A Case Study on the Hybridization of an Electric Vehicle into a Fuel Cell Hybrid Vehicle and the Development of a Solar Powered Hydrogen Generating Station.

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***Abstract*—Because they do not emit carbon dioxide, electric vehicles (EV) have emerged as a non-emission alternative to internal combustion engines. However, their limited driving range and the long time required to charge the battery bank remains a drawback. One solution to improve the driving range of an EV is to integrate a fuel cell (FC) with the battery.**

Like EVs, fuel cell hybrid vehicles (FCHVs) produce no pollutants during operation. However, production of the hydrogen for the fuel cells and the charging current for the batteries requires large amounts of electric energy. Since the vast majority of the energy produced by electric utilities in the US comes from fossil fuels (mostly coal), traditional production of the electricity to fuel FCHVs will still result in high levels of pollution. This pollution could be avoided entirely if the energy to fuel the FCHV was produced from renewable energy sources such as wind or solar. The purpose of this paper is to demonstrate the technical feasibility of FCHV transportation using hydrogen that is produced primarily by solar energy.

The first task on this part of the overall project was to implement a fuel cell (FC) on a Kronosport electric vehicle to convert it to a FCHV.

The second part of this paper demonstrates the generation of hydrogen using solar energy from a photovoltaic array. The electrolyzer will supply hydrogen that will be transferred to a storage tank on the FCHV via a dispenser (fueling station).

***Index Terms*—electric vehicle, electric vehicle hybridization, fuel cell hybrid vehicle, hydrogen economy, photovoltaic array, electrolyzer, hydrogen generation, proton exchange membrane fuel cell.**

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I. Introduction

In 2009, the U.S consumed about 95 quadrillions of Btu according to the Department of Energy (DOE) [3], and fossil fuels (petroleum, natural gas and coal) provided most of the energy. 83% of the energy used came from fossil fuels, 9% originated from nuclear electric power, and 8% came from renewable energy.

Fossil fuel combustion emits pollutants such as carbon dioxide (CO2), carbon monoxide (CO), oxides of nitrogen (NOx), ground level ozone (O3), fine particulate matter (PMx), airborne lead (Pb), and sulfur oxides (SOx) [4]. Those pollutants impact public health, and they create pollution, depletion of the ozone layer, acid rain and global warming. CO2 is now believed to be the leading cause of global warming.

Pollutants affect the health of people in different ways. CO creates visual impairment and reduced work capacity when the subject is exposed to low levels. At high level of exposure, CO causes death. NOx irritates the lungs and lowers the resistance to respiratory diseases. Exposure to O_3 increases respiratory problem and diminishes lung functions. PMx causes allergies, damages the lungs, and creates visibility problems. Pb collects in blood, bones and soft tissues and affects kidney, liver and nervous system functions [4]. As a result, researchers have increased their efforts into finding alternative sources of energies that are renewable and have less impact on the eco-system. The main renewable sources used in the U.S include solar thermal, photovoltaic, wind, biofuels (including hydrogen), geothermal, hydroelectric, and biomass.

In 2009 the transportation sector used 27 quadrillion Btu and accounted for about 29% of all the U.S energy use [3]. Although the transportation sector is the second largest user of fossil fuels, it emits the most CO_2. In 2006, the transportation sector released 1851 million metric tons of carbon dioxide, which accounted for 34% of all the CO_2 emissions from energy use [1]. The Clean Air Act of 1990 has established different strategies to reduce air pollutants at the source of pollution [4]. In the transportation sector, one of the strategies to control the emission of pollutants consists of replacing petroleum with more efficient and eco-friendly alternatives

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fuels such as electricity and biofuels.

Because they do not emit carbon dioxide, electric vehicles (EV) have emerged as a non-emission alternative to internal combustion engines. However, their limited driving range and the long time required to charge the battery bank remains a drawback. One solution to improve the driving range of an EV is to integrate a fuel cell (FC) with the battery.

Like EVs, fuel cell hybrid vehicles (FCHVs) produce no pollutants during operation. However, production of hydrogen for the fuel cells and charging current for the batteries requires large amounts of electric energy. Since the vast majority of the energy produced by electric utilities in the US comes from fossil fuels (mostly coal), traditional production of the electricity to fuel FCHVs will still result in high levels of pollution. This pollution could be avoided entirely if the energy to fuel the FCHV was produced from renewable energy sources such as wind or solar. The purpose of this paper is to demonstrate the technical feasibility of FCHV transportation using hydrogen that is produced primarily by solar energy [5].

First, a fuel cell (FC) was implemented on a Kronosport electric vehicle to convert it to a FCHV. The Kronosport FCHV also complements a GEM 825 FCHV developed earlier by Barakat and Stuart [6].

As noted earlier, FCHVs are powered by hydrogen and produce virtually no pollution during operation, but the power source for generating the hydrogen can generate large amounts of pollution [7]. Electrolysis using electricity is an effective way to produce hydrogen from water, but electrical power from the grid is usually generated from fossil or nuclear power plants. From an environmental standpoint, it is preferable to use alternative energies that are ecologically friendly. The second part of this paper demonstrates the generation of hydrogen using solar energy from a photovoltaic array. An electrolyzer is used to supply hydrogen that is transferred to a storage tank on the FCHV via a dispenser (fueling station).

This was intended to achieve the following objectives:

1. To demonstrate a fuel cell vehicle powered by hydrogen produced from solar power.
2. To hybridize the Kronosport electric vehicle by integrating a fuel cell into the vehicle

First, the previous GEM FCHV was thoroughly studied to assess the strengths and weaknesses of the integration. Based on this study, solutions were proposed to simplify the vehicle and reduce cost. Those solutions were then incorporated in the Kronosport fuel cell integration.

For the second part of the project, a solar power powered hydrogen filling station was designed to include power processing for the output of the solar panels, the electrolyzer, a hydrogen storage tank, and a hydrogen dispenser to fill the tank on the FCHV. The electrolyzer manufacturer, Avalence, LLC, provided training on the electrolyzer operation.

Therefore, this research consists of two parts: the hybridization of the Kronosport electric vehicle by integrating a fuel cell, and the development of a hydrogen generation station powered by a photovoltaic array. Hybridization of the Kronosport Electric Vehicle by Integrating the Fuel Cell

A. *Kronosport Hybrid System*

The electric vehicle to be converted to a hybrid FCHV is a TRUK model from Kronosport. It has a 36 VDC battery bank consisting of (2) parallel strings of (3) 12 V batteries in series. Since each battery is rated at 26 ampere hours (AH), the battery stack provides a total of 52AH. The EV batteries are initially charged via a battery charger using electricity from the grid. In other words, one can plug the Kronosport into a household 120 AC power outlet to charge the batteries. When driving at steady speed, the EV draws a current of about 20ADC from the battery stack and up to 68 ADC during acceleration. The new hybrid FCHV consists of a fuel cell working in parallel with a battery bank as shown in Figure 1. The fuel cell provides power to the load that is inversely proportional to the battery voltage. When the battery bank is fully charged, it provides most of the power to the load and the fuel cell only provides a small amount of power. However, as the battery bank discharges and the voltage decreases, the fuel cell takes on more of the load current. This is illustrated in Figure 2which shows a plot of the increasing fuel cell current (I_{FC}) as the battery voltage (same as load voltage) decreases. A simplified schematic is shown in Figure 3. In Figure 2, as soon as SW2 is closed, the battery voltage V_B is equal to the load voltage V_L. V_{B1}, V_{B2} and V_{B3} show the battery voltage measured at different values of SOC. As a result, V_B fixes V_L and therefore determines the fuel cell operating point. As V_B decreases I_{FC} increases.

Figure 1 shows that the fuel cell can only be on when the key switch is closed and the EV is on. The EV terminal key switch is already part of the EV. When the key is in position 1, the EV is off since no terminals are connected. In position 2 (terminals 2 and 3 are connected) only the accessories are turned on. Finally, in position 3 (terminals 1 and 4 are connected, terminals 2 and 3 are connected), and the ignition and the accessories are activated. Since the FC is enclosed in a Plexiglas case, two fans are used to insure that enough oxidant enters the enclosure for the FC operation. The RS232/485 serial communication port is used to communicate with a PC which provides FC performance data using the Ballard NexaMON software. The RS232/485 draws 500mA and requires a supply voltage in the range of 10-30 VDC. Diode D3 insures the correct polarity to the communication port. F2 is a 1 A fuse for over current protection. F1 is a 75A fuse that protects the FC output. D1 protects the fuel cell from reversed current from the battery. SW1 is a MOSFET output relay, model D0660 from Crydom.

The FC is a 1.2KW Nexa proton exchange membrane (PEM) fuel cell from Ballard and it requires a supply voltage in the range of 18- 30 VDC. The FC characteristic curves supplied by the manufacturer are shown in Figure 4.

Figure 4 shows that as the output current increases from 0 ADC to 45 ADC the output voltage goes from 43VDC to 26VDC.

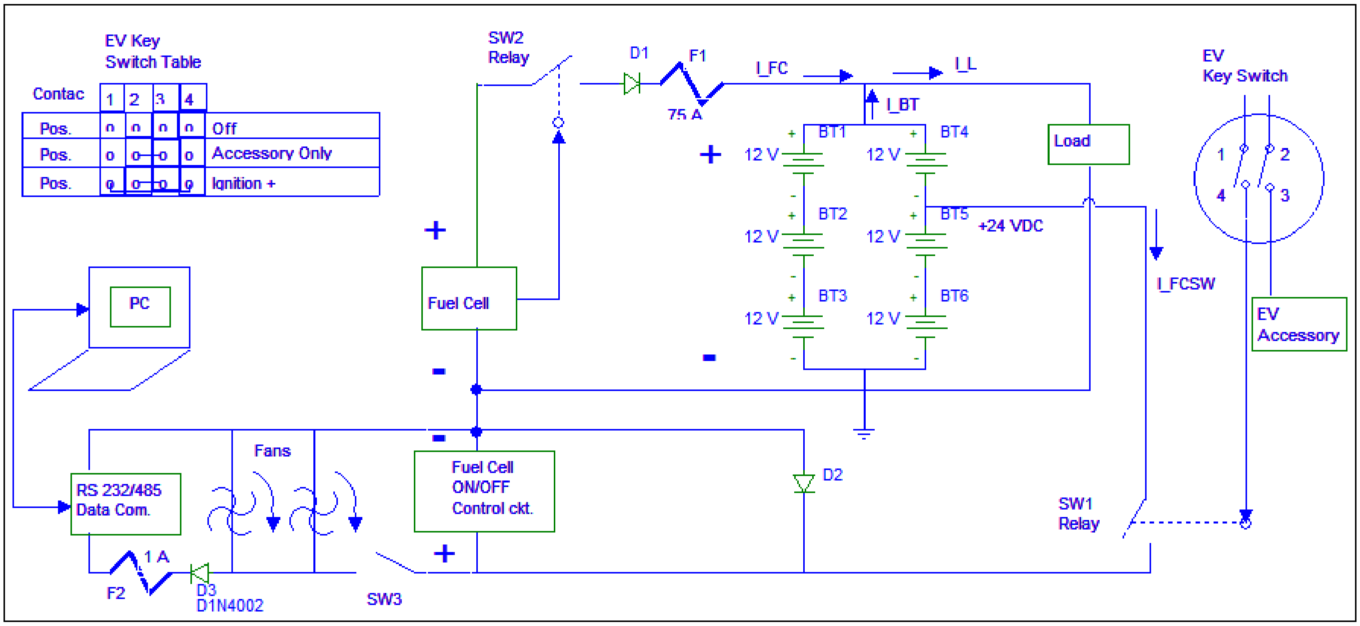

Figure 1: Kronosport Hybrid System

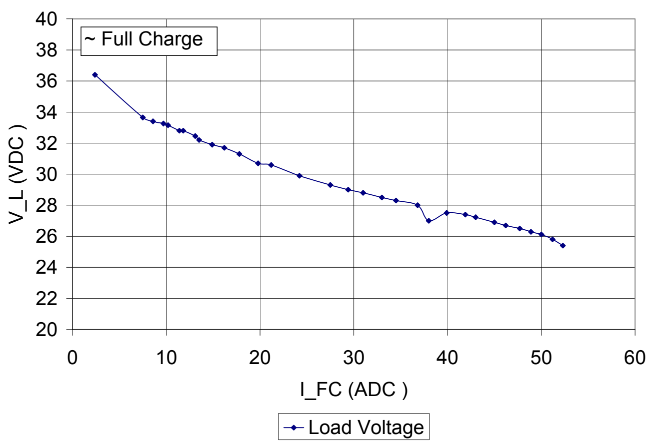

Figure 2: Load Voltage vs. fuel cell current as the battery discharges.

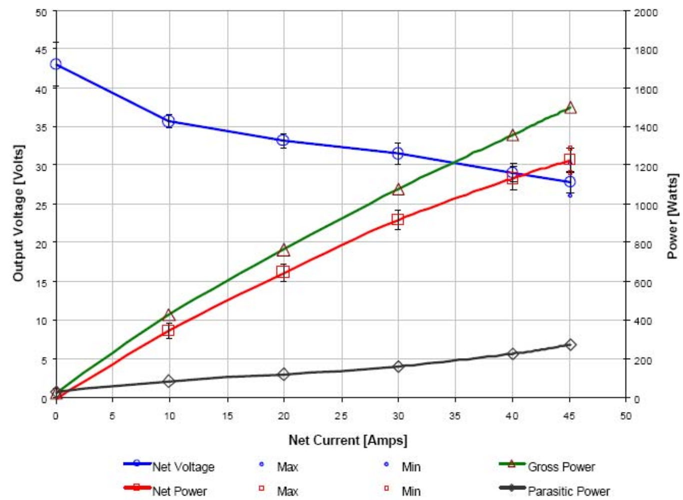

Figure 4: NexaModule Performance Characteristics.

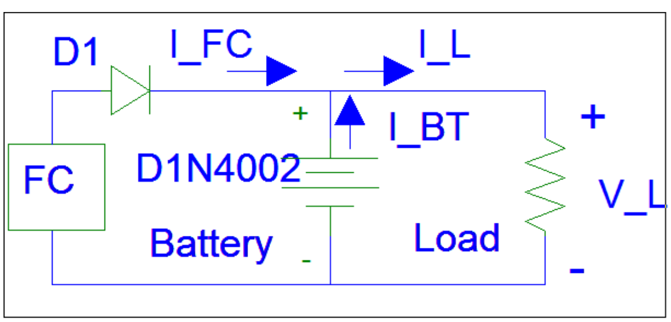

Figure 3: Simplified Circuit.

Since the lead acid battery voltage range is approximately 38.7 VDC to 34.92 VDC, this fuel cell is compatible with the battery, and the two can be connected in parallel. When the battery is fully charged (100% SOC) the open circuit voltage (OCV) is about 12.9 VDC per battery. When it is completely discharged at 0% SOC, the OCV is about 11.64VDC per battery. Therefore, the complete three battery bank OCV will vary from about 38.7 VDC to 34.8 VDC. Because of source resistance, these voltages will be significantly lower under discharge and higher under charge. Figure 5 shows the battery characteristic discharge curves at various rates of discharge. Directly after discharge, the OCV will "bounce back" to the levels shown in Figure 6, depending on residual capacity.

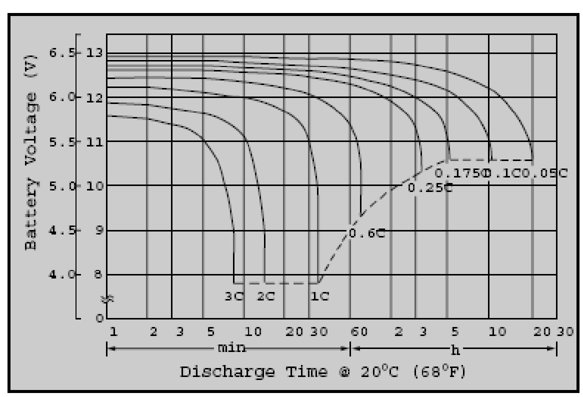

Figure 5: Characteristic Discharge Curves.

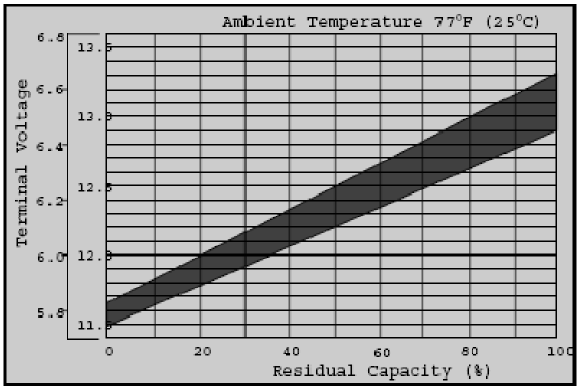

Figure 6: Open-Circuit Voltage Characteristics.

B. *Electrical Integration*

In order to implement the system shown in Figure 1, the FC hybrid system was built in the lab in the following steps. First, the fuel cell functionality was tested. Next, the battery bank was tested. Finally, the complete hybrid FC/battery system was built and tested.

The system in Figure 7 was built and tested in the lab. A 12V signal was used to operate SW1 instead of using the key switch, and a 24 V power supply was used to operate the FC ON/OFF control circuit instead of a tap at BT5.

With a full tank of hydrogen for the FC and a full charge on the battery bank, the system was tested with a resistive load. The test was intended to continue until one of the three following conditions occurred:

- The hydrogen is completely consumed
- The FC supply voltage across BT5 becomes too low (< 18 V) to sustain FC operation
- The load voltage becomes lower than the required value to operate the vehicle.

A resistive load bank was used to simulate the EV load at steady speed of about 15mph. In order to obtain approximately 20 A from the power source with a fully charged battery at 38.7V, the resistance R_L was adjusted to 1.94Ω,

$$R_L = \frac{V}{I_L} \quad (1)$$

$$= \frac{38.7V}{20A}$$

$$= 1.94\Omega$$

Relay SW1 is used to insure that the Kronosport must be turned on before the FC can be activated. To activate the relay, a 12 V signal is applied to the relay coil from a power supply.

The fully charged hydrogen tank contained 200g of hydrogen at 2300psi. A high pressure hydrogen regulator was used between the hydrogen tank and the FC to regulate the hydrogen to the FC at 40psi.

The battery bank voltage, V_BT, the load current, I_L, the current from the battery bank, I_BT, and the current from the FC, I_FC, were recorded for several values in Table 1. The hybrid system ran for approximately 6 hours until the hydrogen was depleted. At that point, the FC stopped with a voltage of 30.53V. Since the FC voltage supply comes from the voltage across the lower 2 series batteries, the FC voltage at that time was (2/3)* 30.53V= 20.35 V. Since 20.35 V lies in the FC operational range (18-30V), the FC supply voltage was still adequate. To measure the stabilized OCV of the battery (SOCV), it is recommended to wait several hours for the battery voltage to stabilize. The SOCV of the battery stack was 34.8 V when measured 17 hours later. This implies that each of the 3 series batteries had a voltage of about 11.6V. Figure 6 indicates that the SOC is approximately 10%. 20A is close to the .4C (C=52 A.hr.) discharge rate, and Figure 5 also indicates that at 11.6V, the remaining discharge time is very small. This indicates that the battery can operate the vehicle for only a few minutes once the FC energy is exhausted.

The results shown in Figure 8 and 9 below show the relative contributions of the FC and the battery as the battery voltage decreases.

These figures show that when the battery bank is fully charged it supplies most of the load current, but the FC provides most of the current when the battery reaches a low SOC. The data point at 39.13V was where the fuel cell first turned on, and no load was applied (the FC was only charging the battery). However, I_FC is very low at this point at about 0.6 A. The fuel cell provides more of the load current as the battery discharges, reaching up to 92.9% of the load current when the battery voltage reached 30.53V.

C. *Mechanical Integration*

The mechanical integration was accomplished in two parts. First, the fuel cell system was designed, built, tested, mounted onto a portable pallet in the laboratory, and an enclosure was built. Then the portable pallet was installed onto the Kronosport load bed, and the system was connected to the vehicle. A computer interface also was implemented, and since this research was meant to demonstrate technology integration to the public, it was imperative to acquire data and display it for the public to view. The mechanical integration offered some challenges because the FC is fragile, and the Kronosport operates in a rugged environment. The fuel cell, which has a fragile plastic frame, was designed for a lab environment, not a vehicle. In addition, the fuel cell operation requires a consistent airflow and protection against a wet environment. Because of its nature as an electric utility vehicle, the Kronosport can be used on uneven terrain that creates shock and vibration. To address these concerns, the GEM was carefully studied, and modifications to the GEM design also were implemented in order to provide a more rugged system[5].

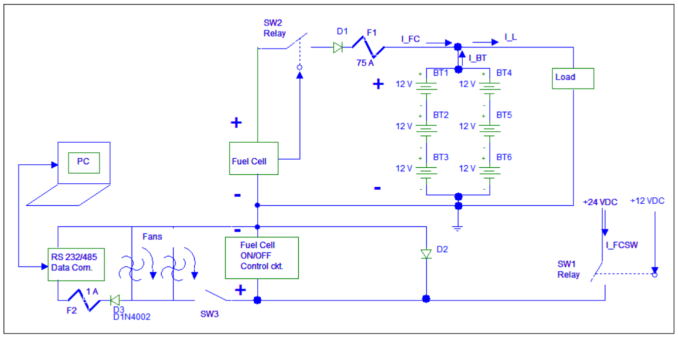

Figure 7: Test Setup for the Hybrid Fuel Cell/Battery System

TABLE 1 TEST RESULT FOR THE HYBRID FUEL CELL/BATTERY SYSTEM WITH 20A LOAD

TIME	I_L (A)	I_FC (A)	I_BT (A)	V_BT (V)
11:34	0	0.6	0	39.129
11:37	21.2	1.7	18.6	36.912
11:41	21.2	2.7	18.5	36.866
12:04	21.2	3.5	17.7	36.431
12:14	20.7	3.3	17.4	36.18
12:29	20.7	3.9	16.8	35.859
12:39	20.4	4.3	16.1	35.612
12:49	20.2	4.6	15.6	35.39
1:03	20.2	5.7	14.5	35.086
1:16	20	6.4	13.6	34.707
1:28	19.8	7.2	12.6	34.489
	21.6	7.5	14.1	34.308
1:35	21.5	8.4	13.1	34.156
1:50	21.5	10	11.5	33.717
1:56	21.1	10.5	10.6	33.52
2:06	20.9	11.7	9.2	33.177
2:13	20.9	12.3	8.6	33.022
2:20	20.7	13	7.7	32.816
2:37	20.5	14.3	6.2	32.43
2:47	20.5	15.2	5.3	32.25
2:58	20.2	15.6	4.6	32.12
3:15	19.9	16.3	3.6	31.79
	21.6	17.6	4	31.3
3:38	21.5	18.7	2.8	31.19
3:43	21.5	18.8	2.7	31.14
3:55	21.4	19.2	2.2	31.036
4:08	21.4	19.3	2.1	31.002
4:20	21.4	19.4	2	30.94
4:32	21.3	19.4	1.9	30.7
4:45	21.3	19.6	1.7	30.695
5:01	21.3	19.6	1.7	30.61
5:13	21	19.5	1.5	30.67
5:22	21	19.5	1.5	30.53
5:34	21	0	21	21.11

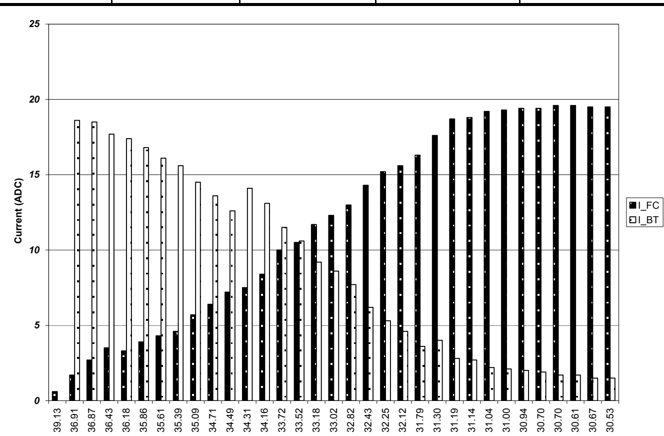

Figure 8: FC and Battery Currents vs. Battery Voltage (Load Voltage).

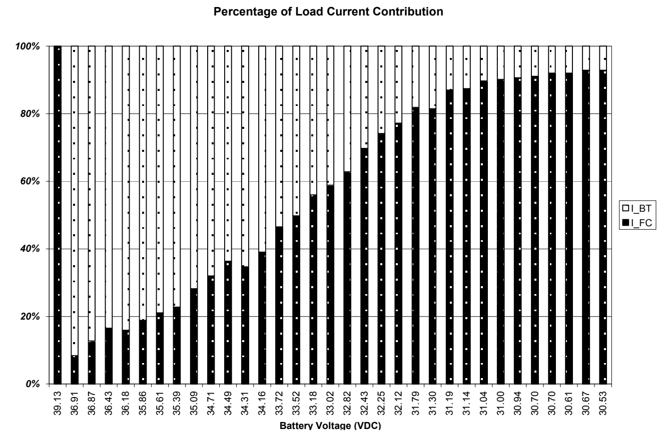

Figure 9: Comparison of Load Current Contribution of Fuel Cell and Battery Stack vs. Battery Voltage (Load Voltage).

II. DEVELOPMENT OF A HYDROGEN GENERATION STATION POWERED BY A PHOTOVOLTAIC ARRAY

A. *Electrolyzer System and Fueling Station*

This system consists of a solar array, a maximum power point tracker, a step down converter, an electrolyzer, a hydrogen storage tank, a hydrogen dispenser station, and an alternate load as shown in Figure 10.

The photovoltaic (PV) array in Figure 10 has a maximum output power of 6 KW. The output voltage varies between 50 and 62 VDC, while the current goes up to 100 A at full load. The electrolyzer, however, only draws 2 KW, so the PV array actually will never be loaded above this level.

A maximum power point tracker system is used to insure that when the PV power output is below 2 KW, a maximum power point tracking algorithm will be implemented.

The maximum power point tracker (MPPT) device was developed by Moening and Stuart [8]. The MPPT control system monitors the voltage and current from the PV and adjusts the voltage to produce maximum power from the PV. In this mode when the maximum PV power is below 2 KW, the remainder of the 2 KW electrolyzer input power will be drawn from the grid. When the maximum PV power reaches 2 KW, the grid turns off, and all of the 2 KW load is provided by the PV.

The electrolyzer is the Hydrofiller 15 from Avalence [9], and it takes water and breaks it down into hydrogen and oxygen. It consumes 2 KW of power, and can generate 750g of hydrogen per day, and it can use DC or AC power, depending on the mode of operation. The oxygen is considered a byproduct and is vented out. The hydrogen is stored in a storage tank at up to 3600psi, which is limited by a back pressure valve (BPV). This valve is set at 3300 psi, and when the pressure in the storage tank reaches 3600 psi, the BPV closes.

The storage tank is a Tufshell model from Lincoln Composites, with a 21-inch diameter and an 80 inch-length. The gas capacity is 3629 standard cubic feet (SCF), and the outer shell is made of fiberglass.

The tank needs to be protected from ultraviolet light, so a

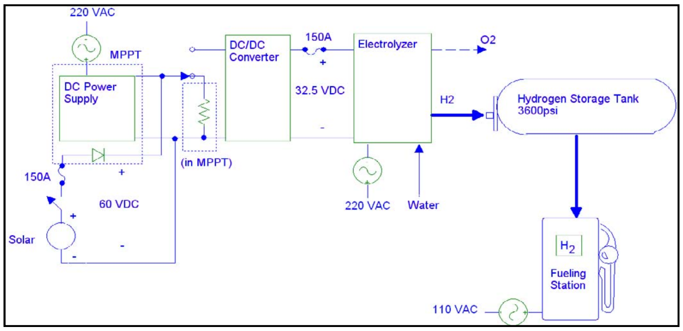

Figure 10: Proposed Electrolyzer System and Fueling Station.

heavy duty tarp enclosure was designed and fabricated to protect the tank.

The hydrogen dispenser is from Kraus Global [10]. It has a flow capacity rated at 8 kilograms per minute (3383 SCF per minute).The site for the electrolyzer system has to be prepared so that it is level, can support the load, and has anchors for the dispenser and the storage tank. It also has to meet certain OSHA requirements.

An alternate resistive load is used to keep the PV under load when the electrolyzer is not operating, e.g. when the hydrogen storage tank is full.

B. *Electrolyzer System Integration*

Once the system was designed, the next step was to integrate the electrolyzer system on a test bed. Because of the safety hazards the system has a signal to meet U.S Occupational Safety and Health Administration (OSHA) regulation standard 1910.103 on hydrogen. The test bed also met the National Fire Protection Agency (NFPA) Standard 50A.

The integration of the electrolyzer system was done on the test bed according to installation requirements that the manufacturers of the electrolyzer, the hydrogen tank and the hydrogen fueling pump had provided. The system shown in Figure 10 was integrated in three stages: site preparation, plumbing, and electrical integration. Figure 11 below shows the complete hydrogen generating station.

Figure II.15: The Hydrogen Generating Fueling Station.

III. Experimental Results

This section starts with a description of the performance metrics, and the performance of the Kronosport then evaluated. First, the Kronosport was tested before the FC integration, i.e., before the hybrid fuel cell/battery system was installed on the vehicle. Next, the FCHV was tested after the HFCBS was installed, i.e., after the fuel cell was installed. Finally, the Kronosport FCHV was tested with the integrated HFCBS turned off. The goal of this section is to show the improvement of the Kronosport FCHV over the original all electric Kronosport.

A. *Performance Metrics*

The Kronosport is a basic electric vehicle which is not equipped with an odometer. For testing purposes, a digital odometer (cyclometer), Blackburn Delphi 3.0, was programmed and installed on the Kronosport. The cyclometer comes with two sensors; one is used for speed, distance and time, and the other is used to measure the cadence. Cadence is defined as the number of rotations of the motor per minute (RPM). The instrument's magnets were glued with epoxy to the Kronosport wheel spade, while the sensor head was secured to the Kronosport frame with wire ties. The sensor is a Hall effect sensor which detects the magnet as the wheel turns, and the signal is sent to a computer which displays the data. The computer was secured to the left steering handle so that it is easily seen. The cyclometer records runtime, total time, speed, average speed, maximum speed, cadence, average cadence, maximum cadence, and distance.

In order to evaluate the performance of the Kronosport FCHV against the GEM, the following performance metrics were chosen runtime, driving range, driving range increase, and fuel consumption.

The runtime is the total time when the wheels of the vehicle are turning. The runtime is measured in minutes (min) and is directly recorded by the cyclometer. The driving range is the distance the vehicle can travel on one full charge. The range is measured in miles (mi) and is recorded by the cyclometer. The driving range increase ($\%D_{Imp.}$) compares the driving range before the FC integration (D) to the driving range after the FC integration (D_{FC}). The driving range increase is a percentage computed as shown in (2):

$$\%D_{imp} = \frac{D_{fc} - D}{D} \times 100\% \qquad (2)$$

Fuel consumption was also a metric. This metric was computed based on the hydrogen regulator pressure reading and the fuel consumption recorded by the NexaMon™ software. The driving range increase and the fuel consumption are computed from the measured results.

B. *Performance Evaluation for the Kronosport Without the FC*

The Kronosport battery bank was fully charged overnight. The battery bank reached 39.3 OCV, which corresponds to 100% SOC. The Kronosport was first driven continuously at an average speed of 18.3 mph until the charge in the battery bank was not sufficient to propel the vehicle. The battery bank voltage at that point was 34.1 V. The vehicle ran for 2h 17min 23sec and covered a range of 42.24 mi. Since the HFCBS was not yet integrated, the Kronosport did not consume any hydrogen. Results are shown in Table 2 below.

TABLE 21: TEST DRIVE RESULTS FOR THE KRONOSPORT WITHOUT THE FC

Date	6/26/08 @10:00AM
Runtime	137 min
Avg. Speed	18.3 mph
Max. Speed	23.6 mph
Driving Range (D)	42.24 mi
Starting Voltage V_B	39.3 V
Final Voltage V_B	34.1 V
Temperature	78.8 °F (26 °C)

C. *Performance Evaluation for the Kronosport FCHV with the FC*

The Kronosport battery bank was first charged overnight to 40.8 OCV, which corresponds to 100% SOC. The pressure inside the full hydrogen tank was 2300 psi, and the tank delivered hydrogen to the FC at 40 psi via the regulator. With the fuel cell turned on, the Kronosport FCHV was driven continuously with an average speed of 18.6 mph until the charge in the battery bank was not sufficient to propel the vehicle and the hydrogen was depleted. A few stops were made during the test to verify that the laptop was still connected and working. The vehicle ran for 6h 21min 24sec and covered a range of 118.75 miles. At the end of the test the battery bank had discharged to 30.93 V. Results are shown in Table 3 below.

TABLE 3: TEST DRIVE RESULTS FOR THE KRONOSPORT FCHV WITH THE FC.

Date	9/3/08 @9:00AM
Runtime	381 min
Avg. Speed	18.6 mph
Max. Speed	23.6 mph
Driving Range (D_{ef})	118.75 mi
Starting H2 Pressure (P1)	2350 psi
Final H2 Pressure (P2)	0 psi
Delta Pressure (P=P2-P1)	2350 psi
Starting Voltage V_B	40.8 V
Final Voltage V_B	30.93 V
H2 tank volume V_S	78 scf
Temperature	72 °F (22.2 °C)

The percentage increase in driving range was,

$$\%D_{imp} = \frac{118.75 - 42.24}{42.24} \times 100\% = 183\% \quad (3)$$

The ideal gas law was used as follows in order to find the mass of the hydrogen consumed.

The ideal gas law states that:

$$P \times V = n \times R \times T \Rightarrow n = \frac{P \times V}{R \times T} \text{ and } R = 8.314 \times 10^3 \frac{Pa \cdot L}{mol \cdot K} \quad (4)$$

where P is the pressure in Pascal (Pa), V is the volume in liters (L), n is the number of moles, T is the temperature in degrees Kelvin (K), and R is the universal gas constant.

The U.S standard units have to be converted to the desired units has follows:

$$P = 2350 psi \times 6894.757 \frac{Pa}{psi} = 16.203 \times 10^6 Pa \quad (5)$$

$$T = (°F - 32) \times \frac{5}{9} + 273.15 = (72 - 32) \times \frac{5}{9} + 273.15 = 295.372K \quad (6)$$

The volume of the tank V_S is given for standard pressure Ps and temperature Ts (Ps=14.7 psi, Ts=273 K). The actual volume for ambient temperature and pressure can then be found, since the number of moles in a closed system, n, is the same for a gas at different temperatures and pressures.

$$n = \frac{Ps \times Vs}{R \times Ts} \text{ , and } n = \frac{P \times V}{R \times T} \Rightarrow \frac{Ps \times Vs}{R \times Ts} = \frac{P \times V}{R \times T} .$$

Therefore,

$$V = Vs \times \frac{Ps}{P} \times \frac{T}{Ts} = 78 \times \frac{14.7}{2350} \times \frac{295.372}{273} = .5361 cf$$

$$= .5361 cf \times 28.32 \frac{L}{cf} = 15.184 L \quad (7)$$

Substituting equations (5), (6) and (7) into (4) yields the number of moles,

$$n = \frac{P \times V}{R \times T} = \frac{16.203 \times 10^6 Pa \times 15.184 L}{8.314 \times 10^3 \frac{Pa \cdot L}{mol \cdot K} \times 295.372 K} = 100 moles$$

The mass m is found by multiplying the number of moles, n, by the molar mass M

$$m = n \times M = 100 mols \times 2g/mol = 200g$$

Therefore, the Kronosport FCHV consumed 200g of hydrogen. Table 4 below shows a summary of the test results.

TABLE 4: SUMMARY OF PERFORMANCE METRICS FOR THE KRONOSPORT FCHV WITH THE FC

Date	9/3/08 @9:00AM
Runtime	381 min
Avg. Speed	18.6 mph
Driving Range (D_{ef})	118.75 mi
Driving Range Increase(% Dimp)	2350 psi
H2 Consumed	200 g

D. *Performance Evaluation for the Kronosport FCHV with the FC Mounted but Turned Off.*

The Kronosport battery bank was first charged overnight to 39.1 OCV, which corresponds to 100% SOC. With the fuel cell turned off, the FCHV was driven continuously at an average speed of 17.6 mph until the charge in the battery bank was not sufficient to maintain the speed of the vehicle. After driving for 1h 40 min, it was noticed that the vehicle was slowing considerably and barely able to reach 12 mph. It was decided to stop the test so that the remaining charge in the battery could be used to drive back to the garage. The range for this test was 29.48 miles. If the vehicle had been driven until it stopped completely, it would probably have reached a range of approximately 30 miles. This decrease in range from the 42 miles without the FC is most likely due to the additional weight of the FC, the hydrogen tank and the laptop, approximately 75 lbs. The manufacturer of the Kronosport has stated that the fully loaded vehicle typically has a 25 mile range.

TABLE 5: TEST DRIVE RESULTS FOR THE KRONOSPORT FCHV WITH THE FC MOUNTED BUT TURNED OFF.

Date	8/29/08
Runtime	100 min
Avg. Speed	17.6 mph
Max. Speed	23.2 mph
Driving Range (D_{ef})	29.48 mi
Starting H2 Pressure (P1)	2350 psi
Final H2 Pressure (P2)	2350 psi
Delta Pressure (P2-P1)	0 psi
Starting Voltage V_B	39.1 V
Final Voltage V_B	35.5 V
H2 tank volume V_S	78 scf
Temperature	63 F

The percentage increase in driving range was,

$$\%D_{imp} = \frac{118.75 - 29.48}{29.48} \times 100\% = 303\%$$

IV. DISCUSSION

A. *Kronosport All Electric vs. Fuel Cell Hybrid*

The driving range for the three test conditions were as follows: #1 Without the FC: 42.24 miles

#2 With the FC turned on: 118.75 miles

#3 With the FC present but turned off: 29.48 miles

This study considers the improvement of case #2 compared to case #1, 183% as the driving range improvement because this represents the actual improvement over a standard vehicle.

The manufacturer specifies a driving range of 25 miles when fully loaded, but the load does include the weight of the driver. However, the test drive yielded a range of about 30 miles with approximately 235 lbs of load and a range of 42 miles with the driver only. The increased range obtained during testing may be due to two main factors. First, a new battery bank was used. Second, the weight of the driver affects the performance of the vehicle, and the person who tested the Kronosport at the factory may weigh more than the driver at UT.

B. *Electrolyzer System Efficiency*

At peak power, the PV array is capable of producing about 6 kW, but the electrolyzer only uses 2 kW. Although a significant amount of power is not harvested, it also means that the electrolyzer will not use any power from the grid (except small amount for controls) unless the PV output drops below 2 kW. The original plan was to use a 7 kW electrolyzer, in which case part of the power would have always been supplied by the grid and the PV would have always been fully utilized at its peak power point. However, budgetary constraints made it necessary to choose the 2 kW unit instead of the 7 kW unit.

V. CONCLUSION

In summary, this research achieved the following goals. A system to generate hydrogen from solar power was designed and installed. A hybrid fuel cell/ battery system was successfully designed and built for the Kronosport, and this hybrid system increased the range of the Kronosport by 183%. The main impact of research is on the environment since it demonstrated that it is possible to use alternative energy technology to produce hydrogen for transportation. However, further advances in several areas such as hydrogen storage and fuel cell technology will be required for this type of system to become commercially viable.

Research in hydrogen storage is needed to provide higher pressure tanks that can fit on a vehicle. In addition, lower weight ion lithium batteries can be used instead of lead acid batteries. The ion lithium battery charge/discharge efficiency is close to 100%, whereas that of lead acid is only probably 80%. However, price is also a factor since lithium ion is much more expensive than lead acid. As stated earlier, another problem is that this FCcannot operate below 3 °C. However, the Kronosport could be winterized by adding a heater to warm the FC before it is started and while it is in operation.

Although the electrolyzer-FC system is good environmentally, it has a very poor efficiency since only approximately 23% of the PV output energy reaches the FC output. This is because about 50% of the energy is lost in the electrolyzer, and about 50% of that is lost in the FC.

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