Electrical Safety Form FSAE-E2014

University of California, Davis

UC Davis Formula Racing

E213

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3 Accumulator

3.1 Accumulator pack

3.1.1 Overview/description/parameters

UC Davis Formula Racing's 2014 Traction Accumulator is designed with the goals of high specific power and high energy density. The pack is contained in a single rectangular prismatic container which is positioned in the vehicle just behind the Driver seat and Firewall. To achieve performance goals pouch-format LiIon NCM-cathode cells from EIG are used. A single centralized BMS system developed for a production EV is used. A single high-current fuse and pair of isolation contactors are used. A charge control contactor and charging circuit fusing are incorporated into the Accumulator enclosure as well as current measurement and other monitoring circuitry.

Maximum Voltage:	116.2 VDC
Nominal Voltage:	102 VDC
Minimum Voltage:	84 VDC
Maximum output current:	600 A
Maximum nominal current:	300 A
Maximum charging current:	30 A
Total number of cells:	84
Cell configuration:	28s3p
Total Capacity:	22 MJ / 6kWh
Number of cell stacks < 120VDC	4

Table 19: Main Accumulator Parameters

3.1.2 Cell description

Pouch format LiIon-NCM/polymer type cells from EIG are use. The model name is C020B. The cells are 3.65V nominal, 20AH nominal. Peak output current is 10C, equating to 200A/cell for 10 seconds. Cell specific energy is 174 Wh/kg and specific power is 2.3kW/kg. Cells are of automotive grade and rated for 1000 cycles to 80% capacity.

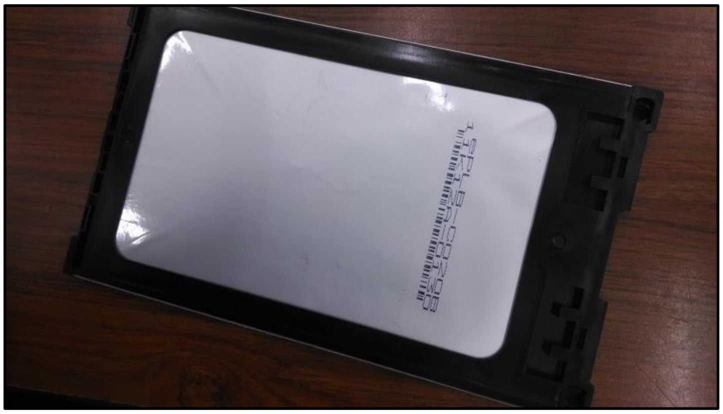

Figure 30: Cell in Case

Cell Manufacturer and Type	EIG C020B
Cell nominal capacity:	20 Ah
Maximum Voltage:	4.15 V
Nominal Voltage:	3.65 V
Minimum Voltage:	3.0 V
Maximum output current:	10C for 10s
Maximum nominal output current:	5 C
Maximum charging current:	.5C
Maximum Cell Temperature (discharging)	55°C
Maximum Cell Temperature (charging)	40°C
Cell chemistry:	Li[NiCoMn]O2

Table 20: Main Cell Specifications

3.1.3 Cell configuration

The accumulator is composed of four submodules of 21 cells each, 7s3p, each separated by a layer of UL94-V0 rated G10/FR4 and service plug.

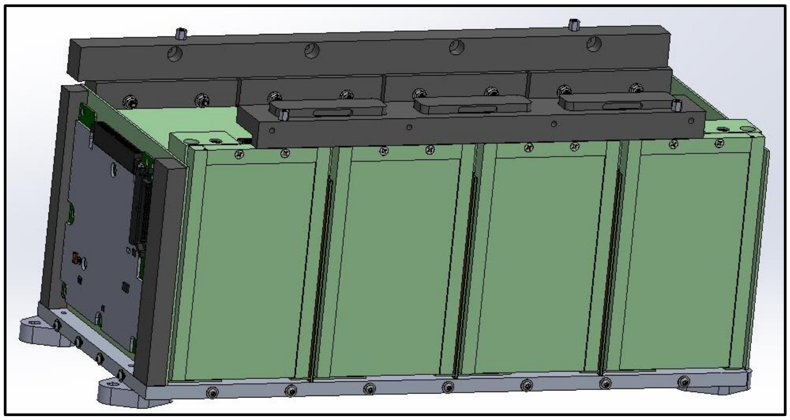

Figure 31: Four Submodules

The maximum voltage of each submodule is 29.1V and the energy contained is 5.54 MJ calculated using nominal voltage and nominal coulombic capacity, or 6.27 MJ calculated using maximum voltage and nominal coulombic capacity. As such the submodule service plug arrangement conforms to EV3.3.3 regardless whether maximum voltage or nominal voltage is used to calculate contained energy.

Each submodule (cell stack) contains 6.27 MJ calculated using maximum voltage multiplied by nominal coulombic capacity. Because this is over the 6 MJ limit described in EV3.4.8 an additional divider of UL94-V0 rated FR4 is inserted between the ninth and tenth cell in each cell stack. This divides the module into a 2.69 MJ and 3.58 MJ section in order to comply with EV3.4.8.

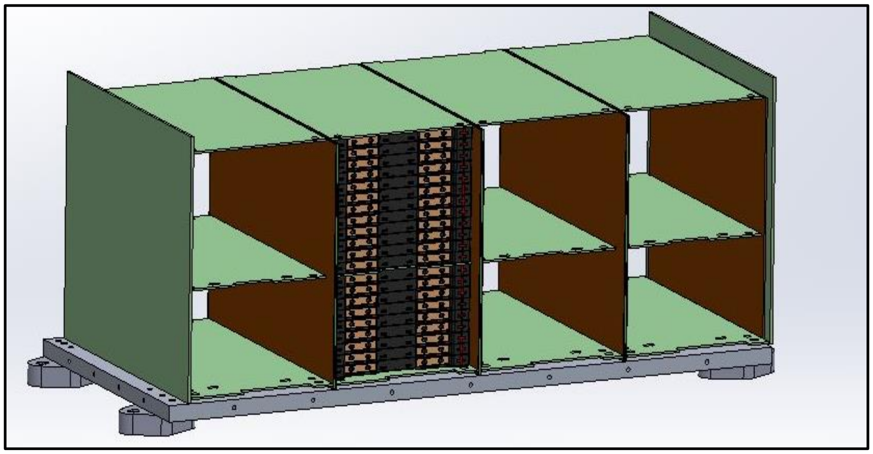

Figure 32: Fire Resistant Dividers

High current electrical connection to the cell is used as supplied from the cell manufacturer. The strategy is as follows: Cell tabs are welded to right-angle bent tabs which are held by the manufacturer supplied cell case. M3 nuts are held by the same cell case and team-designed copper busbars are applied to the tabs. M3 screws are used to clamp the busbars to the tabs. In addition Belleville spring washers and screw-head locking plates are employed to meet the requirement of EV4.6.12.

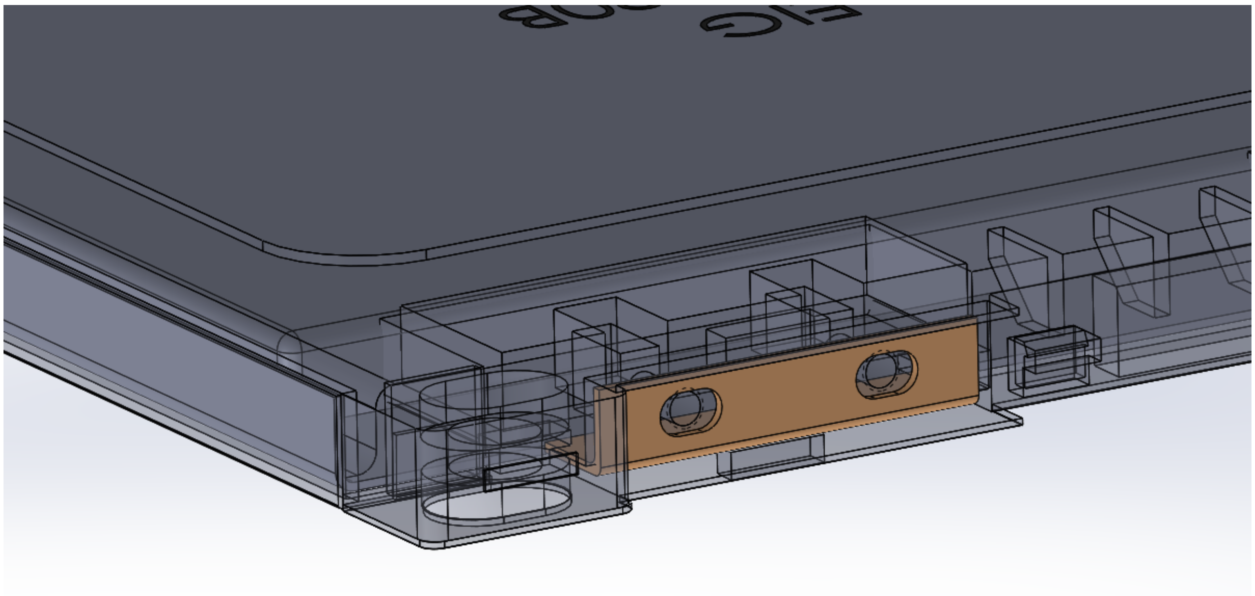

Figure 33: Cell Tab

The cells are placed in a parallel-first, then series arrangement. Each group of three parallel cells is physically in direct proximity to each other and they are paralleled directly with the series/parallel busbars.

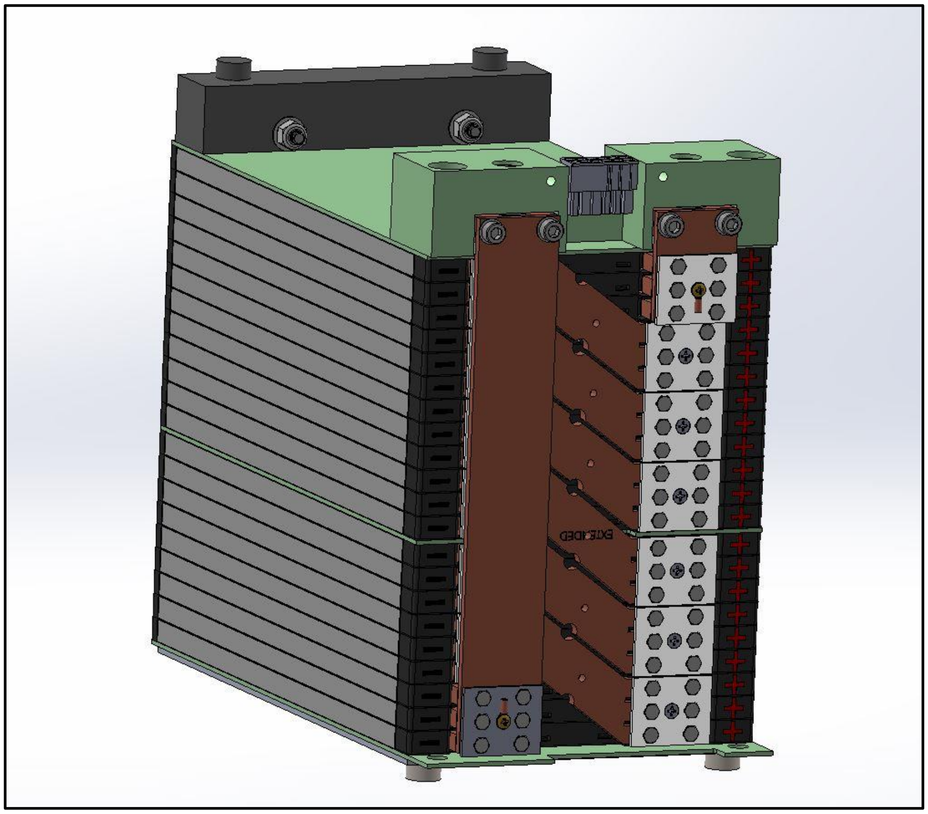

Figure 34: Cell Connections

This configuration is identical to the configuration that EIG supplies as part of their module/system, and is the same configuration style that is used OEM in the Zero Motorcycles 2012 model-year battery packs.

This is compliant with EV6.1.4 because the parallel entities are single cells and are in no sense "strings", so the application of fusible links on each parallel entity is not required. For the remainder of EV6.1.4, all conductors, wires, and busbars are sized to have sufficient ampacity to conduct the full pack current. See Section 3.1.9 Wiring.

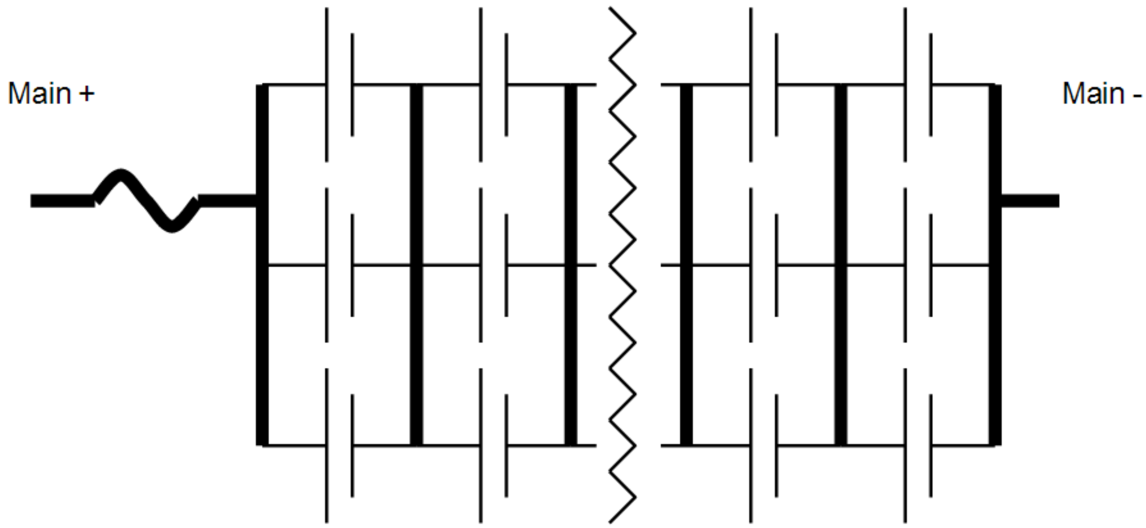

Figure 35 Overall Cell Configuration

Each cell module is protected from inadvertent short-circuits as all conductive materials are covered with insulating material, either UL-94-V0 rated FR4 or PVC material. All segments have insulation above all horizontal surfaces and as such are protected from accidental shorting from parts or tools falling (EV3.3.4). In its exposed condition the cell stack is not touch safe but when it is installed in the accumulator enclosure it is fully touch-safe.

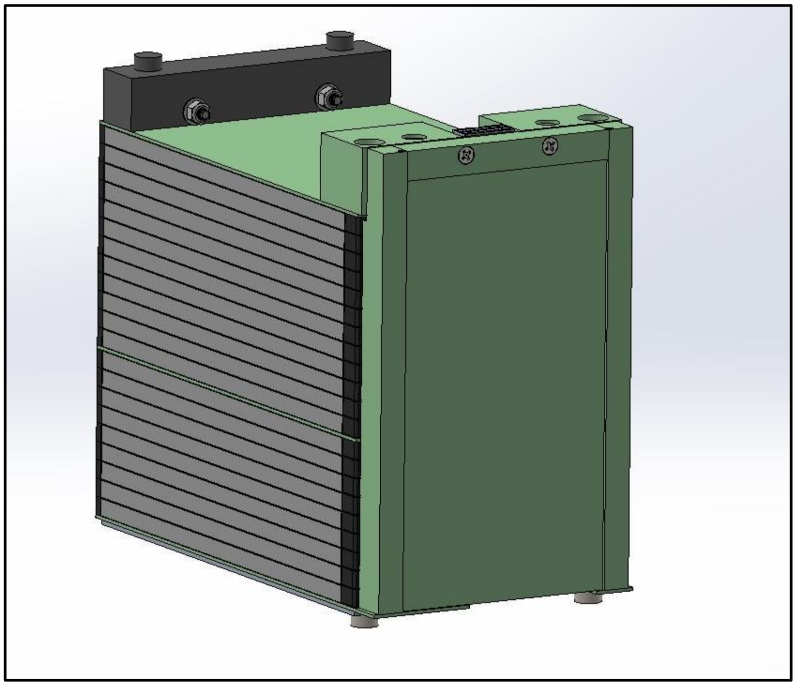

Figure 36: Cell Stack Including Insulation

3.1.4 Cell temperature monitoring

Two parallel temperature monitoring systems are employed to keep the cells operating at or under the spec sheet temperature rating. Four thermistors are quantitatively monitored by the BMS and 28 additional temperature switches are used to provide hotspot-detection away from the primary sensors. Signals from both systems are processed by the BMS which will exit "Running" mode when limits are exceeded and will deactivate the output signal that is used by the team-built latching power-stage to hold the shutdown system continuous. In this way the AIRs will be opened if temperature limits are exceeded. When the BMS exits "Running" mode the red dashboard LED will be illuminated. (As described in Section 3.1.7: Battery Management System)

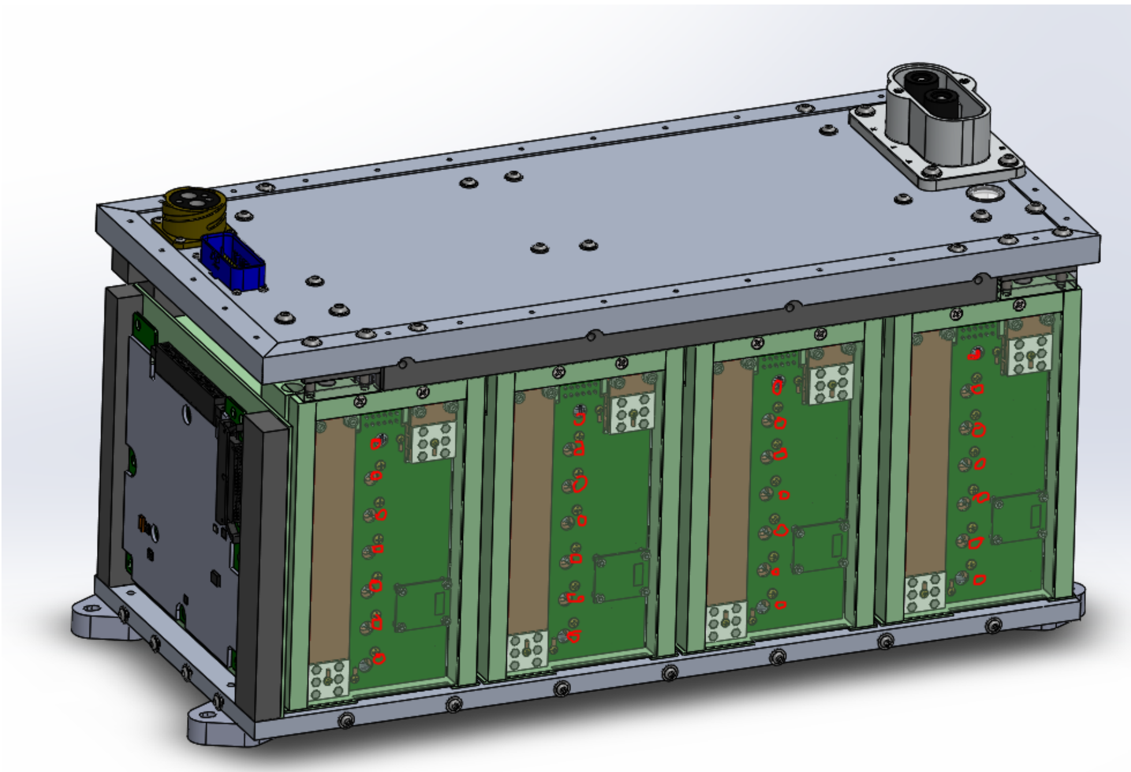

Figure 37 Temperature sensor distribution (marked in red)

Firstly, the BMS continuously monitors four 10K NTC thermistors. One thermistor is installed in a cell close to the center of the stack in each of the four cell stacks. The signal from this device is monitored and logged independently and directly by the BMS.

Secondly, because four sensors total is not enough to conform to EV3.6.6 multiple additional sensors are positioned in the battery pack. The sensors chosen are Microchip MCP9501 silicon temperature switch. The switches are factory-programmed and the part number employed corresponds to the maximum temperature of operation of the cells being used. They are a three-terminal device, power supply, ground and open drain output. The active-LOW (sink to ground when overtemp is present) outputs are placed in a parallel Wired-OR configuration and used to control current in an optoisolator LED. The optoisolator phototransistor parallels a lower value resistor with the primary thermistor, reducing the resistance that the BMS sees which artificially increases the temperature that it interprets. This is ensured because the system uses Negative Temperature Coefficient thermistors. This causes the BMS to exit running mode and trigger shutdown system.

The MCP9501 parts that were subsequently installed in the cell stacks were characterized by the team and found to trigger at or below the datasheet rating (to the accuracy that we were able to measure), allowing EV3.6.7 to be satisfied.

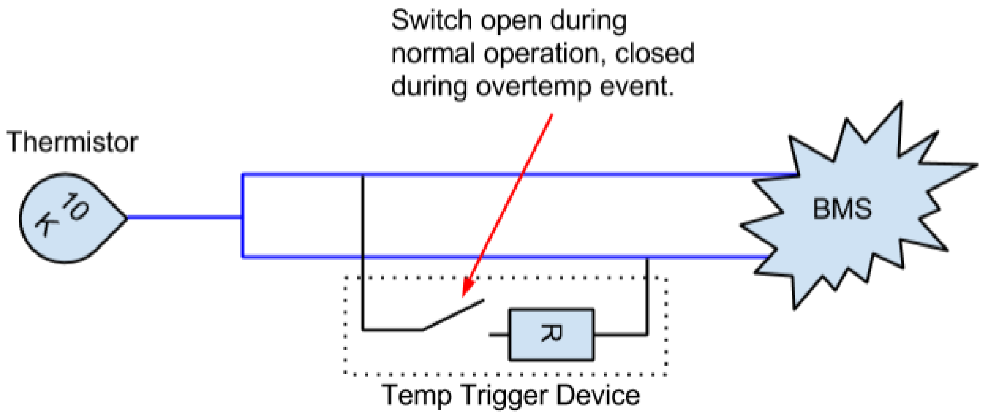

Figure 38 Hotspot detection system topology

Combined these two systems allow the BMS to monitor the temperature of 33% of the cells, spread evenly throughout the pack (one cell in each parallel group is monitored). This allows the accumulator to conform to EV3.6.6 and EV3.6.7.

Both sensors are attached in the same position on the cells, near the tab-end in a space in the cell cassette. The sensors are attached directly to the cell pouch using electronic-grade neutral cure silicone. The position near the tabs was chosen because it is expected to be the highest temperature region of the cell due to the higher current density compared to other areas of the cell.

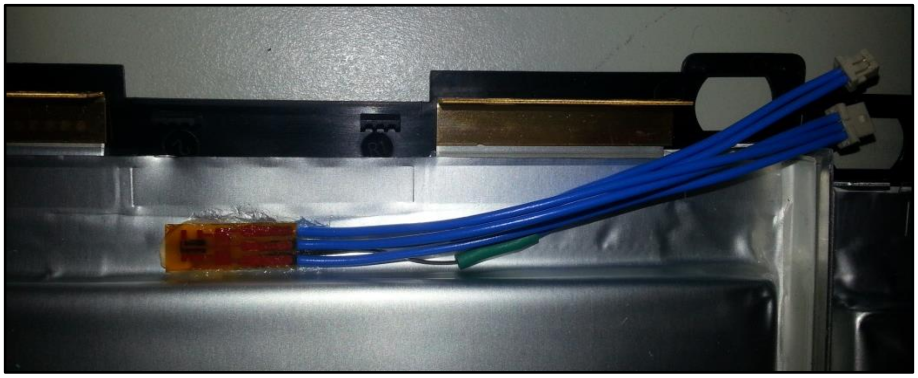

Figure 39: Temperature Switch Attached to Cell

3.1.5 Accumulator isolation relays

Two Gigavac GX-14 relays are employed for the AIR function. The continuous current rating of the contactor is greater than the pack fuse rating.

Relay Type:	Normally Open
Contact arragment:	SPST-NO
Continous DC current rating:	350 A
Overload DC current rating:	1000 A for 100sec
Maximum operation voltage:	800 VDC
Nominal coil voltage:	12 VDC
Normal Load switching:	Make and break up to 350 A
Maximum Load switching	10 times at 600 A

Table 21: Basic AIR Data

The AIR contactors are placed on a sheet of UL 94-V0 rated FR-4 along with the pack fuse which is bolted to the top of the accumulator enclosure. An intermediate sheet of FR-4 is bolted between the contactor plate and the lid to further insulate the fasteners and comply with EV4.1.5. Additional insulation of Calendared Nomex paper and UL94-V0 zip ties will be applied to ensure compliance with EV4.1.5, since the accumulator enclosure is attached to GLV ground and is thus part of the GLV system.

3.1.6 Fusing

A single 350A fuse will be used on the positive battery lead before the AIR.

Fuse type:	Limitrion 300V Class T
Continous current rating:	350 A
Maximum operating voltage	300 VAC, 160 VDC
Type of fuse:	Class T
I2t rating:	400 A
Interrupt Current (maximum current at which the fuse can interrupt the current)	20 kA

Table 22: Basic Fuse Data

Parts protected by the main pack fusing and continuous current ratings:

MAIN FUSING	**350A**
AIR Contactors	350A
Amphenol Epower HVD	400A
Amphenol Radsok service plugs	400A
2/0 EXRAD cabling	390A
2/0 Flex-Whip cabling	400A

Table 23: Fuse Protection Table

Additional high voltage fuses are present for Inverter Precharge/Keyswitch lines and DC/DC converter HV supply.

Fuse Type	ABC Series
Continuous Current rating	7A
Maximum Operating voltage	125VDC, 250 VAC
I2T rating	109.33
Interrupt Current	10 kA

Table 24: Low Current DC Fuse Data

3.1.7 Battery management system

The Battery Management System (BMS) used in UC Davis 2014 Accumulator was developed by Zero Motorcycle for use on their 2013 Model-Year production electric motorcycle. It is centralized style, fully digital computerized. It is powered from the battery pack and has ultra-low current stand-by for continuous application, monitoring and logging over the course of months or years without charging. It is environmentally sealed and contains galvanic isolation of the critical communications interfaces.

Figure 40: Zero Motorcycles BMS

3.1.7.1 Fusing Strategy

Being a centralized BMS, the wires attaching the single BMS board to the cells must be fused to comply with EV3.6.4. In our implementation, the BMS connection is made to the cell bus-bars using a custom made PCB which is screwed using a conductive spacer and brass screw to the face of the busbar. A SMD fuse is placed directly adjacent on the PCB to the cell pack to protect the traces and subsequent wires. The end cell connections have a minimum length jumper wire before entering the PCB and passing through the fuse.

Figure 41: BMS Fusing

3.1.7.2 Fault Reaction Strategy

Being fully programmable, the set-points of temperature and voltage set-points are customizable using a serial terminal interface. The over-voltage limit will be set based on the cell datasheet and allowance for the BMS accuracy. The BMS accuracy tolerance is based on the battery stack monitor IC employed onboard. The IC used is Texas Instruments bq76PL536A. The typical measurement accuracy of the AD converters used in this IC is +/-1mV.

Temperature faults are similarly set in software. Thermistors values are read also using the bq76PL536A IC, using a 14 bit ADC.

Additional temperature faults are detected by the auxiliary temperature monitoring system as described earlier in Section 3.1.4: Cell Temperature Monitoring.

The BMS interaction with the shutdown circuit is described in Section 2.5: Latching Mechanism for IMD and BMS.

Manufacturer and year of production	Zero Motorcycles, 2013 Model Year
Balancing strategy	Resistive bleed
Cell count	28
Stack monitor IC	Texas Instruments
Central Processing Unit	Texas Instruments
Communications interfaces	Digital "System On" input and "System OK" output, Isolated CAN BUS, 3.3V USART Terminal
Additional features	Isolation detection (Not used). Contactor drive (not used), Automatic charger detection (Not used)

Table 25: BMS Specifications

3.1.8 Accumulator Indicator

The accumulator indicator used has been designed and built by the team. It is installed on the accumulator container directly adjacent to the HVD. It is fully potted in electronics grade neutral cure silicone and is wired directly to the terminals of the HVD inside the enclosure.

Voltage range of illumination	40V to 450V
Current consumption	2mA
Topology	Single Red LED with high voltage linear current regulator.

Table 26: Accumulator Indicator Specifications

3.1.9 Wiring, cables, current calculations, connectors

3.1.9.1 External battery cable wiring

Tractive system DC power is carried outside of tractive system enclosures using Champlain Cable EXRAD XLE 2/0 shielded power cable. This is automotive-grade cable. The cable is insulated with an irradiated cross-linked elastomer capable of withstanding temperatures of 240°C. The maximum rated voltage for the cable is 1000V, well above the maximum working voltage of the tractive system.

Expected current through this system varies with drive cycle. Absolute maximum is expected to be 600A (inverters set to limit battery current to protect cells), for less than 10 seconds, and average current will be much lower, on the order of half.

Wire type	Champlain Cable EXRAD XLE 1000V SHIELDED CABLE (EXRAD-XL2/0X)
Cross sectional area, material	67 mm^2, copper
Current rating	390 A
Maximum operating voltage	1000 V
Temperature rating	150°C
Wire Connects	Accumulator, HVD, Power electronics enclosure

Table 27: External Battery Cable Wiring

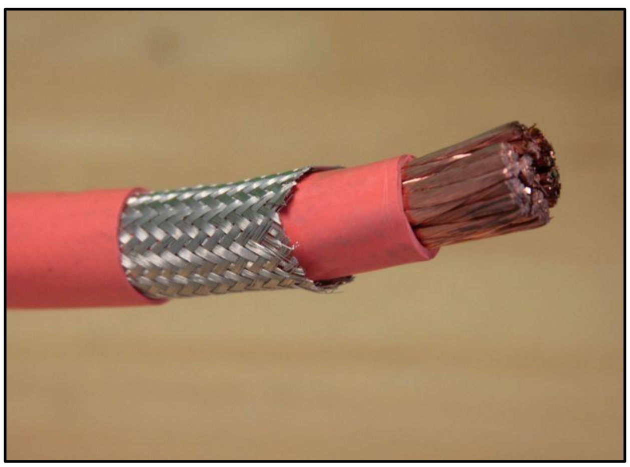

Figure 42: EXRAD Shielded Cable

3.1.9.2 Internal battery cable wiring

Tractive system DC power is carried within tractive system enclosures using Kalas FlexWhip welding cable. Because the current carried is equivalent to the current carried in these cables is the same as the external wiring and the cross-section area of copper is also the same, the same reasoning is applied to this cable as is applied to the external cabling.

Wire type	Kalas FlexWhip 2/0 Welding cable
Cross sectional area, material	67 mm^2, copper
Current rating	400A
Maximum operating voltage	600V
Temperature rating	105°C
Wire Connects	Internal connections in Power electronics enclosure and Accumulator enclosure

Table 28: Internal battery cable wiring

3.1.9.3 Accumulator service plugs

The accumulator service plugs allow tool-less disconnection of both poles of each submodule. The service plugs use 10MM Amphenol Radsok sleeves which are rated for 400A current, which is greater than the pack fuse rating. Refer to Radsok datasheet and Section 3.1.6: Fusing. The service plugs themselves do not require tools to remove but are held in place and not possible to remove when the lid of the container is in operational position.

Figure 43: Accumulator Service Plugs In and Out of Working Position

The components mounted to the lid of the box are electrically connected with additional Radsok based plugs.

3.1.9.4 Accumulator Busbars

Many different designs of busbar are used within the accumulator enclosure to carry the pack current. All busbars are Copper 101. The various busbars are listed, with their minimum cross sectional area below.

Cell parallel series busbar	68 mm^2
Cell pack end busbar	101 mm^2
Service plug busbar	64 mm^2
End Service Plug busbar, HVD busbars, Fuse busbar, Positive Lid Busbar	80 mm^2
Negative Lid Busbar	61 mm^2

Table 29: Busbar Data

3.1.9.5 BMS Cell Voltage Tap Wiring

PTFE insulated wire is used for BMS cell voltage interconnections.

Wire type	MIL-W-16878E/4 Type E
Cross sectional area, material	.33 mm^2, silver plated copper
Current rating	5A
Maximum operating voltage	600V
Temperature rating	105°C
Wire Connects	BMS cell voltage connection

Table 30: BMS Voltage Taps

3.1.10 Charging

The 2014 UC Davis vehicle is charged using a high efficiency air-cooled off-board switchmode power supply. The charger is designed in such a way that it is only possible to charge the cells when the vehicle systems including BMS are active. Charging will only be allowed on the car and requires the tractive system to be enabled (although the inverters will be disabled whenever the charging cable is attached.)

The charger is attached to the car using a 10ft length of 10/4 SO cable which is sleeved in Orange techflex to meet EV8.3.4. The charging connector is located on the top of the accumulator enclosure. The charging connector is a Glenair ITS series military-spec connector with two high current contacts and three signal contacts. The circuit is designed such that two of the pins are shorted inside the cable end of the connector to provide feedback to the car that the charger is attached and the third pin with one of the two shorted pins provide power to a contactor which switches the AC side of the charging power supply on and off based on the car's condition. The onboard E-stop button will disable this contactor as well. (EV8.3.6) This is in addition to a contactor inside of the accumulator container on the DC side, so that the charge port is only live attached to the cells when the charger is attached.

Charger Type:	4 pcs Mean Well HLG320
Maximum charging power:	1.3kW
Maximum charging voltage:	116 V
Maximum charging current:	11A
Interface with accumulator	12V Enable signal
Input voltage:	85-265 VAC
Input current:	15 A @120 VAC

Table 31: General Charger Data

3.1.11 Mechanical Configuration/materials

The four cell modules are placed on a structural base-plate of ½" thick 6061-T6 Aluminum. Attached with pins to the tops of the four cell packs are two structural bars made of PVC material. These bars locate and restrain the tops of the cell packs and are bolted through the sides of the box. This creates a very well supported and monolithic pack. No openings in the container are present except for those required for (sealed, automotive grade) connectors. (EV3.4.9)

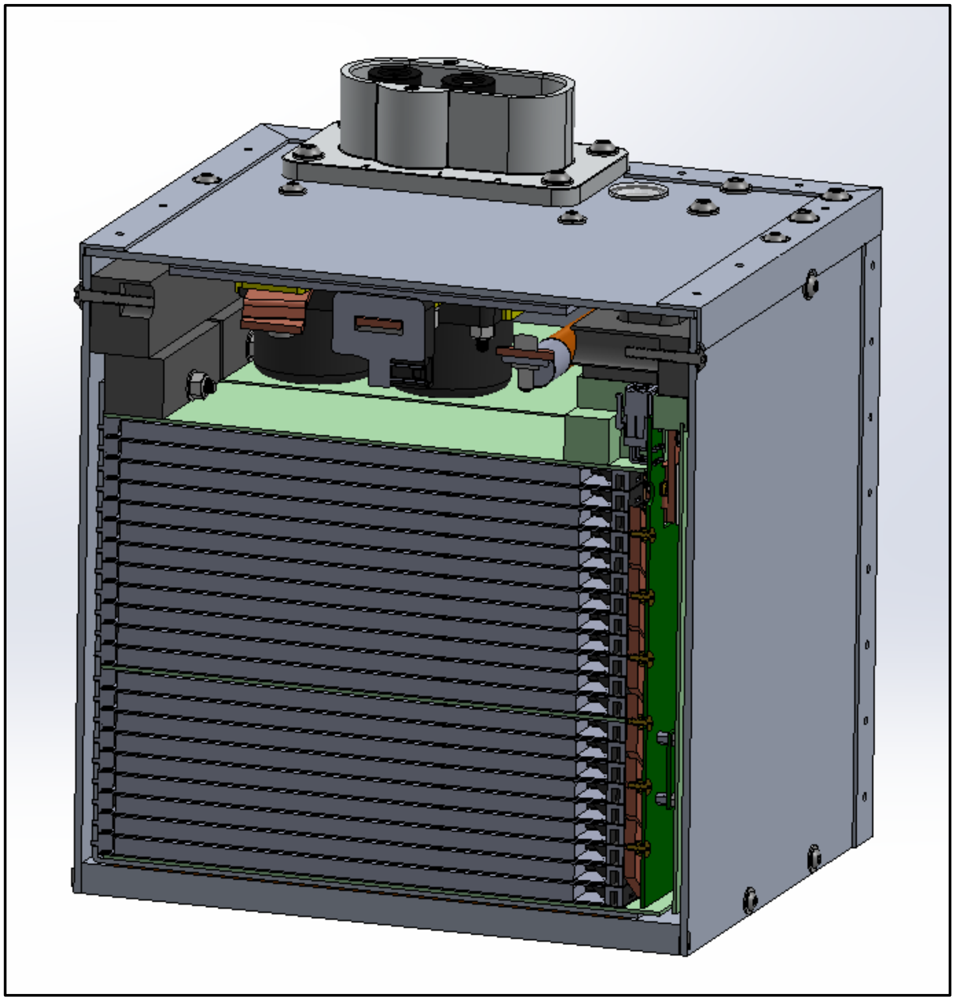

Figure 44: Structural Cutaway

The sides of the box are made of 1/8" 6061-T6 Aluminum and the fasteners used into the restraining bars are #10.

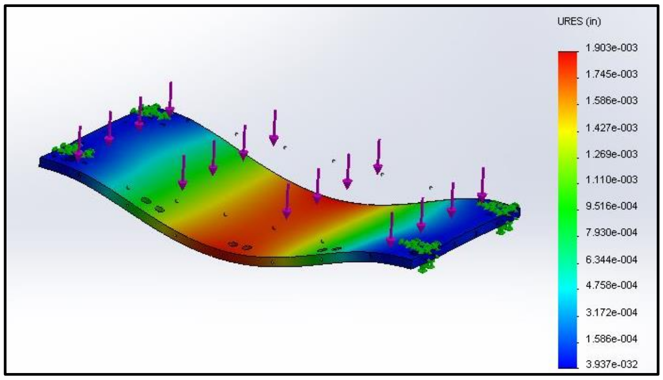

Figure 45: Accumulator Base Plate FEA Simulation

The FEA analysis of the base plate shows that the plate deflects less than .002" with a 1,350 lb. load (10 G's). The FEA shows that vertical loads of this magnitude will not create failure and we can assume that this plate is rigid.

The twenty-two 8-32 bolts holding the sides of the box to the plate can each handle 850 lbs. of force. The eight 10-32 bolts holding the side plates to the top of the box can handle up to 1200 lbs. of force each.

Due to the robust design discussed above it was decided to focus on stress scenarios where lateral loads are present. All lateral loads were evaluated at 20 G's. Considering that each battery pack weighs 25 lbs. the four locating pins holding the packs into place experience a load of 125 lbs. In a worst-case scenario, the tolerance associated with one of these pins is so loose that the full weight at 20G's is applied directly to one of the four pins. To simplify the analysis, we chose to model the pin as a rod coming out of a fixed support with a distributed load applied to it. If you assume the battery packs are rigid, small displacements of the pin concentrate the force near the fixed support. The image below helps clarify this assumption. Using this assumption, we can say that the base of the pin is only experiencing a shear force. The calculation below shows that the max stress on the smallest bolt would not come close to a yielding stress for a Grade 5 bolt.

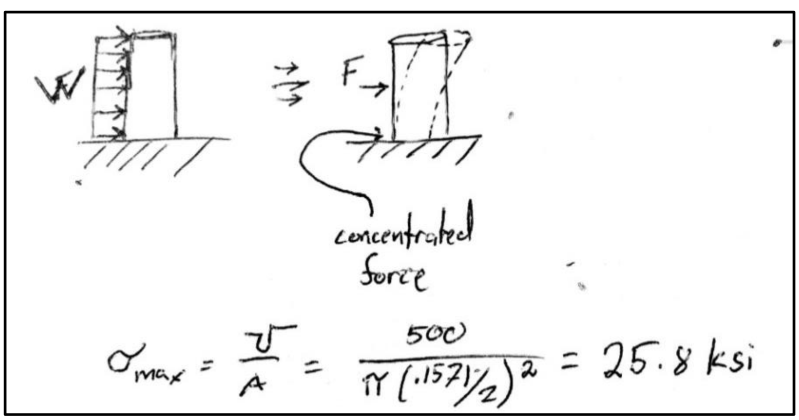

Figure 46: Locating Pin Hand Calculation

3.1.12 Position in car

The accumulator container is attached to the chassis rigidly by brackets attached to the base plate. The chassis fully surrounds the accumulator container for protection (EV3.4).

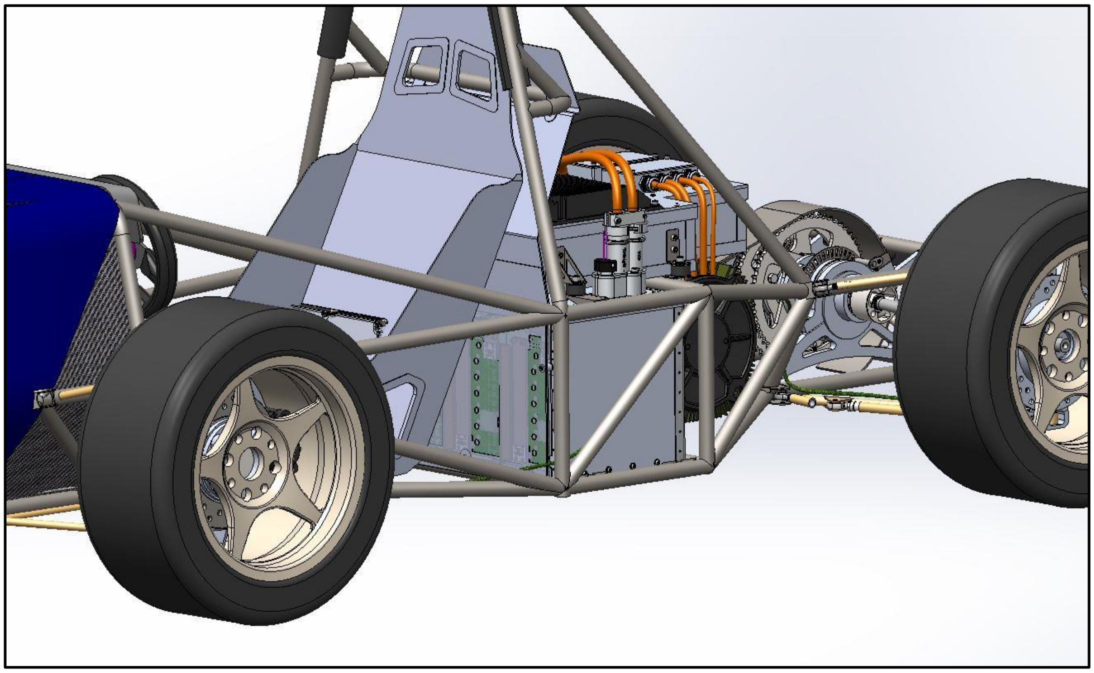

Figure 47: Accumulator Enclosure in Vehicle