Fuel Cell Powered Tricycle
ME 495 Final Report
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Executive Summary

The goal of our project this quarter was to design and develop a fuel cell powered tricycle. Although we did not fully meet our goal of developing a prototype, we were able to iterate through the design process and complete the necessary design framework for future groups to construct and test the tricycle. This section will describe our design process and final design, as well as provide an overview of the analysis, business plan, and future recommendations necessary for the development of a successful prototype.

Our tricycle consists of a modified Merida electric bicycle (with tricycle conversion kit) graciously donated to us by EBikesNW in Freemont. The tricycle is powered by the 1.2kW Ballard Nexa Power module and existing torque sensor electric motor. Our design deals with protecting the fuel cell and hydrogen tank, as well as providing the electrical controls necessary to operate the tricycle.

We benchmarked three different fuel cell powered bicycles in order to gain insight from existing products. We also researched the relevant ASTM and SAE standards for fuel cell powered vehicles. This benchmarking allowed us to create customer requirements and relating engineering characteristics for our fuel cell powered bicycle. After completing a QFD of our design requirements, we found that passenger safety along with cost were the primary requirements. Therefore, our design concepts sought to meet these two characteristics by providing a variety of fail-safe mechanisms, a robust protective structure, safe hydrogen storage, and minimal manufacturing to decrease cost while meeting standard specifications.

After iterating through the design process mid-quarter, we found that our original designs did not meet the comprehensive requirements and we therefore only had time to redesign one concept. We chose the final concept because it met our most important customer requirements as well being applicable to our standards. This concept includes a welded aluminum cage that protects the fuel cell and hydrogen tank. Air flow holes were designed in the cage in order to allow for appropriate air circulation. The cage included an inner aluminum wall that separates the hydrogen tank from the fuel cell stack, thus increasing the failure safety of the system. In addition to hydrogen sensors, our design also considered the ideal hydrogen placement and seeked to maximize the control of the hydrogen tank in case it exploded. A working diagram of our final design is shown below.

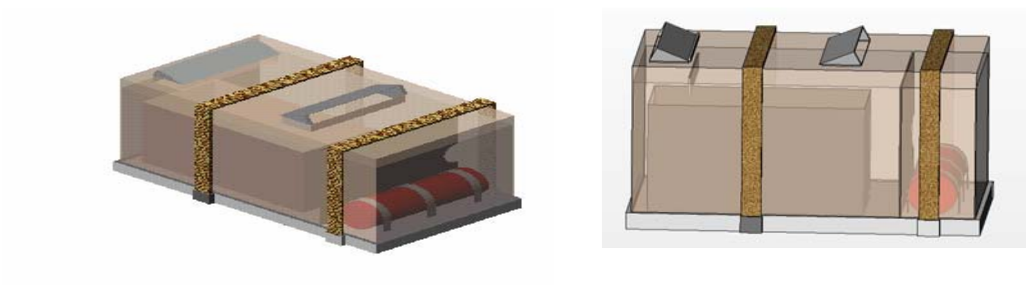

Figure 1: Final Design

With this design, a business plan was made for our fictitious company RevoTrikes Inc. We predict to be unprofitable for the first 4 years of our existence, while we market and optimize our tricycle design. Our product will become profitable during its fifth year on the market as the unit cost of our tricycle drops to $1,700.

In order to become a successful company however, there are a number of items that must be completed in order to market a prototype. First, the electric bicycle must be converted into a tricycle with a new axle. Secondly, the structural analysis of design must be completed as to ensure the safety of our concept. Thirdly, the design must be purchased and assembled as well as tested. This testing should allow iteration to improve upon the current design.

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1.0: Introduction

In the past, ME fuel cell groups have focused on either designing new PEM fuel cells, or optimizing the test stand apparatus. It is was our intention, this quarter, to design an application to be powered by fuel cell technology and to provide a framework for future fuel cell application design groups. Although several different types of applications were considered, we decided to design a tricycle that could be powered by the 1.2 kW Ballard Nexa Power Module. Our design was further constrained by the Merida electric bicycle that was donated to us for this project by Electric Bicycles Northwest (EbikeNW) in Freemont. The goal of this project was to find a way to power the electric bicycle with the Ballard fuel cell and to convert the bicycle into a tricycle capable of safely housing the fuel cell, fuel tank, and other required components.

1.1: Design Problem

The end goal of this project is to create a fuel cell powered electric tricycle. We are also constrained by our decision to use an existing 1.2 kW fuel cell, a 200 W electric motor, and a 24 V lead acid battery. Because the primary components of the vehicle were already determined, we initially broke the design up into two main design components. The first dealt with designing a controls system to manage the fuel cell and charge the battery, while the second was concerned with designing the structure that would support and protect the fuel cell and the fuel tank. Up through the midterm, the design of the bike's systems and the design of its structure were completely split up and worked upon separately. However, working on each design component separately failed to account for many important design considerations that did not clearly fall into one of the two design categories. Therefore, the design requirements were re-analyzed looking at the bike holistically rather than as a group of sub systems.

1.2: Analysis of Design Requirements

A new analysis of design requirements and related performance metrics for the entire vehicle was required. A large list of customer and engineering requirements was created that included characteristics that could be loosely grouped into the categories of production, safety, power/energy, performance, usability, durability, and life cycle. From this list of vehicle requirements, the relevant engineering characteristics were determined. Quality function deployment was used to determine the relative importance of each engineering characteristic as seen in Appendix A (QFD). As determined from the QFD, the ten most important engineering characteristics for the vehicle were: number of parts, tolerances, tank pressure, high endurance limit, high fatigue strength, tank strength, durable tank fixtures, the number of failsafe devices, material types, and heat transfer system. Looking at this list it was immediately apparent that the safety of the vehicle is of greatest concern due to the risks involved when using hydrogen as a fuel source. Surprisingly, vehicle efficiency, power generation, and other performance related characteristics were not very important compared to characteristics dealing with the safety and production of the vehicle. Thus the vehicle’s ability to be easily manufactured and its resistance to catastrophic failure must be given higher priority than its performance characteristics and other features that would make it a more attractive vehicle to purchase.

1.3: Benchmarking

In order to benchmark our tricycle, we looked at other fuel cell powered vehicles with characteristics similar to what we intend to make. We decided which characteristics to compare based on the results of our analysis of design requirements as well as the availability of information given about the vehicles we wanted to compare. Unfortunately, different sources had different information available about their products so it was impossible to make a direct comparison of all the bicycles over every category we were interested in. Also, some information, such as the number of parts or the materials used, was not mentioned by any of our sources so no data is available for those engineering characteristics. In addition to benchmarking electric and fuel cell bicycles, we also benchmarked different structural materials that could be used to build the structure that would support and house the fuel cell.

Our benchmarking of fuel cell and electric bicycles compared the Merida Electric Bicycle, Currie Electric Bike Kit, Aprilia Fuel Cell Bicycle, Palcan Fuel Cell Bicycle, and ENEA Fuel Cell Bicycle. Appendix B1 shows the complete comparison between these vehicles. In general, the electric bicycles have similar performance characteristics while the fuel cell bicycles have significantly greater range, power, and cost. The chief advantage that a fuel cell has over a rechargeable battery for small scale applications is power density [1]. Batteries are rather heavy for their power density and can only store a limited amount of power. While fuel cells may have heavy stacks, they can store a large amount of fuel without drastically increasing the device's weight. This is why the fuel cell bicycles has much greater power and range, compared to the electric bicycles and still have a comparable weight. The high price of the fuel cell bicycle is expected because fuel cell technology is much more expensive than a battery with similar power capacity.

The benchmarking of structural materials examined 316 Stainless Steel, 6061-T6 Aluminum, PVC plastic, and ABS plastic. The material properties compared were the yield strength, ultimate tensile strength, resistance to corrosion, melting point, hardness, density, and cost per foot. The complete results of the materials benchmarking is shown in Appendix B2. The stainless steel is by far the strongest material and the hardest of the metals selected, although it is also the most dense and most expensive. The aluminum was quite strong for its density and was the softest material selected which means that it would also be the easiest to machine. Although, the plastics were significantly lighter, their yield strengths and melting temperature were smaller and they were more expensive. Overall, the aluminum was considered to be the best material for most applications due to its good strength, low density, and its machinability.

A comparison of energy storage devices is also required to determine the most efficient way to incorporate the fuel cell into the electric bicycle. As can be seen in the benchmarking of the fuel cell bicycles, there are several options available for storing power. In fact, each of the three fuel cell bicycles analyzed made use of a different energy storing system. The Aprilia fuel cell bicycle does not include a battery and runs the motor directly off of the fuel cell with a 2 liter fuel tank; the ENEA fuel cell bicycle has 5 liter fuel tank and also uses a battery to store power; and the Palcan bicycle uses metal hydride to store hydrogen. This comparison of vehicles showed us that the method of energy storage will strongly impact the range, weight, cost, and safety of the vehicle but should not directly affect other performance characteristics of the vehicle. More information on fuel tank selection can be found in Appendix C (Liz's section).

1.4: Design Concepts

The next step was to generate some original design concepts for the tricycle. After looking at other fuel cell powered bicycles, we were able to get a general idea of what would and wouldn't work. A functional decomposition (see Appendix D) was used to create a list of sub functions. For each sub function, we brainstormed a short list of different concepts that could be used to perform each function. The morphological chart is shown in Appendix E, which demonstrates a complete list of all of the tricycle's sub functions and the concepts that were generated to perform those functions. From this chart, two design concepts were generated as shown in Appendix F.

Both design concepts shared common characteristics from the morphological chart, with a few key exceptions. Aside from a few minor differences such as the types of fasteners used, the primary difference between the two concepts was their design for protecting the fuel cell and fuel tank and their means of power regulation. The first concept was designed using a solid aluminum box that protected the fuel cell and the fuel tank. This design also included a battery charger and a lead acid battery which is drawn upon by the motor for power. The second concept was designed out of a lighter and cheaper (but also much less durable) expandable metal material, which shaped the outer cage. The cage was then covered by a layer of gortex to protect the fuel cell from dust and water. The second design does not use a secondary means of storing power and runs the electric motor directly off the fuel cell. A weighted decision matrix (see Appendix G) was used to evaluate the designs to see which one is superior. We found that the first design using the full aluminum cage and battery charging power regulation was the better of the two designs because it provided a safer and more reliable design.

2.0: Embodiment of Design

This section outlines and justifies the selection of our full cage design concept. It includes analysis results and suggestions, reliability considerations, and quality issues.

2.1: Design Justification and Product Architecture

The final design concept was evaluated based on engineering characteristics that were evaluated as most important during the quality functional decomposition phase. The top ten engineering characteristics are the following:

- Number of Parts
- Tolerances
- Material Type
- High Endurance Limit and Fatigue Strength
- Tank Pressure
- Durable Tank Inlet and Outlets
- Tank Pressure
- Tank Strength
- Number of Fail Safe Devices
- Heat Transfer System

2.1.1: Design for Fewer Parts and Lower Complexity

The stack, hydrogen tank, and control support structures were integrated in the final design concept in order to decrease the number of parts and the complexity of design. First, as illustrated in the Figure 2, a cage that surrounds the stack, hydrogen tank, and the battery charger was designed in order to reduce the number of parts. Also, as demonstrated in Figure 2-a, the cage is welded together, instead of bolted, in order to simplify manufacturing and assembly processes. Straps that buckle on the side of the tray that aligns the cage onto the bottom tray, allow an easy way to fasten the cage down. Also, as shown in Figure 2-b, holes at the bottom of the container were made in order to have an easy integration between the control cords attached between the bike and the stack. Lastly, Figure 2-c shows how the final design utilizes control parts that are off the shelf, such as the rechargeable battery to decrease costs and simplify the complexity of the design.

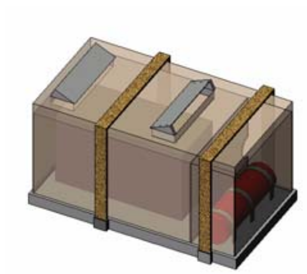

Figure 2: Cage surrounds stack and hydrogen tank in final design

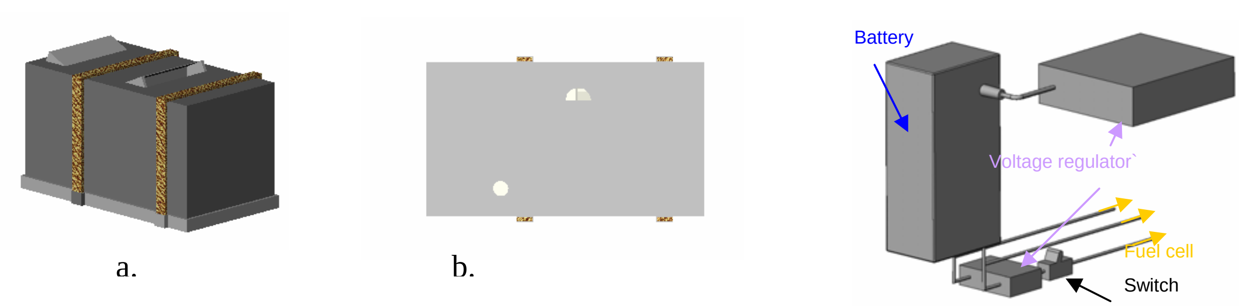

Figure 3: a) welded cage, b) holes in cage bottom for easy access, c) control

2.1.2: Design for Tolerances

The goal of the final design concept was to have a sliding fit between the surrounding cage and tray that will provide rigidity and alignment, but still allow the cage to easily slide into and out of the tray. As a result, the bottom tray has slits milled out so that the cage surrounding can easily slide onto the tray. Figure 4 illustrates the cage surrounding that protects the stack and hydrogen tank, which aligns into the bottom tray.

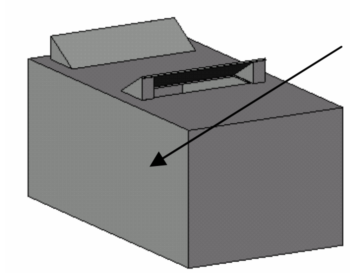

Figure 4: Cage designed for sliding fit

2.1.3: Design for Material Types

For the final concept, materials were chosen that would sufficiently protect the fuel cell and hydrogen tank, would be easy to machine, easy to obtain, cheap, prevent corrosion, and that would still keep the system relatively lightweight. Thus, the availability, machinability, high failure strength, and relatively low costs of aluminum 6061-T6 demonstrated it to be a good material for the supporting structure. The cage was designed of a thicker aluminum sheet so that a reasonable size groove could be cut into it for the cage to slip and align into. Also, the tray is designed of a thicker material in order for a buckle to be able to be placed on it where the straps would fasten. Most importantly, instead of using a steel material that could potentially cause corrosion, a thicker sheet of aluminum is used for the tray in order for it to properly support the weight of the stack, the hydrogen tank, and the outer caging.

Also as shown in Figure 4, on the backside of the cage (the side facing away from the rider), a small section that will be slightly thinner then the rest of the outer caging is designed. The purpose of having a slightly weaker section in the caging is that in case the hydrogen tank does explode, the section that is weaker will most likely explode first, thus ensuring that the hydrogen will explode away from the bicyclist.

2.1.4: Design for Heat Transfer

The heat transfer design aspects looked at maintaining operating temperatures for safety as well as performance of the fuel cell stack. An air divider was placed between the two vents to direct flow of oxygen and to prevent mixing between the exhaust and incoming streams, shown in Figure 5. Incoming air is used to transfer away the heat due to producing electricity and also is needed to complete the reaction. Mixing of the streams would hinder both of these processes. Temperature of the stack would increase if mixing occurs and may become unsafe, possibly leading to burns if handled. Figure 5, shows the design of the air divider to prevent such things from happening.

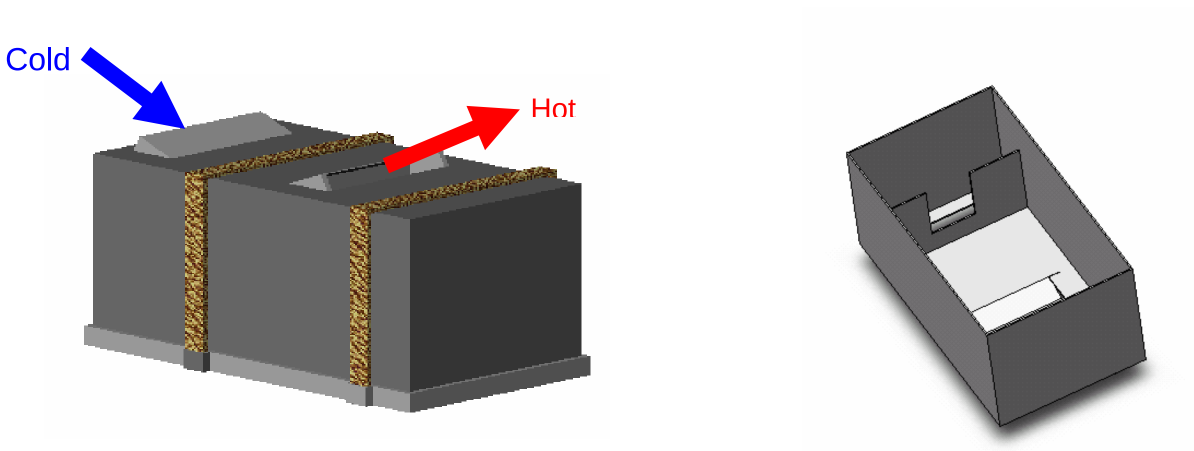

Figure 5: Model of air flow through the stack and the bottom of the cage that allows for better air circulation.

2.2: Product Cost and Parts Analysis

In analyzing the cost of producing our final design concept, we considered the following costs: electronic controls, structural housing, conversion kit, electric vehicle, and hydrogen storage. The final cost of manufacturing everything comes out to be $6,143.46. The breakdown of this cost is seen on the following table.

Table 1: Tricycle Cost breakdown

Item		Cost $
Electronic controls		3516.08
Structural housing		1207.58
Conversion Kit		135.76
Electric vehicle		501.5
Hydrogen Storage		782.54
	Total $	6143.46

A comprehensive cost analysis has been completed and is located in Appendix H. This includes a specific parts list, part quantity, cost, and where it can be purchased.

In addition to a comprehensive part list, specific directions outlining the assembly process for the tricycle has been completed. This can be found in Appendix I.

2.3: Reliability Analysis

Since we came up with our final design late in the quarter, we did not have time to perform adequate testing or analysis. Current completed analysis is seen in this section, and the analysis recommendations can be found in the recommendations section.

2.3.1: High Endurance Limit and Fatigue Strength

To ensure a reasonable lifetime for the fuel cell tricycle, endurance/fatigue was accounted for in the design. The primary concern of this type of failure was for the rear axle, since most of the weight of the supporting system will be centered on the axle. To see all the endurance and fatigue strength calculations please refer to Appendix J. Using 4130- steel for the axle, calculations resulted as following per ME 356 textbook [2]:

Table 2: Axle bending and fatigue results

	Bending	Fatigue
Factor of Safety	1.38	1.03

As demonstrated by the low safety of factors, further analysis are necessary to figure out why the safety of factors are so low and how to increase them. For example, it is possibly that some of our assumptions are too high. Furthermore, we plan to increase the diameter of the axle and possibly change material type in order to increase the overall safety of factors.

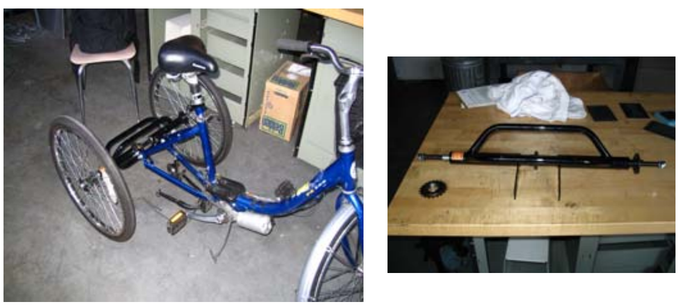

Figure 6: Axle endurance strength and fatigue analysis.

In addition to axle endurance strength and fatigue strength, a vibration analysis will also be performed. This is to test the conditions the fuel cell will experience and assure that it will not fail due to mechanical fatigue. A simple vibration analysis [3] has already been started and its progress is shown in Appendix J. It is important to point out that the shock and impact caused by road surfaces and steering of the bike will not greatly effect the fuel cell operation. The fuel cell is able to withstand greater vibrations and impact than ASTM specified loads listed in appendix J.

2.3.2: Hydrogen Considerations

Calculations for the required tank pressure to allow the vehicle to travel 30 miles using 200 watts for the duration of the trip was done. The pressure calculated made idealistic assumptions to simplify such calculations (Appendix C). The chosen tank is capable of much higher pressures but the decision was made to keep pressure on the lower side for safety to the customers. The average customer is assumed to have little or no experience with handling pressurized gases or refueling such a container. Mistreatment to the tank may cause injury or death. We hope to keep the pressure low to reduce these dangers. Therefore, the lower pressure helps fulfill the requirement of safety. The chosen tank can be bought or rented through the contacted dealer (Appendix C). A smaller and lower rated tank could have been used but would require customization. The decision for this tank was partially because we wanted a stronger tank to compensate for the customers inexperience. This effectively raised the safety factor of the tank making it more robust.

Increasing the user safety also influenced other considerations such as the tank inlet and outlet. Protection of this area of the tank is vital. As stated before, orientation of the tank is the primary way to protect the inlet and outlet when in use. The compartment wall separating the tank will also act as a guide when lowering the cage so the inlets will not have a chance being severed thus causing tank failure.

2.3.3: Number of Fail Safe Devices

The supporting structure was designed to provide three main layers of fail safe devices. First, a separator is welded into the plate in order to divide the hydrogen tank from the fuel cell. Thus, if the either the hydrogen tank or the fuel cell comes loose they will not jam against each other. Secondly, each compartment is insulated with foam, so that in the case that either the tank or the fuel cell comes lose, they will bump into a soft interior as a result avoiding any hard impacts. And thirdly, an aluminum cage surrounds the hydrogen tank and the fuel stack, in order to further isolate it from environment impacts. Figure 7 demonstrates fail safe devices in the structure.

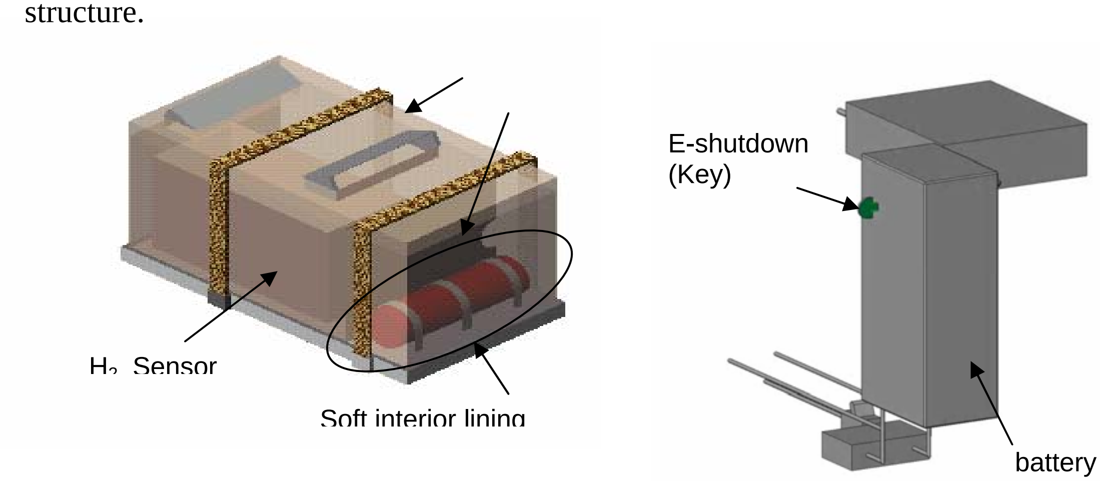

Figure 7: Fail safe devices

In addition to the sensors that the Ballard stack has, the control system also has an emergency shutdown key, as shown in Figure 7, in case the user needs to quickly shutdown the bike. Emergency shut manual shut down instructions can be found in Appendix M.

We also performed a fault tree to analyze the chance of hydrogen explosion as preventing explosion was one of our main design requirements. We found that there is a 1 in 64,850 chance of a hydrogen explosion for any given bike ride. The completed tree is seen in Appendix K.

2.3.4: Controls Analysis

The electronic controls must create compatibility between the fuel cell and electric bike in order for the fuel cell bicycle to be reliable. Several tests will be done to ensure compatibility:

1. Electric bike can successfully send instructions to the fuel cell (Power and voltage signal can be sent correctly to the fuel cell to activate, start up and shut down the fuel cell).
2. Fuel cell can successfully send power to electric bike (Fuel cell output voltage can be regulated to produce desired output and recharge the battery).
3. Demonstrate the product is a fully functional model and operates in acceptable parameters (Final prototype demonstration will be with the fuel cell integrated into the e-bike and motor as load. No over loading/heating of motor, battery or fuel cell).

2.4: Manufacturing, Quality, Legal and Ethical Issues

With the use of a PEM fuel cell in our tricycle design, the use of hydrogen presents a marketing challenge. The current stigma encircling hydrogen is that it is explosion prone and very dangerous. We must therefore ensure the quality of our product by limiting variability during the manufacturing process with routine inspections. These product checks should reduce the number of flaws during production, and over time win the trust of our target market. In addition to economic incentive, we have an ethical obligation and legal interest in creating safe tricycles as hydrogen explosion could prove fatal.

3.0: Contribution to Class Business Plan

The following plan outlines the management, marketing, and financial strategies to be used by RevoTrikes Inc. for successful long term operation.

3.1: The Company

RevoTrikes Inc. specializes in the design and manufacture of fuel cell powered tricycles. Our fictitious, 6 person company is composed of 4 UW mechanical engineers and 2 UW MBA graduates. RevoTrikes Inc. seeks to introduce fuel cell powered tricycles into the existing electric bike industry. As gas prices continue to rise, and environmental factors begin to drive consumer habits, the use of hydrogen fuels toward powering a traditional tricycle will find a lasting market for RevoTrikes Inc.

3.2: The Product

The main product manufactured by RevoTrikes Inc. is a human assisted, fuel cell powered tricycle. This tricycle consists of a modified Merida electric bicycle, a Ballard Nexa Power Module, and a custom designed safety cage. It is rated for 30 miles of operation before necessary refueling, has a maximum speed of 20 mph with a power output of 200 W. In addition to the production of the fuel cell powered tricycle, we also offer consulting services to organizations and/or universities seeking to further their understanding of PEM fuel cells and their applications.

3.3: Industry Analysis

Electric bikes are becoming an increasingly popular method of transportation, especially in dense cities where automobile use lacks practicality. For example, over 1 million electric bicycles have sold in Japan alone over the last five [4] and this trend continues in other large metropolitan cities. This growing market has attracted other fuel cell powered bike companies such as WL Gore and Associates, Intelligent Energy, and Palcan Fuel Cells Inc.

3.4: Market Analysis

As mentioned in the Industry Analysis, RevoTrikes Inc. is targeting the average city slicker looking to find an easier and greener way around town. Therefore, we are developing international contacts to market our tricycle in major metropolitan areas, as domestic and international large cities will be our primary marketing focus. In addition to the city, big businesses and universities have shown an interest in our tricycles as a cost-effective and environmentally friendly courier vehicle to deliver anything from mail and packages, to extra bolts and parts on the manufacturing floor. Although this is our secondary market, we will develop prototypes within the university setting both as a way to defray some of the research and development costs as well as a feasibility study for a potential market we would like to enter.

3.5: Financial Forecast

RevoTrikes Inc, is set to turn a profit in 4 years of successful sales. The related costs are the engineering, manufacture, and marketing of our revolutionary tricycle. The projected costs and resulting profits are shown the following table [5].

Table 3: Financial Forecast for RevoTrikes Inc.

	2005	2006	2007	2008	2009	2010	2011	2012
Sale Price	$0	$2,000	$2,000	$2,000	$3,500	$3,500	$3,500	$3,500
Units Sold	0	50	115	345	1035	1293.75	1617.19	2021.48
Net Sales	$0	$100,000	$230,000	$690,000	$3,622,500	$4,528,125	$5,660,165	$7,075,180
Unit Cost		($10,245)	($7,054)	($5,329)	($3,389)	($3,301)	($3,230)	($3,222)
Development Cost	($10,000)	($10,000)	($10,000)	($5,000)	($5,000)	($1,000)	($1,000)	($500)
Marketing Cost	$0	($30,000)	($40,000)	($50,000)	($55,000)	($60,000)	($60,000)	($60,000)
Manufacturing Cost	$0	($200)	($200)	($200)	($200)	($200)	($200)	($200)
Materials Cost	$0	($1,245)	($1,245)	($1,245)	($1,245)	($1,245)	($1,245)	($1,245)
Other Cost	($250,000)	($250,000)	($250,000)	($250,000)	($400,000)	($400,000)	($400,000)	($500,000)
Fuel Cell Stack	($3,000)	($3,000)	($3,000)	($3,000)	($1,500)	($1,500)	($1,500)	($1,500)
Cost of Product Sold	$0	($512,250)	($811,175)	($1,838,525)	($3,508,075)	($4,271,094)	($5,223,625)	($6,513,759)
Total Sales	$0	$100,000	$230,000	$690,000	$3,622,500	$4,528,125	$5,660,165	$7,075,180
Total Cost	($260,000)	($512,250)	($811,175)	($1,838,525)	($3,508,075)	($4,271,094)	($5,223,625)	($6,513,759)
Profit	($260,000)	($412,250)	($581,175)	($1,148,525)	$114,425	$257,031	$436,540	$561,421

The table above shows that we will turn a profit in four years of sales, at which time we experience a decrease in development costs and a significant increase in other costs which include employee compensation.

4.0: Future Recommendations

Although we were not able to develop a full operating prototype for our tricycle, the majority of the controls and structures research and analysis has been completed. The following section outlines suggested ME 495 or ME 499 projects to be completed in order to carry out the prototype of our design.

4.1: Tricycle Kit Conversion

The tricycle conversion kit was purchased from Electric Bikes NW in Freemont for $100. David is a good contact person at the bike shop and can be reached after 2pm on most days at (206) 547-4621. The problem with the conversion kit is that the axle width is not wide enough to fit the fuel cell between the wheel base. Therefore, we purchased a new axle from online metals for 30 dollars. It is 0.5625 inches in diameter, 48 inches long and is made of 4340 steel. One problem with this axle is that its diameter is too large to fit in the conversion kit (this is due to our measurement error). The conversion kit inner diameter is 15 mm, which is a non-standard size and difficult to match. We found an alternate axle through Specialty Metals in Kent. They were able to make a custom 15 mm rod but it costs $180. Gloria is the salesperson we have been working with and can be reached at (253) 872-0424. Another option is to find new bearings that have the same outer diameter as to fit in the existing conversion kit but a larger inner diameter as to fit the new axle. The bending and fatigue analysis have been completed for the axle.

Once the axle situation is solved, the kit must also be fixed to the bike frame so that it does not rotate about itself during use. The best solution we found was to mount the fork of the conversion kit above the upper bar of the bicycle frame with a steel bar that ran across the structure as to prevent it from rotating.

Finally, a new BMX chain is needed. The current chain is roughly 4 inches too short. Additional links were donated by Recycled Cycles which would will placed on when the final length needed is measured.

4.2: Fuel Cell Protection

An essential part of the tricycle prototype is the fuel cell protection system. Based on our QFD and functional decomposition, we decided to enclose the fuel cell and hydrogen tank in a welded aluminum cage as described in our design section. We considered expanded metal and reinforced steel bars to add structural stability. We have yet to complete the structural analysis on the cage itself to determine the need for the steel. This analysis should be done prior to cage purchase to ensure stability. The analysis should be done per ASTM and SAE Standards [ASTM F1625, F1447, F2043 (15.07), SAE J2578, J2579, J1766 J1739] [6],[7], [8]. After completing the analysis, steel bars made be added to guarantee the structural stability of the cage.

A specific pricing spreadsheet was made comparing the prices of different cage options. This is found on the twiki website and is also in Appendix H. The aluminum sheets are to be purchased at online metals and range in price from $30.49 to $104.78 depending on the structural integrity of the aluminum sheets. A host of other options are documented in the pricing spreadsheet. The manufacturing process needed to complete the cage design can be found in Appendix I.

4.3: Fuel Cell Optimization

The capabilities of the Ballard stack had a far greater capacity than the requirements of the electric bike. The bike only required 1/6 of the power the fuel could produced. Future projects could optimize this relationship through downsizing the fuel cell or better utilization of the capabilities of the fuel cell.

4.4: Controls

As one of required the projects to create a working prototype, initial conceptual efforts have been done and have neared the implementation stage. This work required initial background research into very simple electronics. There are still future steps needed to be to finish this project. Purchasing the required components, and testing the interface of the two devices are the major priorities. The parts list needed was generated from components that can be bought off the shelf. The major purchase component (battery charger) for the controls is a significant percentage of the cost that we prefer not have.

Future groups will most likely want to build their own voltage regulator and battery charger. Although we spent a decent amount of time researching how to build such devices, our expertise in electrical engineering was too limited to create a design that we are confident with. Therefore future groups should use our research in Appendix L as a reference only and consult someone who is much more knowledgeable about electronics (such as an EE faculty member). An estimated cost for the recommended home built battery charger from diagrams would be approximately $200.

4.5: Other Bike Components

In addition to our major design components of the project, the wires, brakes, and gears need some attention to optimize the tricycle. Ideally, the wires would be inside the bike frame to reduce clutter and reduce the risk of exposed wires being snagged.

A significant amount of additional weight will be added to the electric bike. Currently the bike has one caliper brake on the front tire since the rear brake was removed during the tricycle conversion. More extensive analysis should be done to choose the optimal configuration used. For example, disk brakes could be a possibility for the rear wheels. Parameters to examine would be stopping distance, braking force, speed, number of brakes and any others deemed important.

The donated electric bike had internal gears on the rear wheel axle. Unfortunately this wheel was not compatible with the tricycle kit and could not be used. It would be helpful to research a way to integrate a gear system as to reduce the output needed by the motor.

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6.0: APPENDIX

Appendix A: Quality Function Deployment

(SEE HARDCOPY)

Appendix B1: Benchmarking of Electric and Fuel Cell Bicycles

ENGINEERING CHARACTERISTICS	METRICS	UNITS OF MEASURE FOR METRICS	Competing solution 1: Merida Electric Bicycle	Competing solution 2: Currie Electric Bike Kit	Competing solution 3: Aprilia Fuel Cell Bicycle	Competing soutoin 4: ENEA Fuel Cell Bicycle	Competing solution 5: Palcan Fuel Cell Bicycle	Marginal Value	Ideal Value
Mass	Quantitative	kg	29	12.7*	23	?	26	26	23
Range	Quantitative	km	50	32	100	120	65	79	120
Speed	Quantitative	km/h	30	32	32	18 (mean)	25	31	32
Cost	Quantitative	$	500	450**	2300	?	2000	1083	500
Fuel Capacity	Quantitative	L	NA	NA	2	5	500***	2	2
Fuel Tank Pressure	Quantitative	psi	NA	NA	?	2900	4***	2900	2000
Power (Motor)	Quantitative	W	230	450	670	230	200	450	670
Voltage (Motor)	Quantitative	V	24	24	?	26	?	24	24
Batteries	Quantitative	# x V	1 x 24	2 x 12	NA	1 x 26	NA	24	24
Current	Quantitative	A	10	12	?	9	?	11	12

Benchmarking Notes:

* Does not include the mass of the bicycle.

** Does not include the cost of the bicycle.

*** Metal hydride hydrogen storage, not a H_2 pressure vessel

Appendix B2: Benchmarking of Structural Materials

ENGINEERING CHARACTERISTICS	METRICS	UNITS OF MEASURE FOR METRICS	Competing solution 1: Aluminum Rectangle (hollow) 6061 T6	Competing solution 2: Stainless - Steel -316	Competing solution 3: PVC	Competing solution 4: Plastic – ABS Material	Marginal Value	Ideal Value
Yield Strength	Quantitative	MPa	276	434	52	43.4	276	300
Ultimate Tensile Strength	Quantitative	MPa	124	538	180	41.9	300	400
Corrosion	Qualitative	1-3-5	5	5	5	3	3	5
Melting Point	Quantitative	Celsius	582	700 C +	150	93.2	150	200
Hardness	Quantitative	Rockwell	30	64.5	115	74.9	30	35
Density	Quantitative	g/cc	2.7	7.92	1.41	1.05	2.0	1.5
Cost per Foot	Quantitative	$	$2.11 - $3	$10-$15/foot	$2-4/foot	$10/foot	10	5

Justification of Benchmarking:

In order to determine good structural materials, we wanted to compare the strength, impact resistance, corrosion resistance, temperature range, vibration resistance, and weight.

Strength of materials: We used Tensile Strength at Yield to define this property because we want a material that can withstand a lot pressure before yielding.
Impact Resistance: It was difficult to find Charpy Test results for all of the materials. As a result, in order to have some quantitative comparison we used the Ultimate Tensile Strength property to compare the materials in order to define the amount of total energy each material can absorb before yielding. For this design, we want the highest possible ultimate strength in the case if a tree or a large rock falls on the fuel stack.
Corrosion: We used a qualitative metric to compare corrosion resistance properties of each material. 5 denote excellent corrosion resistance, whereas 1 denotes the worst corrosion resistance. Although the structure will be covered by some material to protect the fuel cell, this structure might still be submersed in some water so we want it to be corrosive resistant.
Temperature Range: It is important for the material to have a high melting point, so that it will properly withstand the heat that is emitted by the fuel cell.
Vibration Resistance: Since this application is for a bike it is critical for our structural design to withstand the vibration. For this study, we related vibration resistance to the hardness of each material being compared. However, we will more accurately address vibration in the system by damping the plate that the stack will be placed on.
Weight: In order to reduce additional weight to the structure materials with the smallest densities are desired.
Cost: Definitely the cheaper the part the better. In addition, the feasibility of getting the materials in the give time constraints is also considered.

Appedix C: ME 499 Report by Liz Kurihara

ME 499G

SPRING 2005

FUEL CELL PROJECT – TRICYCLE APPLICATION

(EMPHASIS ON HYRDOGEN STORAGE)

FINAL REPORT

June 8, 2005

ELIZABETH KURIHARA

Table of Contents

Introduction

The fuel cell technology at the UW has been growing and thriving in its works in researching ways to improve the design of the cells. Much of the previous work has centered on the internal components of the cell and testing devices, and minimal work has been done towards applying the fuel cell to a modern device. This quarter, the Ballard fuel cell stack was designed to power an adult size tricycle. The project included design work for the control system for the tricycle and housing unit for the stack and hydrogen fuel tank. As an extension to these design tasks, the best suited type of hydrogen storage for the tricycle was chosen. Important considerations that helped determine the hydrogen storage depended on size, design demands, safety, attainability, and cost of that unit.

Problem Statement

In this project, the Ballard stack which is capable of producing 1.2kW of power was used as the power source to drive the tricycle. As the Ballard stack sits stationary in the lab, it is connected to a large, heavy standard size pressurized hydrogen tank, standing about five feet high. This tank would not be a good candidate to have onboard the tricycle from many safety and logical reasons. Thus, the tricycle will need to be equipped with a smaller hydrogen storage unit that is safe, light, durable, yet still able to power the tricycle for a reasonable ride time.

Literature Review

Due to the fairly new application of the fuel cell to a tricycle, the selection of information available was limited. Literature and standards about hydrogen were adapted from sources that considered hydrogen storage on vehicles and bicycles, different storage methods for hydrogen, and safety practices from the SAE and NFPA, in addition to hydrogen information from the Ballard stacks manual.

Out in the industry, the nearest product similar to the tricycle was a fuel cell powered bicycle made by Manhattan Scientifics', the Hydrocycle™. This bicycle used a two-liter pressurized tank made of carbon fiber and a fuel cell stack outputs 670 W of power (Manhattan Scientifics, 2005). The Hydrocycle™ was made from advanced technologies and materials which surpasses this project's resources. The tricycle's fuel cell has 1.2 kW of power, almost doubling that of the Hydrocycle™, revealing that the tricycle has more power than it really needs. The Hydrocycle™, even though a bicycle and more advanced in its design and materials, upholds a standard where this project's tricycle design and fueling system could aim.

Engineering Concepts

Hydrogen has the lowest density of any gas and the 2^{nd} lowest boiling point. These properties cause storing hydrogen a difficult task. For example, because hydrogen is so light, high pressures must be attain for storage, and also, since it has a low boiling point, storing it at low temperatures requires an abundance of energy. Due to extreme conditions in which hydrogen storage demands, various precautions must be up held to ensure the safety of each storage unit. Some safety codes and standards for hydrogen storage are listed in the Appendix E.

For this project three options have been chosen to fuel the tricycle: 1) in high pressurized tanks, 2) as liquid hydrogen, and 3) in metal hydrides.

Option 1: High-Pressurized Hydrogen Storage

The most common type hydrogen storage is in a high pressurized gas tank. These tanks are typically used for stationary applications due to their heavy and bulky structural design can withstand pressures up to 3600 psi (Ballard), yet can made into a several different sizes and pressures. Tanks are currently made out of entirely steel or aluminum, or lined with strong composite layer. Tanks made out of purely metal are tough, yet hold <1% of the weight of hydrogen, the other 99% of the weight is from the heavy duty materials making up the storage unit (Energy Partners, 1999).

The composite tanks use a combination of fibers and resin to form a tough layer wall within the tank. With composites, it allows the tanks to be lighter and can be very effective if undamaged. However, they are more susceptible to abrasions and scratches which could lead to severe problems. With high-pressure systems (3000 psig and above) such as these, many safety concerns arise such as violent and powerful explosions and fires. Compressed hydrogen can cause severe and/or deadly injuries if punctured and if hydrogen and air mix with an ignition from a heat source, an explosion will occur.

Option 2: Liquid Hydrogen Storage

Another possible way to store hydrogen is in a liquid phase. The advantages for these units are that they are light, compact, and easier to transport (Aceves, 1997). The storage unit for liquid hydrogen does not have to be as strong as the pressurized tanks because high pressures are not necessary for this type of unit, however, the tank still needs to be tough. A down side to this method stems from the large amounts of energy that must be used to acquire this liquid state, at least 30% of the lower heating value (LHV) of hydrogen (Aceves, 1997). Another disadvantage is that over long periods of time, evaporation will occur because of heat loss to the environment. The cryogenic hydrogen storage can warm up to ambient temperatures which would require a release of pressure that accumulates, thus causing a loss of fuel and danger to the surroundings (Aceves, 1997). Some safety concerns include frostbite due to the very low temperatures, brittlement on tanks, and explosions.

Option 3: Metal Hydride Storage

Metal hydride storage method uses a select number of metals such as magnesium, nickel, iron, and titanium which are capable of absorbing hydrogen in the gaseous state and storing the hydrogen molecules within its metal structure. When the metal is heated at a relatively high temperature and low pressure, the hydrogen is released (Ballard). This method delivers hydrogen more safely than the other two options because of its low operating pressure and due to the fact that the metal hydrides stop releasing hydrogen when exposed to cooler air, which would be the case if a puncture occurred on the tank, the hydrides would be cooled by the ambient air. Some down falls include there must be an external source of heat and that “even the best metal hydrides contain only 8% of hydrogen by weight and therefore tend to be very heavy and expensive” (Ballard). Also, pure hydrogen is needed for metal hydride storage and any contamination or impurities would cause problems.

Final Selection

There were many advantages and disadvantages between the three options. The metal hydrides were the safest, being able to operate at low pressures and having the natural ability to stop the flow of hydrogen if the tank was punctured. The cryogenic tanks were lighter and could more transportable and the pressurized tanks are more available. On the other hand, the metal hydrides and cryogenic tanks are expensive and are still under research and development while the pressurized tanks have been used on the market for many years now. Also, the cryogenic and metal hydride tanks would require a unit that keeps the tank at a very low temperature or an external heat source, respectively. These two methods would need extra design items such as ventilation, ridged mounting structure, to accommodate for the cooling or heating sources to reach their operating temperature levels, and not to mention more space to incorporate both the source and tank.

The final selection of the tank was the pressurized tank with a pressure of 2000 psig (13789 kPa(g)) and a diameter of 5" and a length of 18". This decision took into consideration the pros and cons of each tank as well as the amount of design and space required, safety, attainability, and cost. The design and space requirements became the two factors that were focused on the most, as a result of trying to achieve the goal of building a prototype. Pressurized tanks were found to come in many different sizes allowing for more options for the size of the tank to fit within the 25" of space available on the tricycle. Also, no other design work for cooling or heating sources needed to be considered when securing the tank.

If more time was permitted and a group was assigned to focus on designing the mounting of the hydrogen fuel, the metal hydride method may pose a better solution to storing hydrogen aboard the tricycle, assuming a better matched fuel cell stack was used instead of the Ballard stack. Just as mentioned above in section Engineering Concepts – Option 3, using metal hydrides would be much safer because of its lower operating pressure and natural behavior to stop releasing hydrogen if the tank is severed. Yet, an external heat source would be needed and new design aspects would have to be accommodated to ensure the safety of the heating source and tank, along with proper ventilation and protective structures.

Results and Discussion

The group's goal for this project was to have a working prototype of the fuel cell powered tricycle working by the end of the quarter. Unfortunately, this goal was not reached, even with the best efforts to be more efficient by splitting into two smaller groups, one working on the control system and the other designing protective structures for the fuel cell and tank on the back platform of the tricycle. As the weeks progressed, many unexpected obstacles fell along the way. For instance, converting the donated electric bicycle to a tricycle with the purchased conversion kit did not properly fit, causing time spent to create a converter. Also, the braking system of the tricycle needed to be upgraded to accommodate the extra weight on the back of the tricycle due to the fuel cell and the fuel tank.

These surprise problems lead to extra design issues that the members of the group also needed to account for, along with their fuel cell design responsibilities. Therefore, while still trying to build a prototype by the end of the quarter, finding the tank with the least amount of design work was one of the main criteria for the tank selection. As mentioned before, this criteria and the limitation of space on the tricycle for the tank to fit (25" available), were the two major driving factors in selecting the type of tank. From the design aspect, the pressurized tanks do not need any external heating or cooling sources to release or store hydrogen, allowing the mounting design of the tank to be simple and the use of space to be minimal.

Also, more room would have been available if a smaller sized fuel cell stack was used for the tricycle instead of the Ballard stack. The tricycle power required could be thought to be at the same power output as the Hydrocycle™, thus, in this case, the tricycle would only use ~670 W which is about a little less than half the power of the 1.2 kW Ballard stacks. The extra power from the Ballard stacks, are extra cells and take up extra space on the platform that could be used for the tank. If a larger space was allowed, a bigger tank with a lower pressure could be considered, or perhaps even the cryogenic or metal hydrides options because there would be space for the sources to be mounted.

Additional characteristics that also swayed the final selection of the tank along with the design and space factors were the safety, attainability, and cost of the tank.

Many safety concerns arise with the pressurized hydrogen tanks. First, tanks at high pressures, if punctured can cause severe injuries to humans and structures from debris. Secondly, hydrogen is an odorless gas that when mixed with air and ignited, has the potential to cause powerful explosions from leaks causing fatal injuries and devastating destruction. In this project, the hydrogen tank is the part that had the most precautions applied for its protection, especially because the tricycle will be exposed to a moving environment.

For instance, the tank's valve was positioned to face the rider, so in the case of an explosion, the debris would shoot out in the weakest part of the tank which is the bottom. This prevents the rider from being hit. Also, a steel cage was designed to surround the tank which is proposed to help contain most of the explosion if one were to happen, shielding the rider and others from flying metal and gases. However, in any situation where compressed gas is being used, care and caution must be used and the tanks must be inspected and monitored constantly. Please see Appendix E for safety codes and standards from NFPA and SAE.

The availability of smaller sized pressurized hydrogen tanks can be attained through UW Stores, where the cost to rent a tank is fairly reasonable.[1] In fact, the tank supplier to the UW stores, A-L Compressed Gases, has the ability to make special orders for tanks. A representative from A-L Compressed Gases viewed the tricycle and suggested possible tank sizes. He concluded that his company could supply hydrogen tanks ranging from 17 – 20 ft^3, at about 5-6 inches in diameter and about 18-20 inches in length. These tanks would be at 2000 psig (13798.50 kPa(g)). If the tanks were not a standard size, the A-L Compressed Gases has the resources to build custom orders, thus if any changes were done to the tank in the future, for example, acquiring a smaller fuel cell, the option of making a tank for the new fuel cell can become a reality. The representative also concluded that the regulator and connecting tube in the lab would be expectable to use for the tricycle. More information about this company is located in Appendix D.

The tank chosen had a pressure of 2000 psig (13789 kPa(g)) and a diameter of 5” and a length of 18”. This tank was not considered to be at a “high pressure” because it was lower than 3000 psig (Ballard, Section 5), but is still at a pressure that can cause serve injury and damage. With this tank, the maximum capacity of hydrogen that can be stored was calculated to be 0.0644 kg and would last for 268 min or 4.4 hrs (please see Appendix B for calculations).

However, the tank could be used at a lower pressure and still provide reasonable mileage and ride time. For instance, if the tricycle were to travel 30 miles, the ride time would be 86

[1] The rental of a custom tank from the UW Stores has been requested, their response is in pending.

minutes and would require a lower pressure of 643 psig (4521.9 kPa(g)) which would improve the safety concerns when compared at 2000 psig (please see Appendix C for calculations). The Ballard fuel cell regulations for the maximum fuel input is 1720 kPa(g) so if this tank was run at its maximum level or even for 30 miles, a regulator must be used; the regulator already in the lab is an option. (Please see Appendix C for calculations).

Now that the type of tank was selected, the amount of ride time and distance the tricycle would travel was calculated and summarized in Table 1 below. These calculations only include the amount of fuel to power the motor and did not account for pedaling or the fuel needed to move the extra weight the fuel cell stack and tank would present.

To find the length of time the tank would fuel the fuel cell, the Ideal Gas Law was used.

$$m = \frac{PV}{RT} \qquad \text{(Eq. 1)}$$

and using the mass and mass rate the length of time for the tank was,

$$t = \frac{m_{\tan k}}{\dot{m}_{H2}} \qquad \text{(Eq. 2)}$$

$$\text{where} \quad m_{\tan k} = \frac{PV}{RT} \ \text{(Eq. 1a) and} \ \dot{m}_{H2} = \frac{P\dot{V}}{RT} \ \text{(Eq.1b)}$$

Table 1 displays the results of using the tank at its maximum capacity and for only 30 miles.

Table 1. Varying tank pressures of the tank with diameter = 5” and length = 18”.

Use	Tank Pressure, [psig]	$m_{\tan k} = \frac{PV}{RT}$, [kg]	$\dot{m}_{H2} = \frac{P\dot{V}}{RT}$, $\left[\frac{kg}{\min}\right]$	$t = \frac{m_{\tan k}}{\dot{m}_{H2}}$, [min]	Speed, [mph]	Distance, [miles]
Continuous (3 SLPM)	2000	0.0644	2.47e-4	268	20	89
Continuous (3 SLPM)	643	0.021375	2.47e-4	86	20	30

*Please see Appendix B and C for calculations.

Recommendations for Future Work

Here are some suggestions that may help improve the fuel cell tricycle.

- Use a more appropriate size fuel cell stack to power the tricycle
    - Doing this will allow not only more space on the back platform, but also better use of the fuel.
    - If smaller fuel cell stack more room. If there is more room on the platform for the tank,
        - a bigger pressurized tank at a lower pressure could be used
        - other types of pressurized tanks could be used to decrease weight: steel, aluminum core encased with fiber glass (composite), plastic core encased with fiberglass (composite) (Bellona, 2005)
        - metal hydride tanks, its external heat source, and ventilation unit could all fit. Using this method would be safer to have onboard due to their low pressures and natural behavior of the structure. For if the tank is punctured, the ambient air will cool the metal hydride and the hydrogen will not be released any more.
- Find smaller regulators
    - If pressurized tanks are kept as the choice method to fuel the fuel cell, a smaller regulator would be more suitable for the tricycle. The regulator that is down in the lab can be used but is fairly bulky.
- Build converter to make bicycle into tricycle
- Apply braking system to stop both back tricycle wheels

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Appendix A
Information from Ballard Stack and Electric Bicycle

ELECTRIC BICYCLE

The power to run the motor on the tricycle was found to be 200 and 230 W at continuous and peak use, respectively. The corresponding data is given in Table A1 below.

Table A1. Electric Tricycle Data

	Type of Use	Power Demand from Motor, [W]
Rated Power @	Continuous	200
	Peak	230

1.2kW BALLARD STACK FUEL CELL

From Nexa™ Power Module User's Manual, Figure 34: Hydrogen Consumption on pg 87, was used to find the hydrogen consumption values using the H2 Consumption curve and the Power values from the motor. The resulting values of the H2 consumption are displayed in Table A2, below.

Table A2. Fuel Cell Hydrogen Consumption Rates from Figure 9.2 from the Nexa™ Power Module User's Manual

Type of Use	Power, [W]	Hydrogen Consumption, $\dot{V}$ = [SLPM]	Hydrogen Consumption, $\dot{V} = \left[\frac{m^3}{\text{min}}\right]$
Continuous	200	3	0.003
Peak	230	3.5	0.0035

Appendix B
Ride time calculations for chosen fuel tank

The Ideal Gas Law was used to find the time the fuel tank would last.

$$m = \frac{PV}{RT} \qquad \text{(Eq. 1)}$$

where P = Pressure (absolute), $[kPa]$
V = Volume, [m^3]
R = Gas constant for hydrogen $\left[\frac{kPa * m^3}{kg * K}\right]$
T = Temperature, [K]

$$m_{\tan k} = \frac{PV}{RT} \qquad \text{(Eq. 1a)}$$

$$\dot{m}_{H2} = \frac{P\dot{V}}{RT} \qquad \text{(Eq. 1b)}$$

To find the time the tank will last,

$$t = \frac{m_{\tan k}}{\dot{m}_{H2}} \qquad \text{(Eq. 2)}$$

i. *Mass of H2 in the tank (Eq. 1a),*

Assume:
T = 298K
$R_{H2} = 4.124 \frac{kPa * m^3}{kg * K}$

Tank data:
Diameter = 5”
Length = 18"
$V_{\tan k} = 353.42 in^3 = 0.0057 m^3$
$P_{\tan k(gage)}$ = 2000psig = 13789.51 kPa
$P_{\tan k(abs)}$ =13890.79 kPa ($P_{abs} = P_{gage} + P_{atm}$)

Then Eq. 1a, $m_{H2\,\mathrm{int}\,ank} = \dfrac{P_{\tan k}V_{\tan k}}{R_{H2}T}$ becomes,

$$m_{H2\,\mathrm{int}\,ank} = \frac{13890.79kPa * 0.0057m^3}{\left(\dfrac{4.124kPa * m^3}{kg * K}\right) * (298K)}$$

→ $m_{H2\,\mathrm{int}\,ank} = 0.0644kg$

ii. *Mass rate of H2 (Eq. 1b),*

Assume:

T = 298K

$$R_{H2} = 4.124\frac{kPa * m^3}{kg * K}$$

$$P = 101.325kPa$$

Then Eq. 1b, $\dot{m}_{H2} = \dfrac{P\dot{V}}{R_{H2}T}$ becomes,

$$\dot{m}_{H2} = \frac{101.325kPa * \dot{V}}{\left(\dfrac{4.124kPa * m^3}{kg * K}\right) * (298K)}$$

where $\dot{V}$ = volume rate and are found from the data from Appendix A, Table A2.

- At continuous use, $\dot{V} = 3SLPM = 0.003\dfrac{m^3}{\min}$

$$\dot{m}_{H2} = \frac{101.325kPa * 0.003\dfrac{m^3}{\min}}{\left(\dfrac{4.124kPa * m^3}{kg * K}\right) * (298K)}$$

→ $\dot{m}_{H2} = 2.47e - 4\dfrac{kg}{\min}$

- At peak use, $\dot{V} = 3SLPM = 0.0035\frac{m^3}{\min}$

$$\dot{m}_{H2} = \frac{101.325kPa * 0.0035\frac{m^3}{\min}}{\left(\frac{4.124kPa * m^3}{kg * K}\right) * (298K)}$$

→ $\dot{m}_{H2} = 2.885e-4\frac{kg}{\min}$

iii. *<u>Time (Eq. 2),</u>*

Taking the results from parts i and ii, the time length the tank will last is calculated using Eq. 2,

$$t = \frac{m_{\tan k}}{\dot{m}_{H2}}$$

- At continuous use, $\dot{m}_{H2} = 2.47e-4\frac{kg}{\min}$,

$$t = \frac{0.0654kg}{2.47e-4\frac{kg}{\min}}$$

→ $t = 268.98\min$

- At peak use, $\dot{m}_{H2} = 2.88e-4\frac{kg}{\min}$,

$$t = \frac{0.0654kg}{2.885e-4\frac{kg}{\min}}$$

→ $t = 227\min$

* Note: The all calculations in Appendix B assume that the hydrogen does not heat up while being filled up.

Appendix C
Calculations to find the pressure to reach 30 miles

Figure C.1, below, shows a relationship between the horsepower used at varying speeds when considering friction and air resistance when riding a bicycle. The equation of the curve is estimated to be,

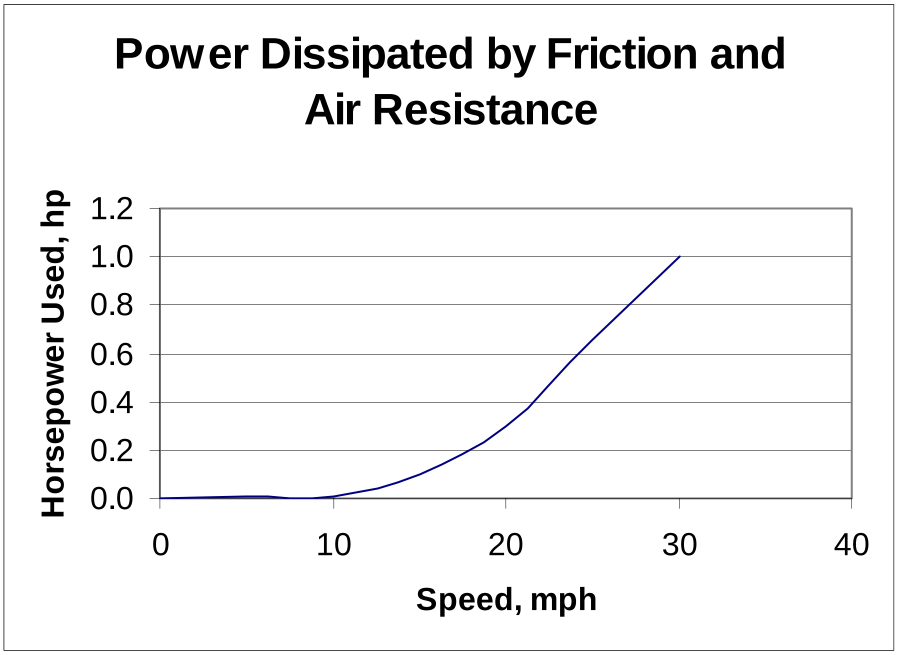


Figure C.1: Power dissipated by friction and air resistance.
**Figure C.1 was re-drawn from "Bicycle efficiency and power -- or, why bikes have gears,"* http://users.frii.com/katana/biketext.html *which found correlations between the bicycle's dissipated power due to friction and air resistance.*

The motor to drive the tricycle at continuous use is 200 W = 0.268 hp. From Figure C.1, the corresponding speed is about 20 mph. Thus, since the goal is to reach 30 miles, the time it takes riding at 20 mph for 30 miles can be calculated.

$$time = \frac{30 miles}{20 mph} = 86.53 \min$$

Then using Eq. 2, $t = \frac{m_{H2in\tan k}}{\dot{m}_{H2}}$, and solving for $m_{H2in\tan k}$ where t = 86.53min and

$\dot{m}_{H2} = 2.47e-4 \frac{kg}{\min}$ (from Appendix B-ii, for continuous use),

$$m_{H2in\tan k} = t * \dot{m}_{H2}$$

$$m_{H2in\tan k} = 86.53\min * \frac{2.47e-4kg}{\min}$$

$$m_{H2in\tan k} = 0.021375kg$$

Then using the ideal gas law, Eq. 1, the pressure required to ride for 30 miles at 20 mph is as follows.

$$P_{\tan k(abs)} = \frac{m_{H2in\tan k} * R_{H2} * T}{V_{\tan k}}$$

$$P_{\tan k(abs)} = \frac{0.021375kg * 4.124\frac{kPa * m^3}{kg * k} * 298K}{0.0057m^3}$$

$$P_{\tan k(abs)} = 4608.57kPa(abs)$$

$$\rightarrow P_{\tan k(g)} = 643.33psig$$

*Note: The calculations above are under the assumption that the power is dissipated by friction and air resistance; no pedaling is involved.

Appendix D
Hydrogen Storage Vendors

Pressurized Hydrogen Tanks	Vendor	Contact
	UW Stores	Website: http://www.washington.edu/admin/purchstores/stores/
	A-L Compressed Gases	Website: http://www.alcompressedgases.com/ Mark Murano (Representative spoke to in person) Account Manager Mobile (206)423-6422 markmurano@alweldpros.com
	FuelCellStore.com	Webstie: http://www.fuelcellstore.com/cgi-bin/fuelweb/action=av/vid=18724

Metal Hydride Tanks	Vendor	Contact
	A-L Compressed Gases	Website: http://www.alcompressedgases.com/ Mark Murano Account Manager Mobile (206)423-6422 markmurano@alweldpros.com
	FuelCellStore.com	Webstie: http://www.fuelcellstore.com/cgi-bin/fuelweb/action=av/vid=18724
	Texaco Ovonic (Ovonic Hydrogen Solutions)	Website: http://www.ovonic-hydrogen.com/solutions/technology.htm# Michael Zelinsky Technical Marketing Manager mzelinsky@ovonic.com
	HERA – Shell Hydrogen	Website: http://www.herahydrogen.com/en/products.html

		March Hubert Director, Business Development mh@herahydrogen.com

Cryogenic Tanks	Vendor	Contact
	Linde	Website: http://www.linde-gas.com/International/Web/LG/COM/likelgcomn.nsf/DocByAlias/hydrogen_storage

Regulators	Vendor	Contact
	A-L Compressed Gases	Website: http://www.alcompressedgases.com/ Mark Murano Account Manager Mobile (206)423-6422 markmurano@alweldpros.com
	FuelCellStore.com	Website: http://www.fuelcellstore.com/cgi-bin/fuelweb/action=av/vid=18724

APPENDIX E
Safety Codes and Standards

Please see attached pages for NFPA and SAE standards and codes.

Also please see,

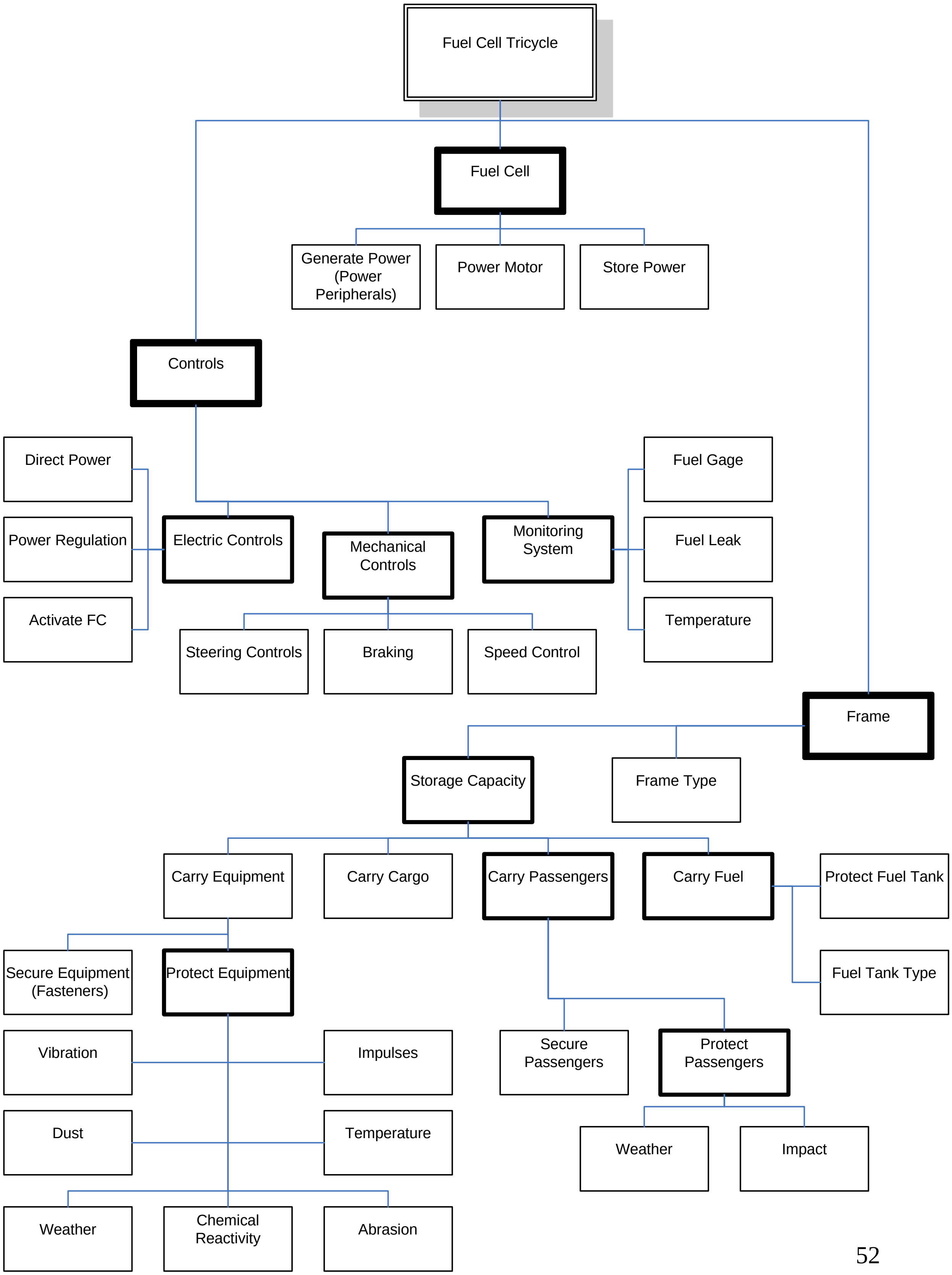
- Lockheed Martin: Safety of Issues with Hydrogen as a Vehicle Fuel (1999), Section 5 – Codes, Standards, and Regulations for Safety. INEEL/EXT-99-00522

- ISO (TC197 WG#6) – Gaseous Hydrogen and Hydrogen Blends – Land Vehicle Fuel Tanks

- ISO (TC 197 WG#7) – Basic Considerations for the Safety of Hydrogen Systems

*(These files were easier to view online from library resources or company websites).

Appendix D: Functional Decomposition



Appendix E: Morphological Chart of Sub-Functions

Sub-Function	**Concept 1**	**Concept 2**	**Concept 3**	**Concept 4**	**Concept 5**
Frame Type	Bicycle	Tricycle	Quadricycle	Moped	Scooter
Carry Passengers	Bicycle seat	Bucket seat	Bench	Foot platform	Kneeling platform
Carry Fuel	Pressurized tank	Metal hydrides	Cryogenic		
Protect Equipment from Impulses	Metal cage	Metal shell	Expandable metal surrounding	Metal ribs	Plastic plates
Protect Equipment from Vibration	Rubber padding	Spring suspension	Foam padding	Neoprene padding	
Protect Equipment from Weather	Goretex	Metal enclosure	Plastic enclosure	Spray on coating	
Protect Equipment from Dust/Dirt	Goretex	Metal enclosure	Plastic enclosure	Spray on coating	
Protection Equipment from Corrosion	Rubber seals	Metal compatibility	Spacers	Spray on coating	
Temperature Protection	Insulation	Fan	Heat pump	Air conditioner	Heater
Exhaust Circulation	Air Vents	Fan	Goretex		
Secure Platform	Bolts	Welds	Straps	Adhesive	Tape
Secure Fuel Cell	Bolts	Welds	Straps	Adhesive	Tape
Secure Fuel Tank	Bolts	Welds	Straps	Adhesive	Tape
Secure Controls	Bolts	Welds	Straps	Adhesive	Tape
Protect Passengers from Weather	Tire Fenders	Wind Shield	Plastic enclosure	Fiberglass enclosure	
Protect Passengers from Impact	Seat belts	Padding	Airbag	Bumpers	Crumple zone
Drive Train	ICE	Electric motor	Rocket thrust	Pedals	
Power Regulation	Alternating	Direct connection	Battery charging		
Temperature Monitor	Thermocouple	Thermostat			
Fuel Gage	Barometer	Mass flow meter	Weight		
Leak Detection	Hydrogen Sensors	Gas Pressure			
Speed Control	Pedal speed / torque sensor	Motorcycle throttle	Gas pedal	Lever	Electronic joystick
Braking System	Caliper brakes	Disk brakes	Regenerative braking		
Steering Control	Handle bars	Steering wheel	Electronic joystick		
Activate Vehicle	Combination pad	Toggle switch	Keys	Voice activation	Biometric lock

Appendix F: Design Concepts

Sub-Function	Concept 1	Concept 2
Frame Type	Tricycle	Tricycle
Carry Passengers	Bicycle seat	Bicycle seat
Carry Fuel	Pressurized tank	Pressurized tank
Protect Equipment from Impulses	Metal shell	Expandable metal surrounding
Protect Equipment from Vibration	Rubber padding	Spring suspension
Protect Equipment from Weather	Metal enclosure	Goretex
Protect Equipment from Dust/Dirt	Metal enclosure	Goretex
Protection Equipment from Corrosion	Metal compatibility	Rubber washers
Temperature Protection	Fan/Heater	Fan/Heater
Exhaust Circulation	Air Vents	Goretex
Secure Platform	Welds	Bolts
Secure Fuel Cell	Bolts	Straps
Secure Fuel Tank	Straps	Bolts
Secure Controls	Bolts	Bolts
Protect Passengers from Weather	Tire Fenders	Plastic enclosure
Protect Passengers from Impact	Padding	Padding
Drive Train	Electric motor	Electric motor
Power Regulation	Battery charging	Direct connection
Temperature Monitor	Thermocouple	Thermocouple
Fuel Gage	Pressure gag	Pressure gage
Leak Detection	Hydrogen Sensors	Gas Pressure
Speed Control	Pedal speed / torque sensor	Pedal speed / torque sensor
Braking System	Caliper brakes	Caliper brakes
Steering Control	Handle bars	Handle bars
Activate Vehicle	Keys	Keys

Appendix G: Weighted Decision Matrix

(SEE HARDCOPY)

Appendix H: Cost Analysis

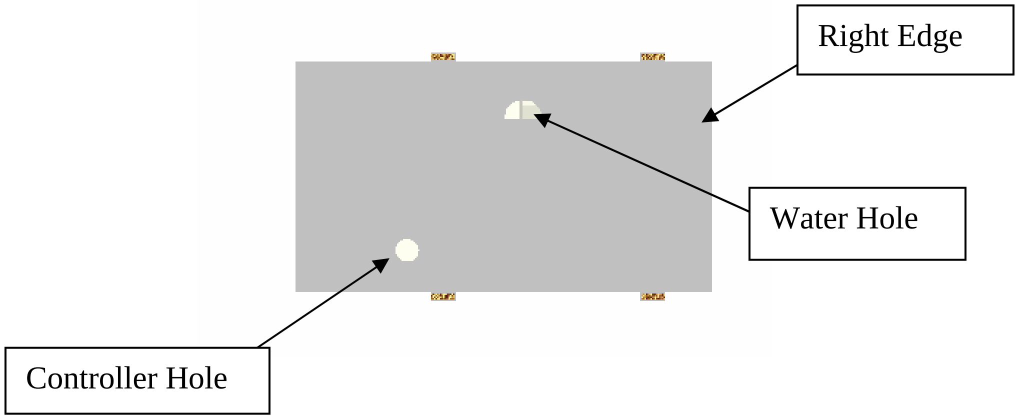
Item	Description	Model #	Qnty	metric	$/Qnty	$
Electronic controls						
Battery charger:	www.analyticsystems.com	BCD300-32-24	1	#	500	500
5V signal Switch	Toggle (Radio Shack)	cat # 275-634	1	#	3.5	3.5
Battery charger connector	XLR Audio Connector (Radio Shack)	cat # 274-010	1	#	5.99	5.99
Wires	www.thewireman.com	AWG 10	15	ft	0.26	3.9
Fuel Cell	1.2kW Ballard Fuel Cell	Nexa Module	1	#	3000	3000
Signal voltage Converter	24V to 5V voltage converter	3800 ohm	1	#	1	1
Battery input connector	www.newark.com	AMP 350777-1	1	#	0.29	0.29
Signal input connector	www.newark.com	AMP 638184-6	1	#	1.4	1.4
					cost	3516.1
Structural housing						
Straps	www.strapworks.com	2" polyprop	24	ft	0.25	6
Strap buckles	www.strapworks.com	2"cam buckles	6	#	3.65	21.9
Aluminum plates 6061-T6	36"x24"x.1785"		3	#	96.4	289.2
	24"x24"x.1785"		4	#	65.73	262.92
Bolts	platform: bolts size:		4	#	0.79	3.16
Washers			8	#	0.2	1.6
Nuts			4	#	0.25	1
Welding Filament	www.welders-direct.com	sizex7-pure	1	pkg	3.81	3.81
Aluminum platform 6061-T6	36"x24"x.75"		1	#	581.19	581.19
Foam board	www.consumermedhelp.com	VM9101	32	ft^2	1	32
adhesive	www.jo-ann.com	"hold the foam"	1	pkg	4.8	4.8
					cost	1207.6
Conversion Kit						
Tricycle converter kit			1	#	100	100
Bolts			4	#	0.79	3.16
Washers			8	#	0.2	1.6
Nuts			4	#	0.25	1
Extended Axle	4031 steel (DxL) .5625" x48"		1	#	30	30
					cost	135.76
Electric vehicle						
Electric Bike	Merida 500 power cycle		1	#	500	500
Extra BMX chain link			15	#	0.1	1.5
					cost	501.5
Hydrogen Storage						
Hydrogen tank	rated 2000 psi DxL: 5.5"x18"		1	#	150	150
Hydrogen tubing			3	ft	100	300
Pressure regulator			1	#	300	300
Straps	www.strapworks.com	2" polyprop	8	ft	0.25	2
Strap buckles	www.strapworks.com	2"cam buckles	6	#	3.65	21.9
Bolts			6	#	0.79	4.74
Washers			12	#	0.2	2.4
Nuts			6	#	0.25	1.5
	*Price & Qnty are approximate				cost	782.54
				total $		6143.5

*Refer to Nexa Power Module User's Manual for verification of connections

Appendix I: Directions to Assembling the Support Structure

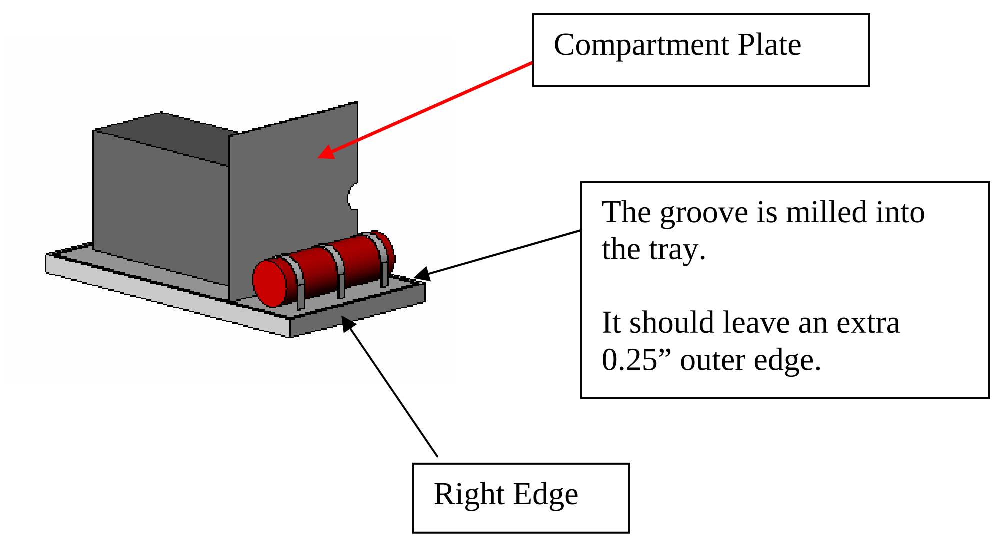
<u>Step 1: Machine the water hole and controller adjustments in the tray</u>

1. Mill out a water hole, in the position shown below
2. Mill out a controller connector hole, in the position shown below.



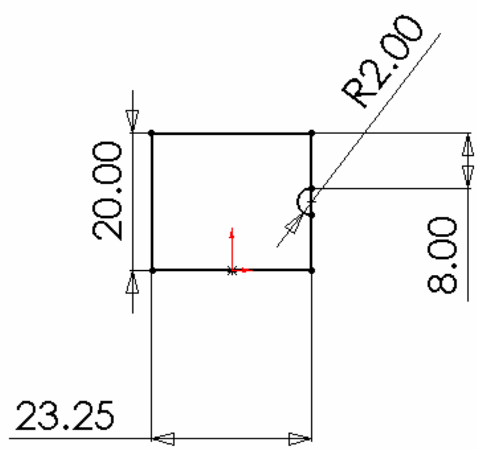
Step 2: Milling the bottom tray

1. Obtain the 36” X 24” 6061- T6 aluminum sheet of thickness of 0.75”.
2. Mill out a groove that is .2” ± 0.05” wide and 0.25” deep into the plate, the groove is 0.25” from the outer edge of the tray. This will create a 0.25” deep edge all around the perimeter of the tray.



Step 3: Welding the compartment plate to the tray

1. Obtain a 24” X 24” X 0.1785” 6061-T6 aluminum plate
2. Machine the width to the dimensions of 23.25” ± 0 .05, so that the cage can still fit over it. Also cut the plate to a height of 20 ± 0.05 inches.
3. Mill a hole into the plate so that the tank inlet and outlets can be attached to the fuel cell through the compartment. The diameter of the hole should be 4 inches wide. The figure below shows where the hole should be placed. The tolerance should be a ± 0.05”.

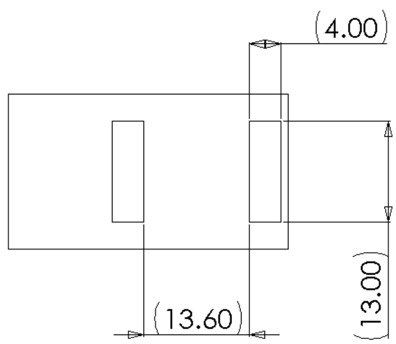


4. Weld the bottom edge of plate onto the tray. The plate should be welded a distance of 7” from the right edge of the tray
5. Glue a soft insulator onto the compartment plate, avoiding the milled hole.

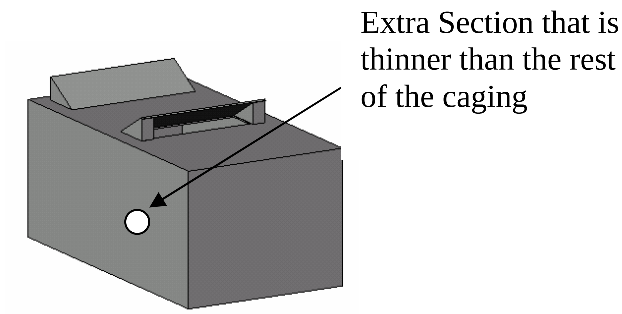
Step 4: Welding the Cage

1. Obtain 3 sheets of 6061- T6 aluminum of dimensions of 36” by 24” of thickness 0.1785”. And 2 6061-T6 aluminum sheets of dimensions 24” x 24” x 0.1785”. This could be bought at Online Metals.

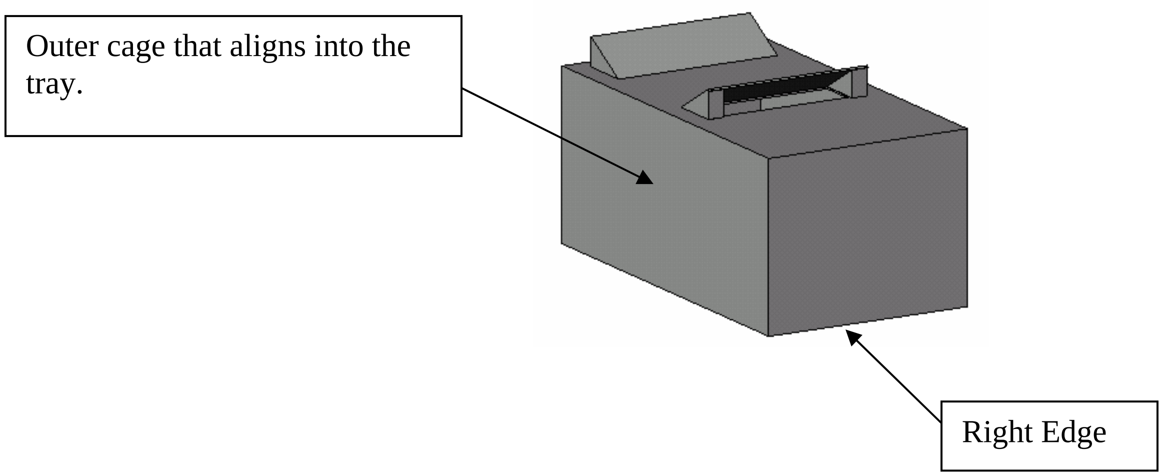
2. Machine the sheets that are of dimensions 36” X 24” to a dimension of 35.45 ± 0.05” by 23.45 ± 0.05”.
3. Machine the sheets that are of dimension 24” X 24” to a dimension of 23.45 ± 0.05” by 23.45 ± 0.05”.
4. Mill 2 openings of dimensions 4” by 13” at the following locations specified in the figure below on a 35.45 ± 0.05” by 23.45 ± 0.05” aluminum sheet. One opening should be 1.4” from the edge and both aligned to the center line of the same edge.



5. Mill a slight groove of at least 0.2 ± 0.05” parallel to the 23.45 dimension inside of each rectangular sheet so the compartment plate can easily slide into the cage. Placement of groove should correspond to location of compartment.
6. Thin out a small section on one side of the 36 X 24” aluminum plate.
    a. By milling out a small circular hole of 2 inch diameter 0.94 ± 0.05” deep. The approximate location of the hole is shown in the figure below. Thinned section should be near rear of tank.



7. Weld the 5 sheets of aluminum together.



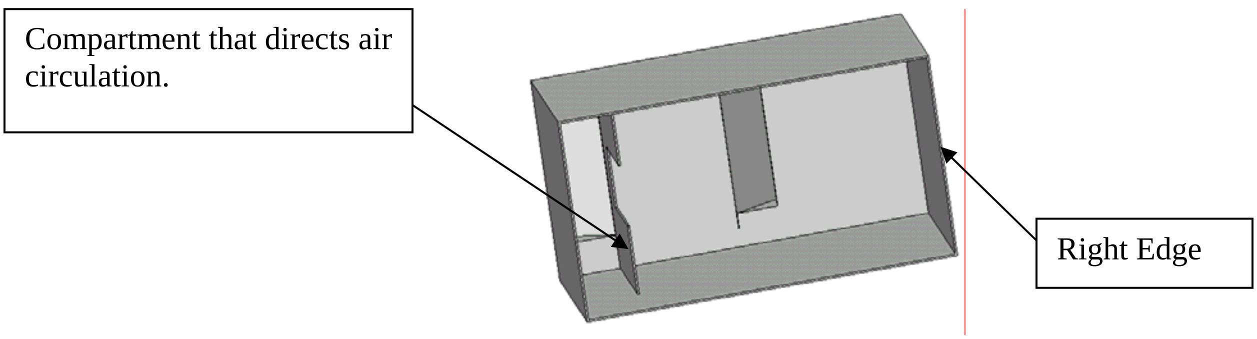
Step 5: Welding the Air Vents

1. Obtain the fourth 24” X 24” X 0.1785” plate.
2. Mill out 2 plates of dimensions 13” X 3.8” for the angles ventilations plates. Plates should be cut in a manner to create a symmetric pattern on the leftover material (Refer to figure in step 5). A single 3.8” edge of each plate should be the same an edge of the plate being cut.
3. Use the scraps from the cut openings to form the ribs. Weld two sheets of thickness 0.1785” together to create a thick enough rib to hold the angled vents.
4. Weld all pieces together

   a. Weld the vents at an angle of approximately 25 degrees from the top of the cage.

Step 6: Controlling the Air Circulation

1. Obtain the left over of the 24” X 24” T6-6061 aluminum plate. Mill out the air divider to the dimension of the cross section of the cell stack. Give 1” clearance around the stack. Cut height dimension to allow electrical wires to be attached to fuel cell.
2. Weld the divider as shown to the bottom the outer cage material.



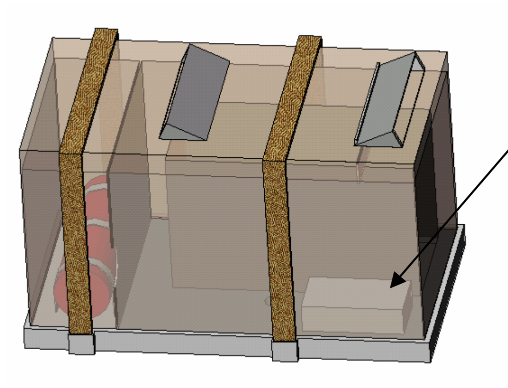
Step 7: Attaching the insulators on the inner surface of outer cage via an adhesive

1. Obtain appropriate amount of insulators
2. Glue to the inside of the cage, avoiding the grooves that the compartment plate slides into.

Step 8: Bolt the straps for the hydrogen tank

1. Bolt the buckles
2. Attach the straps

Step 9: Bolt the battery charger to the tray



Position of battery charger

Step 10: Bolt the Stack to the tray

1. Bolt fuel cell to tray at appropriate location.

2. Holes on tray should align to outlets of water and wires from fuel cell.

Step 11: Attaching the buckles and the straps on the tray

3. Bolt the buckles on the side of the tray

4. Attach the straps to the tray

Step 12: Bolt the tray to the axle

The axle is oriented so that the triangular part is flat.

Bolt the tray onto the flat portion of the axle.

Appendix J: Analysis Calculations

Vibration and Shock Analysis

Stack Standards

Stack Vibration Resistance

The Nex power module has been designed and tested to withstand vibrations loads described in the UL991 standards. UL991 requires shaking the device from 10Hz to 60Hz at a constant displacement of 0.35mm and then a constant acceleration of 5g from 60Hz to 150Hz. A total of ten cycles are performed followed by shaking at any noted resonance frequencies for 10 minutes.

Stack Shock Load Resistance

Free fall drop test from a height of 1.2 m onto a hard surface.

An aluminum frame provides support.

ASTM Standards for Rear-Mounted Bicycle Child Carrier

Vertical Vibration Test

Consisting of 5 mm up and 5 mm down from the central position

Non-sinusoidal motion

The “bump” is an instantaneous rise and instantaneous fall

Motor of the tested machine is adjusted so that the complete vertical cycle is 7 Hz.

Continue the test for 42,000 cycles

Lateral Vibration Test

Load sinusoidally from side to side

At frequency of 0.5 Hz

Analysis

The way the system was modeled as a spring and damper system is demonstrated on the graphing paper. The following demonstrate a preliminary vibration analysis done in Mathametica. All equations and methods for solving standard vibrations problems were taken from the Fourth Edition of the Mechanical Vibrations book.

Also, it is important to note that the system was analyzed with the assumption that the damping is equal to zero. Thus, if any additional damping is added to the system, it will respond even better to vibration.

```
Convulation Intergral - Impact Test

k = 192EI/l^3 = 78000 lb/in --- model as a fixed beam with a load
at the middle

k=(192*26 * 10^6)/(40^3)

m:=60
```

Response of the system:

$$x(t) = X e^{-\zeta \omega_n t} \sin(\omega_d t + \phi)$$

where $X = \left\{ x_0^2 + \left(\frac{\dot{x}_0 + \zeta \omega_n x_0}{\omega_d} \right)^2 \right\}^{\frac{1}{2}}$

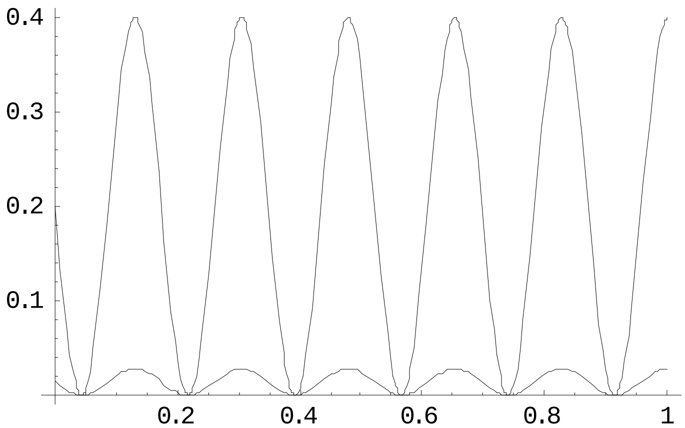
(* , based on instantaneus impact

```
wn := √(k/m)

x[t_] := (.2)*(1-Sin[wn*t])

y[t_] := (.014)*(1-Sin[wn*t])

Plot[{y[t], x[t]},{t,0, 1}]
```



The above graph shows that the ASTM standards require a much higher displacement of the stack than the standards of the stack specify. However, this is a very preliminary vibration analysis. It does not account for the fact that the stack can withstand a constant acceleration of 5g from 60Hz to 150Hz, which is much higher than the 7 Hz vibrations that the ASTM standards specify.

Vibration Test – Lateral

```
w := 0.5
wz := 60
```

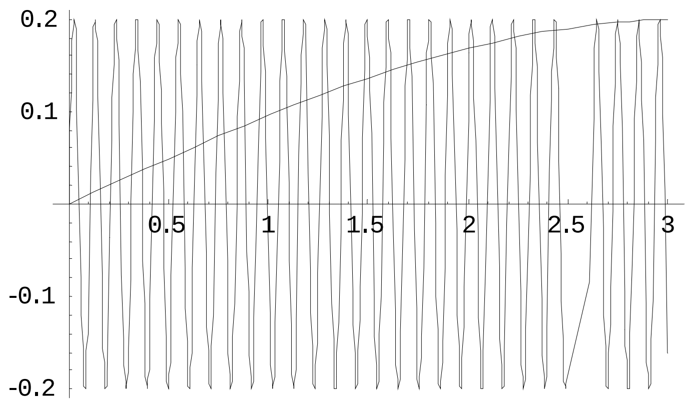
a = y(k^2 + (cw)^2)^(1/2) where c = 0. Estimated the maximum amplitude of the system to be 0.2 inches.

```
y := 1
c :=0
a := .2
phi = ArcTan[ (m*c*w^3)/(((k-m*w^2)*k) + (w*c)^2)] = 0

g[t_]:= a*Sin[w*t]
```

```
b[t_]:= a*Sin[wz*t]

Plot[{g[t], b[t]}, {t,0,3}]
```



The graphic above includes two graphs, one that illustrates the displacement of the system with ASTM standards and another that demonstrates the displacement of the system under stack design specifications.

Since the stack is vibrated at 60 Hz, where as the mounted bike chair vibrated at 0.5 Hz, the cycling of the system is much slower.

It is very hard to obtain any useful information from the vibration analysis because several aspects such as damping, amplitude, and displacement motion were assumed. As a result, further analyses are necessary.

Appendix J: Fault Tree Analysis

(SEE HARDCOPY)

Appendix L: Electric Circuits

Below is a sample circuit diagram for a Lead-Acid battery charger [10]. The charger's input voltage needs to filtered dc voltage that is at least 3 V higher than the maximum required output voltage: approximately 2.5 V per cell. Choose a regulator for the maximum current needed. The circuit initially provides 2.5 V per cell at 25 C to rapidly charge the battery. The charging current decreases as the battery charges, and when the current drops to 180 mA, the charging circuit reduces the output voltage to 2.35 V per cell, leaving the battery at a fully charged state. Temperature compensation held prevent overcharging when the battery undergoes wide temperature changes while being charged. The LM334 temperature sensor should be placed near or on the battery for the best accuracy.

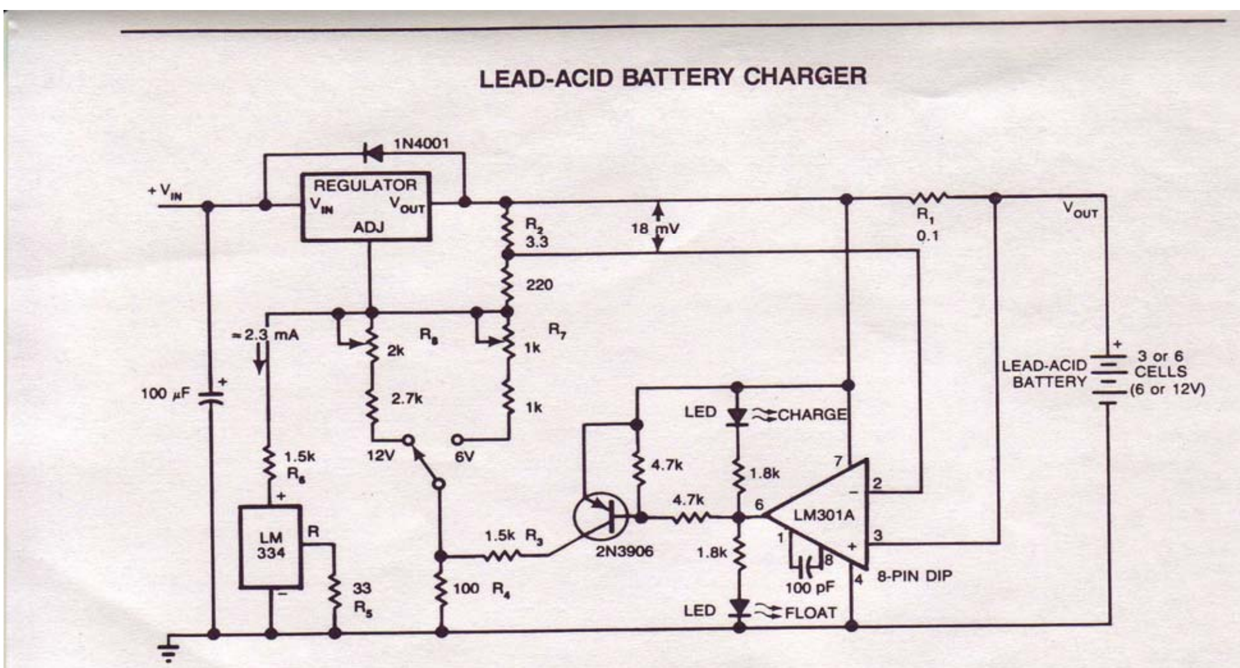


Figure 8: Lead-Acid Battery Charger Circuit Diagram

Because the current produced by the fuel cell is unfiltered and the voltage is unregulated, additional circuitry is required for both of those functions. A step-down voltage regulator would be ideal for this purpose. Linear technology [11] produces a several models of step-down voltage contollers that can accept wide ranges of input voltages and might be suitable for use with the fuel cell. Models LT1680 and LT3800 in particular appear to be good candidates for this application. Neither voltage regulator can accept power in the 200 W range (which would be required for this application) however it would be possible to use multiple step-down voltage regulators in parallel to meet the power demands. The research paper “10-Cell Fuel Cell DC/DC Converter” by Jesse E. Hayes from the University of Connecticut [12] may provide a helpful reference when designing such a voltage regulator. That paper details using parallel voltage controllers to meet the power requirements for a fuel cell application.

Appendix M: Instructions manual for turning on/off and emergency shut down of fuel cell tricycle

Start up:

1. Secure battery onto tricycle.
2. Insert key.
3. Turn key into on position.
4. Flip signal switch into on position.

The fuel cell will be going through a start up sequence when the switch is flipped to on position. This process will last up to 30 seconds. The rider is able to ride the tricycle during this time but no energy from the fuel cell will be used to recharge the battery until start up sequence is complete.

Shut down:

1. Flip signal switch into off position.
2. Wait until fuel cell shut down sequence is completed (45 seconds).
3. Turn key into off position.
4. Remove key

This procedure should be used for normal shut down and not emergency shut down. Normal shut down procedure regulates water content inside fuel cell.

Emergency shut down:

1. Turn key into off position
2. remove key

Emergency shut down should only be used when necessary to avoid danger. Emergency shut down does not allow for typical storage/off condition.