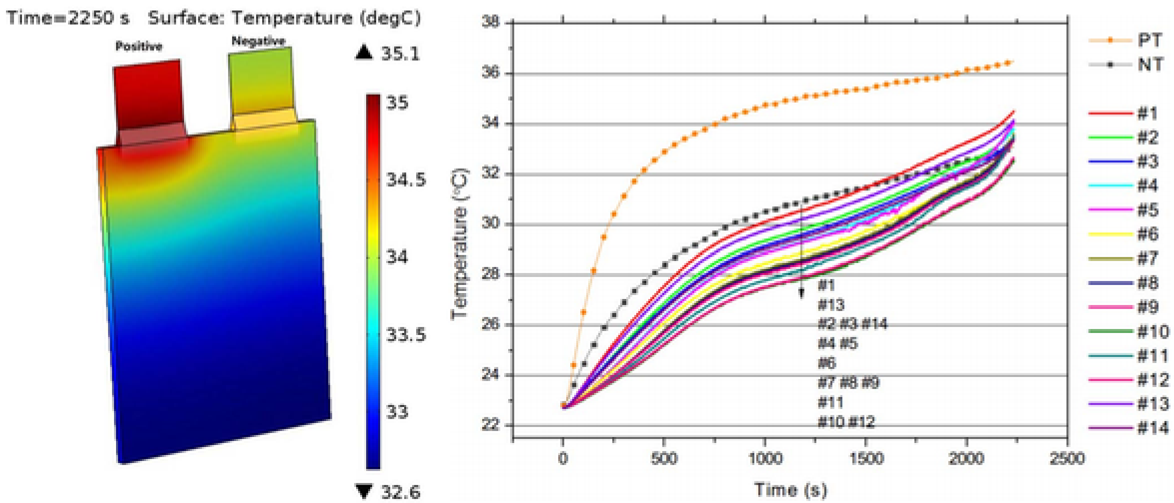
Thermal Design for the Pouch-Type Large-Format Lithium-Ion Batteries : J. Electrochem. Soc.-2015-Wu-A181-91.pdf

@ Joseph Anthony Borromeo 27 May 2020 Read and Summarize this paper

Summary:

- Large pouch cells can have thermal issues such as large temperature variations within the cell which will degrade it faster.
- It is acceptable to model small cells as having a uniform temperature but with large cells a proper thermo-electrical model is needed.
- Contact resistance between cell tab and busbar can significantly influence temperature distribution of the cell
    - This was found to be the largest contributor for the non-uniform temperature in the cell rather than the intrinsic properties of the cell
- Provides a method of experimentally determining the thermal conductivity and specific heat capacities of the cells (Page 3)
- Thermal management of pouch cells should focus on the convective cooling of the tab

Overall: Good paper that dives into great detail about accurate thermal modelling for a pouch cell. Most likely overkill for our team but the main take away is the importance of proper cell tab cooling as that is the main contributor to cell heat generation.



- Shows how the positive tab (PT) heats up the fastest and the most which drives the heating of the rest of the cell

Accumulator Charging

Since a typical battery pack used in Formula SAE events may be up to 10 kWh, charging it quickly is not a trivial task. Modern Lithium Ion cells can be charged very quickly, which allows the battery to absorb huge amounts of energy during regenerative braking. This extends the range of the car and lowers the thermal and mechanical load on the brake system. This space will be used to document charging methods, infrastructure, and ideas.

A Good White Paper on Ultra Fast Charging (10C): Ultra-Fast_Charging.pdf

Charging a battery at a rate ten times higher than it is typically charged at would be a huge advantage.

This paper is written by Isidor Buchmann, CEO & founder of Cadex Electronics Inc.

- Fast charging is charging the battery faster than its one hour discharge load- at a rate higher than 1C. For example, a 6300 mAh cell with an applied load of 6.3 A will be fully drained after one hour. Fast charging would be applying any current higher than 6.3 A to the battery.
- The charging of lithium ion batteries is split up into two parts: the Constant Current phase, where fast or ultrafast charging happens, and the Constant Voltage phase, where the charger maintains the maximum OCV of the battery and allows it to accept the remaining amount of charge.
    - In the constant current phase, the charger applies whatever voltage is required to charge the battery at the set current, which could be up to the 10C rate for ultra-fast charging.
    - In the constant voltage phase, the current is not controlled by the charger meaning that no fast charging can occur.
- Fast or Ultra-fast charging must only be done with cells in good condition and in controlled temperatures. There is a massive risk of battery damage and danger if the charger and BMS cannot monitor and maintain the charging conditions and cease charging in an emergency.

- Fast charging and discharging also wears the battery excessively. In this paper, the example is given of a particular cell that has a capacity of 650 mAh. At 500 cycles at a 1C rate, the battery has a capacity of 550 mAh, but fails after 360 cycles while being loaded and charged at a 3C rate.

@ Calvin Ryan DeKoter 27 May 2020 Read and summarize this paper

Connector Pre-charging and Discharging

Battery Management System 2021

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Summary

Briefly describe the project purpose and current state.

CAD Information

- CAD Design Organization: *Describe how the solid models for the project are organized.*

Design Philosophy

- *"This part improves over last year's component by ____"*
- *"Do not repeat ____ mistake"*
- *"This design fixes ____"*

Explain each feature of the part and how it accomplishes the part's function.

Problem Definition

Rules Compliance

Rule	Status	Notes	Proof of Compliance
A 1.2	Unknown macro: 'status-handy'	**Paraphrase:** For an electric vehicle, the accumulator may have a maximum usable energy of 5.40 kWh, or nominally 6.75 kWh. (Discharge measured at 2C).	The accumulator will be designed to comply and be tested.

Constraints and Criteria

Constraint	Priority	Description	Value	Unit	Validation Method
Current Capability	Unknown macro: 'status-handy'	Each segment must be able to deliver the full rated current of the Tractive System because the segments are in series. By design, this is 135 A RMS. The pack fuse will be 40 A.	135	A	HTHC

Technical Progress

Design Process

Design Analysis and Manufacturing Design

Analysis Validation

Manufacturing and Implementation

Conclusions

Project Procurement:

Follow the procurement procedure as described in the Operations page Purchase and Reimbursement Procedure and then upload the purchase order spreadsheet to the table below. Consolidate as many purchases into one procurement request to simplify the process.

Generate a Jira task in the appropriate Operations Epic. Label it with *proc_ts* and an (*label specific to this page)* so that it shows up in the table below.

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⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Team Member Name	Purchase Order Spreadsheet	Quote / Invoice	Order Description	Company Name	Total Cost [CAD]	Status	Storage Location
						NOT YET PROCESSED	

W20 BMS Wiring and Fusing Evaluation

Project Timeline:

WBS Project Title:

WBS Project Number:

Describe tasks and use the correct tags to show the state of the project.

Status	Unknown macro: 'status-handy
Estimated Completion	25 Mar 2020
Project Deadline	29 Mar 2020
Required to	Yes

Responsibility Cascade:

- *Project Lead:* *@ Joseph Anthony Borromeo*
  - *Enclosure Design:* *@ Rohan Peri*
  - *Assistance:* *@ Caleb David Dueck*
- *Operations sub-team support- Finances, Procurement Project Advisers:*

Design Philosophy:

- *"This part improves over last year's component by ____"*
- *"Do not repeat ____ mistake"*
- *"This design fixes ____"*

Explain each feature of the part and how it accomplishes the part's function.

Run	
Priority	Unknown macro: 'status-handy'

Task list:

- [ ] Check for temperature and voltage rating as well as HV-LV clearances
- [x] Incorporate space for TSAL DC-DC
- [ ] Incorporate space for the TSAL DC-DC into the design of the Enclosure @ Rohan Peri
  - [ ] Check spacing between IMD and Segment Disconnects
  - [ ] Ensure IMD doesn't interfere with handles on acrylic
- [x] DC-DC Isolation not met. Must add insulating cover between board and bus bar @ Rohan Peri 24 Jun 2020

Description

Must Ensure the Accumulator lid meets all the rules and requirements below.

The main checks are for the rated voltage and temperature of the wires within the lid which should be rated for **300V** and **90°C**.

HV/LV clearances should also be checked. TS-TS clearances may not be satisfied for the DC-DC.

Relevant Documentation:

- Confluence page
- Pdf file
- Technical Datasheets.pdf

Rules Compliance

Section	Status	Notes
EV 3.2.2	Unknown macro: 'status-handy'	Soldering in the high current path is prohibited. Exception: surface-mount fuses and similar comp and the rated current
EV 3.2.3	Unknown macro: 'status-handy'	All wires, terminals and other conductors used in the tractive system must be sized appropriately which protects them. Wires must be marked with wire gauge, temperature rating and insulation vo ▪ Alternatively a manufacturer's part number printed on the wire will be sufficient if this numbe to a manufacturer's data sheet.
EV 3.2.4	Unknown macro: 'status-handy'	The minimum acceptable temperature rating for TS wiring is **90°C**
EV 3.2.5	Unknown macro: 'status-handy'	All tractive system wiring that runs outside of electrical enclosures must be either: ▪ (a) Orange shielded, dual-insulated cable rated for automotive application, at least 5 mm ove ▪ (b) Enclosed in ORANGE non-conductive conduit (except for Virtual Accumulator systems w 12)

		Note: UL Listed Conduit of other colors may be painted or wrapped with colored tape
EV3.2.6	Unknown macro: 'status-handy'	Conduit must be non-metallic and UL Listed17 as: (a) Conduit under UL1660, UL651 or UL651A OR (b) Non-Metallic Protective Tubing (NMPT) under UL1696.
EV3.2.7	Unknown macro: 'status-handy'	Conduit runs must be one piece. Conduit splices and/or transitions between conduit and shielded within an enclosure and must comply with section EV3.3.
EV3.2.8	Unknown macro: 'status-handy'	Wiring to outboard wheel motors may be in conduit or may use shielded dual insulated cables. All outside the vehicle frame (but within the roll envelope) must be within conduit.
EV3.2.9	Unknown macro: 'status-handy'	When shielded dual-insulated cable is used the shield must be grounded at both ends of the cabl
	Unknown macro: 'status-handy'	**EV5 TRACTIVE SYSTEM VOLTAGE ISOLATION**
EV5.1.1	Unknown macro: 'status-handy'	All TS wiring and components must be galvanically (electrically) isolated from GLV by separation
EV5.1.2	Unknown macro: 'status-handy'	All interaction between TS and GLV must be by means of galvanically isolated devices such as o isolators or isolated dc-dc converters.
EV5.3.1	Unknown macro: 'status-handy'	Tractive system main current path wiring and any TS circuits that are not protected by overcurren spacing, insulation, or both, in order to prevent short circuits between TS conductors. Minimum sp Insulation used to meet this requirement must adhere to EV5.4.

Maximum Vehicle TS Voltage	TS/TS Within Accumulator Contai	
	Over Surface (Creepage)	Througl
V < 100 VDC	5.3 mm	2.1 m
100 VDC < V < 200 VDC	7.5 mm	4.3 m
V > 200 VDC	9.6 mm	6.4 m

Table 13 – Minimum Spacings[23]

EV5.3.2	Unknown macro: 'status-handy'	Where GLV and TS circuits are present in the same enclosure, they must be segregated (in addit wire) by: ▪ (a) at least the distance specified in Table 13, **OR** ▪ (b) a barrier material meeting the TS/GLV requirements of EV5.4
EV5.3.3	Unknown macro: 'status-handy'	All required spacings must be clearly defined. Components and cables must be securely restraine spacing. **Note**: Grouping TS and GLV wiring into separate regions of an enclosure makes it easier to imple 3.2
EV5.4.2	Unknown macro: 'status-handy'	Insulating materials used for TS/TS insulation or TS/GLV segregation must: ▪ (a) Be UL recognized (i.e., have an Underwriters Laboratories24 or equivalent rating and ce ▪ (b) Must be rated for the maximum expected operating temperatures at the location of use, c (whichever is greater). ▪ (c) Must meet the minimum thickness requirements listed in Table 14

- **Note**: For TS/GLV isolation, insulating material must be used in addition to any insulating covering provided by the wire manufacturer.: For TS/GLV isolation, insulating material must covering provided by the wire manufacturer.

	Minimum Temperature	Minir
TS / GLV (see Note below)	150º C	
TS / TS	90º C	As requi the f

Table 14 - Insulating Material - Minimum Temperat

Expenditures:

Items	Vendor	Payment Method	Cost (CAD/USD)	Form Link	

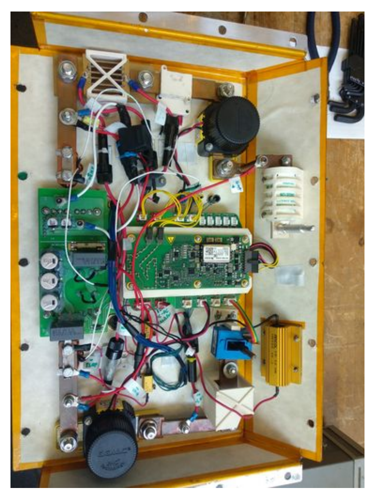
Project Bring-up

Winter 2020 Progress	Details + pictures

BMS 2018-2020

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.



Summary

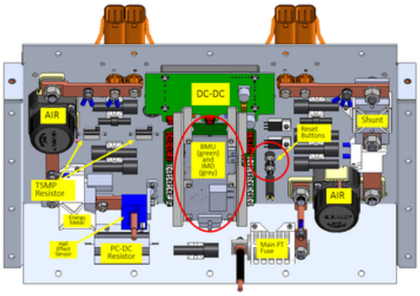
The BMS or Battery Management System is a system found in the Accumulator Lid

CAD Information

Design Philosophy

- The distributed system with the BMU and 6 AMS boards allows separation of

that contains the Accumulator Management System(AMS) and the Battery Management Unit(BMU).
The main goal of the BMS is to ensure the safe operation of the accumulator by taking the signals from the AMS boards, that give voltage and temperature information to the BMU, and uses the information from the BMU in order to make sure that the optimal battery state is maintained.
The BMS also controls the Accumulator Isolation Relays, the precharge/discharge resistors and interfaces with the Insulation Monitoring Device(IMD).



This is the current set up for the BMS system for 2018-2020

- CAD Design Organization: *Describe how the solid models for the project are organized.*

the TS sense and measurement circuits, allowing the BMS to be easily removed from the "Always Energized portion of the Accumulator"

- More care should have been given to cable management.
- This BMS system was designed to be simple and robust, using off the shelf components where safety is critical, such as the IMD.

Technical Details

Insulation Monitoring Device (IMD)

- The IMD is a Commercial Off The Shelf board that determines whether the chassis of the system is electrically isolated from the high voltage systems. To check if the chassis is isolated, the IMD measures the resistance between the high voltage path and a part of the chassis to see if there is any resistance. If the resistance is below a certain threshold(150 kOhm), it will through a fault, signaling that the chassis may not be isolated from the high voltage path.

Precharge/Discharge Resistors(PC/DC)

- The role of the Precharge and Discharge Resistors is to limit the current flowing through the capacitors in the motor controller and DC DC board so that the excess current does not cause the contactors to weld or arc flashes due to the high current. The PC/DC resistor charges the capacitors at around 300mA.

Accumulator Isolation Relays

- The Accumulator Isolation Relays, or the Pack Contactors are electronically controlled switches(similar to relays) that open/close the high voltage path. The current system uses Gigavac GX12B contactors and they are able to shut off all power going through the battery, even while current is running through it, during an emergency.

State of Charge Estimation

1. Introduction

The state of charge of a battery cell is the level of charge relative to the battery capacity, measured as a fraction between 0 and 1. It is beneficial to measure this value for power management purposes. State of charge is not easily directly measured and instead must be estimated based on on constant properties of the cell as well as its dynamic behavior. The general approach is to derive a suitable model for the cell state of charge as a function of several cell parameters. The value of these parameters can be characterized using tests, and the model be used to computationally estimate the battery state during operation.

This process can be described as using these three steps: creating/selecting a suitable battery model, determining the model parameters through battery testing, implementation of model into code as a control algorithm.

2. Battery Modeling

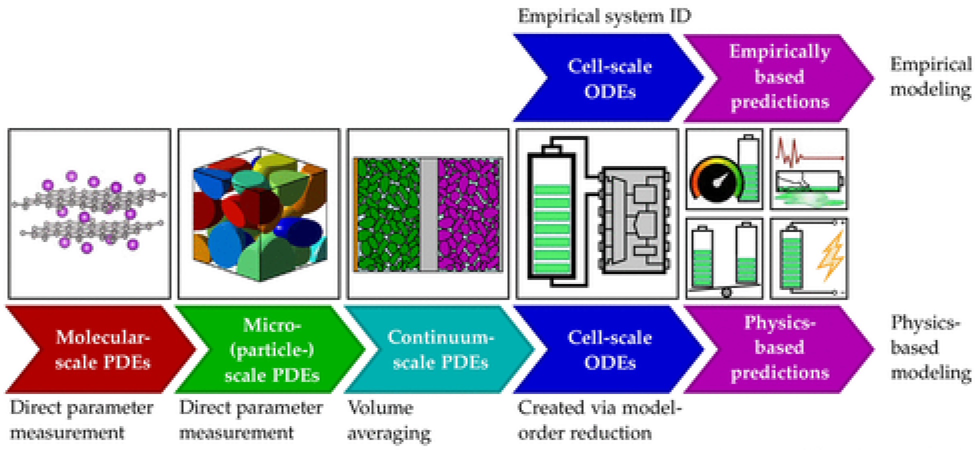


Figure 3.1: Different approaches to making models of lithium-ion cells.

There are two approaches to modeling a cell: physics-based and empirical modeling.

Empirical modeling uses components with mathematically well-defined behaviors to approximate the behavior of a cell, with less concern of what the physical mechanism is that causes the modeled behavior. An example is circuit-based modeling, where cell state-of-charge is modeled using a combination of capacitance, resistance, and efficiency against the cell voltage and current. Since each of these components are well-defined mathematically using at most first-order ODEs, and all components can be combined linearly, the approach leads to a model that is computationally practical to implement in a real-time system. The cell parameters to be evaluated with testing are the constants and scalars in the linear ODE model. That said, empirical modeling is more or less some form of curve fitting, and the model derived, if not comprehensive enough, can be subject to change depending on the operating conditions, like temperature, etc. Therefore, if an empirical model is chosen it is important to test the cell parameters within the full envelope of operating conditions, such that the resulting model can accurately measure state of charge in operation.

Physics-based modeling derives the cell model from physical interactions governing the cell. It is very accurate. However, due to the complexity of the physical relationships themselves (hint: PDEs), complete physical models are computationally impractical to deploy on real-time systems. That said, techniques exist to simplify these models for use on computers.

3. Empirical Models

3.1 Equivalent-Circuit Model

The equivalent-circuit model models a cell is an empirical model (aka behavioral): if it quacks like a goose you better run, whether it is a goose or not. (Do geese quack?) The equivalent-circuit model models a cell in terms of electrical components. Concepts such as hysteresis voltage, internal resistance, etc. are part of this model. We will build this model up from scratch, starting with the components having most effect.

Common notation in this section:

z(t) is state of charge, alternatively referred to as SOC

v(t) is the battery terminal voltage

i(t) is the battery terminal current

Q is the battery capacity

3.1.1 Open-Circuit Voltage

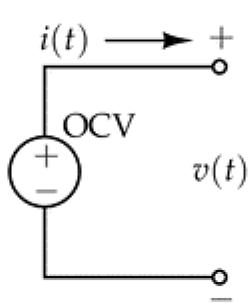


Figure 2.1: Trivial cell model having constant output voltage.

The most basic cell model is a constant voltage source, depicting the voltage measured across cell terminals at no load. It assumes that voltage remains constant regardless of anything else like load current, state-of-charge. It's garbage but it's a starting point, we leave that here.

Open-circuit voltage is dependent on battery state-of-charge, and the latter can be estimated from the former. The OCV may be the most apparent indication of cell state-of-charge.

Firstly, let's define state-of-charge in electrical terms:

$$\dot{z}(t) = -\eta(t)i(t)/Q,$$

Where z_dot(t) is the first derivative of state of charge, z(t). n(t) is a measure of coulombic efficiency, i(t) is current supplied by the cell, and Q is the total cell capacity (Ah). n(t) is difficult to measure, it is <=1, but otherwise depends on SOC, charge/discharge rate, temperature, and internal cell states. We integrate to find z(t):

$$z(t) = z(t_0) - \frac{1}{Q}\int_{t_0}^{t} \eta(\tau)i(\tau)\, \mathrm{d}\tau$$

In discrete-time:

$$z[k+1] = z[k] - \frac{\Delta t}{Q}\eta[k]i[k]$$

Recognizing that open-circuit voltage v(t) depends on state of charge z(t), we can now define v(t) as:

v(t) = OCV(z(t))

Where OCV is the relationship between the two, in other words, it is the equation for any of these lines:

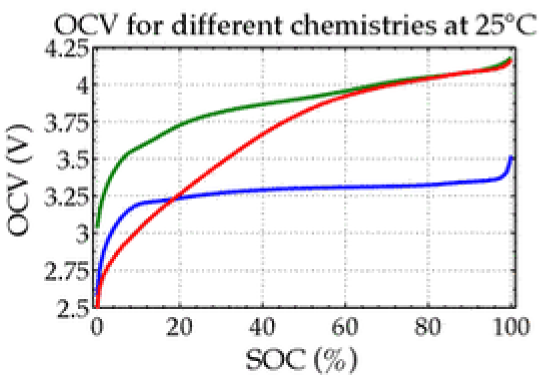


Figure 2.2: Open-circuit voltage as a function of state of charge for several common lithium-ion cell chemistries.

Note that the relationship given is a static relationship, it describes a cell at equilibrium, and ignores changes in the relationship between terminal voltage and state-of-charge as a result of dynamic conditions (ex. if we are drawing current). Our equivalent-circuit model becomes:

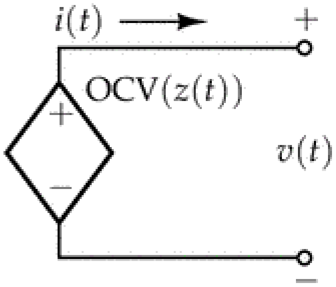


Figure 2.3: Improved cell model, with SOC-dependent voltage.

The above equations tell us two things. Firstly, by measuring open-circuit voltage v(t), we can determine z(t) provided we have tested and curve-fitted a relationship OCV(z(t)). Secondly, we can determine z(t) by knowing z(t0), i(t), Q, and n(t). This already gives us two methods for estimating battery state of charge: measuring the voltage, or counting the time integral of current.

3.1.2 Equivalent Series Resistance

We add the first dynamic elements to our static model: equivalent series resistance.

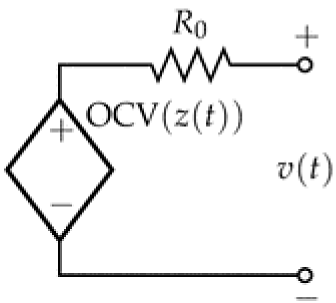


Figure 2.4: Improved cell model, with SOC-dependent voltage and equivalent series resistance R_0.

This resistance causes v(t) to vary with OCV(z(t)) and i(t)*R0. From Kirchoff's voltage law:

v(t) + i(t)*R0 = OCV(z(t))

v(t) = OCV(z(t)) - i(t)*R0

And so: we have, in continuous- and discrete-time (top and bottom, respectively):

$$\dot{z}(t) = -\eta(t)i(t)/Q$$
$$v(t) = \mathrm{OCV}\big(z(t)\big) - i\big(t\big)R_0$$

$$z[k+1] = z[k] - \frac{\Delta t}{Q}\eta[k]i[k]$$
$$v[k] = \mathrm{OCV}\big(z[k]\big) - i[k]R_0$$

It's late at night and I'm just going to quote from the book:

"Finally, we note that the cell’s resistance is often a function of the cell’s state of charge and is always a function of the cell’s internal temperature. The fidelity of the model’s predictions will be enhanced if these dependencies are taken into account in R0. This model of a cell is sufficient for many simple electronic-circuit designs. However, it is not yet adequate for applications in large-scale battery packs, such as for electric-drive vehicles and grid-storage systems. There are several other dynamic features that must be addressed."

3.1.3 Diffusion Voltages

Polarization voltage describes how v(t) deviates from OCV(z(t)) as current is drawn from the cell. i(t)*R0 the equivalent series resistance can tell us the instantaneous polarization, however, real observed cell behavior shows non-instantaneous behavior. Rather than a v(t) decreasing in a step-function as a step-function current is drawn, we see the following:

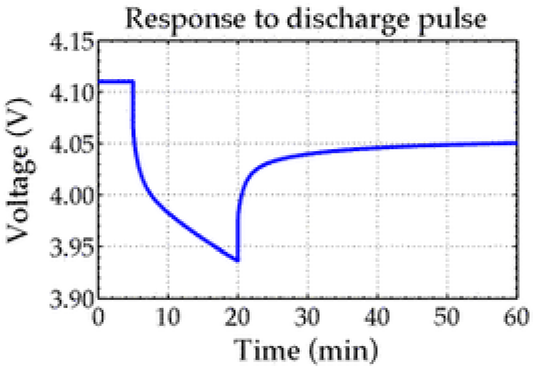


Figure 2.5: Polarization evident when a cell is subjected to a discharge pulse followed by a rest.

This behavior looks convenient like a discharging capacitor, so guess what we'll use:

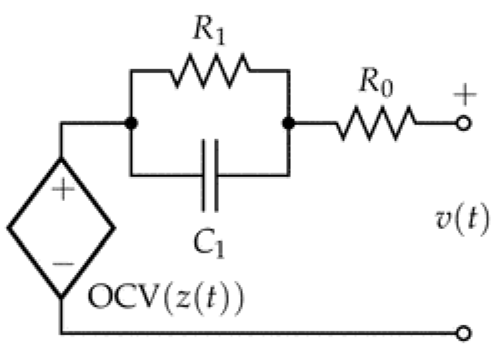


Figure 2.6: Circuit that now models diffusion voltages.

This model now accounts for the behavior of the cell voltage v(t) dropping when a current is drawn, only to recover once the current is removed. From KVL:

$$v(t) = \mathrm{OCV}(z(t)) - v_{C_1}(t) - v_{R_0}(t)$$

We know OCV(z(t)) and VR0(t) = i(t) * R0, but what about Vc1(t)? Recognizing that KCL mandates the current in c1 and R1 to sum to i(t), applying the capacitor equation, and then doing some math, we arrive at this set of equations defining our cell (in continuous time):

$$\begin{aligned} \dot{z}(t) &= -\eta(t)i(t)/Q \\ \frac{\mathrm{d}i_{R_1}(t)}{\mathrm{d}t} &= -\frac{1}{R_1C_1}i_{R_1}(t) + \frac{1}{R_1C_1}i(t) \\ v(t) &= \mathrm{OCV}\big(z(t)\big) - R_1 i_{R_1}(t) - R_0 i\big(t\big). \end{aligned}$$

When I have more time I will detail this proof, for now it is up to the reader (HAHAHAHA).

In discrete time, because that's what the embedded computer will see:

$$z[k+1] = z[k] - \frac{\Delta t}{Q}\eta[k]i[k]$$

$$i_{R_1}[k+1] = \exp\left(-\frac{\Delta t}{R_1C_1}\right)i_{R_1}[k] + \left(1 - \exp\left(-\frac{\Delta t}{R_1C_1}\right)\right)i[k]$$

$$v[k] = \mathrm{OCV}(z[k]) - R_1 i_{R_1}[k] - R_0 i[k].$$

3.1.4 Warburg Impedance

The Randles circuit is a equivalent-circuit model of a cell with some basis in the actual cell electrochemistry. It produces a circuit as follows (OCV not shown):

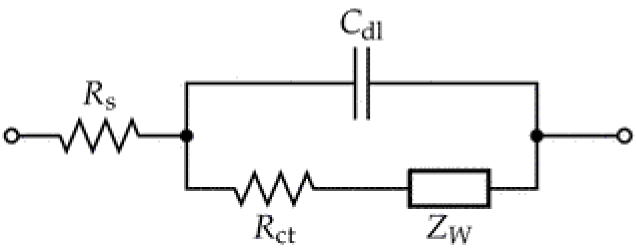


Figure 2.8: The Randles circuit.

Rs models the electrolyte resistance, Rct measures the charge transfer resistance, Cdl is the double-layer capacitance, which models the charge buildup at the contact surface between the electrolyte and electrodes, Zw is the Warburg impedance. The Warburg impedance models diffusion of lithium ions in the electrodes, and is frequency-dependent:

$$Z_W = A_W / \sqrt{j\omega}$$

Aw is the Warburg coefficient. The effect of Zw becomes pronounced at low frequencies (evident from above definition). At intermediate frequencies, the cell impedance is dominated by the charge-transfer dynamics, modeled by the Rct and Cdl. This is visible on the following Nyquist plot:

(Still working on this part, let me figure out how to make sense of the Nyquist plot first - or somebody can add in here if they have knowledge)

The Warburg impedance can be approximated by a series of parallel resistor-capacitor pairs, as follows:

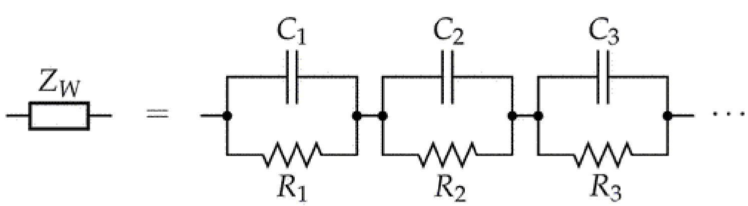


Figure 2.10: Approximating a Warburg impedance with multiple resistor–capacitor subcircuits.

To accurately represent Zw, an infinite number of these RC pairs are needed. However, if the device only needs to operate within a limited frequency, a limited number of RC pairs can be used as required. Furthermore, unless the cell is operated at a very high frequency, the effect of Cdl is usually small. Therefore, the circuit in Figure 2.8 collapses back to Figure 2.6 above, just with more RC pairs than the single one shown.

3.1.5 Hysteresis Voltages

From our existing equivalent-circuit model in Figure 2.6, we would expect that if cell current i(t) = 0, then V across R0 and the R1c1 pair would be 0 (VR0 decays instantly, Vc1 will decay with time). Therefore, the cell terminal voltage v(t) would converge on OCV. However, experiment shows this not to be the case. Instead, the steady-state v(t) value will vary depending on recent history of cell use. If a cell is discharged to 50% SOC, its terminal voltage v(t) may be slightly lower than OCV. If it is charged to 50% SOC, v(t) may be slightly higher. This suggests hysteresis behavior.

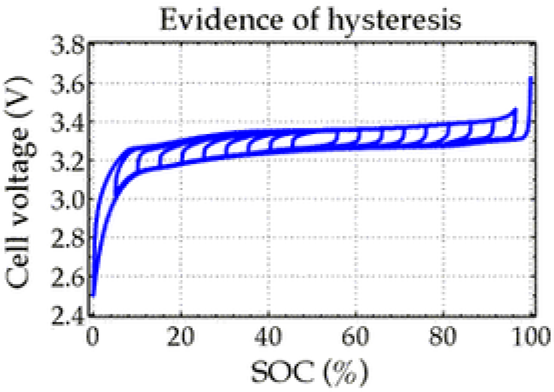


Figure 2.11: Cell test data giving evidence of hysteresis.

The above chart shows the following. 1. fully charged (100% SOC) cell is slowly discharged (rate <= C/30) down to 0%, the slow discharge rate means the cell is basically static, and so v(t) ~ OCV, which in turn depends on z(t) (this is the method to determine the OCV vs. z(t) relationship, as we will discuss later). The cell is charged slowly to 95%, then quickly discharged to 5%. This shows the difference between the supposed equilibrium voltage of a static cell vs the same SOC but arrived at in a dynamic discharge process.

Note that hysteresis voltages are different from diffusion voltages. Although both cause deviation of v(t) from OCV at a certain SOC (z(t)), cell voltage deviation from OCV caused by diffusion voltage recovers with time, while hysteresis voltage does not. Hysteresis effects on the v(t) vs z (t) relationship can be very large.

To make matters worse, it is possible for the amount of hysteresis to vary with z(t). We therefore represent hysteresis voltage h as a function of both z and t: h(z, t). The following differential equation applies:

$$\frac{\mathrm{d}h(z,t)}{\mathrm{d}z} = \gamma \operatorname{sgn}(\dot{z})\big(M(z,\dot{z}) - h(z,t)\big)$$

M(z, z_dot) is the maximum polarization due to hysteresis as a function of SOC and change of SOC. It is positive during charging (z_dot > 0), and negative during discharge (z_dot < 0). M can be thought of as the upper- and lower-most lines on Figure 2.11. h(z,t) is the present hysteresis voltage. Taken together, the term (M(z, z_dot) - h(z, t)) represents the difference between the current hysteresis polarization and the major hysteresis loop, which is bounded by the upper- and lower-most lines of Figure 2.11. Gamma is a positive constant of proportionality, and sgn (z_dot) is is the sign of z_dot (i.e. +1 or -1). The equation states that the rate of change as a function of SOC dh/dz of the hysteresis voltage is proportional to the difference between the current hysteresis voltage and the hysteresis loop, and the rate of change will cause h(z, t) to decay towards the hysteresis loop (top or bottom of the loop, depending on the sign of z_dot).

Every other equation we have used in our model thus far is a function of time, so we multiply both sides of the above equation with dz/dt, and then copy the rest of the explanation shamelessly directly from the book cited:

$$\frac{\mathrm{d}h(z,t)}{\mathrm{d}z}\frac{\mathrm{d}z}{\mathrm{d}t} = \gamma \operatorname{sgn}(\dot{z})\big(M(z,\dot{z}) - h(z,t)\big)\frac{\mathrm{d}z}{\mathrm{d}t}.$$

We use the chain rule to write the left-hand side of the equation as $\mathrm{d}h(z,t)/\mathrm{d}t$, and we substitute $\mathrm{d}z/\mathrm{d}t = -\eta(t)i(t)/Q$ into the right-hand side, noting that $\dot{z}\operatorname{sgn}(\dot{z}) = |\dot{z}|$. Thus,

$$\dot{h}(t) = -\left|\frac{\eta(t)i(t)\gamma}{Q}\right| h(t) + \left|\frac{\eta(t)i(t)\gamma}{Q}\right| M(z,\dot{z}).$$

After integration and discretization, we arrive at the following equation. The intermediate math is important but left out here for brevity, please review the sources.

$$h[k+1] = \exp\left(-\left|\frac{\eta[k]i[k]\gamma\Delta t}{Q}\right|\right)h[k] - \left(1 - \exp\left(-\left|\frac{\eta[k]i[k]\gamma\Delta t}{Q}\right|\right)\right)\operatorname{sgn}(i[k])$$

$$\text{Hysteresis voltage} = Mh[k]$$

h[k] in the above equation is different from h(t) in the previous equations. Rather than representing hysteresis voltage, it represents a value between 0 and 1. M*h[k], in turn, represents the hysteresis voltage. During the derivation,

-M*sgn(i[k]) was used to represent M(z, z_dot). By dividing out M from the equation, we are left with sgn(i[k]). M is a cell parameter that should be tested for.

In addition to hysteresis caused by dynamic operation, we also add an instantaneous hysteresis element for when the direction of current is changed (ex. during charging or regenerative braking, when current direction may switch often).

$$s[k] = \begin{cases} \operatorname{sgn}(i[k]), & |i[k]| > 0; \\ s[k-1], & \text{otherwise.} \end{cases}$$

$$\text{Instantaneous hysteresis voltage} = M_0 s[k]$$

Our overall hysteresis voltage is represented by:

$$\text{Hysteresis voltage} = M_0 s[k] + Mh[k]$$

3.1.6 Enhanced Self-Correcting Model

We now put together everything we've discussed into the ESC model. Enhanced means we're taking into account the hysteresis. Self-correcting means that at no current condition, the predicted cell voltage approaches OCV + hysteresis, and at constant-current conditions, the model gives the OCV + hysteresis - i*Rtotal.

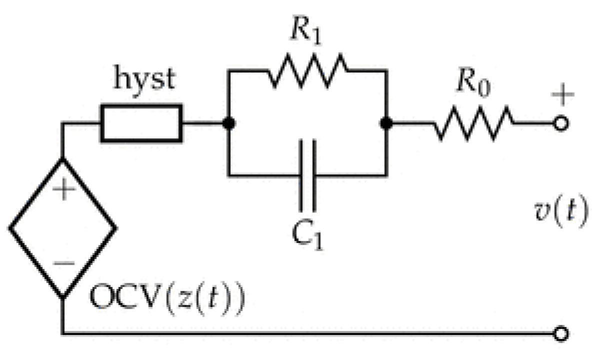


Figure 2.12: The enhanced self-correcting cell model equivalent circuit.

The diagram shows only 1 Warburg impedance/diffusion voltage RC pair. Multiple can be accommodated, with each represented as a series RC group.

3.2 Testing for Equivalent Circuit Model

3.2.1 OCV and n(T) - Static Parameters

OCV is a function of z(t) and temperature. To isolate this parameter (the OCV v. SOC curve), charge and discharge very slowly (C/30) to avoid exciting the dynamic portions of this model while measuring Ah and v(t). Because it is not possible to completely isolate OCV from dynamic components (ex. hysteresis) during testing, test charge and discharge and then average the curves.

To start: charge cell to 100% at 25C (as specified by manufacturer - for example charge at CC until Vmax, then charge at CV until charge current < Imin)

Below is copied from the book:

OCV test script #1 (at test temperature)
1. Soak the fully charged cell at the test temperature for at least 2 h to ensure a uniform temperature throughout the cell.
2. Discharge the cell at a constant-current rate of C/30 until cell terminal voltage equals manufacturer-specified vmin.

OCV test script #2 (at 25C)
3. Soak the cell at 25C for at least 2 h to ensure a uniform temperature throughout the cell.
4. If the cell voltage is below vmin, then charge the cell at a C/30 rate until the voltage is equal to vmin. If the cell voltage is above vmin, then discharge the cell at a C/30 rate until the voltage is equal to vmin.

OCV test script #3 (at test temperature)
5. Soak the cell at the test temperature for at least 2 h to ensure a uniform temperature throughout the cell.
6. Charge the cell at a constant-current rate of C/30 until the cell terminal voltage equals vmax. OCV test script #4 (at 25C)
7. Soak the cell at 25C for at least 2 h to ensure a uniform temperature throughout the cell.
8. If the cell voltage is below vmax, then charge the cell at a C/30 rate until the voltage is equal to vmax. If the cell voltage is above vmax, then discharge the cell at a C/30 rate until the voltage is equal to vmax.

Record voltage, cumulative Ah charged, cumulative Ah discharged periodically. Measure and maintain test temperature during each charge or discharge process.

The above data can be used to determine Coulombic efficiency, at 25C this is most straightforward:

$$\eta(25\,^\circ\mathrm{C}) = \frac{\text{total ampere-hours discharged in all steps at } 25\,^\circ\mathrm{C}}{\text{total ampere-hours charged in all steps at } 25\,^\circ\mathrm{C}}$$

Note that we don't know the SOC of the cell at the end of steps 2 and 6, which is why steps 3-4 and 7-8 are required at 25C to bring the cell to our standard (defined at 25C) 0% or 100% SOC, we use this to find:

$$\eta(T) = \frac{\text{total ampere-hours discharged}}{\text{total ampere-hours charged at temperature } T} - \eta(25\,^\circ\mathrm{C})\frac{\text{total ampere-hours charged at } 25\,^\circ\mathrm{C}}{\text{total ampere-hours charged at temperature } T}.$$

i.e. if you can discharge more Ah at T than at 25C to get to Vmin, then your n(T) is higher than n(25C). Here is some sample data for your viewing pleasure:

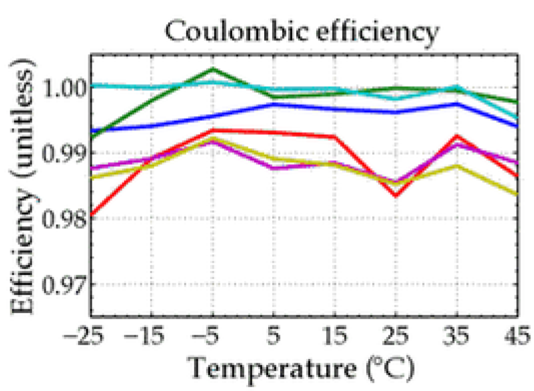


Figure 2.16: Sample coulombic efficiencies for six different lithium-ion cells.

With n(T) and n(25C), we can calculate depth of discharge (t), where depth of discharge is measured in Ah and therefore state of charge z(t) = 1 - depth of discharge(t)/Q:

$$\begin{aligned}&\text{depth of discharge}(t) = \\ &\quad \text{total ampere-hours discharged until } t \\ &\quad - \eta(25\,^\circ\text{C}) \times \text{total ampere-hours charged at } 25\,^\circ\text{C until } t \\ &\quad - \eta(T) \times \text{total ampere-hours charged at temperature } T \text{ until } t.\end{aligned}$$

After step 4 in the procedure above, z(t) = 0, after step 8, z(t) = 1.

Using t as the parameter in a parametric curve, we can plot v(t) as a function of z(t) after some manipulation of the above given formulas, here's some sample data:

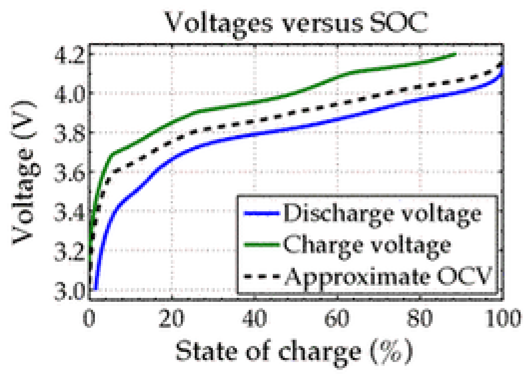


Figure 2.17: Unprocessed voltage data from slow-discharge and slow-charge test, used to determine OCV.

You would need multiple curves to obtain curves at different T. Once you have curves at multiple T, you can create a full OCV model using the following:

$$\text{OCV}(z(t), T(t)) = \text{OCV0}(z(t)) + T(t) \times \text{OCVrel}(z(t))$$

where OCV0(z(t)) is the base OCV curve at 0C (or some other reference temperature), and OCVrel(z(t)) with units (V/C) is a linear correction factor for temperature that varies with z(t).

This can be computed using 2D table lookups and is very efficient. More on that later.

The methods here rely on z(t) being 0% at the end of step 2 and 100% at the end of step 6. However due to hysteresis this may not be totally possible. Experimental evidence suggests that applying a voltage to the cell through a frequency sweep (chirp) of very low amplitude (+/- 0.1V from current cell terminal voltage) which will get rid of any hysteresis effects.

Although cell capacity Q stays the same throughout different temperatures, changes to n(t) and internal resistance with temperature means the discharge capacity of the cell varies with temperature.

3.2.2 Dynamic Parameters

It is beneficial when testing for dynamic properties to exercise the cell at the current v. time profile that is expected of the application.

Fully charge the cell to 100% at 25C, and use the following procedure.

Copied straight from the book:

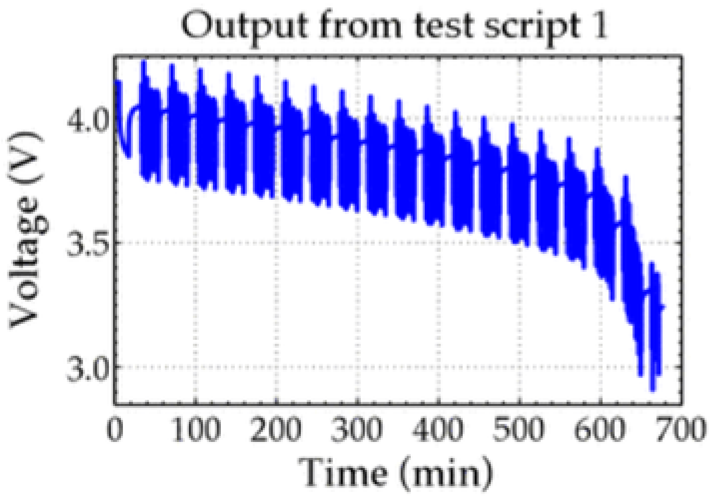
Dynamic test script #1 (at test temperature)
1. Soak the fully charged cell at the test temperature for at least 2 h to ensure a uniform temperature throughout the cell.
2. Discharge the cell using a constant current at a C/1 rate long enough to deplete about 10 % of capacity (helping ensure we avoid over-voltage conditions during random charging portions of the dynamic profile).
3. Execute dynamic profiles over the SOC range of interest, nominally from 90 % SOC down to 10 % SOC.

Dynamic test script #2 (at 25C)
4. Soak the cell at 25C for at least 2 h to ensure a uniform temperature throughout the cell.

5. If the cell voltage is below vmin, then charge the cell at a C/30 rate until the voltage is equal to vmin. If the cell voltage is above vmin, then discharge the cell at a C/30 rate until the voltage is
equal to vmin. Follow-on dither profile(s) can be used to eliminate hysteresis to the greatest degree possible.

Dynamic test script #3 (at 25C)
6. Charge the cell using a constant current at a C/1 rate until voltage is equal to vmax. Then, maintain voltage constant at vmax until current drops below C/30. Follow-on dither profile(s) at the end can be used to help eliminate hysteresis.

V, I, Ah discharged, Ah charged, and temperature data should be collected at frequent time intervals, and can then be used to identify all remaining ESC model parameters with exception of OCV and SOC, as previously determined. The following figure is example data for executing a current v. time test profile repeatedly.



This data can be used to find Q, n, ESR, hysteresis parameters, and RC values for diffusion voltage.

The idea: choose a set of parameter values, simulate to see if it matches the experimental curve, change the values, check again to see if it's closer, rinse and repeat until a good match is found.

Do this through a script.

To ensure the resultant model is not just some local minimum in the error between experiment and model parameters, need to start with reasonable values. For example, at the start of the dynamic testing procedure (script 1), the cell is at 100% SOC, and is 0% at the end of script 2.

Other techniques are available to obtain initial values to the optimization problem.

3.3 Summary

Empirical models are computationally manageable, but lack predictive power over the long term. They cannot account for cell aging (the model must be retuned as the cell ages), predict cell failure, and may provide inaccurate results when used with conditions very different from the stimuli supplied during testing. This lack of predictive power and limitation of usefulness to expected operating conditions makes them less well-suited to highly variable use patterns and for applications where cell usage needs to be controlled to maximize both life and utility. Hence the use of physics-based models.

4. Physics Models

Physics-based models are computationally expensive but can model a cell using very few measured parameters. With some math, the computational complexity can be reduced.

These models range in scale. They can be molecular scale that concerns itself with the behaviors of each molecule, or these individual behaviors can be averaged into a larger, homogenous microscale particle. Going bigger, these particle-scale behaviors can be averaged into continuum scale models, where the electrolyte and solid material is no longer considered separate. Finally, these can be converted to equations describing the cell at the cell-scale, at which point the computational requirement can be similar to the empirical equivalent circuit model.

4.1 Microscale Model

All of these physics models ultimately come down to two things: conservation of charge and conservation of mass.

1. Charge conservation in the homogeneous solid:

$$\nabla \cdot \mathbf{i}_s = \nabla \cdot (-\sigma \nabla \phi_s) = 0.$$

2. Mass conservation in the homogeneous solid:

$$\frac{\partial c_s}{\partial t} = \nabla \cdot (D_s \nabla c_s).$$

3. Mass conservation in the homogeneous electrolyte:

$$\frac{\partial c_e}{\partial t} = \nabla \cdot (D_e \nabla c_e) - \frac{\mathbf{i}_e \cdot \nabla t_+^0}{F} - \nabla \cdot (c_e \mathbf{v}_0)$$

4. Charge conservation in the homogeneous electrolyte:

$$\nabla \cdot \mathbf{i}_e = \nabla \cdot \left(-\kappa \nabla \phi_e - \frac{2\kappa RT}{F} \left(1 + \frac{\partial \ln f_\pm}{\partial \ln c_e} \right) \left(t_+^0 - 1 \right) \nabla \ln c_e \right) = 0$$

5. Lithium movement between the solid and electrolyte phases:

$$j = \frac{i_0}{F} \left\{ \exp\left(\frac{(1-\alpha)F}{RT} \eta \right) - \exp\left(-\frac{\alpha F}{RT} \eta \right) \right\}$$

Starting with the first two equations, describing conservation of mass and charge in the solid electrolyte.

The flow of electricity through a cell is caused by the movement of lithium ions and electrons. The rate at which these move across normal a surface is described as the flux. If we normalize flux across a unit area or volume, it becomes flux density, and is measured in A/m^2 for electrons and mol/m^2/s for lithium ions. The surface across which the ions/electrons are moving can be a physical boundary, such as that separating the electrolyte and electrode, or some imaginary plane within the electrode, the rest of the derivation uses the convention that the flux is across a plane in the x direction, i.e. (x, y, z) and (x+a, y, z). To find flux, we need to know the properties of the area, and also the direction and strength of flow across the area, or the vector field.

Flux only accounts for the flow normal a surface, so we must dot the vector field of flow with the normal vector of the surface:

$$\text{flux} = \iint_S \mathbf{F}(x,y,z) \cdot \hat{\mathbf{n}} \, \mathrm{d}S$$

, or for a closed surface (completely enclosing a volume)

$$\text{flux} = \oiint_S \mathbf{F}(x,y,z) \cdot \hat{\mathbf{n}} \, \mathrm{d}S$$

In addition to flux, we need Ohm's law to model the resistance encountered by the flow. For a microscale model for flow that is not in one linear direction but assumed to flow across a linear medium, we have

$$\mathbf{i} = \sigma \mathbf{E}$$

Where i is the current density, a vector function of (x, y, z, t), sigma is material conductivity (inverse of resistance), a scalar function of (x, y, z, t), E is the electric field, another vector function of (x, y, z, t). Electric field (ignoring magnetic effects) is the gradient of the electric potential at a point (x, y, z, t). Gradient operator points in the direction of steepest ascent. Electric field at a location (x, y, z, t) therefore points in the direction of the greatest change in electric potential relative to that point. We substitute this description into the Ohm's Law we have above.

$$\mathbf{E} = -\nabla \phi$$

$$\mathbf{i} = -\sigma \nabla \phi$$

The negative sign accounts for the factor that positive E is from high to low electric potential, but the gradient (delta) function gives direction of steepest low to high value. Otherwise, this is just the familiar Ohm's Law V=IR, but written with conductivity I=gV, and then made into 3D for microscopic (point form) use.

We model the net current of a particle as current in and out of a volume, which is bounded by a surface:

$$i = -\oiint_S \mathbf{i} \cdot \hat{\mathbf{n}} \, \mathrm{d}S$$

A net charge is supplied to this volume by I over time t, therefore:

$$i = \frac{\mathrm{d}Q}{\mathrm{d}t}$$

The below equation relates charge density of the volume pv to the I over the surface:

$$\oiint_S \mathbf{i} \cdot \hat{\mathbf{n}} \, \mathrm{d}S = -\frac{\mathrm{d}}{\mathrm{d}t} \iiint_V \rho_V \, \mathrm{d}V$$

Some more math - will add later

Basically, all of this fancy math goes to show that within any homogeneous volume inside the cell, charge is conserved (net out net in is 0), i.e. the function describing charge flow at any given point has a divergence of 0.

Conservation of mass in solid and liquid.

Will add explanation for this later - this is derived from some chemical equations.

For now, the following notation is used:

- $\mathbf{N}(x, y, z, t)$ [$\mathrm{mol\,m^{-2}\,s^{-1}}$] is the (vector) *molar flux density* of lithium flowing through a representative cross-sectional area of the solid that is centered at a given location.
- $D(x, y, z, t)$ [$\mathrm{m^2\,s^{-1}}$] is a material-dependent parameter called the *diffusivity*. A large value for D means that it is easy for lithium to move; a small value for D means that it is difficult for lithium to move.
- $c(x, y, z, t)$ [$\mathrm{mol\,m^{-3}}$] is the concentration of lithium in the neighborhood of a given location.

j is the lithium flux out of a particle.

$$D_s \left. \frac{\partial c_s}{\partial r} \right|_{r=R_s} = -\bar{j}$$

4.2 Continuum-Scale Models

Continnum-scale models volume average the properties of microscale models over particles of solid and small volumes of electrolyte. These models provide coupled PDEs that can describe the cell operation and provide cell design parameters related to the size of particles, volume and dimensions of the cell, etc.

4.3 State-Space Models and Discrete-Time Realization Algorithm

We average the coupled PDEs from continuum-scale models further to create cell-level, discrete time, and ODE-based models that conserve some of the fidelity of the previous models.

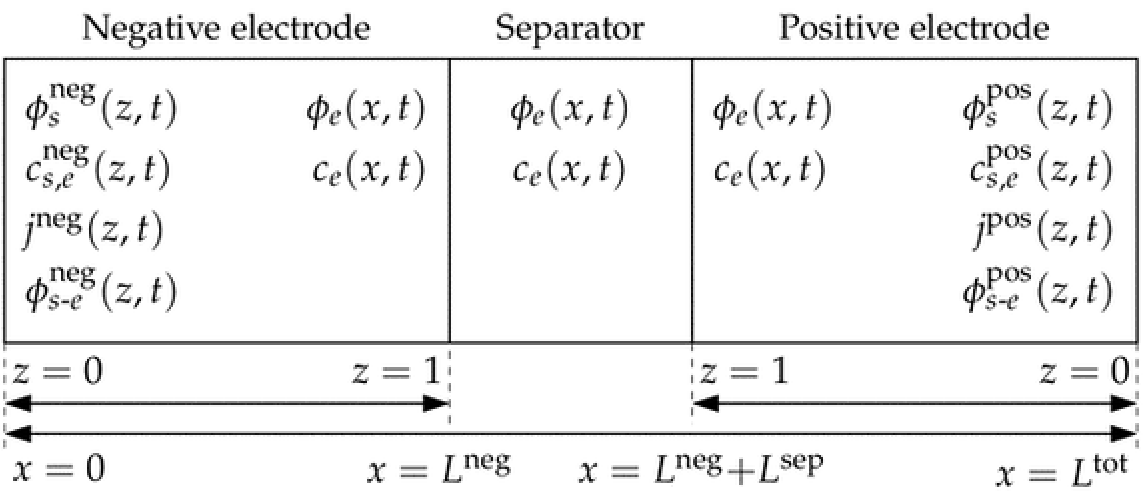
For those unfamiliar - the internal state of a system is the minimum amount of information at t0 that, when combined with the input u(t), t>=t0, can uniquely determine all the system outputs for all t>=t0. That is to say, the state captures the cumulative effect of all past inputs.

This comes from transfer function Csolid(s)/J(s)

$$\widetilde{C}_{s,e}(s) = \frac{R_s}{D_s}\left[\frac{1}{1 - R_s\sqrt{s/D_s}\coth(R_s\sqrt{s/D_s})}\right] J(s)$$

Rs is the radius of the particle of interest.

4.4 Reduced Order Model



5. Pack-Level Cell Simulation - ESC Model

$$v_{\text{pack},k} = \left(\sum_{j=1}^{N_s} v_{j,k}\right) - N_s R_{\text{interconnect}} i_k$$

To get pack voltage, need to account for series cell voltage + interconnect resistance.
Parallel cell modules - for cell j at time k in a parallel cell group, vk is the same but ij,k is different due to individual cell differences.

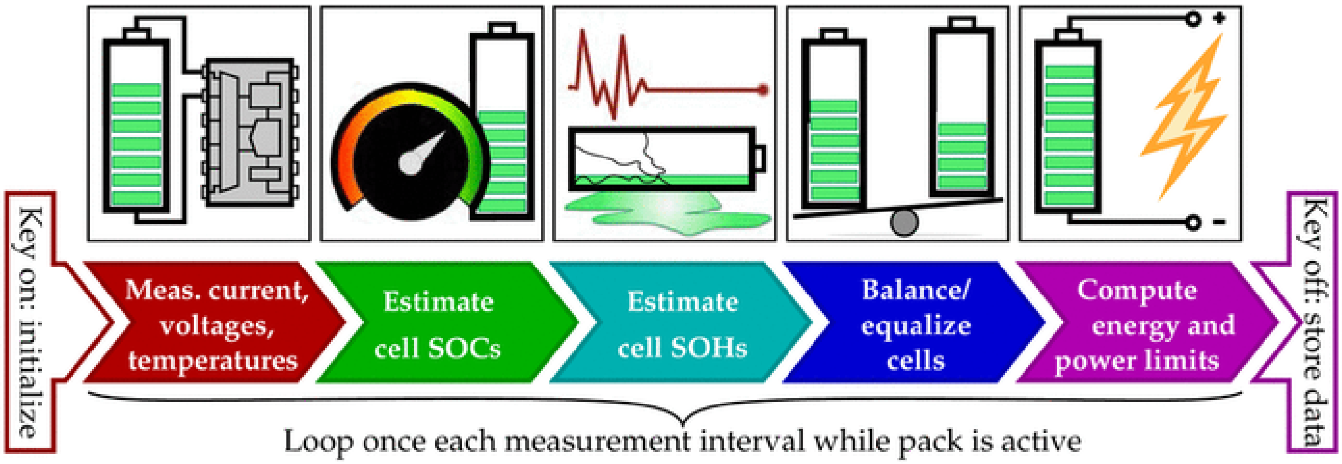
$$i_{j,k} = \frac{v_{fj,k} - v_k}{R_{0,j}}$$

Sum all currents for the module and arrive at overall module voltage:

$$i_k = \sum_{j=1}^{N_p} \frac{v_{fj,k}}{R_{0,j}} - v_k \sum_{j=1}^{N_p} \frac{1}{R_{0,j}}$$

$$v_k = \frac{\sum_{j=1}^{N_p} \frac{v_{fj,k}}{R_{0,j}} - i_k}{\sum_{j=1}^{N_p} \frac{1}{R_{0,j}}}$$

Where vf denotes the "fixed voltage" of the cell, that includes its hysteresis and diffusion voltages as well as its OCV. R0j is a generalized term for the cell internal resistance.



A better definition of state of charge:

$$z_k = \frac{\theta_k - \theta_{0\%}}{\theta_{100\%} - \theta_{0\%}}$$

Where theta is the ratio of c/c_max, where c is the concentration of lithium at the negative electrode.

Cell balancing

Basic definitions: a balanced battery pack is where all cells have the same SOC at some point in the charge-discharge cycle.

i_net = i_app + i_self-discharge + i_leakage

Different values of i_self-discharge + i_leakage between series cells cause imbalance. SOC diverges between "strong" and "weak" cells with each charge-discharge cycle (weak cells don't charge to as high a level, and get discharged deeper, hitting the min. V first).

Based on basic definition of a balanced pack, a few things do not cause cell imbalance:

- Different cell capacities provided the cells charge/discharge at the same rate (i.e. i_self-discharge + i_leakage is the same between the two), they will always arrive at 100% SOC at the same time, thus no divergence in cell SOC throughout charge-discharge cycles. It also satisfies our definition of balanced cells above. You could still use active balancing to keep the SOCs between the two cells identical for optimal performance. But this at least guarantees the condition of the battery won't deteriorate to unusable due to imbalance.
- Different internal resistance may cause the terminal voltage to be higher, but no change to current (KCL)

https://ocul-wtl.primo.exlibrisgroup.com/permalink/01OCUL_WTL/5ob3ju/alma999986623680305162

Vol II

https://ocul-wtl.primo.exlibrisgroup.com/permalink/01OCUL_WTL/5ob3ju/alma999986623688605162

(sorry better citations are coming soon)

W20 Charge Cart Evaluation

Project Timeline:

WBS Project Title:

WBS Project Number:

Describe tasks and use the correct tags to show the state of the project.

Status	Unknown macro: 'status-handy'
Estimated Completion	20 Mar 2019
Project Deadline	20 Mar 2019
Required to Run	
Priority	Unknown macro: 'status-handy'

Responsibility Cascade:

- *Project Lead:* *@ Joseph Anthony Borromeo*
  - *@ Former user (Deleted)*
  - *Sub-team core member*
- *Operations sub-team support- Finances, Procurement Project Advisers:* *@ Former user (Deleted)*

List the people with ultimate responsibility (sub-team leads), project champions, and people who will aid during the 'sprint' phase of the project.

The cascade should also describe the flow of ownership if the original project champion is unable to finish the task.

Design Philosophy:

- *"This part improves over last year's component by ____"*
- *"Do not repeat ____ mistake"*
- *"This design fixes ____"*

Explain each feature of the part and how it accomplishes the part's function.

Task list:

- Ensure all wiring is rated for the proper temperature and voltage. Ensure all grounding is correct @ Joseph Anthony Borromeo, 20 Mar 2020
- Check EV12.2.2 @ **Joseph Anthony Borromeo**, 20 Mar 2020

- Documentation can be found in 2020 Charger Cart and 2020 Charger Controller
- Ground CAN wire shielding Add plug shielding pin into BMU connector ground. On other end ensure shielding is grounded to CCU. Ensure CCU is grounded to the charge cart
- Ensure Charger is grounded
- Ensure charge cart is grounded to the charger case and if the charger case is grounded to the wall earth

Description

Must Check charge cart and charging rules compliance.

The main checks are for the rated voltage and temperature of the wires within the lid which should be rated for **300V** and **90°C**.

HV/LV clearances should also be checked

Relevant Documentation:

- Confluence page
- Pdf file
- Technical Datasheets.pdf

Rules Compliance

Charging Specific Rules

Section	Status	Notes	Documentation
EV 12.2.2	Unknown macro: 'status-handy'	The chassis or frame of the vehicle must be securely connected to earth ground using a (minimum) **16 AWG green wire** during charging. **Note**: Earth ground can be a water pipe or metal electrical conduit permanently installed at the competition site.	@ Former user (Deleted Is taking care of this
EV 12.2.7	Unknown macro: 'status-handy'	All connections of the charger(s) must be isolated and covered, with intact strain relief and no fraying of wires.	
EV 12.2.12	Unknown macro: 'status-handy'	High Voltage wiring in an off board charger does not require conduit; however it must be a UL listed flexible cable that complies with **NEC Article 400; jacketed**.	
EV 12.2.13	Unknown macro: 'status-handy'	All chargers must be UL (Underwriters Laboratories) listed or recognized . Any waivers of this requirement require approval in advance, based on documentation of the safe design and construction of the system, including galvanic isolation between the input and output of the charger. Waivers for chargers must be submitted at least 30 days prior to the start of the competition.	Charger has been approved by Hybrid Judges
EV 12.2.14	Unknown macro: 'status-handy'	The vehicle charging connection must be appropriately fused for the rating of its connector and cabling in accordance with EV6.1.1	
EV 12.2.15	Unknown macro: 'status-handy'	The charging port shall only be energized when the tractive system is energized and the TSAL is flashing. **I.e.** there must be no voltage present on the charging port when the tractive system is deenergized.	Need to add TSAL to charge cart
		EV 12.3 Accumulator Container Hand Cart	
EV 12.3.1	Unknown macro: 'status-handy'	In case removable accumulator containers are used in order to accommodate charging, a hand cart to transport the accumulators must be presented at Electrical Tech Inspection.	
EV 12.3.2	Unknown macro: 'status-handy'	The hand cart must have a brake such that it can only be released using a dead man's switch, i.e. the brake is always on except when someone releases it by pushing a handle for example.	
EV 12.3.3	Unknown macro: 'status-handy'	The brake must be capable to stop the fully loaded accumulator container hand cart.	
EV 12.3.4	Unknown macro: 'status-handy'	The hand cart must be able to carry the load of the accumulator container(s).	
EV		The hand cart(s) must be used whenever the accumulator	

12.3.5	Unknown macro: 'status-handy'	container(s) are transported on the event site.	

Electrical Rules

Section	Status	Notes
EV3.2.2	Unknown macro: 'status-handy'	Soldering in the high current path is prohibited. Exception: surface-mount fuses and similar comp and the rated current
EV3.2.3	Unknown macro: 'status-handy'	All wires, terminals and other conductors used in the tractive system must be sized appropriately which protects them. Wires must be marked with wire gauge, temperature rating and insulation vo • Alternatively a manufacturer's part number printed on the wire will be sufficient if this numbe to a manufacturer's data sheet.
EV3.2.4	Unknown macro: 'status-handy'	The minimum acceptable temperature rating for TS wiring is **90°C**
EV3.2.5	Unknown macro: 'status-handy'	All tractive system wiring that runs outside of electrical enclosures must be either: • (a) Orange shielded, dual-insulated cable rated for automotive application, at least 5 mm ove • (b) Enclosed in ORANGE non-conductive conduit (except for Virtual Accumulator systems w 12) **Note:** UL Listed Conduit of other colors may be painted or wrapped with colored tape
EV3.2.6	Unknown macro: 'status-handy'	Conduit must be non-metallic and UL Listed17 as: (a) Conduit under UL1660, UL651 or UL651A OR (b) Non-Metallic Protective Tubing (NMPT) under UL1696.
EV3.2.7	Unknown macro: 'status-handy'	Conduit runs must be one piece. Conduit splices and/or transitions between conduit and shielded within an enclosure and must comply with section EV3.3.
EV3.2.8	Unknown macro: 'status-handy'	Wiring to outboard wheel motors may be in conduit or may use shielded dual insulated cables. All outside the vehicle frame (but within the roll envelope) must be within conduit.
EV3.2.9	Unknown macro: 'status-handy'	When shielded dual-insulated cable is used the shield must be grounded at both ends of the cabl
	Unknown macro: 'status-handy'	**EV5 TRACTIVE SYSTEM VOLTAGE ISOLATION**
EV5.1.1	Unknown macro: 'status-handy'	All TS wiring and components must be galvanically (electrically) isolated from GLV by separation
EV5.1.2	Unknown macro: 'status-handy'	All interaction between TS and GLV must be by means of galvanically isolated devices such as o isolators or isolated dc-dc converters.
EV5.3.1	Unknown macro: 'status-handy'	Tractive system main current path wiring and any TS circuits that are not protected by overcurren spacing, insulation, or both, in order to prevent short circuits between TS conductors. Minimum sp Insulation used to meet this requirement must adhere to EV5.4.

Maximum Vehicle TS Voltage	TS/TS Within Accumulator Contai	
	Over Surface (Creepage)	Througl
V < 100 VDC	5.3 mm	2.1 m
100 VDC < V < 200 VDC	7.5 mm	4.3 m
V > 200 VDC	9.6 mm	6.4 m

Table 13 – Minimum Spacings[23]

EV5.3.2

Unknown macro: 'status-handy'

Where GLV and TS circuits are present in the same enclosure, they must be segregated (in addit wire) by:

- (a) at least the distance specified in Table 13,

OR

- (b) a barrier material meeting the TS/GLV requirements of EV5.4

EV5.3.3

Unknown macro: 'status-handy'

All required spacings must be clearly defined. Components and cables must be securely restraine spacing.
Note: Grouping TS and GLV wiring into separate regions of an enclosure makes it easier to imple 3.2

EV5.4.2

Unknown macro: 'status-handy'

Insulating materials used for TS/TS insulation or TS/GLV segregation must:

- (a) Be UL recognized (i.e., have an Underwriters Laboratories24 or equivalent rating and ce
- (b) Must be rated for the maximum expected operating temperatures at the location of use, c (whichever is greater).
- (c) Must meet the minimum thickness requirements listed in Table 14
- **Note**: For TS/GLV isolation, insulating material must be used in addition to any insulating covering provided by the wire manufacturer.: For TS/GLV isolation, insulating material must covering provided by the wire manufacturer.

	Minimum Temperature	Minir
TS / GLV (see Note below)	150º C	
TS / TS	90º C	As requi the f

Table 14 - Insulating Material - Minimum Temperat

Expenditures:

Items	Vendor	Payment Method	Cost (CAD/USD)	Form Link	

Project Bring-up

Winter 2020 Progress	Details + pictures

W20 Charger UL Inspection

Project Timeline:

WBS Project Title:

WBS Project Number:

Describe tasks and use the correct tags to show the state of the project.

Status	Unknown macro: 'status-handy'
Estimated Completion	01 Apr 2020
Project Deadline	01 Apr 2020
Required to Run	
Priority	Unknown macro: 'status-handy'

Responsibility Cascade:

- *Project Lead:* *@jlmorabi@uwaterloo.ca*
  - *Sub-team Lead*
  - *Sub-team core member*
- *Operations sub-team support- Finances, Procurement*
- *Project Advisers:*

List the people with ultimate responsibility (sub-team leads), project champions, and people who will aid during the 'sprint' phase of the project.

The cascade should also describe the flow of ownership if the original project champion is unable to finish the task.

Design Philosophy:

- "*This part improves over last year's component by ____"*
- *"Do not repeat ____ mistake"*
- *"This design fixes ____"*

Explain each feature of the part and how it accomplishes the part's function.

Task list:

@person, //date

Description

Current charger is only CE certified, but rules require a UL listed or recognized label on the charger.

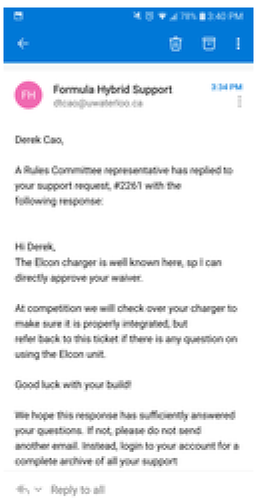
Recognized Certification Markings:

https://www.esasafe.com/electricalproducts/marks

Agencies Who Can Certify Equipment:

https://www.esasafe.com/consumers/safety-and-security/product-safety/who-can-certify-electrical-products-in-ontario

Charger has been approved by Formula Hybrid, but should still undergo CSA certification.



Formula Hybrid Support

Derek Cao,

A Rules Committee representative has replied to your support request, #2261 with the following response:

Hi Derek,
The Elcon charger is well known here, so I can directly approve your waiver.

At competition we will check over your charger to make sure it is properly integrated, but refer back to this ticket if there is any question on using the Elcon unit.

Good luck with your build!

We hope this response has sufficiently answered your questions. If not, please do not send another email. Instead, login to your account for a complete archive of all your support

Reply to all

Relevant Documentation:

- Confluence page
- Pdf file
- Technical Datasheets.pdf

Rules Compliance

Section	Status	Notes	Documentation
EV12.2.13	Unknown macro: 'status-handy'	All chargers must be UL (Underwriters Laboratories) listed or recognized . Any waivers of this requirement require approval in advance, based on documentation of the safe design and construction of the system, including galvanic isolation between the input and output of the charger. Waivers for chargers must be submitted at least 30 days prior to the start of the competition.	Pictures? Logs?

Expenditures:

Items	Vendor	Payment Method	Cost (CAD/USD)	Form Link	

Project Bring-up

Winter 2020 Pro	Details + pictures

gre ss	

Accumulator Current Sense

Background

To understand the accumulator state of charge, the amount of power deployed by the car, and the performance of the battery, it is vital to accurate voltage and current sensing on the output of the accumulator. On the 2022 vehicle, this is accomplished in two ways. First, there is a shunt, measured by a purpose-built IC, that provides a direct measurement of the current leaving the battery. Second, the Hall effect sensor allows the BSPD to calculate the amount of current leaving the battery and ensure safe functionality of the car.

Current Shunt

What is a Current Shunt?

When it comes to current sensing, current shunts are the most commonly used solution due to it being a cost-effective option.

A current shunt or current sense resistor is a precise resistor with extremely low resistance and a high-power rating. By placing a current shunt in a series connection, all the current flowing through the resistor will be measured. However, due to the low resistor value, the voltage drop across the resistor is also very small. This is problematic because that voltage is not in the range of most analog-to-digital converters (ADC). To overcome this issue, an analog front end, or more specifically a current sense amplifier, is utilized to amplify the voltage across the resistor to a voltage within the measurement range of the ADC.

With the known resistor value and measured voltage, the current can be calculated using Ohm's law.

$$V = I \times R$$

Where V is the voltage, R is the shunt's resistor value in Ohms (), and I is the rate of current flow measured in Amperes (A). Based on this formula, it can be seen that the voltage drop is directly proportional to the amount of current flowing through the shunt (i.e., if current increases, voltage drop increases too). Furthermore, the resistance's value is constant meaning voltage is solely dependent on current.

To ensure the selected current shunt matches the desired application and performance of the circuit, the parameters of the shunt must be examined. On the 2022 vehicle, it is equipped with SHL1-600C060DE from Ohmite.

Parameters of a Shunt Resistor

Firstly, the **value of resistance** will dictate the voltage drop across the resistor. Consequently, to gather accurate measurements, the voltage drop and current should not exceed the maximum ratings of the ADC. Thus, the resistance value is mainly dependent on these two factors. Do note that a higher value will result in more power dissipation.

The typical values of a shunt resistor are in the range of milliohms. For the Ohmite current shunt, the provided datasheet merely states 0 Ohms with no further precision. Nevertheless, the chosen model is rated for 600 A (for every 600 A, it produces 60 mV).

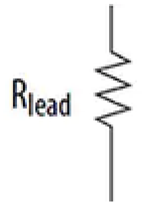
The next parameter to consider is the **tolerance** of the shunt resistor. Generic resistors have tolerances ranging from 1% to 10% and for their use cases, the loose tolerance is perfectly acceptable. However, in our application where accurate measurements are preferred, a tight tolerance is highly desired. Expensive shunt resistors can have tolerance as low as 0.1% and lower quality ones can have tolerance up to 1%. For reference, the Ohmite current shunt has a tolerance of 0.5%.

Another factor to inspect is the **temperature coefficient** of the resistor (TCR). This parameter, measured in ppm/°C, determines how much the resistance will vary due to the change in temperature. The value of TCR is dependent on the material of the resistor, power rating, and the physical size of the resistor. A low TCR will produce accurate measurements with a low-temperature dependency. An ideal TCR value would be below 100 ppm/°C.

Similarly, the resistor's thermal EMF is also an important aspect to consider. In short, thermal EMF is the small voltage (in the microvolt range) produced by the temperature difference between two dissimilar conductors. If the thermal EMF is not accounted for, it can result in inaccurate readings.

Number of Terminals on a Shunt Resistor

Examining any resistors in a micro sense, one can argue there are two additional resistors apart from the resistance of the resistor itself which are the resistance of the leads and leads on the PCB connected to the resistor (Figure 1). For normal resistors, these resistances are negligible; however, in high current measurements, the small resistance from the leads can introduce measurement errors.



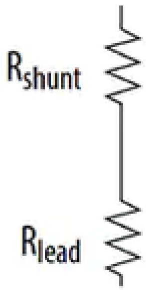


Figure 1: A two-terminal resistor with three resistances.

One way to overcome this problem is to establish a Kelvin connection by separating the sense traces from the high current path (Figure 2).

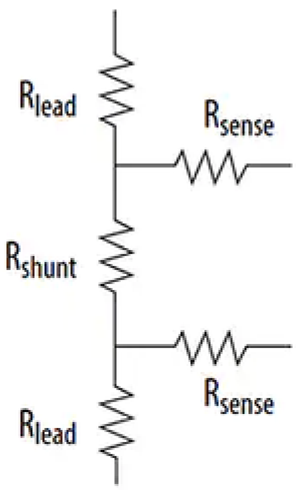


Figure 2: A shunt resistor with the voltage sensing lines separated.

Through using a Kelvin connection, the resistance of the leads is bypassed. Some shunt resistors have four terminals to implement the Kelvin connection in the design. The current shunt in the 2022 vehicle is a two-terminal current sense resistor.

Hall Effect Sensor

What is the Hall effect?

When a current flowing through a conductor is exposed to a magnetic field, a transverse force will be applied to the charges. Consequently, the electrons are pushed to one side, creating a net positive charge on the other side of the conductor as shown in Figure 3 below. This separation of charges produces a measurable voltage, called *Hall emf* (V_h), across the conductor.

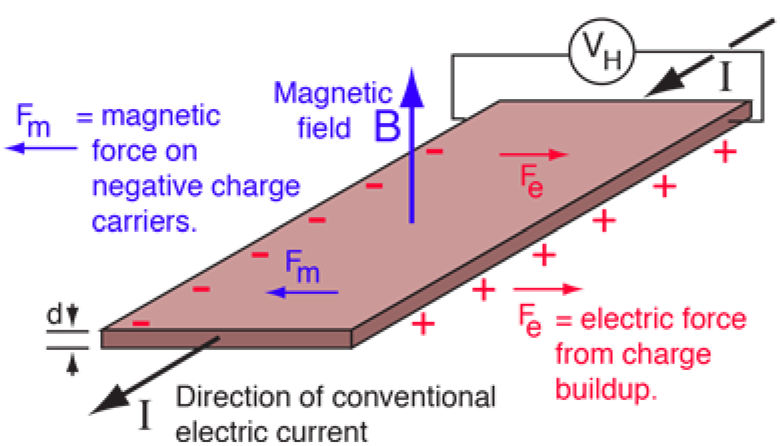


Figure 3: The Hall effect in a flat conductor

Note, for this phenomenon to occur, the magnetic field lines have to be perpendicular to the current and be of the correct polarity which is generally a south pole.

What is a Hall effect sensor?

Hall effect sensors are commonly used in a variety of applications due to their non-contact wear-free operation, low maintenance, resistance to vibration, water, and dust. Some applications include sensing position, distance, and speed in automotive systems. For us, this sensor is utilized to compute the amount of current leaving the car for the brake system plausibility device (BSPD).

A Hall effect sensor is a device that is capable of outputting a signal based on the magnetic field present in its environment. That output signal is a function of the density of the magnetic field. Based on the strength of the magnetic field, the output signal can be used to calculate the current, position of objects and distance. It is important to note that Hall effect sensors have a preset threshold and only once the magnetic flux density surpasses this threshold, the sensor is able to detect a magnetic field by producing a voltage as output, V_h.

There are a few benefits of using a Hall effect sensor over other methods for current sensing. For instance, the output voltage is isolated from the measuring point which makes them a safer testing equipment and eliminates the issue of insertion impedance. Another selling point is that it is capable of producing accurate measurements of both AC and DC current. Note: generally, Hall effect sensors are used to measure DC current and inductive sensors are used for AC power. This is due to the limited range of Hall effect sensors.

How does a Hall effect current transducer work?

Inside a Hall effect sensor contains a thin piece of semiconductor where a constant current is passed through it so that the hall voltage is completely dependent on the external magnet. When placed near a conductive wire with current flowing, the generated magnetic field will exert a force on the charges found on the thin piece of semiconductor. However, the produced voltage is often small (microvolts) so to improve the sensor's sensitivity, Hall effect sensors are pre-built with DC amplifiers, logic switching circuits, and voltage regulators.

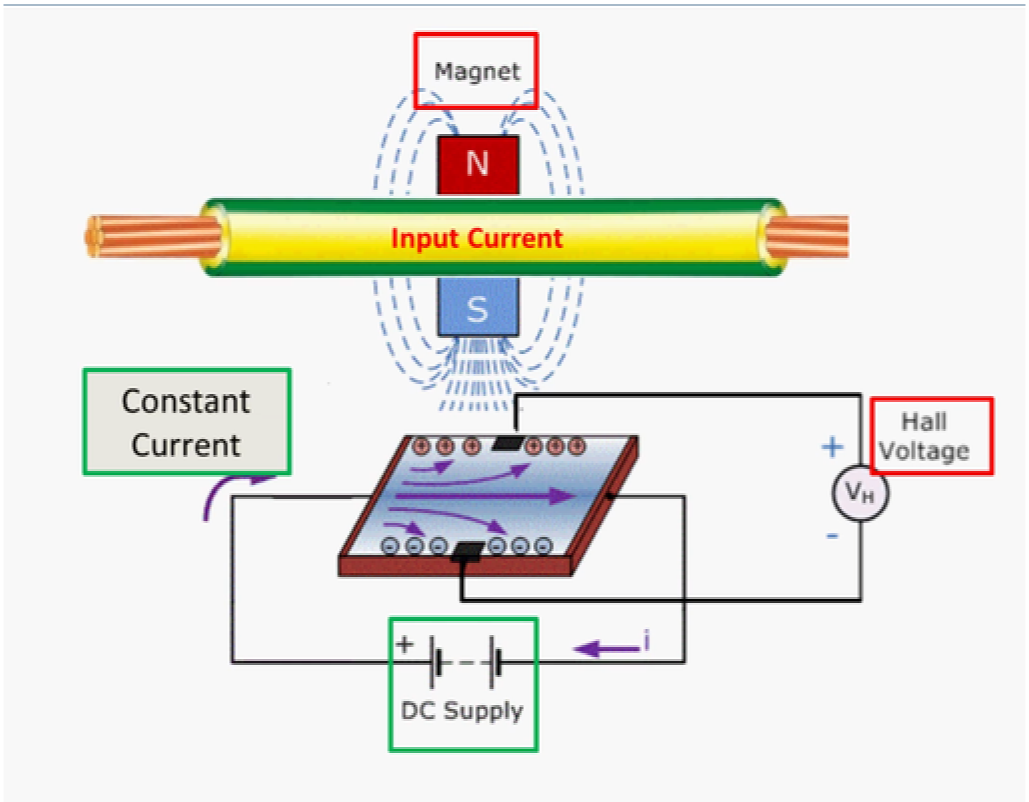


Figure 4: A Hall effect current transducer exposed to an external magnet

A linear or analog hall effect sensor generates a continuous voltage output and increases with a stronger field. If the strength of the field keeps increasing, the output voltage will be eventually limited by the power limit on the amplifier. On the other hand, a digital output sensor has only two states 'ON' and 'OFF' which disregards the oscillation of the magnetic field.

There are two types of Hall effect current transducer, open-loop and closed-loop. The advantages and disadvantages of each type are summarized in Table 1 below.

Table 1

Advantages and disadvantages of open-loop and closed-loop current transducer

Open-loop		**Closed-loop**	
Advantage	Disadvantage	Advantage	Disadvantage
Easy to implement	Poor accuracy	Fast response speed	Narrow range
Low cost	Poor linearity	Low temperature drift	High cost
Highly energy efficient	Slow response speed	High precision	High power consumption
Low power consumption	Large temperature drift	Strong anti-interference capability	
Wide sensing range		Good linearity	

In an open-loop sensor, the magnetic field produced by the current is concentrated by the magnetic core which is then measured by the hall effect sensor located in the air gap of the core. The magnetic core is needed to amplify the field, otherwise, the field produced in free space would yield inaccurate results.

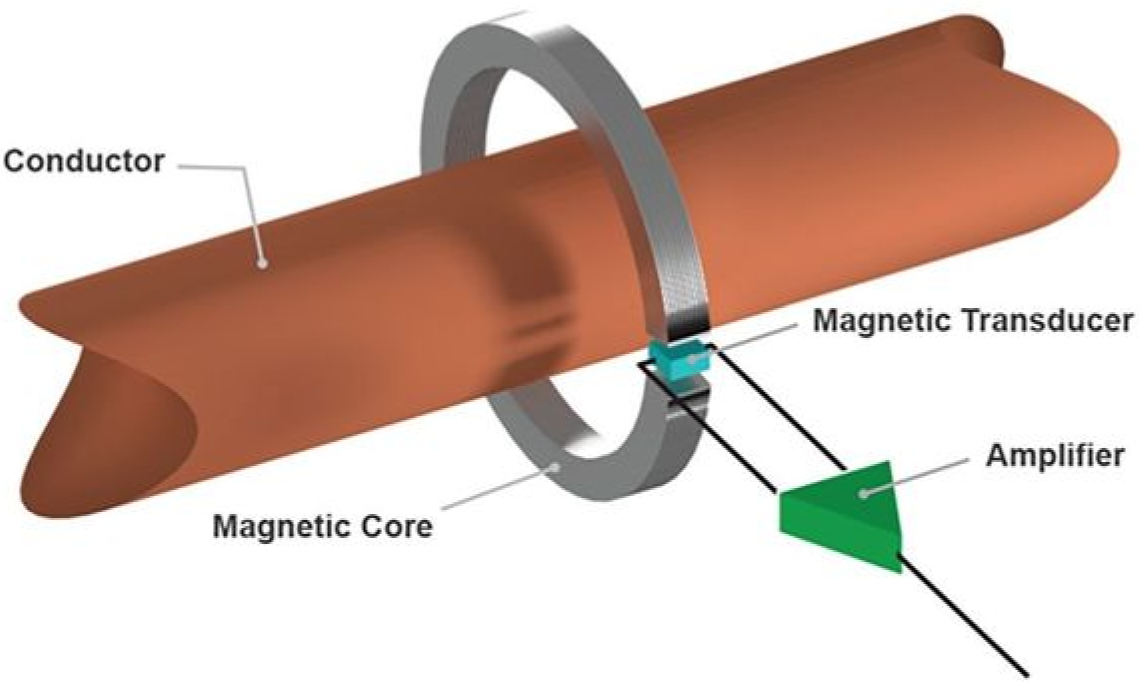
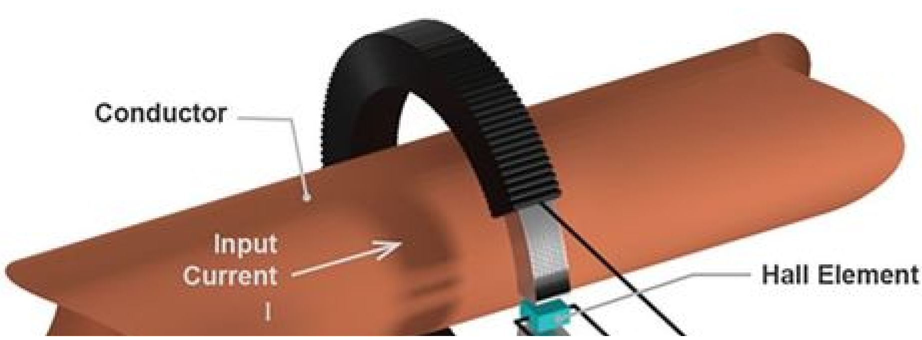


Figure 5: Open-loop current transducer

A closed-loop sensor or 'Zero-Flux' sensor has a secondary coil wrapped around the core to produce a field that opposes the magnetic field of the primary current. This configuration reduces non-ideal effects such as linearity and gain errors. Thus, the better accuracy but at the cost of being more sophisticated and requiring a high-power amplifier to drive the secondary coil.



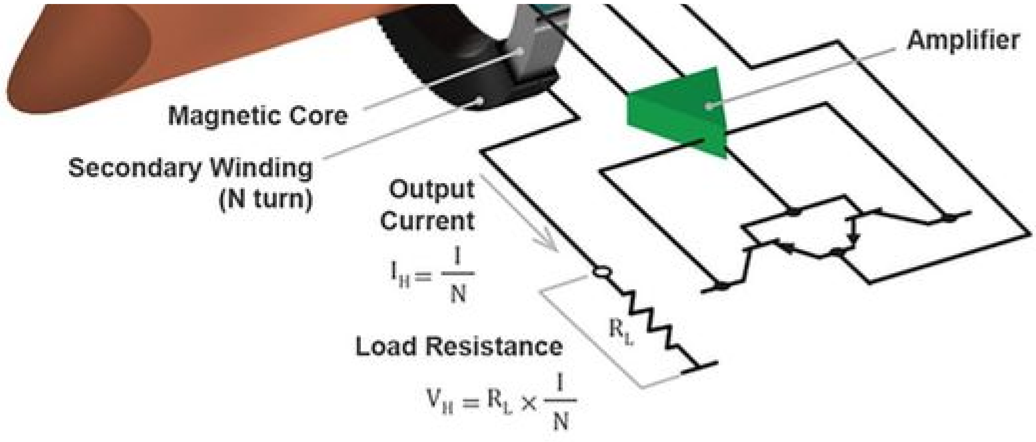


Figure 6: Closed-loop current transducer

The Hall effect transducer installed on the 2022 vehicle is a HASS 200-S from LEM. It is a linear, open-loop current transducer that is capable of measuring ± 600 A.

Lastly, here is a table comparing current sensing techniques found from this source.

Table 2

Comparison of common choices for current sensing techniques

Widely Used Sensors	Power Consumption		Circuit Isolation	Frequency Range	Size	Accuracy	Relative Cost
	Insertion Loss	External Power					
Sense Resistor + Op-Amp	High	Low	Low	DC to 10 MHz	Medium	±3 to 5%	Low
Standard Open Loop Hall-Effect	Low	Low	High	DC to 50 kHz	Small	±5 to 10%	Medium
Hall-Effect Closed-Loop	Low	Medium	High	DC to 1 MHz	Medium to Large	< ±1%	High
Allegro Open-Loop Hall Effect Current Sensor ICs	Low	Low	High	DC to 120 kHz	Small	±2 to 3%	Medium
Current Transformers	Medium (AC)	None	high	60 Hz to 1 MHz*	Medium to Large	±3 to 5%	High

* Current transformers usually operate over a limited frequency range but can be designed for use from low to high frequencies.

High Voltage and Cell Safety

Accumulator Startup Procedure

During the Fall of 2019, team members working with the pack found that a leaking cell polarized the case of the accumulator to the HV output by about 140V. The following procedure is designed to give a procedure to safely inspect the pack before use.

State 1- All segment disconnects removed, accumulator is at Low Voltage

Attach the free TSMP (orange cable with Hirose connector) to the battery

Using the Fluke HV Insulation tester with the banana jack probe tips, measure the voltage between the high voltage path and the case ground. It should be zero. If not, attach a 1 k power resistor between the case ground and high voltage path, then measure again.

Remove the lid of the accumulator, being very careful to not disturb the fan cabling or AMS isoSpi wire

If you are comfortable, very carefully make a resistance measurement from the negative pole, (using the 1507's mode). There should be no connection. Remember that the negative pole is floating, and is still very dangerous. Repeat this measurement for all segments. (Ground to segment negative pole).

Install the segment disconnects, following the prescribed order.

Reattach the lid and all relevant bolts

State 2, Accumulator at HV, Segment Disconnects installed, HVD removed. Car Harness Turned Off

Lift the accumulator into the car, being careful not to break the support tabs. Install all 8 M8 bolts that support the battery.

Remove the handle, install the HVD.

Install the BMU car harness connector.

Turn on the car harness, make sure the other boards get power. Connect to the BMU through CLI.

State 3, Accumulator at HV, Segment Disconnects Installed, HVD Installed. Car Harness On, HV Cabling Disconnected, Dummy Connectors Installed

Check the state of the BMU, check the battery info. Make sure that all temperatures and voltages are nominal.

Send the hvToggle command to precharge the pack. Use the Fluke 1507 to measure the TSMP voltage and verify that it matches the readout voltage from the BMU. It should be within a few percent.

Send the hvToggle command to discharge the pack. Verify that the pack is at low voltage and the AILED is off.

State 4, Accumulator Function Confirmed, Accumulator Off.

Remove the dummy connectors, install the high voltage cabling.

State 5, Accumulator On, Car Ready to Drive

Send the hvToggle command, send the emEnable command and begin checking the functionality of the car. Ensure that the IMD light and TSAL function as intended.

Lithium Ion Battery Cell Safety

Safety of lithium-ion batteries

Recharge: The European Association for Advanced Rechargeable Batteries

Li-ion-safety-Ju...13-Recharge-.pdf

@ Joseph Anthony Borromeo 27 May 2020 Assign this paper to be summarized by a new member

Summary:

- Has a nice table on Page 7 which a nice summary of different lithium-ion chemistries and their advantages
- Battery Hazards can be classified as follows:
  - *Chemical Hazard*
    - The chemicals inside the cells present their own hazards
    - Spillage: hazard linked to the corrosive and flammable properties of the electrolyte.
    - Gas Emission: hazard linked to the flammable properties of volatile organic substances.
  - *Electrical Hazard*
    - Conductive path of the battery generates heat
    - High currents and/or short circuits of the cell can lead to a hot spot on the battery, possibly resulting in a fire
    - Overcharging and over discharging of the cell leads to and accelerated temperature increase and chemical instability of the cell – this is why all cells need protection circuits
  - *Chemical + Electrical*
    - If the temperature of the cell gets too high due to a short circuit, it can lead to the chemicals in the cell escaping through the cell's vent and may ignite in the presence of a hot spot.
- *Causes of Thermal Runaway*
  - Components in the battery are stable up until 80 Celsius.
  - Around 120-130 Celsius is when the interior of the cell will break down, accelerating heat generation
  - The state of charge also plays a role as the higher the state of charge the more stored energy in the cell that will be converted to heat
- The safety and safe management of a cell comes from multiple sources including:
  - The design and material choice of the cell enclosure
  - Cell and battery design to optimize resistance to environmental stresses
  - System design and integration of the cell in the system
- System Safety Hardware:
  - *Electronics Hardware*
    - Over-Voltage protection
    - Over-Temperature
    - Cell balancing circuitry
  - *Electrical Hardware*
    - Fusing for over-current
    - Contactors
  - *Mechanical Hardware at module and systems level*
    - Optimum thermal management (heat and fire)
    - Structural protection
    - Gas containment or evacuation systems
- System Safety Software
  - *Measurement of battery system characteristics*
    - Cell/Pack voltage
    - Temperature
    - Current
    - Device feedback
    - Sensor validity
  - *Default or failure detection and appropriate control actions*
    - Battery status and safety control software

A General Discussion on Battery Safety:

sum12_p037_044.pdf

"A General Discussion of Li-Ion Battery Safety" Paper Summary:

- Lithium-ion batteries are everywhere
- That's why safety is so key
- Failure at a certain level will escalate up and result in the complete destruction of the battery system, and even the whole vehicle that houses it

- **Thermal stability** is the most important parameter for the safety of Li-ion cells, modules, and battery pack

Safety Devices:

- Shutdown separator - between anode and cathode, stopping ionic conduction if the temperature exceeds a threshold, preventing further damage
- Cell Vent or Tear Away Tab - the safe release of gas that builds up in the cells
- Current Interrupt device (CID)
- Positive temperature coefficient
- Current limiting fuses
- Diodes
- Battery management system

- **What are the failure modes of the cell**

A common response of a cell to abusive conditions is producing heat and gas.

Main failure modes:

- **Thermal Abuse** - Heat generation in response to abuse test, can usually trigger thermal runaway Stage 1: Onset, Stage 2: Acceleration, Stage 3: Runaway
- **Physical Damage** - Puncture, crush, vibration, or shock. These could result in a short circuit which will cause great implications
- **Charge and Discharge Failures** - Malfunctions of the BMS can

  cause overcharge and over-discharge (voltage reversal)
- **Short Circuit -** Internal short circuit could occur from abuse conditions that make internal gas generate, and internal electrodes can also contact each other after being displaced.
-

  The state of Charge - The magnitude f the response of a cell to an internal short circuit will be influenced greatly by SOC. When a cell is at 100% SOC, the internal short circuit often results in the thermal runaway of the cell, but if it is at 80% SOC, the max temperature may be reduced to 200 degrees celsius, and 70% SOC is where an internal short circuit can be tolerated easily.

What are the disadvantages and advantages of each cell

- Most commercially viable Li-ion batteries use cathodes made of $LiCoO_2$, anodes made of graphitic carbon.
- Cathodes play a big role in battery safety, and here is a summary of the main cathodes that are commercially available today:

Table I. Characteristics of some positive electrode materials.[19]

Material	Specific capacity mAh/g	Midpoint V vs. Li at C/20	Comments
$LiCoO_2$	155	3.9	Still the most common. Co is expensive.
$LiNi_{1-x-y}Mn_xCo_yO_2$ (NMC)	140-180	~3.8	Capacity depends on upper voltage cut off. Safer and less expensive than $LiCoO_2$
$LiNi_{0.8}Co_{0.15}Al_{x0.05}O_2$ (NCA)	200	3.73	High capacity. About as safe as $LiCoO_2$
$LiMn_2O_4$ (Spinel)	100-120	4.05	Poor hight temperature stability (but improving with R&D). Safer and less expensive than $LiCoO_2$
$LiFePO_4$ (LFP)	160	3.45	Synthesis in inert gas leads to process cost. Very safe. Low volumetric energy
$Li[Li_{1/9}Ni_{1/3}Mn_{5/9}]O_2$	275	3.8	High specific capacity, R&D scale, low rate capability
$LiNi_{0.5}Mn_{1.5}O_2$	130	4.6	Requires an electrolyte that is stable at high voltage

- **<u>What are the implications for our team</u>**

- Since the cell chemistry is a big factor for safety, we must take that into consideration when buying a commercially viable battery for our car.

Cathodes Choice:

- LiCoO2 has been the main cathode o choice for consumer Li-ion cells. Good capacity but most reactive and has poorer thermal stability in comparison to other cathodes.
- Certain Cathodes such as LiFePO4 will show the greatest reduction in self-heating rate and increased onset temperature from thermal runaway (amazing thermal stability)

Anodes Choice:

- Graphite remains the material of choice in commercial cells today, however newer materials are being developed with higher capacity and rate capabilities

- **<u>Search up safety Tests for batteries (like nail test)</u>**

- Module and pack abuse tests (shock, vibration, impact)
- Thermal Ramp Test - Thermal stability of cells can be studied by linear programmed heating to cell failure, sometimes called a Thermal Ramp Experiment. The reaction to overcharge or over-discharge is determined mainly by battery chemistry.
- Overcharge and over-discharge test
- External short circuit - Apply a short circuit with fusing at 50 degrees celsius

@ Rohan Peri 27 May 2020 Assign this paper to be summarized by a new member

Cummins HV DC Webinar Notes

- **What does the training cover?**

The training covers information about direct current (DC) for up to 1500V. The training does not talk about alternating current (AC) and does not provide enough information to safely open a high voltage battery pack.

Activities associated with development and operation of hybrid and electric trucks and buses

Hazard Types	Handling and storage of power pack and vehicle components	Prototype truck or bus retrofit / Repower	Re charging batteries	Driving demonstrator vehicle - product development	Driving production vehicle to demonstrate technology or collect data	EV service & repair. Recovery after breakdown	Frist responder safety after road traffic incident
Electric shock	X	X	X	X	X	X	X
Burns	X	X	X			X	X
Ill health effects		X	X			X	X
Fire	X	X		X	X	X	X
Crush or impact	X	X					
Vehicle Movement (RTA)				X	X	X	
Explosion	X	X	X			X	
Vulnerable or unaware		X	X			X	
Chemical Hazard	X	X	X			X	X
Pressurised systems hazards		X				X	X
Ergonomic Hazard	X	X				X	

Formula SAE use only

Hazard associated with batteries

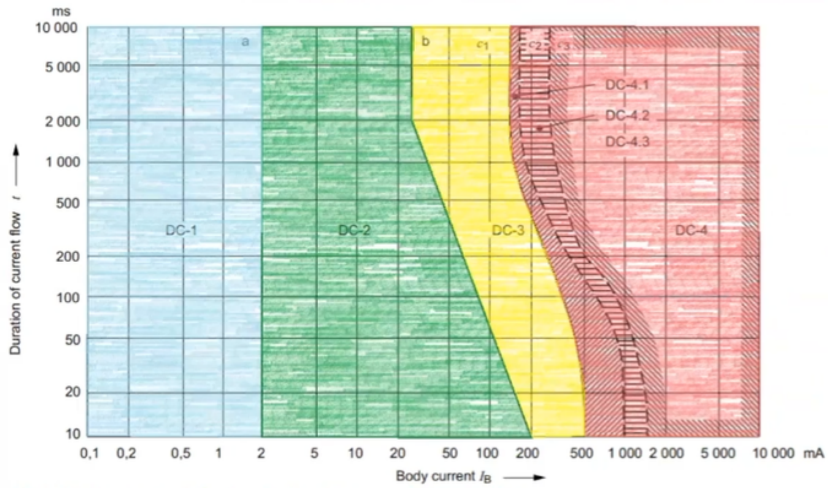
Cummins | 2

- **Why do you need this training?**

Electrical vehicles and batteries are part of a relatively new industry that was not primarily focused upon until recently. Given that, knowledge about batteries and the safe ways to handle them are not universally known and causes individuals to react more dramatically to accidents related to the industry. Therefore, to not only maintain your safety but also to maintain people's belief in the industry, one should take this course.

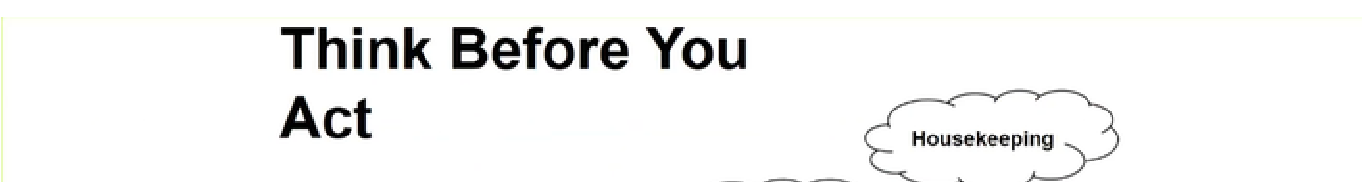
- **List of risks covered in the presentation**
  - The presence of high voltage components and cabling capable of delivering a fatal electric shock
  - The storage of electrical energy with the potential to cause an explosion or a fire
  - Manual handling risks associated with battery replacement
  - The potential for the release of explosive gases and harmful liquids if batteries are damaged or incorrectly modified
  - The potential for the electrical systems on the vehicle to affect medical devices such as pacemakers
- **Potential Safety Hazards**
  - Electric shock
    - Your body conducts electricity
    - When an electric current flows through your body it causes your muscles to contract
    - For a hand-to-hand flow of current to occur, the current must pass through your chest which can then be fatal if the current is too large and if it prevents the heart and lungs from functioning properly
    - The electrical resistance of the body reduces and the flow of current increases as voltage increases
    - Cummins considers a voltage greater than 50V to be a potential for an electric shock in dry conditions, and if a shock is received from 50V they should be reported and treated promptly

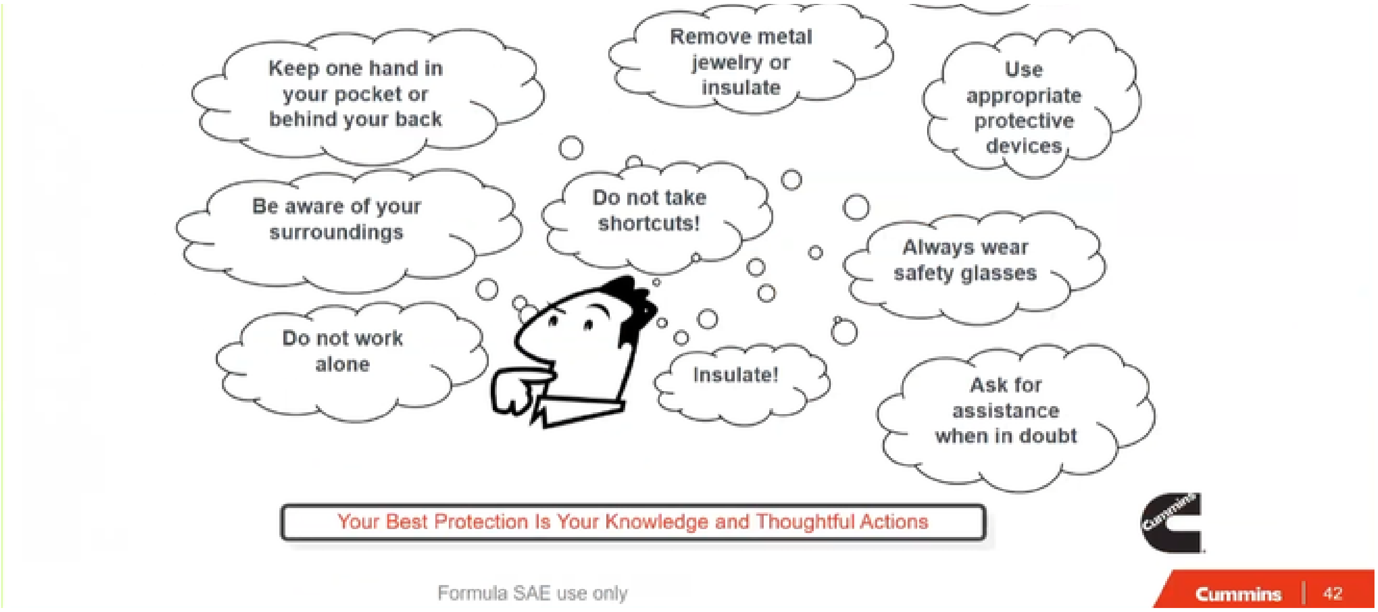
- For safety, follow posted and/or instructed rules, use insulated gloves, maintain distance if not directly working on battery, ensure AED in near proximity, report damaged or leaking batteries to supervisor, work with another individual, and have a rescue stick handy.
- In case of an electric shock, use a rescue stick to pull the victim away from the source of electricity, monitor the victim's vitals, and seek medical assistance immediately (whether that may be you assisting the victim or you having to call 911)



- DC-1 : Slight pricking sensation possible when making, breaking or rapidly altering current flow
- DC-2 : Involuntary muscular contractions likely especially when making, breaking or rapidly altering current flow but usually no harmful electrical physiological effects
- DC-3 : Strong involuntary muscular reactions and reversible disturbances of the heart may occur, increasing with current magnitude and time. Usually no organic damage to be expected
- DC-4 : Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time
  - DC-4.1 Probability of ventricular fibrillation increasing up to about 5 %
  - DC-4.2 Probability of ventricular fibrillation up to about 50 %
  - DC-4.3 Probability of ventricular fibrillation above 50 %

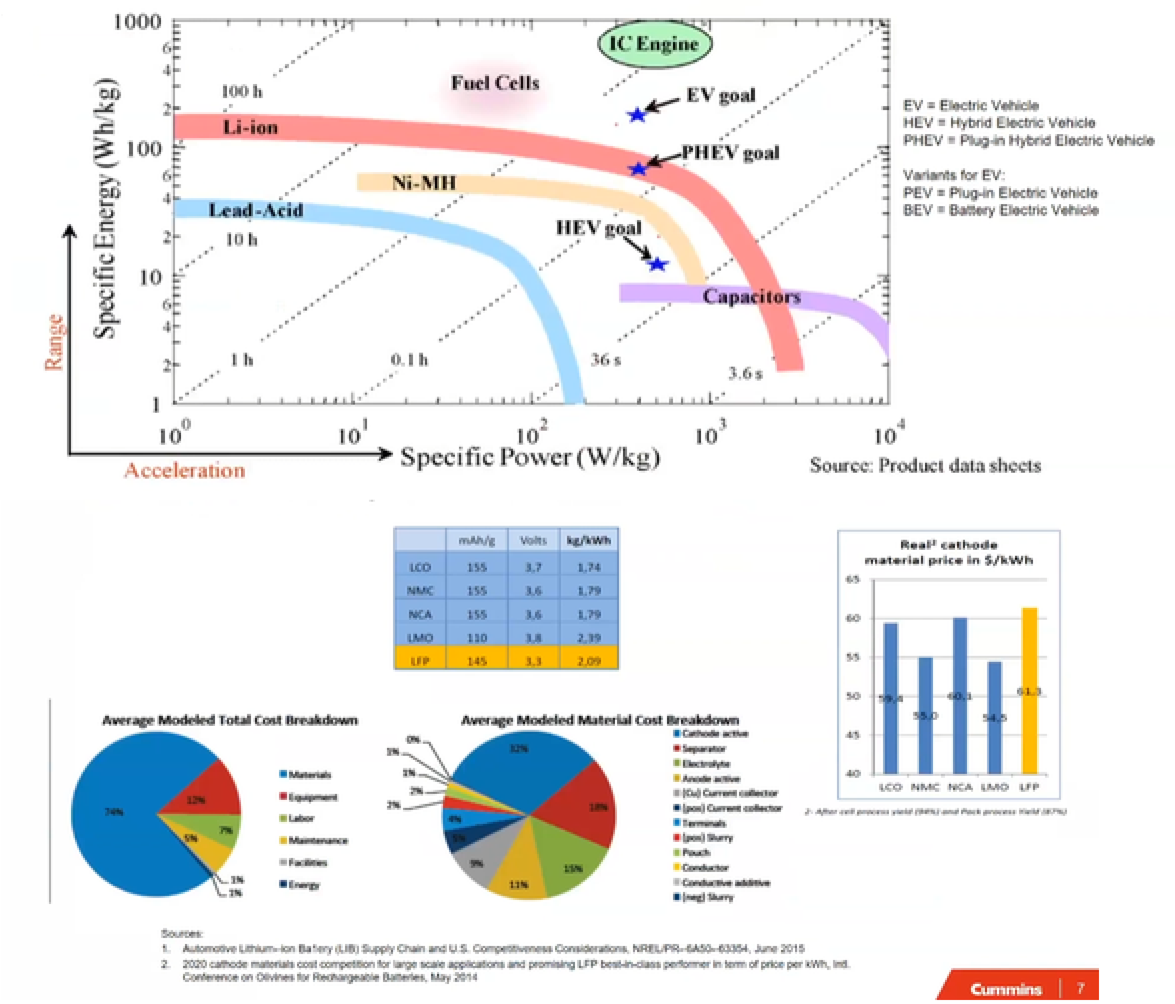
- High currents
  - Can have drastic impacts including inducing other hazards such as magnetic fields and fire.
- Magnetic field
  - Static magnetic fields high enough can cause issues with medical devices such as pacemakers and implanted defibrillators
  - Can create the risk of a projectile
  - Magnetic fields are induced by current flowing in the wiring connected to the battery packs, not by the battery itself
  - External wiring should ideally be done with twin cables as doing so minimizes the external magnetic field created
- Arc
  - An arc is created when a connection carrying a current is interrupted and the current tries to continue flowing.
  - Arcs are extremely hot, about 4 times the temperature of the surface of the sun
  - The intense heat from an arc causes a sudden expansion of the air around the arc, resulting in a blast with remarkably high air pressure
  - An arc will also vaporize any materials near it, especially the metals carrying the current
  - Each year more than 2000 people are treated for severe arc injuries due to their temperature and its affect on the materials around it
- Water ingress
  - When an electric potential is applied to water, electrolysis occurs creating an explosive mixture of oxygen and hydrogen, which can then dramatically increase the flammability of the affected battery pack
  - The minimum voltage required for electrolysis of pure water is 1.23V
- Cell venting
  - If a cell gets too hot – either due to internal heating or due to an external heat source – its internal pressure increases due to the expansion of the electrolyte
  - This pressure then must be released from the cell through a vent, or the cell will explode
  - Material that leaks from a vent is normally very flammable and may even be toxic
  - Potential causes include:
    - Internal defects that cause an internal short circuit
    - Overcharging of cells/pack
    - High temperature of a cell due to overflow of current
    - Failure of pack cooling system
    - Pack being stored in an exceedingly hot location
  - Fire
    - Fire is a potential side effect of cell venting
    - Can be caused by arcing
    - Might be caused by an external source
    - Gases emitted from the pack can include toxic gases such as carbon monoxide and hydrogen fluoride
    - Fire extinguishers are not effective against cell/battery fires, and thus should only be used to evacuate the building safely and not to put out the fire
  - Weight
    - Lithium-ion packs can be very heavy and should only be lifted with appropriate training and equipment

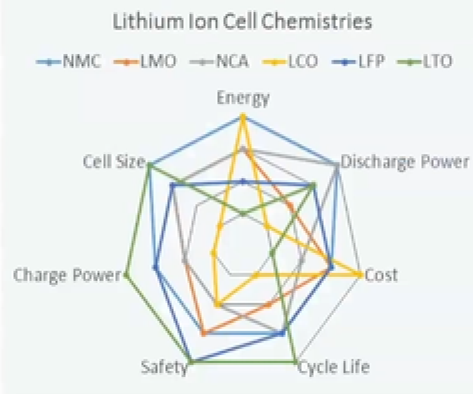




Cummins Battery 101 Notes

- **Li-ion Attributes**
  - Refer to graphs and pictures taken from the presentation



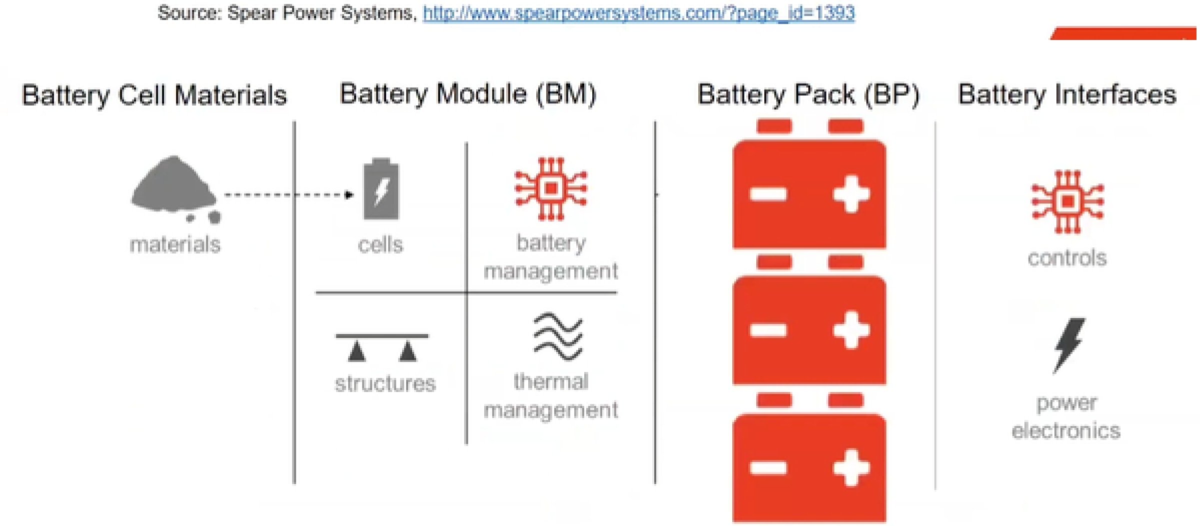


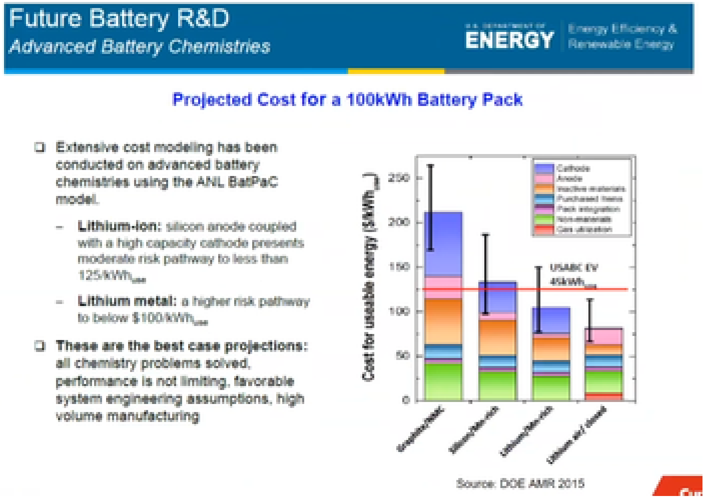
Acronym	Cathode (+ Electrode)	Anode (- Electrode)	Nominal Voltage (V)
NMC	Nickel Manganese Cobalt	Graphite	3.7
LMO	Manganese Spinel	Graphite	3.6
NCA	Nickel Cobalt Aluminium	Graphite	3.7
LCO	Lithium Cobalt Oxide	Graphite	3.6/3.7
LFP	Lithium Iron Phosphate	Graphite	3.2/3.3
LTO	NMC, LMO, NCA, or LFP	Lithium Titanate	2.3

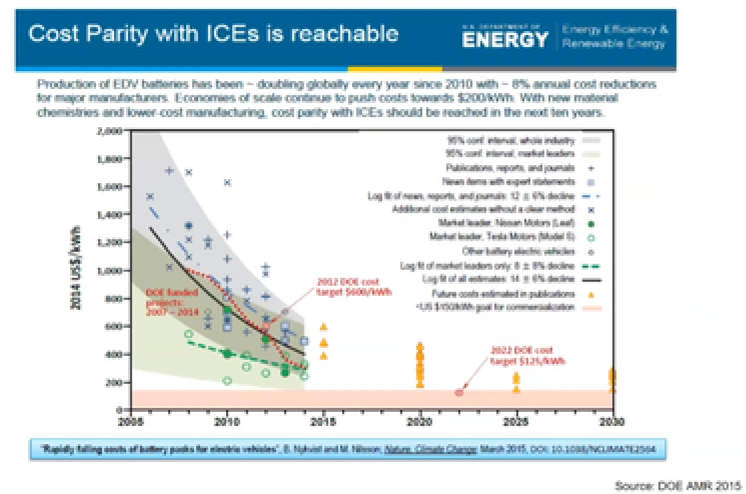
Chemistry Performance Attributes

Energy – specific energy (mass) & energy density (volume)
Discharge Power - maximum continuous discharge rate
Cost - production volume cell cost. Farthest out along axis = lowest cost
Cycle life – Number cycles at the same DOD and temperature to end of life (EOL)
Safety – aggregate of the cell's ability to tolerate destructive overcharge, short circuit, heating, or mechanical abuse.
Charge Power - maximum continuous charge rate
Cell Size - maximum capacity cells commercially available in high quality serial production

Source: Spear Power Systems, http://www.spearpowersystems.com/?page_id=1393

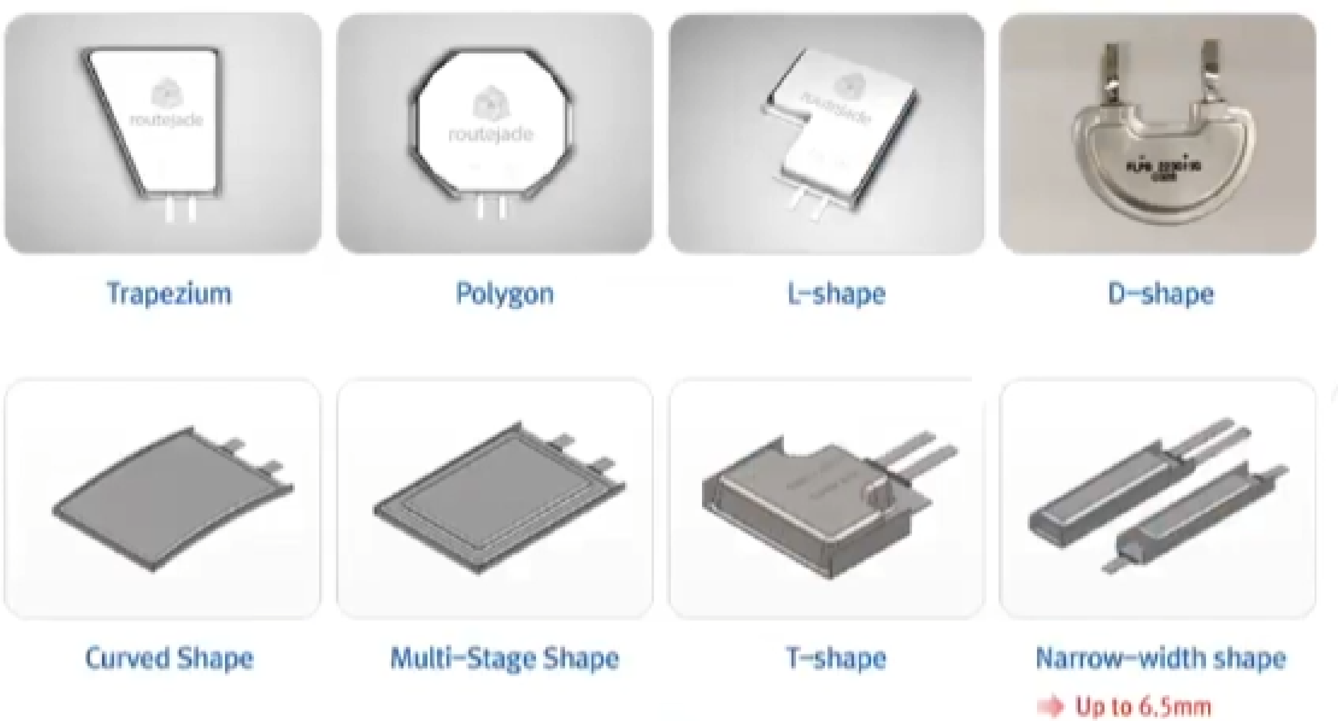






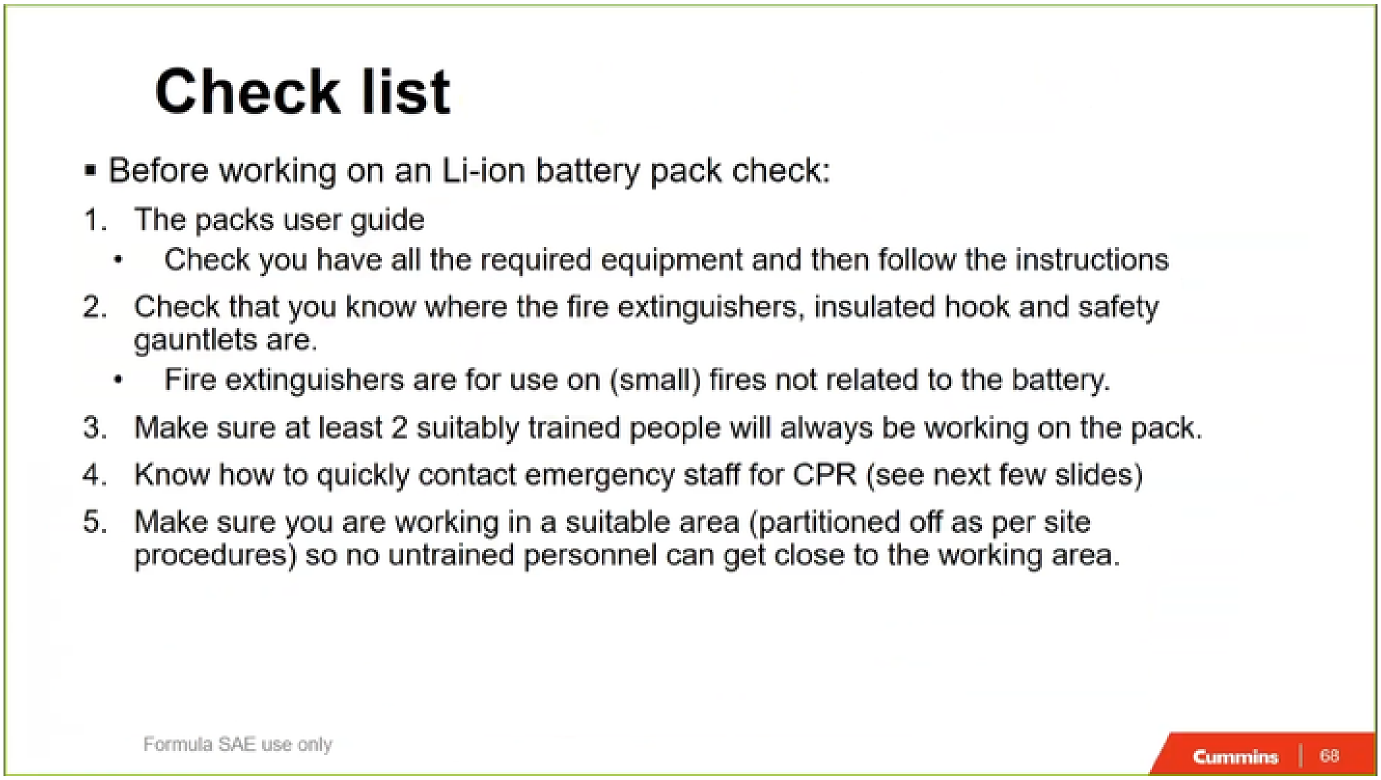
- **Battery Operation and Terminology**
  - Charge
  - Discharge
  - Capacity
    - The amount of charge a battery or cell can store or deliver, measured in Ampere × hours (Ah)
  - Specific Capacity
    - The capacity of a component relative to its mass (Ah/g). This value is most relevant for active material comparison
  - C-Rate
    - A normalized notation of charge or discharge current, relative to capacity
    - C-rate = (Ampere of cycling) / (Capacity)
    - For example, for a 1Ah battery:
      - 1C = 1A
      - 2C = 2A
      - C/2 = 0.5A
    - Cycle Life
      - The total number of charge/discharge cycles the cell can sustain before its capacity is significantly reduced. Typically, this end of life is considered to occur at 80% of original rated capacity
    - Depth of Discharge
      - The fraction or percentage of the capacity which has been removed from the fully charged battery
    - Coulombic Efficiency
      - The capacity retention for each cycle:
      - Determined by the reversibility of the cell
    - Power
      - The ability of a cell to perform work at any given instant
      - It is the product of the voltage of the device times the current the device can produce (measured in Watts)
      - $P = V \times I$
      - Power density is the ratio of power to mass or volume, a more critical comparative value, in units of W/kg or W/L
    - Energy

        - The cumulative work done over time, often expressed in Watt-hour
        - $E = P \times t$
        - Energy density is the ratio of cell energy to the mass or volume of the cell/pack (Watt-hour/kg or Watt-hour/L)
    - **Battery Cell Types**
        - Pouch/Prismatic Cells (housed in a flexible polymer housing)
            - Benefits
                - Minimal mechanical requirements on electrodes
                    - Particularly for flat/stacked/Z-fold pouch cells
                - Flexible on geometry and number of electrode layers
            - Drawbacks
                - More difficult to monitor gassing
                - Less consistency with electrolyte fill and infiltration
            - Pouch cells are housed in a flexible polymer housing whereas prismatic cells are housed in a rectangular aluminum housing



        - Cylindrical Cells
            - Benefits
                - Standardized product
                    - Highly commercially relevant
                - Safety features
                    - Pressure relief valve
                    - Over-temp shut-off
                - Most rigorous test
                    - 1-20 Amps maybe flowing at a time
                    - Contained volume
                    - Electrodes wound around tight mandrels
                - Drawbacks
                    - Most rigorous test
                    - Much more equipment required to fabricate than pouch/prismatic cells
                    - Must fabricate from continuous coating methods
                        - 500-1000mm electrodes typical
- **Battery Modules (BM) and Battery Packs (BP)**
    - These sections cover battery modules and packs manufactured and sold by Cummins
- **Safety and Roadmap**
    - Battery safety is a system engineering problem (affected by materials/cells to vehicle design
    - Typical failure modes: overcharge, internal/external short circuit, thermal run-away
    - Relatively safer chemical exists (such as LTO and LFP) but have other drawbacks

- Operators and supervisory controller must heed battery warnings about limits and unsafe conditions



High Voltage Safety

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

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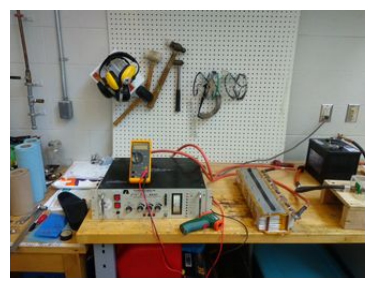


Summary

Briefly describe the project purpose and current state.

CAD Information

- CAD Design Organization: *Describe how the solid models for the project are organized.*

Design Philosophy

- "*This part improves over last year's component by ____*"
- *"Do not repeat ____ mistake"*
- *"This design fixes ____"*

Explain each feature of the part and how it accomplishes the part's function.

Problem Definition

Weber Automotive on Youtube makes some of the most informative and most useful long-format videos on EVs. Please watch their video on HV safety here: Hybrid and Electric Vehicle Personal Protective Equipment (PPE) and Tools.

Rules Compliance

Rule	Status	Notes	Proof of Compliance
A 1.2	Unknown macro: 'status-handy'	**Paraphrase:** For an electric vehicle, the accumulator may have a maximum usable energy of 5.40 kWh, or nominally 6.75 kWh. (Discharge measured at 2C).	The accumulator will be designed to comply and be tested.

Constraints and Criteria

Constraint	Priority	Description	Value	Unit	Validation Method
Current Capability	Unknown macro: 'status-handy'	Each segment must be able to deliver the full rated current of the Tractive System because the segments are in series. By design, this is 135 A RMS. The pack fuse will be 40 A.	135	A	HTHC

High Voltage Safety Gear

After receiving funding from EngSoc during the Fall term, WFE purchased ~$600 of high voltage safety gear, including newly tested rubber gloves, liners, and leather glove covers and a face shield holder and face shield. These items are shown in the table below:
333px

HV Gloves - Class 00 (750V DC)	Face Shield	Face Shield Lens	Leather Overglove (Not Pictured)	Summer Liners (Not Pictured)
			The leather overgloves are a key part of HV electrical safety. They protect the insulating rubber gloves from damage, deterioration from UV, and protect the user from tools or parts puncturing the rubber gloves.	Cotton liners are worn inside the rubber gloves to fill them out (if you have smaller hands) and to absorb small amounts of sweat from your hands, keeping the gloves nice and dry.

It should be noted that the face shield that was ordered doesn't fit with the purchased head gear. One face shield was modified, but it still doesn't fit well - we should order the proper face shield ASAP.

High Voltage Tools

Using the same funding from EngSoc, WFE also purchased high voltage insulated tools, including allen keys and metric socket sets.

Order #2					
Insulated Tools - 1000VTools.com	1000V METRIC SOCKET 5.5MM	EA	1 USD	$19.06	$19.06
	1000V METRIC SOCKET 7MM	EA	1 USD	$19.06	19.06
	1000V METRIC SOCKET 8MM	EA	1 USD	$19.06	$19.06
	1000V METRIC SOCKET 10MM	EA	1 USD	$19.06	$19.06
	HEX WRENCH 2.5MM 6" LONG ARM TYPE T - S2634625	EA	1 USD	$23.83	$23.83
	HEX WRENCH 2.5MM TYPE L LONG ARM - S2615605	EA	1 USD	$19.97	$19.97
	HEX WRENCH 3MM 6" LONG ARM TYPE T - S2634630	EA	1 USD	$20.87	$20.87
	HEX WRENCH 3MM TYPE L LONG ARM - S2615606	EA	1 USD	$23.83	$23.83
	HEX WRENCH 5MM 6" LONG ARM TYPE T - S2634650	EA	1 USD	$19.97	$19.97
	HEX WRENCH 5MM TYPE L LONG ARM - S2615610	EA	1 USD	$23.83	$23.83
Order Total					$587.53

1000Vtools.com Order - Includes sockets and metric allen wrenches.

Project Procurement:

Follow the procurement procedure as described in the Operations page Purchase and Reimbursement Procedure and then upload the purchase order spreadsheet to the table below. Consolidate as many purchases into one procurement request to simplify the process.

Generate a Jira task in the appropriate Operations Epic. Label it with *proc_ts* and an (*label specific to this page)* so that it shows up in the table below.

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Team Member Name	Purchase Order Spreadsheet	Quote / Invoice	Order Description	Company Name	Total Cost [CAD]	Status	Storage Location
						NOT YET PROCESSED	

Lithium Ion Polymer Cell Discharge and Disposal

This page outlines the steps necessary to safely discharge lithium ion polymer pouch cells (LiPo cells), and then work with the university channels to dispose of them

Lithium Ion Battery Safety

LiPo pouch cells present significant danger if mishandled, as they contain a large amount of electrical energy, toxic solvents and electrolytes, and are not well protected by a rigid can like other types of cells are.

Please read all available safety literature before beginning. There is quite a good manual available through UWaterloo safety office here: Lithium Ion Battery Safety

In short, **Do Not:**

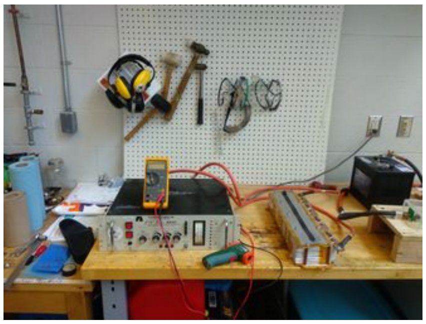
- Overcharge the cells past their voltage- this may cause an internal short, leading to an uncontrolled release of all energy in the cell
- During routine charging / use cycles, do not discharge the cell beyond the cutoff voltage (typically around 3.0 V)
- Drop, crush, puncture, or otherwise damage the case of the cell
- Connect the cell terminals together through a low impedance connection (<0.1) such as a metal bench, dropped tool, or improperly set load bank

While Discharging, **Do**:

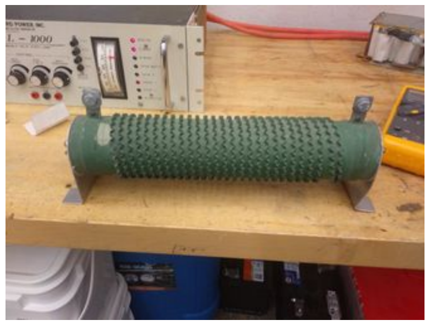
- Work in pairs to monitor cell temperature and voltage- have a minimum of two people in the bay so that one person can support the other in case of an emergency
- Set a timer for yourself to regularly check the cell voltage and temperature
- Use cabling and connection methods appropriate for the maximum output of the cell under load- in most cases, 4/0 AWG with professionally made crimped connections is appropriate.
- Fixture the cell in such a way that if someone bumps the table or touches the discharging setup, nothing will short together. Typically, alligator clips are not appropriate as they have exposed metal which could short the terminals together.
- If the cells are at all damaged (puffy, overcharged, undercharged), exercise extreme caution while discharging. **Do not discharge at more than 1C.**
- If the cells are not damaged, discharge at 5C or the maximum continuous discharge of the cell, whichever is lower. **Cells from Electric Power (Mingda Industrial Co.) tend to have "optimistic" datasheet ratings, so don't discharge cells at that rating.** (Typically 15C for $LiCoO_2$ cells. WFE bench testing found that their internal resistance was 2 to three times higher than datasheet values, which affects heat generation and continuous power output.)

Sample Photos of Discharging Setup

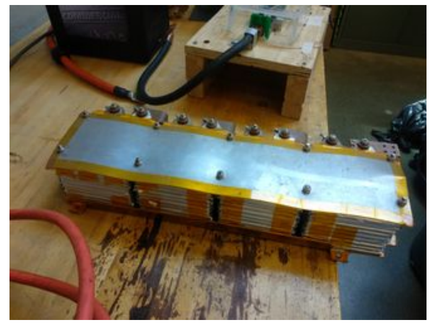
This setup is deprecated. We no longer have the load bank. Use the power resistor instead.



TE Power Resistor: Up to 1kW power dissipation, 2.4 resistance



2014 Accumulator Segment- Electric Power Cells



W20 Accumulator Toolbox and PPE

Project Timeline:

WBS Project Title:

WBS Project Number:

Describe tasks and use the correct tags to show the state of the project.

Status	Unknown macro: 'status-handy'
Estimated Completion	31 Mar 2020
Project Dea	31 Mar 2020

Responsibility Cascade:

- *Project Lead*
    - *Sub-team Lead*
    - *Sub-team core member*
- *Operations sub-team support- Finances, Procurement*
- *Project Advisers:*

List the people with ultimate responsibility (sub-team leads), project champions, and people who will aid during the 'sprint' phase of the project.

The cascade should also describe the flow of ownership if the original project champion is unable to finish the task.

Design Philosophy:

- During the 2019 Competition season, tools used by the Accumulator Subteam were often difficult to find or borrowed by other sub-teams, meaning that work on the accumulator was delayed. For the 2020 and 2021 seasons, an entirely separate toolbox will be maintained with all the tools and supplies needed to maintain the accumulator systems.
- Insulated tools will allow segment assembly without excessive risk of electrical shock or arc flash.
- Custom Nomex guarding will provide an extra barrier for dropped tools and debris.
- Standard test procedures for insulating rubber gloves will be used to ensure their efficacy.

Explain each feature of the part and how it accomplishes the part's function.

dline	
Required to Run	
Priority	Unknown macro: 'status-handy'

Task list:

- wait on response from ENGSoC and WEEF
- Purchase face shield, HV blanket, HV gloves, and insulated tools

Purpose

During the 2019 Competition and 2019 Build season, it was found that the Accumulator Sub-Team needs a separate set of HV insulated tools to safely perform their work on the battery.

The purpose of this project is to document all tools required to work safely on the HV accumulator, design a toolkit to hold the tools, and then document further additions that are required.

Relevant Documentation:

- Confluence page
- Pdf file
- Technical Datasheets.pdf

Required Tool: Insulated Touch Probe

As per rule EV. 7.5.1:

> All parts, especially live wires, contacts, etc. of the Tractive System must be isolated by nonconductive material or covers to be protected from being touched. It must not be possible to touch any Tractive System connections with a 100 mm long, 6 mm diameter insulated test probe when the Tractive System enclosures are in place.

Someone from the powertrain or accumulator sub-team should fabricate such a probe out of non-conductive material so that we can check all of our enclosures before Technical Inspection at competition. Such a probe would be 6mm in diameter, 100 mm long, and have spherical ends so that the length could never be measured more than 100 mm.

This length is also the separation required for un-grounded metal components from the TS, so the probe will come in helpful for that.

Here are some of the tools we'll need for the toolbox and inspection:

- Insulated cable shears
- Insulated screw drivers
- Multimeter with protected probe tips
- Insulated tools, if screwed connections are used in the Tractive System
- Face Shield
- HV insulating gloves which are within test date

- [ ] Two HV insulating blankets of at least 1.0 m²
- [x] Safety glasses with side shields for all team members that might work on the Tractive System or Accumulator
- [x] Insulated tweezers
- [ ] Insulated Magnet (have nice magnetic screwdrivers, but they aren't insulated)
- [ ] Insulated 5.5mm socket
- [x] Small sheets of Nomex for guarding
- [ ] Insulated Needle Nose Pliers
- [ ] Insulated Socket Set and Ratchet Handle

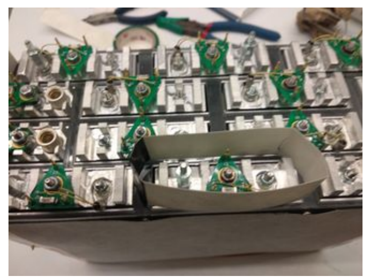
FLUKE 1507 High Voltage Insulation Tester

The Fluke 1507 HV Insulation tester is a tool that applies a high voltage between two probe tips and measures the current that flows between them. It can determine resistances from hundreds of Ohms to 10 GigaOhm on the 1000 V setting, and is an invaluable tool for maintaining galvanic isolation on the vehicle.

See the manual here: fluke_1507_megohmmeter_manual.pdf.

Nomex Segment Assembly Guards

During the segment assembly process, there is a need for a guard that keeps dropped parts or tools from contacting nodes on the segment cover that are a different potential. In the past, simple guards have been made from Nomex card, but these only provided a fence around the bus bar being worked on. Future designs should guard all the bus bars at once, as shown below:

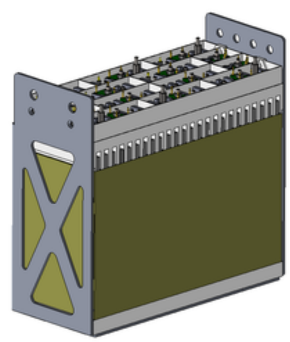


The methods used to join the Nomex card must be waterproof and non-conductive- i.e. no staples. Contact cement is one good option, and can be found in the glue bin in the bay.

The design could also be made from 3D printed plastic, but is sort of a difficult shape to print.

Proposed Design Revision- Nomex Paper or ABS / PVC plastic

Divider RP



Rules Compliance

Section	Status	Notes	Documentation
EV12.4	Unknown macro: 'status-handy'	Required Equipment Each team must have the following equipment accessible at all times during the	Pictures?

		event. The equipment must be in good condition, and must be presented during technical inspection. (See also Appendix F) (a) Multimeter rated for CAT III use with UL approval. (Must accept shrouded banana leads.) (b) Multimeter leads rated for CAT III use with shrouded banana leads at one end and probes at the other end. The probes must have finger guards and no more than 3 mm of exposed metal. (Heat shrink tubing may be used to cover additional exposed metal on probes.) (c) Multimeter leads rated for CAT III use with shrouded banana plugs at both ends. (d) Insulated tools. (I.e. screwdrivers, wrenches etc. compatible with all fasteners used inside the accumulator housing.) (e) Face shield which meets ANSI Z87.1-2003 (f) HV insulating gloves (tested within the last14 Months) plus protective outer gloves. (g) HV insulating blanket(s) of sufficient size and quantity to cover the vehicle's accumulator(s). (h) Safety glasses with side shields (ANSI Z87.1-2003 compliant) for all team members. Note: All electrical safety items must be rated for at least the maximum tractive system voltage.	Logs?

Expenditures:

Items	Vendor	Payment Method	Cost (CAD/USD)	Form Link	

Project Bring-up

2020 Progress	Recommended Safety Lecture from Formula Hybrid:

W20 Lockout Tagout Procedure

Project Timeline:

WBS Project Title:

WBS Project Number:

Describe tasks and use the correct tags to show the state of the project.

Status	Unknown macro: 'status-handy'
Estimated Completion	09 Apr 2020

Responsibility Cascade:

- *Project Lead:* *@ ba2nguye@uwaterloo.ca*
- *Operations sub-team support- Finances, Procurement*
- *Project Advisers:*

List the people with ultimate responsibility (sub-team leads), project champions, and people who will aid during the 'sprint' phase of the project.

The cascade should also describe the flow of ownership if the original project champion is unable to finish the task.

Design Philosophy:

- *"This part improves over last year's component by ____"*
- *"Do not repeat ____ mistake"*
- *"This design fixes ____"*

Explain each feature of the part and how it accomplishes the part's function.

Project Deadline	01 Apr 2020
Required to Run	
Priority	Unknown macro: 'status-handy'

Task list:

- [ ] Validate rules and write the SOP, @ ba2nguye@uwaterloo.ca, 05 Mar 2020

Description

General description including *purpose*.

Relevant Documentation:

- Confluence page
- Pdf file
- Technical Datasheets.pdf

Rules Compliance

Section	Status	Notes	Documentation
EV2.2.6	Unknown macro: 'status-handy'	- Something something, fails this, questions that.	Pictures? Logs?

Expenditures:

Items	Vendor	Payment Method	Cost (CAD/USD)	Form Link	

Project Bring-up

Winter 2020 Pro	Details + pictures

Progress	

High Voltage Board Mechanical Component Outline

Project Properties

Project ID	AC-07
Status	Unknown macro: 'status-handy'
Upcoming Deadline	18 Nov 2017
Project Deadline	17 Oct 2017
Manager	@ Former user (Deleted)
Project Lead	@ Former user (Deleted)
Support	@ Former user (Deleted)

Project Deliverables and Timeline

New Deliverable

Title
No content found.

Project Description

Design the AMS board mechanical layout. Think cooling for balance resistors. Make sure the pogo pins don't become misaligned

Bus bar measurement boards, how do they interface with the busbars? how do we tolerance the pogo pins

Design the mechanical layout for the electronics portion of the battery. Design connector ports, all bus bar wiring.

Supporting Information, Project Details

The main HV electronic components that need to be designed /integrated in the accumulator container are:

1) AMS/Busbar Board Stack

- Define connector requirements, select connectors
- Define Board MCO

2) BMU Board

- Define connector requirements, select connectors
- Define Board MCO

3) DC/DC Convertor Board

- Define connector requirements, select connectors
- Define Board MCO
- DC/DC Converter requires cooling

4) Contactors

- Package into container

5) HVD

- Decide between on-box or auxiliary
- Package and integrate safely, including interlock

6) Pre/Discharge Resistors

- Requires cooling

7) Output Connectors (to MCs)

- Package and integrate safely, including interlock

8) Energy Meter

- Pre-allocate space assuming 2017 Energy Meter

9) Current Measurement Sensors

- Package and integrate shunt/Hall effect sensors

Requirements and Considerations

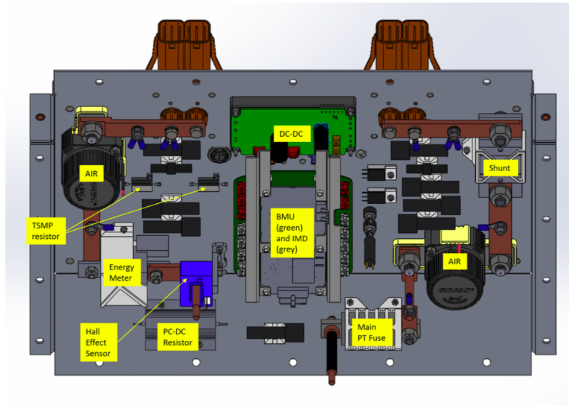
- *Sufficient Analysis needs to be done to ensure the DC/DC Convertor and Pre/Discharge Resistors will receive enough cooling*
- *Any connections in the tractive system current path must have positive locking mechanisms*
- *All sealing/outside world interfaces need to be detailed as part of this project*
- *Any additional busbars and/or mounting brackets outside of the scope of the main box structure and/or cell segment structure fall under the scope of this project.*

Relevant Rules

Rule Number	Rule Description

Precharge/Discharge Circuit Details

- Resistor: HS Series
- Contactor: GV220

- 

Progress Outline and Documentation

- *This section should be completed as the project progresses.*
- *Provide a concise report of the results and accomplishments throughout the project.*
- *Show how the requirements were met and how they were met.*
- *Outline findings and provide backing to decisions.*

High Voltage Board Mechanical Component 2018-2020

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Summary

Ensure rules compliance and ensure that design constraints are met. Include all information so that future projects don't make the same mistakes.

Current State: Incomplete

CAD Information

- CAD design information on GrabCAD.

Design Philosophy

Improve design by ensuring rule compliance.

Problem Definition

Rules Compliance

Rule	Status	Notes	Proof of Compliance
EV.7.5.5.	Unknown macro: 'status-handy'	**Paraphrase :** High voltage spacing between components must be >30 mm.	Insulation will be added between components not in compliance.
A 1.2	Unknown macro: 'status-handy'	**Paraphrase:** For an electric vehicle, the accumulator may have a maximum usable energy of 5.40 kWh, or nominally 6.75 kWh. (Discharge measured at 2C).	The accumulator will be designed to comply and be tested.

Constraints and Criteria

Constraint	Priority	Description	Value	Unit	Validation Method
Curr		Each segment must be able to deliver the full rated current of	135	A	HTHC

ent Cap ability	Unknown macro: 'status-handy'	the Tractive System because the segments are in series. By design, this is 135 A RMS. The pack fuse will be 40 A.			

Technical Progress

Design Process

Design Analysis and Manufacturing Design

Analysis Validation

Manufacturing and Implementation

Conclusions

Project Procurement:

Follow the procurement procedure as described in the Operations page Purchase and Reimbursement Procedure and then upload the purchase order spreadsheet to the table below. Consolidate as many purchases into one procurement request to simplify the process.

Generate a Jira task in the appropriate Operations Epic. Label with *proc_ts* and an (*label specific to this page)* so that it shows up in the table below.

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Team Member Name	Purchase Order Spreadsheet	Quote / Invoice	Order Description	Company Name	Total Cost [CAD]	Status	Storage Location
						NOT YET PROCESSED	

HV MCO 2021

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Summary

@adestefa@uwaterloo.ca

Briefly describe the project purpose and current state.

The BMU, AMS, DC DC, and TSAL circuits designed by the Electrical Subteam must be laid out on a PCB. It is critical that the person who designs the PCB layout understands high voltage separation and safety designs.

The AMS has been designed and manufactured. When back in person, and after the new AMS boards are installed, verify the high voltage creepage and clearance around the AMS, BMS, DC DC,

CAD Information

- CAD Design Organization: *Describe how the solid models for the project are organized*
- CAD for the High Voltage Board Mechanical Component Outline is currently stored in the conceptual designs folder on GrabCAD - \GrabCAD\2021 Vehicle\2 - Conceptual Designs\05-ACC-000\21-5-ACC-000

Design Philosophy

Explain each feature of the part and how it accomplishes the part's function

On the AMS:

Cell balance connectors and cutouts in the board were used to improve airflow and cooling of the resistors

Components were placed on both sides to greatly simplify the layout

and bus bars are sufficiently insulated and
far away from any LV components,
including the grounded aluminum box.

Problem Definition

Rules Compliance

Rule	Status	Notes	Proof of Compliance
EV.7.5.5	Unknown macro: 'status-handy'	**Paraphrase :** High voltage spacing between components must be >30 mm.	Insulation will be added between components not in compliance.
A 1.2	Unknown macro: 'status-handy'	**Paraphrase:** For an electric vehicle, the accumulator may have a maximum usable energy of 5.40 kWh, or nominally 6.75 kWh. (Discharge measured at 2C).	The accumulator will be designed to comply and be tested.

Constraints and Criteria

Constraint	Priority	Description	Value	Unit	Validation Method
Current Capability	Unknown macro: 'status-handy'	Each segment must be able to deliver the full rated current of the Tractive System because the segments are in series. By design, this is 135 A RMS. The pack fuse will be 40 A.	135	A	HTHC

Technical Progress

Design Process

1) AMS/Busbar Board Stack

- Define connector requirements, select connectors
- Define Board MCO

2) BMU Board

- Define connector requirements, select connectors
- Define Board MCO

3) DC/DC Convertor Board

- Define connector requirements, select connectors
- Define Board MCO
- DC/DC Converter requires cooling

4) Contactors

- Package into container

5) HVD

- Decide between on-box or auxiliary
- Package and integrate safely, including interlock

6) Pre/Discharge Resistors

- Requires cooling

7) Output Connectors (to MCs)

- Package and integrate safely, including interlock

8) Energy Meter

- Pre-allocate space assuming 2017 Energy Meter

9) Current Measurement Sensors

- Package and integrate shunt/Hall effect sensors

The BMU, AMS, DC DC, and TSAL circuits designed by the Electrical Subteam must be laid out on a PCB. It is critical that the person who design s the PCB layout understands high voltage separation and safety designs. The AMS has been designed and manufactured. When back in person, and after the new AMS boards are installed, verify the high voltage creepage and clearance around the AMS, BMS, DC DC, and bus bars are sufficiently insulated and far away from any LV components, including the grounded aluminum box.

Pictures of the high voltage boards:

BMU, DC DC:

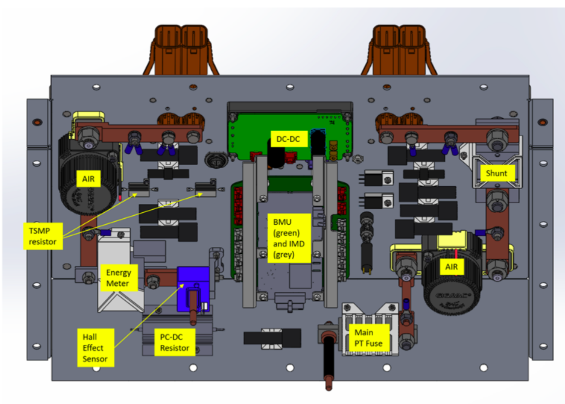
AMS :

Design Analysis and Manufacturing Design

Analysis Validation

Precharge/Discharge Circuit Details

- Resistor: HS Series
- Contactor: GV220



Manufacturing and Implementation

Conclusions

Project Procurement:

Follow the procurement procedure as described in the Operations page Purchase and Reimbursement Procedure and then upload the purchase order spreadsheet to the table below. Consolidate as many purchases into one procurement request to simplify the process.

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Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Team Member Name	Purchase Order Spreadsheet	Quote / Invoice	Order Description	Company Name	Total Cost [CAD]	Status	Storage Location

						NOT YET PROCESSED	

High Voltage Current Path

The Tractive System High Voltage Current Path delivers energy from the accumulator cells to the motor controllers. It is critical that the rules mandated current capacity and isolation requirements are met for safe operation.

General Design Requirements

Conductive Materials in HVCP

High Temperature Materials in Bolted Connections

Positively Locked Fasteners

Ampacity and Thermal Calculations

Rough numbers for the ampacity of the HVCP were obtained by calculating the heat generation in each bus bar using the length, area, and resistivity of copper and balanced with the heat rejection by convection and radiation. Heat loss due to conduction was not considered because the conductor should not be touching any other surfaces.

The Excel Calculator sheet can be found in the Custom Tools section of GrabCAD in the Tractive_System folder, available here: HV_Resistance_Measurements.

Isolation and Spacing Verification

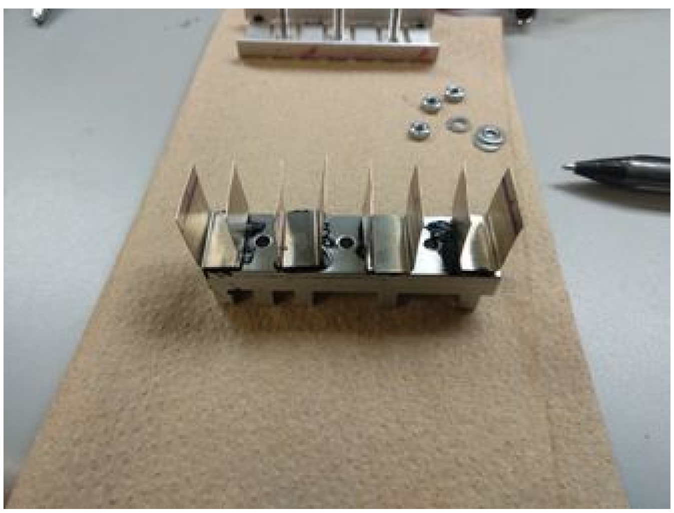
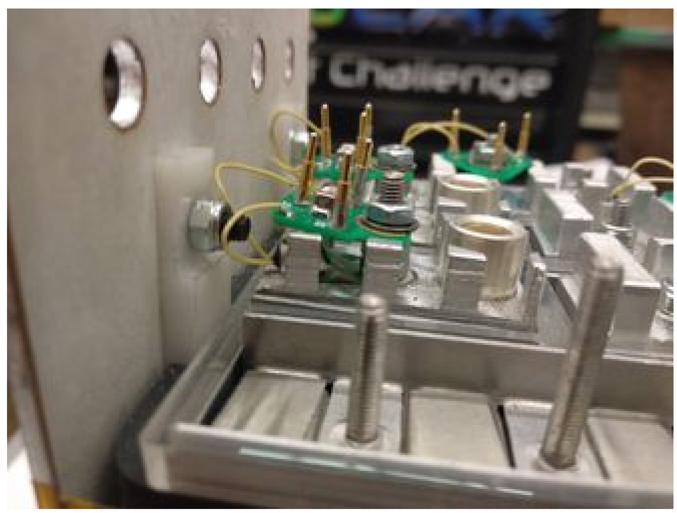
The isolation and spacing is a design feature verified with a ruler once the accumulator is built. No calculations are necessary.

Resources

Copper for Busbars Guidance for Design and Installation: copper_for_busbars_book_web_version.pdf

Bus Bar-Cell Tab Contact Resistance and Overheat

Final Bus Bar Assembly

Cell Tab Test Specimens with Carbon Grease	**Cell Tabs Assembled in the Segment**
	

In order to minimize heat generation during accumulator use, the contact resistance between the cell tabs and aluminum bus bars must be as low as possible. There are three different types of bus bars that connect the cells together in the battery.

Steps taken to do this include:

- Estimating contact pressure between the cell tabs and the bus bars through FEA method (refer pics)
  - Contact resistance is a direct function of contact pressure
  - Predicting contact pressure gives a rough estimate of contact resistance
- Sanding off oxide layers from bus bars

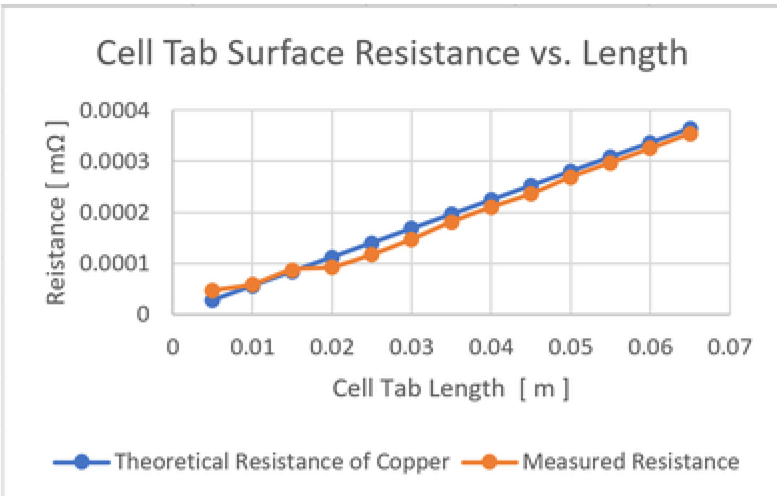
- Oxide layers have higher resistance than the bus bar material
- Verifying calculated resistance values using 2-Way/4-Way Ohmic measurements

3 M3 x 0.5 Studs, 8 Cell Tabs	2 M3 x 0.5 Studs, 8 Cell Tabs	1 M3 x 0.5 Stud, 4 Cell Tabs

Cell Tab Technical Data

Each cell tab is 15 mm wide, 0.2 mm thick, and protrudes about 15 mm from the battery pouch. From measuring the conductivity, each cell tab appears to be pure copper, with a nickel coating.

The resistance along the cell tab was measured at 13 different points, every 5 mm. The measured values match closely with the theoretical resistance of a copper cell tab.



Clamping Stud Technical Data

Each bus bar is clamped by M3 x 0.5 PEM self clinching studs.

These studs have properties similar to Grade 8.8 bolts, but due to the shape of the head and the production method, may not meet ISO requirements. Thus, a yield strength of 640 MPa was used to find the maximum torque applied to the studs. Three studs will be broken in order to validate this assumption.

It is critical that the M3 x 0.5 PEM clinch studs which secure the copper cell tabs are not stretched to the yield point during normal battery operation. This could occur if too much torque is applied to stud originally or if the stud is torqued past the safe torque and the expansion of the bus bar due to the temperature rise of the bus bar stretches the stud excessively.

During subjective testing with the Wera Torque Limiting Screwdriver, the studs stretched but did not yield when torqued to 1.0 Nm. No stud has been broken with the torque limiting screwdriver, yet.

Part Stackup	Material	Thickness [mm]	CTE [mm / °C]	Expansion at ▲T = 40 °C [mm]	Force in Stud [N]	Screw Force [N]	Required Torque [Nm]	Yields?
8 Tab, 3 Stud, Left Post								
Cell Tab Tray	6061 Aluminum	1.02	2.38E-05	9.71E-04				No
Cell Tab Under	Copper	0.2	1.65E-05	1.32E-04				No
Cell Tab Over	Copper	0.2	1.65E-05	1.32E-04				No
Bus Bar	6061 Aluminum	6.35	2.38E-05	6.05E-03				No
Washer	Steel	0.5	1.10E-05	2.20E-04				No
Total Bus Bar	N/A	8.27	2.27E-05	7.50E-03				No
Stud	PEM 3x0.5 Stud	8.27	1.10E-05	3.64E-03	381.639633884	1832.85	1.1	No
8 Tab, 3 Stud, Center Post								
Cell Tab Tray	6061 Aluminum	1.02	2.38E-05	9.71E-04				No
Cell Tab Under	Copper	0.2	1.65E-05	1.32E-04				No
Cell Tab Over	Copper	0.2	1.65E-05	1.32E-04				No
Bus Bar	6061 Aluminum	8.96	2.38E-05	8.53E-03				No
Washer	Steel	0.5	1.10E-05	2.20E-04				No
Total Bus Bar	N/A	10.88	2.27E-05	9.98E-03				No
Stud	PEM 3x0.5 Stud	10.88	1.10E-05	4.79E-03	390.478401080	1797.97	1.1	No

Calvin:
worst case scenario

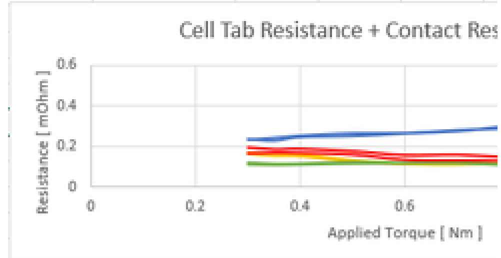
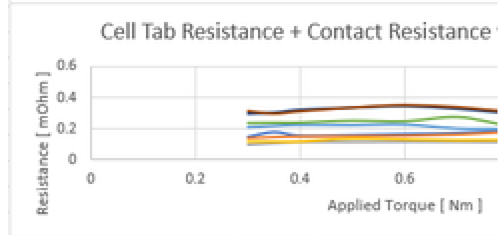
Calvin:
Peak Torque derated by 0.7

DMM Ohmic Measurements(4-Wire):

4 Wire resistance measurement was used to find the resistance of the cell tabs, the aluminum bus bars, and the interface resistance. A Keysight DMM and power supply (from the 3D Print Centre) was used with low resistance measurement probes on the DMM to find the voltage drop across the cell tab to the bus bar. The constant current mode was used to flow 5 amperes of current for the test, and the DMM had a scaling factor of 0.2 so that the resistance could be read off directly.

From previous testing, it is known that the cell tab, over the ~10 mm length from the cell pouch to the bus bar, has a resistance of 50 µ. When the bend is added, is measured to be 120 µ from the cell pouch to the centre of the bus bar contact area. The bus bar resistance has yet to be quantified.

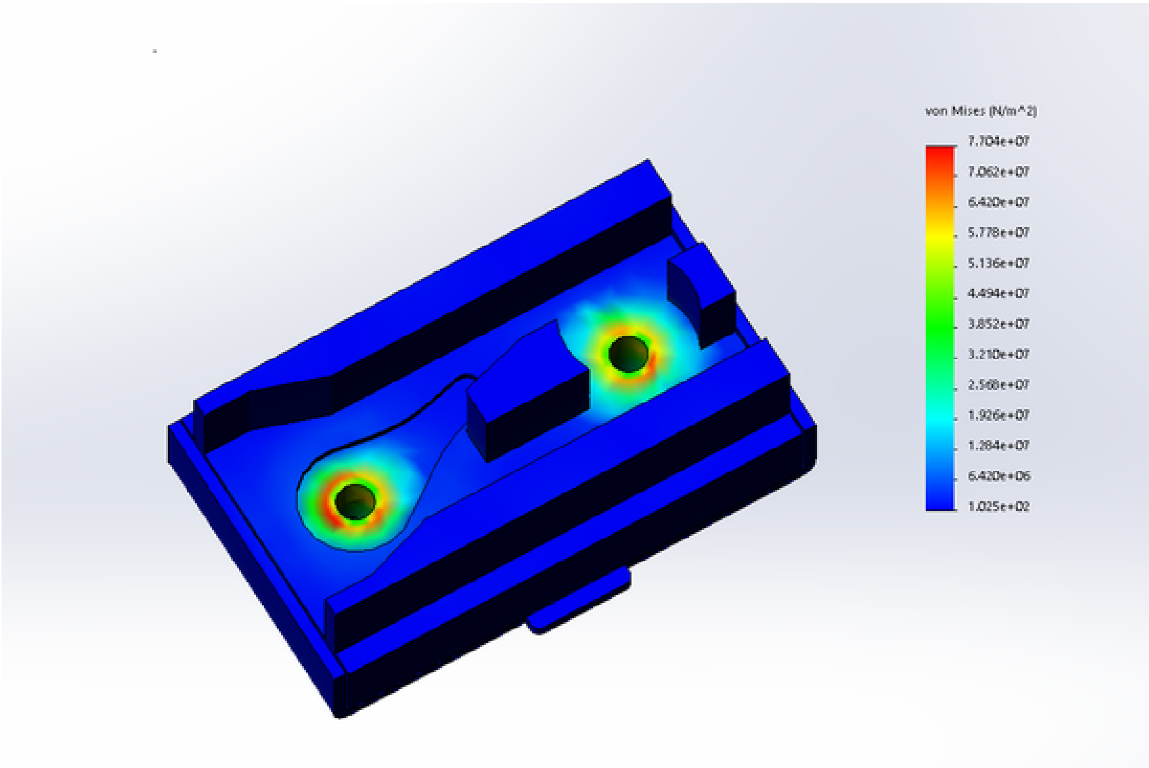
Contact Resistance Measurements - Tab to Tab	Test Current	Preparation Method	Average Contact Resistance @ 0.8 Nm	Pics	Overall Graph- Contact Resistance vs. Torque
Bus Bar: 3 Studs, 8 Tabs, tor	5 A	Scotchbrite, Acetone	165 µ		

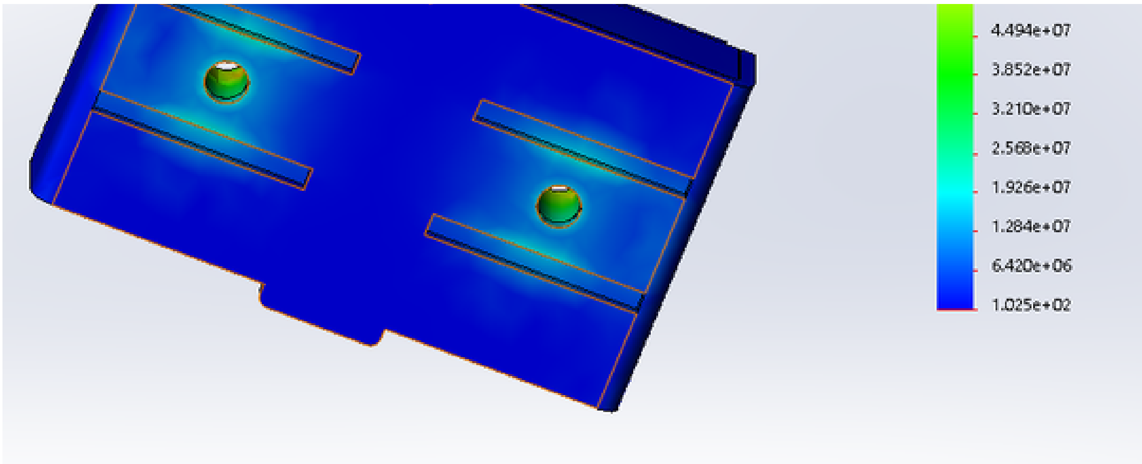
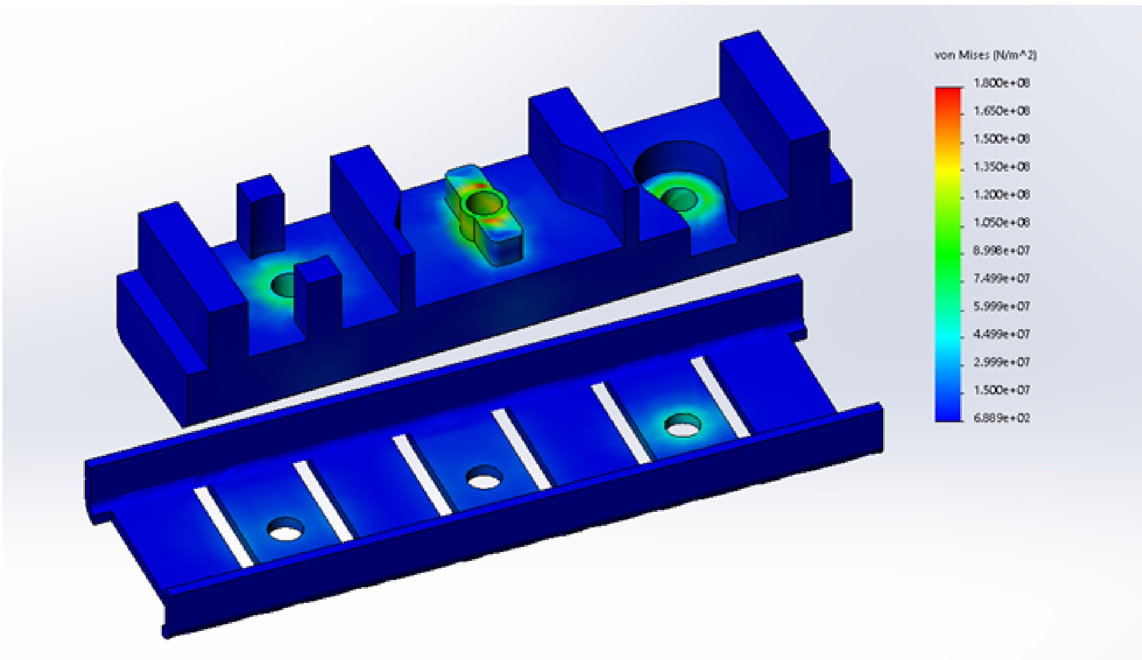
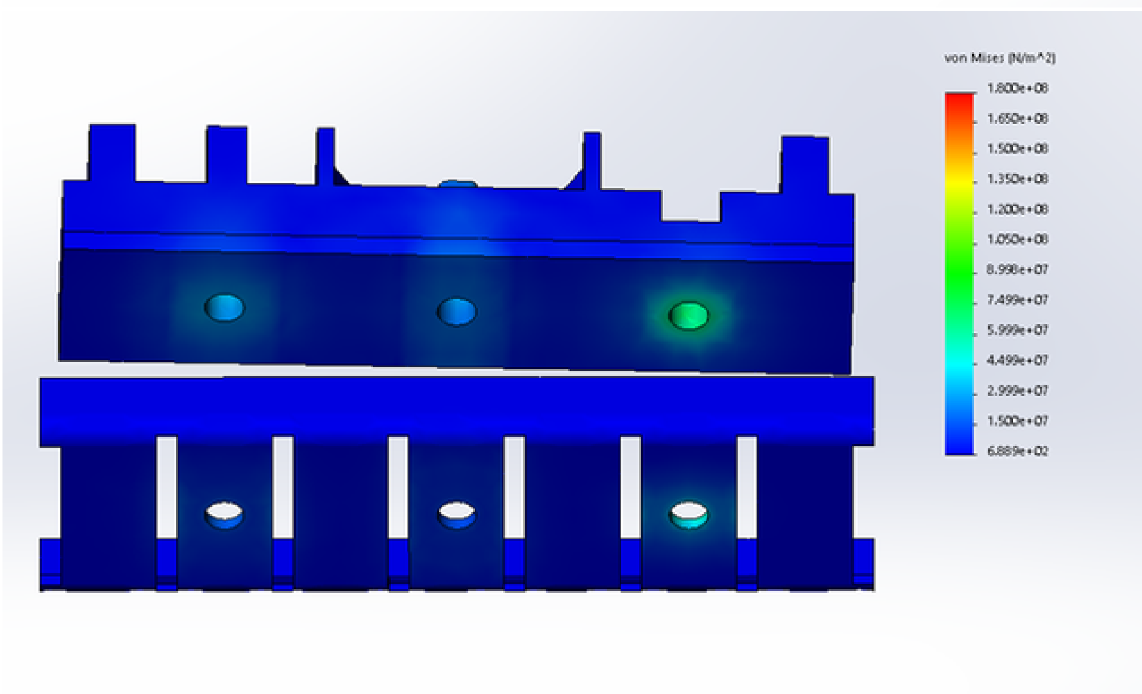
qued to 0.3 Nm to 1 Nm 2 overlapping 1, 4 overlapping 3, etc.					
Bus Bar: 3 Studs, 8 Tabs, torqued to 0.3 Nm to 1 Nm 2 overlapping 1, 4 overlapping 3, etc. Carbon grease applied at all interfaces	5 A	Scotchbrite, Acetone, Carbon Grease	201 µ		

FEA Results:

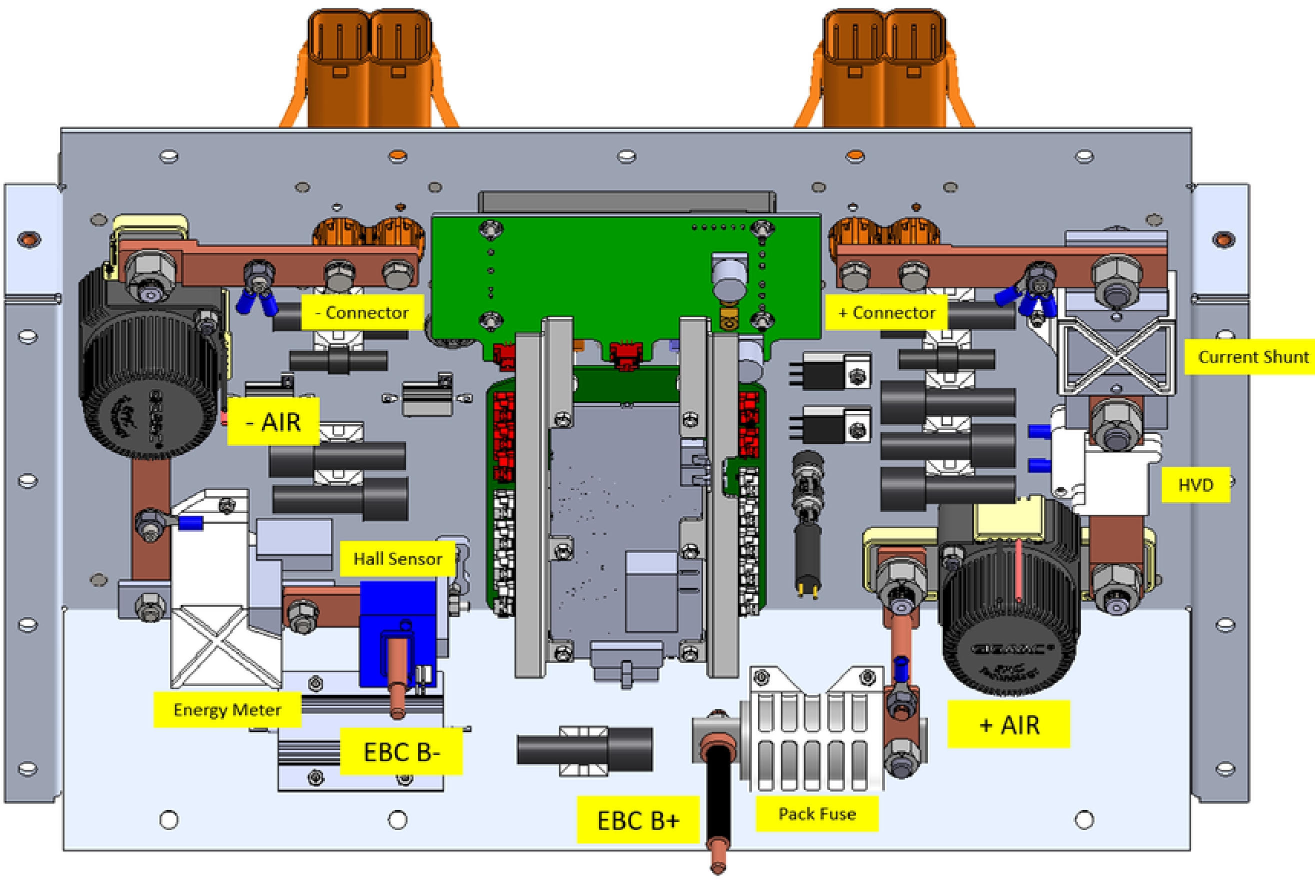
Note:

1. Preload tension is offered by bolt tightening torque
2. The pressure values in regions which are ~ 1.5 mm from the bolts are exaggerated

Arrangement	Preload Tension (Nm)	Fixed plane(s)	Result	Simul
4 Tabs, 2 Studs	1	Bottom face of Celltab carrier	 	

			
8 tabs, 3 studs		Bottom face of Cell tab carrier	

High Voltage Current Path 2018-2020



Summary

The High Voltage Current Path in the accumulator delivers power to the rest of the Tractive System. Each accumulator segment has a 5.7 mm Methode Embedded Bud Connector that accepts a copper pin from the bus bar. The system must be able to deliver up to 400 A peak and 135 A continuously in order to allow the car to operate near the competition limits.

Before the connector but after the precharge / discharge circuit, a team-designed HVD is used to open the circuit while work is being done on the battery or in the event of an emergency.

Design consists of mechanical component layout, spacing analysis, and thermal calculations to find the steady state temperature of elements in the system.

CAD Information

CAD Design Organization- See Accumulator File

The HVCP parts are all included in the Accumulator Lid assembly, except for the Segment Disconnects.

Design Philosophy:

- This design leaves no conductive, energized surfaces exposed while working on the accumulator.
- Wide, flat copper bus bars are used extensively to allow simple connections, easy fabrication, and replacement if required.
- The segment disconnects and EBC connectors allow very quick assembly and disassembly of the accumulator, key to safe operation.

Project Design Process

Problem Definition

The Tractive System for E-Model 2 requires up to 80 kW peak power and 35 kW average power during endurance. The high voltage current path transfers that electrical power from the battery cells and to the accumulator connectors. The HVCP must be designed to carry the electrical load without excessive heat generation, maintain isolation and spacing requirements, and be appropriately fused. It must also have an emergency disconnect allowing the path to be opened in the event of an emergency.

Tractive System High Current Path Requirements

Attribute	Value	Units	Justification
Maximum Voltage	300	V	Formula Hybrid Rule
Maximum Current	550	A	Fuse TTB Graph for 1 s - should be investigated
RMS Current	125	A	Fuse Size
Maximum Temperature	60	°C	Cell Thermal Limit
Insulation Requirements	5	M	General Value

Rules Compliance

Rule	Status	Notes	Proof of Compliance
EV2.6.1	Unknown macro: 'status-handy'	Every accumulator container must contain at least one fuse in the high-current TS path, located on the same side of the AIRs as the battery or capacitor. These fuses must comply with EV6.1.	Pack Fuse L50QS125 is installed and functional.
EV2.6.3	Unknown macro: 'status-handy'	If more than one battery cell or capacitor is used to form a set of cells in parallel and those parallel groups are then combined in series (Figure 29) then either: Each cell must be protected with a fuse or fusible link with a current rating less than or equal to the maximum continuous discharge current of the cell or capacitor. The fuse or fusible link must be rated for the full tractive system voltage, unless the special conditions in EV2.6.5 (Fuse Voltage Ratings) are met.	
EV2.6.5	Unknown macro: 'status-handy'	Although fuses in the tractive system must normally be rated for the full tractive system voltage, under certain conditions an exception can be made for fuses or fusible links for individual cells or capacitors. These conditions apply to fuses or fusible links used to meet EV2.6.3, and to fusible links that are included in the accumulator construction even if the fusible links are not required to meet any other rules.	
EV2.6.6	Unknown macro: 'status-handy'	**Paraphrase:** The fuses that protects cells in parallel must not sum to more than one third of the sum of the parallel cell fuses. In this case, it is 40A.	The selected fuse, L50QS40, meets this requirement.
EV2.7	Unknown macro: 'status-handy'	**Paraphrase:** The accumulator segments must be connected with segment disconnects. They must not be able to cause a short if dropped into the box.	The exposed surfaces are protected.
EV5.3	Unknown macro: 'status-handy'	**Paraphrase:** Spacing according to Table 13 must be used to isolate TS conductors from TS voltages and GLV systems. Insulation must meet EV5.4.	DC-DC board does not have minimum spacing to + connector
EV6.1	Unknown macro: 'status-handy'	**Paraphrase:** All wiring must be appropriately fused, allowing for peak / constant ratings and voltage limits.	Fusing documentation for vehicle in progress.
EV3.4.3	Unknown macro: 'status-handy'	Conductors and terminals must not be modified from their original size/shape and must be appropriate for the connection being made. Shaving of lugs is not visible from a front view.	Pictures? Logs?
EV3.3.1	Unknown macro: 'status-handy'	Cable or conduit exiting or entering a tractive system enclosure or the drive motor must use a liquid-tight fitting proving strain relief to the cable or conduit such that it will withstand a force of 200N without straining the cable	

		Performed strain relief test by manually pulling apart HV cable at a tensile force over 200N (45lbf). Measured the wire length before and after applying force; no deformation occurred.	

Constraints and Criteria

Design considerations based on testing and analysis of past designs, as well as feedback from competition judges and professionals.

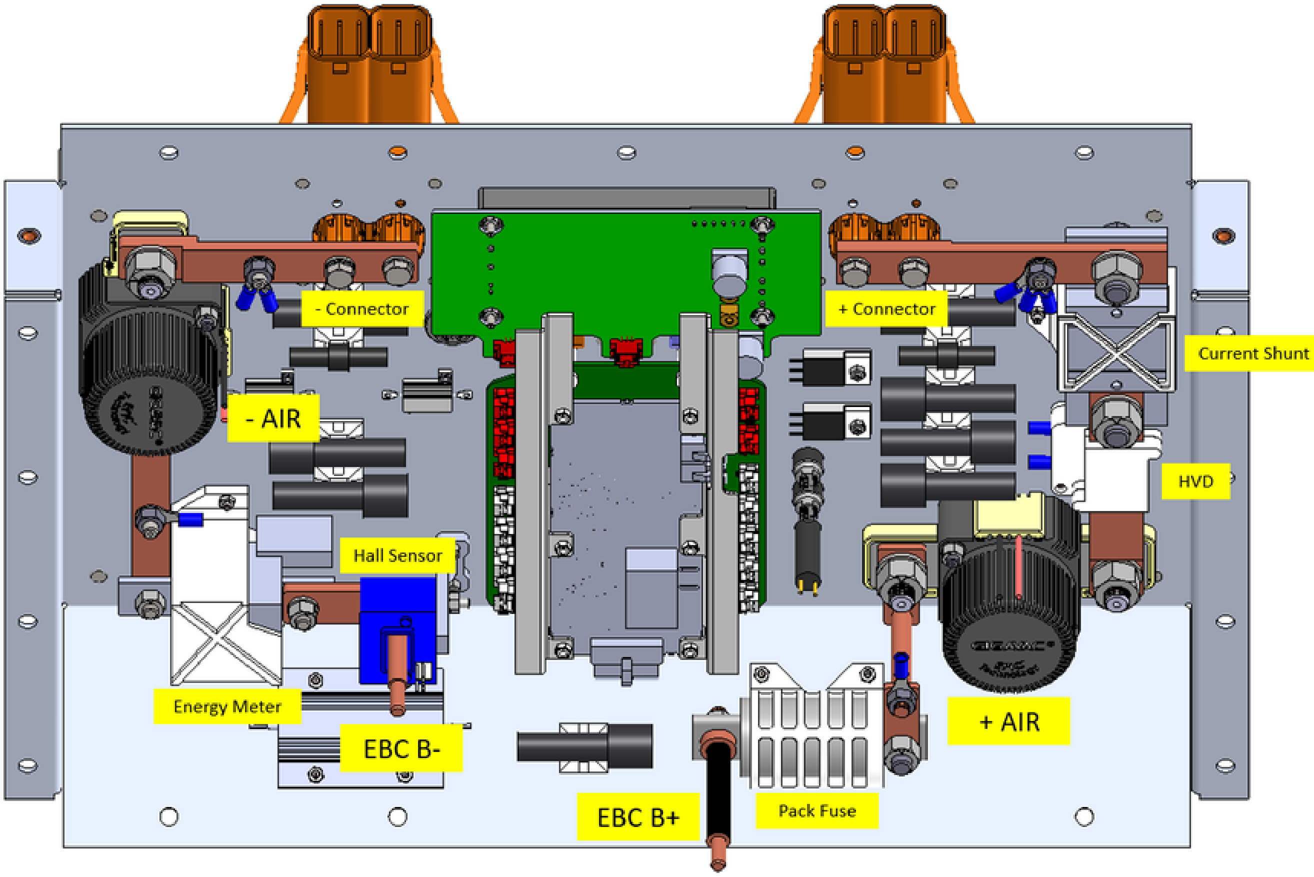
Constraint	Priority	Description	Value	Unit	Verification Method
Current Capability	Unknown macro: 'status-handy'	Higher current capability means that more power can be output to the components. This allows the subsystems to be more effective.	135	A, RMS	HITL Load Test
Isolation and Spacing	Unknown macro: 'status-handy'	The tractive system must be completely isolated from the grounded accumulator case. The spacing requirements are outlined in EV 5.3.3	Compliant		Ruler
Manufacturing	Unknown macro: 'status-handy'	The high current path must be made of simple shapes able to be manufactured in the student machine shop with standard stock sizes.	N/A	N/A	Design Review
Weight	Unknown macro: 'status-handy'	Lower component weight means better efficiency and performance. The HVCP weight is not a significant factor in the mass of the accumulator, so it has a low priority.	.5	kg	Electronic Scale

Technical Progress

This section details solutions to the problem definition, describes a test or simulation plan, and an analysis of completed tests.

- Design Solutions
  - Selected Design and Design Values
  - Alternate Designs
- Solution Test Plan: Setup and Procedure
  - Simulation Test Plan (FEA, CFD)
  - Physical Subsystem Test Plan (HITL, Load Bank, Static Vehicle Testing)
  - Vehicle Testing

General Accumulator Schematic



The current path in the accumulator lid travels from the positive battery terminal, B+, to the negative battery terminal, B-.

Each connection is made with a copper bus bar, bolted to the connection point on the component. Both rectangular and cylindrical bus bars are used. In general, the cylindrical bus bars have a lower ampacity, due to the lower cross sectional area.

Main Series Fuse Selection

The series fuse must be selected to protect the battery cells and motor controllers in the current path. From EV2.6, the series fuse must have a continuous current capability less than one third of the sum of the parallel cell fuses. By physical testing, each cell fuse has an ampacity of 30 A. This rating has not yet been fully tested due to the sudden end of the winter term. Thus, the main pack fuse must have a rating not more than 40 A. This is due to the difference in fuse design between the Formula SAE Electric goals and the Formula Hybrid fuse rules. Unfortunately, this series fuse is de-rates the power of the vehicle. The L50QS40 from Littelfuse is similar to the current fuse in the pack, but is much smaller. The fuse datasheet is attached here: l50qs_high_speed_fuse_datasheet.pdf. This 40 A limit is much less than the designed ampacity of the current path.

Heat Rejection Calculations:

From the handbook on Copper BusBars, published by the Copper Alliance. It can be found in the at the bottom of this page. Specifically, heat rejection from convection and radiation was considered. The temperature rise of the bus bar was 20 °C- from an ambient temperature of 40 °C to 60 °C.

Bus Bars- Positive Side	Surface	Cross-Sectional Area [m^2]	Resistance- Connection to Connection [ ]	Ampacity @ 60 °C [A]
Positive EBC to Pack Fuse	Insulated	0.0000694		334
Pack Fuse to +AIR Bus Bar	Bare	0.0000445		286
+AIR Bus Bar: Cylindrical	Bare	0.0000503		268
+AIR Bus Bar	Bare	0.0000445		286
+AIR to HVD	Bare	0.0001000		499
HVD Pin	Insulated	0.0000445		TBD
HVD Shorting Bar	Insulated	0.0000255		168
HVD to Shunt	Bare	0.0001000		499

Shunt to +Connector	Bare	0.0000857		443

Bus Bars- Negative Side	Surface	Cross-Sectional Area [mm^2]	Resistance- Connection to Connection [ ]	Ampacity @ 60 °C [A]
Negative EBC to Hall Sensor	Insulated	0.0000857		443
Hall Sensor to Energy Meter	Bare	0.0000714		385
Energy Meter to -AIR	Bare	0.0000857		443
-AIR to -Connector	Bare	0.0000442		245

Segment Aluminum Bus Bars

Aluminum Bus Bars	Surface	Cross-Sectional Area [mm^2]	Resistance- Connection to Connection [ ]	Ampacity @ 60 °C [A]
3 Studs, 8 Cells	Bare		Cell to Bus Bar- 0.000150 (Typical for middle)	
2 Studs, 8 Cells	Bare			
1 Stud, 4 Cells	Bare			

Accumulator Connectors - 2018 - 2020 Season

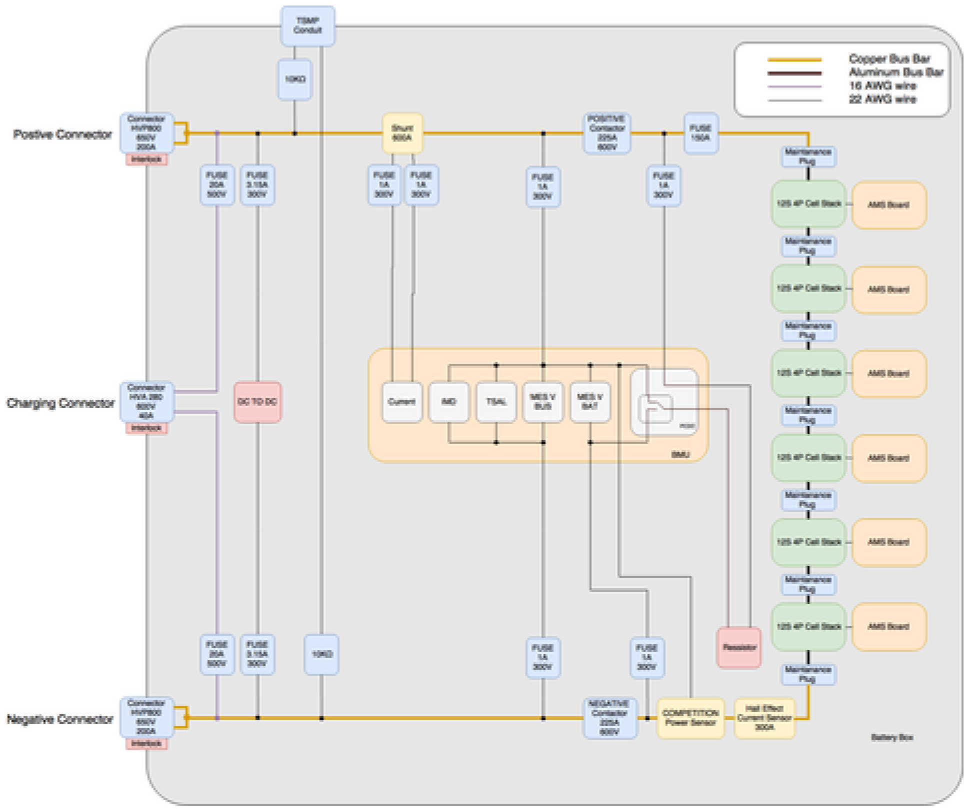
HVP-800 Connectors

Segment Disconnect Bus Bars

Each segment must be able to be fully disconnected (both poles) from the rest of the accumulator segments. This requirement is satisfied by connecting the aluminum bus bar on each segment with a 5.7 mm Methode Embedded Bud Connector. Based on Rule **EV2.7**, the segment disconnects must not have exposed surfaces that could cause a short if they were dropped into the battery box. During the ESF-2 review, the reviewers indicated that our solution with the acrylic guard was acceptable if channels were added to guide segment disconnect pin into the hole.

Maintenance Disconnects	Surface	Cross-Sectional Area [mm^2]	Resistance- Connection to Connection [ ]	Ampacity @ 60 °C [A]
Disconnect Pins	Insulated- Heat Shrink and UL94-V0 ABS			
Disconnect Bar	Insulated- Heat Shrink and UL94-V0 ABS			

Tractive System Component Interconnect Diagram



Assembly Guide for Segments: Assembly Guide.pdf

All cells in parallel must have a voltage difference of less than 10mV. Follow groupings.

Things that need to go into the battery box:

Name	PN	Description	qty
TSMP resistor	**RH01010K00FE02**	https://www.digikey.com/product-detail/en/vishay-dale/RH01010K00FE02/RHRB-10K-ND/1166274	2
BMU		team	1

		designed BMU	
AMS		team designed AMS	6
DC to DC	PAF600F280-12	12V 600W	1
1A fuse	0508001.MXP	1 amp measurement fuse (3AG)	6
3.15A fuse	0001.2509	3.15 DC-DC fuse (2AG)	2
20A fuse	0505020.MXP	20A charging Fuse (3AG)	2
150A Fuse	L50QS150.V	Main PT fuse	1
Inline Fuse Holder	01500274Z	10A inline fuse Holder (2AG)	8
inline Fuse Holder	01500603Z	20A inline fuse (3AG)	2
Energy Meter			1
Contactor	GX12B		2
Thermistor	Vishay 10k NTCALUG02A103G	https://www.digikey.ca/pro	

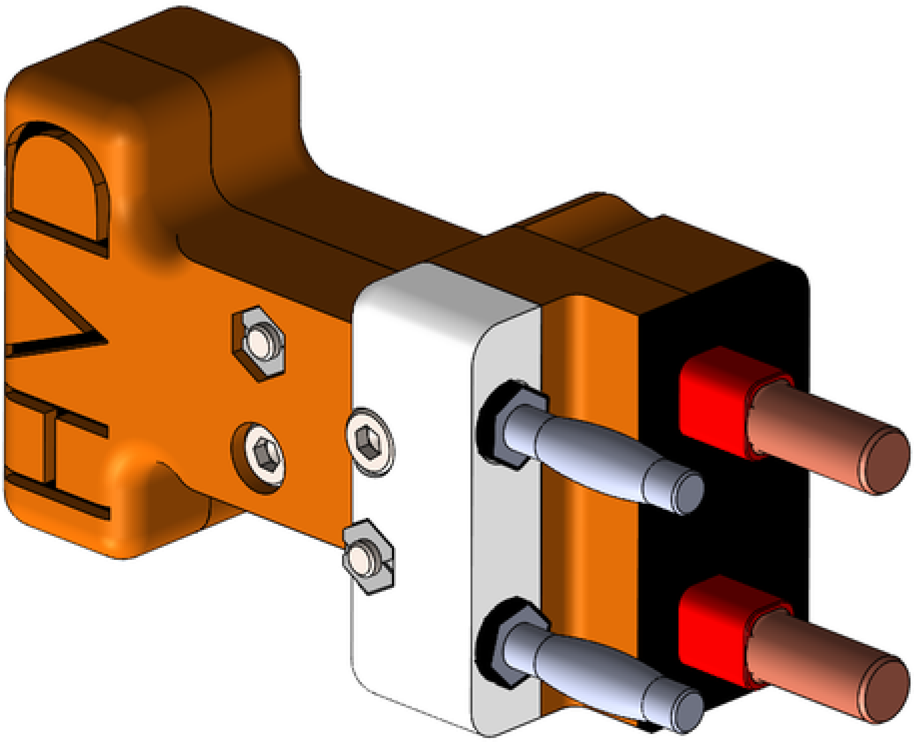
		duct-detail/en/NTCALUG02A103G/BC2741-ND/2640539/?itemSeq=294318522	
PC DC resistor			1
DC to DC			1

High Voltage Disconnect - 2019 Season

High Voltage Disconnect Operating Requirements:

Requirement			Notes
Burst Current	Relevant to design	520 A for 1 second	Based on pack fuse sizing
Device Footprint	Relevant to design	50 mm x 50 mm	Must not take up excessive space on the lid
Operating Current	Required	320 A for 100s	Based on pack fuse sizing
Operating Voltage	Required	300 V	Based on maximum pack voltage
TS Connections	Relevant to design	Bolted Bus Bar	Must respect clearance and creepage requirements for accumulator lid

CAD (Solidworks) of Handle type HVD- 2019, No two stage IL	**HVD Fabrication- Copper Bus Bars**



Finished HVD

Lessons Learned:

Component Attribute	Manufacturable?	Works as Intended?	Serviceability	Notes
3D Printed HVD Handle	Yes- the HVD was machined and printed	Yes, but is not fail-safe	No- HVD assembly cannot be removed without opening the accumulator	The HVD is a copper bus bar which connects two bus bars together in the tractive system path. It is interlocked.
No two-stage interlock	Very manufacturable- no moving parts	Unsafe design	N/A	If pulled under load, the interlock loop doesn't have time to open the contactors before the HVD is pulled

The next design of the HVD absolutely needs to be a design where two actions are needed to release the HVD- first, a button is pushed to break the interlock loop which also unlocks the body of the HVD. After this, the high current path can be pulled under no load. The circuit **must** be broken in the AIRs before the HVD is pulled.

Alternate Designs

Describe other designs for the HVD that were considered in this area.

Product name	Supplier	Notes	Specs	Random
Hirose EM30MSD	Hirose, fulfilled through Digikey	Need to apply some sort of heat rejection calculation to prove adequacy- only specced for 200 A at 60 °C, but 400A for 350 seconds	750 V, 200 A continuous	Looks sick, small footprint
TE 2315855-6	TE	Works continuous at 750V, 250A with variable fuses ranging from 200A-630A! Check here	750V, 250A continuous	Small, orange, variable, Beautiful

Conclusions

- Lessons Learned

    - Description of design improvements
    - Description of design disadvantages
- Estimation of project cost and engineering hours

Project Procurement:

Follow the procurement procedure as described in the Operations page Purchase and Reimbursement Procedure and then upload the purchase order spreadsheet to the table below. Consolidate as many purchases into one procurement request to simplify the process.

Generate a Jira task in the appropriate Operations Epic. Label it with *proc_ts* and an (*label specific to this page)* so that it shows up in the table below.

Team Member Name	Purchase Order Spreadsheet	Quote / Invoice	Order Description	Company Name	Total Cost [CAD]	Status	Storage Location
						Unknown macro: 'status-handy'	

High Voltage Current Path 2021-2022

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Summary

Briefly describe the project purpose and current state.

CAD Information

- CAD Design Organization: *Describe how the solid models for the project are organized.*

Design Philosophy

- "*This part improves over last year's component by ____"*
- *"Do not repeat ____ mistake"*
- *"This design fixes ____"*

Explain each feature of the part and how it accomplishes the part's function.

Problem Definition

Rules Compliance

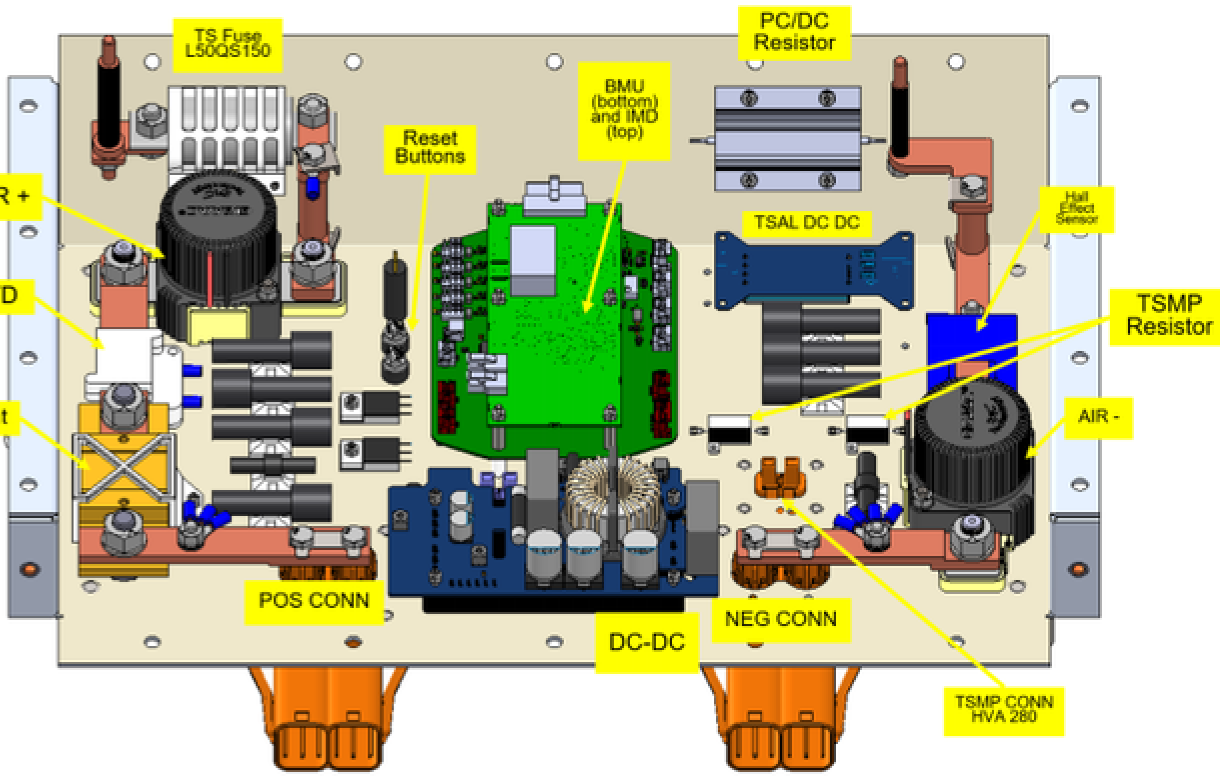
Rule	Status	Notes	Proof of Compliance
A 1.2	Unknown macro: 'status-handy'	**Paraphrase:** For an electric vehicle, the accumulator may have a maximum usable energy of 5.40 kWh, or nominally 6.75 kWh. (Discharge measured at 2C).	The accumulator will be designed to comply and be tested.
EV 2.6.1		Every accumulator container must contain at least one fuse in the high-current TS path, located on the same side of the AIRs as the battery or capacitor. These fuses must comply with EV6.1.	Previous fuse (L50QS125A) has been replaced with L50QS150A.

Constraints and Criteria

Constraint	Priority	Description	Value	Unit	Validation Method

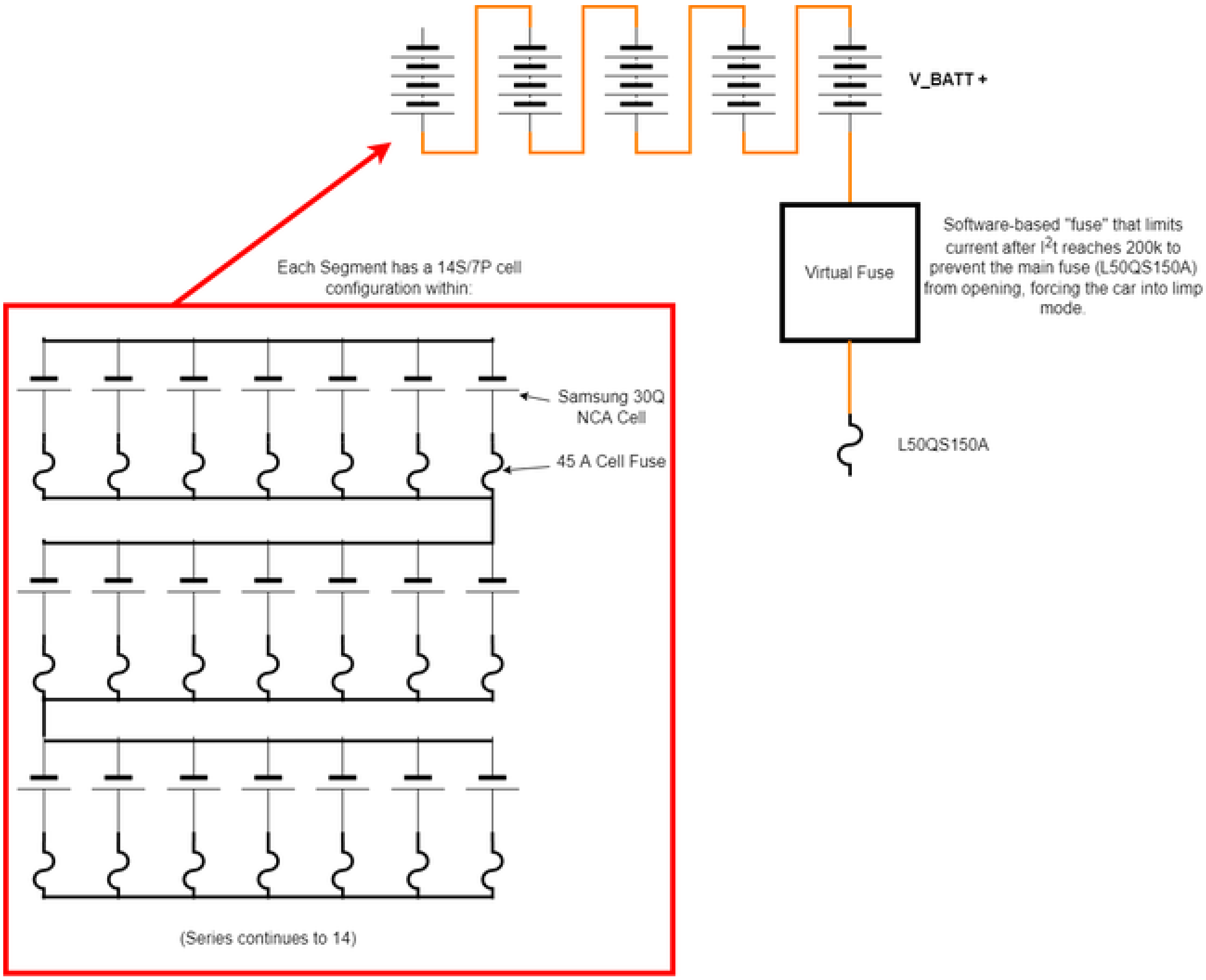
Current Capability	Unknown macro: 'status-handy'	Each segment must be able to deliver the full rated current of the Tractive System because the segments are in series. By design, this is 135 A RMS. The pack fuse will be 40 A.	135	A	HTHC

General Accumulator Lid Schematic (Labeled)



(Sourced from ESF2, Fig. 44)

Fuse Diagram



Justification for use of L50QS150A

The accumulator fuse must be less than all the continuous current ratings of the bus bars, while also being less than half the sum of the cell fuse continuous currents. For the 2022 accumulator, each cell has a continuous current of 45 A and is placed in a 14s7p configuration. As a result, the accumulator fuse must be less than (45*7)/2, or 157.5A. Thus, the 150A variant of the L50QS-series fuse was chosen as the main fuse.

Details on L50QS-series Fuse

Datasheet available here (Incl. graphs for temperature derating/uprating, time-current curve, etc).

The L50QS-series is a bolted-style fuse design. The variation used as the main accumulator fuse is the 150A variant, rated for 150A and 500V.

Technical Progress

Design Process

Design Analysis and Manufacturing Design

Analysis Validation

Manufacturing and Implementation

Conclusions

Project Procurement:

Follow the procurement procedure as described in the Operations page Purchase and Reimbursement Procedure and then upload the purchase order spreadsheet to the table below. Consolidate as many purchases into one procurement request to simplify the process.

Generate a Jira task in the appropriate Operations Epic. Label it with *proc_ts* and an (*label specific to this page)* so that it shows up in the table below.

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

Team Member Name	Purchase Order Spreadsheet	Quote / Invoice	Order Description	Company Name	Total Cost [CAD]	Status	Storage Location
						NOT YET PROCESSED	

W20 High Voltage Disconnect (HVD)

Project Timeline:

WBS Project Title: High Voltage Disconnect (HVD)

WBS Project Number: 1.2.1.3.3

Describe tasks and use the correct tags to show the state of the project.

Status	Unknown macro: 'status-handy'
Estimated Completion	22 Mar 2020
Project Deadline	22 Mar 2020
Required to	Yes

Responsibility Cascade:

- *Project Lead:* *@ Joseph Anthony Borromeo*
  - @ Former user (Deleted) - Machining

Design Philosophy:

- This part improves over last year's HVD because it will be professionally manufactured.
- It will be a two stage design, where the release button breaks the IL

Run	
Priority	Unknown macro: 'status-handy'

Task list:

- ~~Change Busbar to bent 8mm copper rod, ends must be turned down for embedded bud connector~~ - **DONE**
- Add hex cutouts for nuts
- Increase spacing to account for heatshrink
- Add skirt to help waterproofing
- ~~Print test holes for banana plug tolerances~~ - **DONE**
  - ~~Fix 90 degree aluminum adapter and change sizing based on above~~ - **DONE**
- ~~Change banana plug or change key sizing to fix the banana plugs~~ - **DONE**
- Close holes on aluminum adapter cover
- Split key in half and add fasteners so it's possible to assemble
- Move bottom screw up to ensure HV/LV clearance for the copper busbar
- Change Smart fasteners to the fasteners found in the template folder on GrabCad
- Generate Drawings for parts needing machining
- Print new HVD

Ensure 2mm HV-LV spacing

Description

HVD Fabrication

Segment Disconnect Insulation + Re-Fabrication

Relevant Documentation:

- Confluence page
- Pdf file
- Technical Datasheets.pdf

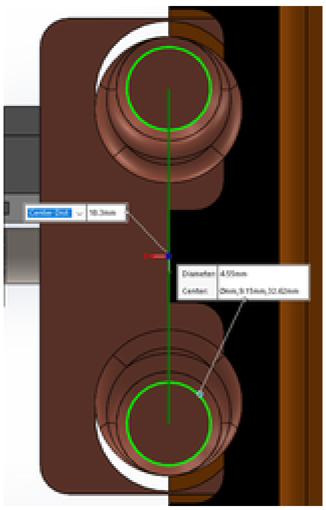
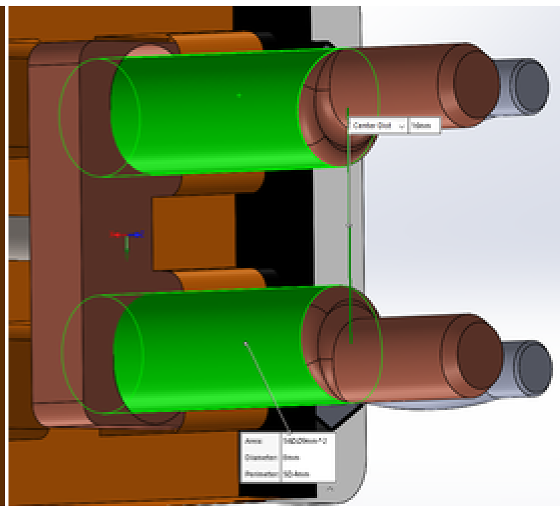
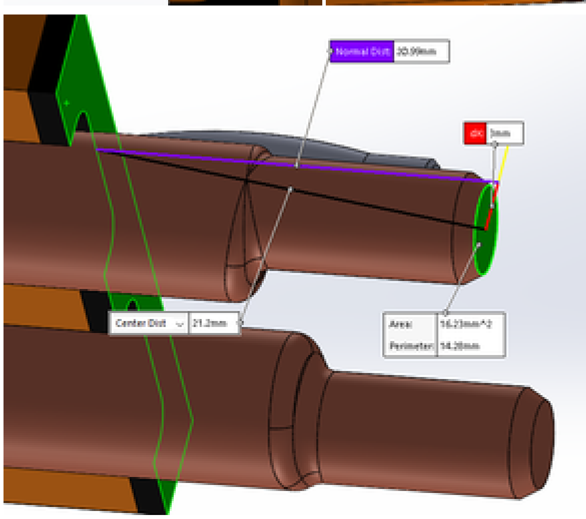
Rules Compliance

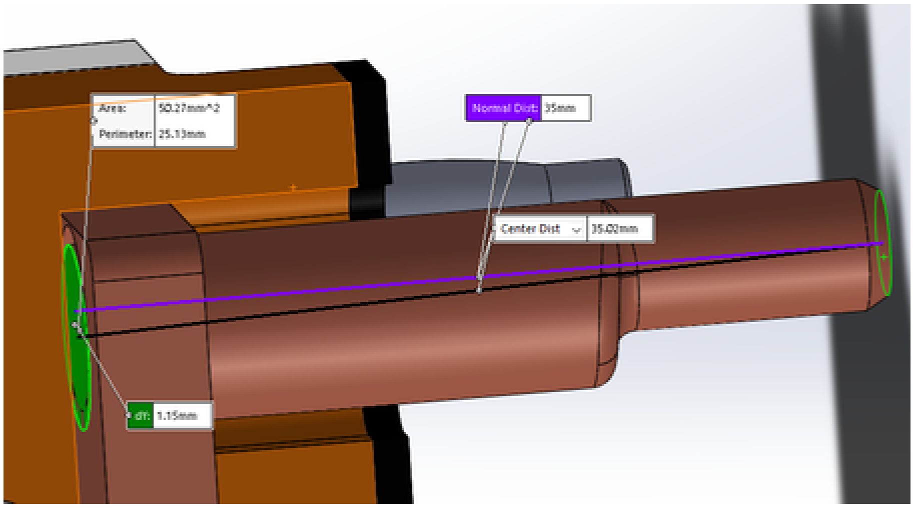
Section	Status	Notes	Documentation
EV 2.9.2	Unknown macro: 'status-handy'	The HVD must be operable without the use of tools.	
EV 2.9.3	Unknown macro: 'status-handy'	It must be possible to disconnect the HVD within 10 seconds in ready-to-race condition. **Note**: Ready-to-race means that the car is fully assembled, including having all body panels in position, with a driver seated in the vehicle and without the car jacked up.	
EV 2.9.5	Unknown macro: 'status-handy'	The disconnect must be clearly marked with "HVD". Multiple disconnects must be marked “HVD n of m”, such as “HVD 1 of 3”, HVD 2 of 3”, etc	
EV 2.9.6	Unknown macro: 'status-handy'	There must be a positive means of securing the HVD in the disconnected state; for example, a lockable switch can be secured with a zip-tie or a clip. **Note**: A removable plug will meet this requirement if the plug is secured or fully removed such that it cannot accidentally reconnect.	

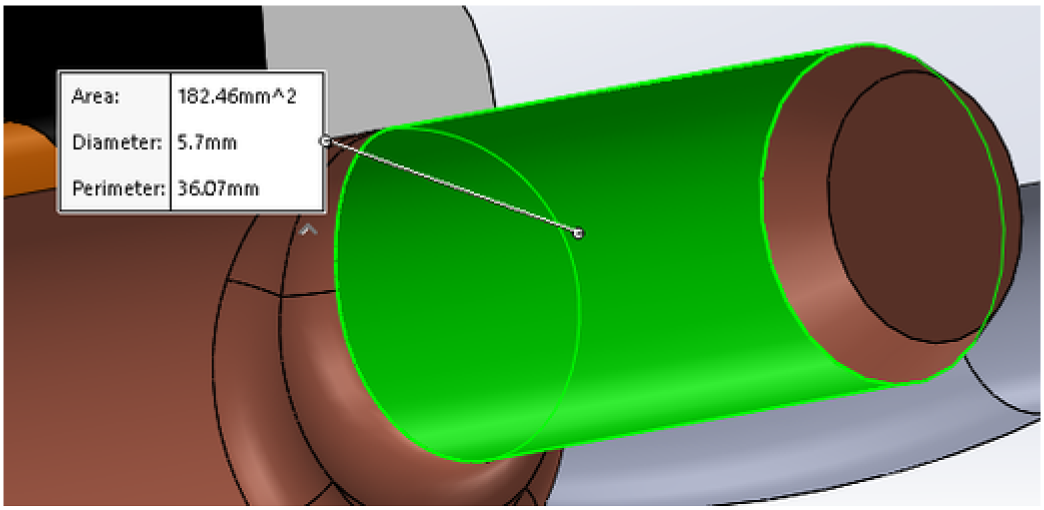
Expenditures:

Items	Vendor	Payment Method	Cost (CAD/USD)	Form Link	
Banana Plug x2	Digikey		$4.12		

Project Bring-up

Winter 2020 Progress	Details + pictures
March 5th, 2020	  





Original Busbar design and dimensions. This design was harder to manufacture and solder was required to hold the cylindrical pins to the rectangular bus bar which does not meet rules.

The new design will be made from a single piece of 8mm copper with ends turned down to 5.7mm to fit into the embedded bud connectors P/N: 1101-06630-01104.

Actual center to center distance of the cylindrical busbars is 19.6mm

Banana plug sticks out ~9mm when flush with a 10mm jack

New Shorter Banana Plug: https://www.digikey.ca/product-detail/en/cinch-connectivity-solutions-johnson/108-0753-001/J149-ND/5927

Description	Due date	Assignee	Task appears on
Acquire current readout for high current test fixture @ Former user (Deleted) 25 Jan 2020	25 Jan 2020	Former user (Deleted)	Cell Packaging 2018-2020
@ a2ivanch@uwaterloo.ca Finalize mold design and procure nylon material 31 Jan 2020	31 Jan 2020	a2ivanch@uwaterloo.ca	20-4-PWT-381-Powertrain Inboard Boots
@ jlmorabi@uwaterloo.ca @ a2ivanch@uwaterloo.ca Cast three silicone parts 29 Feb 2020	29 Feb 2020	jlmorabi@uwaterloo.ca	20-4-PWT-381-Powertrain Inboard Boots
Validate rules and write the SOP, @ ba2nguye@uwaterloo.ca , 05 Mar 2020	05 Mar 2020	ba2nguye@uwaterloo.ca	W20 Lockout Tagout Procedure
Update template for powertrain homepage @ Chris Xie 05 Jun 2021	05 Jun 2021	Chris Xie	Powertrain Documentation Project Template
Click to add a new task...			Motor Controllers 2018-2020
Click to add a new task...			Motor Controllers 2018-2020
@ Former user (Deleted) Purchase appropriate amounts of nylon stock from EMS- we already have a bit in the stock rack on the bay, hopefully enough for the bottom section. 3" round is enough for the top mold		Former user (Deleted)	W20 Inboard Boots Fabrication
@ jlmorabi@uwaterloo.ca design / borrow a vacuum chamber to degas the silicone, as seen here: Vacuum Degassing Chamber and Pump		jlmorabi@uwaterloo.ca	W20 Inboard Boots Fabrication
Mechanical drive line design freeze			Powertrain Deadline Summary
Manufacturing documents complete			Powertrain Deadline Summary
Dyno testing start			Powertrain Deadline Summary
Fully assembled on vehicle			Powertrain Deadline Summary
Two HV insulating blankets of at least 1.0 m^2			W20 Accumulator Toolbox and PPE
Insulated Magnet (have nice magnetic screwdrivers, but they aren't insulated)			W20 Accumulator Toolbox and PPE

- [ ] Insulated 5.5mm socket	W20 Accumulator Toolbox and PPE
- [ ] Insulated Needle Nose Pliers	W20 Accumulator Toolbox and PPE
- [ ] Insulated Socket Set and Ratchet Handle	W20 Accumulator Toolbox and PPE
- [ ] Ground CAN wire shielding Add plug shielding pin into BMU connector ground. On other end ensure shielding is grounded to CCU. Ensure CCU is grounded to the charge cart	W20 Charge Cart Evaluation
- [ ] Check spacing between IMD and Segment Disconnects	W20 BMS Wiring and Fusing Evaluation

Tractive System Meeting Notes:

This space will contain only outstanding meeting notes that have not been properly documented.

Long Term Tractive System Goals - Updated 2021-02-04

- Fully dyno test powertrain system, or test on chassis dyno at **** (secret location in E3)
- Build more accumulator segments with higher spec batteries, or for different purposes (tentative)
- Design new accumulator container to comply with 8 corner mounting (tentative)

Impromptu Task List

Use this space for tasks that don't fit anywhere else

- [x] Create Jira Issue for completing all powertrain CAD @ Chris Xie
- [ ] Label accumulator with HV / Always Energized sign @ jlmorabi@uwaterloo.ca
- [ ] Evaluate wire rating for all BMS connection @ Joseph Anthony Borromeo
- [ ] EV12.1- Lockout Tagout Procedure for TS @ jlmorabi@uwaterloo.ca @ ba2nguye@uwaterloo.ca
- [ ] Charge Cart- Grounding and Wiring Standards- Need to be improved @ jlmorabi@uwaterloo.ca @ ba2nguye@uwaterloo.ca
- [ ] Charger Inspection- need a CSA equivalent stamp on it , confirm charger fuse, confirm charger has UL listed wiring @ ba2nguye@uwaterloo.ca @ jlmorabi@uwaterloo.ca

Fall 2019: Accumulator Projects for New Members

Accumulator Low Voltage Maintenance Guards:

Purpose:

Design insulating, fire retardant guards to shield the exposed bus bars during maintenance.

Requirements:

The solution must be:

- Completely made of fire retardant, insulating material- Nomex card is a great solution. Be sure to design the seams to have overlap.
- Completely protect bus bars other than the bus bar being worked on. See the picture in the Accumulator Box Page.
- Easy to install, easy to remove, and work for most busbar/segment configurations.

Implementation

Source the Nomex or other fireproof card, make a paper mockup that protects most of the cells/bus bars, and then cut and bend the Nomex into shape. If the accumulator is sealed while you are working on the design, talk to an upper year about getting CAD of the segment.

Accumulator Thermal Management:

Purpose:

Adapt @ Calvin Ryan DeKoter 's Excel sheet to calculate all heat generation in the accumulator, allowing the team to build up a thermal model.

Requirements:

The Excel Sheet must include:

- Colour-coded cells relating to inputs, intermediate calculations, and outputs, documentation of all assumptions, and a brief guide about how to use the sheet.
- Input Cells to add data about the current carrying path in the accumulator.
- Input Cells to define the operating conditions of the accumulator- such as load, ambient temperature, and the time the accumulator is under load for.
- Outputs which define the maximum temperature rise inside the battery, and our colour-coded to clearly show passing criteria.

Implementation:

- Learn about heat transfer by the three methods found in the battery box- convection, radiation, and conduction (hopefully not from the HV Bus Bars!).
- Reach out to Calvin about getting the Excel sheet- it should be in a decent condition when you get it, but you may have to clean it up slightly or adapt it to the accumulator, as built.
- Package the results attractively- plot the maximum temperature of the pack vs. time, if possible, or at the very least, make an annotated drawing with component temperatures at the RMS endurance steady state.

Task Template Spring 2022

Key	Summary	Type	Created	Updated	Due	Assignee	Reporter	Priority	Status	Resolution

⚠ Unable to locate JIRA server for this macro. It may be due to Application Link configuration.

The tasks for the coming term will be structured as the following.

1. Document 2021 Design / Concepts
2. Concept Design + Bounding Box (All mounting holes + key features in CAD)
3. Subteam review with hand calculations or rough CAE
4. Detailed Design (Component is ready to be put in final designs)
5. Validation (CAE, detailed test plan, or hand calculations)
6. Subteam Review - final acceptance by subteam lead / technical lead
7. Manufacturing Drawings
8. Manufacturing
9. Manufacturing Validation + Quality Assurance

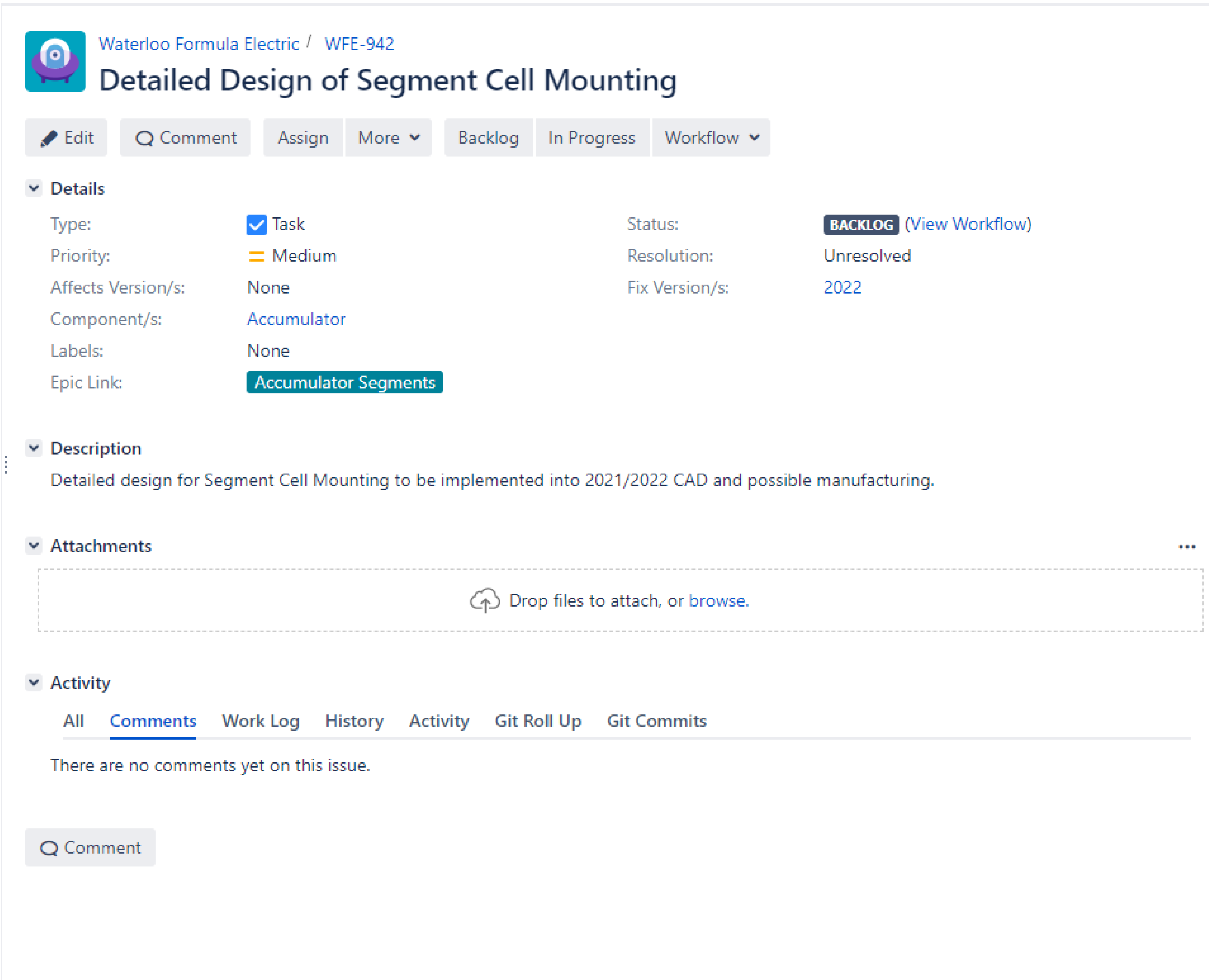
10. Installation
11. Documentation (pictures of manufacturing, installation, any issues)

This year due to tasks following the workflow, all tasks will follow the above structure. When assigned a task, members will create their own tasks with the following template.

Title example: Document 2021 Design / Concepts of ______________________ **specify component**

Description example: Documentation 2021 Design and Review 2021 Concepts and documentation for the _________________________ **specify component and include minor details on task.**

Note that all stories with the label TS_eleven will have the 11 specified tasks under them.



A vague set of these tasks have been created under WFE-871 Accumulator Box which can be referred to when creating tasks.

Accumulator Lessons

Accumulator Overview

Note: This overview skips over some important electrical aspects of the car particularly the LV system

For further learnings I would recommend reading some other guides I have written:

Firmware Overview for Non-Technical Driver

Overview of Acronyms, Terms, Definitions

If you are confused about an acronym I use please checkout the above “Overview of Acronyms, Terms and Definitions“. If it’s not in there please let me @ Owen Brake know and we can add it.

Also checkout the ESF-2 (https://jira.uwaterloo.ca/browse/WFE-864)

Safety

Danger

Electrical Shock

- The accumulator has the potential to cause permanent brain damage and death
  - It is extremely dangerous
  - No one wants their last moments to be working on a design team
  - It is the most dangerous thing in the bay
- Danger Calculation:
  - Body resistance can fluctuate between 1k to 100k. The skin contact resistance will quickly degrade when HV is applied to it, lead to approximately 500
  - Accumulator fully charged voltage is 294V
  - Using Ohm’s law, the current flowing through your body will be: ~588mA
  - At 1mA you can feel it
  - At 10mA you feel significant pain and lose control of your muscles
  - 30mA you stop breathing
  - 75mA ventricular fibrillation, death within minutes

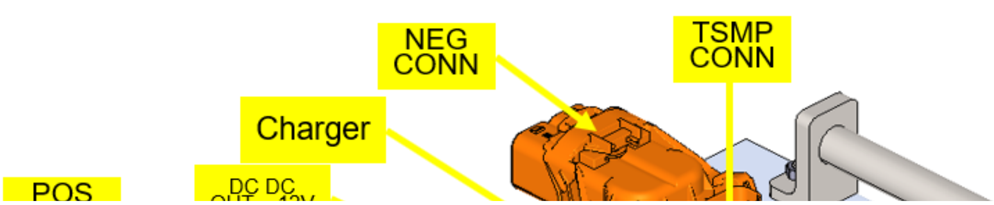
Thermal Runaway

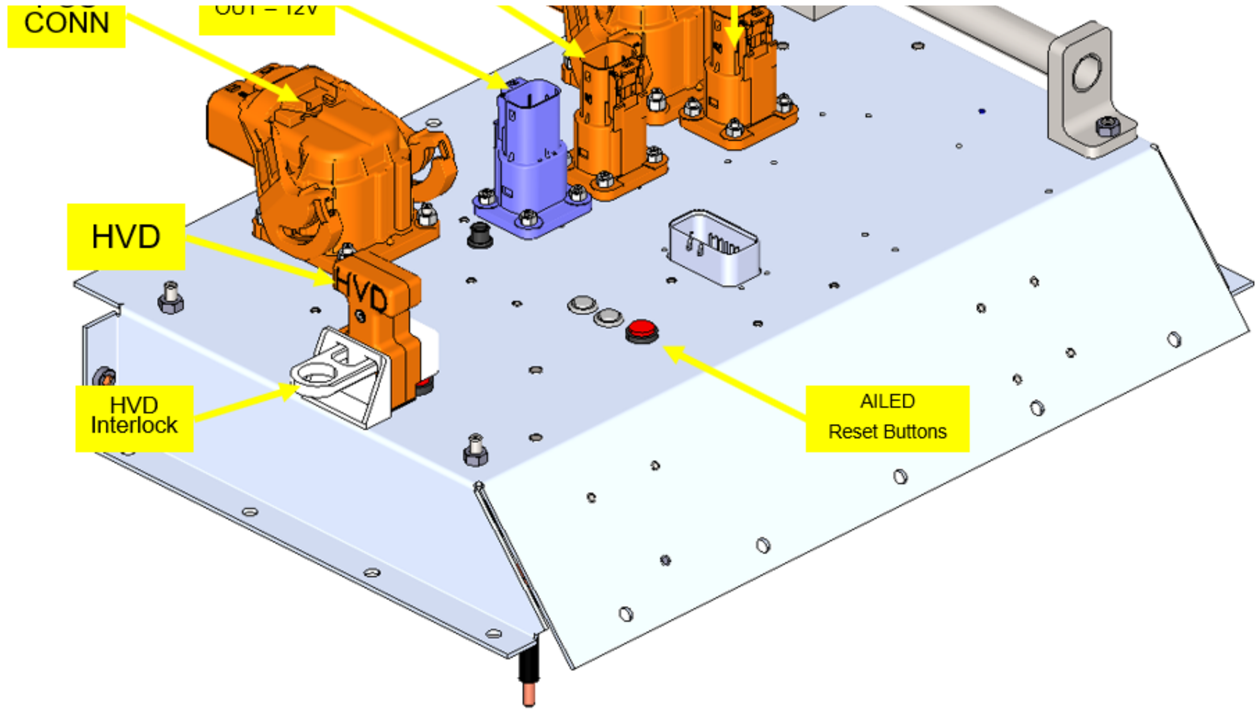
- We use lithium ion batteries (490 individual Samsung 30Q 18650)
- Lithium ion batteries when damaged can undergo thermal runaway
- Thermal runaway is when the lithium ion battery goes through a chemical reaction where it releases all it’s energy at once, causing electrical fires, toxic gas release and explosion
- We have 490 cells so a thermal runaway can happen very quickly and be very violent.
- You cannot use water to put out the electrical fire you can try to use a Class C Fire extinguisher
- This also means that we cannot allow anything to be dropped in the accumulator, if it does it should be reported immediately, as a small component could short out a battery and cause thermal runaway.

Rules

1. No one should touch the accumulator without @ Joseph Anthony Borromeo , or @ Owen Brake 's explicit permission and instruction
   a. Don’t even touch the accumulator box
   b. This includes any HV cables (orange)
   c. This includes the charge cart if the accumulator is on it
2. When the accumulator is open it should be open in a wide open space. No one should be within 3 feet of the accumulator unless assisting or supporting
3. Whenever the accumulator is open there should be one person working in it, with an assistant to react if there is a loss of muscle control
4. Whenever working at high voltage insulating tools, safety glasses and HV gloves should be used
   a. Within reason, currently our SMDs are an issue and HV gloves cannot be used.
   b. Try to use only one hand in the accumulator
5. Whenever the accumulator lid is off and being worked on, while the segments aren’t, the HV blanket should be placed on it
6. The accumulator should always be near a class C fire extinguisher
   a. At all testing events we need one
7. If there is any potential safety concern at all report it immediately. We would rather know you had a mistake then cause a safety hazard. There is no such thing as a stupid question or comment if it involves safety

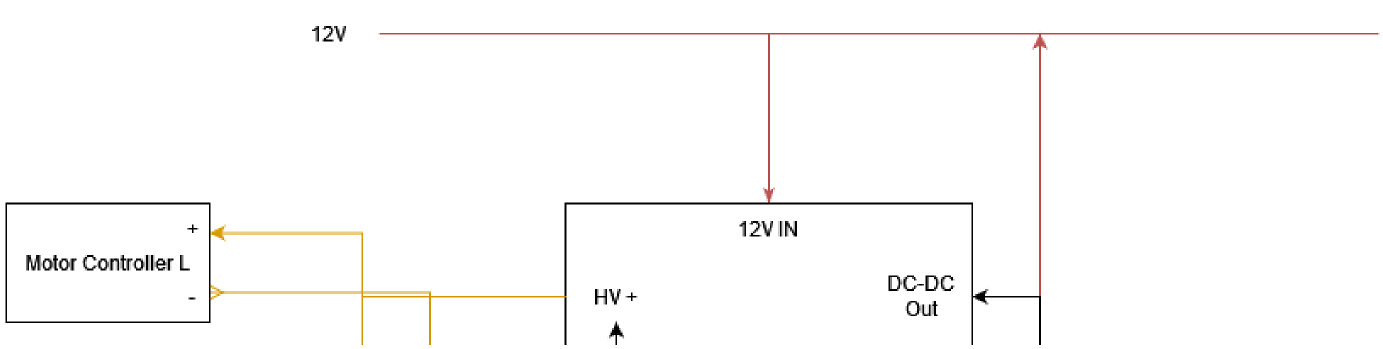
Box

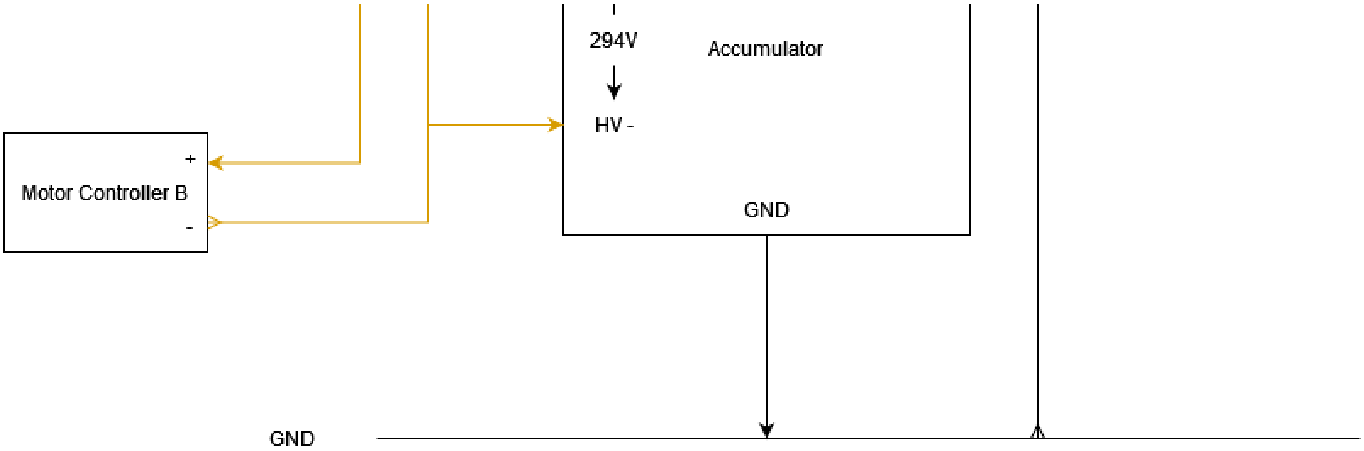




- POS CONN - Positive Connector
  - HV (Orange) cable carrying DC voltage to the motor controllers
  - Why 2 cables on the POS CONN connector? Because, we have 2 motor controllers
- NEG CONN - Negative Connector
  - HV (Orange cable acting as return wire for DC voltage to the motor controllers
- HVD - High Voltage Disconnect
  - Directly disconnects the HV path of the accumulator when removed.
  - Used only in emergency situations to shutdown the car
- HVD Interlock
  - Key required to be pulled to pull the HVD
  - Shuts down the car more gracefully by cutting the interlock loop
- TSMP CONN - Tractive System Measuring Point connector
  - Connects to a device we have where one can measure the voltage on the accumulator
- Charger
  - Connects to our Charger
- DC DC Out - 12V
  - Uses power from the accumulator for our LV bus (which powers our boards)
  - Steps down accumulator voltage (~250-294V to 12V)
- AILED - Accumulator Indicator LED
  - Blue LED on lid of accumulator, if it is on indicates we are at HV
- Reset Buttons
  - Switches which reset the latching circuits for: IMD, AMS, BSPD
  - Part of the startup procedure.

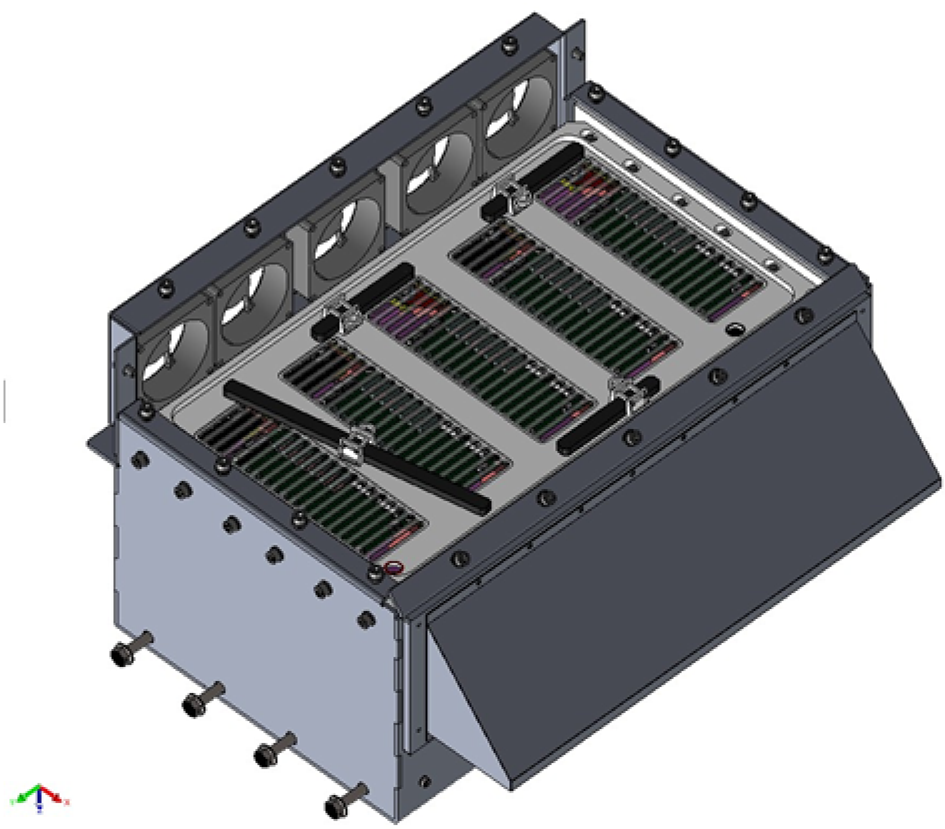
High Level Overview



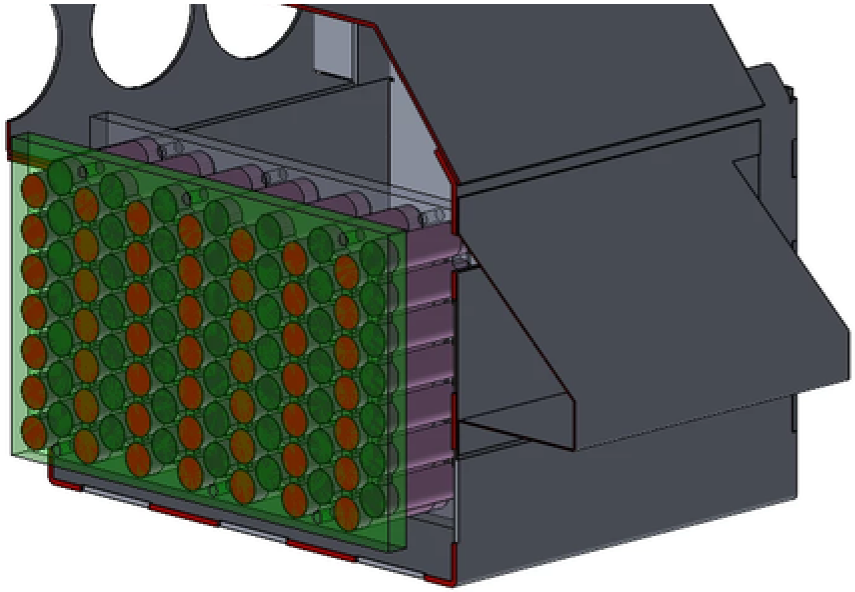


- From a high level:
  - We have the accumulator applies HV to the Motor Controllers
  - The accumulator can step this 294V to 12V and power the low voltage electronics
  - We can power down the car by:
    - Triggering the interlock
    - Pulling the HVD
  - We can charge the accumulator

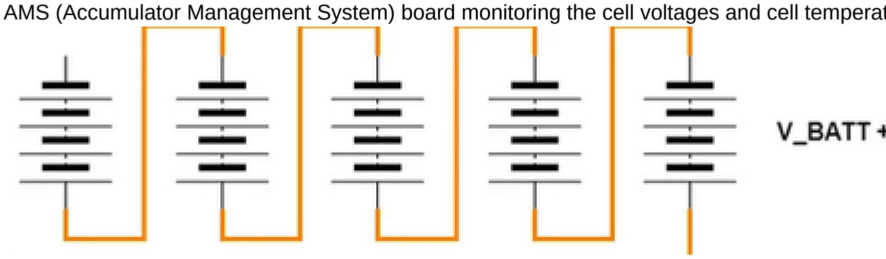
Segments



- Our accumulator is divided into 5 “segments“. Segments are essentially large collection of battery cells.



- Each segment is ~60V they consist of 98 Cylindrical Lithium ion batteries (18650 Samsung 30Qs)
- Each segment has an AMS (Accumulator Management System) board monitoring the cell voltages and cell temperatures.



- Each segment is ~60V and when connected together in series this leads to a ~300V accumulator
- Each segment is connected in series using the SMDs “segment maintenance disconnects“

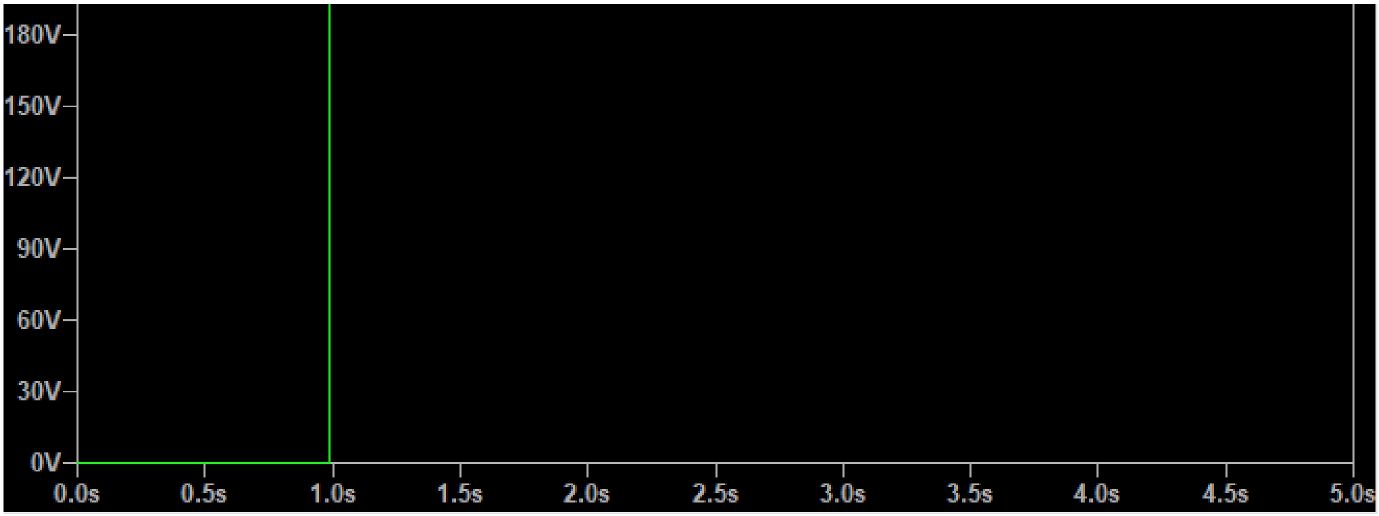
Accumulator Specs

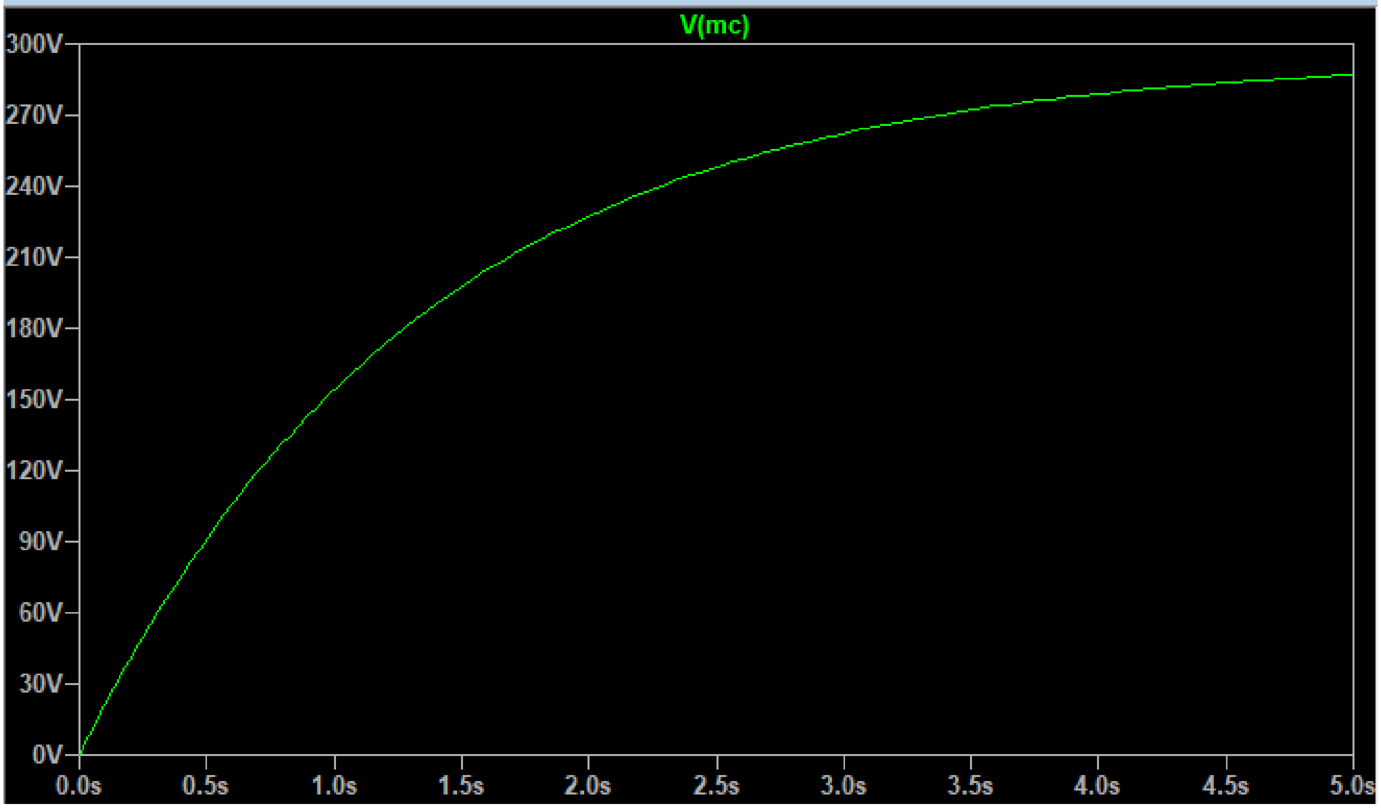
- Voltage:
  - Max 294V
  - Nominal 252V
- Capacity:
  - 4.06 kWh
    - This is specced using the Formula Hybrid energy capacity rules

Precharge Overview

What is Precharge?

- When we refer to precharge we are talking about the connection of internal HV power in the pack to the HV loads (Motor Controllers, DC-DCs)
- By precharging we are applying steadily applying voltage to the HV bus rather than instantaneously applying 300V onto all our loads





Why do we need Precharge?

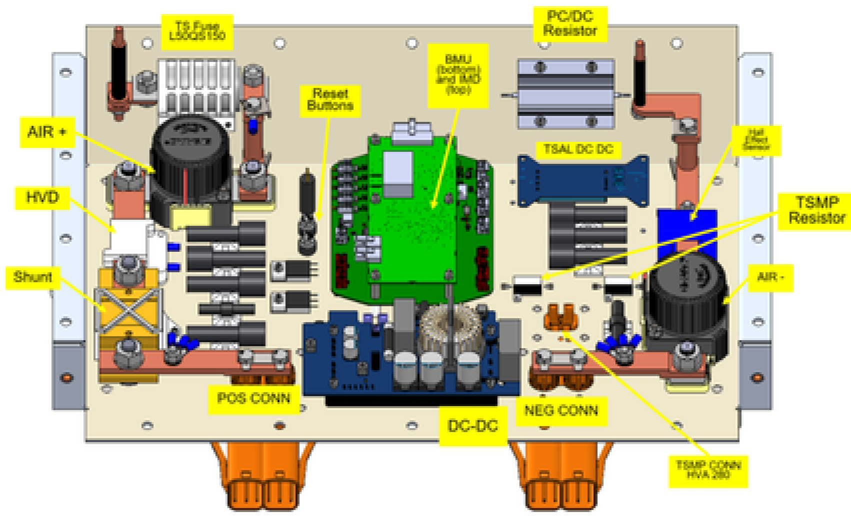
- Our motor controllers have tremendous capacitance. In total all of our HV loads lead to a capacitance of 1.346mF
- The formula for a capacitor is:

$$i = C\frac{dv}{dt}$$

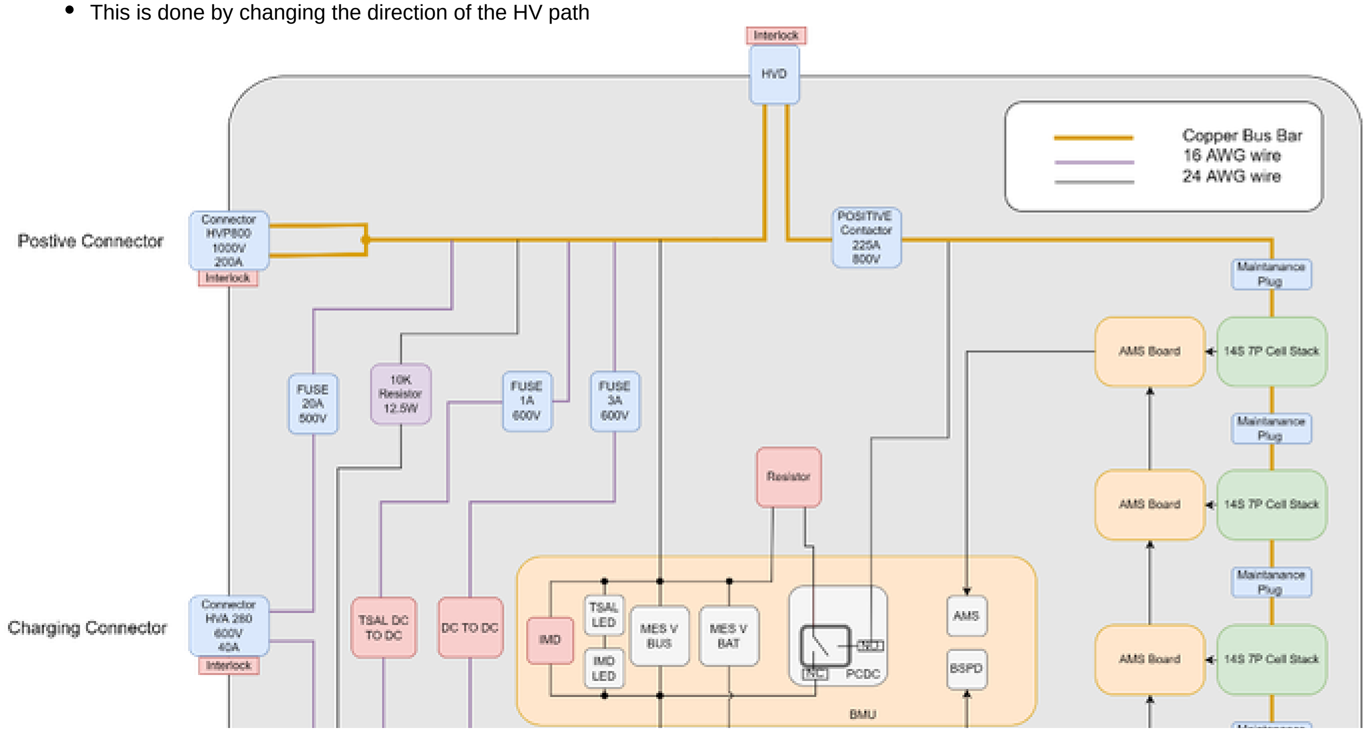
- Our C capacitance is very high.
  - So if our dv/dt is very high, we will have very high current draw through these capacitive elements and apply a tremendous strain on our HV bus.
  - This pure step function technically draws an infinite amount of current.
- Our HV electronics are designed to support large amounts of current as the Motor Controllers could draw hundreds of amps.
- However, we have limits
- A big source of concern is the contactors

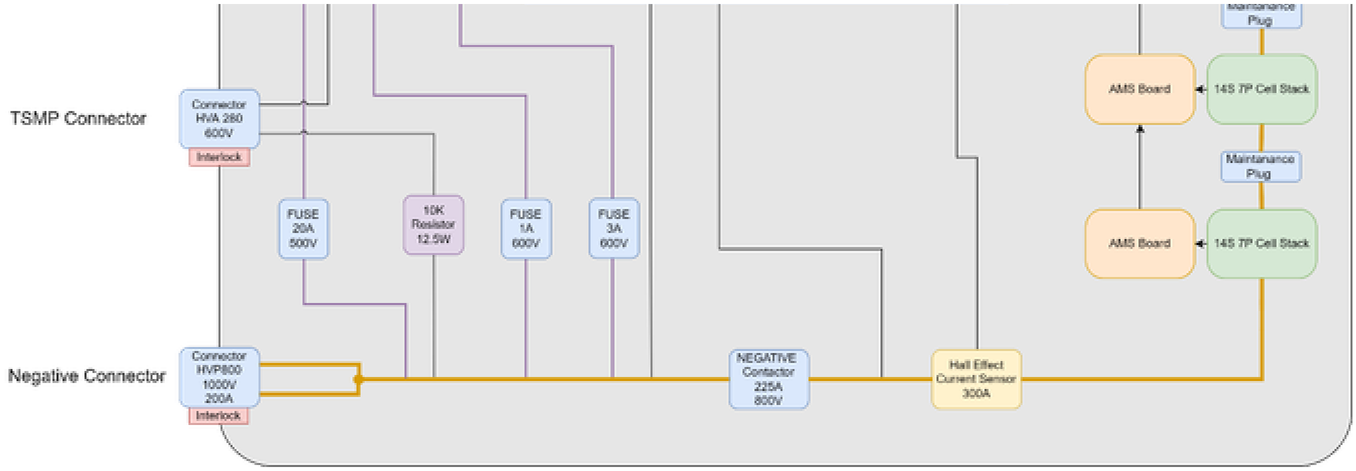
- Contactors are big electrically controlled switches which connect the power in our pack to power on our HV bus
- They are essentially HV, high current Relays
- If too much current passes through them they will heat up and will get welded at a contact point.
- A source of danger is if the contactors get welded closed then the vehicle will not be able to get down from HV, HV will still be applied to the bus.
- So if we do not use precharge and just instantaneously apply 300V to the bus then we likely will not be able to leave the HV state which is very dangerous. You would have to pull the HVD.

Our Precharge Circuit



- AIR+, AIR- are equivalent to the “positive contactor“ and the “negative contactor“
  - A contactor is in effect a high voltage, high current relay (switch)
  - We can control via low voltage the power to the contactors and toggle on and off the connection to HV of the positive and negative side of the HV path
  - We use Gigavac GX12B contactors
- PC/DC Resistor stands for Pre-Charge/Dis-charge resistor
- The long thin rods are the contacts that connect the lid HV path to the HV bus
- Our Summary:
  - Positive Contactor controls current from pack to positive connection of HV bus
  - Negative Contactor controls current from pack to negative connection of HV bus
  - PCDC relay/contactor controls whether to use precharge or discharge across the resistor
    - This is done by changing the direction of the HV path

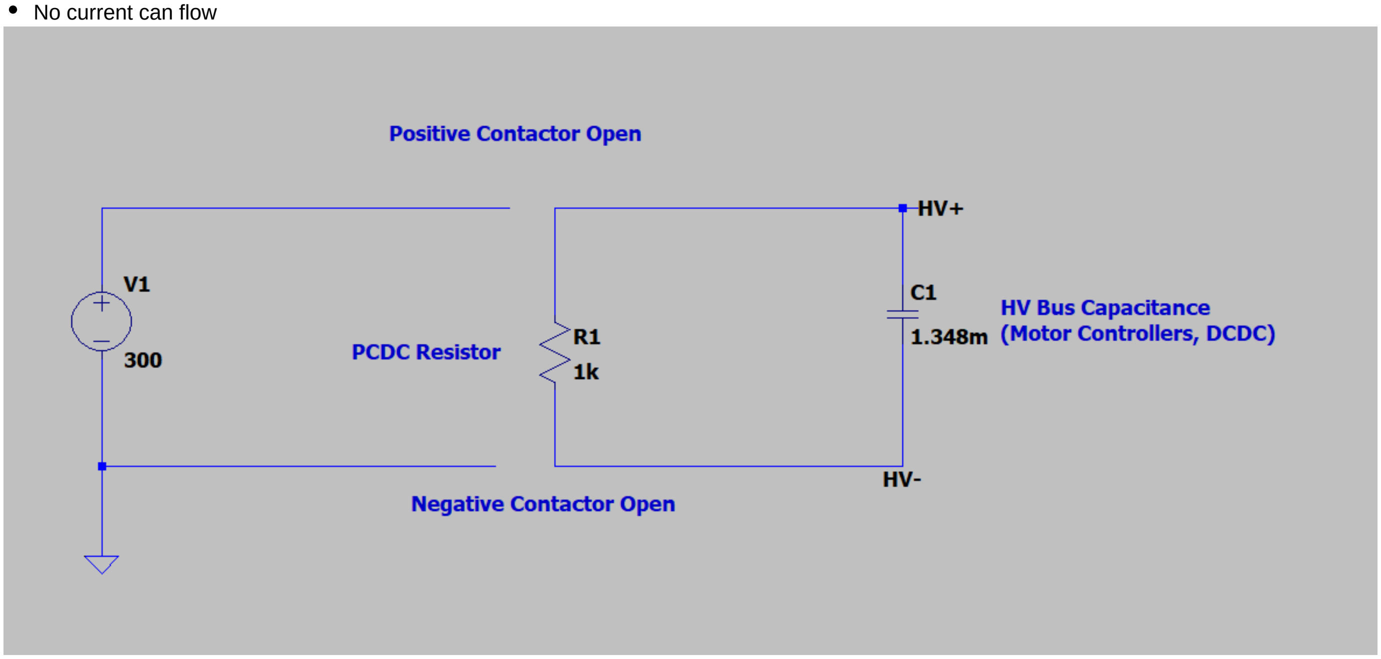




- This is the diagram for our entire precharge/discharge circuit. It can take a little while to view how everything is done so I'll try to get step by step
- Our Precharge process has 5 steps
  - Typical teams only have like a 1/2 step precharge process
  - We perform a bunch of self/sanity checks:
    - Ensure contactors haven't failed open/closed
    - Ensure PC/DC relay works
    - Ensure we precharge to the right voltage (enter FH 2022 story at the end)
    - Ensure our current shunts and all our resistors are good and aren't like improper/shorted

Step 1: Initial Sanity Check

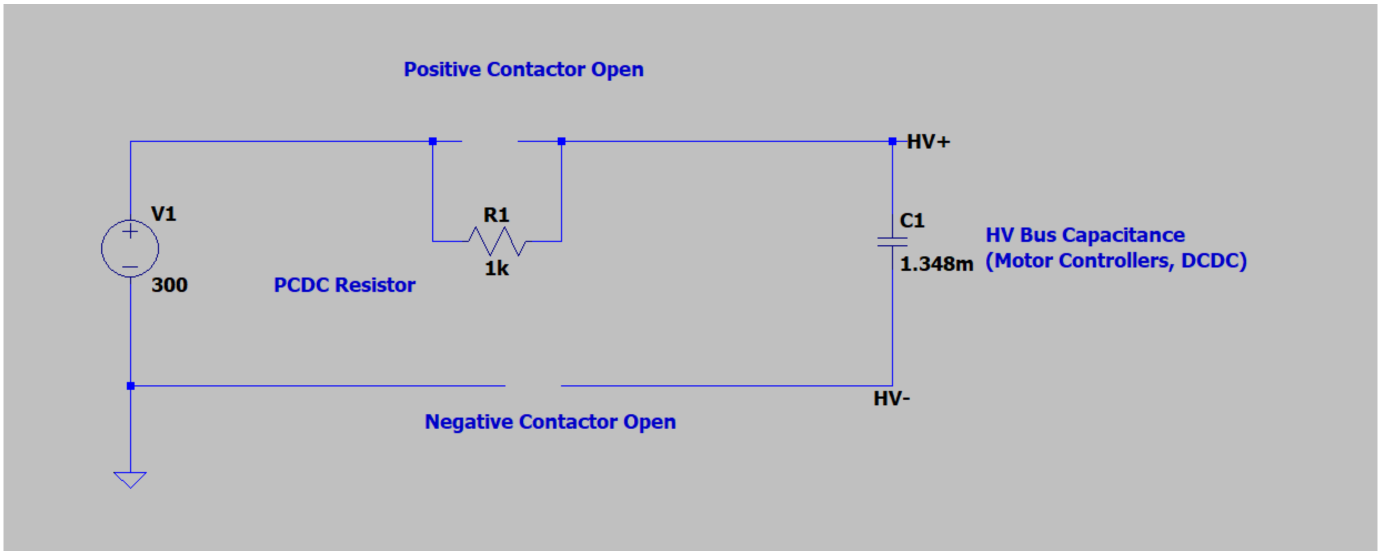
- We start off with our PC/DC relay in the Discharge state
- Both contactors are open
- No current can flow



- Checks we perform
  - Current flowing to HV Bus loads is 0 (IBus == 0)
    - If current flowing through the HV bus when both contactors are open this is very bad!!
    - Could mean contactors have failed closed (welded contactors)!!
    - Very bad
  - Voltage between HV+ and HV- is 0 (VBus = 0)
    - Other sanity check that no current is flowing through our HV bus yet
  - Voltage between HV+ and Battery GND is ~1/2 pack voltage so should be like 150V (VBatt ~ VPack). This is due to the IMD biasing.
    - Validated positive contactor is open and not closed, otherwise VBatt would be equal to the pack voltage

Step 2: Switch to Precharge

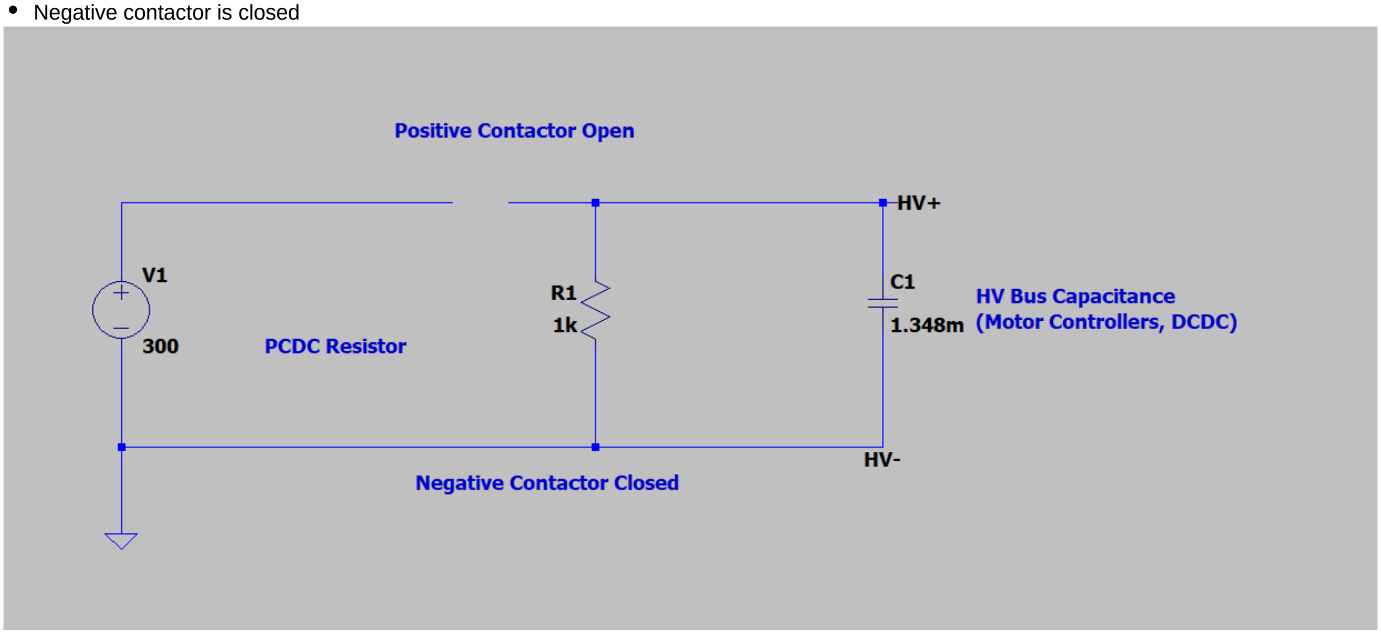
- PC/DC relay switches to the precharge state
- Both contactors are still open
- No current can still flow



- Checks we perform
  - Current flowing to HV bus loads is 0 (IBus == 0)
    - Same as before, current flowing would indicate contactors have failed closed
  - Voltage between HV+ and HV- is 0 (VBus == 0)
    - Same as before, voltage across HV+ and HV- indicates current flow which means contactors have failed closed
  - Voltage between HV+ and Battery GND is the Pack Voltage (VBatt ~ VPack)
    - Validates the switching our PC-DC relay works, PC-DC relay is not failed open

Step 3: Discharge Relay + Close Negative Contactor

- PC-DC Relay is set to discharge state (this is done before closing negative contactor)
- Positive contactor is still open
- Negative contactor is closed

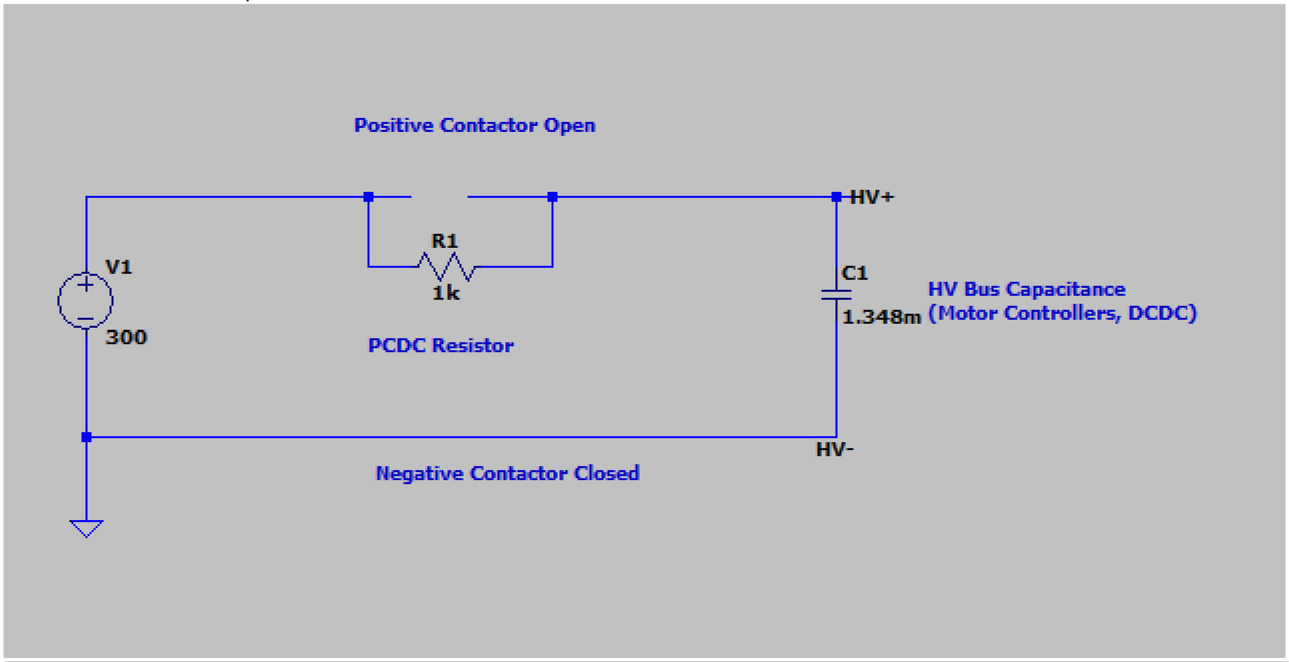


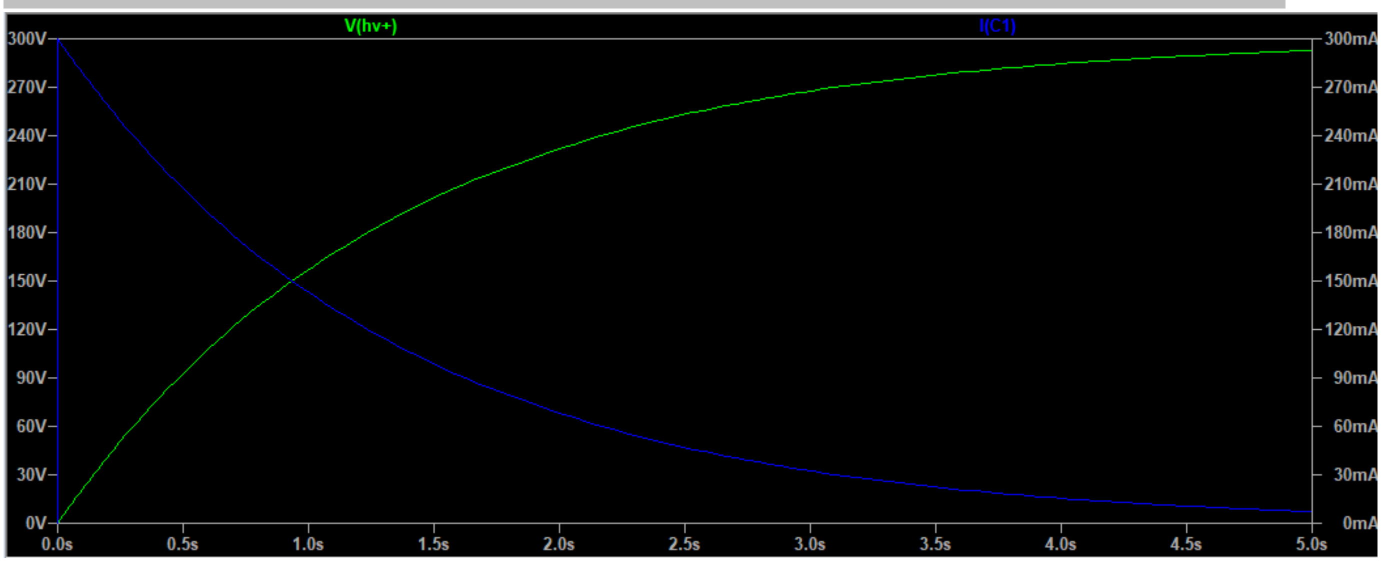
- Checks we perform
  - Current flowing to HV loads is 0 (IBus == 0)
  - Voltage across the HV+ and HV- is 0 (VBus == 0)

- Voltage from HV+ to Battery GND is VBatt ~ VPack

Step 4: Precharge

- PC-DC Relay is set to Precharge state
- Negative Contactor is closed
- Positive Contactor is open



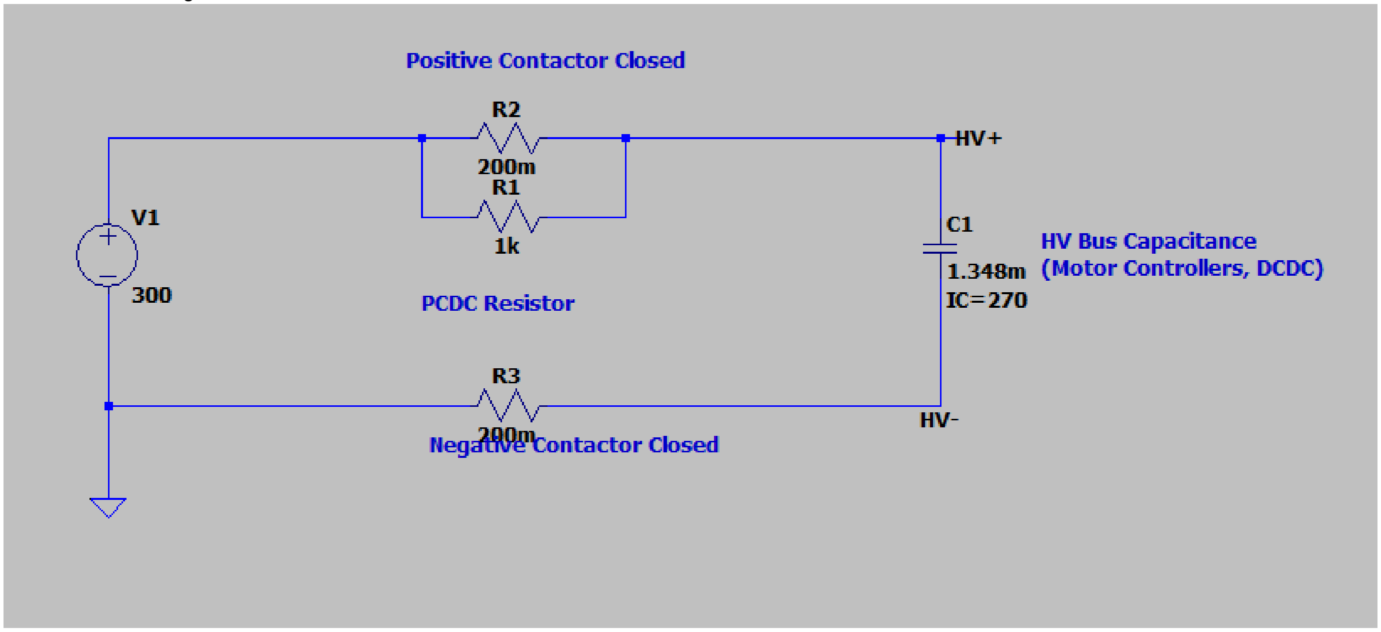


- Here we actually start precharging
  - We reach about 292V at around 5s with this precharge resistor of 1k
  - We get a maximum inrush current of 300mA
    - One thing to watch is the power the precharge resistor can handle. With this configuration the max power is 90W so you need a large resistor
- Checks we perform
  - Wait until VBus is >90% of VPack
    - This is a requirement for the rules, we have to precharge to >90% of the pack voltage before closing positive contactor
    - 90% of 300V is 270V
    - With this configuration we could stop at ~3s

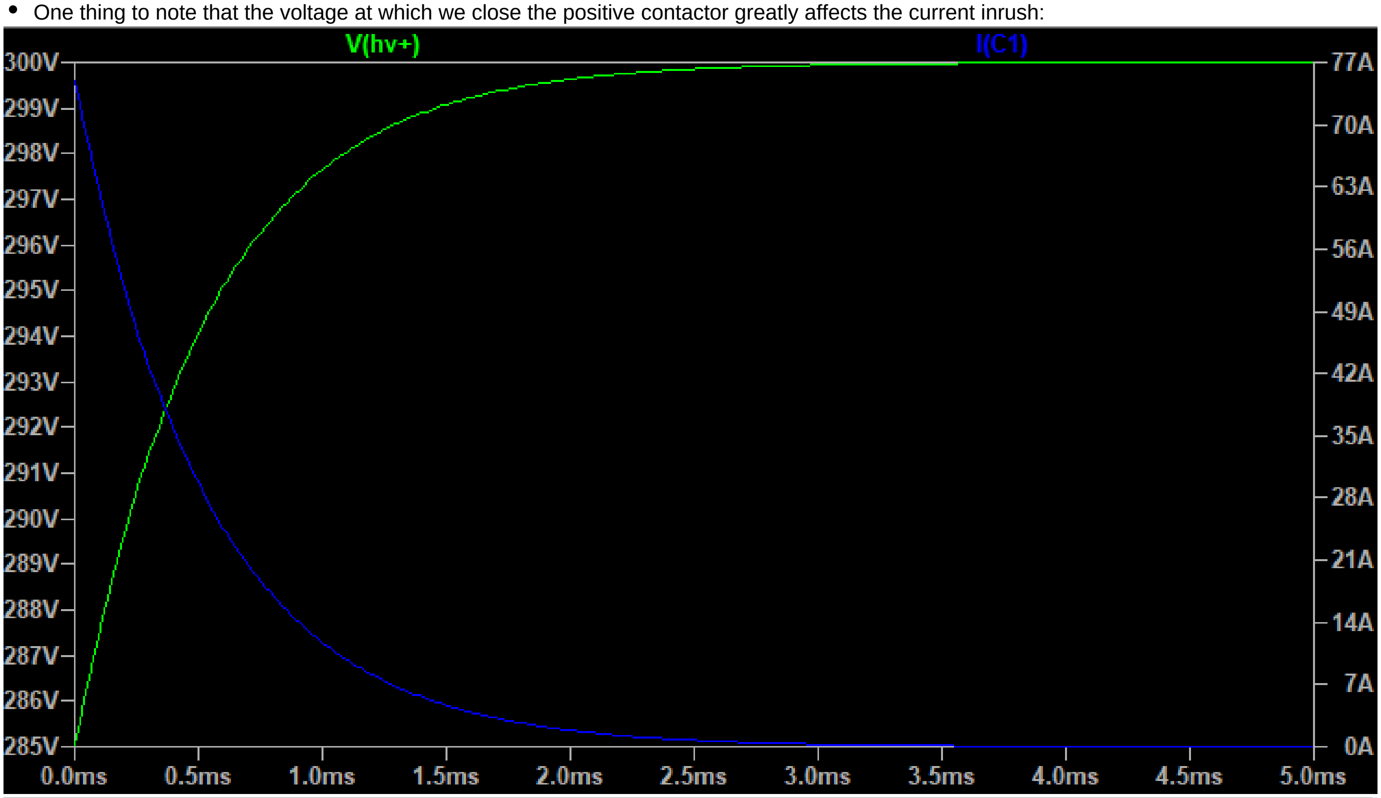
Step 5: Positive Contactor Close

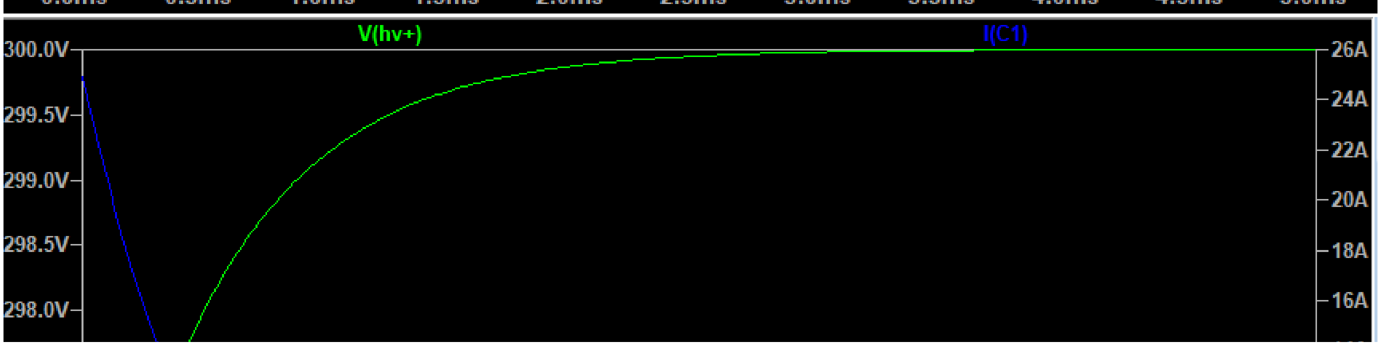
- PCDC Relay is in the Precharge State

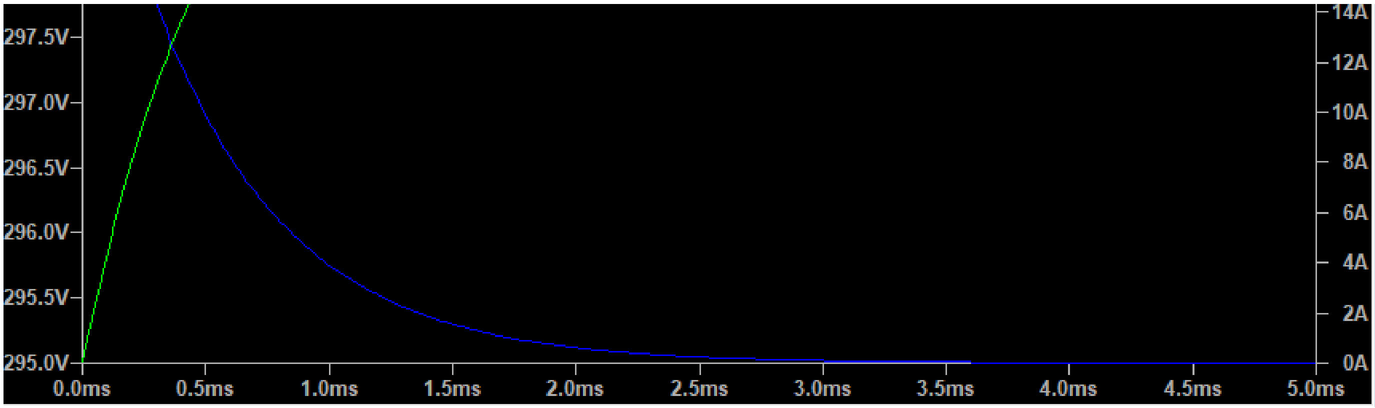
- Positive and Negative Contactors are closed



- * Gigavac contactors have 150-300m ohm resistance so I included them for our simulations
- At this point we are at HV, we can validate that our VPack ~ VBatt
- One thing to note that the voltage at which we close the positive contactor greatly affects the current inrush:

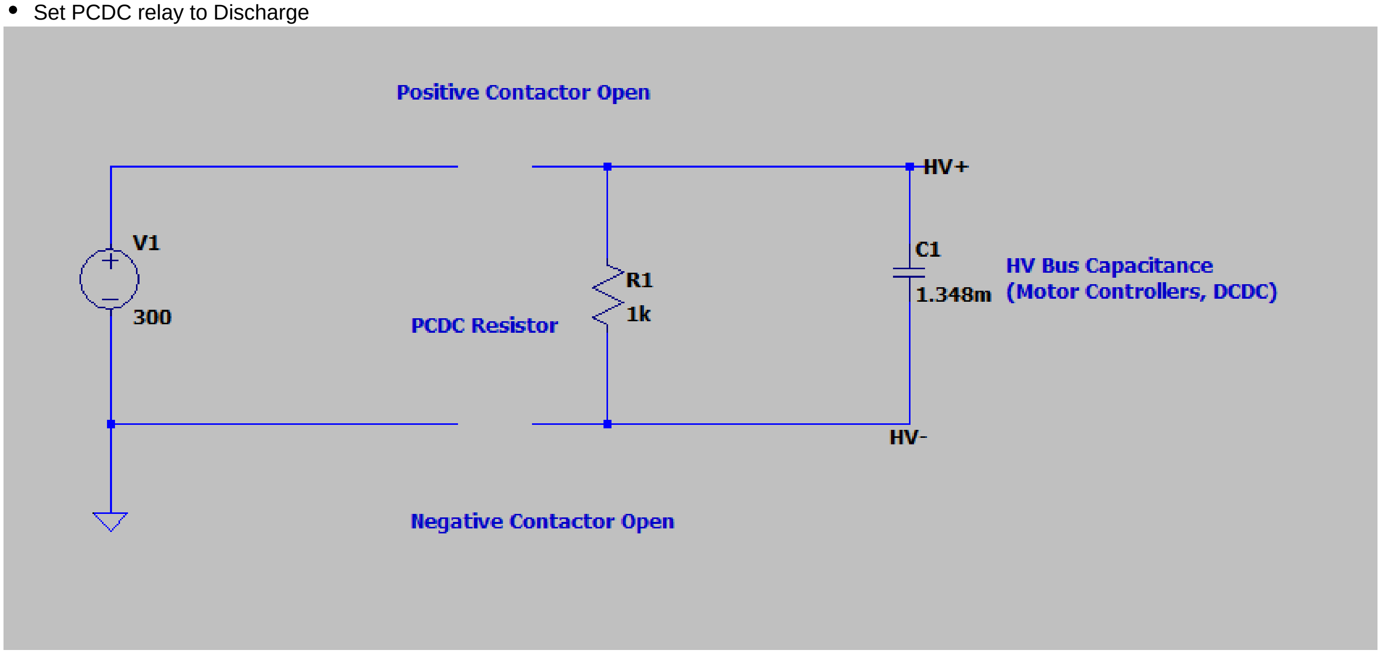






Discharge Process

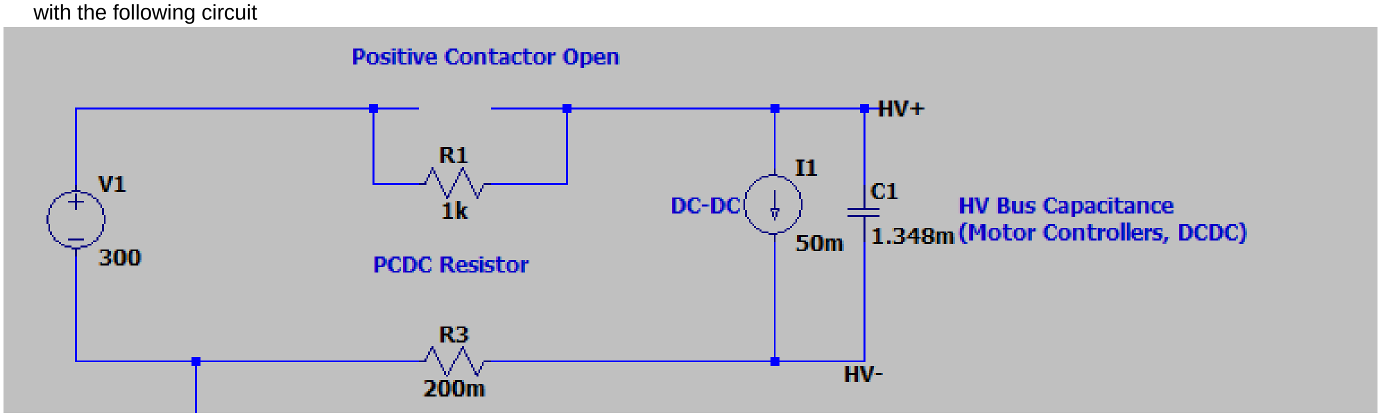
- Open both contactors
- Set PCDC relay to Discharge



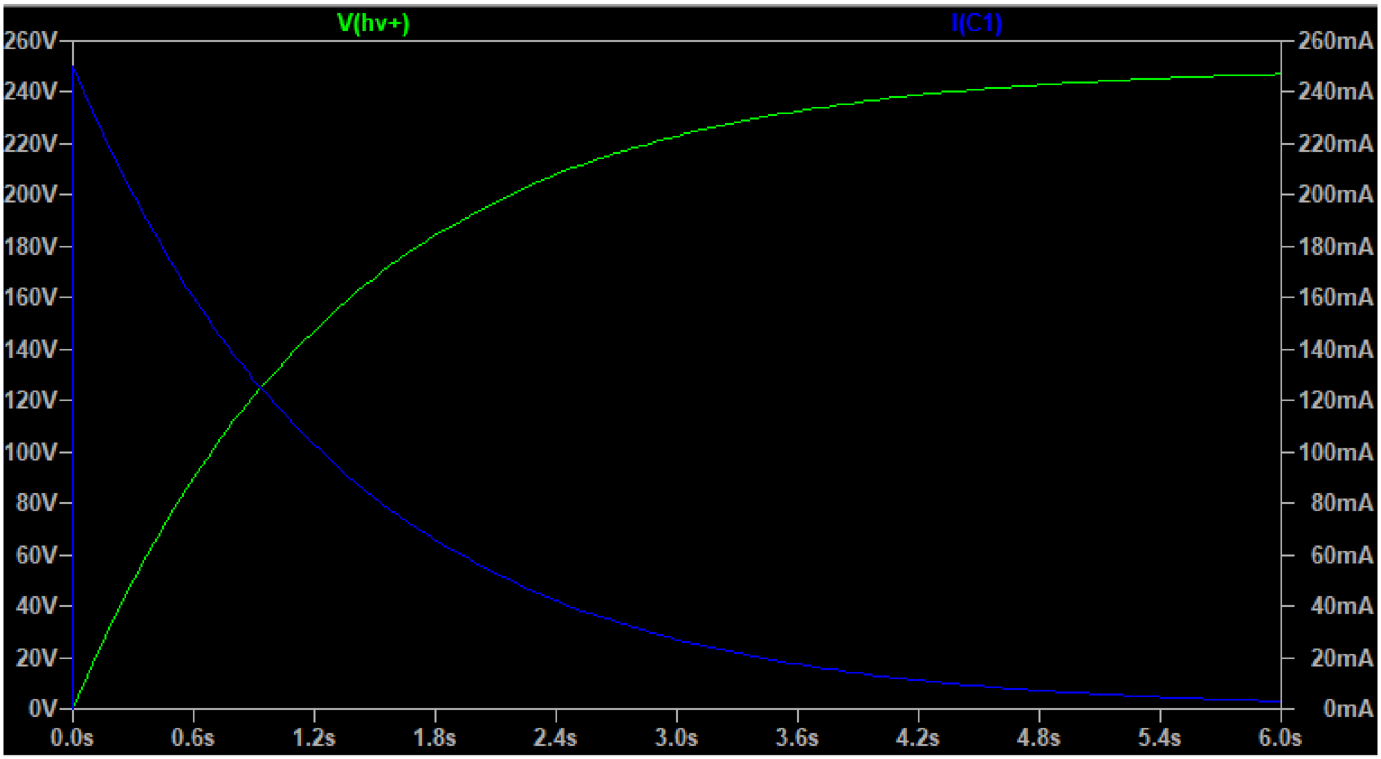
- Charged capacitance discharges across PCDC resistor

Competition Story

- Precharge has worked fine forever.
- In 2022 we got the big DC-DC for the entire LV system working and the new TSAL draws a lot of current (it's bright)
- These DC-DCs can be modelled as current source for our case.
- These our great features but when we are precharging, the TSAL DC-DC comes on and draws current from our precharge circuit. We end up with the following circuit

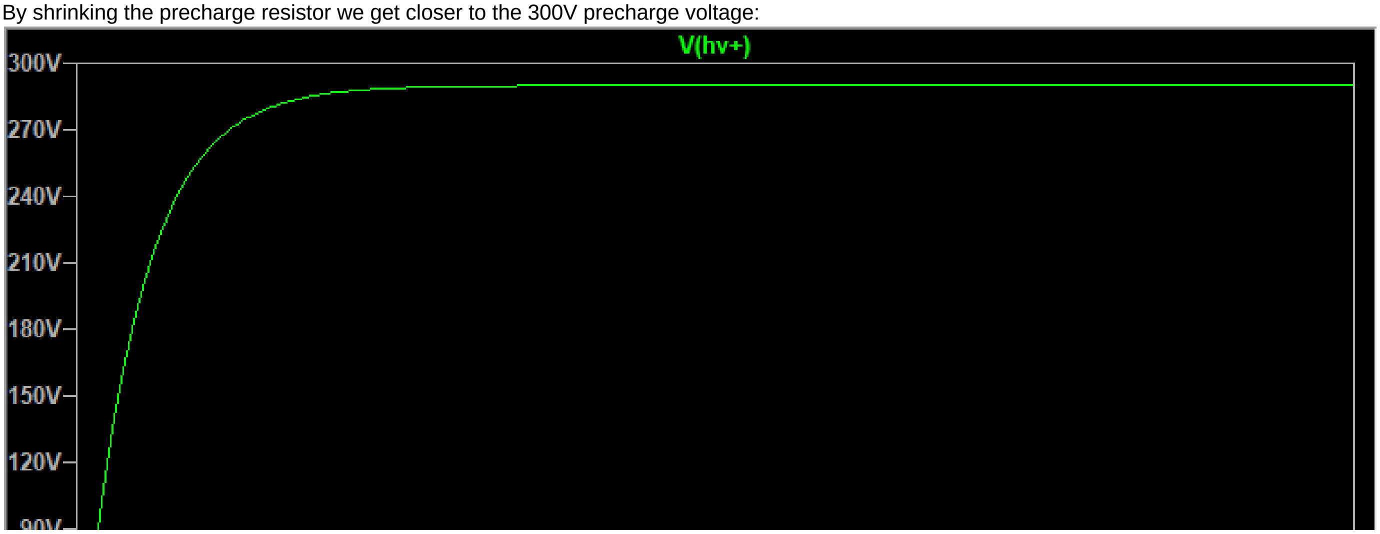


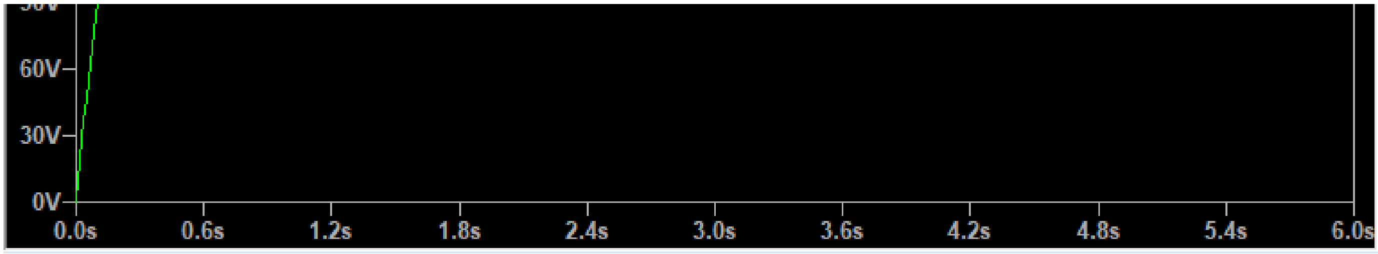
- The DC-DC draws current, which pulls more current through the 1k resistor and causes a voltage drop between HV+ and Battery +
- This creates an offset, meaning that the system will never be able to charge up to the proper 90% threshold. See here the effect of 50mA current draw:



- HV+ levels off at ~250V. If we were to close the contactors now a fairly large inrush of current would occur
  - Maybe not enough to weld contactors, but not a small amount
- We tried to find a small precharge resistor but could not find one before competition
  - This was a product of lack of testing, and not enough reading of the rules
- So I designed a method to sense for when the voltage was level off in the firmware and try to precharge enough as possible so as to get past technical inspection. Since at technical inspection they measure your precharge level.
- Frank the judge infamously remarked “You guys have the slowest precharge I’ve seen“. (Because I had it so it kept precharging for a long time to try and reach as close as possible to 90%)
  - He kept telling people about it but luckily no one put 2 and 2 together

By shrinking the precharge resistor we get closer to the 300V precharge voltage:





Battery Box Cooling (2016)

Unknown Attachment

Pump:

Pierburg CWA50

Unknown Attachment

Unknown Attachment

Rad:

Tubing:

Heat Exchanger:

Fittings: