KETTERING UNIVERSITY'S RAINMAKER TEAM

Formula Zero Fuel Cell Vehicle Design Evolution and Performance

A team of Kettering undergraduate and graduate students design and build a fuel cell powered go-kart that is innovative and highly competitive.

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I. INTRODUCTION

Formula Zero was founded in 2006 in the Netherlands and has been organizing international events and demonstrations annually. Dr. Joel K. Berry initiated a team at Kettering and involved graduate research assistants to provide continuity between the academic and work terms that the undergraduate students rotated through. This project was a profound learning experience for everyone involved. Unfortunately, at the time of writing this report, Formula Zero made the hard decision to not continue the competition. Team Rainmaker sees this as an opportunity to find another venue or organize an independent event.

Problem Topic

As a team, design and build from the ground up a fuel cell powered go-kart that is innovative and award winning. The ultimate goal is to excel in both parts of the international competition; 1) sprint race on a straightaway and 2) main race consisting of laps on a track. Identifying components based on capability, size, weight and compatibility of integration is the first step. Formula Zero (FZ) is allowing a steady variety of component types and systems as they plan to scale up. The major updates to the latest rules and regulations include the option to use any fuel cell stack that runs off of pure hydrogen and a custom hydrogen storage solution.

Once all components are identified, packaging and integration is the next step. Troubleshooting and refinement happen throughout the whole process. Communication and data acquisition is key to the components working harmoniously together as well as provide insight of performance and also as how to tune the go-kart.

Background

The world is dependent on fossil fuels. As the solutions to wean machines off these non-renewable resources become technologically and economically feasible, the next generation of engineers and scientists are doing their part. The quality of Kettering students is internationally recognized. The students also realize the importance of this global issue and that there are many rewarding career paths that are in the alternative energy sector to sustain them after they graduate. Success is secured with the state-of-the-art laboratories that are continuously updated, the professors who have industry and/or research experience, and most importantly the relevant courses and extra-curricular activities that allow the students to be prepared in the sustainable energy and hybrid technology areas. With the highly regarded co-op education requirement, it is not uncommon for students that take these environmentally conscience classes obtain a co-op sponsor in a closely related field.

Applied Physics, Chemistry, Electrical Engineering, Mechanical Engineering students can obtain their Bachelors of Science with a minor in "Fuel Cells and Hybrid Technology". Graduate students setting up their classes for their Master of Science in Engineering have a concentration in "Sustainable Energy and Hybrid Technology" available.

Formula Zero was started in 2006 in the Netherlands with the goal of reaching F1 racing size by year 2015 as shown in the following figure. They too have the goal of making an impact of reducing the world's reliance on fossil fuels. By understanding the sport and culture of automotive racing, successful fuel cell powered vehicles will have its innovative strategies and features implemented into military, commercial and civilian vehicles.

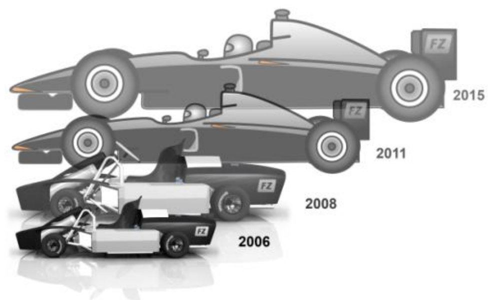

Figure 1: Projection of competition chassis size

The pace at which fuel cell powered vehicles are developing is astounding. The efficiency of hybrid systems also keeps increasing as innovation occurs. By getting students, faculty and industry sponsors working together as Team RainMaker, we can cause a positive impact with everyone involved. Formula Zero is a community as well, with the list of all the teams that have competed since 2006 below.

	GREENCHOICE FORZE **TU Delft, The Netherlands** **http://www.formulazero.tudelft.nl/**
	UNIZARTECH2 **unizartecH2, Spain** **http://unizartech2.wordpress.com/**
	IMPERIAL RACING GREEN **Imperial College London, UK** **http://www3.imperial.ac.uk/racinggreen**
	ELEMENT ONE **Lawrence Technological University, USA** **http://www.ltu.edu/element1/**
	HERCUCLAS **UCLA, USA** **http://www.herc.ucla.edu/hercuclas/**
	ZERO EMISSION RACING TEAM **Groep T, Belgium** **http://www.formulazero.be/projects/53.html**
	RAINMAKER **Kettering University, USA** **www.kuRainMaker.com**

Table 1: List of team logos and contact info

Criteria and Parameter Restrictions

The top priority for both FZ and Team RainMaker was safety. Each individual involved was provided an overview of Kettering's safety concerns and practices, as well as having either an experienced technician or graduate research assistant present during electrical component operation and testing. Many compenents onboard monitor themselves and will shutdown if a problem occurs. A main kill switch, shut-off vavles, enclosures and visual warning signs are some of the main FZ requirements to protect any person that might come into contact with the vehicle. Drivers must wear FIA homologated safety equipment.

A copy of the latest FZ Cup Regulations can be found in Appendix A. The main summary is a fuel cell powered go-kart that converts hydrogen into electricity to power an electric motor. Energy storage takes form as either batteries, ultra capacitor bank or a combination.

Methodology

The quarterly Kettering academic calendar where the two separate student bodies rotated every three months was utilized so that a team was in place year-round. Recruitment was ongoing, but the most noticeable success in obtaining new teammates is through current ones. A group of graduate research assistants, technicians and advisors were available every term and provided continuity. As project manager, I was responsible for handling the majority of emails that notified teammates of meetings as well as continuous updates with supporting presentations and documents. Academics remained the top priority for all the individuals of the team.

Before any preliminary design; the FZ organization, the latest published rules and regulations and the list of competitors were thoroughly studied. Significant changes were made to the 2010 FZ Cup Regulations (Published on November 27, 2009) mainly expanding the criteria of fuel cell type and hydrogen storage allowed. The team saw this as an opportunity to break away from the competition by selecting components that were more powerful, stored more energy, and provided a more even distribution of weight on the chassis.

Primary Purpose

The final design of the chassis, the selection of components, packaging and layout were calculated or simulated to gauge performance and limitations. The team composing of a diverse range of expertise openly discussed the current design and possible advantages and disadvantages from each of the engineering perspectives that a design change would create. This process is the evolution that occurred through the collaboration of the team with the final goal to measure performance of the vehicle in competition.

Overview

This report will cover the progression of the topology to where it is currently. The chassis was developed in parallel with the topology in order to handle the stresses that result from the orientation and packaging of the components as well as the forces the vehicle undergoes during operation in racing conditions.

II. COMPONENT SELECTION AND TOPOLOGY EVOLUTION

Formula Zero only allowed Hydrogenics low temperature PEM fuel cell to power the vehicle in competitions for the first three years. The hydrogen storage was also limited to a single 5L aluminum Linde tank. The team decided that an ultra capacitor (UC) bank would be ideal energy storage for a racing application, due to the potential amount of energy release in a short period of time, and can be seen in all versions of the topology.

Version 1.0

The initial topology, shown on Figure 2, adopted by the Kettering team to meet the FZ performance requirements included the following main components:

1. (1) 5 Liter Linde Tank for Storing Hydrogen www.linde-gas.com
2. (1) 8kW Hydrogenics Low Temperature PEM Fuel Cell Module www.hydrogenics.com
3. (1) Zahn Electronics Boost DC/DC Converter, (1) Zahn Electronics Buck DC/DC Converter www.zahninc.com
4. (1) Pilot Controller Between the Boost and Buck DC/DC Converters
5. (1) Custom Preco Ultra Cap (UC) Bank www.precoinc.com
6. (2) 48V Curtis Motor Controllers www.curtisinstruments.com
7. (1) Green Motor Sports Dual AC Induction Motor www.greenmotorsport.com

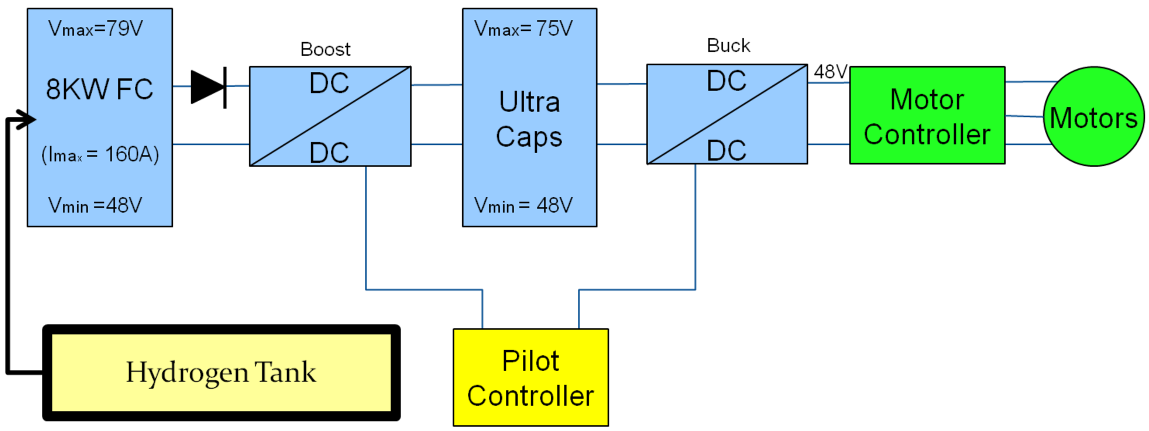

Figure 2: Version 1.0 Topology

II.1 5 Liter Linde Tank

A 5L aluminum tank from Linde was the only hydrogen storage allowed into the FZ competition due to a contract with the manufacturers. The team was provided with the following specifications:

- Diameter = 140mm (5.5 inches)
- Diameter of the collar is up to 146mm (5.7 inches)
- The overall length of the cylinder and collar is 672mm (26.5 inches)
- Maximum fill pressure of 20,000 kPa (2,901 psi)

Figure 3: Picture of a Linde tank provided by Formula Zero

II.2 8kW Hydrogenics Low Temperature PEM Fuel Cell Module

This water cooled Proton Exchange Membrane (PEM) Fuel Cell by Hydrogenics came in both 8.5 and 12 kW models that were suitable for the competition. Due to tight weight restrictions, the team opted for the 8.5 kW to maintain a lower weight. This model was also in use by the in earlier competitions. The Formula Zero website stated for the world premiere in 2008 "the six teams competing in the Championship each received a Hydrogenics HyPM8 fuel cell from Formula Zero, financed with the support of the Rotterdam Climate Initiative." This jumpstarted the teams, with the most significant and expensive component ready in their inventory, they were powered to the finish line. Since the Hydrogenics proved itself on the track, starting the first topology based on the 8kW gave the team a good overview, one that would lead to incremental improvements.

Figure 4: Two views of a Hydrogenics Fuel Cell

Module Specification [1]		HyPM® XR 8	HyPM® XR 12
Maximum Power [2]	(kW)	8.5	12.5
Voltage Range	(VDC)	20 to 40	30 to 60
Maximum Operating Current	(A)	350	350
Dimensions [3] (L x W x H)	(cm)	75.4 x 46.4 x 31.6	86.5 x 44.6 x 31.6
	(in)	29.7 x 18.3 x 12.4	34.1 x 17.6 x 12.4
Mass	(kgs)	75	83
	(lbs)	165	183
Peak Net Efficiency	(%)	51	53
Time from Idle to Peak Power	(s)	≤ 5	≤ 5

(1) All modules use 500 series stack
(2) Beginning of life, continuous power
(3) Dimensions include covers which can be removed to decrease volume

Table 2: Specifications of Hydrogenics Power Fuel Cell Modules accepted by FZ Rules and Regulations

II.3 Zahn Electronics Boost and Buck DC/DC Converter

A DC/DC converter is used to regulate the voltage and current from one component to another. One converter is used to step up, or “boost”, the voltage from the fuel cell to the UC and another converter is required to step down, or “buck”, the voltage from the UC to the motor controllers. The specifications for both controllers are shown on the table below:

Part Number	Specifications
CH150160F-SSU	**Step Up** Input: 24-100VDC Output: 0 - 92VDC @ 90A flat Output Current Limit: 160A Output Power: 11,776W Unit programmed for Voltage Loop (VLP) and as 2 Quad
CH100210F-SS	**Step Down** Input: 49-79VDC Output: 48VDC @ 250A for 8 seconds, then 210A for continuous Output Current Limit: 210A Output Power: 15,540W Unit programmed for Voltage Loop (VLP) and as 1 Quad

Table 3: Converter Electronic Specifications

Both DC/DC converters are unidirectional, which for the buck converter does not allow for the option of regenerative braking. The team desires for the vehicle to have as many open-ended details that can be expanded upon as possible. The fewer amounts of limitations, the longer this project can be improved upon by the rotating bodies of Kettering students. Regenerative braking is low priority for the team and the components needed to achieve this ability are costly in terms of additional weight. The timeline does not allow this beneficial and green solution to become a permanent fixture in the design. This allows the unidirectional nature of the converters to not implicate the first generation build.

Figure 5: Converter pictured on the left with required filters on the right

II.4 Pilot Controller Between the Boost and Buck DC/DC Converters

The flow of power going in and out of the UC bank must be regulated and synchronized in order to effectively supply the motor controllers with on-demand power. Lag must be minimized throughout the system, and communication between components exists on many levels. This component would be designed and built by students on campus.

II.5 Custom Preco Ultra Cap (UC) Bank

An ultra cap bank from Preco Inc. with the range of 48-75V served as storage for the energy produced by the Hydrogenics fuel cell. To improve efficiency and cut down on size of the bank, the boost DC/DC converter was selected at the same time as the bank. The pairing of a fuel cell with ultra capacitors is very beneficial in a racing application. Fuel cells have a very high energy density and a bank of ultra capacitors has comparatively a very high power density. The ability to store and release energy quickly results in keeping up with the motor demands. Conventional batteries have a very high energy density but a poor power density. Acceleration is limited without the use of ultra capacitors.

II.6 48V Curtis Motor Controllers

The pair of master/slave motor controllers made by Curtis were included in the purchase of the dual AC induction motor as shown in Figure 6 on the following page. Green Motor Sports programmed both controllers prior to shipping. An optional handheld programmer was purchased for our own troubleshooting and modifications.

II.7 Green Motor Sports Dual AC Induction Motor

The team took great care to select and match components for the vehicle. Components were selected also for their versatility. This is especially true for the dual motor selected. The electronic differential can be programmed to spin the wheels at different rates when turning. This is already in practice in the automotive racing industry. This motor was intentionally designed for a full sized electric vehicle, with mounts on each motor for the 48V controllers.

Green Motor Sports Specifications	
Dual motor system unit	REF : GMS-DUAL-36N
Product Name	GMS Dual drive motor powertrain system
Power rating	36kW Nominal. 70 BHP peak, depending on parameters.
Torque	300 NM or 221.2 foot pounds at the drive shaft can be obtained.
System Voltage	48V or 96V
System Profile	Motor, controller, Dual preset profile with electronic differential
Reduction Gearing	3.75:1 (more details of the gearbox on request)
Regen Braking	Fully adjustable, pedal release & brake pedal initiation
Materials	C250 Aluminum
Weight	52.5KG (with 48V controllers, without liquid coolant)

Table 4: Specifications of the Green Motor Sports Duel AC Induction Motor

Figure 6: The motor and components included in the purchase

<u>Version 2.0</u>

Formula Zero expanded their criteria, most notable were additional safety regulations and allowing for custom hydrogen storage.

“16.3. Teams can use one of the following hydrogen storage systems:

• Standard 5 litre at 200 bar hydrogen cylinders supplied by the organizers.

• Hydrogen storage and refuelling system, compliant with safety certifications from ISO. Proposals for such systems must be sent to the Technical Delegate three months before application in a race, including specifications and certification details." The following is the list of the main components with beneficial upgrades that are in direct influence of the new FZ rules and regulations:

1. (1) 5 Liter Linde tank for storing hydrogen www.linde-gas.com
2. (2) 3.5kW Serenergy high temperature PEM Fuel Cell modules www.serenergy.dk
3. (2) Buck DC/DC converters www.zahninc.com
4. (1) Custom Ultra Cap (UC) bank www.precoinc.com
5. (2) 96 V Motor controllers (master and slave) www.curtisinstruments.com
6. (1) Green Motor Sports Dual AC induction motor www.greenmotorsport.com

This setup utilizes two 3.5kW Serenergy FCs in series with a set of DC/DC converter and filter in two separate enclosures. The system could potentially run off of a single Serenergy FC, but using two allows us to achieve symmetrical weight distribution and a low center of gravity. The enclosures are required in order to be within the rules and regulations to limit the electric potential to be under 120V. The original voltage out of each FCs is 147V, but will be bucked down to 96V. The baseline of the whole system became 96V when it was identified that Green Motor Sports offers 96V motor controllers to work with the current Dual AC Induction motor. The only drawback is that the controllers rated for higher voltage are significantly heavier but have the potential to yield more power from the motors. An ultra cap bank with the range of 60-100V needed to be designed and built by Preco Inc. in order to directly feed power into the 96V motor controllers. Another benefit to the 96V baseline, is that the UC bank can be more compact while attaining a higher capacity for energy storage. Approximate weight savings for the second custom UC bank is 25%. A DC/DC converter is not needed after the UC bank, reducing weight further and allowing for the possibility of regenerative braking.

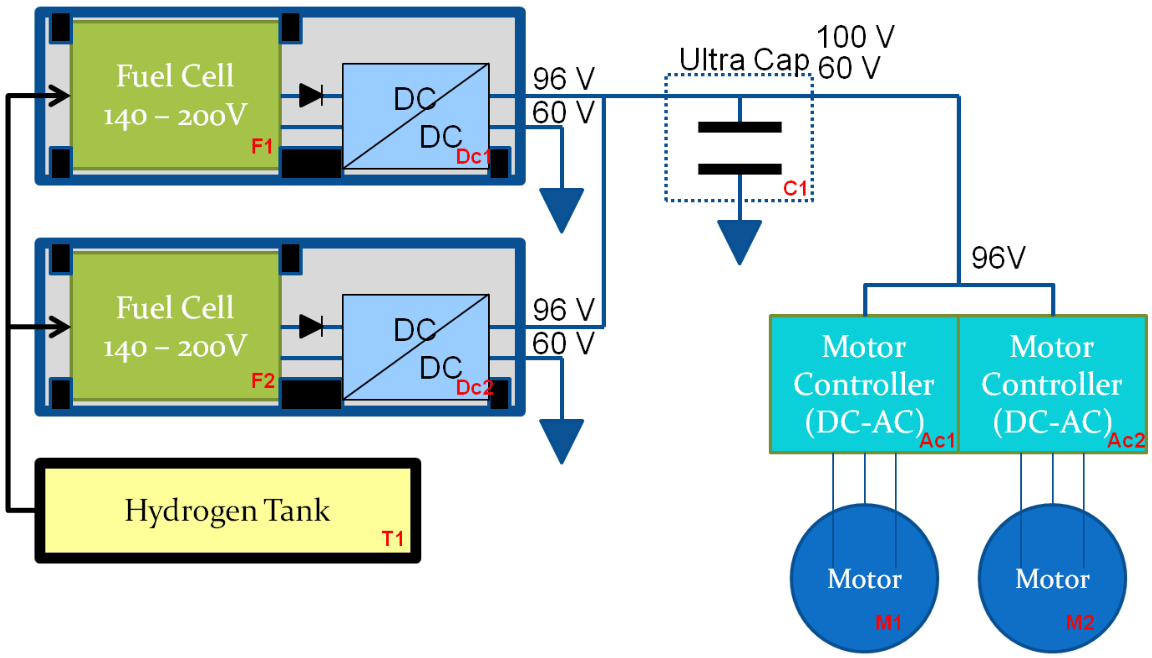

Figure 7: Version 2.0 Topology

II.8 Serenus 390 Fuel Cell Modules

Manufactured by Serenergy, this model is a high temperature, air cooled fuel cell stack that nominally produces 3.5kW. Some of the characters outlined by Serenergy include:

- High temperature PEM technology (op. temp. 100-175°C)
- Very high system efficiency measured up to 57%, 40% at nominal load
- Simple system design – low pressure, air cooled and no humidification required
- High fuel flexibility and CO tolerance

- Embedded control software for easy and safe module operation
- An "Evaluation Kit" is available (includes a hydrogen proportional valve, hydrogen purge valve, hydrogen over/under pressure relief valves, inlet and outlet piping, hydrogen pressure sensor, power relay, emergency stop button, power supply, and a CAN USB interface to PC)

Parameter		Serenus 390 Air C
Nominal power	(W)	3200
Peak power	(W)	5550
Nominal voltage	(V_{dc})	140
Idle Voltage	(V_{dc})	≈200 (spikes to 267)
Nominal current	(A)	23
Peak current	(A)	35

Table 5: Serenus 390 electrical characteristics

When comparing one Hydrogenics HyPM8 fuel cells (overview in II.2) with two Serenus 390 fuel cells, maximum power improves from 8.5kW to 11kW. The Formula Zero director was concerned for safety and required enclosures for the Serenergy fuel cells, resulting in no weight savings from the choice of new components.

Figure 8: Fuel cell module Serenus 390

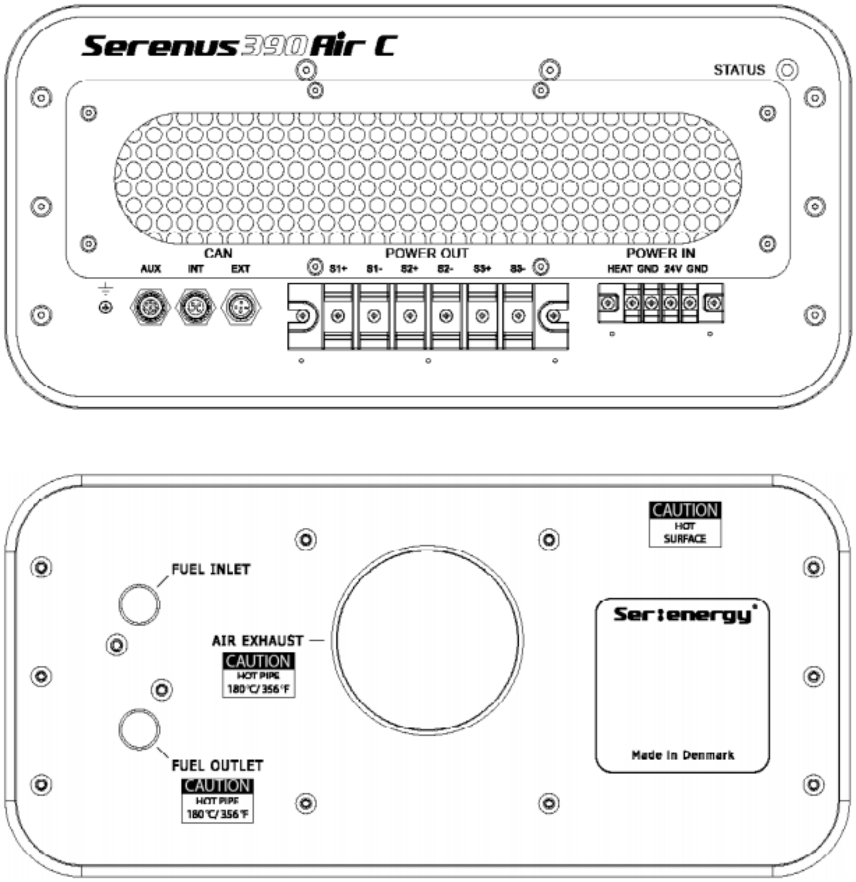

Figure 9: Serenus 390 front and rear panel connections

II.9 Step Down DC/DC Converters

An individual converter to buck down the voltage is needed for each of the two Serenergy fuel cells. These converters are different than in II.3 due to the high voltage being generated by the fuel cells. As mentioned in the overview of this topology, the 96V baseline (or measureable electric potential) is in direct result in selecting the 96V motor controllers. The higher voltage affected the specifications of the ultra cap bank as described in the next sub chapter.

Part Number	Specifications
CH25090F-SS	BUCK (These are the adjusted parameters per our system requirements): Step Down DC/DC Input: 200 - 147VDC Output: 0 - 96VDC @ 90A flat Current controlled at 50A w/ Max Output 96V Unit programmed for Current Loop (ILP) and as 1 Quad

Table 6: Converter Electronic Specifications

II.10 Preco Ultra Cap Bank

Smaller in size and weight with high energy storage potential makes the selection of this component highly beneficial for the go kart.

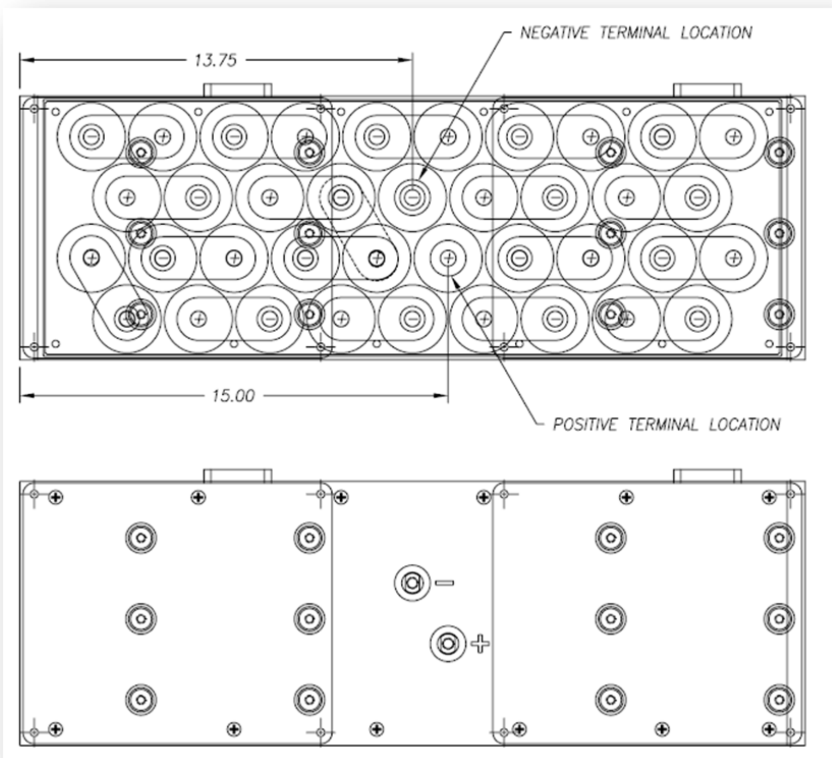

Figure 10: CAD drawings of the custom second generation Preco ultra cap bank showing the interior layout of the individual ultra cap cells and mounting points for the 96V motor controllers

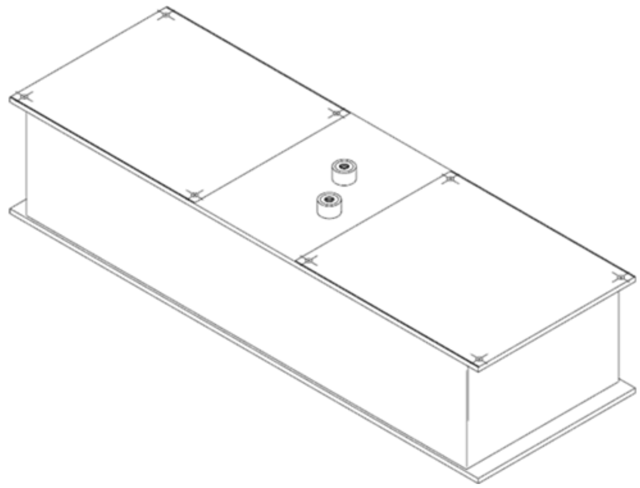

Figure 11: Isometric view of the custom second generation Preco ultra cap bank

Version 2.1

This topology is very similar to the version 2.0 topology. Instead of two enclosures for each pair of FC and DC/DC convertor, the two 3.5kW Serenergy FCs are placed in one rectangular enclosure with one DC/DC converter and filter. The change mainly happened to reduce weight, even though the overall balance of the vehicle will be more complicated with such a large box that will increase the vehicle's center of gravity.

1. (1) Carleton Composite Pressure Vessel 550ci at 4500 psi for storing hydrogen www.resources.carltech.com/CylinderSafety/default.html
2. (2) 3.5kW Serenergy high temperature PEM Fuel Cell modules www.serenergy.dk
3. (2) Buck DC/DC converters www.zahninc.com
4. (1) Custom Ultra Cap (UC) bank www.precoinc.com
5. (2) 96 V Motor controllers (master and slave) www.curtisinstruments.com
6. (1) Green Motor Sports Dual AC induction motor www.greenmotorsport.com

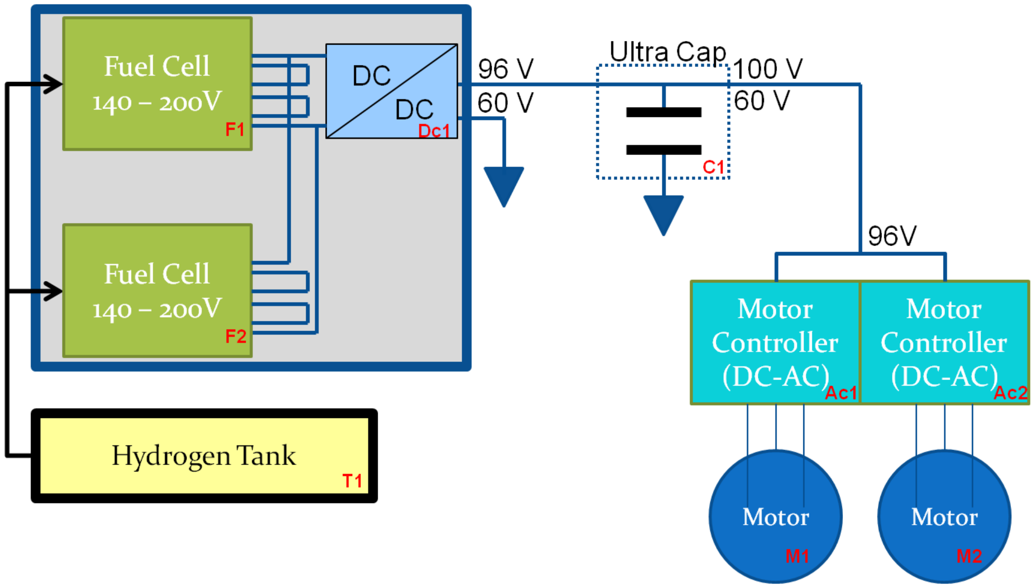

Figure 12: Version 2.1 Topology

II.11 Carleton Composite Pressure Vessel 550ci at 4500 psi for storing hydrogen

The demand of hydrogen is higher with the use of two fuel cell modules. Calculations are shown on the following page using Boyle's law to find the expected duration a Linde tank vs a composite tank would last:

$$P_1V_1 = P_2V_2 \therefore V_2 = \frac{P_1V_1}{P_2}$$

where:

P_1 = initial pressure (Pa)
P_2 = final pressure (Pa)
V_1 = initial volume (L)
V_2 = final volume (L)

Linde (Aluminum)

$$V_2 = \frac{(20{,}000{,}000\ Pa)(5.0\ L)}{(101{,}300\ Pa)} = 987\ L$$

Carleton (Composite)

$$V_2 = \frac{(31{,}026{,}408\ Pa)(9.0\ L)}{(101{,}300\ Pa)} = 2{,}757\ L$$

$$\Delta t = \frac{V_2}{\dot{V} \cdot n_{FC}}$$

where:

Δt = time it takes for fuel cell modules to drain hydrogen storage

$\dot{V}$ = nominal volumetric rate (L/min)
n_{FC} = number of fuel cell modules

Linde (Aluminum)

$$\Delta t = \frac{987\ L}{(67\ L/\text{min})(2\ Fuel\ Cell\ Modules)} = 7.37\ min$$

Carleton (Composite)

$$\Delta t = \frac{2{,}757\ L}{(67\ L/\text{min})(2\ Fuel\ Cell\ Modules)} = 41.1\ min$$

Figure 13: Carleton Composite Pressure Vessel

Version 2.2

Using two (2) 3.5kW Serenergy FCs with one (1) DC/DC converter and filter enclosed within the body panel. This change was the result of cardboard mock-ups of all the components in place on the chasses showing that there was not enough clearance to operate the steering fully, as well as some other issues.

IIV. Reception and Current Status

Kettering students are very independent and take advantage of opportunities that they quickly find out in a comparatively small university campus. Dr. Berry promoted a fuel cell powered go-kart that would compete internationally in the Formula Zero circuit. Word was also passed along to other professors and classmates. To ensure the success of the team and maintain continuity, graduate students were assigned to manage and oversee their areas of expertise.

Initial Reaction from Recruited Students

Recruitment went on regularly, mainly concentrating at the beginning of the term of both A and B section when students did not yet feel the full burden of academic work. Flyers were posted throughout campus and had the weekly meetings posted on Kettering's web-based calendar. Any promotion made it clear that all majors and concentrations were needed because of the interdisciplinary mix of mechanical and electrical engineering. There was also a significant portion of programming and computer engineering involved. Business students were also sought after for their strengths to run and maintain organization of the group. Many advertisements focused on the fact that Team RainMaker was the newest racing group on campus, which meant that anyone that worked well both in groups and on their own would be given significant responsibility of the project. This sense of immediate ownership brought many talented individuals to the team.

Keeping students involved throughout the term and subsequent terms after that was complex due to variables such as:

- **An individual student's academic workload.** Dr. Berry made academics the priority of Team RainMaker. The graduate research assistants would personally talk to students about how they are doing throughout the term, and encourage them to focus on their studies. Common hour tests are a normal occurrence for core classes and would conflict with weekly meeting times at lunch. Students carrying a 20 hour course load would often not be available for the latter half of the term.
- **Varying rates of progress.** If there was no new information to present at a meeting, students would lose interest quickly. Their email address would be part of a mailing list to give updates to both sections after a meeting. These emails often had the power point presentation attached. This helped to remind students on their work term that we are moving ahead and accomplishing milestones. The sense of ownership comes into play again in the aspect of slow progress, because if there is no responsibility to give the undergraduate student members, they will get bored and seek another extracurricular activity.

After these dynamics were understood more, a real team came out of the woodwork. We all shared the passion to learn about new technology and see together that alternative energy has huge potential. RainMaker was the name picked by popular vote with the idea that we would produce a significant amount of water vapor in the clean emissions of the fuel cells during a race.

Reception Outside of the University

The graduate research assistants started attending the Fuel Cell Seminar & Exposition (http://www.fuelcellseminar.com/) for feedback from manufacturers and suppliers of fuel cells and related products. Kettering University had a booth, from which we presented our design to anyone that was interested. First year of attendance was 2009 and we started gathering fans. They were very interested in seeing the team and the vehicle the following year, and to witness the progress personally. The topology shifted dramatically after attending the 2009 Expo, resulting in Serenergy becoming a sponsor and giving us a discount for two Serenus 390 units.

Up-to-date Progress

I finished my required graduate classes the Fall term of 2010. I stayed involved voluntarily to transition the new graduate research assistants and other leaders into their role, providing complete access to the website (www.kurainmaker.com), social media network page (www.facebook.com) , online planner (www.liquidplanner.com), storage space in the cloud (www.dropbox.com), and all documents or emails that I had in my possession that directly related to the team project.

The team worked well and fast to refine the chassis, reconfigure the layout and packaging while taking into account driver mobility requirements (being able to bound out of the seat in case of an emergency and to have full steering capability while racing), select the remaining components to connect the composite tank to the FCs, build a custom wire harness, and design and build body panels to cover components and provide aerodynamics.