James Madison Undergraduate Research Journal

Volume 1 | Issue 1

2013-2014

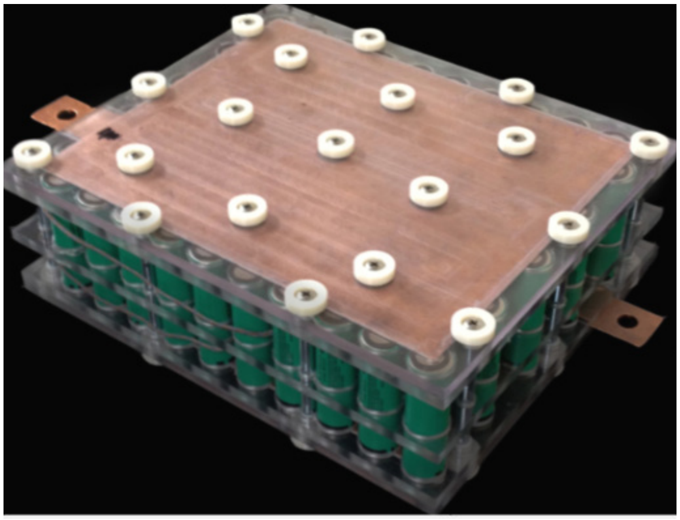
High Energy Battery Team: Capstone Project Report

Evan Bowen, Brandon Cash, John Edinger, and Matt Muller
James Madison University

Recommended IEEE Citation
E. Bowen, B. Cash, J. Edinger, and M. Muller, “High Energy Battery Team Capstone Project Report,” *James Madison Undergraduate Research Journal*, vol. 1, pp. 6-15, 2014.
Available at: **http://commons.lib.jmu.edu/jmurj/vol1/iss1/3**

High Energy Battery Team

Capstone Project Report



Evan Bowen
Brandon Cash
John Edinger
Matt Muller

James Madison University's High Energy Battery Team was commissioned in Fall 2011 to conceptualize, design, prototype, test, and construct a high voltage, high amperage battery pack capable of powering an all-electric motorcycle at a speed of 70 miles per hour for a minimum of 150 miles. Key design goals were to minimize volume and weight and to maximize power output, reliability, and serviceability. This project report details the Team's work to develop a battery "sub-pack" using 18650-type lithium ion cells which could be used (in a full-size battery pack) to power a future version of the motorcycle. The ultimate project goal is to supply an all-electric commuter motorcycle to a new market segment, reducing dependency on fossil fuels and eliminating vehicle emissions.

1 Introduction

This report highlights the processes, analyses, concepts, and experiments used by the High Energy Battery Team (the "Team") to develop a battery "sub-pack" that, as part of a full-size battery pack, could power an all-electric, street-legal touring motorcycle. Based on the preliminary data presented in this report, the Team concluded that a full-size battery pack constructed from thirty-two of the Team's battery sub-packs would exceed the energy density of the battery pack now installed on a prototype motorcycle, and could possibly outperform most of the batteries currently available for electric vehicles and other energy storage applications.

1.1 Problem Statement

In Fall 2011, Dr. John Lowitz, the project client and stakeholder, commissioned the Team and a second Engineering Capstone team—the Vehicle Integration Team—to build an electric motorcycle able to travel 150 miles at 70 miles per hour on a single charge. While the client's vision is to create the first electric "touring" motorcycle, the Team's goal over the next two years was to design a battery pack that will allow him to realize his vision. The Team produced a single battery sub-pack by the end of the project. Thirty-two sub-packs compose a full-size battery pack, and the client may choose to build and integrate a full-size battery pack into the motorcycle at a later date.

1.2 Broader Impacts

The key objective of this project, from the outset, was to create a battery pack using existing technology—18650-type lithium ion cells—that could power a commercially viable electric touring motorcycle. By manufacturing vehicles using the Team's design, Dr. Lowitz hopes to increase the demand for electric and hybrid vehicles, to reduce pollution, and to reduce the nation's dependency on foreign oil.

A focus on lithium ion batteries and in particular on 18650 lithium ion batteries in electric/hybrid vehicles will necessitate advancements in their internal construction and composition. The proliferation of 18650 batteries should reduce their cost and increase their availability. Similarly, the increasing popularity and presence of electric/hybrid vehicles will increase public curiosity and, eventually, raise public awareness. Vehicles using the Team's design would respond to the public's demand for increased fuel efficiency. Range is one of the largest concerns associated with battery-powered vehicles, and the appeal of electric/hybrid vehicles will increase as the range per charge increases.

2 Life Cycle Analysis

Currently, all-electric vehicles have three limitations compared to their gasoline-powered counterparts: lower range, the paucity of electric charging stations compared to the ubiquity of gas stations, and the time required to recharge an electric vehicle compared to the time required to refuel a gas vehicle. Most charging stations require 6–8 hours to recharge a vehicle battery, although existing battery chemistries allow for much faster recharges (about 2 hours) (1). These limitations make it easy to see why all-electric vehicles have not gained a larger market share.

However, a comparison of the total environmental impact of electric and gas powered vehicles (measured by their relative effects on Overall Human Health, Ecosystem Quality, Climate Change, and Resources Used) highlights the benefits of using an all-electric vehicle over the life of the vehicle. To make this comparison (known as a Life Cycle Analysis), the Team used SimaPro, popular LCA software "chosen by industry, research institutes, and consultants in more than 80 countries" (2).

SimaPro required several metrics and assumptions to perform its analysis. The first input variable was the average miles a typical vehicle is driven each year by all age groups in the United States (13,476 miles) (3). The Team compared the total impact of producing and consuming the gasoline required to travel this distance to the total impact of producing the Team's sub-pack design and charging the sub-pack to travel the same distance. In 2011, the average age of light vehicles in the United States was 10.8 years (4). The Team used this age for the life cycle comparison, as a 10.8 year lifespan is feasible for electric vehicles; some manufacturers currently offer 8-year/125,000-mile factory warranties on electric vehicle batteries (5).The Team's life cycle analysis does not include the impacts of manufacturing any of the vehicles or their components, nor does it include the cost of properly disposing of the vehicles and their subcomponents at the end of their usable lives.

Figure 2. 1 is the life cycle analysis comparison of three of the best-selling gas-powered vehicles in the United States against a typical electric vehicle powered by a 60 kilowatt hour (kWh) battery pack (chosen to approximate vehicles such as the Tesla Model S, which uses a 60 kWh battery pack). The mpg rating for each vehicle is from www.fueleconomy.gov. The SimaPro value of electricity used for recharging the battery pack is the value given by the program for average electricity of the electrical infrastructure of the United States, imported into the electric grid.

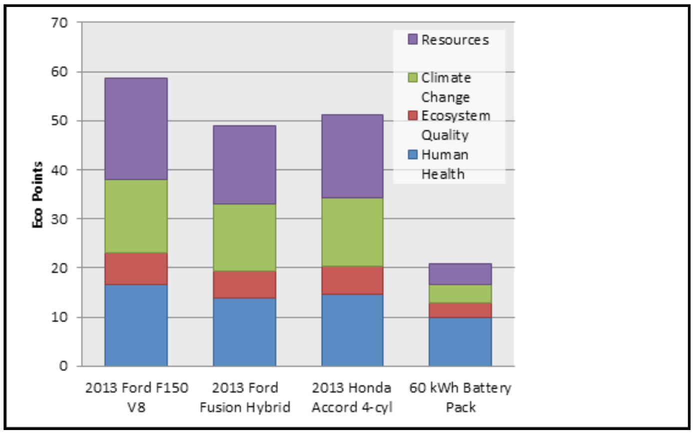


Fig. 2. 1: SimaPro life cycle comparison of a 60 kWh battery pack

Figure 2. 1 shows that the impact of using the battery pack as an energy source for vehicles is less than the impact of using gasoline for similar vehicles. In particular, the battery pack most dramatically reduces CO_2 emissions and total resources used.

Figure 2. 2 is the life cycle analysis comparison of two gasoline powered touring motorcycles sold in the United States and a motorcycle powered by a 30 kWh battery pack. The mpg rating for each motorcycle is published by their respective manufacturers. The SimaPro value of electricity used for recharging the battery pack is the value given by the program for average electricity of the electrical infrastructure of the United States, imported into the electric grid.

Figure 2. 2 shows that the battery pack has a lower overall impact compared to the impact of using gasoline to power motorcycles. Figure 2. 2's comparison is especially relevant because the Team designed the pack to fit a 2003 Honda Goldwing motorcycle frame.

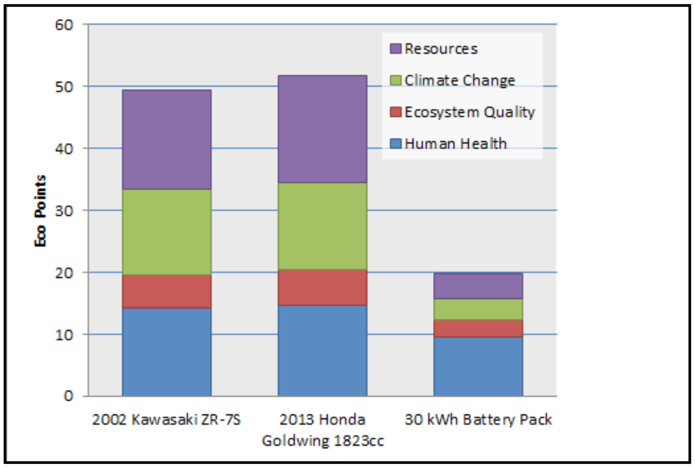


Fig. 2. 2: SimaPro life cycle comparison of a 30 kWh battery pack

3 Project Management

3.1 Team Organization

The Team operated with two leadership positions: team leader and treasurer. The team leader led meetings, assigned tasks, and ensured the project accomplished its intended goals. The position of team leader was filled by the person who worked as an intern on the project the previous summer. The knowledge the team leader gained in the internship gave him the perspective necessary to determine the project's needs and direction. Evan Bowen led the team in the project's first year, and John Edinger led the team in the second year. The treasurer's duties included purchasing all the equipment and materials that team members requested and enforcing the $500 annual budget. Brandon Cash served as treasurer for both years of the project.

3.2 Budget

The James Madison University Department of Engineering provided the Team $500 each year. The Team used these funds to purchase items that fulfilled specific needs for research for the project. The client provided additional funds necessary to complete the project's deliverables.

3.3 Project Progression and Timeframe

The Team's Capstone Project spanned four semesters, from Fall 2011 through Spring 2013.

- Fall 2011: The Team did not begin work on the battery pack until October. Early in the semester, Dr. Lowitz challenged the Team and the Vehicle Integration Team to build an electric motorcycle for him to race in Maxton, North Carolina, on September 24, 2011. Through herculean labors, the two teams produced a motorcycle incorporating commercially designed and manufactured prismatic lithium ion batteries in time for the race. This effort did not significantly influence the Team's later battery pack design. In October, the Team began the process of selecting a battery for the pack.
- Spring 2012: The Team continued its work to select a battery for the pack, which in turn influenced the pack's design. The Team's considerations in choosing the battery are detailed in Sections 4.1, 5.1, and 6.1. Concurrently, the Team began designing the battery pack.
- Fall 2012: The Team continued to design the battery pack. The Team's work is detailed in Sections 4.2, 5.2, and 6.2.
- Spring 2013: The Team finalized its battery pack design, built a fully-functional sub-pack, and then designed a protocol to test the effectiveness of the design. Using real highway data gathered by the Vehicle Integration Team, the Team devised a "Road Test" to estimate the likely performance of a full-size battery pack. The test's design, results, and conclusions are detailed in Sections 4.3, 5.3, and 6.3.

4 Approaches and Method

4.1 Battery Testing and Selection

The first design choice the Team faced was to determine what type of 18650 battery to use. With price no object (as the client insisted many times), the Team selected the most energy-dense 18650 battery commercially available. While energy density appears to be a very straightforward calculation, battery capacity varies significantly depending on the rate that current is drawn. The Team determined to collect firsthand data to guide such an important decision. The Team reasoned that if each battery type were tested enough, the data for each battery could be organized by price per kWh, volume per kWh, and weight per kWh. This data would make it simple for the Team to select a battery. In order to gather the data required, the Team built a discharge circuit, seen in Figure 4.1. 1. The Team's "Battery Discharging Circuit" contains six complete circuits, three that are connected to LabView for data collection and three that discharge the battery at rates of

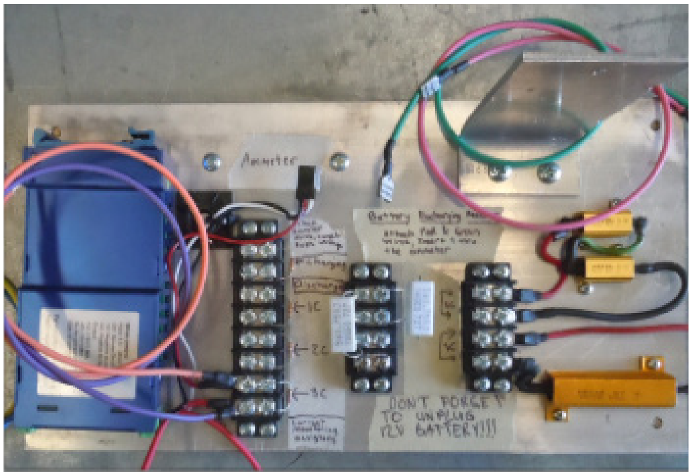


Fig. 4.1. 1: Battery discharging circuit

2.4 amps, 4.8 amps, or 7.2 amps. The Team did not use the 7.2 amp circuit because protective circuits in most of the batteries would not allow them to discharge at that quick a rate.

During each test, the Team ran a LabView program to record the amount of energy discharged and exported the data to Excel. Each program was built off of the LabView program shown in Figure 4.1. 2.

The experiment discharged batteries at 2.1 amps and 3.1 amps. Circuit inefficiencies caused rates to be short of nominal rates of 2.4 amps and 4.8 amps. The Team therefore used tests done in Denmark (6) that discharged batteries at constant discharge rates of 2 and 5 amps to supplement its data. The Team used this data to compare different batteries' weight, price, and volume per kWh.

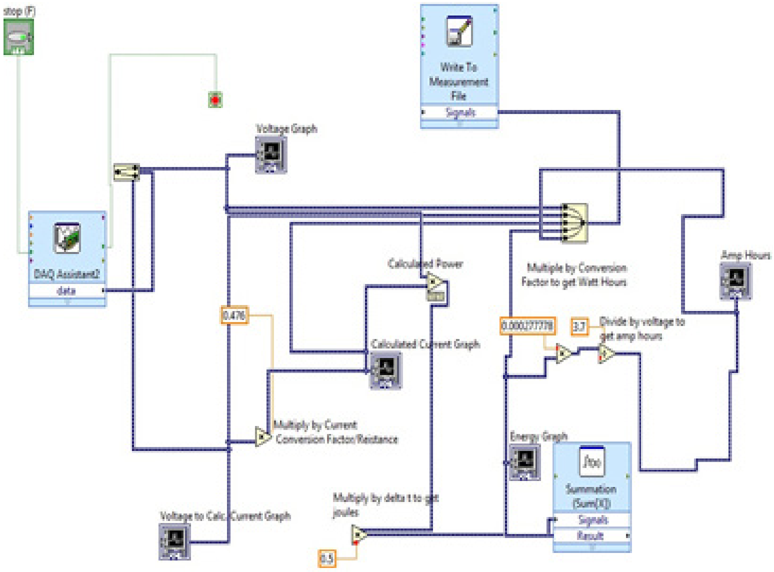
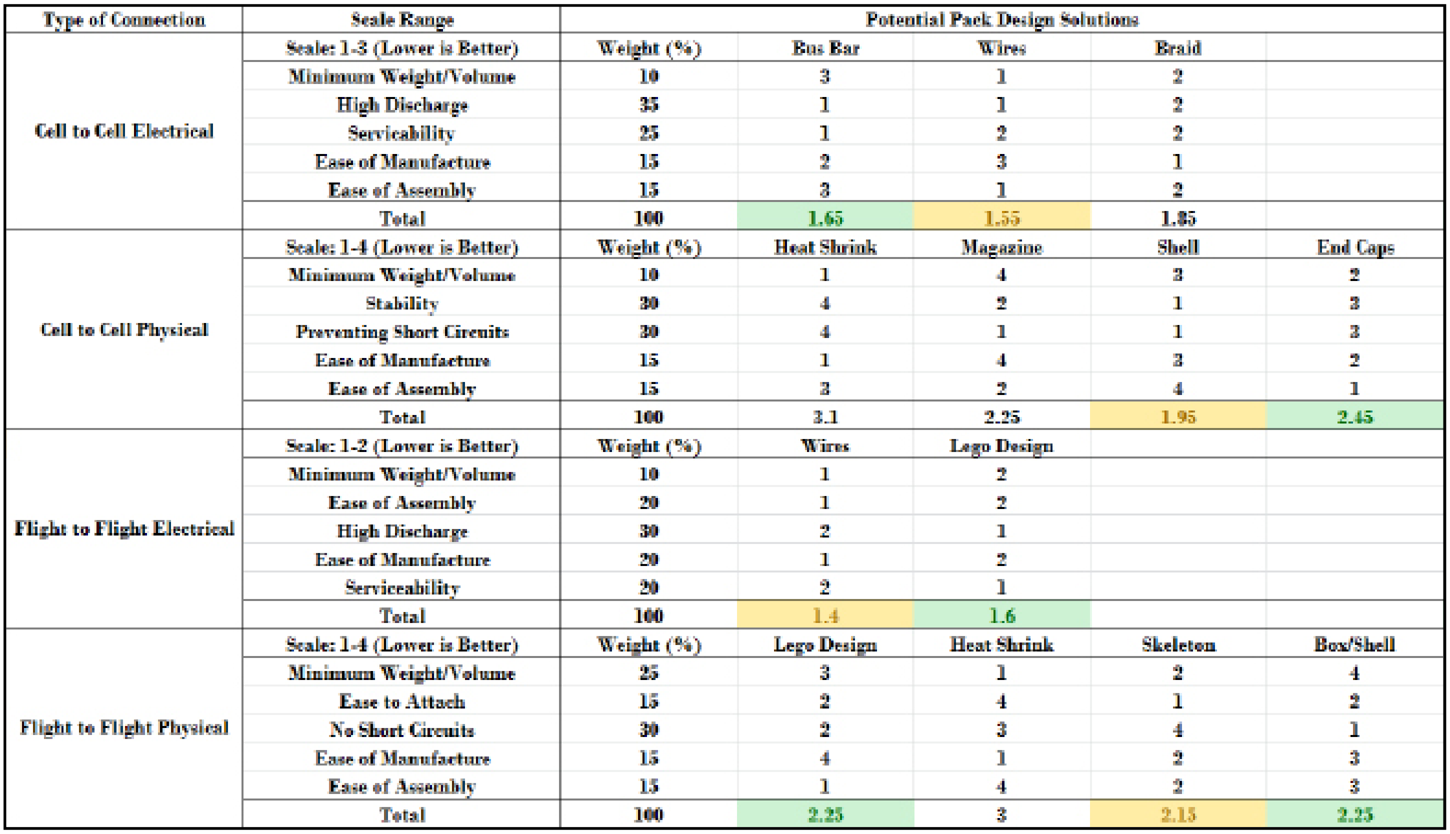


Fig. 4.1. 2: Block diagram of a typical LabView circuit

4.2 Design Requirements and Preferred Solution Strategies

To create a battery that met the client's goals, the Team had to overcome several design obstacles. Using preliminary research from an independent 2010 study done for the client, the Team chose to create a pack comprised of thirty-two sub-packs. Each sub-pack has a nominal voltage of 3.7 volts and a rated capacity of 300 amp-hours. This decision required that each sub-pack use one hundred 18650 batteries in parallel, as the typical 18650 has a nominal voltage of 3.7 volts and a rated capacity of about 3 amp-hours.



Type of Connection	Scale Range	Potential Pack Design Solutions				
Cell to Cell Electrical	Scale: 1-3 (Lower is Better)	Weight (%)	Bus Bar	Wires	Braid	
	Minimum Weight/Volume	10	3	1	2	
	High Discharge	35	1	1	2	
	Servicability	25	1	2	2	
	Ease of Manufacture	15	2	3	1	
	Ease of Assembly	15	3	1	2	
	Total	100	1.65	1.55	1.85	
Cell to Cell Physical	Scale: 1-4 (Lower is Better)	Weight (%)	Heat Shrink	Magazine	Shell	End Caps
	Minimum Weight/Volume	10	1	4	3	2
	Stability	30	4	2	1	3
	Preventing Short Circuits	30	4	1	1	3
	Ease of Manufacture	15	1	4	3	2
	Ease of Assembly	15	3	2	4	1
	Total	100	3.1	2.25	1.95	2.45
Flight to Flight Electrical	Scale: 1-2 (Lower is Better)	Weight (%)	Wires	Lego Design		
	Minimum Weight/Volume	10	1	2		
	Ease of Assembly	20	1	2		
	High Discharge	30	2	1		
	Ease of Manufacture	20	1	2		
	Serviceability	20	2	1		
	Total	100	1.4	1.6		
Flight to Flight Physical	Scale: 1-4 (Lower is Better)	Weight (%)	Lego Design	Heat Shrink	Skeleton	Box/Shell
	Minimum Weight/Volume	25	3	1	2	4
	Ease to Attach	15	2	4	1	2
	No Short Circuits	30	2	3	4	1
	Ease of Manufacture	15	4	1	2	3
	Ease of Assembly	15	1	4	2	3
	Total	100	2.25	3	2.15	2.25

Fig. 4.2.1: Morphological matrices for sub-pack connections

After determining the requirements for the battery pack, the Team broke the design down into four specific components and brainstormed solutions for each using a design tool called a Morphological Matrix, shown in Figure 4.2. 1.

The first two components were electrical connections required in each sub-pack. The first electrical component, referred to in Figure 4.2. 1 as "Cell to Cell Electrical," connects all the cells inside the sub-pack together in parallel. The second electrical component, referred to in the figure as "Flight to Flight Electrical," connects the thirty-two sub-packs to each other in series. The remaining two components are the physical connections required by the design. The first physical connection, "Cell to Cell Physical," prevents the cells from moving inside the sub-pack. The second physical connection, "Flight to Flight Physical," secures the sub-pack inside the motorcycle's body.

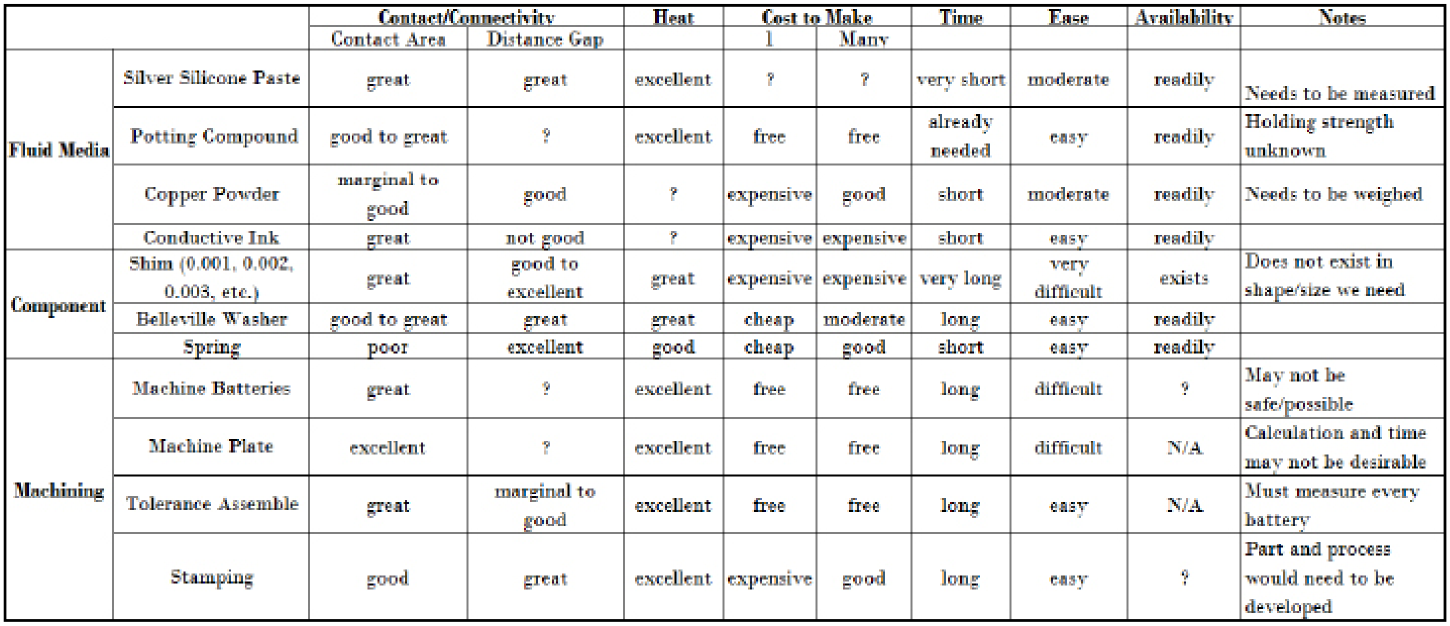
The blocks highlighted in green in Figure 4.2. 1 show which solutions would work best for each type of connection. After discussion, the Team determined that it should have placed a higher importance on the "Ease of Manufacture" category, and that it should therefore use the solution set highlighted in gold in Figure 4.2. 1.

Other design problems arose during the course of the project, including the need to explore heat mitigation techniques and the need to redesign the "Cell to Cell Electrical" connection. To solve these problems, the Team looked to Morphological Matrices as its preferred method of brainstorming, which the Team combined with results from its research and direct experimentation. To appreciate how the Team's strategy worked, consider the following example concerning electrical connections.

The Team made a number of material and design choices in the project's first three semesters, including to use a common bus plate and to use the thickness of the bus plate to control heat generation). In turn, the rigidity of the bus plate necessitated an adjustable connection between the positive and negative terminals of the battery and the bus plates. The Team used a matrix to evaluate each possible solution based on several factors, including cost, availability, and the quality of the electrical contact. The matrix shown in Figure 4.2. 2 highlights three different connection types: fluid media, the addition of a physical component, and machining and assembling.

The Team conducted research on a championed selection from each category. Fluid media demonstrated excellent contact area and compliance but had unknown amperage capacity and a fluctuating cost. Team members contacted online distributors and Master Bond Inc. to identify several viable solutions, but limited resources, time, and capital led the Team to abandon a fluid media solution set.

Machining and assembling offered excellent contact area but reduced flexibility in the electrical connection. It also created a long wait time, with extensive labor required for assembly and measurement. All potential machining solutions involved physically measuring the 18650 batteries. The Team measured a sample of 25 batteries selected at random from 100 batteries on hand. The Team found a maximum height differential of 0.009". The time required to machine both copper bus plates to match the individual tolerances of each battery would have equated to ten man-hours per sub-pack. The machining process would also have added complexity to the assembly process, as it emphasized the importance of each battery's specific position in the sub-pack. The Team decided that adding such a large amount of complexity was unacceptable and ultimately determined that a physical connection component offered the best combination of cost, time, and functionality. The Team



		Contact/Connectivity		Heat	Cost to Make		Time	Ease	Availability	Notes
		Contact Area	Distance Gap		1	Many				
Fluid Media	Silver Silicone Paste	great	great	excellent	?	?	very short	moderate	readily	Needs to be measured
	Potting Compound	good to great	?	excellent	free	free	already needed	easy	readily	Holding strength unknown
	Copper Powder	marginal to good	good	?	expensive	good	short	moderate	readily	Needs to be weighed
	Conductive Ink	great	not good	?	expensive	expensive	short	easy	readily	
Component	Shim (0.001, 0.002, 0.003, etc.)	great	good to excellent	great	expensive	expensive	very long	very difficult	exists	Does not exist in shape/size we need
	Belleville Washer	good to great	great	great	cheap	moderate	long	easy	readily	
	Spring	poor	excellent	good	cheap	good	short	easy	readily	
Machining	Machine Batteries	great	?	excellent	free	free	long	difficult	?	May not be safe/possible
	Machine Plate	excellent	?	excellent	free	free	long	difficult	N/A	Calculation and time may not be desirable
	Tolerance Assemble	great	marginal to good	excellent	free	free	long	easy	N/A	Must measure every battery
	Stamping	good	great	excellent	expensive	good	long	easy	?	Part and process would need to be developed

Fig. 4.2. 2: Connection matrix for compliance electrical connection

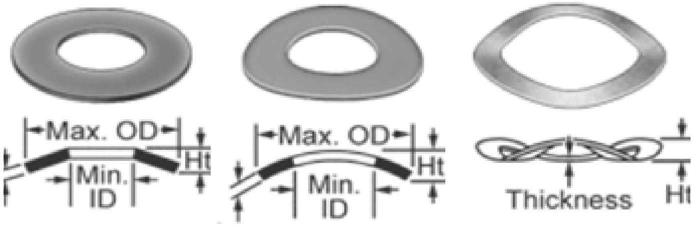


*Fig. 4.2. 3: Washer Profiles (from left: Belleville washer, curved washer, wave washer) *Images from www.mcmaster.com*

therefore concentrated on a physical component solution for the "Cell to Cell Electrical" connection.

The Team decided to champion an electrically conductive spring washer, selecting a type of disc spring washer readily available in a variety of material choices and spring stiffness that can span large distance gaps, up to 0.040". Figure 4.2. 3 shows the profiles of a Belleville washer, a curved washer, and a wave washer.

Testing conducted on these different washers produced a clear choice. Theoretical analysis helped the Team to determine the spring stiffness. Equations from www.engineeringtoolbox.com led to a dynamic Microsoft Excel spreadsheet. The force that the Belleville and curved washer springs exert is dependent on the composition material, thickness, and inner-to-outer diameter ratio. Equation 4.2. 1 is the governing equation for the force.

$$F = \frac{4E\times t^4}{(1-\mu^2)\times\alpha\times D^2}\times\frac{s}{t}\times\left[\left(\frac{h}{t}-\frac{s}{t}\right)\times\left(\frac{h}{t}-\frac{s}{2t}\right)+1\right]\ [N, lb]$$

Equation 4.2. 1

The maximum forces exerted by the 0.006" and 0.008" wave washers were taken from their respective data sheets. The Team used an Instron 5966 10kN Mechanical Tester to measure the force exerted by the wave washers at the expected range of compliance needed for the team's application. Figure 4.2. 4 shows the average force exerted by each type of washer.

From the graph shown in Figure 4.2. 4, the feasible solutions were the curved washer and the 0.008" wave washer. The 0.006" wave washer displayed inconsistent force and the Belleville washer did not offer a large displacement. A comparison of each washer's contact area aided the Team's final decision between the two feasible options. A layer of blue indelible ink on small samples of beryllium copper highlighted the contact areas of the compressed washers.

As the contact "footprints" in Figure 4.2. 5 show, the Belleville washer possesses the largest contact area but does not offer the necessary compliance travel. The curved washer has two contact points on the concave side of the washer. The convex side of the washer has a much smaller contact area—barely visible lines at the washer's edge—and could not be seen using the ink method. By design, the wave washer offers the same contact area between both surfaces. That fact, along with a beneficial force profile, led the Team to select the 0.008" wave washer for the electrical contact between the bus plate and each of the 100 lithium ion cells.

Fig. 4.2. 5: Washer contact footprints: (from left) Belleville washer, curved washer, wave washer

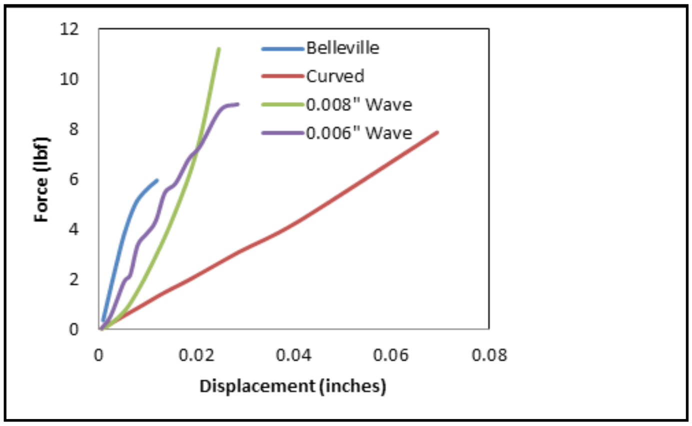


Fig. 4.2. 4:Washer load testing

4.3 Developing the Road Test

In order to determine whether the battery pack the team created could take the Vehicle Integration Team's motorcycle 150 miles at 70 miles per hour, the Team had to follow one of two test paths. The first path meant building thirty-two sub-packs, installing them on the motorcycle, and conducting a real-world test by driving the bike down Interstate 81 until it ran out of energy. Building a full-size battery pack would have cost over $30,000 and over a decade of the James Madison University machine shop's spare time. The second path meant building a single sub-pack, which could then be tested using a scaled Road Test to simulate a real-world ride. Time and monetary constraints helped the Team to choose the second path. While the Team would have liked to create a full-scale battery pack, a properly scaled test still yielded valuable relevant data for the Team to analyze and use to make a preliminary estimate of the battery pack's range.

To run a simulated Road Test, the Team used a BK Precision 8514 DC Electronic Programmable Load device to draw various amperages in order to best mimic road conditions. The Team also used amperage and voltage data supplied by the Vehicle Integration Team; the amperage data provided changed on the basis of various speeds and terrain changes encountered by the motorcycle. The Team ran the Road Test on the individual prismatic batteries and on the Team's battery sub-pack to directly compare the prismatic battery pack used in the real road test and the team's full-size battery pack design.

5 Detailed Design Review

5.1 Battery Testing Results

Using the research performed in Denmark as a basis, the Team selected four different brands of 18650 batteries to test: Panasonic, TrustFire, AW, and Tenergy. The Team used its discharge test circuit to test six batteries from each brand at two different current rates (2 and 3.3 amps). The calculated capacity in milliamp hours of each cell were recorded and averaged for each brand. Figure 5.1. 1 shows the results of the test. The Team also evaluated the energy density of each battery brand in terms of cost and weight. These comparisons are shown in Figure 5.1. 2 and Figure 5.1. 3.

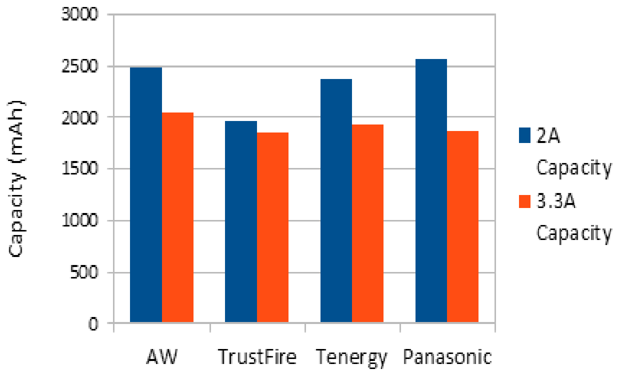


Fig. 5.1. 1: Average measured capacity of each battery brand

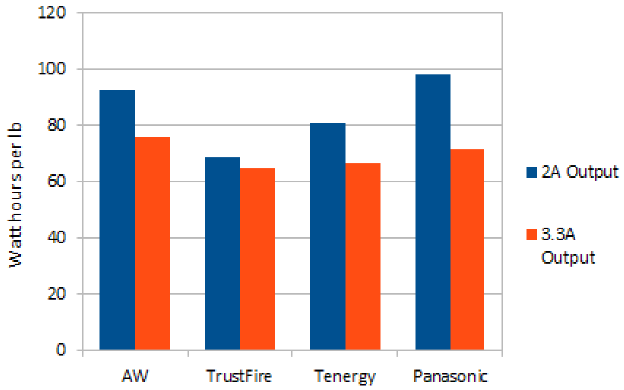


Fig. 5.1. 2: Energy density of batteries vs. weight

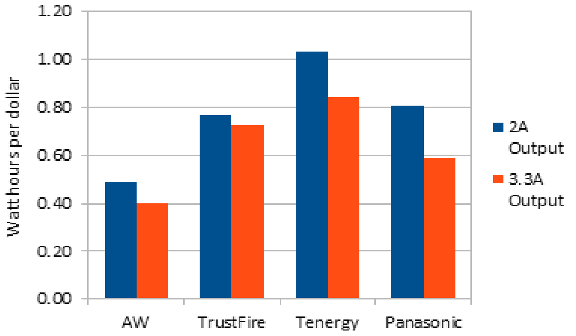


Fig. 5.1. 3: Energy density of batteries vs. cost

5.2 Evolution of the Sub-Pack Design

As the Team built the sub-pack, moving from design concept to reality, it made several substantial changes to the original design. The first iteration of the design called for an enclosed container made of acrylic to protect the battery pack from inclement weather. Heat buildup and difficulties in manufacturing acrylic required this design concept to be eliminated. The material championed for the functional prototype is polycarbonate, chosen with the input of Casey Flanagan and Mark Starnes (JMU Engineering's Machine Tech and Machine Shop Supervisor, respectively).

The current functional design uses a common bus plate to handle the current through the battery sub-pack. The Team performed calculations using a modified version of the resistivity equation, shown in Equation 5.2. 1 where ρ is the resistivity of the material, i is the current through the battery sub-pack, l is the length across the battery sub-pack, V is the voltage drop, and w is the width the current is expected to travel through. The Team used this formula to choose the material for the bus plate. Figure 5.2. 1 shows the analysis.

$$\boxed{t=\frac{pil}{Vw}}$$

Equation 5.2. 1

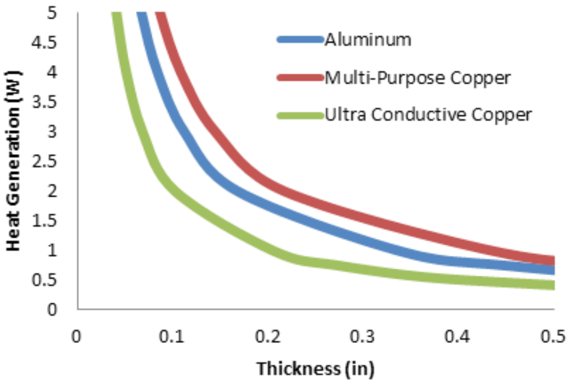


Fig. 5.2. 1: Sub-pack bus plate thickness

The Team also made many changes to the construction of the sub-pack's casing, ranging from the materials used to the overall size and shape. The Team also modified the configuration of the battery placement within the sub-pack several times. Figure 5.2. 2 shows the initial placement of the batteries. This original design would have allowed future service monitoring of as few as ten individual batteries The Team abandoned the design due to possible heat issues and the battery management system's inability to monitor each

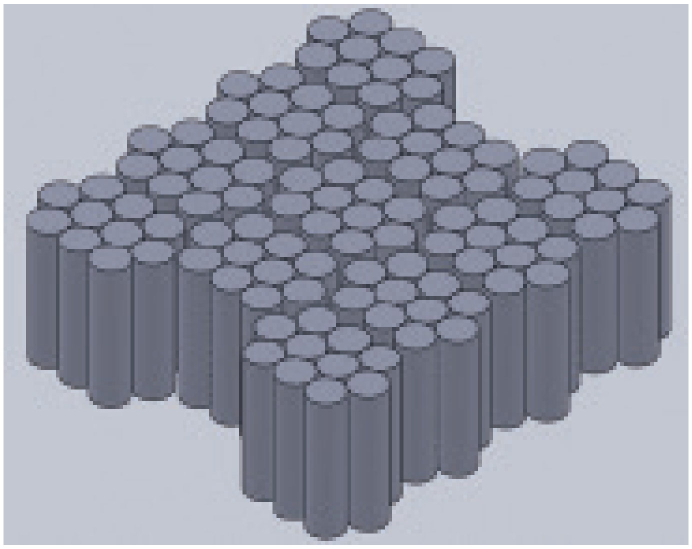


Fig. 5.2. 2: Initial battery placement

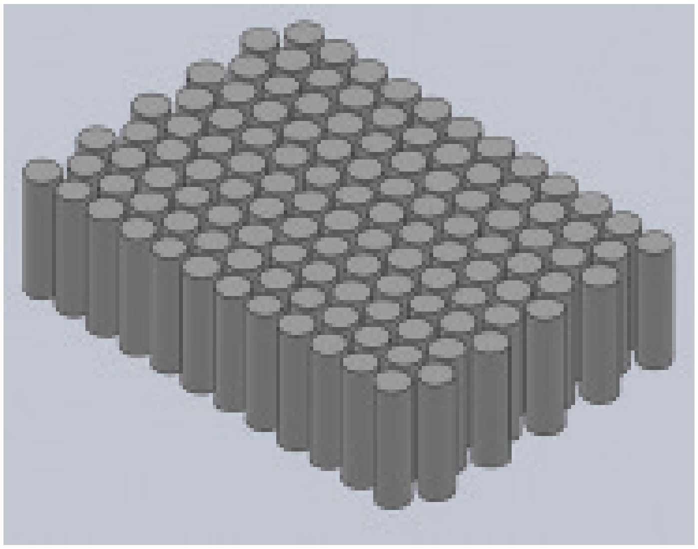


Fig. 5.2. 4: Current battery configuration

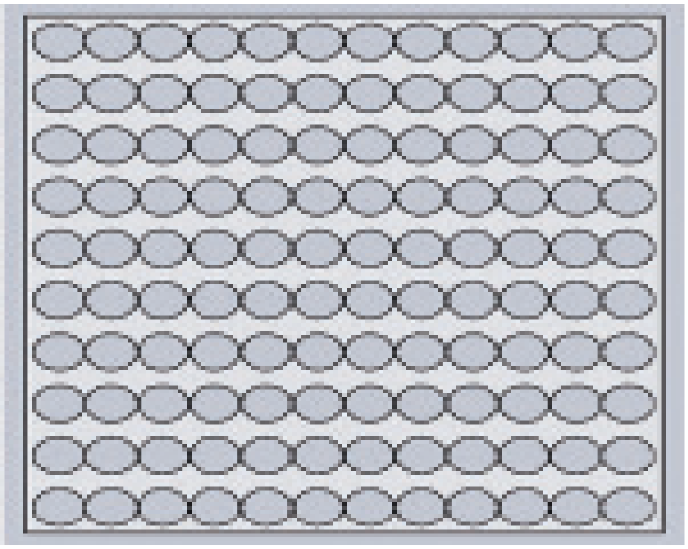


Fig. 5.2. 3: Second battery configuration

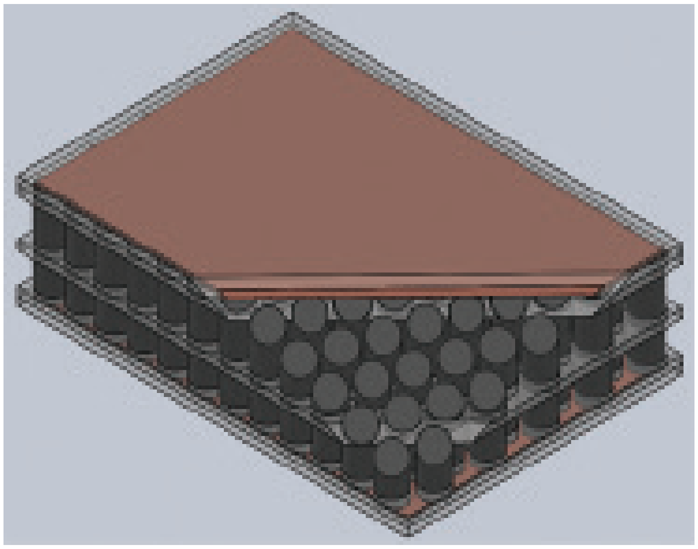


Fig. 5.2. 5: Final sub-pack design

group of ten individually. The Team also rejected a second battery configuration, shown in Figure 5.2 3, due to possible heat issues and for better integration of forced convection.

The Team anticipates taking greater advantage of forced convection with its current concept. The current battery configuration, shown in Figure 5.2. 4, was chosen to keep a minimum spacing between each battery to prevent heat transfer. The Team ultimately chose the design in Figure 5.2. 5 to induce turbulent air flow through the batteries to aid in cooling. The battery sub-pack design the Team developed into a functional prototype is shown in Figure 5.2. 5.

5.3 Road Test Results

In order to ensure that its testing procedure was a valid approximation of real-world road conditions, the Team tested several of the Vehicle Integration Team's prismatic cells to check for validity. The results from one of these tests are shown in Figure 5.3. 1.

Figure 5.3. 1 contains voltage and amperage versus time for the prismatic battery which the team had labeled "2D." The red amperage line changes periodically over time, matching the data provided by the Vehicle Integration Team. The blue voltage line steadily declines from a nominal value of 4.2 volts and ends at 2.75 volts. This particular prismatic battery, containing 8.4 kWh of energy, used 4.5 kWh of energy during the road test, defined by the beginning of the straight red line at about 1750 seconds. The programmable load was temporarily set at drawing constant 100 amp current after the road test was completed. This was done because 100 amps was the average draw throughout the test, and because the energy remaining in the battery could be easily calculated by subtracting the nominal energy of the pack and the energy used. Eight prismatic batteries were discharged, with the average total energy contained in each battery totaling to 8.26 kWh, and the average total energy used during each road test by a single battery totaling to 4.4 kWh. Dividing the second number by the first number results in the "percentage of energy remaining." The calculation showed that there was 47 percent of energy remaining after the test.

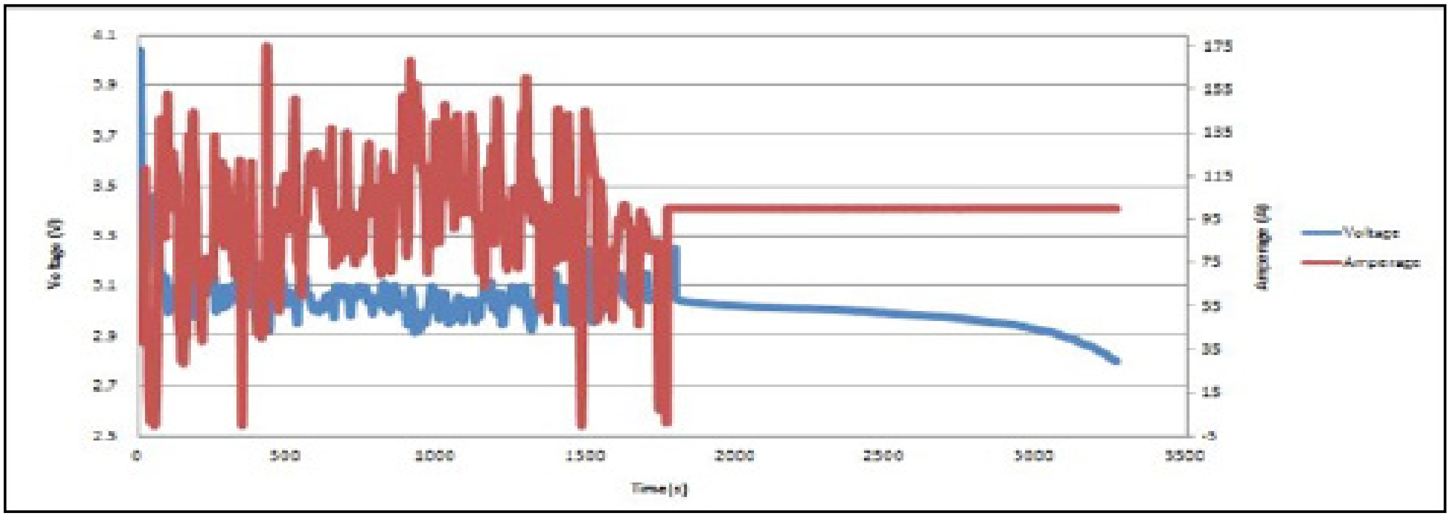


Fig. 5.3. 1: Simulated road test performed on prismatic battery "2D"

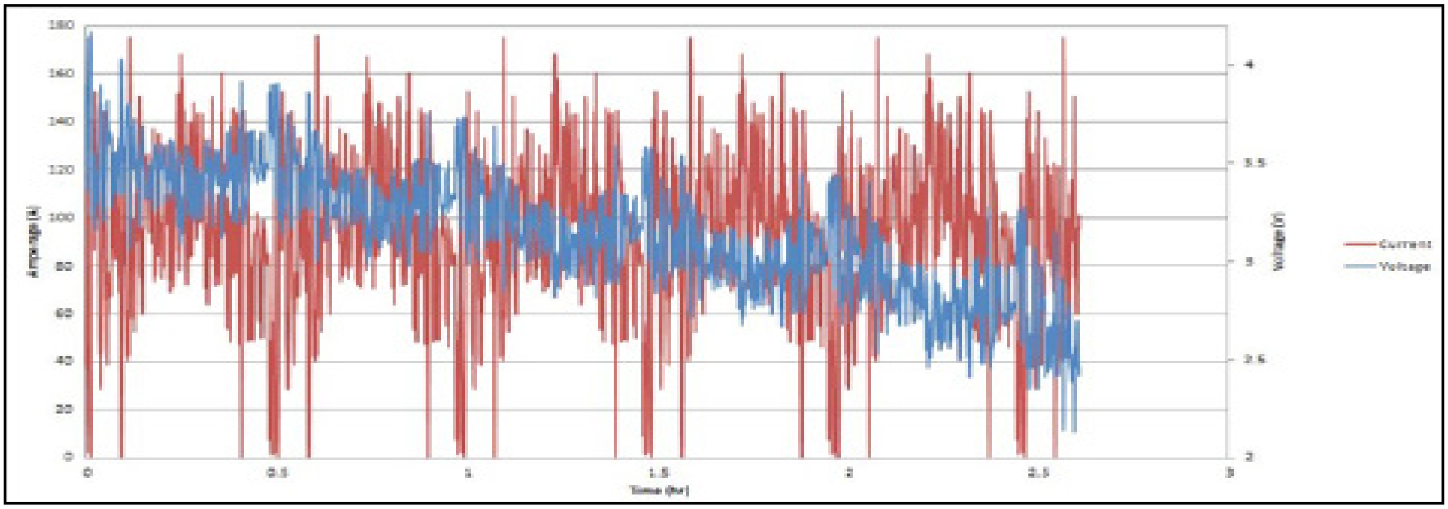


Fig. 5.3. 2: Simulated road test performed on sub-pack

After comparing these results against the real-world data that the Vehicle Integration Team collected, the Team concluded that the testing process it had created was a valid test for its battery pack. The Team then looped the coding for the test and used it to estimate the range of the Team's sub-pack. The results of this test can be seen in Figure 5.3. 2.

Figure 5.3. 2 shows that the sub-pack completed over five loops of the road test before the battery was exhausted. An advantage of using the road test is that each complete iteration translates into 31 miles of real-world distance traveled. Based on the data provided by the Vehicle Integration Team and the number of loops the battery performed, the data suggests that the battery pack would travel a theoretical 168 miles, exceeding the initial goal of 150 miles.

6 DISCUSSION

6.1 Selecting a Battery

After analyzing the data, the Team concluded that the 18650 battery best suited for the prototype sub-pack was the Panasonic NCR18650A. The Team chose the NCR18650A because it had both the highest rated and the highest actual capacity of all the 18650 batteries. The Team also chose the NCR18650A for its excellent performance at higher discharge rates. Inefficiencies associated with discharging batteries at rates typically seen in electric vehicles affect the NCR18650A less than most of its competitors.

6.2 Implications of the Final Design Solution Set

Every redesign of each sub-pack component changed the sub-pack's properties and specifications. As a result of the evolving design process, the Team's final sub-pack design resulted in several very exciting and impressive qualities. One of the sub-pack's most important qualities is an extremely large capacity at a comparatively low voltage. The result of this design feature is that each individual 18650 battery experiences a smaller proportional current draw than most rival designs (most commercially available vehicles' battery packs are designed as "High Voltage, (relatively) Low Current" packs, while the Team's pack is designed to be a "Low Voltage, High Current" pack). This feature helps increase the energy efficiency of the system. Additionally, increased efficiency enabled the Team to calculate with a reasonable degree of certainty that no heat mitigation (other than the direct convection that the pack would experience while on the motorcycle) would be necessary to keep the battery pack within the optimal temperature range. Avoiding the need for heat mitigation measures eliminates an entire subsystem from the pack's design, thus saving weight, money, and volume, and creating (as confirmed by the road test) an incredibly energy dense battery pack.

7.3 Interpreting the Road Test

Even given the data in reported in Section 5.3 and shown in Figure 5.3. 2, the Team hesitates to assert that its battery pack will take an electric motorcycle 168 miles at 70 mph. This hesitation exists for two reasons: the future design changes the Vehicle Integration Team plans on making to the motorcycle, and the inevitable differences between the current motorcycle and any future iteration's road load. "Road load," defined as the sum of all the forces that act on a vehicle as it propels itself down the road, can be drastically changed by an increase in weight and frontal area, both of which are expected to increase when the Team's battery pack is attached to the motorcycle's frame. While these factors will decrease the motorcycle's range, the Vehicle Integration Team will attempt to offset possible range losses with new design features, such as improved gearing and the installation of a drag-reducing fairing. Calculating the motorcycle's road load is the Vehicle Integration Team's responsibility, and the Vehicle Integration Team currently does not have enough information about the aforementioned changes to make any accurate estimation of the bike's future road load. Still, the sub-pack used 0.32 kWh of energy during the road test. Based on publically available test data on other lithium ion batteries, the team believes that at the time the Team's battery pack was completed, it had one of the most energy-dense lithium ion battery pack designs (by volume) in the world.

7 Conclusion

After two years of work, the Team is glad to report that its project was a success. The Team constructed a fully functional sub-pack and proved (to the fullest extent possible without building a full battery pack and installing it on a motorcycle) that a full-size battery pack would have sufficient energy density to meet the client's original design criteria. The Team also concluded that its design has sufficient energy density to meet the range requirement, an adequate heat dissipation system, and a design flexible enough that it can be adapted to function in a variety of layouts. Overall, client John Lowitz appears to be extremely pleased with the Team's results.

The success of this project could lead to a number of benefits in the electric vehicle market. As the popularity of electric and alternative vehicles rises, the market will look for designs that contain more energy, recharge faster, and cost less. The Team's design represents a data point on the continuum of battery technology, a snapshot of what lithium ion batteries are capable of at this time. While the Team is proud of what it has managed to accomplish with the state of the art, one of the most exciting aspects of the team's design is that it can be applied to future versions of the 18650 battery, allowing the design to stay relevant as lithium batteries power more and more of the vehicles on our roads.

Fig. 7. 1: The Team's electric motorcycle on Interstate 81

Acknowledgements

The High Energy Battery Team would like to acknowledge the following individuals, as without their help this project would not have been a success: Dr. John Lowitz, Dr. Robert Prins, John Wild, Scott Padgett, Mark Starnes, Samuel Osterhout, Travis Knight, Grant Haskins, Richard Arena.

References

1. Tesla Motors. Supercharging. *www.teslamotors.com.* [Online] [Cited: April 30, 2013.] http://www.teslamotors.com/supercharger.
2. About Sima Pro. *PRé Sustainability*. [Online] 2013. [Cited: November 16, 2013] http://www.pre-sustainability.com/simapro-lca-software.
3. Federal Highway Administration. Average Annual Miles per Driver by Age Group. *U.S. Department of Transportation.* [Online] April 4, 2011. [Cited: April 29, 2013.] http://www.fhwa.dot.gov/ohim/onh00/bar8.htm.
4. Bureau of Transportation Statistics. *Research and Innovative Technology Administration*. [Online] January 2013. [Cited: April 29, 2013.] http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_01_26.html.
5. Valdes-Dapena, Peter. Tesla offers idiot-proof battery warranty. *CNNMoney*. [Online] April 26, 2013. [Cited: April 30, 2013.] http://money.cnn.com/2013/04/26/autos/tesla-service-gaurantee/.
6. 18650 Battery Test. [Online] 2011. [Cited: April 26, 2012.] http://lygte-info.dk/info/Batteries18650-2011%20UK.html.

For additional information, visit the Team's website, outlierev.com. For access the Team's documentation, please send an email to GoldwingDocumentation@gmail.com