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# Fabrication and Testing of a Hybrid Electric Vehicle Utilizing a Proton Exchange Membrane (PEM) Fuel Cell

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## ABSTRACT

Hydrogen fuel cell powered systems might soon replace the conventional combustion engines used in today's vehicles. Fuel cells hold a great deal of promise for mobile applications including vehicles because they are environmentally friendly and can provide an alternative power supply. They may prove to be the keystone in making traditional electric vehicles a feasible everyday and long-range alternative to conventional combustion driven vehicles. One example of this type of electric vehicle is the New Jersey Venturer, which was equipped with a PEM fuel cell system to demonstrate the use of this new technology.

## INTRODUCTION

Currently a vast majority of vehicles on the roadways use a standard 4-cycle gasoline combustion engine. Using this process these engines have dominated the vehicle production industry for most of the 20$^{th}$ century. The biggest disadvantages of these engines are that they directly produce emissions, have fairly low efficiencies, have a few hundred moving parts that can fail, and require regular maintenance. Hydrogen fuel cells have many advantages over combustion engines. However, they are not used in vehicles today because it is only within the past few years that the expense of manufacturing fuel cells was thought justifiable in anything other than aerospace applications. Also, researchers have only recently developed new methods of producing fuel cells at relatively lower expense and with greater efficiencies. As well as the fact that unlike gasoline there is not an existing hydrogen delivery infrastructure or publicly accessible refueling stations. Despite these drawbacks the fuel cell may allow electric vehicles to become an alternative for the combustion engine in the near future. In this research project an electric vehicle was retrofitted with a hydrogen fuel cell. After incorporating the fuel cell systems and creating the required support subsystems the vehicle was field-tested.

The New Jersey Venturer, the hydrogen powered zero emission electric vehicle, is the newest addition to the ever expanding technological applications of hydrogen fuel cells. The vehicle was designed and built to meet the specifications of the Northeast Sustainable Energy Association (NESEA) 1999 American Tour de Sol by various government agencies, companies, universities, and schools in New Jersey. The tour itself consisted of technical testing, an autocross event, a range event, and a 362 kilometer (225 mile) road rally that was spread out over the course of one week. Successful integration of a hydrogen fuel cell into an electric car had yet to be accomplished in the Tour de Sol.[1] Team New Jersey had the challenge of integrating many different components, or more specifically systems into the Venturer. Their efforts consisted of the initial planning and construction of the vehicle, followed by its participation in the Tour de Sol. Many lessons were learned in the past year from this thought-provoking project.

The main goal of the NESEA Tour de Sol is to educate the public about the development of environmentally friendly vehicles that are customer ready. Teams were responsible for displaying information to the public about their specific vehicle on every stop along the tour.[2] Another goal of the Tour de Sol is to encourage people to design and use new technologies. It should be noted that the NESEA Tour de Sol is not considered a race in any way; all scores depended on engineering aspects and overall completion of the tour. There were various categories in which the vehicles could be classified. 'Production' vehicles were those in which a company had sold at least five duplicate models of the vehicle prior to the competition. A 'commuter' was defined as being a vehicle designed for efficiency and performance optimization. A 'hybrid' vehicle which used liquid or gaseous fuel in a combustion engine, fuel cell or other type of energy converter in combination with an electric drive train. Hybrids are optimized for long distance travel with excellent fuel economy and ultra low emissions. A 'solar commuter' was classified as a vehicle to be used daily while exploiting the sun's energy through solar cells. The last category was 'demonstration' which was classified as any vehicle that did not wish to enter into the competition, but wanted to take part in the Tour de Sol's goal to educate the public.[2] The Venturer was placed into the 'hybrid' vehicle category, since the vehicle has a power source of a hydrogen fuel cell and nickel cadmium (NiCad) batteries in conjunction with an electric drive train.

## TEAM NEW JERSEY'S HYBRID ELECTRIC VEHICLE

The New Jersey Venturer was originally a Solectria Force® (retrofitted 1996 Geo Metro®) battery powered vehicle that was previously purchased by the New Jersey Department of Transportation (NJDOT) as part of an electric vehicle research project. The vehicle was retrofitted to enable a fuel cell to recharge the batteries and to provide additional power.[1] Many of the systems and subsystems were specifically designed for this project, mainly due to the use of the fuel cell. This provided Team New Jersey with systems that required testing and analyzing. The development of the Venturer for the Tour de Sol, the problems encountered during the retrofit, and possible solutions will be discussed in detail**.** The fact that this type of project was never done before makes reporting this data very important in laying the groundwork for future hydrogen fuel cell powered electric vehicle projects. Also included will be recommendations as to how to avoid the issues that were encountered during the field testing.

## THE BEGINNINGS OF THE VENTURER

In the past few years the New Jersey Department of Transportation (NJDOT) has been working to reduce pollution by researching alternatives to today's gas powered combustion vehicles, which are causing a large portion of the world's pollution problems. Initial research conducted by the NJDOT consisted of testing a fleet of Solectria electric vehicles. These vehicles however have a limited range before the batteries will need to be recharged, for this model charging takes several hours to complete and there is a lack of charging stations. The NJDOT was also planning to invest in a new Solectria vehicle, one that was more advanced than the original electric fleet. This vehicle was never purchased such that the NJDOT could conduct more extensive research in the advancement of electric vehicles themselves. The NJDOT was searching for new ways to improve the range of electric vehicles in order to make them more practical. At the same time the NJDOT had began to look into the possibility of using fuel cells in conjunction with batteries as a means of elongating the time between charges for other devices that used electric motors. The first project to be completed was the retrofit of variable message boards, in which the boards were powered by a fuel cell system, and batteries. With the success of the variable message boards NJDOT began to wonder if the same technology could be used in an electric vehicle.

The NJDOT now had the interest of performing a research project with fuel cells in an electric vehicle. It was understood that in order for this technology to continue to improve and eventually help develop an awareness, the public as well as industry had to be informed of this new concept for electric vehicles. The NJDOT had sponsored the NESEA Tour de Sol for the past three years and began to realize the extent that NESEA emphasizes education throughout the tour. The NJDOT decided that entering an electric vehicle with a fuel cell would help to accomplish the goal of demonstrating the use of this new technology. A few months later the Governor of New Jersey announced that the state would be joining other states in creating incentives by enacting legislation to support advanced technology vehicles. This added to the general feeling that a fuel cell powered electric vehicle had the support needed to see the possibility of the New Jersey Venturer's technology becoming reality.

## FUEL CELLS: A NEW ENGINE FOR ELECTRIC VEHICLES

Fuel cell technology is the latest experimental improvement to the modern electric vehicle. The average electric vehicle is composed of an electric motor and an array of batteries that run the vehicle. It is limited by the amount of energy stored in the battery pack and the time needed to recharge. The base vehicle for the project came equipped with lead acid batteries and an electric motor, which could run approximately 72 kilometers (45 miles) without recharging. Once the batteries were drained it would have to be parked and charged for approximately 3.5 hours.

This same vehicle, with the fuel cell and NiCad batteries was able to drive over 645 kilometers (400 miles) before it needed to be charged off a power grid or receive more hydrogen.[1] The fuel cell provides the energy to recharge the batteries while the car is in use. This has many advantages over the original design. Since the vehicle has this ability to charge the batteries while it is running there is no longer a need to wait for the batteries to be replenished.

It should be noted, that there is a processing time of approximately 3 hours associated with the vehicle being refueled once all of the hydrogen and battery energy has been consumed. However the distance that could be traveled by the vehicle has been enhanced by nearly 900% without increasing the refuel time. Since the vehicle was only designed and built as a prototype the hydrogen "fill-up" was performed by forcing the hydrogen gas through the critical orifice of the storage tanks. There are other faster methods that could have been implemented to refuel the vehicle but this method seemed the most appropriate to meet the NESEA refueling monitoring guidelines. These refueling methods will not be discussed, however Team New Jersey hopes to make modifications to the vehicle in the future to shorten the time of the refuel.

The range of the vehicle has been extended from a mere 72 kilometers (45 miles) to over 645 kilometers (400 miles). The base vehicle came equipped with 13 lead acid batteries, during the retrofit these batteries were removed and replaced with 27 NiCad batteries. The overall weight of the vehicle increased by approximately 450 kg (1000 lbs) as a direct result of the additional number of batteries, the newly installed fuel cell, and related components. Even though the NiCad batteries have better energy storage than the lead acid batteries, the battery effect on the range was an improvement of only 72 kilometers (45 miles). The Venturer with its 27 NiCad batteries and associated weight change can operate from battery power alone for approximately 145 kilometers (90 miles). This means that the additional 500 kilometers (310 miles) the Venturer can travel between refueling comes solely from the fuel cell system and not the batteries.

The electricity used to recharge the batteries in conventional electric vehicles should be considered. Where did it come from? Many agree that electric vehicles shift the blame of pollution to the power companies, basically designing a vehicle that is pollution free but at the same time significantly increasing the amount of pollution generated by the power suppliers. It has been well documented in the past ten years that many of today's means of providing electrical power are not fossil fuel conservative or environmentally friendly.[2] An electric vehicle with a direct hydrogen PEM fuel cell like the Venturer theoretically only needs enough energy to allow the fuel cell to become active. Once the fuel cell is active or 'warmed up' it is able to produce power, it will continue to produce power and recharge the batteries as long as there is hydrogen and oxygen being delivered to the system. Hence, theoretically the Venturer never needs to be charged from the main power grid and does not contribute to the pollution produced by the power suppliers. This means that the fuel cell's emissions and the production of the fuel are the only true sources of pollution that come from the operation of the vehicle. Since the only byproducts of a fuel cell that uses pure hydrogen as it's fuel is heat and water, there is no pollution generated by this process.

The pollution generated during the process of obtaining the hydrogen itself is dependent on the extraction process. The hydrogen used to fuel the Venturer is derived from the electrolysis of water. The whole process was maintained through the use of hydroelectric power, which is virtually pollution free. Therefore there was very little pollution generated during the production of the hydrogen used on the Tour de Sol.[1] Conversely, hydroelectric power could also be used to recharge the batteries in an electric vehicle, making that vehicle also pollution free. However when taking into consideration that only 9% of the country's power is derived from hydroelectric power plants, the chance that this source will be utilized by these electric vehicles, hence reducing the pollution produced by them is minimal. Potential sources of hydrogen include fossil fuels, chemical intermediates, other alternative resources, and water electrolysis. Regardless of the method of hydrogen generation or extraction used, the power consumption would still be less for a standard electric vehicle battery charge. However the hydrogen gas and fuel cell systems allow the vehicle to store considerably more energy than by using batteries alone. The additional stored energy enables the Venturer to travel an extra 500 kilometers (310 miles). This makes the use of a direct hydrogen fuel cell in an electric vehicle very appealing to environmentally conscious individuals who want to reduce pollution and yet still require a practical vehicle.

## FUEL CELLS

Fuel cells, like batteries generate an electric current without the use of combustion. However, unlike batteries they are not limited to the fuel contained within the unit. A fuel cell can continue to produce power as long as it is supplied with fuel, whereas a battery will only last as long there are chemicals remaining to form electricity.[3]

## VARIOUS TYPES OF FUEL CELLS

Fuel cells are available in a wide range of types dependent upon the variety of electrolyte used in the reaction.

**Table 1. Types of Fuel Cells.[4]**

| | Proton Exchange Membrane | Phosphoric Acid | Molten Carbonate | Solid Oxide |
|---|---|---|---|---|
| Fuel ($H_2$ and $O_2$ sources) | $H_2$ | $H_2$ | $H_2$, $CO_3^{2-}$ | $H_2$, CO, $CH_4$ |
| Opp. Temp Degrees Celsius | 60 | 190 | 650 | 1000 |
| Products | $H_2O$ | $H_2O$ | $CO_2$, $H_2O$ | $CO_2$, $H_2O$ |

The mentioned types of fuel cells in *Table 1* mainly depend on operational temperature. Slight temperature variations can cause a number of problems ranging from melting the electrolyte to noticeable drops in efficiency depending on the type of fuel cell.[5]

The power source used for the Venturer project is a Proton Exchange Membrane (PEM) fuel cell. These types of cells are advantageous because they operate at lower temperatures (approximately 60$^o$C). This low temperature is important to Team New Jersey for a number of reasons. Firstly, the fuel cell system needs little thermal shielding to protect persons working near the fuel cell stack.[6] Utilizing a fuel cell with an operational temperature of 1000$^o$C would be impractical in this project due to the extensive cooling system that would have to be included in the limited space of the vehicle. Also as a consequence of the low operational temperature, PEM systems have a fairly rapid warm-up time (maximum five minutes). This is convenient since the driver can get in the vehicle and drive using the batteries without having to wait for the PEM to become fully functional. Once the PEM fuel cell becomes active at 60$^o$C it would begin producing electricity to power the vehicle and recharge the batteries. Another issue is that other types of fuel cells, excluding PEM have the potential of forming an electrolyte leakage problem.[7] This type of problem could not only damage other electrical components in the vehicle's engine compartment, but could potentially harm anyone attempting to work around the fuel cell. A final consideration, since the car was designed to compete in an environmentally friendly competition, is the vehicle's emissions. The PEM fuel cell in the Venturer runs solely on hydrogen ($H_2$) and has byproducts consisting only of water and heat.[4] There are no emissions from this PEM system, therefore making the car very environmentally friendly.

## HYDROGEN, A NEW FUEL FOR VEHICLES

All fuel cells consume hydrogen and oxygen to create electricity. However different types of cells can utilize hydrogen from a variety of sources. Methane, and hydrocarbons are all excellent sources to extract hydrogen for a fuel cell system.[11] Reforming hydrocarbon fuels require extra chemical processing to obtain the actual hydrogen that the fuel cell needs to operate. The Venturer uses pure diatomic hydrogen gas $H_2$, instead of a reformed source of hydrogen. This is a more economical form of fuel for many reasons. Fuel cells that run on pure hydrogen, like the proton exchange membrane (PEM) have only byproducts consisting of heat and water. Other types of fuel cells can have byproducts and may require additional containment devices, which increase the complexity and volume of the system. Reformed fuels require units in which the initial reaction can take place to ensure that hydrogen will be obtained for the cell. This adds bulk and weight to the overall mechanism. Considering the limitations of a vehicle engine compartment, and that this is a system, which will be mobile, a smaller and less bulky PEM fuel cell that runs off pure hydrogen was chosen for the project.

## HOW A PROTON EXCHANGE MEMBRANE FUEL CELL PRODUCES ELECTRICITY

A Proton Exchange Membrane fuel cell is a device that generates DC current by an electrochemical process. The cells of the stack are made up of an anode, cathode, and an electrolyte. The electrodes (anode and cathode) are made of a very thin sheet of porous paper that is coated with Teflon® and then platinum. The platinum acts as a catalyst, causing hydrogen oxidation to occur. Oxidation is the process by which a molecule loses electrons in order to occupy a more favorable electrical state. Next to the electrodes there are graphite plates, which contain flow fields, that allow the gas (hydrogen or oxygen) to reach the electrodes.[6] The electrolyte, which is an electric insulator and an excellent conductor of hydrogen ions, is composed of a fluorocarbon polymer that has sulfonic acid ($SO^{3-}$) side groups.[8] The electrolyte is placed between the electrodes to become a single 'membrane/electrode cell' which is less than a millimeter thick.

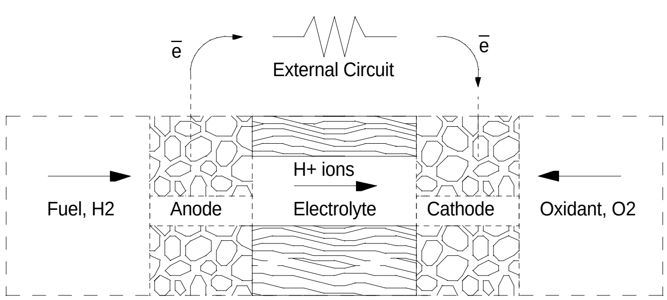


**Figure 1. Cross sectional illustration of a Proton Exchange Membrane fuel cell producing electricity.[6]**

As illustrated in *Figure 1*, a diatomic hydrogen molecule enters the cell through the flow field by the anode. It passes over the anode to the catalytic layer where is loses two of its electrons. The half cell reaction of this process is $H_2 \rightarrow 2H^+ + 2e^-$. These 'lost' electrons, which make up the DC current are attracted to the anode.[6] Water molecules on the membrane assist the hydrogen ion ($H^+$) through the electrolyte to the cathode. This is possible because the electrolyte is made up of small nano-channels lined with $SO_3^-$ acid groups in which the $H^+$ attach to form $SO_3H$. It is the water molecules that allow the $H^+$ to jump from one $SO_3^-$ group to the next $SO_3^-$ group until it ultimately reaches the cathode.[8] Once the $H^+$ ions come in contact with the cathode they combine with oxygen being fed into the system via the flow fields. Naturally occurring oxygen in ambient air can be utilized. This air can be fed directly into the fuel cell, after it is filtered for particulate matter and humidified. Consequently, onboard storage of pure oxygen is not required, ambient air will suffice to react with the $H^+$ ions. This reaction produces chemically pure water and since it occurs at 60°C based on thermodynamic principals the water contained in the stack will be in a vapor form. The chemical reaction for the synthesis of water that takes place in the cathode is $4H^+ + O_2 \rightarrow 2H_2O$.[6]

## THE VENTURER FUEL CELL SYSTEM

The fuel cell used in the Venturer has an output voltage of 38.4 volts (110 amps) and a nominal power output of 4.2 kW. The stack is composed of 64 'membrane/electrode' cells, each having a voltage of 0.6 volts/cell. It has a current density of 440 mA/cm$^2$ and an active area of 250 cm$^2$.[6] The stack weighs 56.7 kg (125 lbs) with the entire stack having dimensions of 348x190.5x343 mm (13.7x9.9x13.5 inches).[3]

## NEW JERSEY VENTURER SYSTEM COMPONENTS

The Venturer is a very unique vehicle in that it uses a PEM fuel cell as the main source of driving power. However, the Venturer is not made up of a fuel cell alone. There are many components in the vehicle, which assist the fuel cell in performing properly. Some of these include a fuel cell controller, boost converter, and an on board data acquisition unit.

## PROTON EXCHANGE MEMBRANE FUEL CELL SYSTEM

The fuel cell used in the Venturer project required a controller to regulate the components of the vehicle's subsystems including the air pump motor and the heat exchanger, *Figure 2* illustrates the layout of these systems. The air being delivered to the fuel cell must first be filtered, to remove any large particles that could plug or damage the cell. Also this air must be humidified before it can enter the stack.[6]

Moisture is a very critical factor that significantly affects the efficiency of the cell membrane. The reaction in which the electron deficient hydrogen mixes with oxygen to make water creates heat, which tends to dehydrate the electrolyte membrane. This dehydration increases the resistance of the membrane, which in turn lowers the driving forces of the chemical reactions in the fuel cell. The membrane must be kept moist at all times, to maintain its conductivity and performance. Conversely if the membrane becomes too wet, a condition referred to as 'flooding' occurs. The 'flooded' state will prohibit the reactant gases, mainly the oxygen from reaching the catalyst. As excess moisture accumulates in the stack the number of reactions decrease because is cannot perform hydrogen reduction. Consequently the stack will no longer be able to produce electricity efficiently.[7]

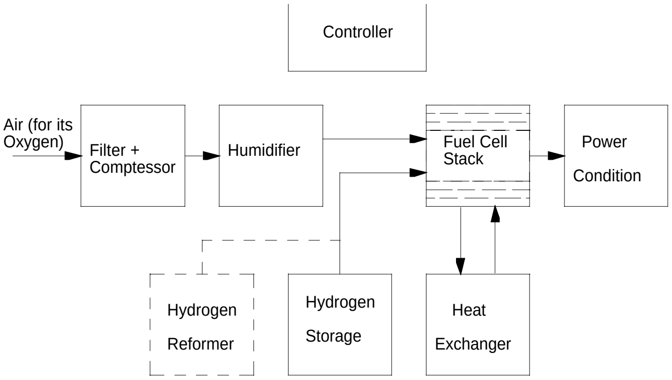


**Figure 2. This diagram shows the order and placement of some of the components included in a PEM fuel cell system.[6]**

The humidified air used to moisten the cell membrane becomes heated as the reactions take place. The heated water from moistening the stack and the residual water from chemical reactions must be periodically purged from the cell. The purged water then enters a heat exchange device, which works much like a car radiator to cool the water temperature.[6] The cooled water will then be re-circulated into the air humidifier for the fuel cell system. The air humidifier system has vessels which are also a part of the fuel cell gas system, these containers hold approximately five gallons of water and need to be maintained at all times to sustain peak efficiency.[6]

## BOOST CONVERTER

The boost converter is a part of the electrical system in the Venturer. The converter acts as the main voltage regulation device between the fuel cell and the batteries. This component is necessary since the fuel cell has an output voltage of approximately 36 volts while the batteries require approximately 200 volts and 20 amperes for charging. The main job of the converter is to step up the voltage to the appropriate level for the batteries while providing constant voltage and constant current. It also acts as a power regulator, insuring that the fuel cell system is running at the maximum power output for optimum efficiency. Included in the boost converter is a microprocessor, which allows the vehicle operator to adjust the threshold, or output voltage and current, via an interfaced laptop computer. This added flexibility was included into the system to give operators the ability to control the power systems in case a problem arises. The controller also permits tracking the battery temperature with adjustments in the output voltage to insure the optimum recommended parameters specified by the battery manufacturer are maintained. This feature will keep the battery pack fully charged and avoid faulty battery cycles, thus extending its useful life.[10]

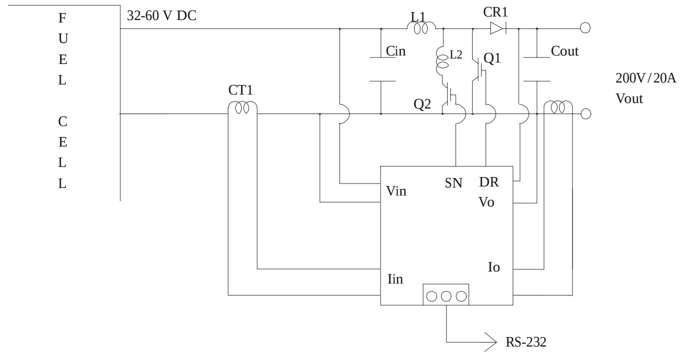


**Figure 3. Circuit block diagram of the boost converter used in the New Jersey Venturer.[10]**

## TECHNICAL ASPECTS OF THE BOOST CONVERTER

The fuel cell provides the input current to the circuit. As shown in *Figure 3.* switch $Q_1$ has a 40 kHertz frequency with a variable duty cycle, which controls the closed positions. As switch $Q_1$ closes the current from the fuel cell passes through it and the input inductor, which causes a linear increase in current throughout the 'on' period.

In this phase the energy is stored in the inductor and is equal to $E=1/2LI^2$, were 'L' is the rating of the inductor and 'I' is the current in amps. [10]

When the switch $Q_1$ opens this energy is transferred to the output capacitor $C_{out}$ at a higher voltage determined by the duty cycle. If the output current demand exceeds the 20A threshold, a new control loop is opened which will maintain a constant current even if the output is short circuited.[10]

If the voltage coming from the fuel cell (input voltage to the boost converter) drops below 36 volts, which is the point of maximum efficiency for the fuel cell system, the boost converter will react by lowering it's output voltage. This reduces the load as seen by the fuel cell and will force the voltage to return to the optimum point again. In order to minimize the switching losses an active snubber is implemented with the switch $Q_2$, see *Figure 3*. With an overall efficiency of about 93% the converter avoids using bulky cooling equipment. Since the efficiency is so high, very little energy is converted or lost to heat generation, thus it remains at a cool temperature.[10]

## ON BOARD DIAGNOSTIC SYSTEM

The Venturer was equipped with an on-board diagnostic (OBD) system designed and built by Rowan University. The system consists of components that perform data acquisition, data logging, and real time displaying of the vehicle status. A majority of the information gathered during the tour from the Venturer systems has come from this unit. The data measurements collected on the tour include both fuel cell parameters and general parameters of the vehicle. The fuel cell itself has a microprocessor, which monitors the fuel cell system. This information was then fed to the display of the OBD system in the passenger compartment of the vehicle for monitoring purposes. This data includes stack temperature, stack voltage, and stack current. The remaining information, including battery voltage, water temperature, fan usage, and pump usage; were collected from the data acquisition unit. A laptop computer was used as the central information hub of the system, which allowed a Graphical User Interface (GUI) to be installed to give the passengers of the vehicle the ability to monitor any of the above mentioned parameters. The laptop computer was also used such that the data could be saved for report generation purposes.[11]

Analog Data Acquisition

The Analog Data Acquisition (DAQ) system is used to acquire information that the fuel cell controller will not gather. After consulting with various team members, the three parameters chosen for monitoring were the current going to the motor to drive the vehicle, the current coming out of the DC-DC boost converter, and the temperature of the batteries. Sensors were selected to measure these values. The DAQ that delivered these measurements to the laptop computer was integrated into the vehicle.[11]

Serial Communications

The second part of the data acquisition is the digital communication between the OBD system and the fuel cell controller in order to acquire the information that the controller processes. The controller sends out its operating string approximately four times a second as a single command line that contains the values of each parameter. This situation presented a few challenges when developing the interface. The first challenge was to find a software library that allowed an interface with the serial port of a computer. The language chosen to create the software was C++, therefore the library must also be designed to use C++. Another challenge faced was finding a way to make use of the text string that was received. It was not difficult to get the software working, but the text was sent so fast that the available software was unable to interpret it. To resolve this, code was developed to force the software to read the output at a lower frequency. Once this was done the text string had to be separated so that the individual values could be used to refresh the virtual gauges used. The virtual gauges then had to be programmed to read the specific values that were being captured for the display.[11]

Graphical User Interface

The Graphical User Interface (GUI) or virtual gauges is the main link between the OBD system and the user. It had to be custom-designed for all the information it would display. The laptop computer would display the incoming data on various dials and gauges while at the same time controlling the logging of the data. The system also implemented timers, buttons, and other controls to give the user other useful features. A passenger was able to begin and terminate the acquisition/display mode and to specify the frequency that the data logging would occur.[6]

## 1999 NESEA TOUR DE SOL

The 1999 NESEA Tour de Sol took place May 22-May 29, 1999 in various locations across Connecticut, New York, and Massachusetts. Involved in the tour were various colleges, companies, and automotive manufacturers, as well as many other independent environmentally friendly individuals. One purpose of the Tour de Sol is to encourage experimentation with solar power and other emission-free or emission reduced vehicles while educating the public about various potentially ‘clean’ technologies. Participants get the chance to illustrate that it is possible to design and build environmentally friendly vehicles today, rather than wait for the technology to be commercially produced in the near future.

## TECHNICAL TESTING

Check Lists

The first part of technical testing is the compliance with a checklist of physical vehicle parameters determined by NESEA. This technical checklist varies depending on the classification of the vehicle competing. All vehicles must comply with the equipment, signage, electrical, and construction safety rules that NESEA has mandated. The criteria that hybrid electric vehicles are checked for include:

- Approved fuel lines and fittings depending on fuel type.
- Approved fuel cylinder/container.
- Check for fuel leaks.
- Exhaust is released at the rear of the vehicle.
- Exhaust leaks are not present.
- Adequate clearance is between fuel lines and exhaust.
- Engine noise test.

## MOVING TESTS

Breaking

Another criteria is the ability for the vehicle to perform an emergency stop. Vehicles should be able to stop with a deceleration that is comparable to 5 meters per square second for the main brakes and 2.5 meters per square second for the auxiliary brakes. This is tested with the conventional speed and stopping-distance method. The strength of the brake operating lever is also tested by applying the worst case braking pressure.[2]

Acceleration Testing

This test records the time it takes the vehicle to travel 0.4 kilometers (a quarter of a mile). It provides an estimate of how much distance the vehicle was able to travel in an amount of time. This test is designed to ensure that the vehicle will be able to enter traffic patterns and will not pose as a hazard to anyone while driving on the highway.[2]

Handling/Stability

Vehicles were weighed to see if they exceeded the designated weight limits. Weight distributions were also noted. Vehicles exceeding the allowable weight restriction needed to identify suspension and supporting structure modifications to account for and safely handle the extra weight. A cone test was performed to demonstrate minimum handling and breaking requirements. All vehicles must also support a lateral acceleration of 0.6 g's and a steering response time above 0.25 Hz under load. Furthermore, vehicles needed able to execute a U-turn within a 15 meter lane.[2]

Hill Climbing

This test ensured that all vehicles were able to maintain a minimum safe speed of 48 km/hr (30 mph) up a 10% grade incline. The vehicle also needed to drive up a 15% incline, stop, remain motionless with the support of a parking break, and then continue driving.[2]

## ROAD TESTING

The road-testing portion of the competition consisted of five separate components. The first was the road rally event, where the vehicles were driven under normal everyday driving conditions. Each vehicle needed to be able to handle obstacles such as traffic delays, road construction, and other real world conditions. Teams were required to finish each leg of the rally, described in *Table 2* in a specified amount of time.[2]

**Table 2. Road Rally information for the 1999 NESEA Tour de Sol.[12]**

| Date | Start Location | Finish Location | Distance km (mile) | Minimum Elevation m (ft) | Maximum Elevation m (ft) |
|---|---|---|---|---|---|
| 5/24/1999 | Waterbury CT | Hartford CT | 50.8 (31.6) | 24 (80) | 216 (710) |
| 5/24/1999 | Hartford CT | Torrington CT | 46.3 (28.8) | 18 (60) | 308 (1010) |
| 5/25/1999 | Torrington CT | Pittsfield MA | 89.5 (55.6) | 180 (590) | 479 (1570) |
| 5/26/1999 | New Lebanon NY | Albany NY | 33.5 (20.8) | 6 (20) | 479 (1570) |
| 5/27/1999 | Latham NY | Saratoga | 58.6 (36.4) | 12 (40) | 155 (510) |

The second event was designed to determine the maximum distance the vehicles could travel without refueling. There were two types of laps in which the vehicles could travel as shown in *Table 3*.

**Table 3. Range event information for the 1999 NESEA Tour de Sol.[12]**

| Lap | Length kM (mile) | Min. Time | Max. Time |
|---|---|---|---|
| Short | 13.6 (8.5) | 11 min | 20 min |
| Long | 60.8 (38) | 38 min | 55 min |

The short lap could be driven a maximum of five times. Any vehicle that wished to travel more mileage than five short laps must drive the long lap.[2] The third event tested the handling of the vehicle in extreme turns. This is the actual testing for the handling/stability, which was mentioned in technical testing.[12] In the fourth component, greenhouse gas emissions of the vehicle as well as the emissions from the production of the fuel itself were considered. This way the pollution is accounted for the whole life cycle of the fuel, in an effort to make people more aware of all of the sources of greenhouse gasses. Finally, the fifth component is fuel economy, which is a measure of the equivalent miles per gallon of gasoline that a vehicle uses for some specified amount of distance traveled. It is an indication of how well the vehicle is using its fuel.[2]

# Design

Encouraging people to design and use new technologies is a very important goal. Vehicles are not rewarded for being fast or exceptionally sporty. The vehicles are judged on how well they utilize environmentally considerate and energy efficient technology. NESEA has three categories in the Tour de Sol which evaluate these criteria. 'Consumer acceptability' is the first of these criteria. This is when the practicality of the vehicle's design is judged. This is done to promote the development of marketable and practical vehicles. This category is concerned with the comfort of the driver and any passengers.[2] 'Engineering elegance' is also evaluated. This is a ranking of the vehicles in terms of new and innovative system designs. The quality of the design is the main area of concentration.[2] The last design factor considered is the specific teams attempt to include an 'educational display' as part of the tour. Part of the purpose of the NESEA Tour de Sol is to educate the public about electric and hybrid vehicles. Teams are required to have educational materials on display and teammates available at all times during the tour to help inform the public of new and upcoming technologies.[2]

## SOLECTRIA FORCE® VEHICLES ON THE TOUR DE SOL

The New Jersey Venturer prior to the fuel cell retrofit was a NJDOT owned Solectria Force®. These Solectrias are retrofitted Geo Metro® vehicles that are equipped with the latest electric vehicle motor systems. Many groups including Team New Jersey used commercially sold vehicles, which were modified for the Tour de Sol. This retrofit method avoids the team from having to build the vehicle from the ground up. Meaning that the teams can concentrate on the design and construction of specific systems without having to worry about building standard electric vehicle systems. Such systems may include regeneration brakes, steering, drive train, and other typical components of a vehicle. However, some teams do choose to build a vehicle without a base design. These teams then can customize the vehicle in every way to optimize performance, however much time can be lost redeveloping proven systems and technology.

Consequently, the retrofit method appears to be very popular. There were six teams that used the Solectria Force® as their base design for the 1999 Tour de Sol, as shown in *Table 4*.

**Table 4. Solectria Force® vehicles involved in the 1999 NESEA Tour de Sol.** [13]

| Name | Category | Vehicle Type | Motor | Batteries |
|---|---|---|---|---|
| Sunergy | Production | 92 Geo Metro® | Solectria 25kW cont. | Interstate Wet PbA 10 kWh/ 144V |
| Venturer | Hybrid | 96 Geo Metro® | Solectria 25kW cont. | SAFT NiCad 15600 Wh/156 V |
| NiCad Force | Production | Geo Metro® | Solectria 12kW cont. | SAFT NiCad 15600 Wh/156 V |
| C.A.T.S. | Production | Geo Metro® | Solectria 35kW cont. | Solectra PbA 38000 Wh/156 V |
| Ovonic | Production | Geo Metro® | Solectria 15kW cont. | Ovonic NiMH 27000 Wh/180 V |
| Challenger | Production | Geo Metro® | Solectria | GP Industries NiMH |

All of the vehicles except for the Venturer were classified in the production category since they were commercially produced. The Venturer is a hybrid vehicle, and not classified as production. The fuel cell adds a second source of electricity for the motor, and it is not currently possible to buy a vehicle with this technology pre-installed.

Most of the Solectria drive train remained unchanged in the Venturer, including the electric motor. Therefore, a comparison between the Venturer and the other entered Solectria Force® vehicles on the tour could give an accurate representation of how a fuel cell system can effect the overall performance of an electric vehicle.

**Table 5. A comparison of the above mentioned Solectria Force® vehicles with the New Jersey Venturer.**[13]

| | Noise dba | Fuel Economy MPG (eq.) | Emissions GHG | Expected Range km (miles) |
|---|---|---|---|---|
| Sunergy | 69 | 78.01 | 103.06 | 112.63 (70) |
| Venturer | 69 | 31.37 | 21 | 643.6 (400) |
| NiCad Force | 68 | 86.01 | 120.69 | 144.8 (90) |
| C.A.T.S. | 70 | 67.59 | 117.02 | 80.5 (50) |
| Ovonic | 67 | 57.69 | 114.25 | 241.4 (150) |
| Challenger | 70 | 73.38 | 107.37 | 128.72 (80) |

**Table 6. A comparison of the above mentioned Solectria Force® vehicles with the New Jersey Venturer.**[13]

| | Actual Tour Range | Expected Max Speed km/hr (mph) | 1/3 mile Acceleration km/hr (mph) | 1/3 mile Acceleration seconds |
|---|---|---|---|---|
| Sunergy | 11.9 | 104.6 (45) | 72.5 (45.09) | 26.45 |
| Venturer | 71.9 | 96.5 (60) | 74.6 (46.35) | 25.89 |
| NiCad Force | 85.7 | 104.6 (65) | 87.5 (54.36) | 24.79 |
| C.A.T.S. | 20.4 | 112.63 (70) | 86.7 (53.87) | 24.09 |
| Ovonic | 172.7 | 120.6 (75) | 92.08 (57.23) | 23.17 |
| Challenger | 68.7 | 120.6 (75) | 93.4 (58.04) | 22.11 |

The fuel economy for the Venturer, calculated by NESEA, is significantly lower than the other Solectria vehicles involved in the tour, this is illustrated in *Table 5*. It should be mentioned that NESEA included into the calculations the use of the diesel fuel that would be consumed transporting the hydrogen from where it is produced in Canada, to the vehicle.[2] This has significantly enlarged the amount of equivalent fuel needed to run the Venturer according to their calculations. The Venturer and the Sunergy, as noted in *Table 4*, both had Solectria motors with the same power rating of 25 kW, they also had accelerations that were similar, as shown in *Table 6*. Although this in not conclusive evidence, the fuel cell had no apparent effects, positive or negative, on the acceleration of the vehicle. However, this could be disputed when the weights of the vehicles are considered. The Venturer weighed approximately 1550 kilograms (3400 lbs), which is 320 kilograms (700 lbs) heavier than the Sunergy. Which indicates that the heavier Venturer still maintained it's ability to accelerate, therefore the fuel cell did boost the Venturer's acceleration ability.

Due to technical problems with the boost converter, the actual tour range is not an accurate representation of the potential range of the Venturer. The power to drive the 115.7 kilometers (71.9 miles) that were recorded on range day came solely from the batteries, this is due to the fact that the boost converter was not operating correctly and the fuel cell was not able to recharge the batteries.[10] The comparison of the ranges of the Venturer to the other Solectria Force® vehicles therefore only demonstrates that the batteries were operating efficiently.

The Venturer has a significant reduction in greenhouse gas emissions as compared to the other Solectria vehicles, as seen in *Table 5*. This may be confusing since all of these vehicles listed in *Table 5* only have electric motors and therefore should have no direct combustion emissions. It has been acknowledged by NESEA that greenhouse gases are generated when electricity is produced. Fossil fuels such as coal and natural gas were incorporated into the calculations to determine the electric usage emissions. Therefore calculations of the greenhouse gas produced includes the emissions from the production of the energy used to charge the batteries of these vehicles.[2] The Venturer received power from the supplied power grid only once during the Tour de Sol. This power, 4.28 kW, was used to top off the batteries to insure a full charge for the range event. This demonstrates that the Venturer has reached the goal of being a vehicle with very little overall polluting emissions.

## SCORES AND AWARDS

The 1999 NESEA Tour de Sol was an excellent experience for Team New Jersey despite the various challenges faced by the team over the course of the tour. The Venturer placed second in the hybrid electric vehicle category. The vehicle also won the Engineering Excellence Award for the successful demonstration of a PEM fuel cell, and a special award for being the first fuel cell hybrid vehicle to complete a competition like the Tour de Sol.

## TECHNICAL PROBLEMS OF THE NEW JERSEY VENTURER ON THE TOUR DE SOL

The Venturer is a first generation vehicle. The successes of the design have been well documented, however with any new technology there have been many unexpected issues with various systems in the vehicle. Team New Jersey, has had various team members working to ascertain the causes of the issues that were experienced on the tour and to determine feasible solutions.

Boost Converter

During the range event on May 27, 1999 it was noticed that the fuel cell was not recharging the batteries, as it should have been. The Venturer was then only able to finish 115.7 (71.9 miles) of the 645 kilometer (400 miles) that it was expected to complete. The fuel cell was producing power at the usual efficiency, however the problem was that the boost converter was not providing the correct output voltage for the batteries to charge. The oscillatory crystal that functioned as the clock or controller of the microprocessor for the boost converter began to have intermittent problems. The clock was no longer keeping a steady pulse, and rapidly began to fail. The Venturer was forced to end the range event early to repair the faulty equipment. The oscillatory crystal was replaced and the boost converter's output voltage was restored to a level that allowed the batteries to be charged.[10] After a forensic investigation into the failure, it was determined that the failed crystal was not caused by the vehicle or the boost converter. Rather the failure was a result of a construction defect by the crystal manufacturer or possibly during shipping.

Fuel Cell Controller

It has been concluded that the efficiency of the fuel cell on the tour was below anticipated projections. The fuel cell was not producing the level of current or power expected. One of the explanations for this is that the controller for the fuel cell was not able to handle the high power systems in the Venturer. The speed of the air pump motor, which is integrated into the controller, ran outside the design speeds during the tour. The efficiency of the power generation is dependent upon this speed because the air pump is controlling the air that enters the fuel cell stack. If improper air flow occurs the stoichiometric ratio, or amount of reactants in the chemical equation, will be unbalanced.[6] This means that less electricity and water will be produced and either excess hydrogen or air will remain in the fuel cell stack waiting to react.[14] Finally the stack temperature was also not maintained at the correct level by the controller. This too could also effect the output of the fuel cell since the fuel cell reaches peak efficiency for a very narrow temperature range.

Another problem probably caused by the controller was that high current surges were experienced throughout the Venturer's electrical systems. This could have potentially damaged or destroyed other electrical components that were running during a surge.[6]

The original controller for the fuel cell is being exchanged for one that has the ability to handle high power systems. There will now be an isolated current in order to protect other electrical systems from destructive high current spikes. The new controller will also be equipped with more voltage and communication interfaces. These are needed since a large fuel cell system, such as the one used in the Venturer, has many additional auxiliary devices that need to be monitored and controlled.[6]

Data Acquisition Unit

Upon analyzing the data that was logged by the data acquisition unit during the tour, it has been realized that some important measurements were overlooked. There were various problems with the sensors on the tour, which only made the situation worse because the data was not always collected when the vehicle systems were operating. The combination of these factors has rendered the information from the data acquisition unit incomplete. In the next generation vehicle an onboard data logger will be used in place of the OBD unit. This logger will take readings on a specified time schedule from more of the sub-systems, average the data, and record the measurements. It will also have a real time monitor with display in which vehicle operators can easily view real time incoming measurements. A number of data collecting sensors will be incorporated into the vehicle system and sub-systems. Some of the new sensors will collect the power output data from the fuel cell to the boost converter, the output power data from the boost converter to the batteries, the power output to the load from the batteries, and a hydrogen pressure transducer sensor, which will measure hydrogen consumption. Most of the new measurements will aid in making the overall power efficiency calculations more accurate such that power drains and losses can be more easily identified.[6]

## CONCLUSIONS AND FUTURE WORK

The Tour de Sol proved to be an excellent learning experience, not only for the many students involved, but also for the many business and government partners. The team members had never worked on a fuel cell project of this scale. The new understanding of fuel cell technology used in an electric vehicle that has been illustrated during the Tour de Sol made the Venturer project successful. The team felt this project was a tremendous achievement despite technological problems that were encountered in the Venturer systems.

Future Work

The Venturer was equipped with a 5 kW fuel cell and 27 NiCad batteries. One of the technological limits of electric vehicles in today's market is the battery system. Batteries are expensive, heavy, and most of all they are bulky. They also have a relatively short life span before they become completely exhausted and inactive, at which time they must be replaced. There is a definite limit to the amount of power one battery can store before the system becomes inefficient, this makes it mandatory to add more individual batteries to any system to fill the storage capacity required. The fact that the Venturer had 27 batteries is a good illustration of what happens when a large amount of energy storage is required. The next generation Venturer will include two PEM fuel cells with a total of 10 kW power produced. This will reduce the amount of batteries incorporated into the vehicle. Clearly this will also decrease the overall weight of the vehicle and provide more space for other components or passengers. The Venturer was designed and built to prove that fuel cell technology is one solution to the problem of further improving the existing electric vehicle technology. The next generation vehicle will take the next step, relying more on a fuel cell and decrease the batteries used to power the vehicle's systems.[6]

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