6-14-2013

Formula electric : powertrain

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Date: June 14, 2013

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FORMULA ELECTRIC: POWERTRAIN

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FOR THE DEGREE OF

BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING
AND
ELECTRICAL ENGINEERING

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Formula Electric: Powertrain

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THESIS

Submitted in Partial Fulfillment of the Requirements for the
Bachelor of Science Degree in
Mechanical Engineering and Electrical Engineering
in the School of Engineering
Santa Clara University

June 2013

Formula Electric: Powertrain

Departments of Mechanical and Electrical Engineering
Santa Clara University Santa Clara, California
2013

ABSTRACT

The Santa Clara Formula Electric team designed, and manufactured a powertrain for an electric racecar according to the rules prescribed by the SAE International Formula Electric competition. The powertrain is divided into subsystems: the battery pack, battery pack cooling system, motor controller, and the motor. The battery pack was constructed, but full electrical connection of all cells were not made. The pack was not integrated with the motor and motor controller. In Addition, due to time constraints, extensive testing could not be completed.

ACKNOWLEDGEMENTS

The authors would like to thank the following sponsors for their support and helped making this project possible: Bob Fox of Fox Racing, the IEEE Santa Clara Valley Section, Pacific Traders Inc., Amtec Solar, Mersen, SAE Mid-California Section, Xerox, Pacific Custom Fabrication, and the Santa Clara University School of Engineering. The authors would also like to thank Yohannes Kahsai (Electrical Engineering Lab manager), Don MacCubbin (Mechancial Engineering machine shop manager) and Shane Wibeto (Engineering school) for their assistance throughout this project. A big thank you to Dante Zeviar, who graciously donated his expertise and his time to help the project be a success, while ensuring that the project was as safe as possible. A special thank you to Chris and Thomas Cook of Lithiumstart, LLC. for their generosity, priceless consultation,hardware donations, and for making their workshop open for our use. Lastly, thank you to our families for their unconditional support of our education.

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PART I

PROJECT OVERVIEW

1 INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

In the last two decades, the world has become increasingly more conscious of the planets limited natural resources, as well as the exceedingly high resource consumption rate. Specifically, the human race has very quickly expended much of the available carbon based energy sources, including coal, oil, and natural gases. Fossil fuel harvesting processes as well as consumption of these fuel sources creates high quantities of greenhouse gases, polluting the environment and adversely affecting climate change.

The energy crises has emerged as one of the most significant challenges the global community faces in the 21st century, and presents obstacles that extend beyond the environmental realm. A solution to the energy crisis would help resolve other global issues, such as water pollution, disease, food shortages, poverty, education, and international security. For the continued progress of science, technology, and the human race, it is imperative that the remaining energy sources be used as efficiently and cleanly as possible.

Currently, the majority of global energy is harvested from fossil fuel combustion, which is the largest contributor to the concentration of greenhouse gases in the atmosphere. In 2007, the U.S. Energy Information Administration (EIA) reported that the transportation industry consumed 30% of the national energy reserves and 70% of the national fossil fuel reserves thus; the automobile industry has one of the two largest carbon footprints of any business sector in the United States, second only to commercial building [20].

As a world leader in gas and energy consumption, as well as energy-to-power conversion technologies, the US automotive industry is uniquely positioned to lead the scientific and technological progress in using cleaner, more efficient energy. By progressing toward using more sustainable sources of energy to power vehicles, the automotive industry can be a major leader in the progress toward sustainable energy practices and cleaner energy technologies. Already, significant progress had been made in the electric vehicle industry led by newly formed automotive ventures such as Tesla Motors, Lightning Car Company, and Detroit Electric. Automobile giants such as Ford, GM, Toyota, Mercedes, Audi and even Ferrari have also implemented research and development efforts in the clean vehicle sector with the likes of the Volt, Prius, and many more. This progress is centered on exploring the benefits to electric drivetrains as well as producing more efficient methods to utilize electric energy.

1.2 Project Statement

The Santa Clara University Formula Electric (SCUFE) team had two main purposes. The first purpose of the SCUFE team was to complete phase 1 of a two phase project. Phase 1 was the design and manufacturing an electric power system that optimizes vehicle energy and power efficiency while minimizing cost for a formula race car for the purpose of competing in the 2014 SAE Formula competition. Phase 2 consists of the design and manufacturing of the chassis, suspension, steering and drivetrain, as well as the powertrain integration, to be completed during the 2013-14 academic school year by a team selected from the class of 2014. This power system was composed of a battery pack, motor, motor controller and subsequent cooling systems. Notably, the overall system was designed according to the specifications and rules set forth by SAE International Collegiate Design Competition.

The second purpose of the SCUFE team was to continue the transportation sustainability legacy at Santa Clara University begun by the 2012 Santa Clara University Formula Hybrid team. This legacy exists in order to inspire current and future SCU undergraduate engineering students to innovate in the field automotive and transportation technology with a focus on energy and power efficiency and sustainability.

1.3 Team Structure

The SCUFE team was composed of two sub-teams: the thermal management team and the systems integration team. Despite the functional organization, the team in reality existed as one united group which completed Phase 1.

The purpose of splitting the main team into two sub teams was to ensure that adequate focus be concentrated on designing the cooling system. The overall efficiency of the system depends significantly upon the thermal state of the battery cells, as the performance of a lithium ion cell increases with temperature, while the total cell life decreases as the cell is operated at higher temperatures. There exists an optimum cell operating temperature that ensures the cells perform at their maximum efficiency while still delivering the desired power output. In order to reach this optimum temperature, and thus optimize overall system efficiency, it was necessary to actively cool the battery cells and the motor.

A battery pack presents an interesting thermal balance challenge. The thermal management team sought to identify the ideal operating temperature and design a cooling package accordingly. The thermal management design scheme includes strategically located vents and automatic actuators to allow air to circulate over the cells and prevent outside containment from reaching the surface of the battery cells. The tests results show that the proposed design allows a smart control of the battery cells temperature to provide maximum efficiency and performance.

The systems integration team was tasked with manufacturing the battery pack accumulator enclosure; selecting and wiring the battery cells and all necessary connections within the battery pack accumulator; selecting the motor and motor controller; and ensuring correct communication between accumulator, thermal management system and motor controller.

2 Main System and Subsystems

Figure 1 shows the systems level diagram of the project. The diagram illustrates how each major subsystem interacts within the main system.

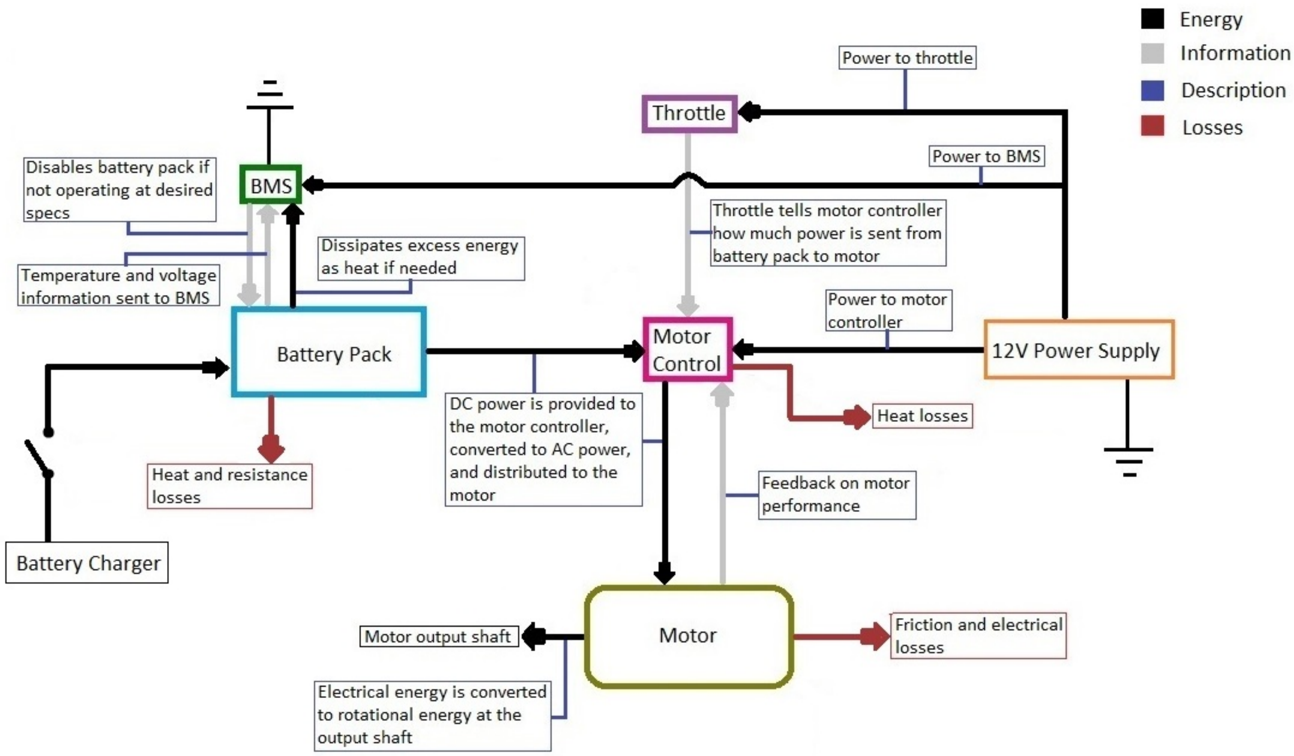

Figure 1: Main systems level diagram. All major subsystems are displayed, as well as locations were energy loss causes drops in system efficiency.

2.1 Conceptualization

The battery pack provides high voltage DC power to the motor controller through a high voltage conduit. The motor controller sends high voltage 3-phase AC power through a high voltage conduit to the motor. The Battery Management System (BMS) monitors and controls the battery pack through a network of low voltage connections; if the BMS senses a battery cell has dropped to critical levels, or the cell temperature has reached critical levels, it will disengage all physical connections in the battery pack. The throttle inputs an analog signal to the motor controller to control the inflow of DC electrical energy. The motor converts the high voltage AC power to mechanical energy. The structural components attach all these systems to the rest of the car. The motor controller and BMS are powered by an auxiliary 12 V supply. The vehicle chassis will act as the electrical grounding.

2.2 Functional Analysis

The vehicle is designed to receive an input from the driver and translate that information into a mechanical response from the vehicle on the road. The driver uses the throttle to control how the vehicle will perform. The throttle sends an input to the motor controller signaling the amount of power desired by the driver. The motor controller routes electrical energy in the form of DC current from the batteries to the motor. The motor controller then converts the DC current to 3 phase AC current. The motor converts that energy into mechanical rotational energy.

The Battery Management System (BMS) maintains a level state of charge across the battery pack by discharging small amounts of energy from over charged cells. The BMS also outputs a signal to shut down the battery pack if a fault is detected. A 12 Volt power supply powers the BMS, motor controller, and throttle assembly.

As far as the user is concerned, this system would be implemented into an electric vehicle in a similar manner as an internal combustion vehicle. The user would control the speed of the vehicle using the accelerator and braking system, and control the charge state of the battery pack by plugging the vehicle into an external energy source while the vehicle is not in operation. As with gas-powered vehicles, it is easy for someone to use this system with minimal prior experience.

2.3 Project Design Specifications and System Requirements

The SCUFE power train system was compared to the SCU Formula Hybrid 2012 project in order to formulate the project design specifications. Table 1 shows these specifications.

Table 1: Project design specifications

ELEMENTS/REQUIREMENTS		PARAMETERS	
	UNITS	DATUM	TARGET-RANGE
Performance			
Range at 40 MPH	*Miles*	N/A	80-120
75 m Acceleration	*sec*	8.8	6.0-8.0
Top Speed	*MPH*	N/A	70-100
Max Torque	*Nm*	N/A	135-163
Max Voltage	*V*	N/A	280-300
Max Power Draw	*kW*	N/A	60-85
Storage Capacity	*kWh*	2	5-7
Thermal Control	°C	N/A	25-35
Design			
Cost	$	40,000	13,000-18,000
Mass	*kg*	62	64-73
Size	m^3	0.085	0.11-0.14
Time Scale	*Months*	8	7-9
Usability/Safety			
Removale of Battery Pack	*sec*	N/A	110-140
Useful Life	*Charge Cycles*	1800	500-700
Deceleration Resistance	20g	N/A	20g

3 BUSINESS MODEL

3.1 BUSINESS PLAN

The Santa Clara Formula Electric teams business is to design and manufacture electric powertrain systems for vehicles. SCUFE aims to target three markets. First, the company will design powertrain systems as a contractor for original car manufacturers. The secondary market will be businesses seeking to convert vehicle fleets from internal combustion systems to electric systems in order to save on transportation fuel costs. The tertiary market will be race car drivers and race teams looking to build electric race cars. This business requires a large investment in order to rent necessary shop space and purchase necessary materials. In order to reduce cost, SCUFE aims to partner with Batterist to reduce the cost of battery module.

Our product is an automotive electric powertrain, which consists of the battery pack, electric motor, motor controller, and necessary management and safety systems. The idea behind this product consistently breaks down into three main components that can be easily implemented into a vehicle. The target market includes major car manufacturers that traditionally lack the expertise in electric powertrains. Other potential buyers might wish to enter the electric vehicle market without investing the human resources into developing a new technology. The team comprises of a list of highly qualified engineers with diversified background and a passion for electric vehicles. Some of the competitors are Mission Motors, ALT—e Powertrain Technologies, and VIA Motors. These companies focus on creating electric drivetrains, either for use on their own or added to ICE vehicles.

The team envisions the company serving as a subcontractor and consulting firm for a large array of electric vehicle and energy storage applications. In the short term, the company objective is to bring a viable product to market and become profitable. In the longer term, the goal remains to build a very successful company that impacts the world in a positive way.

In most cases, a startup company such that of Formula Electric does not know exactly where the first customers will come from, therefore it is important to remain ready to adjust at any moment. The Formula Electric project has a wide range of potential customers. Potential customers could encompass racing teams, large scale car manufacturers, or businesses looking to convert corporate fleet vehicles from combustion engine powertrains to electric powertrains. As our customer range is broad, it is difficult to determine a specific set of customer needs, since each customer type will require a different set of system specifications.

The team realized that narrowing the targeted consumer base is inhibitive to the potential applications of the proposed product. The proposed project demonstrates that the project team could design powertrain and power storage units to meet any customer application on the basis that the Formula Electric system operates at extremely high stress conditions: the Formula SAE competition. The competition will require an efficient, powerful, and robust powertrain with a long power storage unit life. The specific design specifications of the proposed system are limited by what the competition rules allow, but by demonstrating the systems ability to operate at a racing level, the Formula Electric team simultaneously demonstrates the system ability to operate at less stressful levels.

Although the proposed power train and power storage units will be designed with top performance in mind, the system can be modified for any low stress application. The Formula Electric team calls this the trickle down effect. This effect details how cutting edge technologies can be modified for less extreme conditions, such as commercial use. An example of this is the inclusion of paddle gear shifters in contemporary vehicles. Paddle gear shifters were initially developed to allow Formula 1 race car drivers quicker and easier gear shifting, as opposed to manual gear shifting. This technology is now widely available at the consumer level.

The SCUFE company would look to sell their service to three potential markets. First, the company would sell their design services to original car manufacturers. These manufacturers would contract SCUFE to design a high power, light weight power train system for specific vehicle types, then use that powertrain design to manufacture and market full vehicles.

A secondary market would be businesses looking to convert pre-existing fleets of vehicles to electric power in order to cut transportation and fuel costs without purchasing new vehicles. Examples include towing companies looking to convert tow trucks to electric power systems, or moving companies looking to convert storage vehicles. These businesses would specify their design specifications in terms of vehicle range, and necessary power and torque, and SCUFE would design battery packs and power train systems to meet these requirements. The fleets would then be delivered, and all internal power trains systems converted from internal combustion systems to electric systems.

The tertiary market would be individual race car drives and racing teams looking to implement electric power train systems in their vehicles. This market functions much like businesses looking to convert fleets; however, race car drivers and race teams have much stricter design specifications in terms of overall system power, as well as necessary volume restraints. Race cars must be small in size in order to optimize speed, which introduces stringent space requirements for powertrain designs.

The electric car market is still relatively young, so there is room for growth as the economic benefits of electric vehicles become more apparent to businesses and corporations. Many large automobile manufacturers have begun offering popular vehicle models in electric versions. and Tesla Motors has seen increased production within the past 6 months. Since the majority of electric vehicles offered by original car manufacturers are small economy cars, such as four-door sedans, these vehicles cannot meet the power requirements needed by large scale vehicles. SCUFE aims to deliver high torque and high power electric power trains systems to meet these demands.

Car owners may not want to purchase a brand new vehicle or lose money selling a newer vehicle in order to benefits from an electric vehicle. Electric powertrains can be retrofitted into their current vehicle. The amount of electric vehicles sold yearly are increasing due to the innovations in technology, which allows a price reduction on electric vehicles. In 2012 56,000 electric vehicles were sold. The reduction in the price of technology for electric vehicles will allow us to target middle to high income businesses that are looking to reduce overhead costs. The incentive to switch to electric powertrains would be the long term reduction in gasoline bills. On average electric vehicle owners saw an increase of $18 in their electric bill when they used electric vehicles as opposed to the $147 they would be paying for gasoline.

3.2 Consumer Needs

The SCUFE project was modeled as a technology start-up company. In most cases, a startup company such that of Formula Electric does not know know exactly where the first customers will come from; therefore, it is important to remain ready to readjust business models and strategies to meet necessary challenges.

The Formula Electric project has a wide range of potential customers. These potential customers include racing teams, large scale car manufacturers, and individuals looking to convert personal vehicles from internal combustion engine powertrains to electric powertrains. As our customer range is broad, it is difficult to determine a specific set of customer needs, since each customer type will require a different set of system specifications.

It was determined that narrowing the targeted consumer base is inhibitive to the potential applications of the proposed product. This project demonstrates that the project team could design powertrain and power storage units to meet any customer application, as the system implented in the SCUFE vehicle is able to operate at extremely high stress conditions: the Formula SAE competition. The competition will require an efficient, high performance powertrain that maintains a high top speed and long power storage unit life. The specific design specifications of the proposed system are limited by what the competition rules allow, but by demonstrating the systems ability to operate at a racing level, the Formula Electric team simultaneously demonstrates the system ability to operate at less stressful levels.

Although the proposed power train and power storage units will be designed with top performance in mind, the system can be modified for any low stress application, and can be easily modified to meet the power and voltage demands far exceeding 300 *V*. The Formula Electric team calls this the trickle down effect. This effect details how cutting edge technologies can be modified for less extreme conditions, such as for commercial use; an example is the inclusion of paddle gear shifters in contemporary vehicles. Paddle gear shifters were initially developed to allow Formula 1 race car drivers quicker and easier gear shifting, as opposed to stick gear shifting. This technology is slowly becoming available at the consumer level.

3.3 Sales and Marketing Strategy

SCUFE would focus on providing customers with custom designed power train systems which are reliable, inexpensive to maintain, high quality, and will give the best return on their investment. The advertising for our product should highlight the strong points of our system, specifically the power outputs and efficiency ratings, accompanied with a display of unique technologies and components implemented within the powertrain system. It is important to differentiate our products from the competition and to show the consumer market why they should choose our product. Since our system was designed to be custom based on the contract, we can work with any customer to meet their exact needs.

The salespeople must be knowledgeable enough to fully explain to customers what makes our system special, and be able to field most technical questions. They can also direct questions to the engineers as needed. They can be trained to know the highlights of the system and how they compare to competitors systems.

If we were to continue with our current strategy then we would acquire our parts from around the world, and assemble them together in the U.S. for distribution. This strategy allows us to make changes to parts as needed, such a change to the module layout to better fit the customers system or due to a change in the battery pack design. By having a modular design focus, we are able to implement these design changes without having to disassemble or throw remake the current product. Close business ties with our parts suppliers will allow us to secure quick product replacement and priority warranty repair. With larger orders we will be able to save on shipping and per unit costs, and become a higher valued customer to the supplier. One company we would hope to partner with would be Batterist. Not only would this help us secure parts easier, but by allying ourselves with a reputable company we will be better regarded in the industry.

3.4 Manufacturing Plans

Manufacturing will depend largely on the customer and application. Initial prototyping and design will occur at the headquarters location in the U.S. in order to ensure the first products meet our design specifications and quality assurance. At that point, manufacturing decisions will be made based on the volume of the contract/application. Generally, low volume orders (¡100 units) will require higher levels of expertise and require less human resources. High volume (¿100 units) contracts, such as that of a GM or Ford, will require manufacturing in a facility owned by customer. The idea here is that large buyers such as big auto manufacturers already have the resources in space, manpower and machines to produce high volume vehicles. Formula Electric would supply the technological design in these cases.

Low volume contracts give us the ability to produce in house since less resources are required on the company end. Furthermore, customers with low-volume orders will not have the means of manpower to be able to manufacture our product themselves. The contract based manufacturing plan allows the company to maintain a high level of mobility and a smaller number of employees while still having the ability to expand in sales.

It is estimated that Formula Electrics current technology and setup would require 6 man hours in order to fully assemble the system assuming little to no manufacturing. Assembly time would change based on the alterations in future technology and the application. We will keep a minimal inventory of assembled systems; our product will be on a made to order basis.

3.5 Financial Plan

The financial outlook of the company possesses significant assurance relative to most startups given the beta product has already been produced. The beta product costed $17,500 excluding compensation of the team and free shop time due to the university environment. Assuming the company had a great two years gaining a contract for 500 units of the generation one powertrain built this year. The expense to fulfill the contract would project as follows:

- **$8,750,000** in components assuming no price deduction from suppliers despite increases in volume.
- **25%** profit margin based off other competitive R&D companies.
- **$10,937,500** placed bid amount for contract leaving about $2,187,500 in profit.

In order to launch the company, the team anticipates an initial seed investment of approximately 1 million dollars for the first two years external to any sales contracts. The seed funding will be allocated as follows:

- **$100,000** for office space over the first two years based off the going rate of $10 per square foot in Santa Clara and an estimated space requirement of 5,000 square feet.
- **$60,000** for utilities and insurance expense assuming a small business spends approximately $2,700 per month over a two year period.
- **$70,000** for equipment and machinery investment including: three Bridgeport mills, ultrasonic welding unit, welders, drills, hand tools, chargers, and other electronic instrumentation
- **$770,000** in compensation expenses to the team assuming seven people at $55,000 per year.

After the first two years, the company will undergo an overall re-evaluation in order to understand the direction and profitability of the company. Assuming the company gains some degree of success, the company will approach venture capitalists for series A funding which is estimated at 5 million. The series A funding remains highly dependent on the profitability of the company and how it might offset the required cost of producing a new and better product. If the company lands a contract similar to the hypothetical situation outlined above, the company in turn becomes profitable. At this point, the strategy begins to focus more on eliminating the company debt and pursuing a IPO situation. New expenses will fall under the umbrella of new research and development and the necessary equipment associated with it. The income statement attached demonstrates an overall 2 year evaluation of the company as well as the net worth of the company.

3.6 Service and Warranties

Li-ion cells can have a longer or shorter life based upon how they are discharged and the conditions that they are operated under. This means that by operating them within a specific operating range, it is possible to maximize their lifespan and prevent the requirement of frequent battery replacements. With proper usage techniques the cells implemented into the beta model can be expected to last 500 to 700 charge cycles, or three to four years. If there are issues with cells fails sooner than expected it is possible to prorate the sale of a replacement cell, i.e. sell the customer a new cell at a discounted price based upon how long the damaged cell lasted.

Repairing and maintaining the electrical system could prove problematic since not every automotive mechanic is experienced with high voltage electrical systems. The current scenario would be to do all repairs in house, but that would limit our customer base to those who are near or would require locations across the country or world. If companies resell our system to customers they might also provide most repairs and then can send anything to us that proves too complicated to repair themselves.

The type of service will determine who is required to pay for it, depending on if it is a regular maintenance or warranty issue. Generally speaking, the customer is expected to pay for all regular maintenance or other issues that come up outside of warranty or other unexpected failure.

3.7 Market Analysis and Existing Technologies

There are several companies that provide services similar to the proposed project. In order to determine market competition, three companies were analyzed: Mission Motors, VIA Motor, and ALTe Powertrain Technologies.

Mission Motors
Price: Customer Specific
Sales: N/A

Mission Motors designs and builds custom powertrain systems and components for original equipment manufacturers, including large scale automobile designers and manufacturers. They are known for their compact, yet powerful and efficient designs. Mission Motors designs and manufactures their own battery storage units, motor controllers and traction motors.

Mission Motors made a name for themselves in the electric motorcycle racing circuit. Their high performance powertrains drew attention and they became a (potential vendor?) target for hybrid and electric vehicle manufacturers looking to improve their products.

Mission Motors is currently focusing on producing high performance powertrains for the hybrid and electric vehicle markets. They work with their customers from the design phase through to the testing phase in order to ensure they are providing a working product that will meet all their customers needs. Mission Motors focuses on working closely with electric and hybrid car manufacturers from the early design stage to the production and distribution stages. Figure 2 shows an illustration of their full power train system.

Possible Improvements:
Mission Motors focuses on providing a customized system for each of their customers unique applications. In order to target a wider customer base, a line of more generic powertrain systems could be offered to increase sales, as well as offering their products to individual customers looking to implement electric powertrain technologies into personal vehicles.

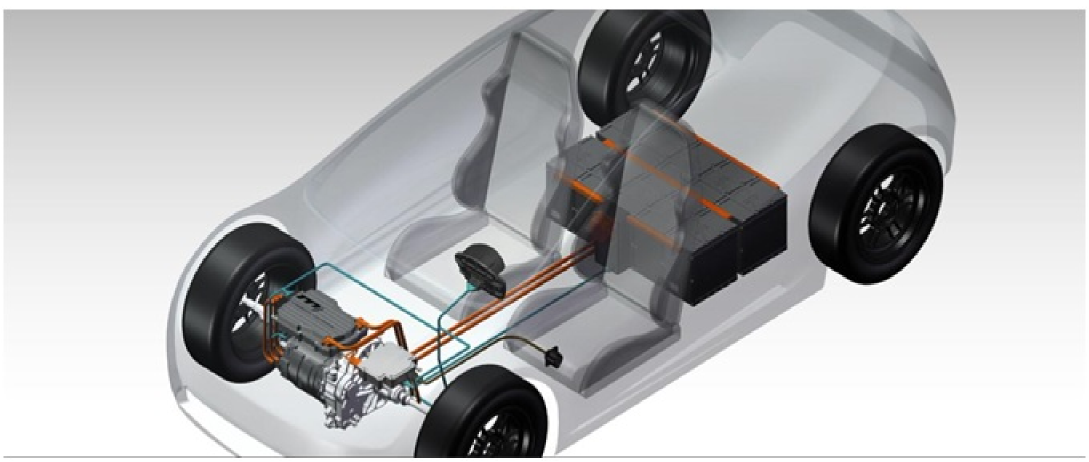

Figure 2: Rendered Image of Mission Motors' power train system.

VIA Motors
Price: $79,000 per vehicle
Sales: Not yet selling vehicles, anticipates 2013 deliveries.

VIA motors is a startup company that designs and manufactures "Extended-Range Electric Vehicles (E-REV)." These vehicles are heavy duty fleet vehicles, including trucks, vans, and SUVs.

Although the vehicle powertrains are solely electric, the vehicles themselves are a unique form of hybrid vehicle. VIA Motors vehicles include an on-board gas powered electric generator. The electric generator is connected to a 4.3L combustion engine that automatically recharges the batteries when they run low to improve the range of the vehicle. The motor/battery/generator system is controlled by a dual-drive motor controller.

This vehicles use of an electric generator also allows it to be used as a mobile power source. The driver could utilize this power source to run various power tools on a construction site or provide electricity in remote locations. Figure 3 shows an illustration of a VIA Motors power train.

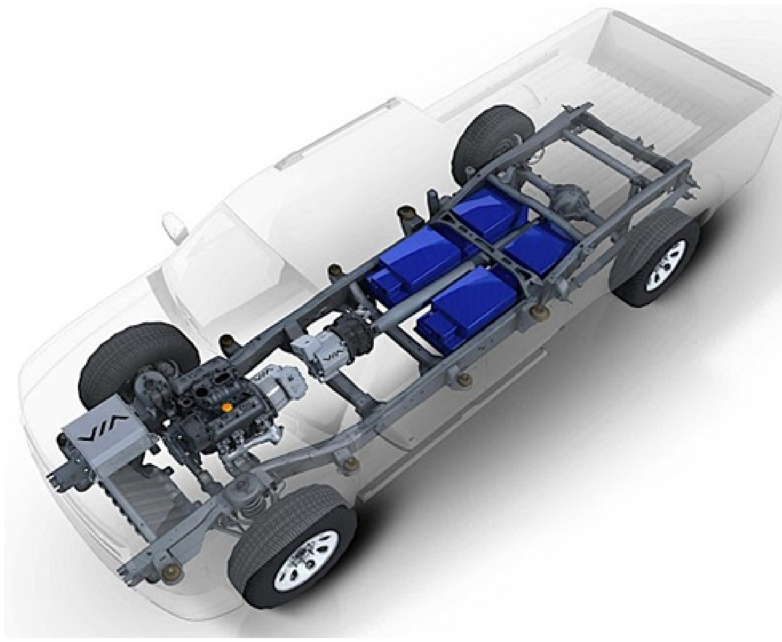

Figure 3: Rendered Image of VIA Motors' power train system. Figure shows battery pack location and electric generator.

Possible Improvements:
Via Motors market is very narrow. They could potentially improve sales by implementing their technology into a smaller vehicle. This would mean opening their business up to a new market without having to compromise their unique design goals. Having a unique powertrain design, Via Motors could benefit from selling just their powertrains to established vehicle manufacturers as opposed to selling finished vehicles.

<u>ALTe Powertrain Technologies</u>
Price: $26,500 per vehicle conversion
Sales: Based on customer specifications.

ALTe develops modular electric powertrain systems for retrofitted light to medium duty fleet and niche vehicles. They add their own powertrain equipment as well as modify the current powertrain. The company focuses on increasing vehicle fuel economy and reducing vehicle emissions by utilizing electric power in conjunction with a gasoline powered motor. ALTe develops these systems for vehicle fleets and do not offer retail services. Like the Formula Electric team, ALTe has the mission to reduce US dependency on fossil fuels and to transform the nations automobile transportation system from one based on gasoline to one based on electricity. Figure 4 shows a photograph of a converted heavy duty vehicle power train.

Figure 4: Photograph of ALTe converted power train.

Possible Improvements:
Because their design still incorporates a gasoline powered engine, they have a smaller impact on the reduction in use of gasoline. Their goals consist of being able to travel 40 miles solely on electric power. This range works for anyone who may drive short distances in a day, or doesnt drive as often. They could improve by increasing the battery capacity or efficiency in order to achieve a longer range. They could also look into alternative ways to recharge the batteries while driving, which would allow them to travel farther.

Table 2 shows a summary of existing market competitors.

Table 2: Add caption

Company	Product	Key Features	Price
Mission Motors	Custom power-train systems and custom power-train components	Energy storage systems, motor control units, traction motors, on board chargers, Skyline Data management and visualization software	Unavailable
VIA Motors	Extended-Range Electric Vehicles	402 hp high torque electric motor, 201 hp electric generator, dual-drive motor controller, 24 kWh Li-ion battery located under bed of truck	Anticipated selling price $79,000 in volume
ALTe Powertrain technologies	Retrofitted light to medium duty fleet vehicles	40 miles per total charge, 4 cylinder engine generator	$26,500

4 Management

4.1 Budget and Investment Allocation

The SCUFE approached sponsors during the duration of the 2012/2013 academic year to raise necessary funds for the components that needed to be bought. A business presentation was developed, then modified for each potential sponsor. The team successfully raised a total of $17,950, which is sufficient to cover all project costs. Major contributions came from Fox Racing, IEEE, Pacific Traders, SCU School of Engineering and the Deans Fund.

The largest expenses for the SCUFE team were the battery cells, motor and the motor controller. The budget was split between the three major subsystems. Each of these components used between $4,000 and $5,000. The remaining money was spent on other parts such as the BMS, $2,000; the battery box, and other miscellaneous connecting components. Appendix F has a detailed budget, showing the cost of each component. The teams purchases along with the money spent were put on a spreadsheet, so that the SCUFE team has a reference to how much money we had. The SCU School of Engineering also keeps an account of our current expenses.

4.2 Timeline

The timeline was split into three quarters to coincide with the three quarters of the SCU academic year.

The fall quarter was dedicated to completing research necessary to complete the project, as well as decide upon which battery cell to implement. This was a critical step to the overall success of the project as finding components that operate to the desired specifications, are mechanically and electrically compatible, while staying within budget was a difficult task. In addition, sponsors were approached in order to obtain funding necessary to buy the components. At the end of the fall quarter, a battery cell had been selected, the preliminary design had been established and $2,000 were raised.

The winter quarter was dedicated to raising the majority of funding needed to buy component, buy the components, and complete the structural and electrical design of the battery pack. There were alterations in the initial designs due to monetary limitations, availability of battery cells and motor controller compatibility with the motor. This forced a redesign and reevaluation of the powertrain system with new components. This limited the number of components that were purchased and received during the winter quarter.

All necessary battery modules and the motor were received during the winter quarter. In addition, the team raised approximately $10,000.

During the spring quarter the remainder of the components were purchased and acquired. The rest of the quarter was spent assembling the battery pack, cooling equipment, battery management system, motor and motor controller. The end of the quarter was spent preparing the battery pack for future work done with the battery pack.

4.3 Project Challenges

The major objective is to design and fabricate an electric car that maximizes vehicle energy and power efficiency, while minimizing cost. The vehicle design will conform to the rules specified by Formula SAE with the anticipation to race in the 2014 Formula SAE Electric competition. Major constraints will include size limitations, weight limitations, power limitations, as well as budget limitations. The two greatest constraints to the success of the project are time and cost. The challenge is to get funding for the project as well as successfully integrating many distinct systems.

4.4 Risk and Mitigation

Since the powertrain system will be high voltage, there is a health risk associated with working on the system. High voltage systems have an inherently high level of danger due to the large amounts of electrical current flowing through the system. The common phrase is that current kills and voltage burns. Therefore, it is important to minimize the current with a very high resistance. Dry skin can be up to a thousand times more resistant than wet skin. It is also important to keep one hand free so a persons body does not become part of the circuit and have current pass through it. High voltage gloves rated up to 500 V were used at all times when working on the live pack. In order to minimize the risk, it is important that the Formula Electric team conform to both SAE Formula Electric and SCU high voltage system regulations.

Other safety risks include battery malfunctions that result in catastrophic failure due to the cell overheating. That is why it is imperative to implement a proper cooling system. Each cell has a maximum temperature rating of 60o C, which has been reached during cell discharge tests, so a reliable cooling system will be essential.

The last risk is insufficient funding. If the Formula Electric team does not procure sufficient funding to purchase all the necessary parts, the project cannot be completed. The team hopes to mitigate this risk by approaching as many different sponsors as possible. In addition, the team will work to present a comprehensive project plan to sponsors and provide periodic, detailed reports on the progress of the project.

4.4.1 SAE International Rulebook

The SAE Formula International Competition Rulebook may be viewed at: http://students.sae.org/competitions/formulaseries/rules/2013fsaerules.pdf.

Part II

Subsystems

5 Battery Pack

5.1 Requirements

In the projects earliest stages, before design, before conceptualization and perhaps even prior to approval, it was understood that much of the project would revolve around the battery pack design. Given that the battery pack defined the entirety of the project, great efforts and attention was placed into every stage of development. The project goal was to have the most powerful and capable battery pack at the competition and as allowed by the rules of the SAE organization. This goal was quantified by the power and voltage requirements of the pack: a peak power output of 85 kW and a maximum voltage potential of 300 V. These values are absolute ceiling limits dictated by the SAE International rules.

Understanding that the power loss of the battery was quadratically related to the current through the battery helped determine the decision of how exactly to reach 85 kW, in terms of how to balance the voltage versus the current. The pack design focused on maximizing the voltage by reach the 300V ceiling value first to reach the power goal.

In addition to the power requirements, the pack was designed to meet a series of structural goals. Given the power requirements of pack, weight became a point of emphasis. Although weight considerations typically surface in future design iterations and succeeding generations of product, through material selection the pack was designed to weight less than 70 kg. Somewhat counter to the weight requirement, the pack needed withstand a 20g horizontal deceleration while maintaining structural integrity.

The pack was designed in a way that emphasized a theme of modularity and simplicity. A modular design allows easy customization of the pack, as well as easy replacement of damaged parts. A simple design allows those without technical training to use and operate the battery pack effectively and safely. The themes of modularity and simplicity derived from a combination of capabilities that the team wanted to address. Imagine a competition or racing situation where time is of the essence and components will and do brake. Having a pack that allows a pit crew to quickly remove a dead cell or malfunctioning component could provide huge value and mean the difference between winning or losing.

The competition upholds a long list of requirements that have less of an effect on the design of the pack and more so stand as rules of the pack must follow and assembly must execute.

5.2 Battery Cell Selection and Electrical Design

The project began with an extensive research effort profiling the continually evolving battery market. Energy storage alternatives to batteries were researched; however, the SAE rulebook disallowed the use of fuel cells as alternative storage. Preliminary findings on supercapacitors revealed that the technology lacked overall maturity and availability for current designs. Thus, it was determined that batteries were the most viable solution.

The two chemistries of battery cell that were considered were Lithium Iron Phosphate ($LiFePO_4$) and Lithium Nickel Manganese Cobalt Oxide (LiMnNCo), due to their high energy densities, as well as meeting our system requirements. Lithium Iron phosphate cells typically have max voltages around 3.65 V; 83 cells in series are required to reach 300 V. There are many manufacturers of LiMnNCo cells, because they are easily usable in a large variety of commercial applications, including automotive hobbyist RC devices and power tools. These types of cells typically have max voltages around 4.2 V; thus, 72 cells are required to reach 300 V. Both these cell types come in smaller capacity cells as well as large monolithic cells.

The team examined nearly 20 different cells of different manufacturers. Table 3 shows the cells considered for the battery pack. Table 4 shows extrapolated pack data using the individual cell specifications.

Table 3: Specifications for cells considered for battery pack.

	Single Cell Data						
Cell	Nominal Voltage(V)	Amp Hours (Ah)	Volume (cm^3)	Weight (kg)	Continuous Discharge Rate C	Max Discharge Rate ($Amps$)	Operating Temp. ($^\circ C$)
1	2.26	13	200.55	0.4	6	130	-40 to 55
2	3.65	20	231.03	0.43	5	100	-30 to 55
3	3.3	20	263.35	0.5	18	363	-30 to 55
4	3.3	4.4	90.76	0.2	38	167	-30 to 55
5	3.7	25	345.46	0.57	5	125	-30 to 60
6	3.2	20	709.33	0.83	3	60	-20 to 60
7	3.2	40	1,044.89	3.4	3	120	-20 to 70
8	12.8	40	4,672.26	14.33	0.75	30	-20 to 60
9	3.7	20	110.43	0.53	1	20	-10 to 60
10	3.7	2.8	38.56	0.22	14.3	40	-20 to 60
11	11.1	7.2	266.94	1.15	0.8	6	-20 to 60
12	3.6	17.5	290	0.95	2	35	-20 to 55
13	3.7	5.2	52.42	0.12	20	156	-30 to 60

Table 4: Extrapolated data for a battery pack manufactured using each type of cell.

Cell	Battery Pack Data							
	# Cells to reach 300 V, Series	# Cells to reach 20 Ah, Parallel	Amp Hours	Total # of Cells	Volume (m^3)	Weight (kg)	Max Discharge Rate ($Amps$)	Max Power Draw (kW)
1	132	1	13	132	26.47	52.75	130	38.78
2	82	1	20	82	18.94	35.1	100	29.93
3	90	1	20	90	23.7	44.64	363	107.81
4	90	5	17.6	450	40.84	91.85	835	248
5	81	1	25	81	27.98	46.17	125	37.46
6	93	1	20	93	65.97	77.2	60	17.86
7	93	1	40	93	97.17	316.2	120	35.71
8	23	1	40	23	107.46	329.59	30	8.83
9	81	1	20	81	8.95	42.85	20	5.99
10	81	7	19.6	567	21.86	126.16	280	83.92
11	27	2	14.4	54	14.41	61.91	12	3.6
12	83	1	17.5	83	24.07	78.68	35	10.46
13	81	4	20.8	324	16.98	37.26	624	187.01

Data of each cell was gathered via data specification sheets distributed by the manufacturer. The data from each cell was then extrapolated into a projected battery pack that represented the performance capabilities of a battery pack built from each respective cell. The characteristics of each simulated battery pack were intended to reach as close as possible to the system requirements in order to determine which cells could adequately meet the project specifications while remaining within budget.

In order to narrow down the options, each simulated battery pack was scored based on physical specifications including weight, volume, discharge rate, max power output and voltage. Each quality was weighted based on importance to meeting the main project specifications. Each cell and simulated battery pack was ranked by score and the top four choices were evaluated in a second stage. The second stage accounted for less quantifiable factors including product cost, availability, customization and ease of implementation.

Cell 13 was chosen as it scored the highest out of all possible cells. These cells delivered the best power density per cost, as well as delivering sufficient discharge rates necessary to meet the system requirements. Figure 5 shows a CAD drawing of the cell dimensions, while Figure 6 shows a photograph of the cell.

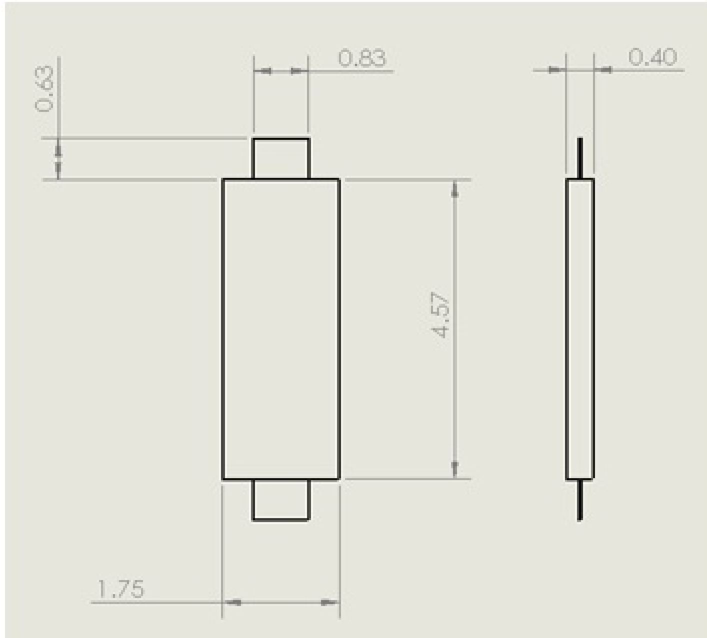

Figure 5: Part drawing of the cell. All units are in inches.

Figure 6: Photograph of cell 13.

Cell 13 is a pouch style cell. The cell chemistry is lithium manganese cobalt (LiMnNCo). Appendix B shows a full cell specifications data sheet. One of the major advantages of cell 13 was the control over how the cells were manufactured. Sticking with the modularity ideal, the team opted wantedfor a cell level arrangement in which each cell could be removed fairly easily in the case of failure or malfunction. In order to reach the 300 *V*, 85 *kW* power specifications, the pack would require 288 cells. The extra weight and space in infrastructure necessary to house each cell individually in a way that allows interchangeability becomes inefficient due to the sheer number of cells. Instead, the team decided to have the cells manufactured in small modules in a *4s1p* arrangement.

The *4s1p* arrangement stands for four cells in series and one in parallel, denoting a grid style format. Therefore, each module consists of four cells wired in series and structurally joined by an adhesive.

The challenge with pouch cells lies in connecting the positive and negative tabs of each succeeding and preceding cell. In to make stable inter-tab connections, the team instructed the manufacturer to ultrasonically weld the tab connections and leads. The ultrasonic weld proves advantageous due to the exceptional strength of the connection, as well as removing an external connection device and the added volume and weight associated with it. The leads feature JST-XH balancing connectors for data transfer to the battery management system and connectors for the positive and negative leads. Modules are connected using deans connectors. Both the deans and JST-XH connectors allow for quick removal of individual modules. The ability to quickly remove a module demonstrated a happy medium between the design theme of modularity and the overall system weight requirements.

As previously mentioned the batteries chosen have slightly more losses than some of the more expensive batteries; their internal resistances are on the order of approximately 3.5 $m\Omega$, as opposed to 1 $m\Omega$. This in turn leads to higher electrical losses when only a single string of cells is considered such as many of the 20Ah cells we were considering; but because the Batterist cells are small, 5.2Ah, and 4 need to be put in parallel to achieve the desired pack capacity, it actually turns out to be an advantage, especially at higher discharge rates. The cells are configured into modules with 4 cells in series and 1 in parallel. Electrically the module can be accurately described (in the worst case) by Figure 7.

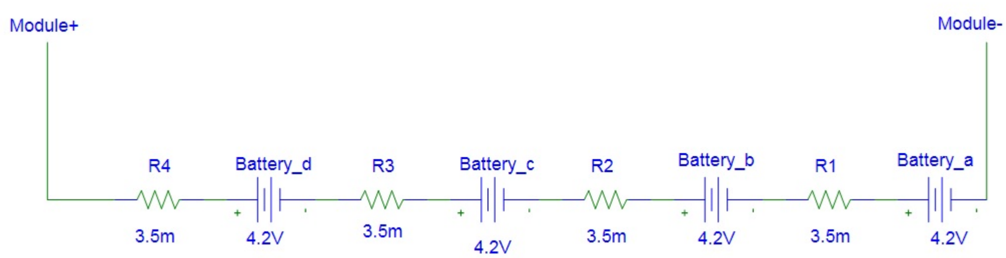

Figure 7: Electrical schematic of four cells in series, demonstrating one module.

We can then compare how 4 of the modules in parallel compare to a 4 single large cells in series by looking at the relationships in loss as described by Equation 2. For example, if 4 single cells were discharged at a rate of 20 Amps, the power output would equal:

$$(20\ Amps)^2 * 0.001\ \Omega = 0.4\ W$$

Whereas with four modules in parallel the power output becomes:

$$4 * [5\ Amps)^2 * .0035\ \Omega] = 0.35\ W$$

As the amperage increases, the advantage over the single monolithic cells will continue to increase. However, there are two primary disadvantages of using many smaller cells over larger ones. First, the complexity of making all the electrical connections is much higher with more cells, as they all have to be properly connected or the pack can fail. With four times as many connections comes four times as many chances for mechanical or electrical failure. Also, it is often heavier to have many smaller cells than larger ones because all the connections between cells require additional components, which significantly adds to the overall weight. The total weight was successfully minimized by choosing pouch cells, which have minimal packaging weight, and by finding a simple, light, reliable way to connect the cells with the use of ultra sonic welding within the modules and Deans connectors between modules for series connections, and custom printed circuit boards (PCB) for the parallel module connections.

The PCBs used to create the parallel connections between modules were a custom design developed with aid from the SCUFE team's industry partners. They have several features to increase the safety of the pack and reduce wiring issues that come with using a centralized Battery Management System (BMS). The primary safety feature of the PCBs is small traces that act as fuses between the cells in parallel. One of the primary safety concerns for Lithium ion batteries is that a short occurs inside the battery causing it to fail catastrophically. The fuses between parallel connections prevent the parallel batteries from discharging their energy in to neighboring cells if an internal short were to occur and stopping the parallel cells from forcing a catastrophic failure in a shorted cell if one did not occur from the short alone. Also, the fuses prevent wiring mistakes or other human error from causing massive failures of the cells. The fuses have been tested twice and on both occasions the small traces blew as they were supposed to and the batteries sustain no damage. The other feature that the second generation PCBs have is they condense all the wiring for the BMS for 4 parallel modules into a single plug removing much of the clutter in the battery enclosure and make it much easier and safer to work on. Figure 8 shows one PCB.

Figure 8: Photograph of a custom designed PCB.

Figure 9 shows four modules connected to a single PCB.

Figure 9: Four modules connected to a single PCB.

The pack as a whole is divided into three subsections as per the formula electric rules for 2013. The pack is electrically described by Figure 10.

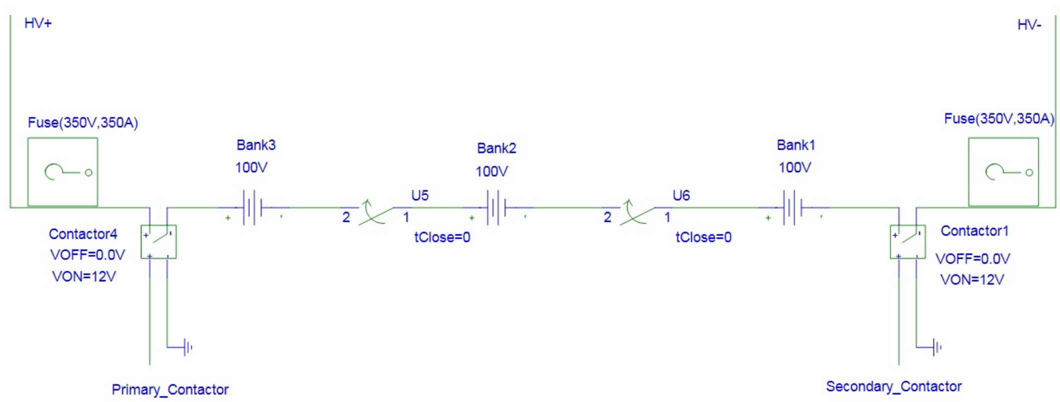

Figure 10: Electrical schematic for entire battery pack.

Each of the banks in the pack represents 6 series modules each with 4 in parallel as shown by Figure 11.

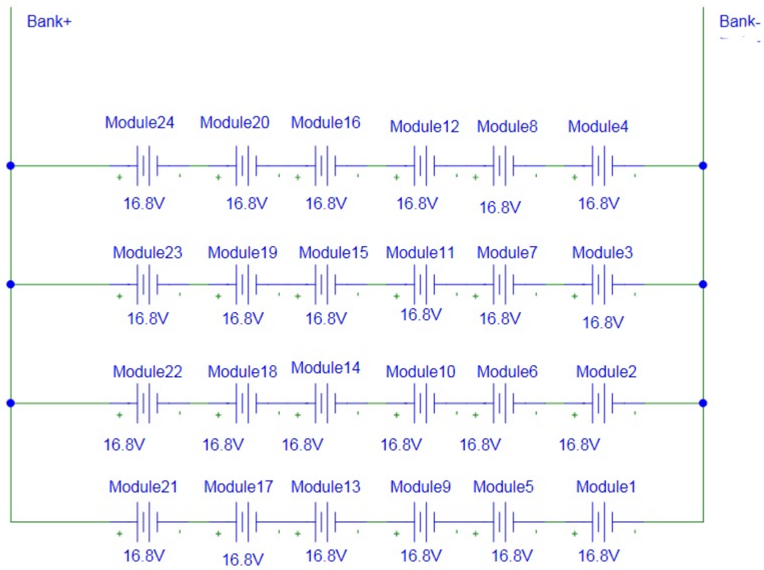

Figure 11: Electrical schematic for a bank of cells, or a single slider package.

This design uses industry best practices to ensure that the battery pack performs at its best for racing while still being safe in all circumstances. The fuses on both ends protect the battery pack from over discharging into other expensive components such as the motor controller as well as preventing those components from hurting the batteries. The contactors are high power relays designed to deal with the abuse of high power connects and disconnects. They prevent high voltage from being outside the battery pack when the system is unpowered and they act as actuators for the primary safety system of the battery pack, the BMS.

Lithium Nickel Manganese Cobalt cells must be carefully monitored because they can become unstable and potentially dangerous if it allowed to operate outside their specified parameters. This task falls to the battery management system, the Orion BMS by Ewert Energy Systems. It keeps track of a number of parameters about the cells such as voltage, temperature, discharge rate, internal resistance, and State of Charge. It uses these metrics to determine if the batteries are healthy and operating correctly. If one of the parameters begins to get worse the BMS acts to lessen the load on the batteries by lowering the maximum discharge or charge currents. If all else fails the BMS can shut off the contactors to prevent a system failure such as overheating to thermal runaway over charging or over discharging.

The Orion BMS was chosen due to its list advanced features that help it to integrate with other system components, as well as it staying within the budget. The other option for a smart BMS at this price point was the Elithion Lite BMS. Smart in this instance means that the BMS uses digital control and not analog, improving the accuracy as well as more having greater capability of integration with other system components. The Orion BMS has a Control Area Network (CAN) interface which allows it to integrate with all the other parts of the system such as an Arduino Controller and the Motor controller. The Elithion Lite did not include this interface feature. Also, the 2012 Formula Hybrid team used the Elithion Lite for their battery pack, which ended up failing for them at a critical point during the competition. The team's industry partners recommend the Orion BMs as a reliable low cost solution that had great support.

However, there are disadvantages to working with the Orion system. The main issue is that the Orion system a centralized BMS, as opposed to the Elithion Lite, which is a distributed BMS. This means that the Orion has wires that connect its central unit to every cell, as well two wires for every thermistor. As 64 modules needed temperature sensing through thermistors (as per SAE Internation rules), there was a large number of wires connecting the battery pack to the BMS. This creates problems assembling the pack, making sure all wires are connected correctly. In addition, the large number of wires reduces the aesthetic quality of the pack.. A distribute BMS, like the Elithion, has a single small board on every battery which are daisy chained back to the control unit with a single wire, making it much easier to work with than the hundreds of wires from the centralized unit.

Figure 12 shows the Orion BMS system.

Figure 12: Photograph of the Orion BMS system.

5.3 Battery Accumulator Designs

5.3.1 Structural Design

In addition to the design themes, the battery pack design centered around safety. The FSAE Competition rule book discusses in depth design standards, safety procedures and team Regulations and Safety Officers. However, the presence of high voltage yields significant dangers that cannot be undermined. The team perceived the system safety from two angles: from an ergonomics approach that accounted for assembly of the pack and periodic maintenance, and from a crash situation in which the pack might experience high impact.

Development of the battery pack began at level 1 which denotes the conglomeration of slider packages. The slider package sub-assembly may be viewed in Figure 13. Figure 14 shows all the sliders together, which constitutes level 1 of the battery accumulator.

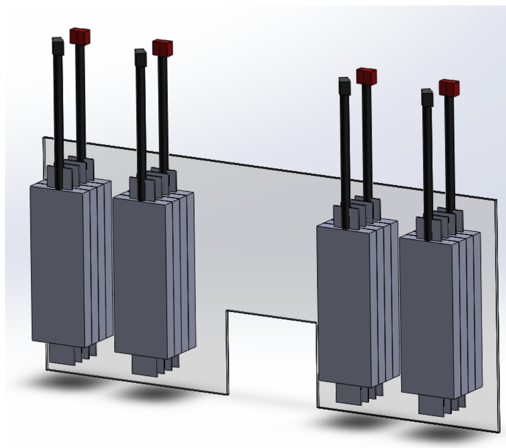

Figure 13: A slider package, showing four battery modules attached to polycarbonate backing.

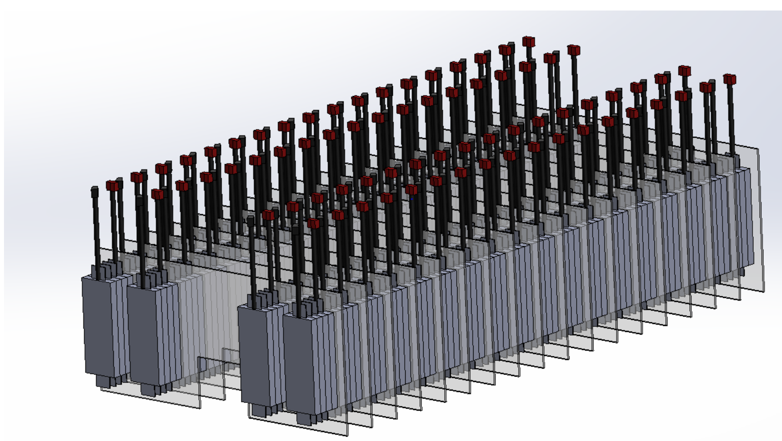

Figure 14: All battery sliders, constituting level 1 of the battery pack.

Given the relative delicate nature of the pouch cells and risk of puncture, the safest way to hold the cell is by the front and rear faces. The slider holds a row of four cells via an adhesive providing both structural stiffness and a level of protection due to the inherent division of cells. Level 1 consists of 18 sliders, or four strings of 18 modules, a total of 288 cells.

The overall geometric structure of the battery pack named level 2 was generated to house the volume of cells and measures 0.84 x 0.41 x 0.38 m^3. The pack weighs approximately 70 kg and features half inch polycarbonate. See structural analysis for further explanation of the strength requirements and joint analysis. See Thermal Management System Design for an Electric Vehicle Battery-Pack for an in depth analysis the thermal management and cooling considerations of the pack.

Atop level 1 of the pack lies the main shelf that physically divides the internal space of the pack into two halves. The shelve houses the level 3, which contains the main wiring harness and electrical system within the pack. The fuses and contactors are bolted onto the lid, separated from the cells. The shelf has a series of holes to allow the positive and negative leads of the modules into the area above the shelf. This allows for easily connections of all modules in series and in parallel. In addition, these holes guide air flow through the batter pack in order to keep the cells at the optimum operating temperature.

Assembly of the battery pack begins with level 1 in which the slider packages are aligned atop the base plate. The battery enclosure, level 2, minus the top lid are bolted in. Notably, the face of the pack parallel to the face of the modules is the final assembly piece of level 2. The panel is screwed in slightly compressing level 1. The shelf drops into place above the sliders and the pack is then ready for electrical assembly. Figure 15 shows a CAD rendered image of the fully constructed battery pack.

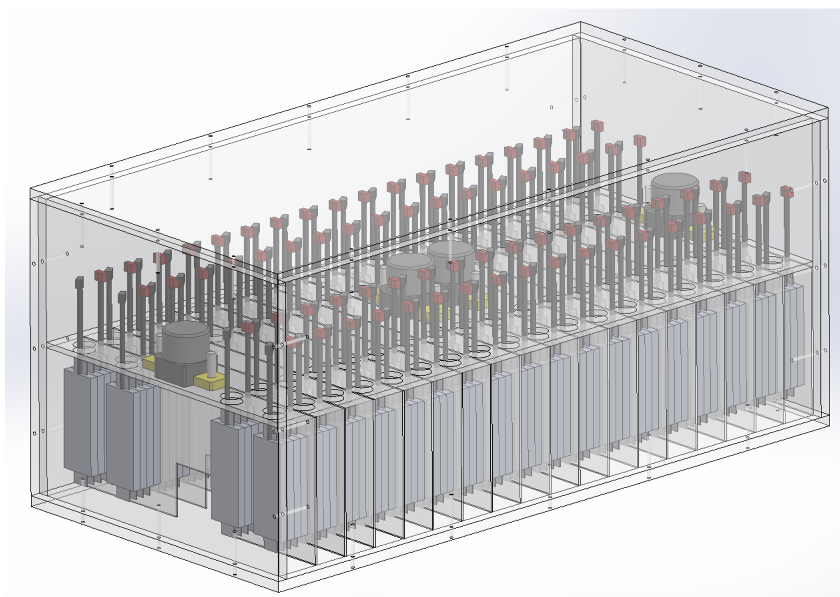

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Figure 15: CAD rendered image of the fully constructed battery pack with all slider packages and contactors.

Appendix A shows detailed drawings of all manufactured battery enclosure components.

The material chosen to construct the battery enclosure was polycarbonate plastic. The benefits of using polycarbonate over traditional plastics are that polycarbonate has superior impact strength as well as better electrical properties. Polycarbonate has a high electrical resistivity, which makes it beneficial as a battery enclosure because this prevents any high voltage from escaping to the environment. Polycarbonate is also a very durable material and extremely ductile; under yielding conditions, the material resists shattering. This makes it ideal in our application, where protecting the contents of the enclosure, preventing contents from escaping the enclosure, and preventing the enclosure from creating harmful debris is essential.

Oftentimes, polycarbonate is used in applications where bullet-proof windows are required. A half-inch thick sheet of polycarbonate absorbs the impact of the bullet, deforming plastically at the impact site, resisting a brittle failure. Polycarbonate can be used for a broad range of applications which makes it a very versatile material. Another reason why Formula Electric decided to go with polycarbonate is due its strength to density ratio which is very high for a plastic. This will allow us to have a strong battery enclosure while still being relatively low weight. The Ultimate Tensile strength of polycarbonate is 65 MPa and the ultimate shear strength is 69 MPa. The material properties for the polycarbonate being used can be found in Appendix E. The polycarbonate that will be used for the battery enclosure will be fireproof, which in the case of an accident, prevents potentially dangerous battery cells from igniting the enclosure.

Steel screws were chosen due to their high strength properties including a yield strength of 240 MPa. Steel screws are relatively inexpensive and are also a very strong. It can be seen throughout results that when under extreme loads, the polycarbonate would fail before the steel screws.

5.4 System Analysis

5.4.1 Previous Design Iterations

Two battery pack enclosure designs were proposed. The first design assumed that the battery pack enclosure panels were secured using a tab and slot system. This design assumed that no screws were used to secure the panels together, and that the force due to the acceleration would be absorbed by the tabs as shear and normal stresses. The tabs provide very desirable strength insurance, especially in the application of a race car. However, the tabs require significantly more manufacturing time and could add a potential source for cracking if not machined properly.

The second design used only screw fasteners to secure the panels together without the tab and slot system. In this design, the force due to acceleration would be absorbed by the screws as a shear stress.

The two designs were analyzed based on the manufacturability, weight and strength of each design. Strength is the most important determining factor as it directly pertains to the system requirements. Manufacturability is the second most important factor, as ease of manufacturability is important due to the limited time scale. The team estimates the weight differential between the extra screw and polycarbonate to be very small and consequently least important.

This report explains the calculations to determine the how each design behaves under load. It explains how many screws are necessary to possess the strength necessary to hold together in the case of a high acceleration. In addition, the calculations used to determine the appropriate size of the screw and screw thread are explained.

The enclosure will consist largely of polycarbonate sheets which offer substantial strength properties as well as relatively desirable conductivity qualities for safety. However, the teams research of the material in similar applications where polycarbonate had been drilled and tapped heavily led us to have cracking and manufacturing concerns. Consequently, the enclosure design drew debate regarding a particular structural detail of the walls. Tabs external to the typical rectangular profile were added in order distribute the forces through the box in the case of a high G turn or acceleration. Figure 16 shows the front panel profile with tabs.

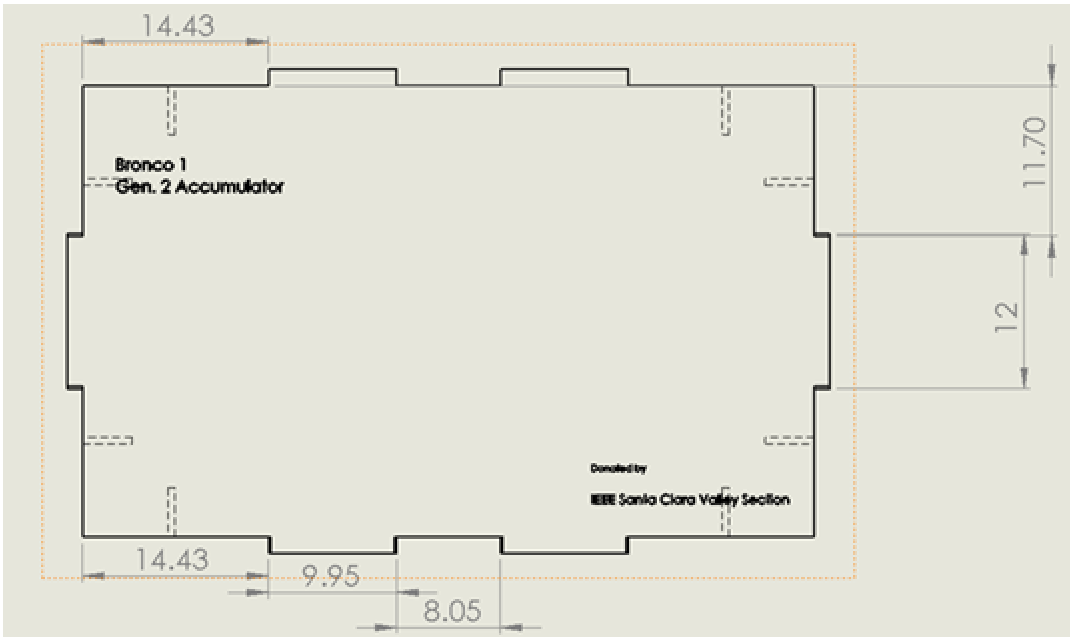


Figure 16: Part drawing of the battery pack front panel with tabs.

In order to simulate the enclosure and analyze potential failure points, the team utilized a combination of software including Matlab, Solid Works Simulation Express, and Ansys Workbench, as well as hand model calculations.

5.4.2 Structural Analysis

The mass of the battery enclosure was approximated to 80 *kg*; however, a mass of 100 *kg* was assumed to account for any additional mass. The SAE International Rules state that the battery enclosure has to be able to withstand a $20g$ acceleration frontal force and a $10g$ acceleration force from the side. The $20g$ acceleration would typically occur during heavy braking, frontal impact or side impact. The $10g$ force from the side would typically occur when the car is turning sharply, due to a shift in momentum. When a car takes a left turn the momentum of the car and its contents tend to put forces on the right side of the car; the momentum of the car wants to keep it moving forward.

In order to begin a structural analysis of the battery enclosure, the external forces were determined. In order to determine the effect these forces would have on the walls of the enclosure, the strength of the material compared to the stresses being imparted on it had to be considered. In order to determine the stress on the front panel of the battery enclosure the panel was assumed to be a flat plate clamped on two edges. Figure 17 shows a flat plat simplification model; Equations 1 and 2 show the maximum stress and maximum deflection of a flat plate under load, respectively.

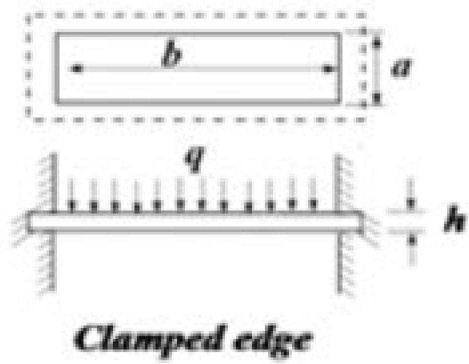


Figure 17: Flat plate supported by clamped edges.

$$\sigma_x = \frac{qa^2}{2h^2\left[0.623\left(\frac{a}{b}\right)^6 + 1\right]}\ at\ x = \frac{a}{2},\ y = 0 \tag{1}$$

$$\nu = \frac{0.0284qa^4}{Eh^3\left[1.056\left(\frac{a}{b}\right)^5 + 1\right]} \tag{2}$$

q is the distributed load; *a* is the width of the plate; *b* is the length of the plate; *h* is the thickness of the plate; and *E* is the modulus of elasticity of the plate material

These assumptions were made because the front panel would experience the full force due to the acceleration mass of the battery cells as well as the mass of the battery pack enclosure. This means that the panels cannot rely on its adjacent panels for support. The only opposing forces in this case come from threaded fasteners oriented parallel to the driving direction. This simplification made it possible to determine the maximum stress and deflection at the center of the plate with relative ease.

In terms of CAD and FEM software, various assumptions including fixed geometries and structural substitutions helped accelerate the analysis while not significantly affecting results. FEA software offers great power in evaluating systems, but it is important to understand the context of analysis and the nature of estimation. While applying loads to pack panels, screw holes served as locations of fixed geometry in order to mimic the panel joint within the greater assembly. The load applied to the panels summed safety factors of three and worst possible cases to further ensure the system and to account for any more margin of error. Lastly, all FEA models were executed with parts, not assemblies. Loads were applied to contact regions of the part, simulating the loading effects of the assembly.

Figures 3 and 4 depict free body force diagrams (FBD) of the battery enclosure and the screws, respectively, with loads corresponding to the $20g$ and $10g$ forces that are applied to the enclosure in such cases.

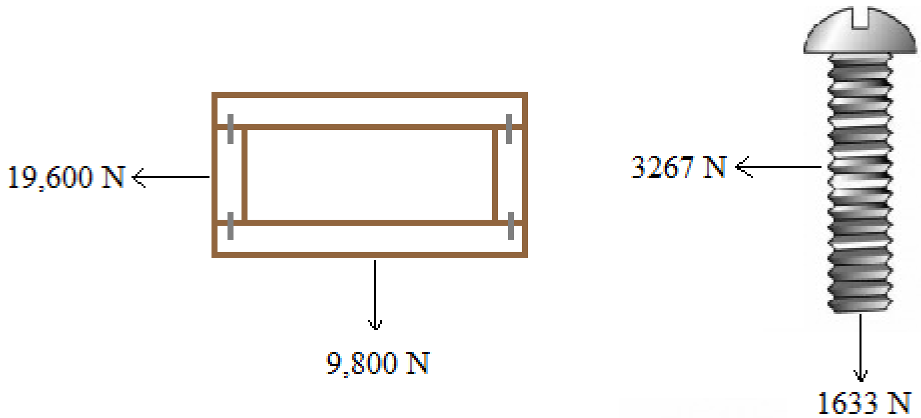


Figure 18: Free body diagrams of front panel and on individual screws.

The force due to the 20G acceleration was defined as:

$$F = g_{dec} m \tag{3}$$

where g_{dec} is 20 times the gravitational acceleration constant 9.81 m/s^2 and m is the total mass of the enclosure.

The area of the distributed load on the front plate was defined as:

$$q = \frac{F}{ab} \tag{4}$$

where a is the height of the plate and b is the width of the plate. The maximum stress σ was found using Equation 1, and the maximum deflection ν was found using Equation 2. Solving these equations gives the maximum stress and maximum deflection of the plate:

$$\sigma = 3.0118x10^7\ Pa$$

$$\nu = 8.416x10^-7\ m$$

the MATLAB scripts gave equivalent values.

The shear area for the external threads on the screw was determined using equation 5

$$A_s = \pi n L_e K_n \left[\frac{1}{2n} + 0.57735(E_s - K_n)\right] \tag{5}$$

Where n is the number of threads per millimeter; L_e is the length of the screw; K_n is the maximum minor diameter of the interal threads; and E_s is the minimum pitch diameter of the external threads.

The shear area for the internal threads was found using equation 6:

$$A_n = \pi n L_e D_s \left[\frac{1}{2n} + 0.57735(D_s - E_n) \right] \tag{6}$$

Where D_s is the minimum major diamter of the external threads; E_n is the maximum pitch diamter of the internal threads; and all other variables are the same as above.

The stress σ_e on the external threads was calculated with equation 7:

$$\sigma_e = \frac{F}{b_{num} \frac{A_s}{10^6}} \tag{7}$$

Where b_{num} is the number of screws. The stress σ_i on the internal threads was calculated using equation 8:

$$\sigma_e = \frac{F}{b_{num} \frac{A_n}{10^6}} \tag{8}$$

Solving these equations using three screws and a factor of safety of 5, the stress on the external threads σ_e was found to be:

$$\sigma_e = 3.678x10^{10}\ Pa$$

The stress on the internal threads σ_i was calculated to be:

$$\sigma_e = 2.749x10^{10}\ Pa$$

Both values were consistent with the MATLAB scripts.

Next, calculations to determine the force on the tabs and slots of the panels were used. Only the tbs of the front panel were analyzed, as those tabs experience the highest stress of any tabs. The following assumptions were made:

- The force incident on the tabs was distributed equally among all the tabs, and that the front tab of the enclosure would experience the highest magnitude stress.
- No screws were incorporated in the design.

The design uses two sizes of tabs. Figure 19 shows the front panel with the two sizes of tabs.

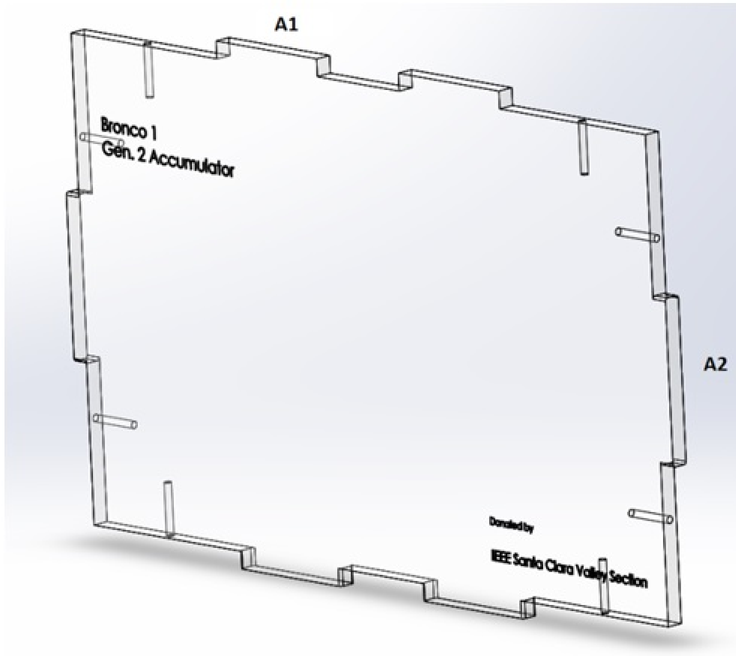


Figure 19: Battery pack front panel. A_1 denotes shearing area of the smaller size tab, while A_2 denotes shearing area of the larger size tab.

The shearing areas are equal to:

$$A_{s.1} = (0.0127\,m)(0.0995\,m) = 1.26x10^{-3}\,m^2$$

$$A_{s.2} = (0.0127\,m)(0.0995\,m) = 1.26x10^{-3}\,m^2$$

The mass of each tab is negligible compared to the pack itself, so gravitational weight force was assumed negligible. The average shear stress in each tab was calculated using Equation 9

$$\tau = \frac{V}{A_s} \tag{9}$$

Where V is the shearing force. This equation was assumed sufficient to calculate shear as the shearing area of the tab is small. In addition, the each tab is much wider than it is longer, thus the shear stress would be significantly greater than the bending stress. The total are is equal to the sum of the shearing areas of each tab:

$$\Sigma A = 4(A_{s,1}) + 2(A_{s,2})$$

$$\Sigma A = 4(1.26x10^{-3}\,m^2) + 2(1.20x10^{-3}\,m^2)$$

$$\Sigma A = 8.08x10^{-3}\ m^2$$

The shearing force in the tabs was caclulated as:

$$\tau = \frac{20mg}{\Sigma A} = \frac{20(100\ kg)(9.81\ m/s^2)}{8.08x10^{-3}\ m^2} = 2.48\ MPa$$

The shear yield strength of polycarbonate is 33 *MPa*. With a factor of safety of 3:

$$\tau \leq \frac{\sigma_{sp}}{N_{fs}}$$

$$2.48\ MPa \leq \frac{33\ MPa}{3} = 11\ MPa$$

THus, the tabs are safe from failure by shearing.

Next, the slots themselves were analyzed in order to determine if the brackets that secure the tabs would fail. Figure 20 shows the slots that would secure the front panel tabs.

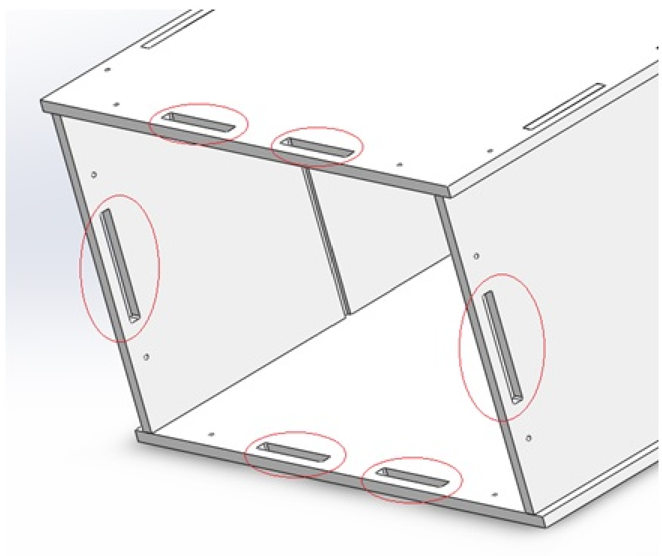


Figure 20: Battery pack enclosure with front panel removed. Red circles show where tabs from panel fit.

The weakest part of the structure is the thin, rectangular sections that hold the tabs in place. Thus, it was assumed that these sections were in the most danger of failing under load. Te maximum distortion energy theory of failure was used to determine whether these sections would fail.

In order to use the maximum distortion theory of failure, the following additional assumptions were made to analyze the tab holes:

- The tabs were under a biaxial state of stress. A biaxial state of stress is described by Figure 21:

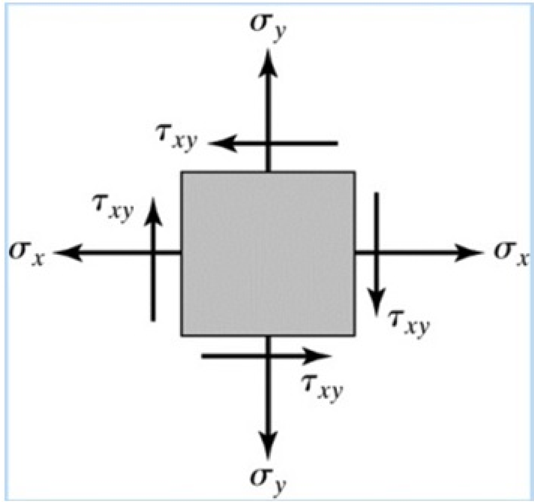


Figure 21: Depiction of an object under a biaxial state of stress.

- $\sigma_y = 0$.

First, the normal stress and shear stresses were determined:

$$A_n = 4(0.0127\,m)(0.0995\,m) + 2(0.0127\,m)(0.120\,m = 8.10x10^(-3)\,m^2$$

$$A_s = 12(0.0127\,m)^2 = 1.94x10^(-3)\,m^2$$

Using these areas, the normal stress σ_x and the shear stress τ_{xy} were calculated:

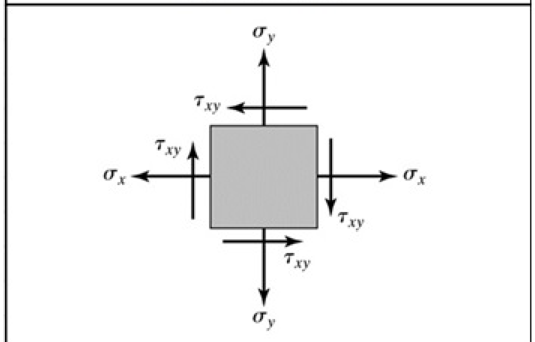
$$\sigma_x = \frac{20,000\,N}{8.10x10^{-3}\,m^2} = 2.47\,MPa$$

$$\sigma_x = \frac{20,000\,N}{1.94x10^{-3}\,m^2} = 10.3\,Mpa$$

The principle stresses S_1 and S_2 were then determined using Microsoft Excel macros, depicted in Figure 22.

Module 1-4
Biaxial Stress Computations
(Mohr's Circle)

This module finds the principal normal stresses for a 2-d stress tensor.



Input the stress components:

S_x =	2.47	MPa
S_y =	0.00	MPa
t_{xy} =	10.30	MPa

The principal normal stresses are:

S_1 =	**11.61**	**MPa**
S_2 =	**-9.14**	**MPa**

Figure 22: Excel macro that calculates principle stresses S_1 and S_2 for a biaxial state of stress.

The principle stresses were then implemented into a second excel macro to determine if the hole sections fail under the maximum distortion energy theory of failure, shown in Figure 23.

Module 2-4
Maximum Distortion Energy Theory of Failure

$$(S_1^2 + S_2^2 + S_3^2 - S_1 S_2 - S_1 S_3 - S_2 S_3) \leq \left(\frac{S_{yp}}{N_{fs}} \right)^2$$

Input the principal normal stresses and their units:

S_1 =	11.61	MPa	
S_2 =	-9.14	MPa	
S_3 =	0	MPa	

Input the Yield point and the Factor of Safety:

S_{yp} =	33	MPa	(Yield Strength)
N_{fs} =	3	MPa	(Factor of Safety)

The result from the failure equation is:

Left-hand side =	**3.24E+02**
Right-hand side =	**1.21E+02**
Status =	**Fails**

Figure 23: Excel macro that calculates if stresses are within acceptable ranges for the maximum distortion energy theory of failure.

Figure 23 shows that the stresses are not within acceptable ranges, and by the maximum distortion energy theory of failure, the slots would fail. Thus, a new enclosure was designed to make use of screws rather than a tab and slot system.

The calculations done to determine the necessary fixtures to maintain the structural integrity of the battery enclosure yielded a variety of options. By utilizing a MATLAB script to determine the thread strength, it was easy to run the calculations many times for variations in screw size and number of screws to see what factors of safety were possible in various screw configurations. Table 5 shows the data from this MATLAB script, and whether the polycarbonate threads will fail under the assumed load for varying numbers of screws and factors of safety.

Table 5: Screw thread shear strength results.

Run #	Length of threaded connection (mm)	# of screws in plate	Screw Class	Factor of Safety Nfs	Polycarbonate thread Safe/Fails
1	35	6	M3	2	Safe
2	35	6	M3	3	Fails
3	35	8	M3	3	Safe
4	35	8	M3	4	Fails
5	35	6	M4	3	Safe
6	35	6	M4	4	Fails
7	35	8	M2	2	Safe
8	35	8	M2	3	Fails

These results showed that even with as few as eight M3 screws or six M4 screws, a factor of safety of 3 was possible. This is promising as the number of screws included in this analysis is only representative of a portion of the total screws that will be present in the panel. By running the analysis for the least supportive situation, it ensures that the enclosure will withstand the necessary strength requirements.

A second script was then utilized to determine the structural integrity of the screws in shear loading. This script determines the deflection and the maximum stress on the front panel due to the $20g$ acceleration force. This script was then run as a function of the screws necessary to withstand the acceleration force and the corresponding factor of safety. Table 6 shows the results showed the safe yet relatively low factor of safety orientation of M3 screws.

Table 6: Screw Shear Strength Results for a 35 *mm* M3 class screw.

Run #	# of screws in plate	Factor of Safety N_{fs}	Safe/Fails
1	4	1	Safe
2	4	1.5	Fails
3	6	1	Safe
4	6	1.5	Safe
5	6	2	Fails
6	8	2	Safe
7	8	2.25	Fails
8	8	2.5	Fails

The MATLAB scripts used to generate these results are shown in Appendix G.

In terms of the FEM analysis, the programs produced results that concurred with the MATLAB scripts, reinforcing our conclusions. Two Solidworks Simulation Express programs were used to evaluate tab deflection and panel deflection. Panel supports were placed at screw locations and a distributed static load of 19,000 N was placed on the face of the panel. The panel deflected a maximum of 5 *mm*, concentrated mainly in the center, show in Figure 24. A second program placed a load on the tab profile of the panel in order to find at what point the structures would shear. As it turns out, the tabs deflected a maximum of 1 *mm* at the very edge of the corner. Through the Solidworks simulations, the enclosure the deflection of the tabs and panel proved rather minor and ultimately safe.

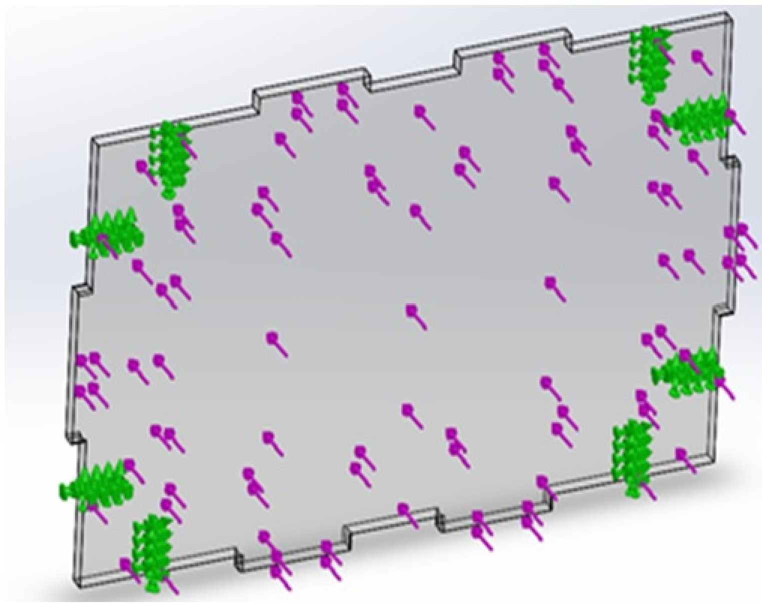


Figure 24: Solidworks Simulation Express model of panel and tab deflection. Figure shows loading conditions (purple) as well as fixture conditions (green).

In addition, an Ansys program evaluated the tab slots and a second program evaluated deflection to compare results to the Solidworks Simulation Express. The deflection case from the Solidworks Simulation was recreated in Ansys to maintain consistency in terms of supports and loading. The program yielded a maximum deflection 10 *mm*, double the deflection of the Solidworks program. Interestingly, the step function applied the 19,000 *N* load for 1 second. The load was static, but on impact of the force, the material deflected only 2 *mm*, eventually increasing to 10 *mm* as the load applied for the full second. The experiment demonstrated the impact resistance of the polycarbonate which is a highly desirable quality in a racecar susceptible to high impact crashes. Despite the doubled deflection, the Ansys results did not prove the failure of the system. The final program sought to determine the viability of the tab slots. A 10,000 *N* load was distributed within a single slot with the greater structure supported at the screw holes. Unfortunately, the slots proved unfit to handle the load of the worst case scenario. Figure 25 shows the Ansys evaluation of slot failure.

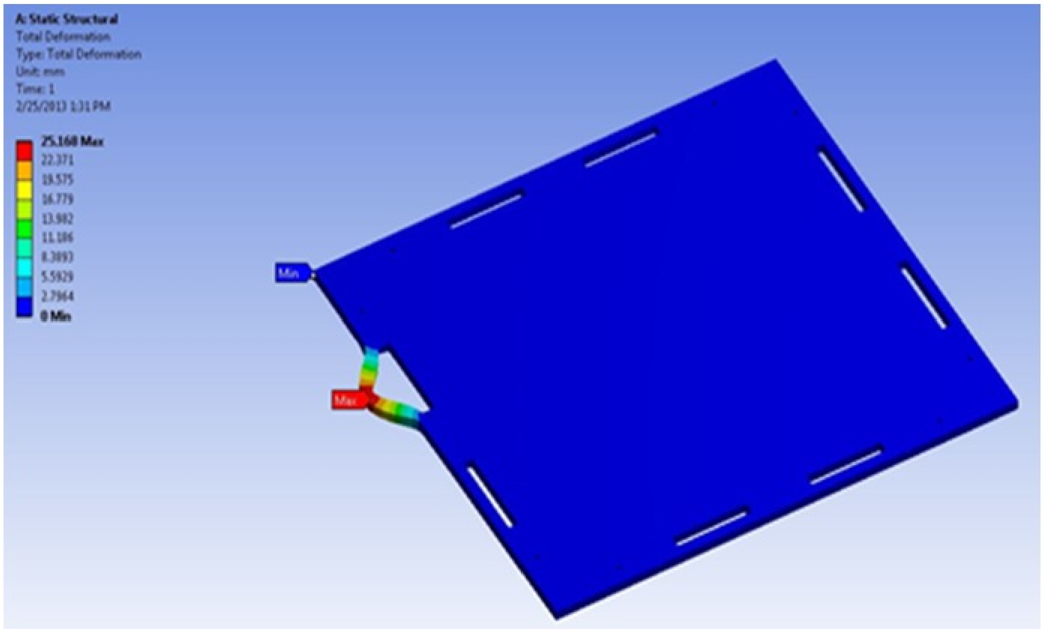


Figure 25: Ansys Workbench evaluation of the slot deflection. Blue shows minimum stress, while red shows maximum stress.

The results from both the manual calculations and the finite element model analysis show that the tab and slot system design is not acceptable. The tabs themselves would not shear under the assumed 20g acceleration. However, the brackets that secure the tabs in place would fail under the assumed load. Thus, the tab design is unsuitable for the battery pack enclosure design and will not be used.

Calculations show that the screw fastener system design is safe with a high factor of safety. The MATLAB screw analysis scripts show that the correct number of screw can safely secure the panels together. Using the data shown in Table 5 and Table 6, a screw fastener design can be decided upon that maximizes the structural integrity of the battery pack enclosure.

The analysis report introduced many team members to finite element software for the first time. Attempting to figure out how to use the software itself was a learning experience.

This analysis processes demonstrated the importance of clear and organized note taking in conjunction with the MATLAB script. Since the script was written in the order of several days, it was important to keep a clear record of all variables and equations used, not only for the sake of writing a properly functioning script, but so that future users can understand and use the script easily. The integration of comments on each line of the script also legitimizes our calculations; people reviewing the calculations are able to see an explanation and sometimes a source. This was found to be particularly effective, especially when explaining calculations.

It was initially assumed that a 20g acceleration would have detrimental effects on the structural integrity of the box. It was initially assumed that the tabs in conjunction with screws was the only way to keep it from falling apart. However, the battery pack enclosure would hold up quite well and with high factors of safety with just screws. The calculations show that a tab and slot design does not exhibit acceptable structural integrity. In addition, by removing tabs and slots from the design, the manufacturing time per panel was reduced significantly.

The next step is to put a new design into finite element analysis software. The analysis done in Ansys Workbench and Solidworks accounted for a design with tabs. The next step would be to do the same software analysis on a box with no tabs; a box with the optimum number of screws and screw diameter calculated from the script.

5.5 Conclusion

6 Thermal Management

6.1 Requirements

This section presents the thermal management analysis performed on lithium polymer cells designed for High Performance Electric Vehicle (HPEV) applications. The objective was to choose an optimum temperature range for the cells to operate at, determine the thermal response of the cells under their full spectrum of discharge capabilities, calculate the necessary convective heat transfer necessary to maintain the cells within said temperature range, then to create a thermal management solution to incorporate into a battery pack composed of 288 cells. Thermal testing and modeling on individual lithium polymer cells determined the total heat generation and amount of convection cooling required for the cells over their intended duty cycles. A convective heat transfer coefficient of 50 W/m^2K was determined to be sufficient to prevent the proposed cell from exceeding the optimum temperature range during its most strenuous duty cycle. The design scheme utilized a fan to force air circulation up along the side of modules, where each module consists of four cells connected in series. A proposed feedback control loop system allowed for active control of the battery cells temperature resulting in an increase in efficiency and overall performance for HPEV applications.

6.2 Conceptual Design

During operation, lithium polymer pouch cells generate heat as a function of the electrochemical process of the cell and other parameters including heat capacity, discharge rate, discharge duration, and internal impedance [18]. The discharge profile and efficiency of a lithium polymer cell increases with temperature while the number of life cycles decreases with temperature; hence there existed an optimum operating temperature range to ensure the cell performed up to specifications and maintained a life expectancy that met the design requirements. The temperature distribution of the battery pack is also important, as an uneven temperature profile can lead to different discharge behaviors of cells in different regions of the battery pack, which hinders performance and prevents proper battery pack operation and control [11]. Since temperature has a direct effect on the performance of a lithium polymer cell during discharge, an even temperature distribution of all cells is vital to the overall performance within the battery pack. The thermal management system was designed to maintain an even temperature distribution of the cells and to prevent the battery cell temperatures from exceeding the proposed temperature range.

The thermal response data of the proposed lithium polymer cells was not readily available. This made determining the thermal behavior of the proposed cell arrangement more difficult. It was decided not to solve the problem with an analytical approach due to the high level of abstraction needed to obtain a usable model. An experimental approach was chosen in order to most accurately model the system and provide usable data in developing a battery thermal management system. The following sections will discuss the thermal testing and modeling conducted in order to achieve a suitable thermal management solution.

The list of cell specifications used can be found in Appendix B. The manufacturer suggests the cell is safe to operate between -254 to 334 *K* (-20 to 60 °C). First, it was determined whether the cell would exceed the manufacturers recommended operating range during the strenuous operation the application demanded. Then, the required amount of convective cooling it would take to maintain the cell within the optimum temperature range during said discharge cycles was determined. Ideally, to optimize performance, the cell should be maintained at a temperature near the upper bounds of the manufacturers specifications. As temperature increases, the internal impedance and overall cell efficiency increases; however, the life expectancy of the cell is greatly reduced as it operates at this upper bound. This life expectancy issue demands attention. Although a cell will perform better as temperature increases, it does so at a cost. With these characteristics in mind, it was decided that the optimal operating temperature range was 298 to 308 *K* (25 to 35°C) [18]. This provided an overall efficient battery pack while still providing hundreds of charging cycles, ensuring the cells will meet their expected design criteria.

6.3 Thermal Modeling

Lithium polymer cells generate the most heat at their positive and negative terminals due to contact resistances [11]. Through experimentation, these findings were confirmed for the lithium polymer pouch cell considered. This region of the cell is where experimental temperature measurements during cell discharge were measured.

The next step taken was to determine the necessary amount of heat transfer to maintain the lithium polymer cell temperature within the desired range. As the discharge rate of the lithium polymer cell increased, heat generation also increased due to the effects of the cells electrochemical process. Duration of discharge was also an important factor in shaping the cells transient temperature profile.

The proposed thermal management solution was to use fans to set a convective heat transfer coefficient h, resulting in a higher heat transfer rate into the environment. The variable chosen to control the heat transfer coefficient was the volumetric flow rate of the fan. Using the volumetric flow rate as a variable was beneficial as it could be controlled by varying the voltage input to the fan. Equation 10 below shows the relationship between h and the amount of heat transfer occurring at the cells frontal surface area A [7].

$$Q = hA\Delta T \tag{10}$$

The first step toward determining the convective heat transfer coefficient was to determine which variables could be manipulated in order to change the h value. A relationship of the velocity of the airflow over the cells frontal surface area to the h value was determined by use of Equations 11 and 12. A diagram of the air flow path over the battery cell can be seen in Figure 26.

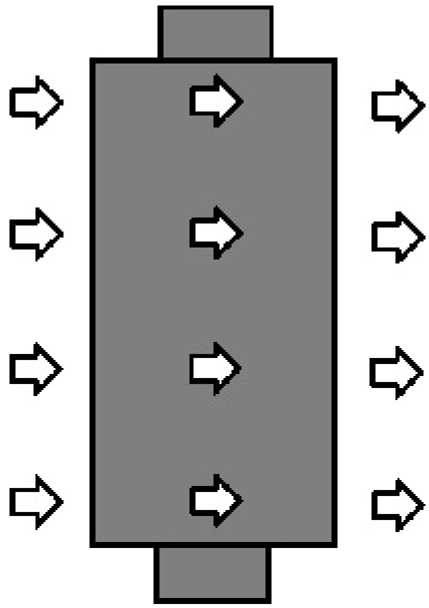


Figure 26: Top view of the air flow path over the frontal surface area of the battery cell.

In Equation 11 the length *L* corresponds to the width of the cell that was contacted by the flow of air. In Equation 12 the velocity was found by relating the mass flow rate of the fan to its cross sectional area. Equation 12 shows the Nusselt number equation for turbulent flow [4].

$$h = \frac{Nu * k}{L} \tag{11}$$

$$Nu = 0.037Re^{8}Pr^{0.43} \tag{12}$$

6.4 Experimental Setups

An experiment was setup to analyze the cells thermal and electrical characteristics under load. For discharge currents below 30 *A*, a computerized battery analyzer (CBA) was used. The CBA maintained a pre-set current, which was useful during early testing to minimize the number of variables influencing the thermal response. By removing the effects of varying current on the temperature profile, a clearer transient temperature response was found. This setup gave experiment provided data while the cell was discharging. The discharge test was programmed to cut off the voltage when it reached 2.8 *V*, the cell voltage cutoff point specified by the manufacturer.

The CBA discharge test resulted in an orderly and uniform temperature growth profile, demonstrating the cells heat generation with respect to time. As mentioned earlier, all experimental temperature data was recorded at the cells maximum temperature; that is, the temperature at the base of an arbitrary cell terminal.

In order to investigate the effects of induced convection heat transfer, a brushless fan was connected to a DC power supply, where changing the voltage controlled the fan speed, which varied the free stream velocity across the frontal surface area of an arbitrary side. Only one side of the cell was exposed to convective cooling; the other side was thermally insulated, shown in Figure 27. An array of convective heat transfer coefficients was calculated and their effects on the temperature growth profile of the sample cell were determined. It became quite evident that convective heat transfer greatly affected the rate of temperature growth of a cell during discharge.

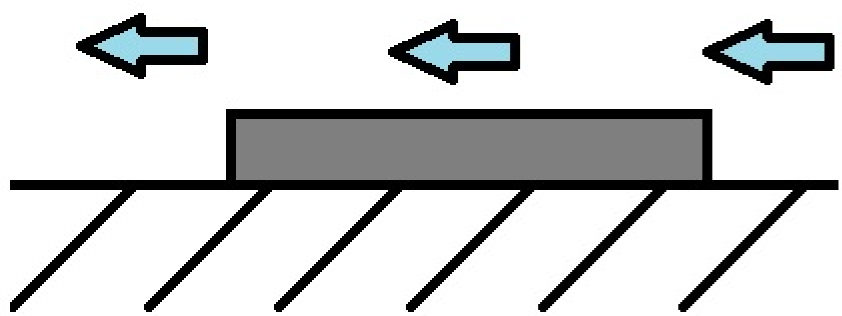


Figure 27: Side view of the air flow pattern over a battery cell during CBA testing. Blue arrows represent air flow.

Although the CBA provided a constant current test bench for discharge rates below 30 *A*, in order to fully understand the thermal response of a cell, it was vital to examine the temperature growth at all the discharge rates that are possible. Since the lithium polymer cells are capable of providing a continuous discharge rating equal to 108 *A*, a method of discharging the sample cell at higher current rates was necessary to develop a similar temperature growth pattern.

A test bench was developed that permitted such experiments. Four resistors were connected in parallel to a busbar in which the sample cells terminals were clamped. Each resistor was designed to dissipate a specific amount of energy as heat. A new resistor design was necessary as conventional resistors of this Ohm rating are not capable of dissipating the energy required for this experiment. Each resistor was composed of a length of 18 American Wire Gauge (AWG) solid core non-insulated wire wrapped into a coil pattern whose ends were soldered to 4 AWG stranded wire. Each resistor was submerged in water up to its solder joints in order to dissipate the heat as high current passes through it. Since the 4 AWG wire has negligible resistance at short lengths, it did not produce nearly as much heat; therefore, it could be insulated and used to connect the busbar to the 18 AWG resistors. Figure 28 shows an electrical schematic of the test bench. Figure 29 shows a picture of the constructed test bench.

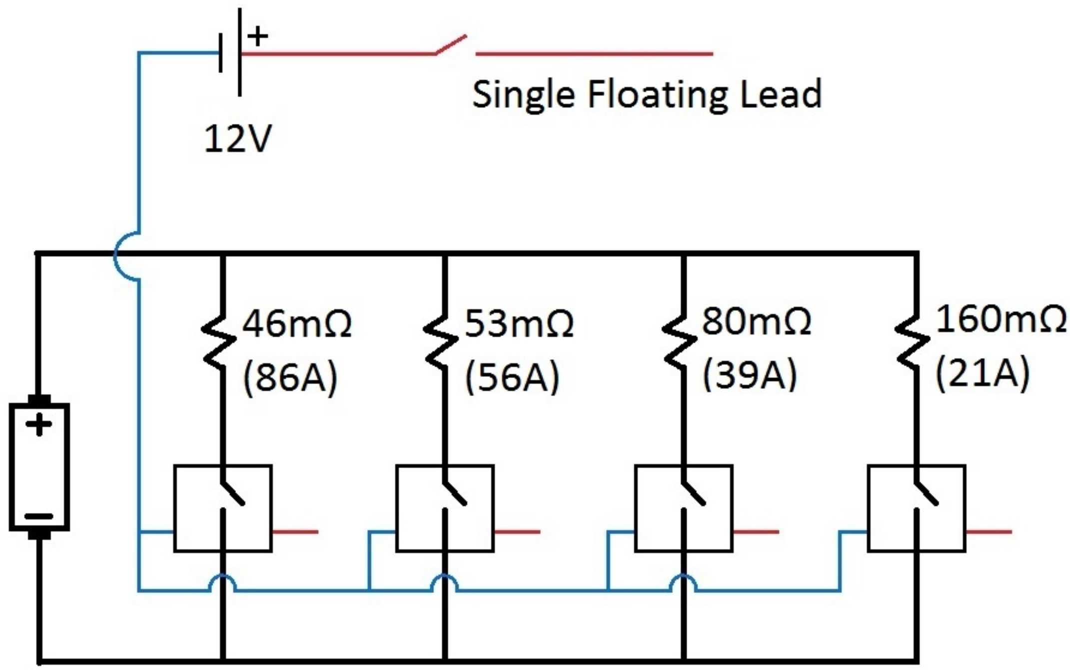


Figure 28: Electrical schematic of a variable resistor current discharge test bench. The single floating lead closes the 12 V loop to power each contactor.

Figure 29: Picture of the constructed test bench.

Each resistor was connected in series to a contactor, which made it possible to switch between resistors by turning on or off the contactors. All four contactors were powered by the same 12 V DC power source. A single floating lead off the positive terminal of the 12 VDC power source ensured that only one contactor could be closed at a time. Each resistor, 37, 60, 92, and 167 $m\Omega$, corresponds to average currents 86, 56, 39, and 21 A respectively. This gave a broader spectrum of discharge rates than the CBA could provide.

The method of measuring maximum cell temperature remained unchanged from the CBA to the new test bench. Although the variable discharge current test bench could not maintain a constant current throughout, it was sufficient in providing a thermal response under heavy load.

Since the cell current can be adjusted on the time scale of seconds, the next step is to more accurately simulate the intended real-world application. The throttle mapping of the acceleration pedal of a racecar is proportional to the current draw profile of the proposed battery pack. The SAE Formula Electric competition has several different events: endurance, acceleration, autocross, skidpad, and efficiency competitions. Each of these competitions has a unique throttle map, which in turn, results in a different discharge profile of the battery pack. The variable discharge current test bench gave a way to more closely simulate these discharge profiles and get more accurate thermal modeling of the battery pack under realistic loads.

The first discharge profile simulated was an acceleration test. When a vehicle of a given mass has zero initial velocity, the motor controller is designed not to pull maximum power from the battery pack. If it were to do so, there would be an excess amount of torque, which would cause loss of traction or even stress failure of drive shaft components. Instead of this step input, the motor controller provides a ramp-like current output, which was simulated by discharging the sample lithium polymer cell in sequential steps of 21, 39, and 56 A for 15 seconds each and then discharging it at 86 A until the cut-off voltage was reached. This was done in increments of 15 seconds as this best reflects the time it would take for the vehicle to reach each of these current ratings. The test bench was only equipped with four resistors which influenced the step input time increments as well. Further SAE competitions were replicated by adjusting the sequence and duration of resistor connections.

6.5 Results and Discussion

This section will discuss the results of the lithium polymer battery discharge tests and the thermal management design solutions that were developed as a product of these results. The results of the constant 30 A discharge cycles can be seen in Figure 30, which displays the temperature development over the duration of the discharge.

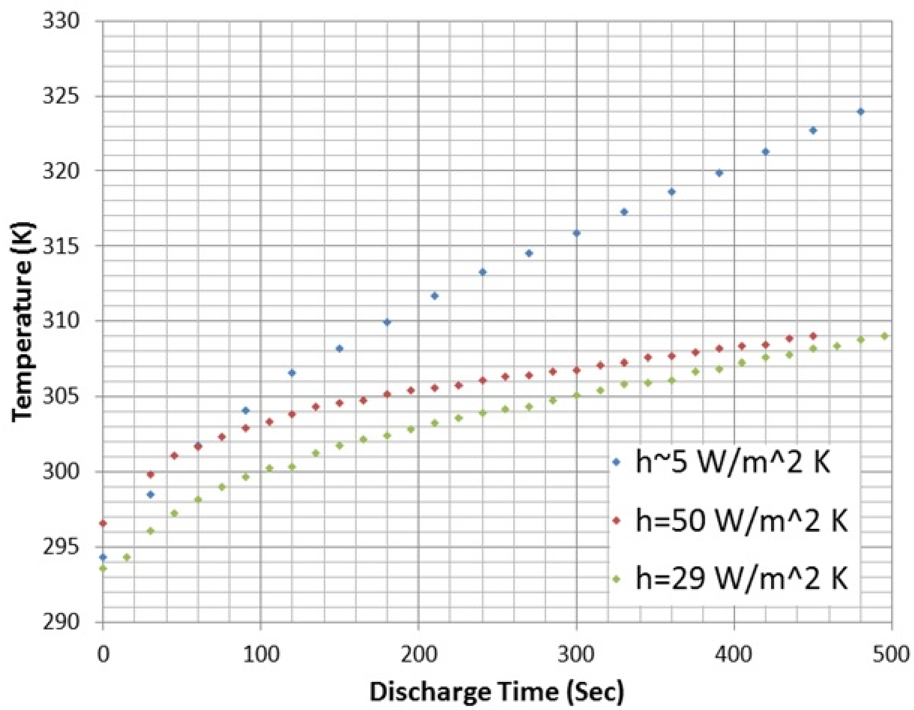


Figure 30: Experimental data from CBA of maximum cell temperature versus duration of discharge at a constant 30 A discharge current.

The temperature readings taken with a free stream velocity perpendicular to the cell terminal were substantially lower than the readings taken without the fan. These results emphasized the importance of a thermal management system, as the cell exceeded the optimum temperature range when not being actively cooled.

Separate experiments were run using the test bench to obtain the temperature, voltage and current profiles over the duration of a cells discharge cycle. These results are displayed in Figures 31 through 33.

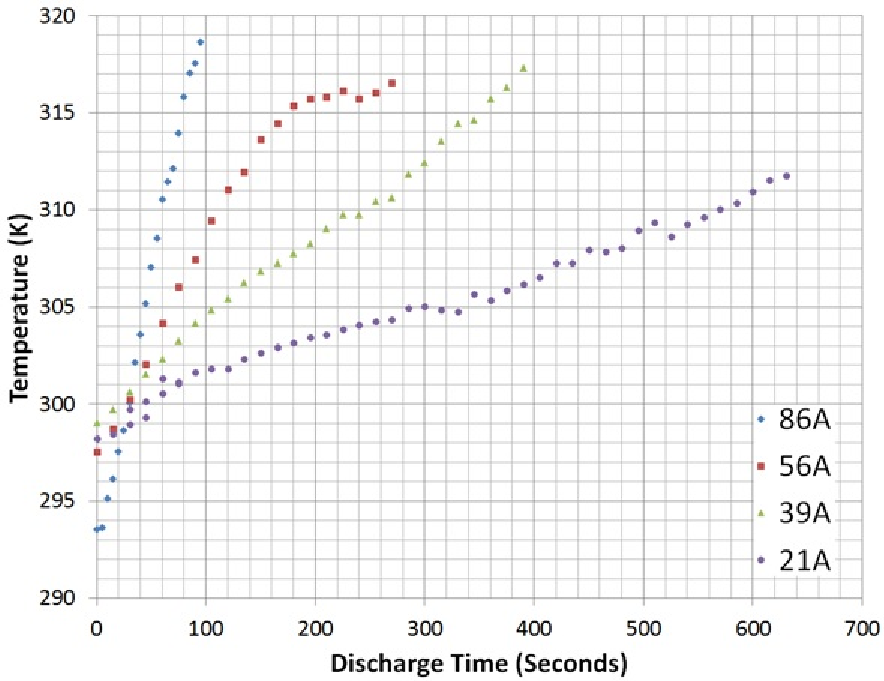


Figure 31: Experimental temperature vs time data from cell discharged at different resistances.

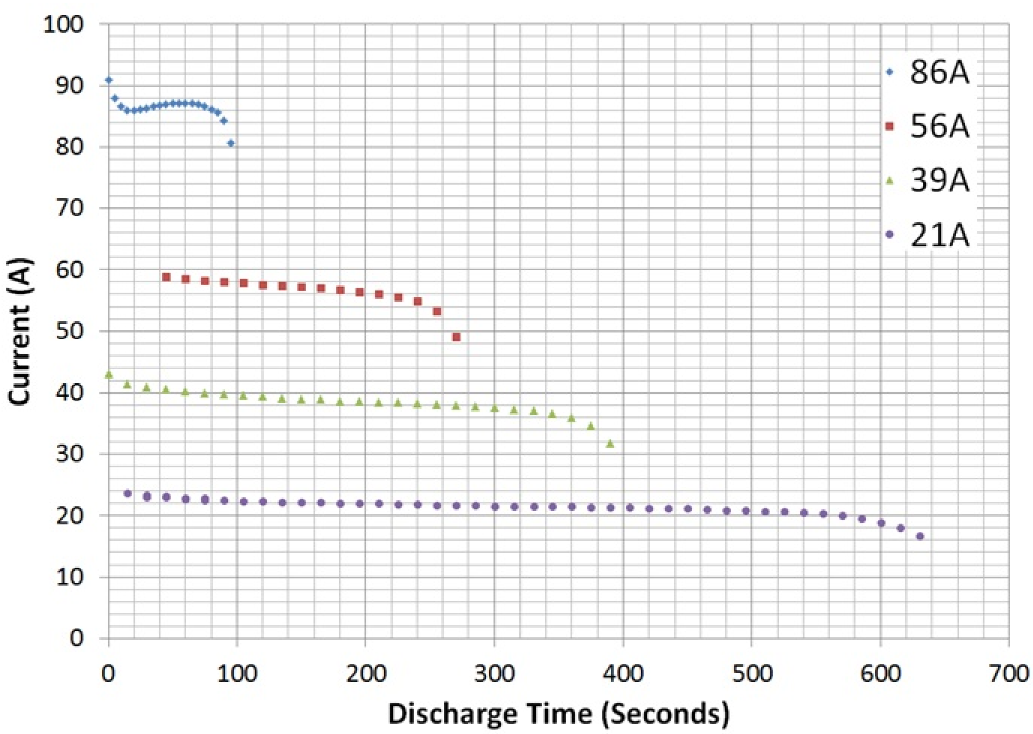


Figure 32: Experimental current vs time data from cell discharged at different resistances.

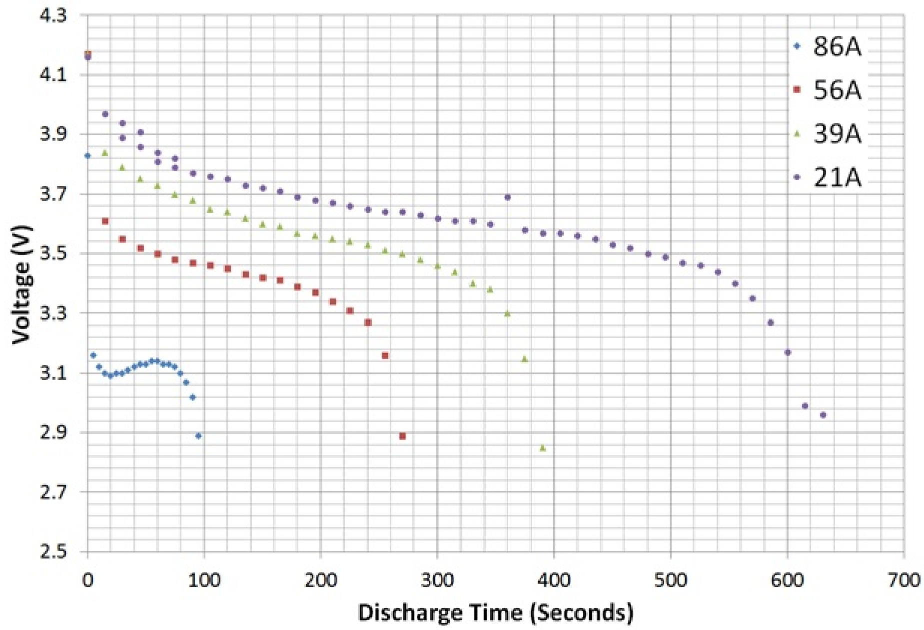


Figure 33: Experimental voltage vs time data from cell discharged at different resistances.

The temperature profiles in Figure 31 show the effect that cell discharge current has on cell temperature and heat generation. When run at the highest discharge rate, the cell had a relatively constant slope for the duration of the test and its temperature rose quickly out of the optimal temperature range. At lower discharge rates the temperature did not exceed the optimum range as quickly but reached similar temperatures by the end of the cells discharge. Therefore the rate of discharge was determined to be directly proportional to the slope of the temperature change. In Figure 32, the relationship of the current output to the discharge rate was analyzed. The results showed that at a fast discharge rate, the amount of current drawn from the batteries was high but could not be sustained for long periods of time. At lower discharge rates, the output current was lower but was sustained for a longer period of time. This result confirmed that by operating the battery pack at these different discharge profiles, one could optimize the overall vehicles performance for the varying driving conditions encountered during the SAE Formula Electric competition. Having the temperature, voltage and current profile data allowed for a greater understanding of the state of the battery during its discharge cycle.

The results in Figure 34 show the discharge profiles for the sequential step input test. As the discharge rate was increased, the slope of the temperature readings increased. These results reinforced the same assumptions as the earlier discharge tests. The cell was able to complete its discharge cycle without exceeding the manufacturers maximum operating temperature, but it did not operate within the cells optimum temperature range.

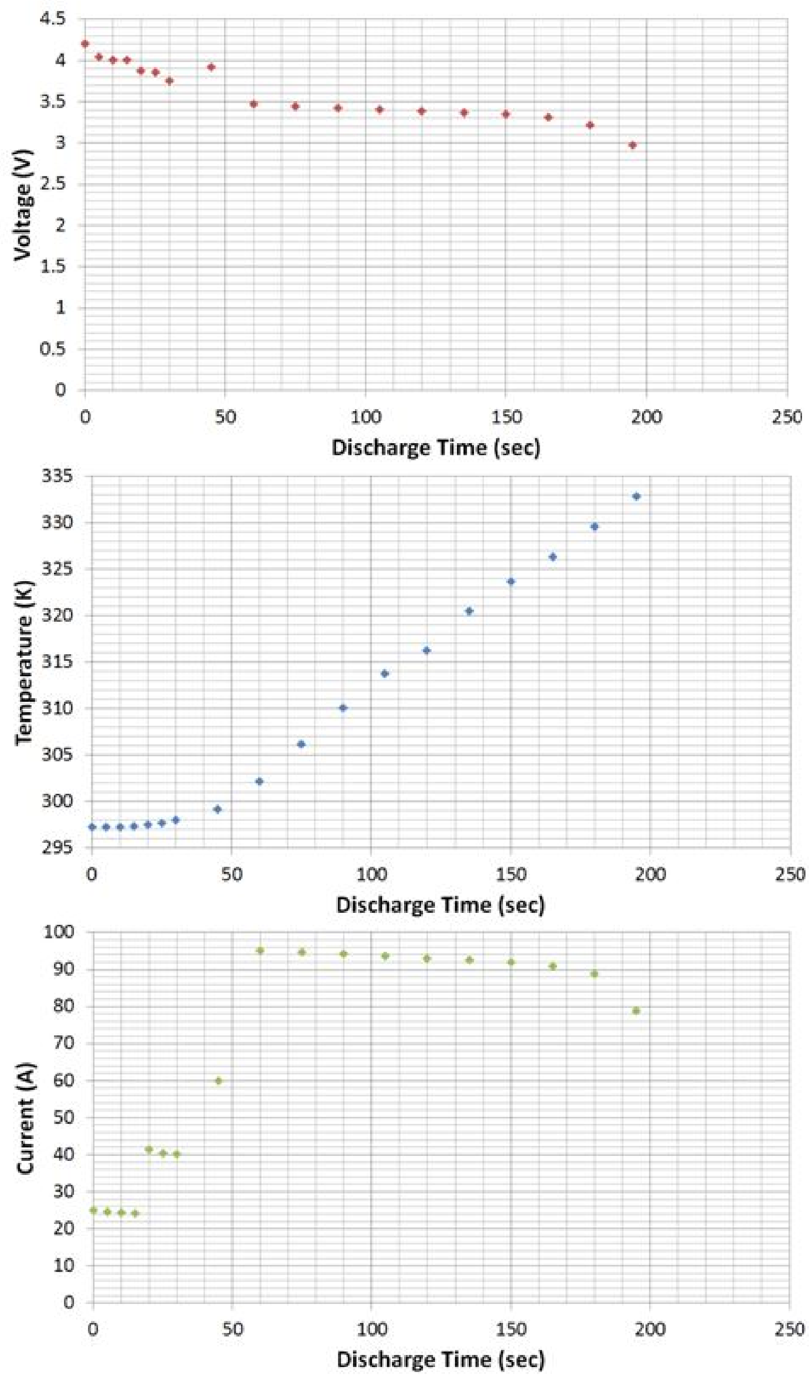


Figure 34: Experimental voltage vs time data from cell discharged at different resistances.

In the voltage profile in Figure 34, a spike in the voltage occurred when the transitional step from 56 to 86 A was made. This spike in voltage occurred while the cell was under zero load, which showed that as the current decreased, the voltage and capacity of the cell increased. This zero load condition occurs at any point in time when the vehicles driver is not engaging the throttle.

The experimental results showed that the lithium polymer cell could not operate within the optimum temperature range without an active thermal management system. This led to the development of an active system to maintain the battery cell temperature during all duty cycles of the battery pack. The airflow field inside of the battery pack can be seen in Figures 35-36.

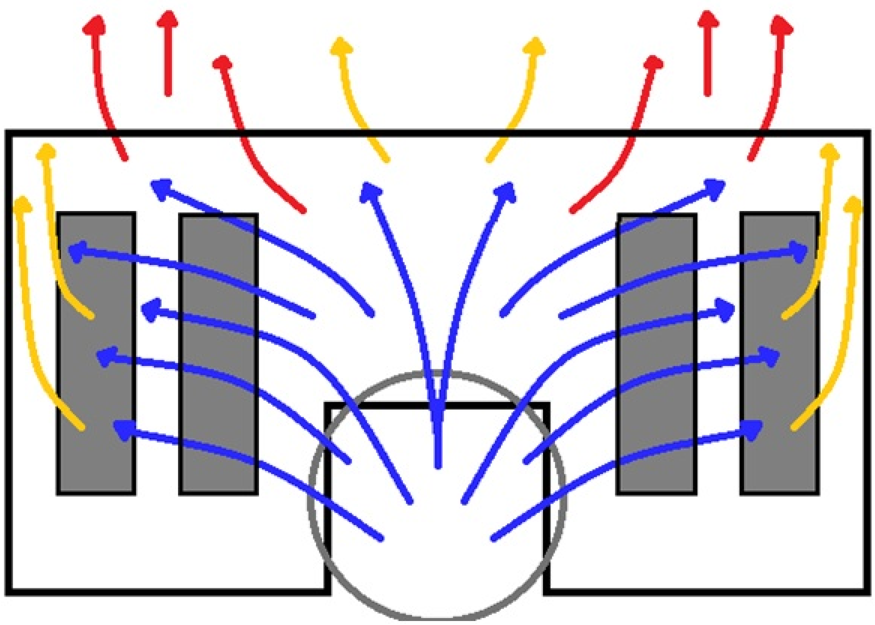


Figure 35: Frontal view of flow field over cell module arrangement for proposed fan-powered feedback loop control system.

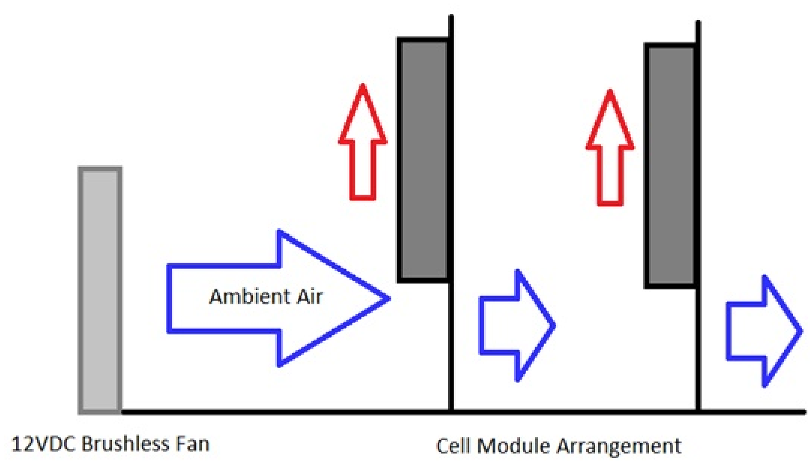


Figure 36: Side view of flow field over cell module arrangement for first-iteration.

Although this fan layout was effective in theory, it did not lend well to the physical system it was intended for. Due to the geometric constraints of the battery pack design; this fan layout could not maintain the battery modules at a uniform temperature. A new design was necessary to provide a more consistent free stream velocity over all the modules in the pack.

By changing the flow field design, it is possible to provide a more uniform temperature distribution within the battery pack. By positioning the inlet location at the bottom of the pack, it was possible to change the flow direction from perpendicular across the frontal surface of the cell modules to flowing bottom to top along the side of the modules. This alteration was accomplished by creating perforations in the bottom panel of the enclosure, which was strategically placed to aim directly in between the modules. A fan was then attached to a plenum directing the flow under the enclosure into a channel. The plenum was designed to establish a uniform pressure along the bottom surface of the pack. This was vital in providing a uniform flow field along the battery modules. If the fan were directed at the perforated bottom without the channel, the first few holes would not receive equal flow rates due to Bernoullis principle and the turbulent nature of the flow. The plenum acted to accumulate a uniform, pressurized flow before entering the perforated bottom. A pressure difference developed between the bottom of the enclosure and the top, effectively pushing the airflow upward along the side the modules. A similar perforated top guided the exiting air into the environment.

A prototype consisting of two modules side-by-side was built and tested in order to determine the viability of this thermal management design. The results were not desirable at first. Upon further examination, it was found that the wrapping of the module created a layer of air between the wrapping and the side surface of the cell. This greatly hindered the heat transfer and the decision was made to remove the wrapping in order to provide better contact between the lithium polymer cells and free flowing air.

A second step taken to improve the heat transfer from the battery cells to the surrounding environment; was to unfold the edges of the cells. Each of the cells had edges that extended beyond the contents of the cell on either of their sides, which were folded flat against the edges of the modules during manufacturing. By unfolding these edges, the cells surface was exposed which allowed for greater heat transfer. It was important that these sides be exposed as the battery pack arrangement only allowed heat transfer from these surfaces on the modules. A proposed flow path for this battery pack arrangement can be seen in Figure 37.

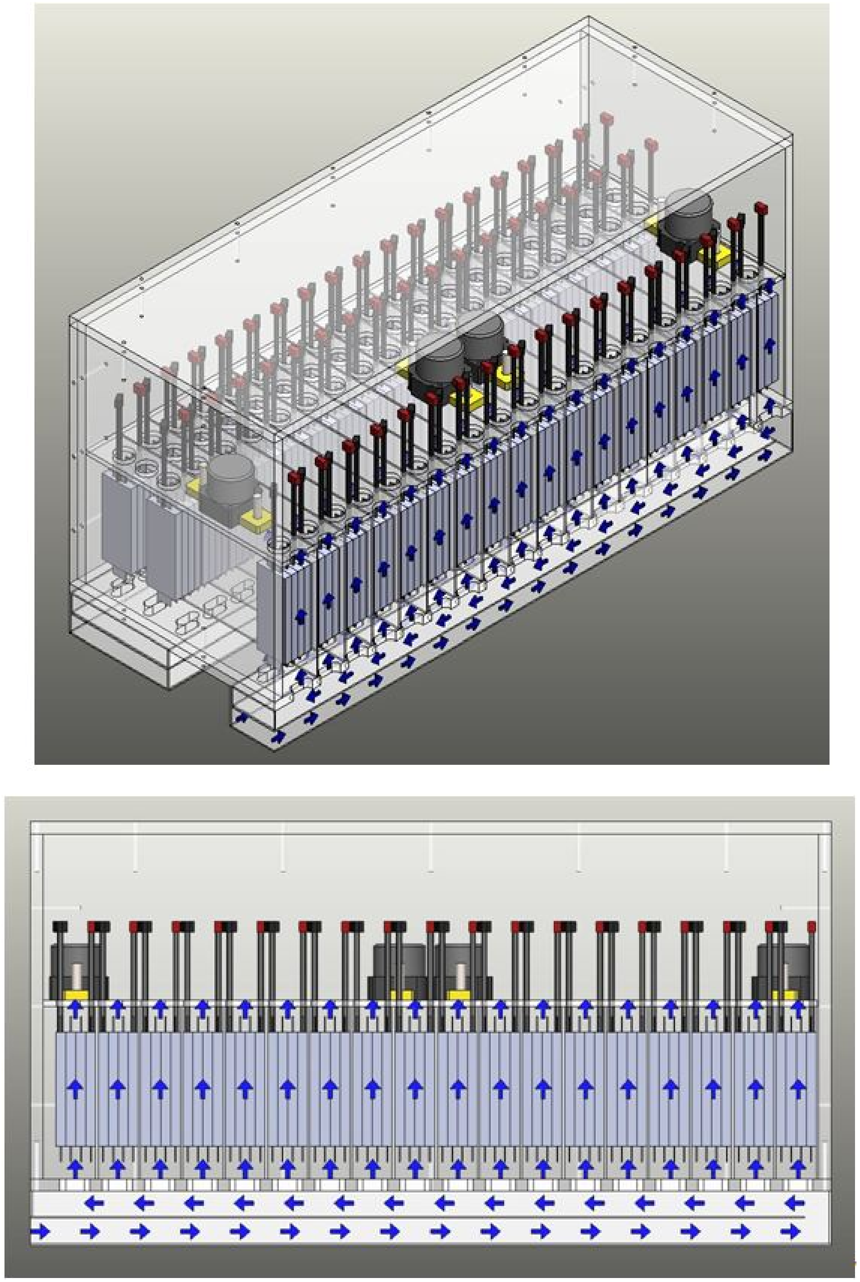


Figure 37: Rendered CAD image of batterpack with plenum, showing airflow through plenum and pack.

In order to determine the benefit of unfolding the edges, temperature readings were taken during testing done on the prototype while the cell tabs were folded out and while folded in. The results of this experiment can be seen in Figure 38.

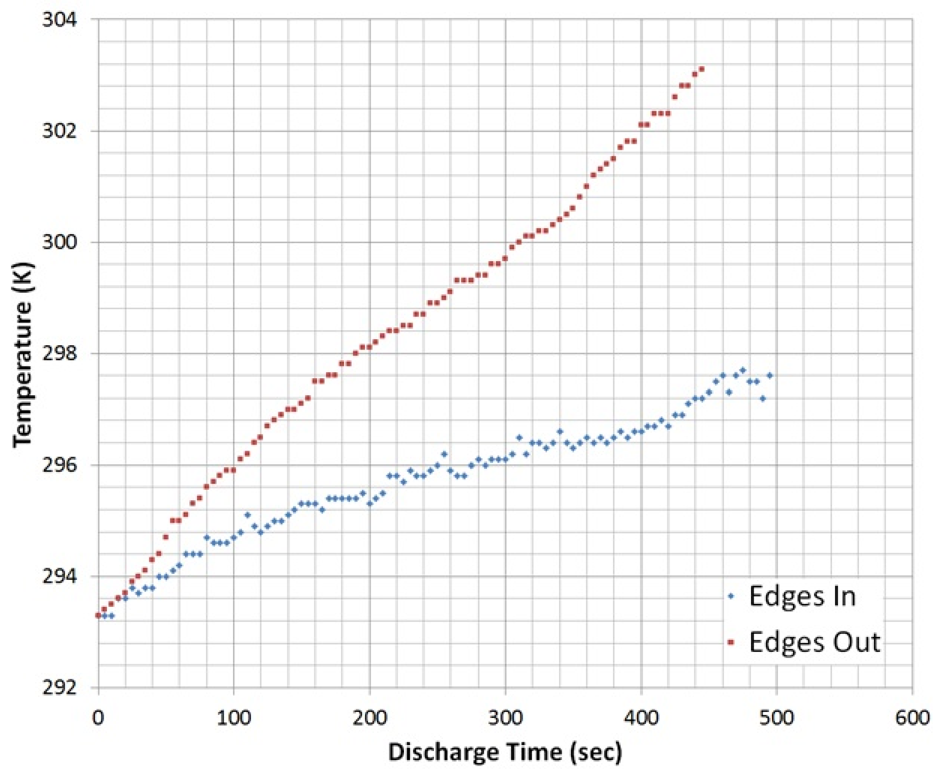


Figure 38: Outflow temperature vs time data for testing done at 75 *A* on two-module prototype.

By unfolding these edges, the outlet flow temperature readings reached 303 *K* (30°C) as opposed to readings of 297 *K* (24°C) when the edges were folded inward. By comparing these outlet temperature results to their respective inlet temperature readings, it was possible to determine the temperature change over the length of the module and subsequently the amount of heat transfer from the module to the surrounding air using Equation 10.

Utilizing the prototype, testing was done to simulate an autocross event. This was done by discharging the two-module prototype at maximum discharge but opening and closing the circuit at five-second intervals. This was done to more accurately simulate racing conditions as an autocross event would consist of frequent heavy breaking and accelerating. The temperature response and discharge current profiles over the duty cycle can be seen in Figures 39-40.

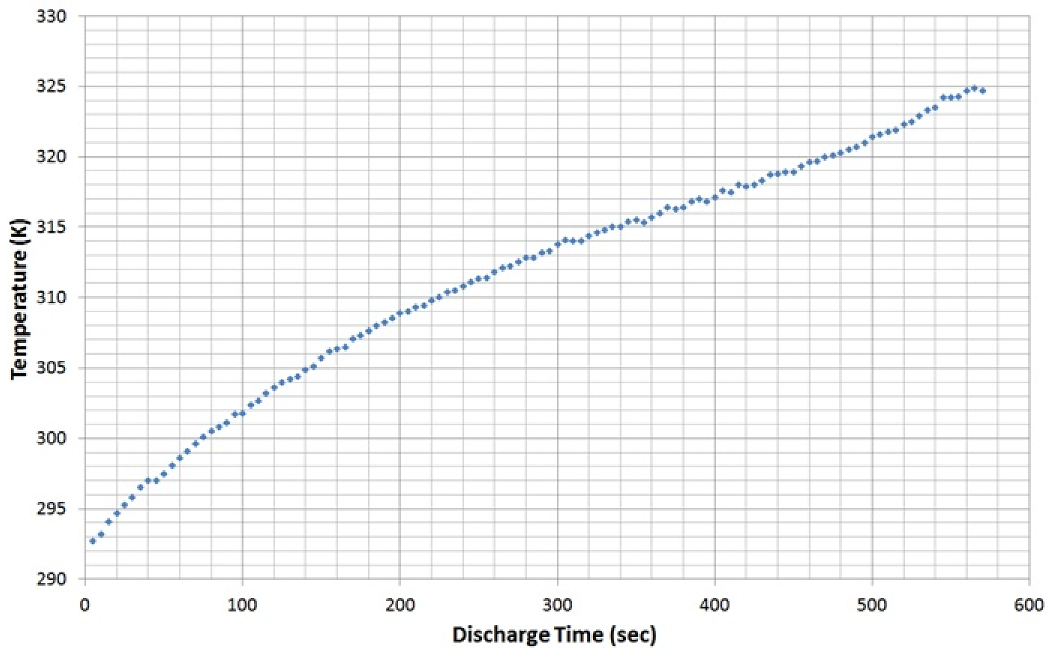


Figure 39: Temperature vs discharge time response of two-module prototype for autocross simulation.

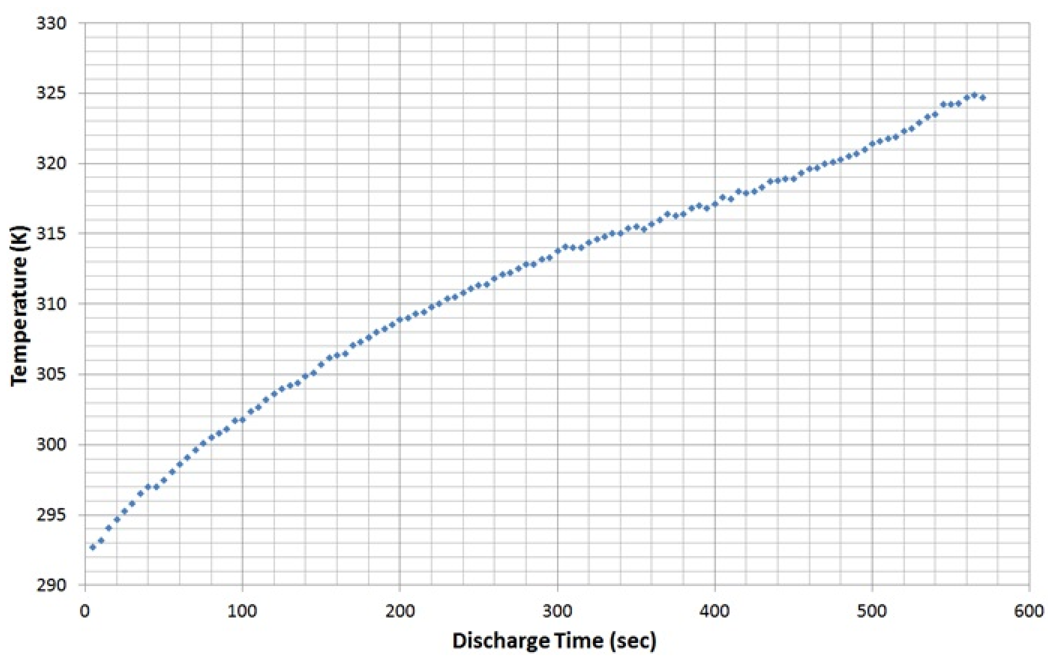


Figure 40: Temperature vs discharge time response of two-module prototype for autocross simulation.

Figure 39 shows the temperature response of the two-module prototype during the autocross simulation test. The modules reached a max temperature of 325 K (52°C) at the end of their duty cycle. Surprisingly, the modules ran for a total time of over 600 seconds; all previous tests runs at maximum discharge had a duty cycle of 150 seconds or less. This was a dramatic increase in the duration of the modules duty cycle compared to a test run while not opening and closing the circuit. Figure 40 shows the step response of the discharge current as the circuit was opened and closed. The discharge current readings reflect the fact that the circuit was closed during only half of the total duration of the test. Because the modules were not being discharge during the full duration of the test, the modules chemistry was paused during these intervals of zero discharge. These pauses allowed the modules time to recharge, which resulted in a significantly longer duty cycle. These results showed that when the modules are not being continuously discharged, the length of duty cycle increased dramatically. By utilizing this varying discharge current testing method, throttle mapping of actual race tracks could be done to simulate the output of the battery pack in a racing environment.

The thermal management solution for the battery pack can be improved by the implementation of a feedback control loop designed to input temperature readings of all modules within the battery pack and in turn, control the output of a fan providing a free stream velocity over the cells. Although it has not been built, the proposed block diagram of the feedback control loop can be seen in Figure 41.

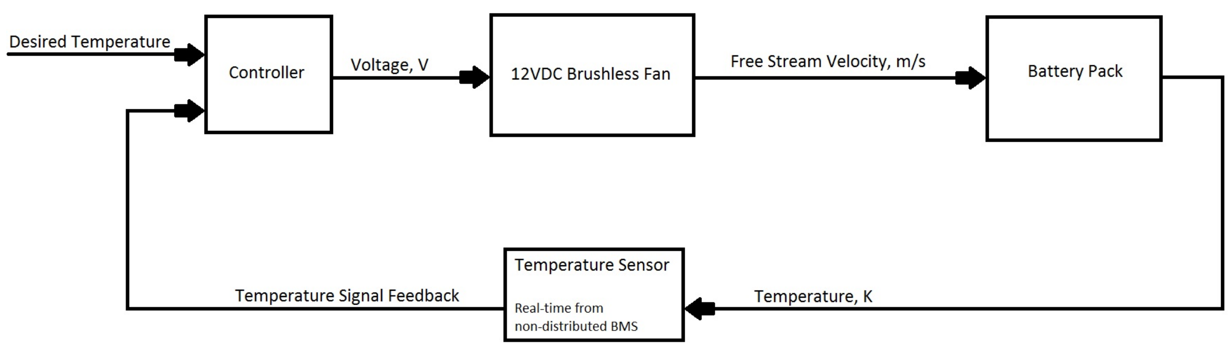


Figure 41: Control system schematic for thermal management system.

By recording the real time temperature of the battery cells inside the battery pack enclosure, the input voltage and subsequently the resulting free stream velocity over the cells can be controlled. This method would allow the ability to control the convective heat transfer coefficient as needed to maintain the internal temperature of the battery pack and individual modules. This is the desired goal of the control system. The array of temperature readings being sensed in real time by the BMS would provide the control system with the necessary temperature signal feedback. The 64 thermistors were strategically placed to measure 128 individual cells evenly distributed throughout the pack. Once it is built, it will be experimentally tested and tuned in order to assess its viability.

Based on the uncertainty analysis, the steady state uncertainty of the collected data was evaluated. The uncertainty in the temperature measurement was +/- 0.1%. The uncertainty in the

DC current measurement was +/- 1.5%. The uncertainty in the DC voltage measurement was +/- 0.025%. The uncertainty in the resistance measurement was +/- 0.05%. The uncertainty in the DC current measurement from the CBA was +/- .045 *A*.

6.6 Conclusion

The thermal response of battery cells under different duty cycles was not well documented in industry. Battery manufacturers tend to leave out valuable thermal data on their specification documents. Granted, the thermal responses of cells depend on a number of variables such as specific heat, environmental temperature, duration of discharge, discharge rate, and internal impedance. These variables were either not easily controllable from an engineering point of view, or were not intended for variation. Furthermore, the growing number of battery manufacturers resulted in a lack of thermal data for the growing number of various cell chemistries. While researching and designing a powerful, efficient, compact, and lightweight battery pack, it was important to create thermal data for the cell chosen and implement that data into a fully functional thermal management system.

In order to create a solvable analytical model of the system, the number of assumptions necessary would be inaccurate for the application. An experimental approach was chosen instead and results show a clear illustration of the thermal response of high power density lithium polymer pouch cells under duty cycles for an HPEV application. It was found that convective heat transfer of air was a highly effective method of preventing overheating of the cells during duty cycles. A convective heat transfer coefficient, h, of 50 W/m^2K flowing alongside a module was enough to prevent the proposed cells from exceeding the optimum temperature range during its most strenuous duty cycle.

The research showed that an air convection system was sufficient to maintain the battery pack at its optimum temperature range while also maintaining a uniform temperature distribution among the cells. The proposed design scheme utilizes fans to force air circulation over a battery pack composed of modules of cells. A feedback loop system allowed for active control of the battery cells temperature resulting in optimum efficiency and performance for HPEV applications.

7 Motor

The only significant criteria for the motor was the 85 kW power requirement. However, selecting a motor for the powertrain quickly developed into a challenge after factoring in the project budget. The motor selected was the EMRAX liquid cooled, axial flux synchronous electric motor by Enstroj [3]. The EMRAX has proved to be the perfect motor for SCUFE application considering the combination of its output capabilities, and weight of only 12 *kg*. This motor was the only motor that fulfilled all the necessary specifications while staying within budget. Figure 42 shows the EMRAX motor.

Figure 42: EMRAX brushless 3 phase AC induction electric motor.

In order to test the motor, a steel bracket was designed to support the motor in operation. Figure 43 shows the motor attached to the bracket. More detailed motor system parameters can be found in Appendix C. Dimensions for the bracket can be found in Appendix A.

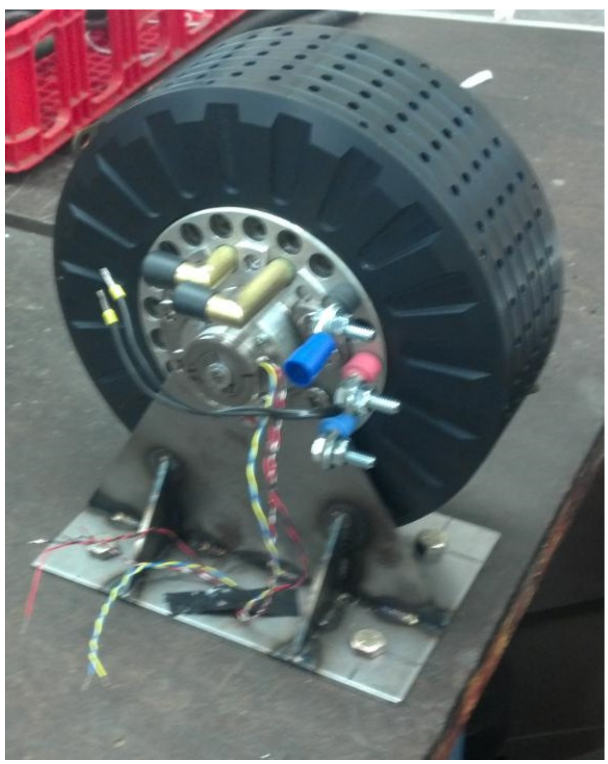


Figure 43: EMRAX electric motor attached to a steel bracket.

8 Motor Controller

The motor controller was selected based on its ability to interface, communicate and connect to the chosen motor correctly and effectively. As motor controllers are generally tuned to an individual motor or type of motor, the list of acceptable controllers was limited.

The motor controller chosen was the 810 Unitek D3 Bamocar D3-400-400 RS motor control, manufactured by Unitek Industrie Elektronik [21]. Besides meeting each power requirement, the Unitek motor controller offered a series of benefits. First, Enstroj has successfully paired the controller and motor and recommended the combination. Among all the suitable controllers, the Bamocar controller weighed the least at 8.5 kg. The controller included desirable features such as regenerative braking and CAN-bus interface. The controller required liquid cooling due to the high power requirements of the overall system; however, the weight addition drew little concern as the EMRAX motor required liquid cooling as well. The cooling hardware will be shared between to the two components. Figure 44 shows the Bamocar D3 motor controller.

Figure 44: Unitek Bamocar D3 series motor controller. Water inlet and outlet nozzles for liquid cooling can be seen on bottom of controller.

Full specifications of the motor controller can be found in Appendix D.

Other motor controllers considered were the Piktronik SAC50 Sensorless AC drive controller [13], and the Sevcon Gen 4 line of motor controllers designed for 4 wheel pure electric vehicles [17]. The Piktronik motor controllers specifications surpassed all desired design specifications: it could handle a maximum battery voltage of 370 V as well as a maximum power peak of 140 kW. However, this motor controller was not within the acceptable budget range.

PART III

PROJECT CONCLUSIONS AND IMPACT

9 IMPACT

9.1 SOCIETAL IMPACT

The full industry integration of electric vehicles in the United States will cause significant societal and environmental benefits, which will allow the United States to move their economy away from a petroleum based economy to a more sustainable economy.

Many would argue that the U.S. dependence on oil imports has lead to political turmoil, economic instabilities and even wars. In fact, many of the challenges facing our country stem from energy related issues and the root remains quite clear. The U.S. expends significant resources each year securing energy to power its mighty state. By eliminating the need for oil imports and gaining a certain level of energy independence, significant challenges essentially go away. There are currently 250 million registered passenger vehicles in the United States. On average, these passenger vehicles consume 8.7 millions of barrels a day [19]. Of these 250 million registered vehicles, electric vehicles make up a mere 200,000. This resulted in an accumulated .032 million barrels saved over the past three years [23].

Although this seems insignificant, the number of millions of barrels saved and metric tons saved was zero approximately five years ago. As this number begins to increase, we would expect another 0.1 millions of barrels saved within the next five years[2][23], further reducing US dependence on foreign sources of fossil fuels.

9.2 ENVIRONMENTAL IMPACT

Progress in the 21^{st} century has been largely powered by the combustion of fossil fuels for electricity and energy generation. The development of the internal combustion engine in transportation and industrial machinery has allowed for quality improvement of life, population growth and leaps in technology.

However, the United States dependency on oil as an energy source has proved troublesome and unsustainable. Based upon the 2011 Energy Use Chart from Lawrence Livermore National Laboratory, shown in Figure 45, 35.3% of the United States energy production comes from petroleum sources. Of this 35.3% from petroleum, 71.1% is used for transportation. Of all the energy used for transportation, including the 2% from sources other than petroleum, 75.2% is rejected, or wasted energy. This is in large part due to the natural inefficiencies in internal combustion engines. Internal Combustion Engines are at best 35% energy efficient.

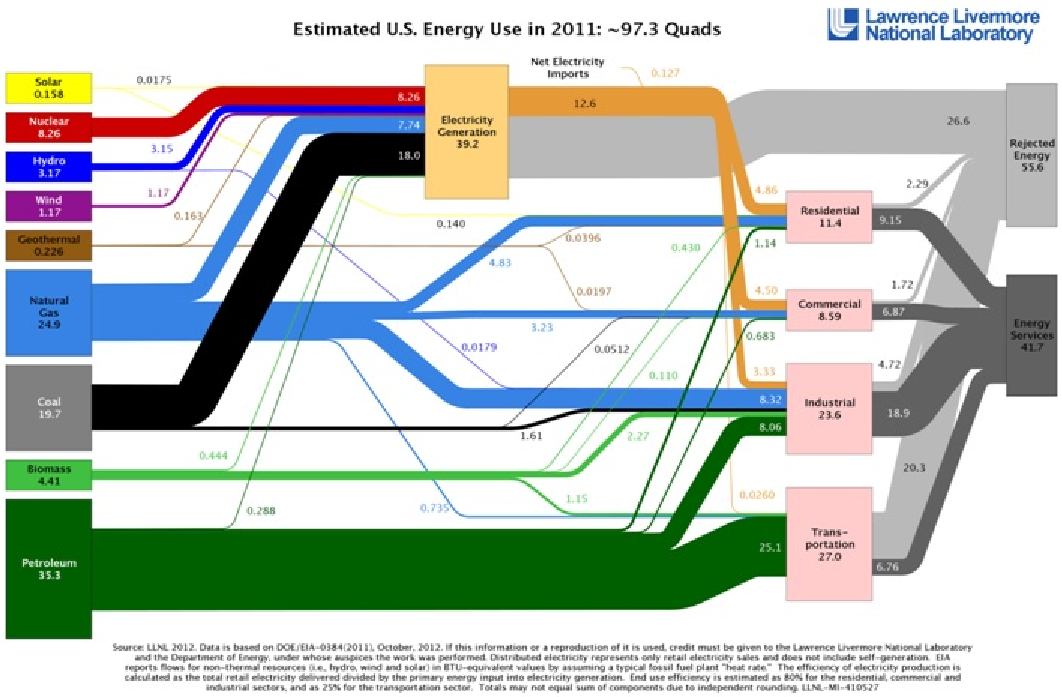


Figure 45: Estimated US energy use in 2011, presented by Lawrence Livermore National Laboratory.

In addition, the harvesting and consumption of fossil fuels has well documented harmful side effects on natural ecosystems. High levels of carbon dioxide and other greenhouse gases continue to contribute to an array of unintended consequences. Figure 47 shows that the transportation industry is the second largest contributor (33%) of CO_2 generation from fossil fuels, producing 1,850.10 terragrams. Being that electricity generation is the first contributor it is clear that remedying these two will reduce pollution. The use of electric vehicles powered by cleanly produced electricity would have a profound impact. The United States is a very high producer of CO2 emissions per capita of larger countries, as shown in Figure 3. This data shows that the US is among the highest producers, with a large part of this coming from the US automobile industry.

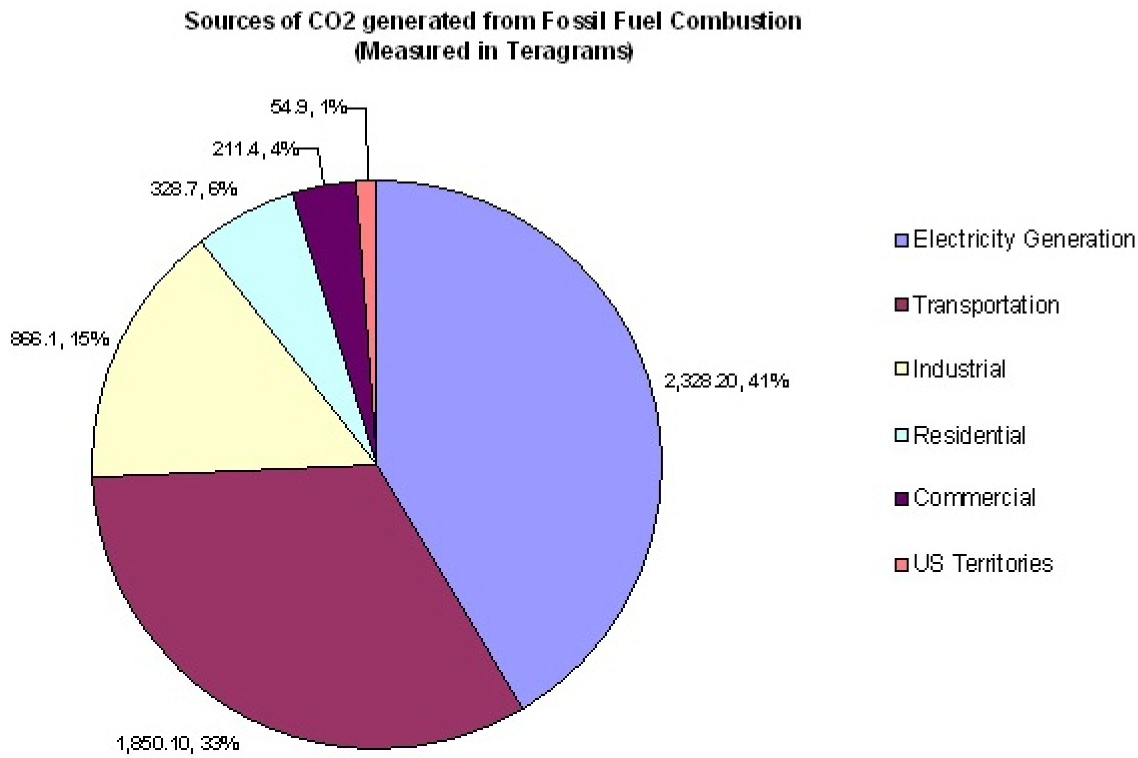


Figure 46: Sources of CO_2 generated from fossil fuel combustion in the United States.

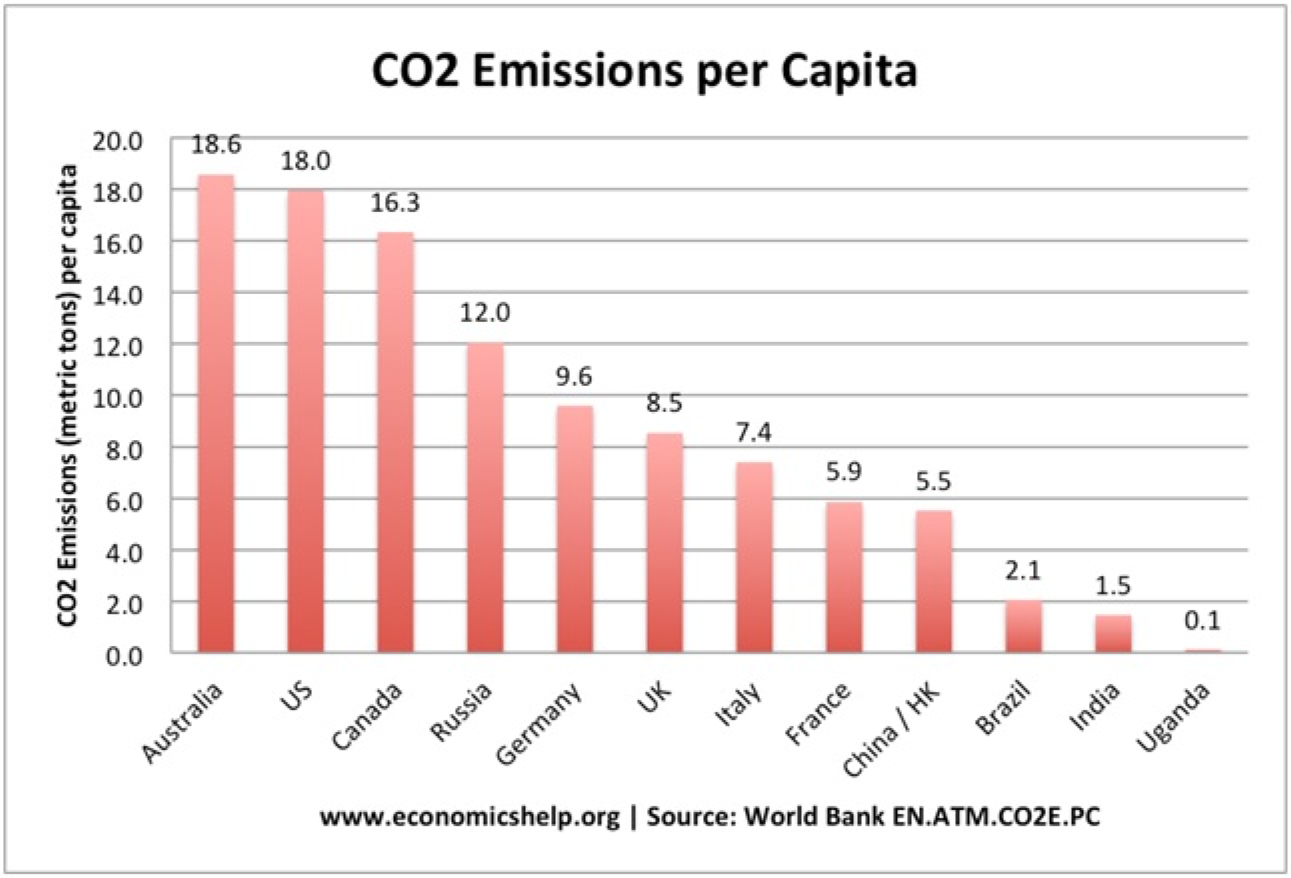


Figure 47: CO_2 emissions per capita for several countries.

The task of developing a fully sustainable product reaches far beyond the design phase. In order to understand sustainability, one must understand scope. Consider electric vehicles as the relevant example. Electric vehicles offer a great solution to sustainable transportation, but not perfect. EVs solve both end use and primary use challenges of transportation. The primary use is the method by which the energy is harvested. The majority of U.S. electricity is generated from combustion of carbon sources such as coal and gasoline. The US Environmental Protection Agency reported that in the United States 49.61% of electricity is generated through burning coal and 3.03% through oil combustion [5]. ,However, electric energy has the potential to be harvested using environmentally benign methods. These methods include solar energy, hydroelectric generation and generation through wind turbines. Advancements in electric vehicle technology should produce a greater incentive in progressing sustainable energy harvesting methods to reduce the overall carbon emissions produced by the automobile industry. It does not make sense to focus on progressing electric vehicle technology in areas in which electricity is solely produced through fossil fuel combustion, as this places a heavier burden on power plants to produce more electricity, producing no overall environmental benefit. Therefore, electricity has the potential to have clean beginnings. Lastly, the end use of electricity, specifically in EVs, exemplifies a clean method of consumption. By replacing 200,000 internal combustion engine vehicles with electric vehicles, 8,700 metric tons of carbon dioxide emissions were prevented from being dispersed into the atmosphere [23].

However, this only describes the benefits of the operational use of the vehicle by the consumer. What is not readily apparent is that electric vehicle production has about twice the global warming potential of conventional internal combustion engine vehicles. Battery, motor and electrical component production contribute the largest portion to electric vehicle GWP due to the toxic byproducts of the methods used to process nickel, copper, aluminum and platinum that constitute electric vehicle components. These methods produce chemicals that are terrestrially toxic and harmful particulate matter along with greenhouse carbon emissions into the environment, which negate the beneficial effects of reduced CO_2 generation [6].

Most importantly, electric vehicle production has a significantly greater harmful toxic effect on human health than internal combustion vehicle production. Electric vehicle production is 180% to 290% more harmful to human health than their internal combustion counterparts, due to the same toxic byproducts of the EV component manufacturing [6].

Overall, these issues must be addressed if electric vehicles are to become a viable sustainable alternative to internal combustion engines. These changes must begin with the metal refinery industry, as EV technology is inherently dependent on the metal industry. If these environmental and human health issues are not addressed, then there is no overall benefit to using electric vehicles over internal combustion engines, and a full transition to electric vehicles may actually cause more acute harm in the future.

Electric vehicle sales are expected to increase, as the president has set a goal to see one million electric vehicles on the road by 2015 siresa. More known manufacturers producing electric vehicles like the Nissan Leaf and Chevy Volt are helping to boost the numbers, but smaller start-up companies and research projects like Santa Clara Formula Electric are helping inspire innovation in the industry. This is important as the future of electric vehicles has been brought into question due to their range, affordability, as well as the lack of power grid infrastructure to support them. In order to allow the growth of the electric vehicle market to continue in the coming decades, these challenges must be addressed and technological advances must continue.

The electric vehicle market has the potential to lower the environmental impact that fossil fuel consumption has on the modern world. By advancement of such technologies and the use of more efficient and sustainable energy sources, Santa Clara Formula Electric works to improve the state of electric power as a viable alternative to the the use of internal combustion engines in order to produce a cleaner future.

10 Ethics

10.1 Team Ethics

Developing successful team dynamics is a stressed project priority in regards to both technical and management goals. The team is organized into a loose hierarchy of leadership. The project is led by the team manager, who organizes goals and accomplished tasks, and also directs team meetings. Under the manager, there are two individuals who are managers when the leader is not present. All major project decisions are made as a team; each team members opinions and ideas are accounted for during the decision making process.

Individual responsibilities and weekly tasks are determined by the team leader. In order to hold each individual accountable for their responsibilities, the team meets multiple times a week to determine weekly responsibilities. The purpose of these meetings is also to review each individual's progress in completing long term goals. The weekly team meetings have proved an invaluable tool to maintaining a high standard of work ethic and accountability. Enthusiasm, creativity and team camaraderie are encouraged during these meeting, while negativity is discouraged.

Issues that arise between teammates are discussed with the entire team. The team mediates issues between teammates to offer suggestions how specific problems are resolved quickly and efficiently. This method also ensures that each individual is treated fairly and equally, as is their right as members of this project. Members are encouraged to voice whether they feel they are treated with respect during team meetings and to voice any concerns they have.

10.2 Transparency and Business Ethics

The Formula Electric team will maintain a high level of project transparency in order to maintain good team dynamics and professional relationships with sponsors, advisors and other project supporters. All progress, accomplished tasks, setbacks and new goals are made available to all teammates, sponsors, advisors, and department administration.

The team understands its responsibility to provide complete and timely knowledge of the project to its sponsors. These sponsors are investing resources into this project with expectations to see a return on their investments. By accepting these investments, the Formula Electric team enters into a business agreement with the sponsors, agreeing to strive to progress the relevant technological fields and to expand the sponsors reputation by attaching their name to the project. As a result, a lasting relationship is created benefiting both parties.

If the project managed to stray from the project mission statement, the project would then lack validity and purpose. The project would lose the education value as well as the potential to make the world a better place. At this point, walking away from the project becomes a possibility because the project would lack purpose and outcome.

10.3 Responsibility to Consumer

The potential users of this product deserve a product that is safe, energy efficient, and meets their expectations. As a supplier of this product, it is the SCUFE team's duty to ensure that the user will be completely safe. The system contains a 300 V battery pack and moving transmission parts, which makes our product potentially dangerous to the user. The team is ethically and morally obligated to make a safe product for the consumer. It is the SCUFE team's responsible to ensure that the customer is aware of the limitations of the product, especially in terms of lifespan, prior to allowing them to purchase it. The issue is that we have an ethical obligation to our customers to provide a quality product that they understand well so they do not feel duped by declining performance over the life of the vehicle. This is good for business because it will keep people coming back to us and referring friends because of honest support and sales.

10.4 Ethics in Research and Findings

The accuracy and integrity of the information used in the design of the project is ensured by drawing information from credible sources. . Also, by holding fellow team members accountable for the safety and success of specific aspects of the design, individual members become responsible for the livelihood of those components and will be inclined to do what is necessary to design and construct a proper product. Ensuring that all actions being taken in our experiment are documented and well planned out before being done confirms that the entire group knows what is being done during various experiments. This is beneficial, as it means that experiments are well planned out and therefore can be scrutinized for accuracy, whereas a less planned out experiment leaves room for error by way of rash decision making.

Experiments performed and results collected will be made completely transparent to any who wish to view the information. This is to allow scrutiny of our project to ensure that all experiments were conducted logically and that all information was made public. It would be highly unethical if the team withheld information that would foster uncertainty in the integrity of the project.

10.5 Ethics of Error

Errors of commission occur when a team member makes a mistake, which could range from misinformed judgments to mathematical errors. Errors of omission occur when team members omit important information for a particular element of the design or fail to respond to project issues in a timely, responsible fashion.

Errors of omission present a unique problem because the Formula Electric project spans over two academic years. There exists a definite risk that the succeeding project team could make serious errors of design and judgment with their phase of the project due to lack of information of Phase 1. As the succeeding team is relying on the current team to build a solid project foundation, the current team understands it has an ethical duty to complete their project to the best of its abilities. The current Formula Electric team will produce and meticulously document as much information as possible, and will deliver the whole of that information to the succeeding team to give that team the tools necessary to complete the project safely, efficiently and to the best of their ability.

This is ethically important because each senior design team is equal in the eyes of the University; therefore, each team must have an equal opportunity to succeed in their projects. If the current Formula Electric team does not deliver the necessary progress and information to the succeeding years team, then it is essentially inhibiting the succeeding team's opportunity to succeed.

10.6 Risk and Safety Ethics

The Formula Electric team will deal with all safety hazards in a efficient and complete way. Systems will be designed in order to minimize safety risks as much as possible. All parties involved with the project, including administration, sponsors and teammates will be made aware of all hazards, how to operate the systems safely, and all system safety measures. The team will maintain a good relationship with the Environmental Health and Safety Commission in order to ensure the wellbeing of the project and all parties operating the project systems.

These measures are ethically important because they take into account the well-being of human lives. As the ASME Code of Ethics states, Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties. The team understands the sanctity of human life and safety. All parties involved in this project have invested time and resources to ensure the success of the project. Therefore, these investors have the basic right to operate the systems without risk to their health. It is the duty of the project team to ensure that all investors have all the knowledge necessary to operate the systems safely to their full capacity.

10.7 Technological Ethics

The overall goal of this project is to optimize electric vehicle powertrain efficiency as a means to move the automobile industry away from using systems that rely on fossil fuels and other environmentally damaging energy sources. This project will strive to improve current powertrain designs, incorporating methods and components to produce a more sustainable and energy efficient system. It is ethically important that all technology in the project is well documented, in terms of raw material usage, manufacturing and end usage in order to ensure that all technologies involved were produced cleanly and ethically, without harm to human safety.

All technologies have the capacity for violence; the use of technology depends on the choices of the operator. The Formula Electric team understands that it is partially responsible for this risk even though it should not be held accountable for the choices of the system operators. The team will implement as many design characteristics as possible in order to ensure the proper use of the system; however, the team understands that the product will only be as useful as the operators use it to be.

11 Outcomes

11.1 Systems Outcome

Table 7 shows the project specification outcomes, compared against the goal requirements.

Table 7: Project design specifications outcomes

ELEMENTS/REQUIREMENTS		PARAMETERS		
	UNITS	DATUM	TARGET-RANGE	OUTCOME
Performance				
Range at 40 MPH	*Miles*	N/A	80-120	N/A
75 *m* Acceleration	*sec*	8.8	6.0-8.0	N/A
Top Speed	*MPH*	N/A	70-100	N/A
Max Torque	*Nm*	N/A	135-163	N/A
Max Voltage	*V*	N/A	280-300	299
Max Power Draw	*kW*	N/A	60-85	85 kW
Storage Capacity	*kWh*	2	5-7	
Thermal Control	°C	N/A	25-35	N/A
Design				
Cost	$	40,000	13,000-18,000	17,227
Mass	*kg*	62	64-73	
Size	m^3	0.085	0.11-0.14	
Time Scale	Months	8	7-9	9
Usability/Safety				
Removal of Battery Pack	*sec*	N/A	110-140	N/A
Useful Life	Charge Cyles	1800	500-700	N/A
Deceleration Resistance	20*g*	N/A	20*g*	20*g*

Due to project time restraints, full system testing could not be completed. As the battery pack was not fully electrically connected, the full thermal control system could not be tested. Much of the data can only be gathered at the end of Phase 2, as the final design of the vehicle affects the final specifications of the system, such as top speed and acceleration.

11.2 Overall Project Outcome

At the conclusion of the 2012-13 academic year, the SCUFE project Phase 1 has not been fully completed. All major components have been purchased, including all battery cells, electric motor, and motor controller. The battery pack has been fully manufactured, but has not been fully assembled. Due to time and safety constraints, the battery cells could not be connected.

This project has been an invaluable learning experience for every member of the team. As the team's first real engineering project, many assumptions about time constraints, budget constraints and progress estimations were made. The team realizes it underestimated the amount of work involved, and even after significantly re-evaluating the major goals of the project, the team could not complete the project.

Some of the major lessons learned from this project:

- Engineering projects are by necessity economic projects as well. The team spent a significant portion of time and effort designing business plans and presentations to present to potential sponsors in order to procure project funding. It was quickly learned that each plan and presentation has to be uniquely designed for each sponsor.

- Mistakes will be made. Through out Phase 1 of the project, several PC boards were short circuited, several fuses were blown, and one cell was ruptured. Figure 48 shows a short circuited PCB board. Through each mistake, however, each member of the team realized how to avoid those mistakes in the future, and how to proceed with caution and safety in mind.

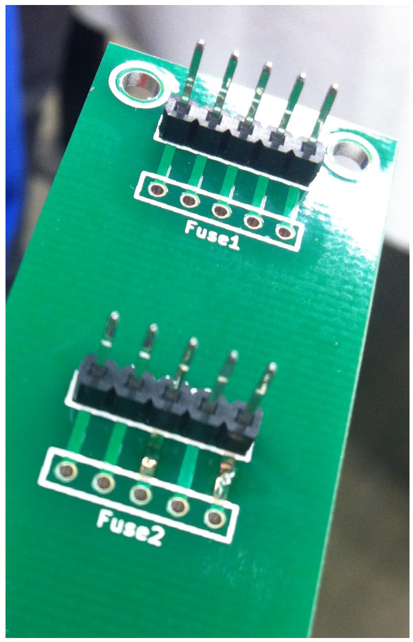


Figure 48: A short circuited PCB board, resulting in a blown fuse. Short circuit occurred when module was connected incorrectly.

- The true success of an engineering project lies in the details of the design. This includes analyzing screw choice, polycarbonate thickness choice, choosing between soft- and firm-core foam, and many other fine details. An engineer must scrutinize every detail in a design to ensure the integrity, quality and success of any engineering project.

11.3 Future Work

The majority of Phase 1 was completed during the 2012-13 academic year. However, the design has not been optimized. Several suggestions for design improvement are described:

- Controller/motor and controller/battery connectors which connect the high voltage systems must be purchased or manufactured. The system was designed to use 3/O wire in high voltage pathways. However, the high voltage connectors included with the motor controller only fit 1 gauge and lower wire sizes. Figure 49 shows the included high voltage connectors.

Figure 49: High voltage connectors to connect high voltage wire to motor controller from either the battery pack or motor. Connector is shown to the left, with the plastic protective casing shown to the right of it.

- A method to connect the four module strings in parallel without using solder must be developed, as using solder in high voltage pathways is prohibited by the SAE rules. The current version of the battery pack uses a soldered connection in order to begin testing. A method has been designed that uses four male deans connectors welded or bolted to a small copper bus bar.

- The wire harness must be redesigned in order to position thermistor wires out of thermal pathways, as well as protect them in case of collision situations. This can be done by utilizing PET flame retardant wire sheathing. The non-flame retardant PET sheathing is commonly used in computer construction in order to manage wires and cables. Sheathing keeps all wires nicely organized and protected from damage, separates them from other critical components in the battery pack, as well as adding a more professional look to the manufacturing.

- The current battery enclosure design does not allow for ease of assembly. An unanticipated challenge in constructing the pack was setting the inner shelf lid in place on top of the battery modules: while the shelf easily held the contactors and fuses separated from the the batter modules, it was extremely difficult and time consuming to thread the positive and negative terminals of the modules through the small shelf holes. The terminals themselves were unwieldy; string was tied to the end of each terminal to thread the terminals through the holes. Originally, the pack was intended to be assembled by removing the bottom panel and inserting the slider packages one at a time. The pack had to be unassembled and reassembled multiple times before completion. It is suggested that either the shelf be redesigned, or a new method of assembly be devised.

During the 2013-14 academic year, Phase 2 of the project will be completed. This includes building the chassis, suspension, and data acquisition systems, as well as integrating the power train system. Figure 50 shows a CAD rendered image of the current design car.

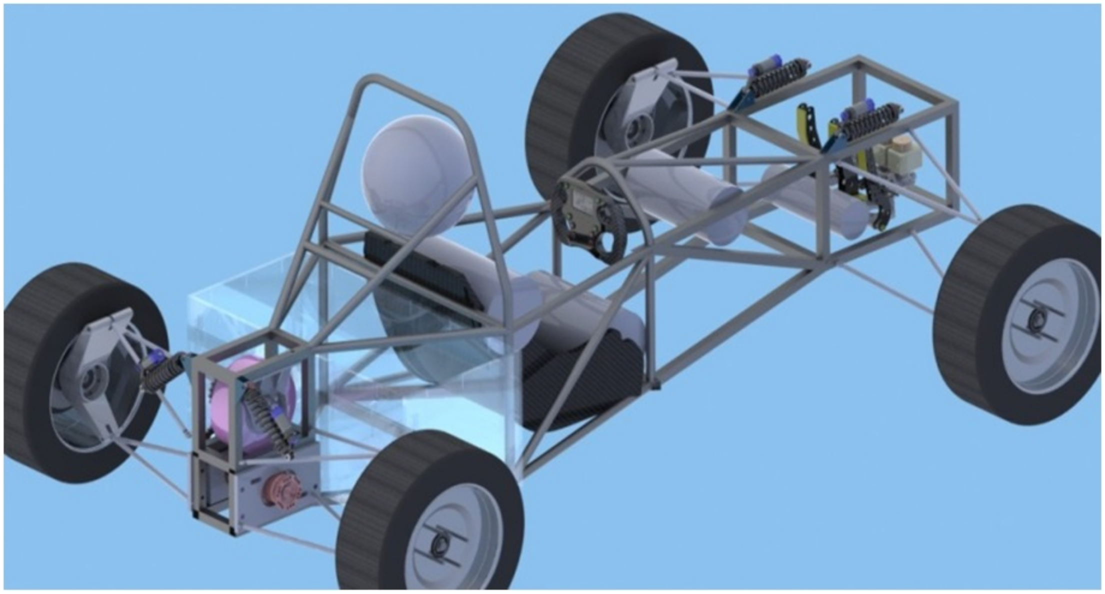


Figure 50: CAD rendered image of the completed SCUFE vehicle. Figure shows rear of the car in order to illustrate placement of the power train system.

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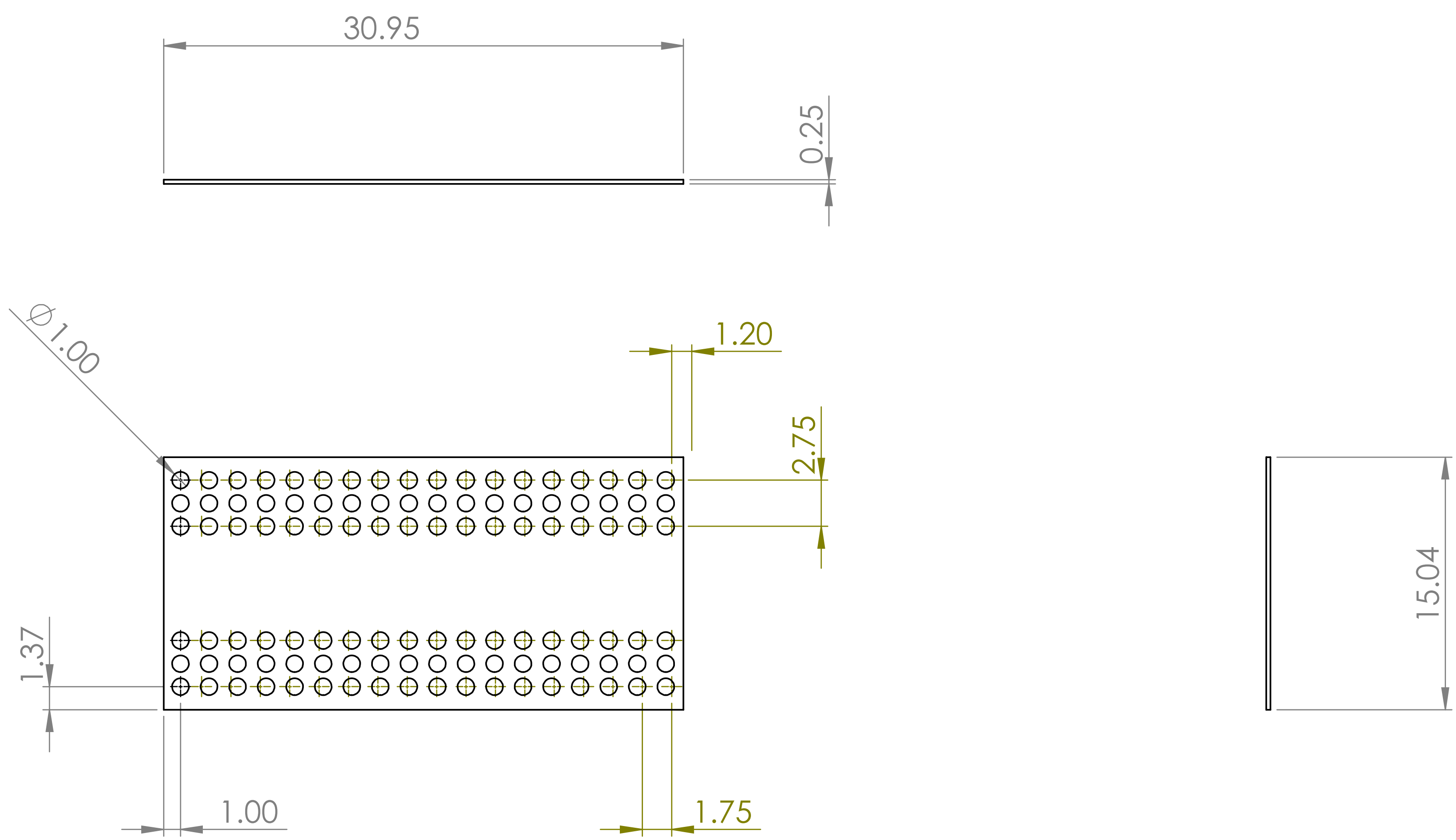
A PART CAD DRAWINGS



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			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL Polycarbonate	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

PROPRIETARY AND CONFIDENTIAL

Formula Electric

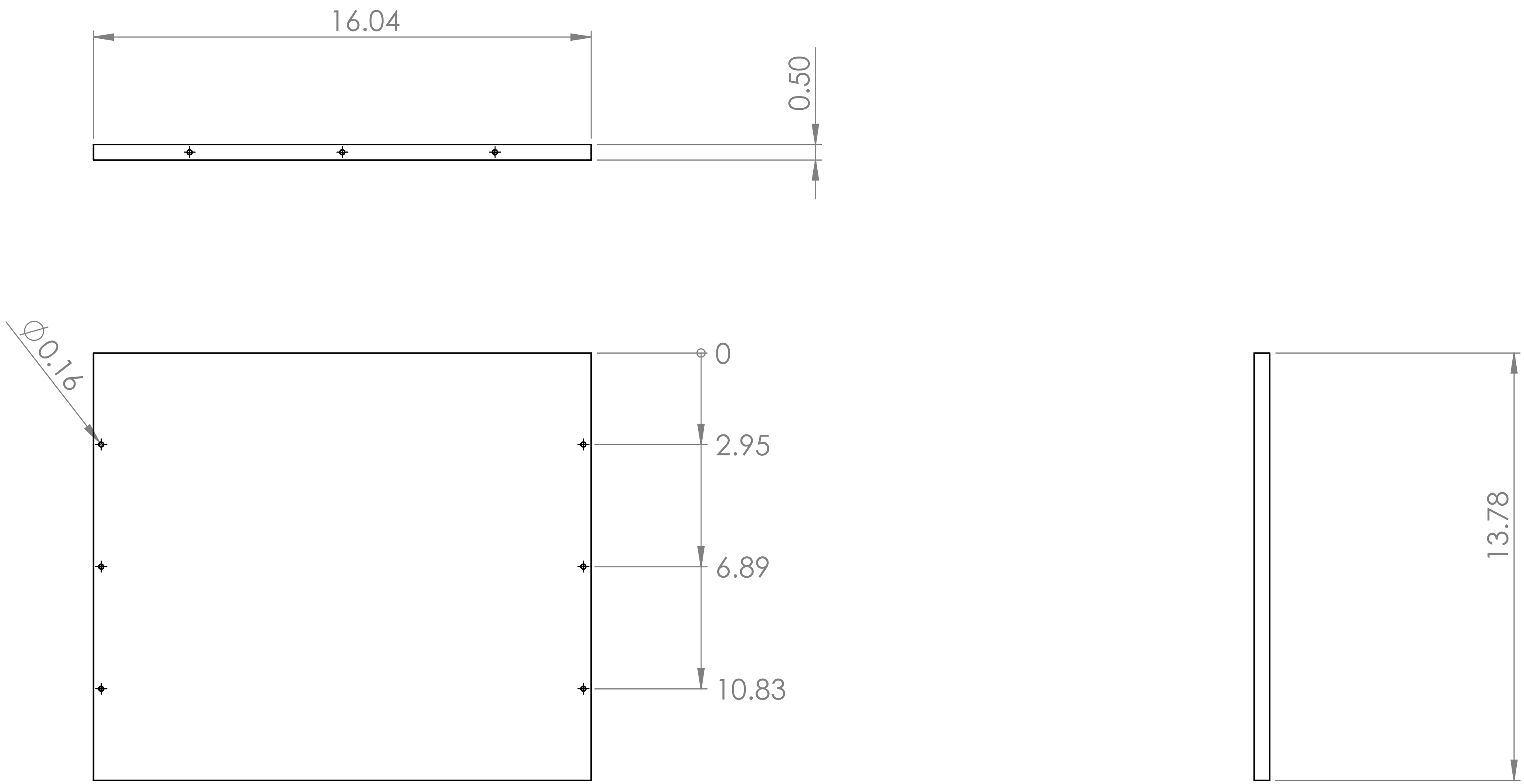
TITLE:

Inner Platform

SIZE A | DWG. NO. BP-009 | REV 1

SCALE: 1:10 | SHEET 1 OF 1

5 4 3 2 1



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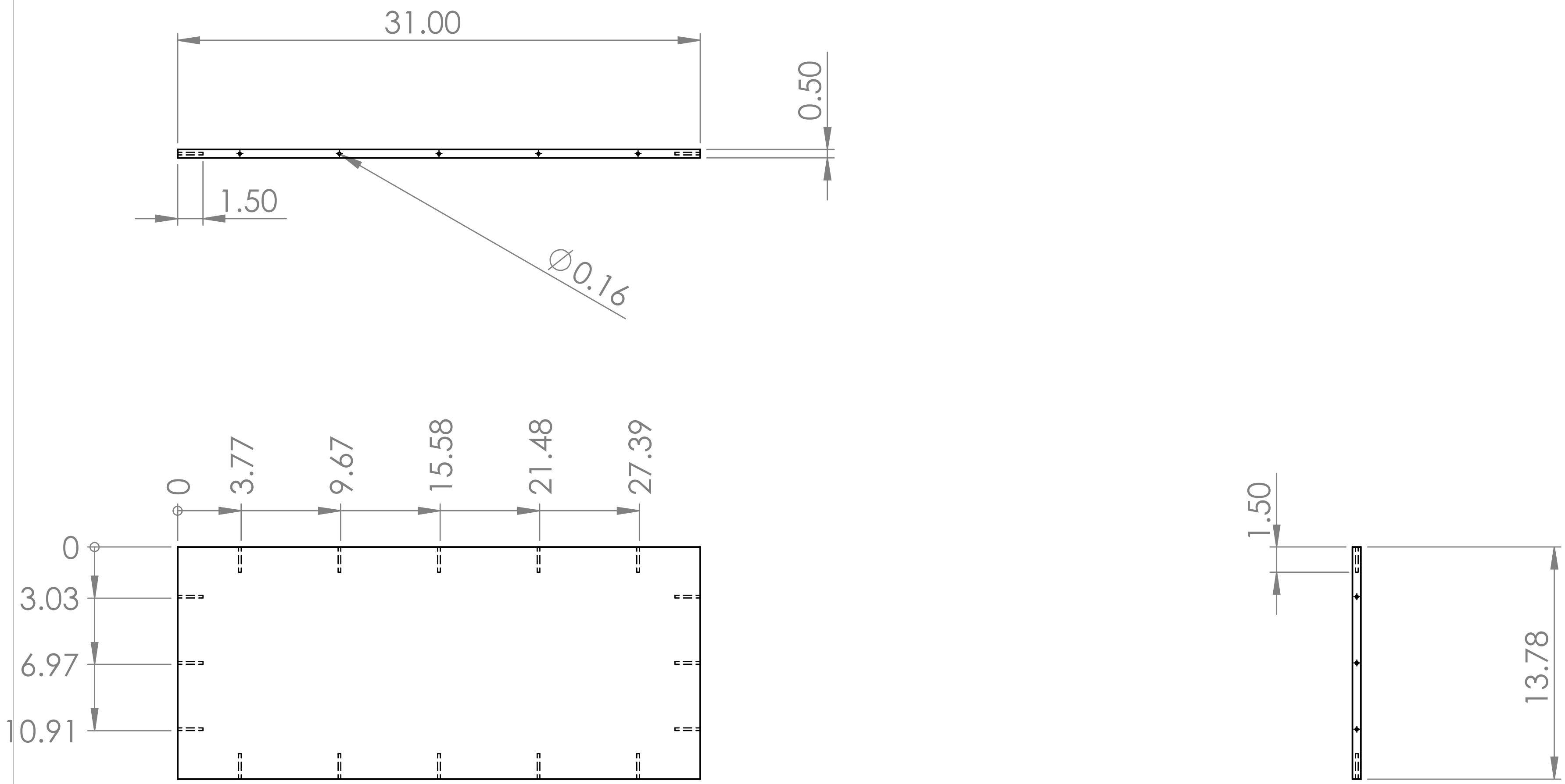
			CHECKED			Side Panel (Left and Right)
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Polycarbonate	COMMENTS:			SIZE A DWG. NO. BP-010 REV 2
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:5

5 4 3 2 1



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.005
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polycarbonate

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DV	3/19
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
Use #29 drill and tap M4 X 0.7

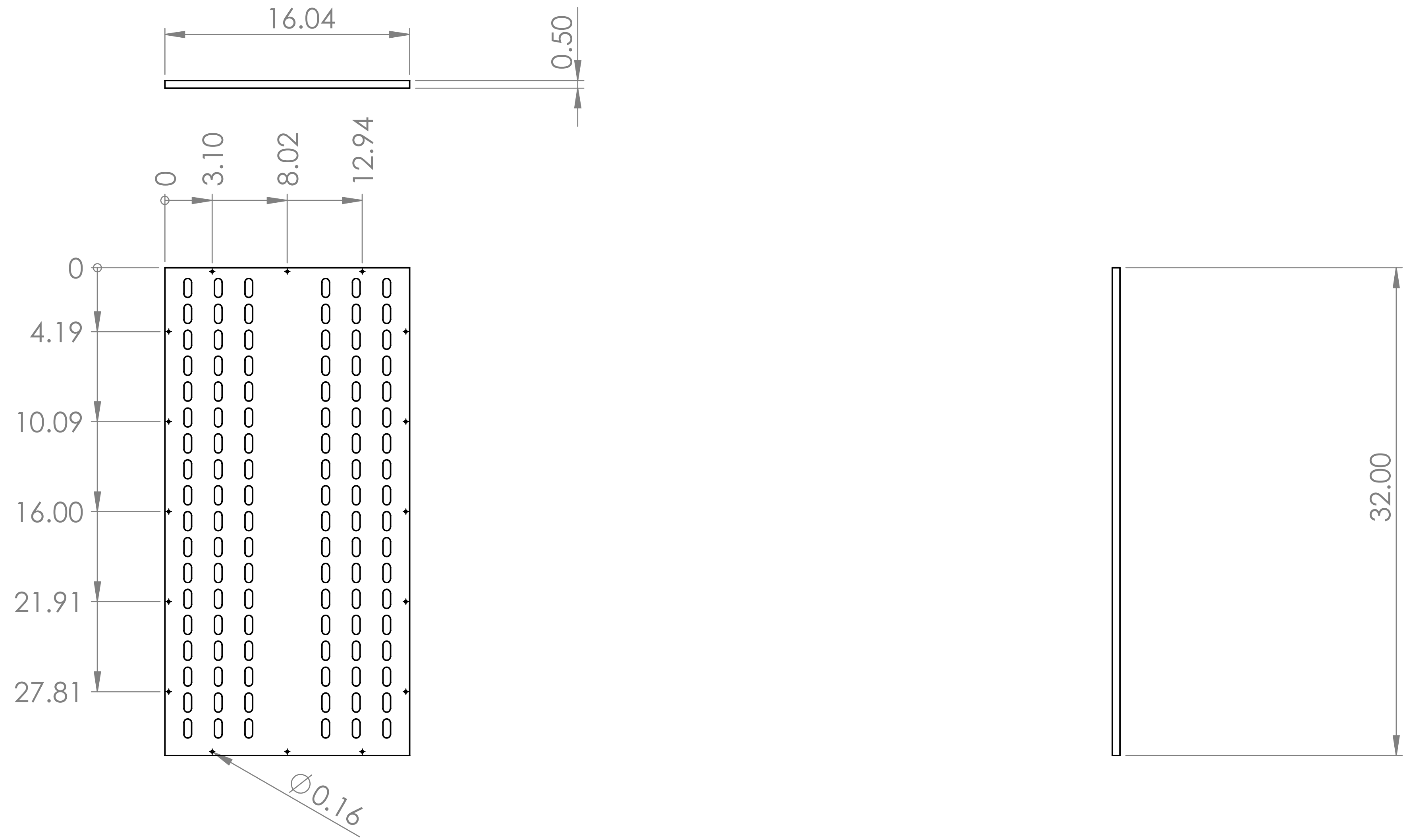
Formula Electric

TITLE:

Front and Back Panel

SIZE	DWG. NO.	REV
A	BP-011	2
SCALE: 1:10		SHEET 1 OF 1

5 4 3 2 1



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			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL Polycarbonate	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

Formula Electric

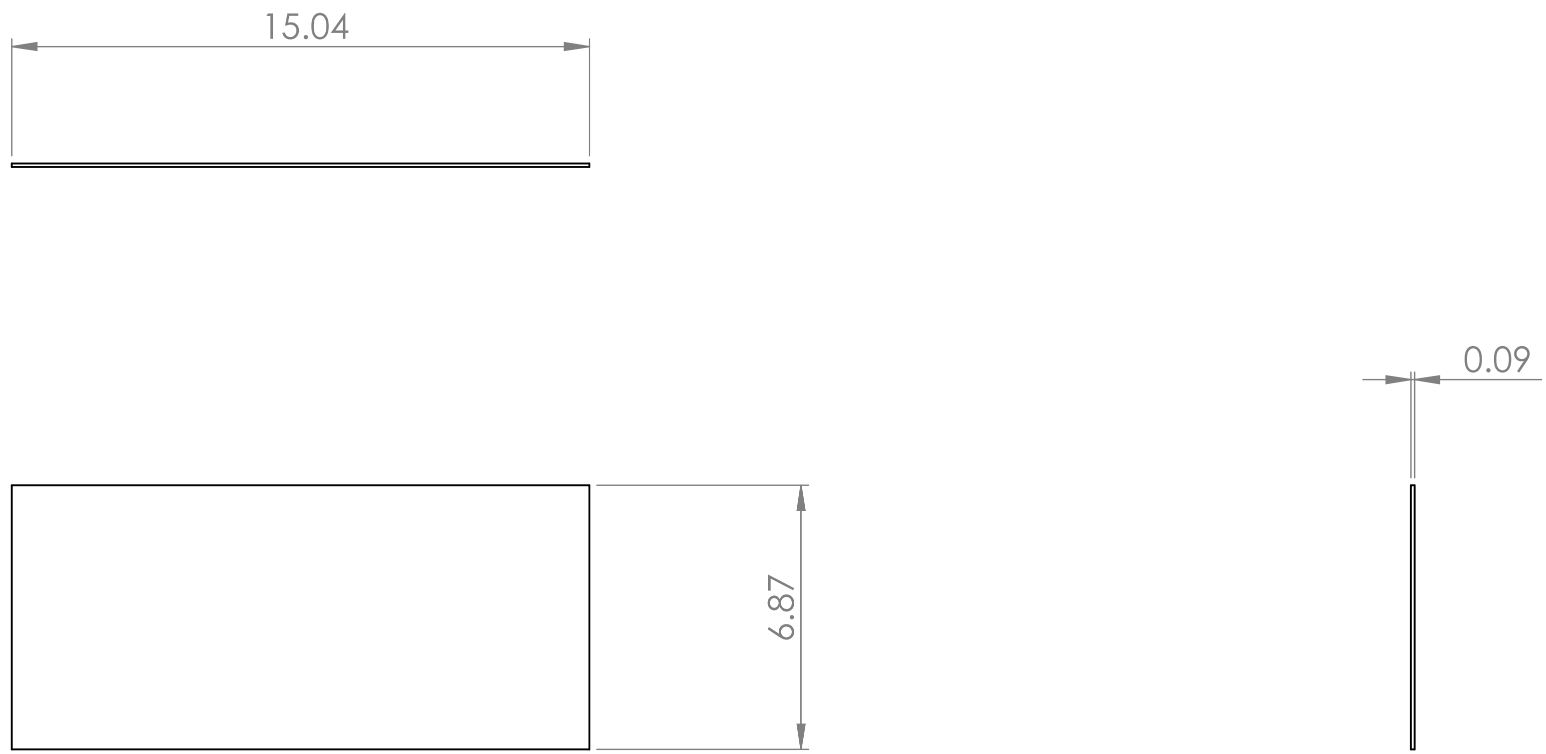
TITLE:

Top and Bottom Panels

SIZE	DWG. NO.	REV
A	BP-012	2

SCALE: 1:10

5 4 3 2 1



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			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL Polycarbonate	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

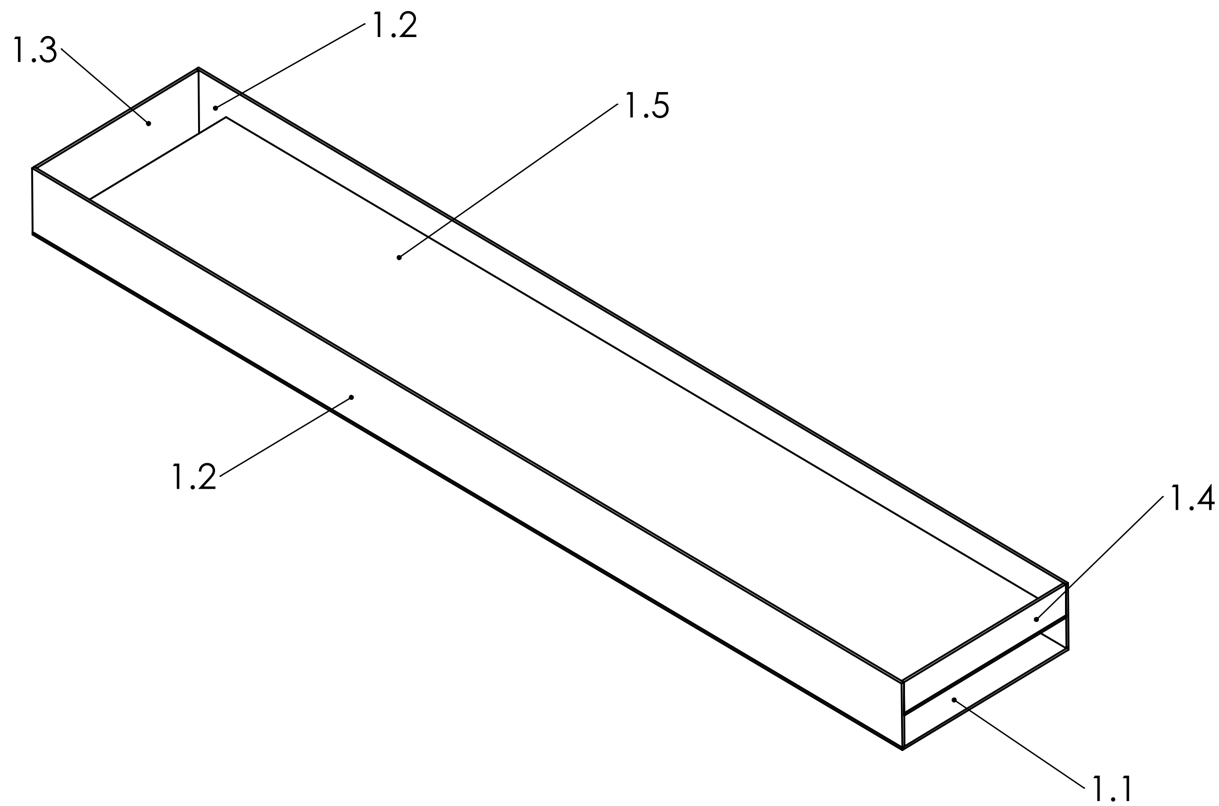
Formula Electric

TITLE:

Cell Divider

SIZE	DWG. NO.	REV
A	BP-013	2
SCALE: 1:5		SHEET 1 OF 1

5 4 3 2 1



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APPLICATION	

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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

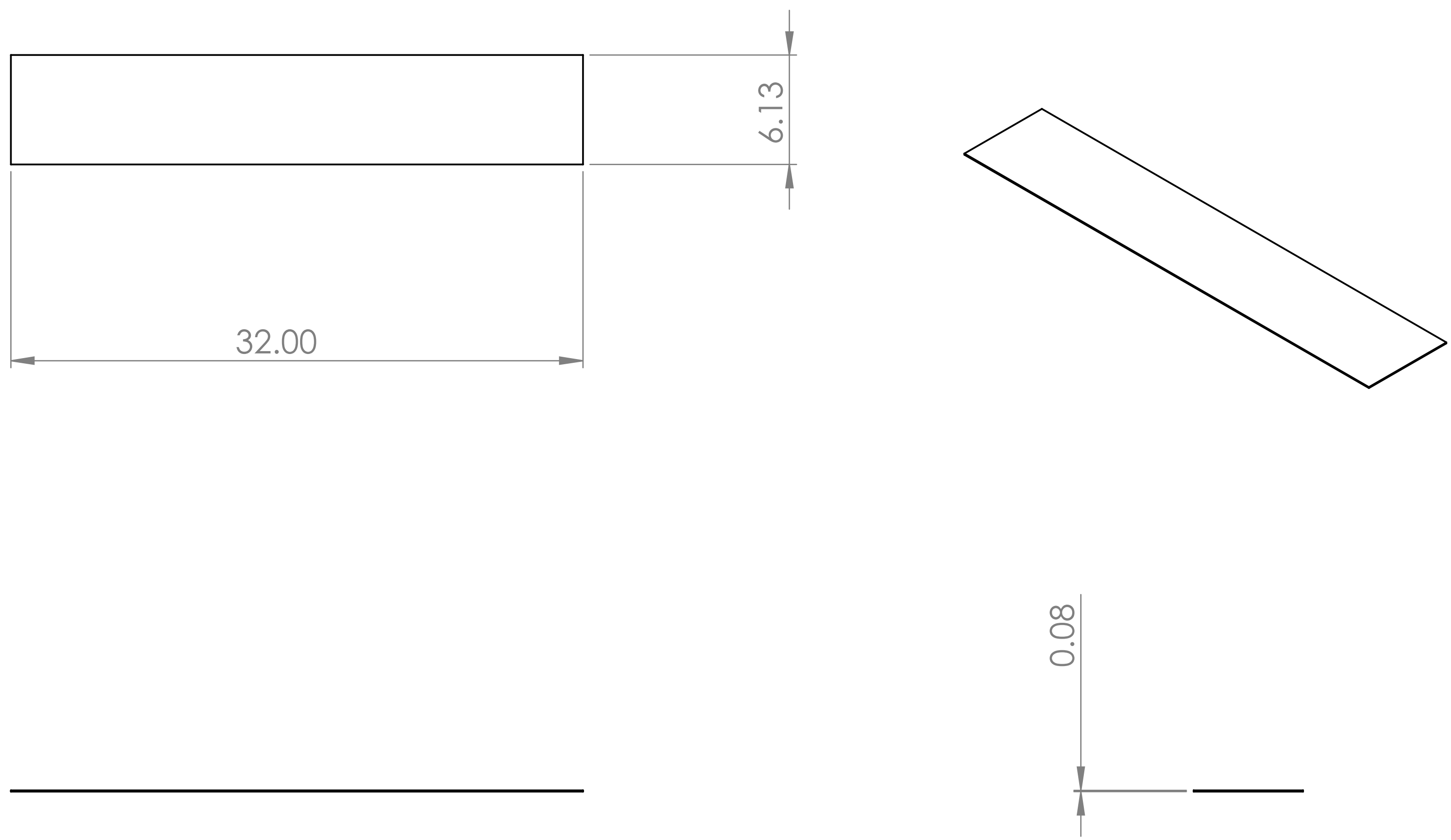
COMMENTS:

TITLE:

Plenum Assembly

SIZE	DWG. NO.	REV
A	1.0	
SCALE: 1:10	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



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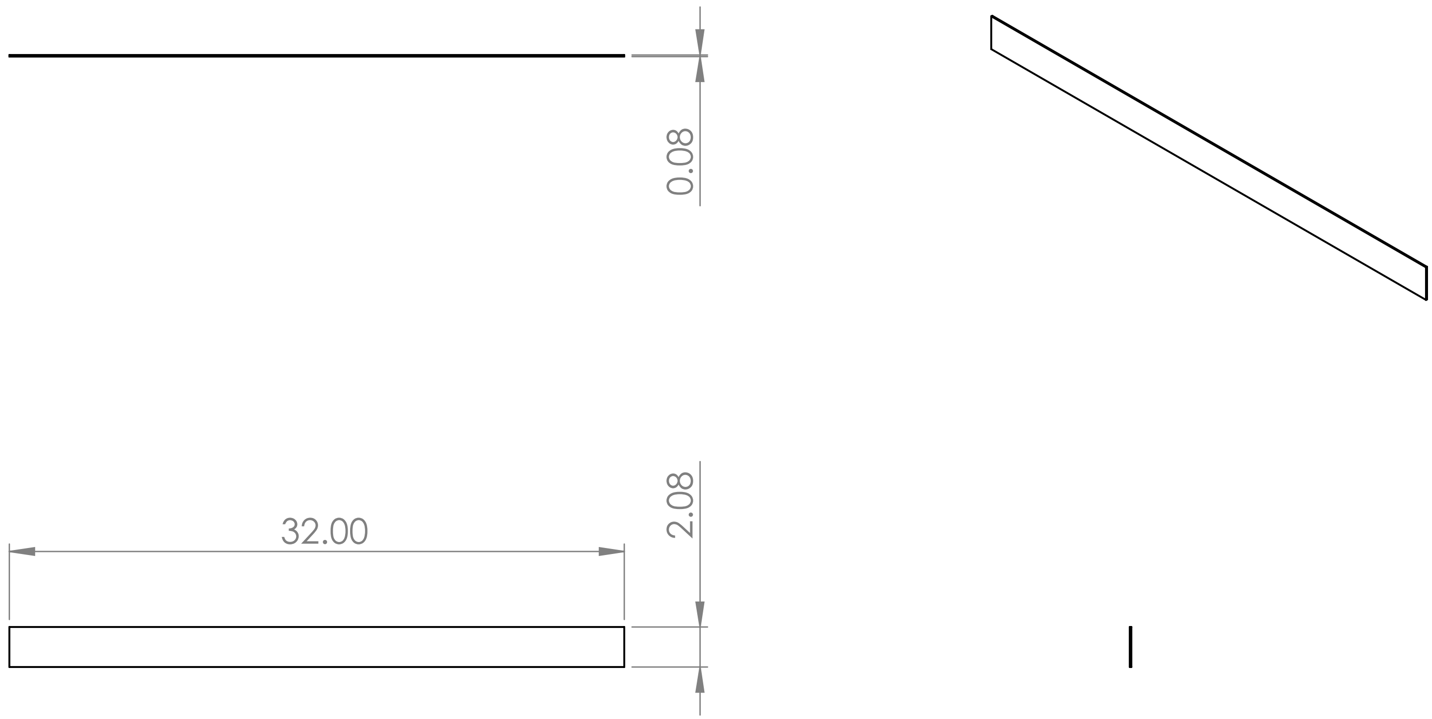
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

Plenum Bottom Plate

SIZE	DWG. NO.	REV
A	1.1	
SCALE: 1:10	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



Plenum Side Panel

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± .01 ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN			TITLE: Plenum Side Panel
	CHECKED			
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE: A · DWG. NO. 1.2 · REV
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:10 · WEIGHT: · SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

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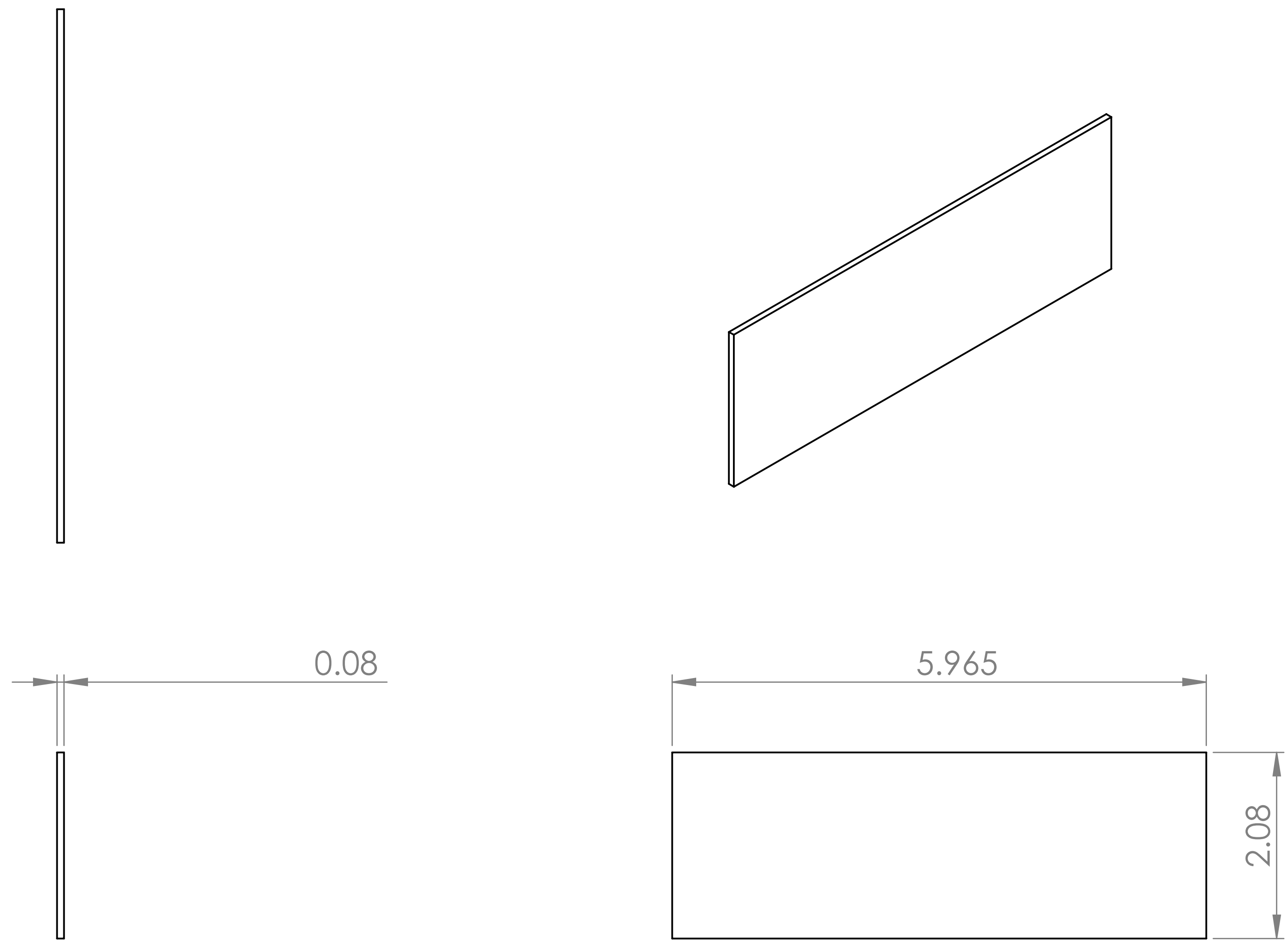
5 4 3 2 1



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APPLICATION	

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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± .01
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

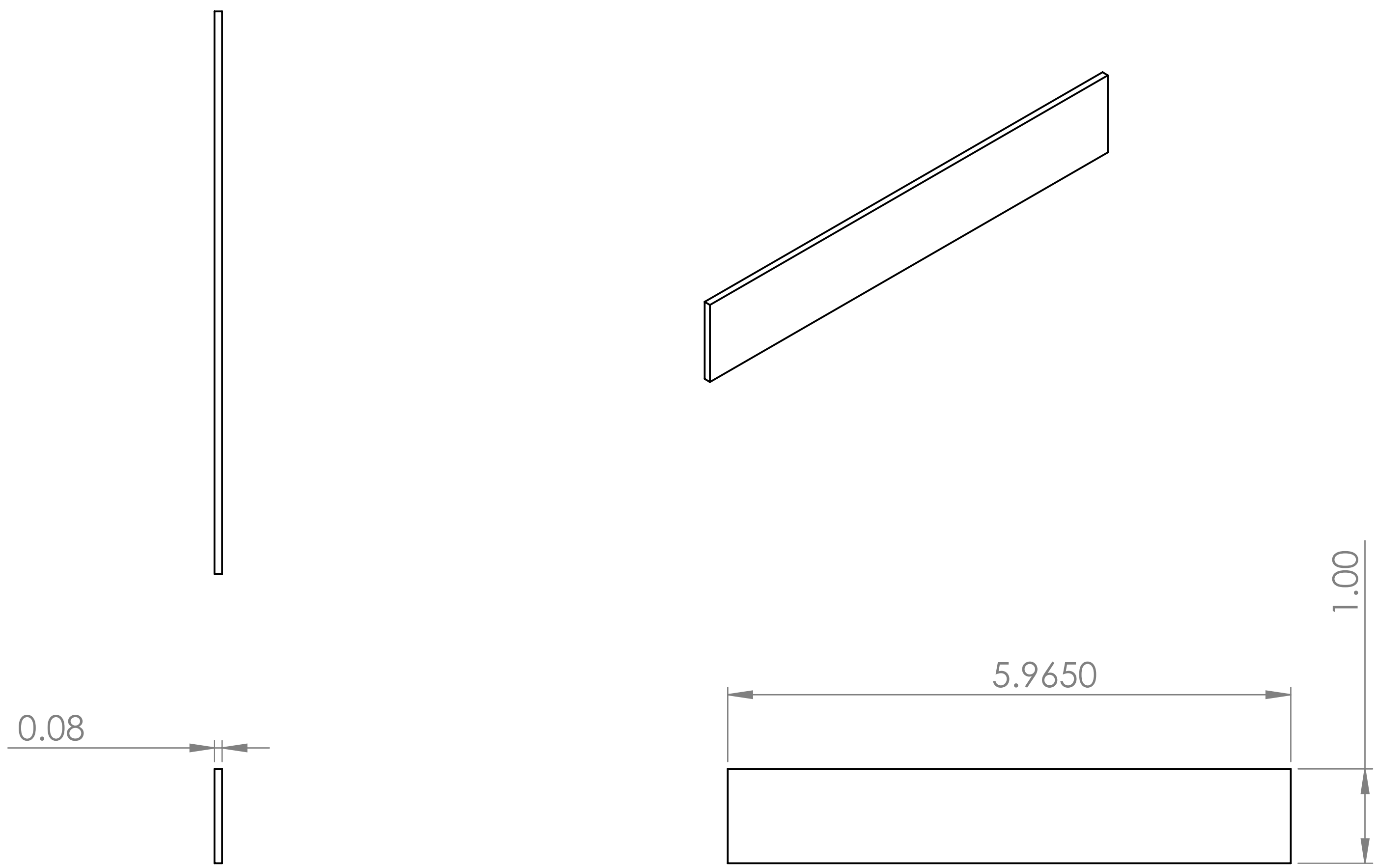
TITLE:

Plenum Back Panel

SIZE A | DWG. NO. 1.3 | REV

SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



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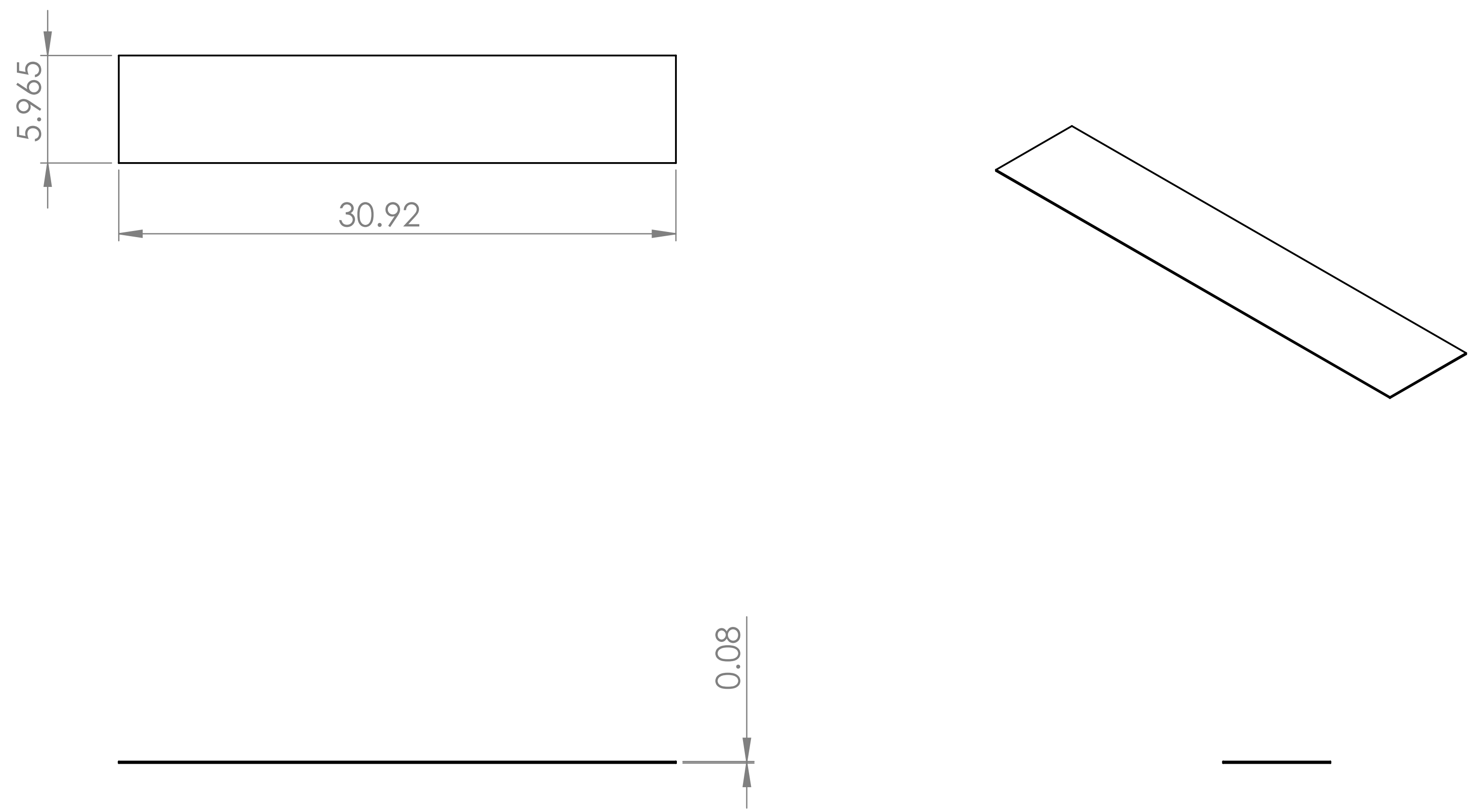
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

Plenum Front Panel

SIZE	DWG. NO.	REV
A	1.4	
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± .01
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

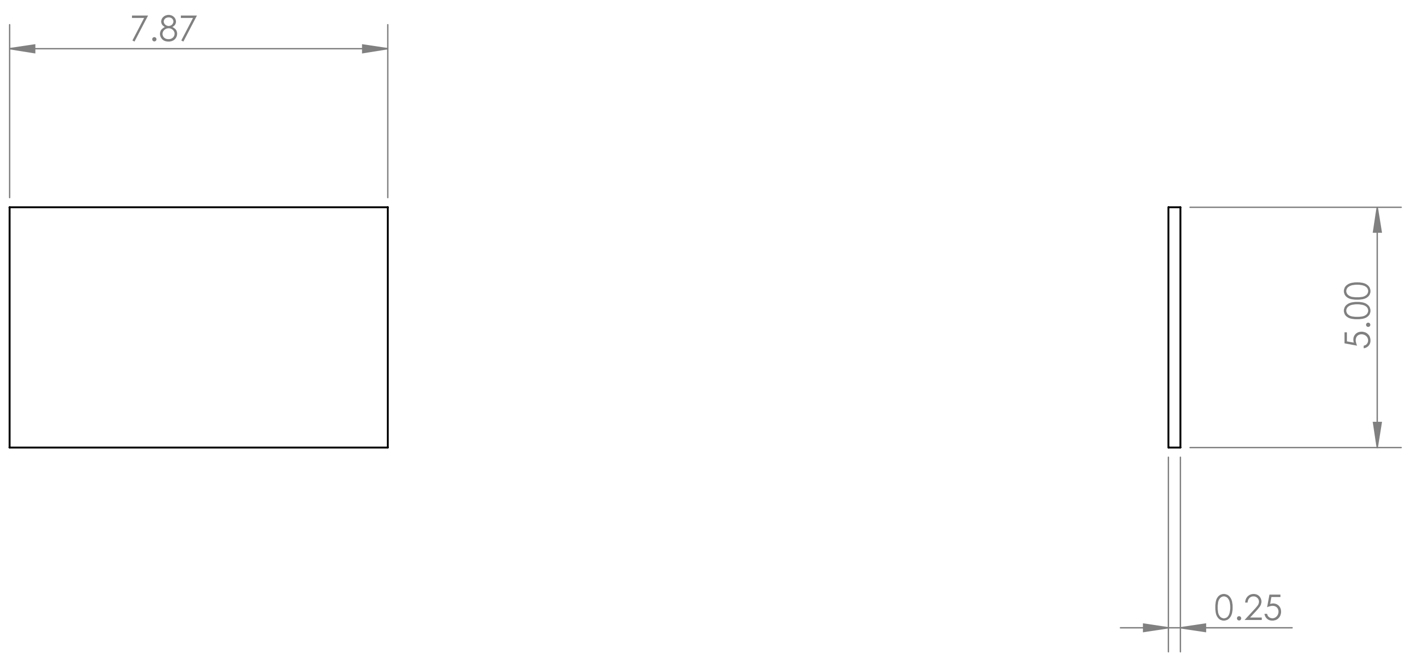
TITLE:

Plenum Divider Plate

SIZE	DWG. NO.	REV
A	1.5	

SCALE: 1:10 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

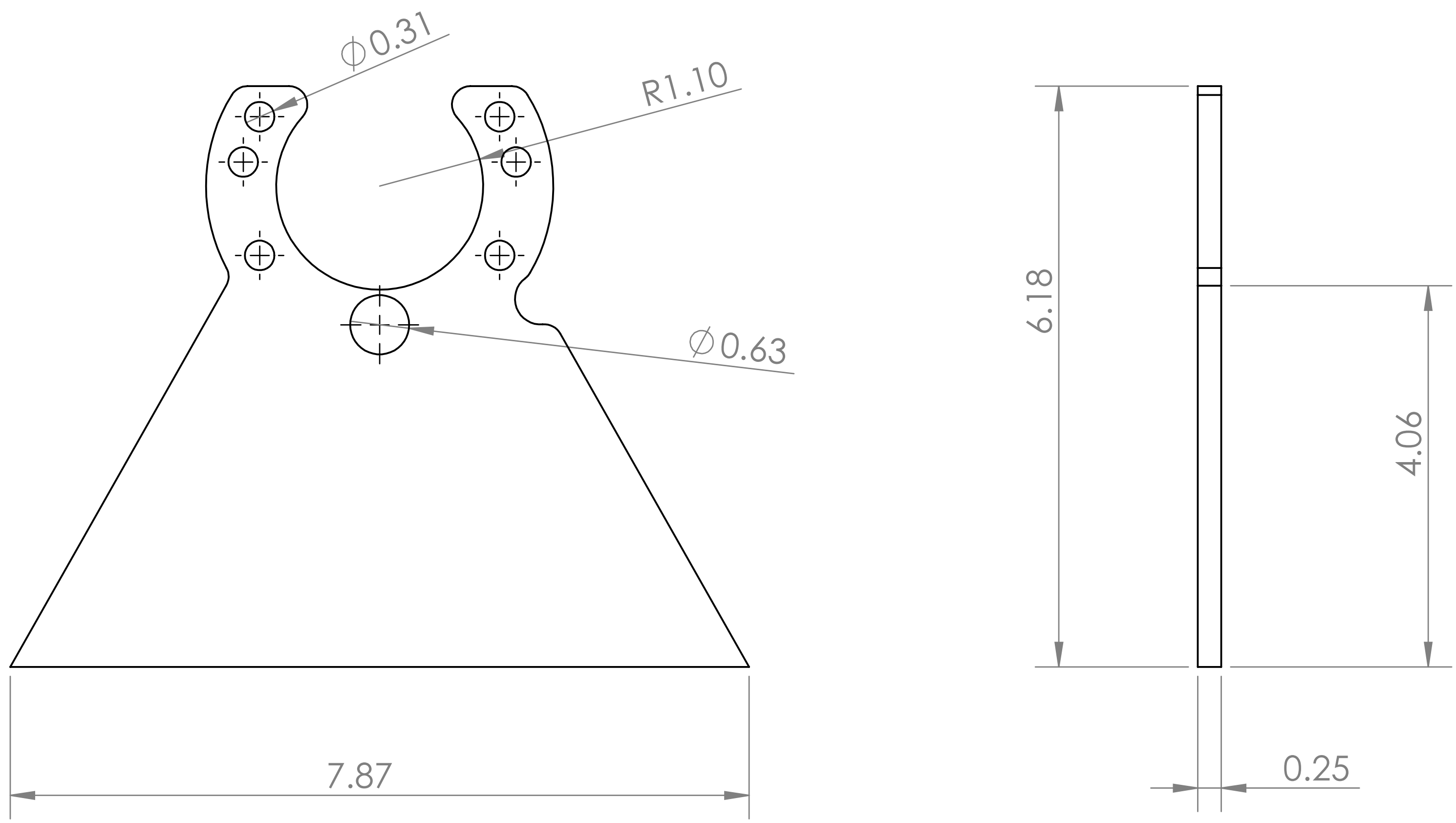
COMMENTS:

TITLE:

SIZE **A** | DWG. NO. | REV

SCALE: 1:4 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



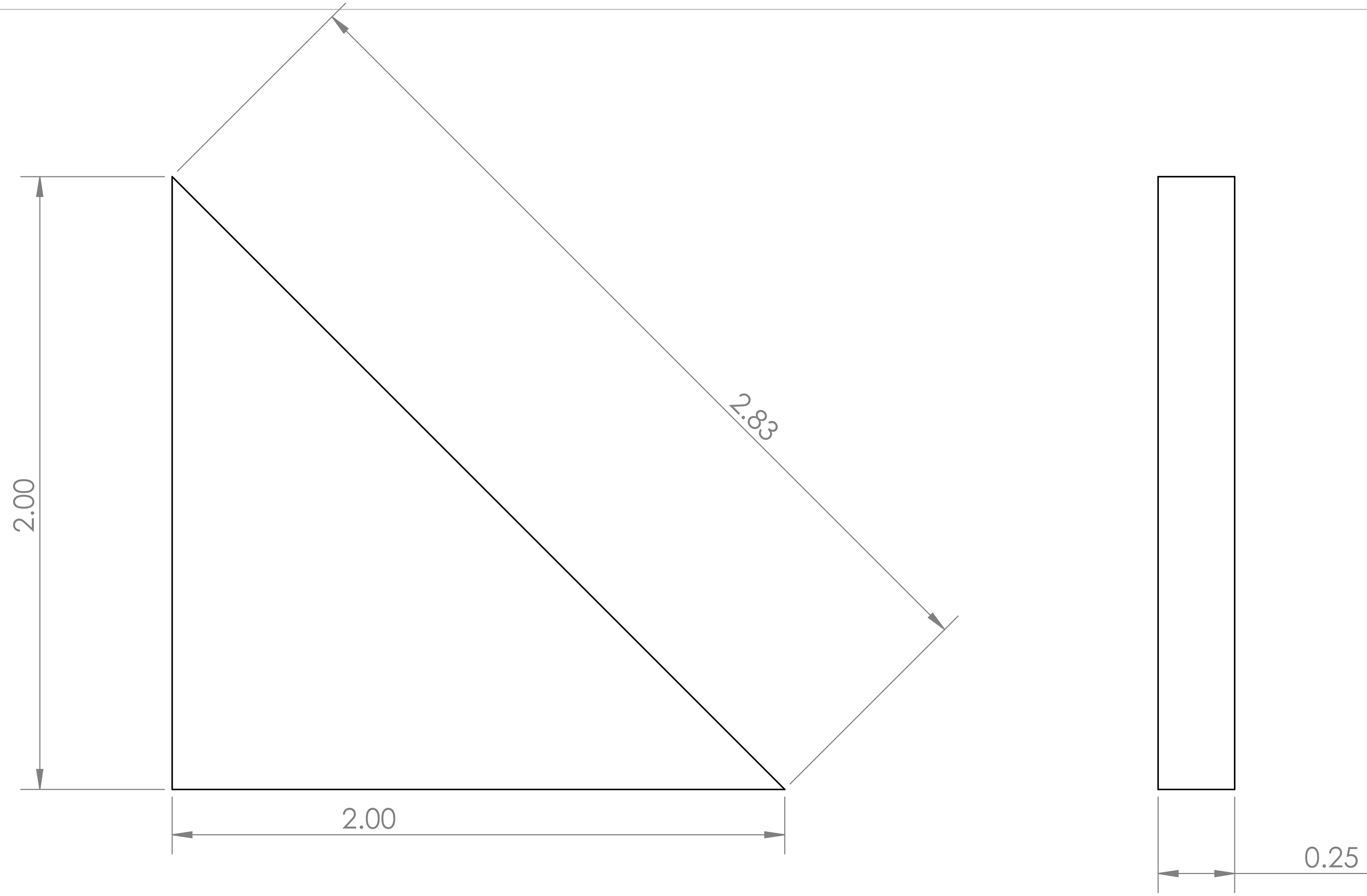
NEXT ASSY	USED ON	UNLESS OTHERWISE SPECIFIED:		
APPLICATION		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±		
		INTERPRET GEOMETRIC TOLERANCING PER:		
		MATERIAL		
		FINISH		
		DO NOT SCALE DRAWING		

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE:

SIZE	DWG. NO.	REV
A		
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



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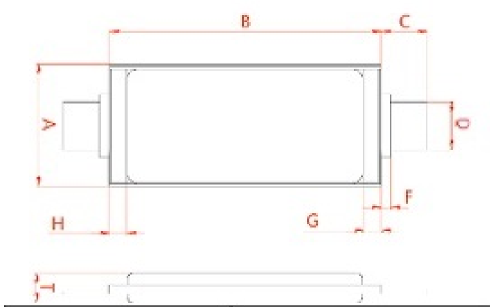
			CHECKED			TITLE:
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL	COMMENTS:			SIZE A · DWG. NO. · REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 2:1 · WEIGHT: · SHEET 1 OF 1

5 4 3 2 1

B Battery Cell Specification Sheet

Edit Date : June.2011

Specification



ITEMS		(mm)	
CELL DIMENSION	T	9.9	+0.2 / -0.2
	A	43.0	+1.0 / -1.0
	B	127.0	+2.0 / -1.0
WEIGHT	gram	Max. 115.0	
	ounce		

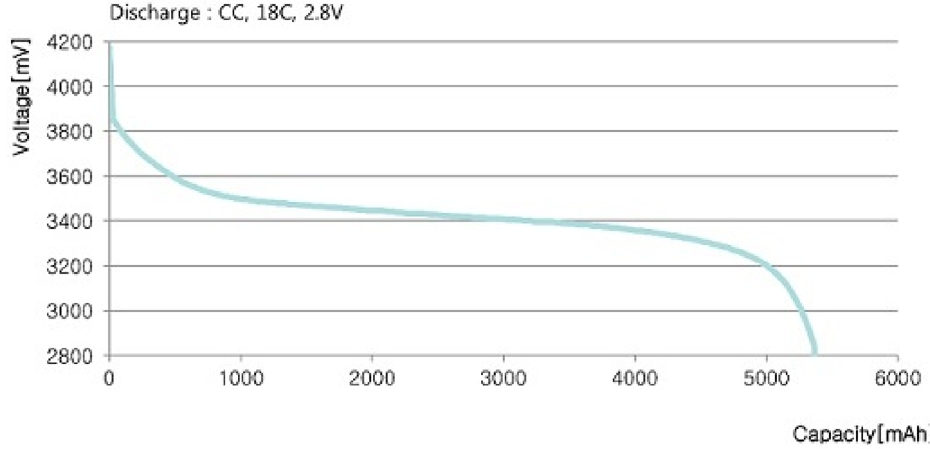
TYPE : Li-ion Polymer Battery		PF9943127SScLP
NOMINAL CAPACITY (mAh)		5400 mAh
NOMINAL VOLTAGE (Volt)		3.7V
IMPEDANCE at 1KHz (mΩ)		Max3.5 mΩ
CHARGE	Nominal Current (A)	2700 (0.5C)
	VOLTAGE (V)	Max. 4.2V
DISCHARGE	CONTINUOUS(A)	Max. 108A (20C)
	BURST(A)	Max. 162A (30C)
	VOLTAGE (V)	Min. 2.8V
CYCLE LIFE	0.5C/0.5C (DOD80%)	500cycle
	Retention	80%
CELL STATUS ON SHIPMENT		Half Charged 3.7V

Rate Characteristics

PF9943127SScLP. 18C Discharging Profile

Charge : CCCV, 0.5C, 4.2V, Cut off = 0.1C

Discharge : CC, 18C, 2.8V



C EMRAX Motor Parameters

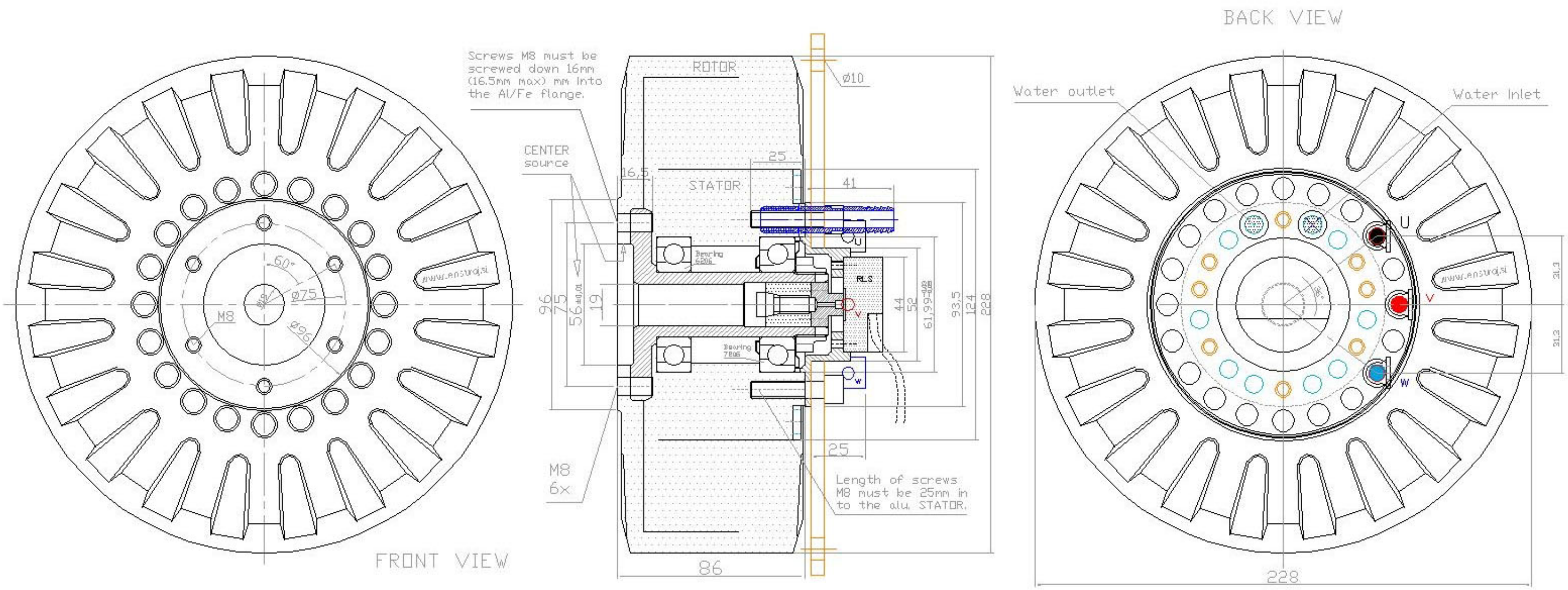


Figure 51: Enstroj EMRAX electric motor physical dimensions.

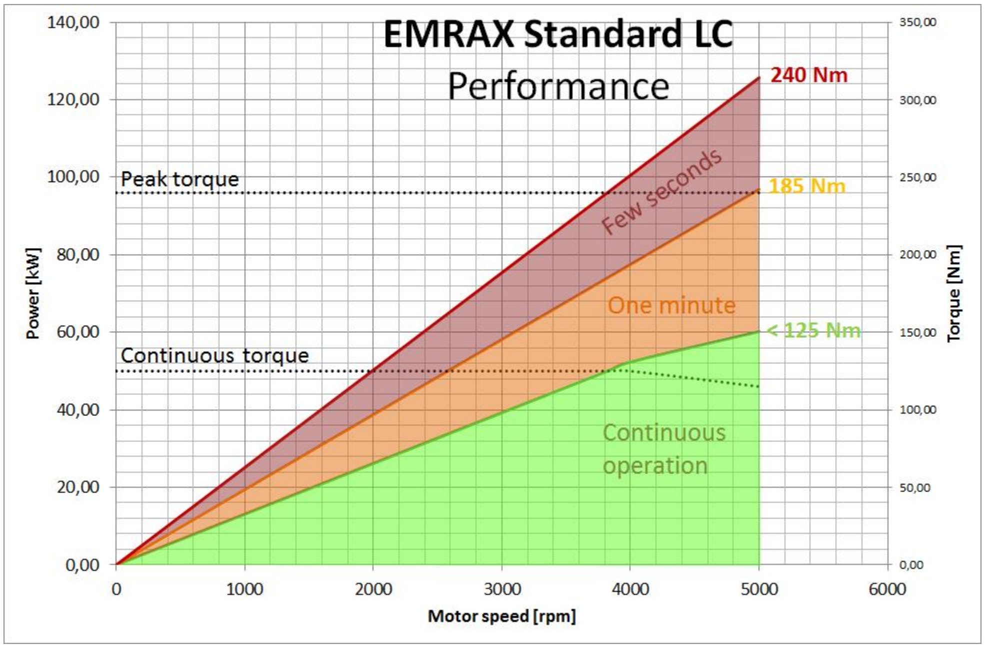


Figure 52: Enstroj EMRAX motor performance.

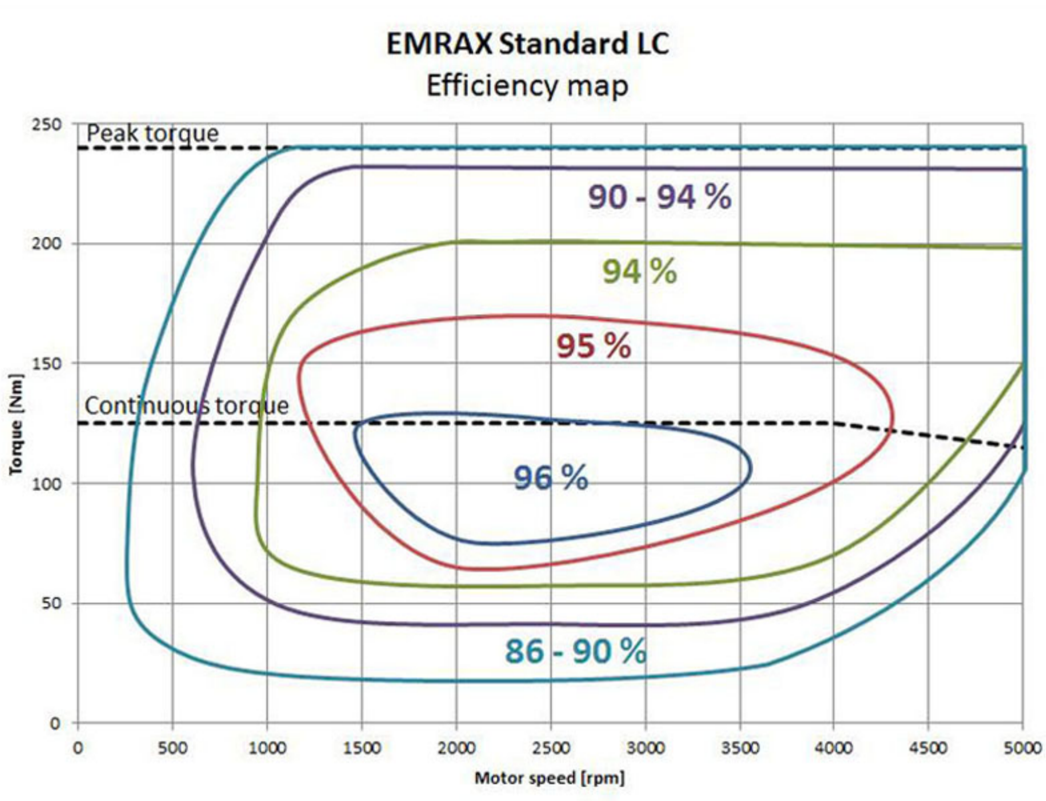


Figure 53: Enstroj EMRAX motor efficiency at varying torque loads.

Table 8: Enstroj EMRAX electric motor physical parameters.

Technical data	EMRAX Standard Liquid Cooled, water, flow 0.2 *L/sec* at 20°C
Weight	12 kg
Dimensions (diameter / width)	228 / 86 mm
Voltage range	50 - 400 Vdc (*600 Vdc)
Peak motor power (for a few seconds)	100 kW
Continuous motor power	30 - 50 kW - depends on the motor rotation
Maximal motor torque (for a few seconds)	240 Nm
Continuous motor torque	128 Nm
Maximal temperature of the copper windings on the stator	110 C
Nominal motor efficiency	93 - 96 % - depends on the motor rotation and torque (current)
Internal phase resistant [at 25C]	18 m
Input phase wire Induction in d/q axis	10,2 mm2 Ld= 175H; Lq= 180H
controller / motor signal	sine wave
Specific idle speed (no load rotation speed)	10 RPM / 1 Vdc
Specific load rotation speed	8,5 to 10 RPM / 1 Vdc depends on the SW settings
Magnetic field weakening	possible up to 20% to get the same power at higher rotation
Magnetic flux	Axial (0,53 Vs)
Temperature sensor in the motor	kty 81/210
Number of pole pairs	10
Ingrees protection	IP21 (we can also make IP54, but peak power is the same, load time is shorter and continuous power is approximately 20 to 30% lower compared to IP21)

D UNITEK BAMOCAR D3-400-400 RS MOTOR CONTROLLER PARAMETERS

Technical Data

Device for EC/AC-motors

Power supply voltage	12V= to 700V=
Auxiliary supply	12V= or (24V=) ± 10% / 4a (2a) Ripple voltage <10%, self-resttable fuse

Data BAMOCAR-D3-400- (700)-	dim.		125/250	200/400	125/250	200/400
Rated supply voltage	V=		24 bis max .400		24 bis max .700	
Rated output voltage	V~eff		to 3x260		to 3x450	
Continue current rms	A_{eff}		125	200	125	200
Peak current	A_{io}		250	400	250	400
Dissipation max.	kW		2	3	2.6	4
Clock frequency	kHz		8-24		8-16	
Level Over voltage	V=		440		800	
External fusing	A		160	250	160	250
Weight	kg		5.8	6,8	5.8	6.8
Dimension HxWxD	mm	403x250x145				
Size			2	2	2	2

Device for DC-Motors

Power supply voltage	12V= to 400V=
Auxiliary supply	12V= or (24V=) ± 10% / 4a (2a) Ripple voltage <10%, self-resttable fuse

Data BAMOCAR-D2-	dim.		125/250	200/400		
Rated supply voltage	V=	24 bis max. 400				
Rated output voltage	V=	20 to 360				
Continue current rms	A=		125	200		
Peak current	A_{io}		250	400		
Dissipation max.	kW		2	3		
Clock frequency	kHz	8-16				
Level Over voltage	V=	programable to max 440v				
External fusing	A		160	250		
Weight	kg		5.8	6,8		
Dimension HxWxD	mm	403x250x145				
Size			2	2		

Input / Outpu	v	A	Funktion	Connector
Analog Input	± 10	0.005	Differential input	x1
Digital input ON OFF	10-30 <6	0.010 0	Logic io (opto)	x1
Digital output	+24	1	Transitor-output open emitter (opto)	x1
Resolver input			Differential input	x7
Encoder input	>3.6v		Opto	x7
Encoder output	>4.7v		Opto	x8
CAN-interface			Logik io (opto)	x9
RS232-interface			Logik io	x10

Ambient conditions	
Enclosure protection	IP65
Norms	EN 60204, ISO 16750
Ambient temperature	-10 to +45°C
Maximum ambient temperature	-30 to +65 ab +45°C to +65°C with power derating 2%/°C
Storage temperature	-30°c to +80°c
Humidity in operation	Klasse F rel. humidity <85% ,**no condensation !**
Site altitude	≤ 1000m ü.nn 100%, >1000m with power derating 2%/100m
Cooling	liquid cooler max 65°c , 12 l/min , precher max 1,3 bar
Mounting position	equal

Program	Type	Software-version	
BAMOCAR-D3(D2)-xx-rs	resolver		
BAMOCAR-D3-(D2)xx-in	encoder-ttl		
BAMOCAR-D3-(D2)xx-sc	encoder-sincos 1vss		
BAMOCAR-D3-(D2)xx-bl	rotorlage+bl-tacho		
BAMOCAR xx-DC	dc-tacho, armature voltage		

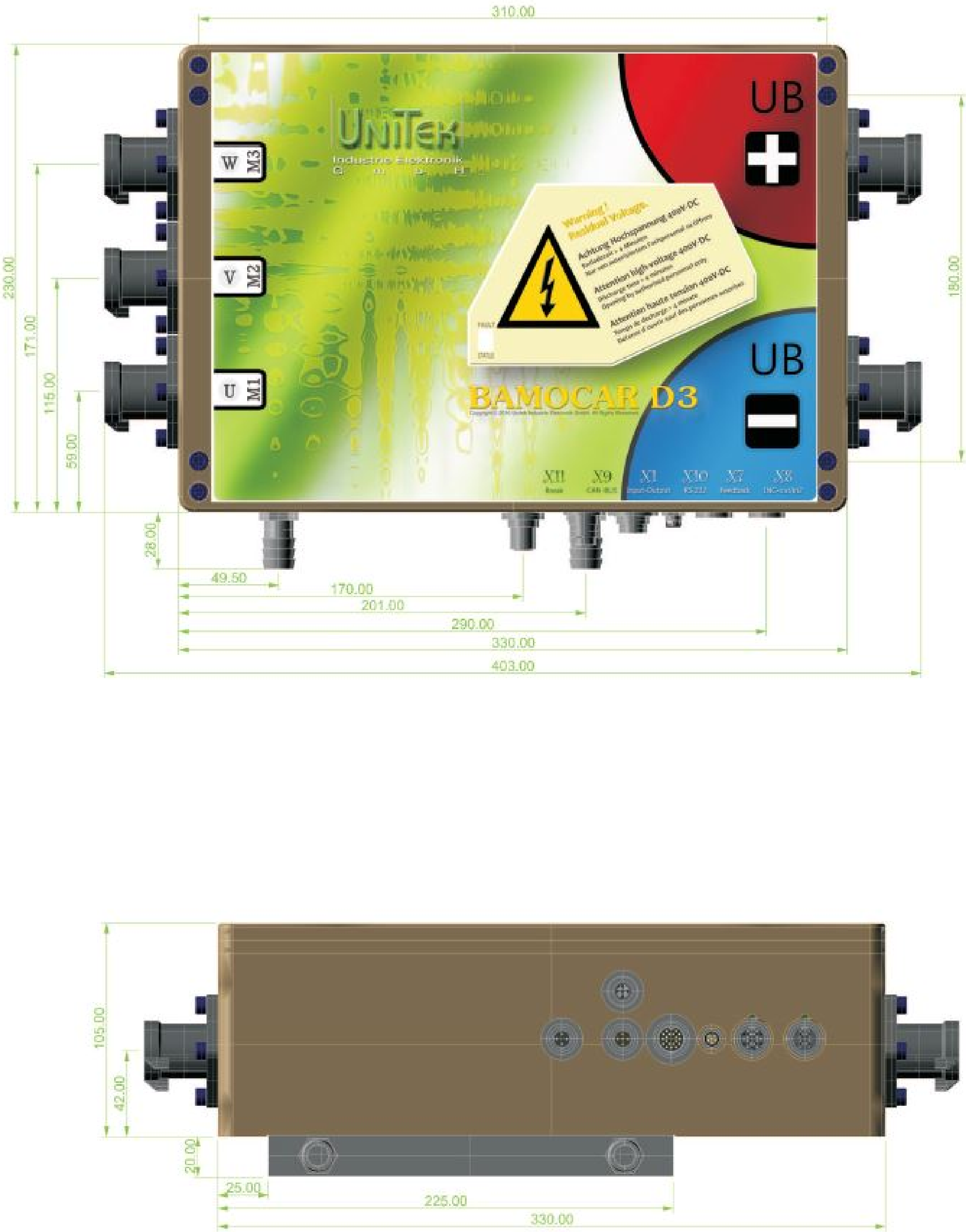


Figure 54: Unitek Bamocar D3 motor controller physical dimensions. Units are in *mm*.

Makrolon® GP sheet

General purpose

Makrolon® GP sheet is a polished surface, UV stabilized, transparent polycarbonate product. It features outstanding impact strength, superior dimensional stability, high temperature resistance, and high clarity. This lightweight thermoformable sheet is also easy to fabricate and decorate. Makrolon GP sheet is offered with a five (5) year Limited Product Warranty against breakage. The terms of the warranty are available upon request.

Applications

Industrial glazing, machine guards, structural parts, thermoformed and fabricated components

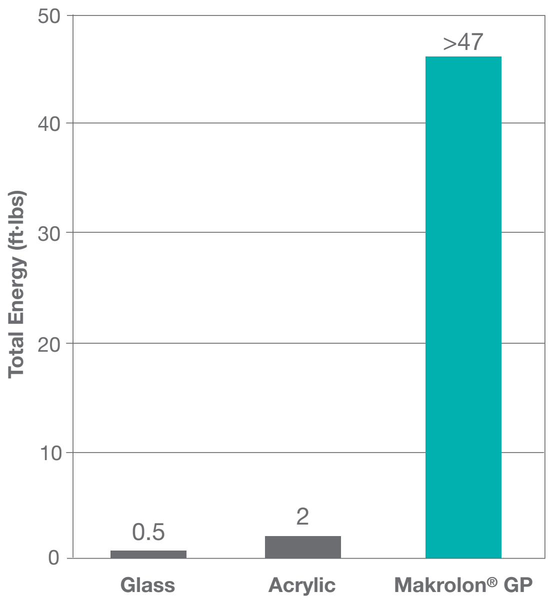
Typical Properties

Property	Test Method	Units	Values
PHYSICAL			
Specific Gravity	ASTM D 792	–	1.2
Refractive Index	ASTM D 542	–	1.586
Light Transmission, Clear @ 0.118″	ASTM D 1003	%	86
Light Transmission, I30 Gray @ 0.118″	ASTM D 1003	%	50
Light Transmission, K09 Bronze @ 0.118″	ASTM D 1003	%	50
Light Transmission, I35 Dark Gray @ 0.118″	ASTM D 1003	%	18
Water Absorption, 24 hours	ASTM D 570	%	0.15
Poisson's Ratio	ASTM E 132	–	0.38
MECHANICAL			
Tensile Strength, Ultimate	ASTM D 638	psi	9,500
Tensile Strength, Yield	ASTM D 638	psi	9,000
Tensile Modulus	ASTM D 638	psi	340,000
Elongation	ASTM D 638	%	110
Flexural Strength	ASTM D 790	psi	13,500
Flexural Modulus	ASTM D 790	psi	345,000
Compressive Strength	ASTM D 695	psi	12,500
Compressive Modulus	ASTM D 695	psi	345,000
Izod Impact Strength, Notched @ 0.125″	ASTM D 256	ft·lbs/in	18
Izod Impact Strength, Unnotched @ 0.125″	ASTM D 256	ft·lbs/in	60 (no failure)
Instrumented Impact @ 0.125″	ASTM D 3763	ft·lbs	>47
Shear Strength, Ultimate	ASTM D 732	psi	10,000
Shear Strength, Yield	ASTM D 732	psi	6,000
Shear Modulus	ASTM D 732	psi	114,000
Rockwell Hardness	ASTM D 785	–	M70 / R118
THERMAL			
Coefficient of Thermal Expansion	ASTM D 696	in/in/°F	3.75×10^{-5}
Coefficient of Thermal Conductivity	ASTM C 177	BTU·in/hr·ft²·°F	1.35
Heat Deflection Temperature @ 264 psi	ASTM D 648	°F	270
Heat Deflection Temperature @ 66 psi	ASTM D 648	°F	280
Brittleness Temperature	ASTM D 746	°F	-200
Shading Coefficient, clear @ 0.236″	NFRC 100-2010	–	0.97
Shading Coefficient, Gray or Bronze @ 0.236″	NFRC 100-2010	–	0.77
U factor @ 0.236″ (summer, winter)	NFRC 100-2010	BTU/hr·ft²·°F	0.85, 0.92
U factor @ 0.375″ (summer, winter)	NFRC 100-2010	BTU/hr·ft²·°F	0.78, 0.85
ELECTRICAL			
Dielectric Constant @ 10 Hz	ASTM D 150	–	2.96
Dielectric Constant @ 60 Hz	ASTM D 150	–	3.17
Volume Resistivity	ASTM D 257	Ohm·cm	8.2×10^{16}
Dissipation Factor @ 60 Hz	ASTM D 150	–	0.0009
Arc Resistance			
Stainless Steel Strip electrode	ASTM D 495	Seconds	10
Tungsten Electrodes	ASTM D 495	Seconds	120
Dielectric Strength, in air @ 0.125″	ASTM D 149	V/mil	380
FLAMMABILITY			
Horizontal Burn, AEB	ASTM D 635	in	<1
Ignition Temperature, Self	ASTM D 1929	°F	1022
Ignition Temperature, Flash	ASTM D 1929	°F	824
Flame Class @ 0.060″	UL 94	–	HB

*Typical properties are not intended for specification purposes.
**Some properties characterized using non-textured sheet.

Makrolon® GP sheet

Impact Resistance*



*Instrumented Impact per ASTM D 3763, sample thickness 0.125˝ nominal

Standard Products Comparison

Property		Polycarbonate	Acrylic	Glass
Impact Resistance	Drop Ball Test, 0.5 lb	No Break	1.75 ft·lbs	0.7 ft·lbs
Cold Bend	Bend Radius	100x material thickness	180x material thickness	Not possible
Sheet Weight	0.125˝	0.78 lb/ft^2	0.75 lb/ft^2	1.60 lbs/ft^2
Thermal Expansion Rate	–	3.75 x 10^{-5} in/in/°F	4.10 x 10^{-5} in/in/°F	5.0 x 10^{-6} in/in/°F
Shading Coefficient	0.236˝ clear sheet	0.97	1.01	1.03
U Factor – Summer U Factor – Winter	0.236˝	0.85 BTU/hr·ft^2·°F 0.92 BTU/hr·ft^2·°F	0.83 BTU/hr·ft^2·°F 0.91 BTU/hr·ft^2·°F	0.92 BTU/hr·ft^2·°F 1.02 BTU/hr·ft^2·°F
Sound Transmission Class	0.236˝	29	30	27

Regulatory code compliance and certifications

- ICC-ES Evaluation Report ESR-2728
- Miami-Dade NOA #12-0605.05
- CPSC 16 CFR 1201 Category I and Category II: Safety Standard for Architectural Glazing Materials
- ANSI Z97.1-2004: American National Standard for Safety Glazing Materials Used in Buildings - Safety Performance Specifications and Methods of Test. Class A
- UL 972: Burglary Resistant Glazing Materials, UL File #BP2126
- UL 94: Flammability, UL File #E351891

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F BUDGET

Budget Update

TEAM	Formula Electric
Date	6/13/2013
Updated by	Jackson Smith

INCOME

Category	Source	Sought	Committed	Pending	
Grants	School of Engineering	$3,500.00	$3,500.00	$0.00	
	Dean's fund	$4,000.00	$4,000.00	$0.00	
Fundraising	IEEE	$3,000.00	$2,500.00	$0.00	
	Fox Racing	$5,350.00	$5,350.00	$0.00	
	SAE	$1,000.00	$400.00	$0.00	
	Xerox	$1,200.00	$1,200.00	$0.00	
	Pacific Traders	$1,000.00	$1,000.00	$0.00	
	TOTAL	$19,050.00	$17,950.00	$0.00	$17,950.00

EXPENSES

Category	Description	Estimated	Spent	Pending	**Sub-Total**
Battery Pack	Cells	$4,875.22	$4,875.22	$0.00	
	Polycarbonate (1/2")	$417.63	$417.63	$0.00	
	Polycarbonate (1/4")	$110.00	$110.00	$0.00	
	Polycarbonate (3/32")	$200.00	$137.43	$0.00	
	Connectors	$254.32	$313.15	$0.00	
	BMS Components	$1,919.00	$1,919.00	$0.00	
	Contactors*	$450.00	$0.00	$0.00	
	Contactor Insulation	$15.00	$17.69	$0.00	
	Misc. Bolts	$14.87	$14.87	$0.00	
	Misc. Nuts	$4.27	$4.27	$0.00	
	Misc. Electrical	$146.74	$146.74	$0.00	
	M4 x 45 Screws	$5.23	$5.23	$0.00	
	PCB manufacturing	$199.56	$199.56	$0.00	
	Charger Reprogram	$45.00	$45.00	$0.00	
	Garolite (1/32")	$17.02	$17.02	$0.00	
	High-Voltage Gloves	$57.33	$57.33	$0.00	**$8,280.14**
Battery Pack Cooling	Duraplex (Acrylic Sheet)	$40.00	$40.00	$0.00	**$40.00**
Motor	AC Induction Motor	$3,994.51	$3,994.51	$0.00	
	Inlet Pipe	$91.45	$91.45	$0.00	
	Shipping Box	$65.32	$65.32	$0.00	
	Resolver	$509.50	$509.50	$0.00	**$4,660.78**
Controller	Motor Controller	$2,698.89	$2,698.89	$0.00	
	(5) Power Conector	$627.07	$627.07	$0.00	
	Feed Back Conector	$32.92	$32.92	$0.00	
	Steder rund M18	$25.87	$25.87	$0.00	
	Can Conector	$19.60	$19.60	$0.00	
	Kabel RS232	$52.26	$52.26	$0.00	
	Shipping	$150.00	$40.00	$0.00	
	Customs	$599.00	$599.00	$0.00	**$4,095.61**
Test Bench	CBA 4 (Computerized Battery Analyzer)	$218.00	$218.00	$0.00	
	AeroMicro - Deans	$7.06	$7.06	$0.00	
	Home Depot - Wire	$4.40	$4.40	$0.00	
	Lowe's - Wire	$9.79	$9.79	$0.00	
	Tap Plastics - Samples	$14.86	$14.86	$0.00	
	Home Depot - Bucket	$17.66	$17.66	$0.00	
	West Mount. Adapter	$18.95	$19.85	$0.00	**$291.62**
	TOTAL	$17,909.35	$17,348.30	$0.00	$17,348.30
	Net Reserve (Deficit)		$601.70	$0.00	$601.70

*donation

G MATLAB SCRIPTS

Battery Pack Enclosure Shear Calculations

```
function Enclosureshear(bnum,Nfs)
%Shear Test of Bolted Fasteners on Enclosure Wall
%
%   The purpose of this function is to allow the user to determine the
%   necessary number of 3M bolts to support the accumulator enclosure
%   plates from failing in shear.
%
%   bnum = number of bolts used in fastening the plate
%   Nfs  = factor of safety
%
%
%
% Variables
m=100; %% (kg) This is the weight of content of the enclosure
g=9.81; %% (m/sec^2) Gravitational constant

%% Deceleration that the enclosure must be able to withtand
gdec=20*g;

%% (m) thickness of polycarbonate
t=0.0127;

%% (m) width of plate
b=.6096;

%% (m) height of plate
a=.3048;

%% (Pa) modulus of elasticity of Polycarbonate
E=2.344*10^9;

%% force on plate during deceleration
F=gdec*m;

%% pressure on area of front plate
q=F/(a*b);

boltw=.003; %%(m) bolt width that is in contact with sheet
```

```
%% (m) bolt length that is in contact with sheet thickness (t)
boltl=.0127;

boltarea=boltw*boltl; %%(m^2) bolt area supporting  sheet
sigmayp=2.4*10^8;  %%yield point strength(McMaster-Carr)
tauyp=0.6*sigmayp;  %%yield point shear strength(McMaster-Carr)

%plate deflection and stress applied on it by 20g force

s=(q*a^2)/(2*t^2*(.623*((a/b)^6)+1))/10^6;  %% (MPa) maximum stress

% (um) deflection of front plate due to pressure q
w=(.0284*q*a^4)/(E*t*(1.056*((a/b)^5)+1))*10^6;

%Failure Test

leftside=F/(boltarea*bnum);
rightside=tauyp/Nfs;

if leftside > rightside
    display('fails')
else
    display('safe')
end

LS=leftside/10^6;  %% (MPa) conversion from Pa to MPa
RS=rightside/10^6; %% (MPa) conversion from Pa to MPa

fprintf('stress= %0.2f MPa \r',s)
fprintf('deflection= %0.2f um \r',w)
fprintf('20g Force on plate= %d N \r',F)
fprintf('failure equation RS= %0.2f MPa \r',RS)
fprintf('failure equation LS= %0.2f MPa \r',LS)
end
```

Screw Thread Pullout Shear Calculations

```
function threadpullout(Le,bnum,bsize,N)
%Thread Pullout Test
%Formula Electric
%
%
%
% all screw dimensions from Engineersedge.com
if bsize==4   %% data for M4 bolt
    Kn=3.220; %%(mm) maximum minor diameter of internal threads
    Es=3.433; %%(mm) minimum pitch diameter of external threads
    En=3.523; %%(mm) maximum pitch diameter of internal threads
    Ds=3.838; %%(mm) minimum major diameter of external threads
    p=0.7;    %%(mm) pitch of a M4 bolt
    n=1/p;    %%(threads/mm) threads per millimeter
    display('M4')
elseif bsize==3%% data for M3 bolt
    Kn=2.439; %%(mm) maximum minor diameter of internal threads
    Es=2.580; %%(mm) minimum pitch diameter of external threads
    En=2.655; %%(mm) maximum pitch diameter of internal threads
    Ds=2.874; %%(mm) minimum major diameter of external threads
    p=0.5;    %%(mm) pitch of a M3 bolt
    n=1/p;    %%(threads/mm) threads per millimeter
    display('M3')
elseif bsize==2%% data for M2 bolt
    Kn=1.548; %%(mm) maximum minor diameter of internal threads
    Es=1.654; %%(mm) minimum pitch diameter of external threads
    En=1.721; %%(mm) maximum pitch diameter of internal threads
    Ds=1.886; %%(mm) minimum major diameter of external threads
    p=0.4;    %%(mm) pitch of a M2 bolt
    n=1/p;    %%(threads/mm) threads per millimeter
    display('M2')
end

%thread contact areas

%%(mm^2) thread contact area for external threads
As=pi*n*Le*Kn*((1/(2*n))+0.57735*(Es-Kn));

%%(mm^2) thread contact area for internal threads
An=pi*n*Le*Ds*((1/(2*n))+0.57735*(Ds-En));
```

```
TSe=2.4*10^8;     %%(Pa) external material yield strength
TSi=5.500*10^7;  %%(Pa) internal material yield strength
TAUe=TSe*.6;      %%(Pa) external material shear strength
TAUi=TSi*.6;      %%(Pa) internal material shear strength

g=9.81; %%gravitational constant
gdec=20*g; %%(m/sec^2) 20 g deceleration
m=100; %%(kg) mass of the contents of the enclosure
F=m*gdec;

LSe=F/(bnum*As/10^6); %% left side of shear failure test for fastener
RSe=TAUe/N;           %% right side of shear failure test for fastener
LSi=F/(bnum*An/10^6); %% left side of shear failure test for material
RSi=TAUi/N;           %% right side of shear failure test for material


%%Provides feedback for Shear Failure Equation
if LSe<=RSe
    display('Bolts:safe')
elseif LSe>RSe
    display('Bolts:fails')
end
if LSi<=RSi
    display('Material:safe')
elseif LSi>RSi
    display('Material:fails')
end
fprintf('Force= %d N \r',F)
end
```