DOE Final Scientific/Technical Report

Project Title: Direct Methanol Fuel Cell Power Supply For All-Day True Wireless Mobile Computing

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1 Executive Summary

PolyFuel has developed state-of-the-art portable fuel cell technology for the portable computing market. A novel approach to passive water recycling within the MEA has led to significant system simplification and size reduction. Miniature stack technology with very high area utilization and minimalist seals has been developed. A highly integrated balance of plant with very low parasitic losses has been constructed around the new stack design. Demonstration prototype systems integrated with laptop computers have been shown in recent months to leading OEM computer manufacturers. PolyFuel intends to provide this technology to its customers as a reference design as a means of accelerating the commercialization of portable fuel cell technology.

The primary goal of the project was to match the energy density of a commercial lithium ion battery for laptop computers. PolyFuel made large strides against this goal and has now demonstrated 270 Wh/liter compared with lithium ion energy densities of 300 Wh/liter. Further, more incremental, improvements in energy density are envisioned with an additional 20-30% gains possible in each of the next two years given further research and development.

2 Accomplishments

The primary goal of the project was to deliver fully a functional fuel cell system integrated into a laptop computer. PolyFuel has built 3 such systems and now has 8 months of operating experience with the complete systems. Demonstrations of these units have been conducted for DOE personnel at a meeting in Golden, CO in September, 2008 and at the Fuel Cell Seminar in Phoenix, AZ in October, 2008. Below is a table showing the original targets for the project as well as the current status.

Characteristic	Original Target	Current Status
Net System Power (Beginning of Life)	15 Watts	• 18 Watts
Operating Life	1000 hours	• 1800 hours demonstrated on stack • 160 hours demonstrated on system
Energy Density	325 Wh/liter	• Measured: 270 Wh/liter (current controls) • Projected: 300 Wh/liter (with controls adjustments – Note: achieved after project ended)
Ambient Temperature	5 to 40 C	• De-rating in power is required above 30 C
Orientation	Completely Independent	• Tilting to +/- 45 degrees is allowable • Design improvements required to reach full orientation independence
Noise level	40 dBA	• 43 dBA

3 Project Activity Summary

3.1 System Simplification Goal with Passive Water Recycling

In order to achieve the large gains in overall energy density set out in the objectives of the project, PolyFuel chose to develop a systems strategy of simplification and integration. The alternative path of working to miniaturize a conventional system could make incremental gains, but they are insufficient to reach the aggressive goals required for portable electronic devices.

Conventional DMFC systems typically are very large and complex because of the need to recover water from the cathode stream by condensing and separating it from the exhaust. In addition to the large condensing and separating components, an air compressor with a significant pressure capability is required to move the two phase (air and water) mixture on the cathode. This compressor is also large, loud, and power hungry, leading to a larger stack to power the peripheral components.

PolyFuel's first priority was to develop a unit cell that would recycle the required 1/3 of the product water internal to the Membrane Electrode Assembly (MEA). The half reactions of a DMFC cell are shown below.

Equation #1: Cathode: $6H^+ + 6e^- + 3/2\ O_2 \rightarrow 3\ H_2O$

Equation #2: Anode: $CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$

Of the three water molecules produced on the cathode, one needs to be recycled to the anode while two need to be vented. By internally recycling the water, PolyFuel is able to make a further large improvement in system simplification by running the fuel cell cathode entirely in the gas phase. This strategy permits the replacement of the high power air compressor with a low power fan that can provide both the cooling for the fuel cell and the oxidant air.

3.2 System Model

In order to facilitate the evaluation of several different design approaches as well as several different packaging options, PolyFuel developed three different, though related, models of the complete fuel cell system. The first model is used to predict the overall size of the system, its efficiency, and expected runtime, given the characteristics of the individual components.

The second model is able to do a complete heat transfer and fluid mechanics analysis for the fuel cell stack, based on gross external parameters such as cell aspect ratio, ambient temperature, and desired stack power. The second model iteratively adjusts the geometry of the cell, particularly the cooling passage dimensions, to balance the heat removal from the cooling fans with the heat generation of the fuel cell stack. This model can be used to evaluate multiple cases such as finding the optimal design for a particular packaging arrangement or predicting the required pressure and flow characteristics of the recirculation pump.

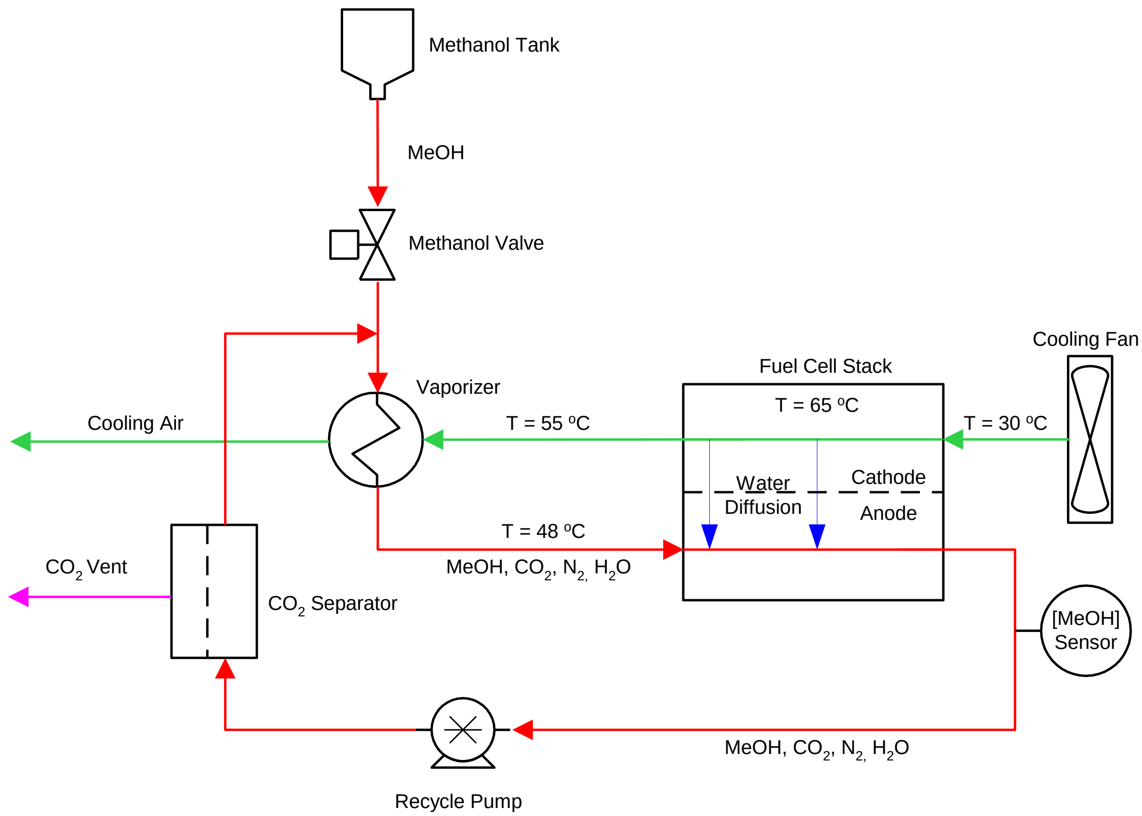
The third model is used to predict off design performance. Once a particular set of geometry is selected, the third layer of the model can be used to predict the performance of the system with different variants. For example, this model can examine the effect on fuel cell power and run time at different ambient temperatures or examine the effect on overall efficiency of the system with a reduced crossover membrane.

All three models are constructed in Microsoft Excel and are linked together. The most complex mathematics involves the use of curve fits for heat transfer and pressure drop in a rectangular channel for developing flow. These formulae were adopted from standard advanced texts in heat transfer and fluid mechanics. The outputs of all aspects of the model have matched remarkably well with the performance characteristics of the completed prototypes.

3.3 First Approach: Gaseous Anode

PolyFuel's first approach to making water diffuse back through the membrane to achieve water balance used gas phase methanol on the anode loop. The idea was to arrange the cell such that the water concentration was low on the anode and high on the cathode. The resulting diffusion gradient drove water back from the cathode to the anode. A barrier to water diffusion on the cathode was also put in place to direct the correct amount of water back to the anode at the desired operating point. See Figure 1 for a system diagram of this approach.

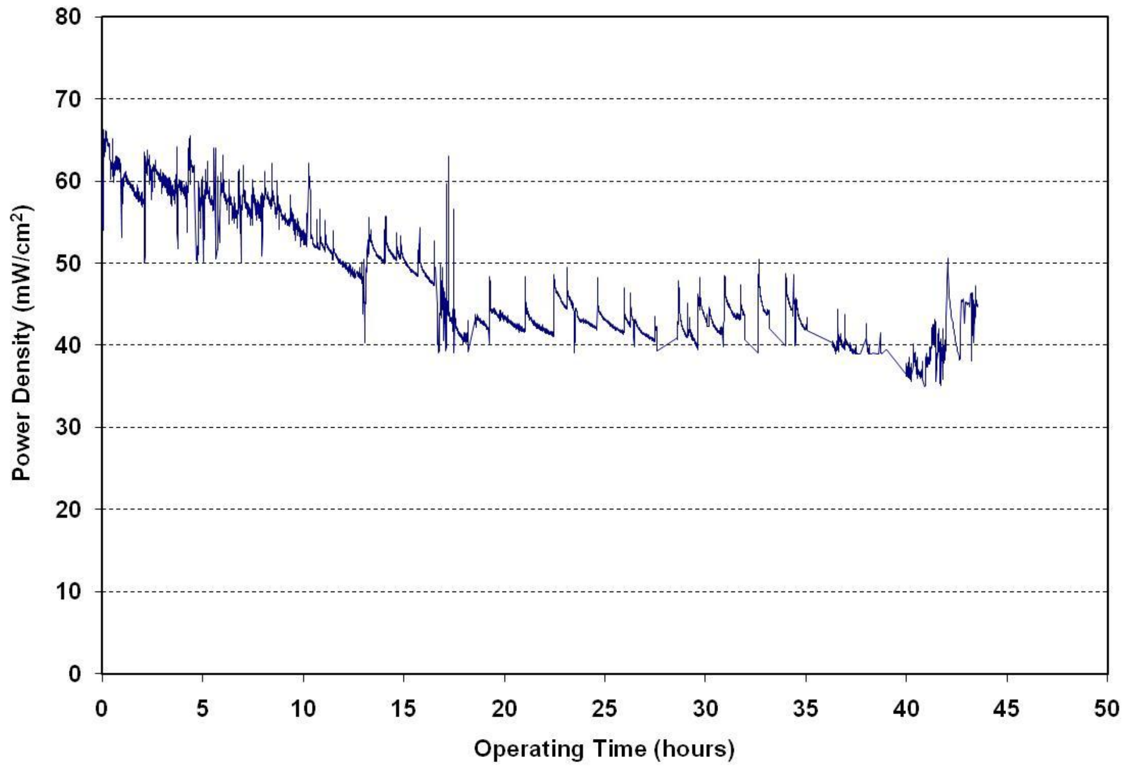
Figure 1: System Diagram for Gaseous Anode Approach



The mixture on the anode was recirculated so that the product carbon dioxide could be used to reduce the methanol concentration to acceptable levels for good cell operation. The range of methanol concentration of interest was from 1 mol% to 5 mol%. In this range, sufficient methanol was available within the cell for good current distribution throughout the cell active area without causing excessive methanol crossover.

The results of this first attempt were mixed. PolyFuel was successful at internally recovering water and transferring it directly in the MEA from the cathode to the anode and the initial power density was more than sufficient to build a complete system around, but the power degradation rate was severe. After only 40 hours of operation, the amount of degradation was such that the cell was considered to be below the threshold to progress further in the system design. Longer operation showed that the degradation continued and showed no signs of stabilization. See Figure 2 for a plot of the degradation rate.

Figure 2: Vapour Anode Cell with Internal Water Recovery Degradation



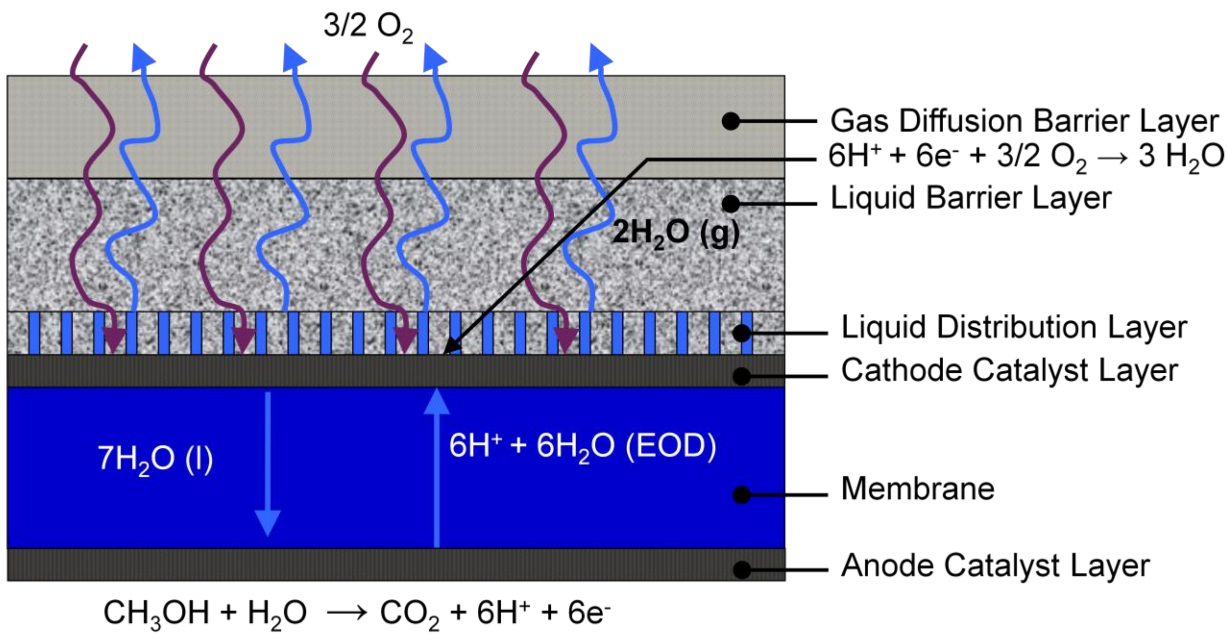
Investigation of the reason for the severe degradation showed that the conditions created on the anode to induce water transport were conducive to side reactions that inadvertently produced methyl formate in significant quantities. Methyl formate is always produced in small amounts in DMFC cells which use liquid water/methanol mixtures, but these cells using vapor phase water/methanol produced significantly more than conventional cells did. The methyl formate concentrations in the anode loop could range anywhere from 500 ppm to over 10,000 ppm, depending on the exact conditions. The methyl formate acted as a poison for the anode catalyst and reduced its effectiveness. Further investigation revealed that the low water concentration on the anode was responsible for the high rate of methyl formate production. Experts in DMFC catalysis were consulted but this phenomena was not known and solutions were not available. Ultimately, the degradation was deemed severe enough to abandon the gaseous anode approach in favor of a liquid anode.

3.4 Second Approach: Liquid Anode, Novel Membrane and MEA

The second approach to create a simplified overall system with internal passive water recovery involved a more conventional liquid fuel anode. The water recycling technique in this design is significantly different. In addition to using a diffusion barrier to limit the rate of water vapor egress, a high porosity, hydrophobic layer was added to the cathode to prevent any liquid water from exiting the cell cathode. A specially engineered membrane with low methanol transport, but high water permeability allowed the trapped liquid water to be pushed hydraulically through the membrane to the anode.

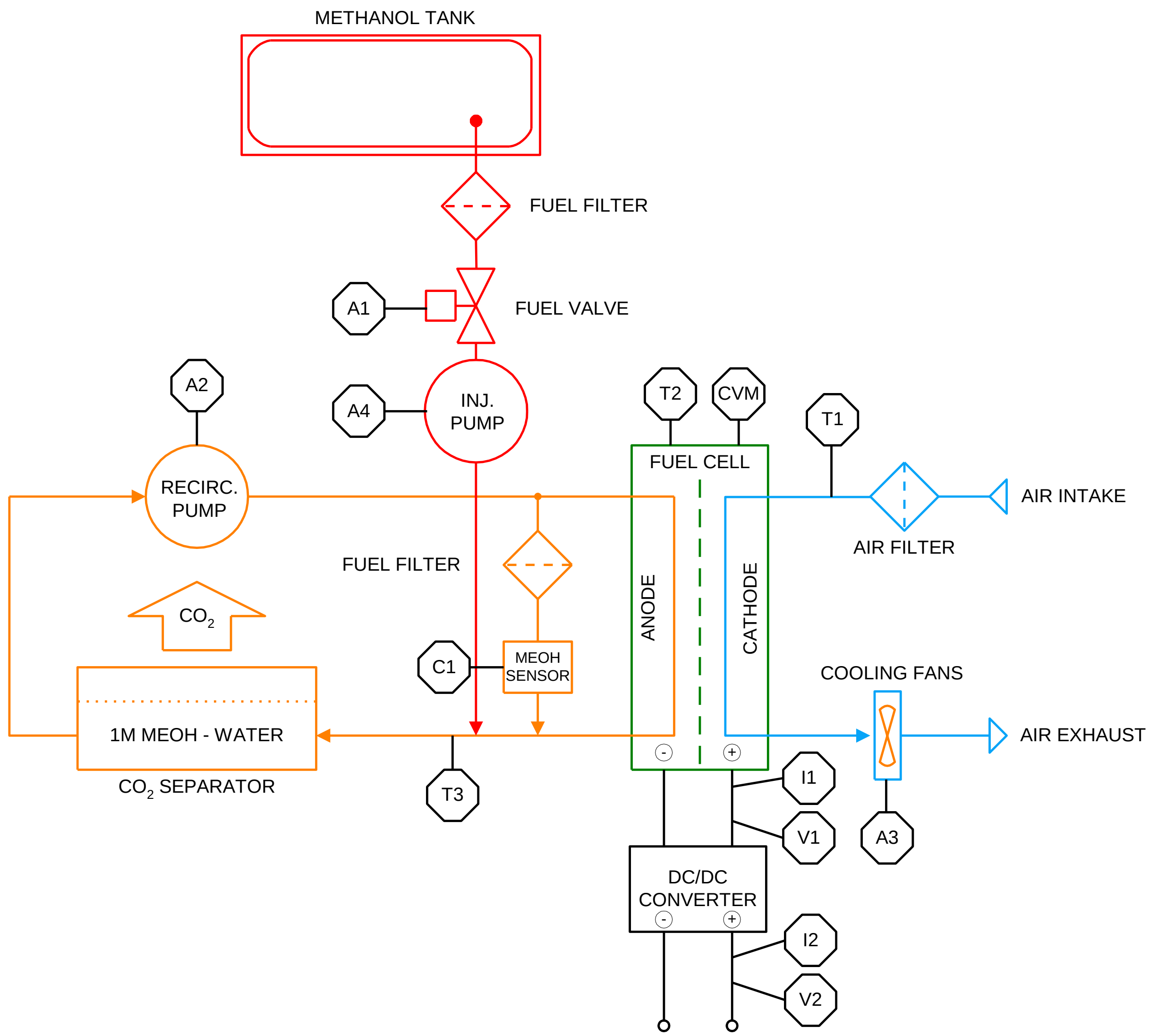
Figure 3 shows in greater detail the mechanism PolyFuel developed for passive water recovery in the second approach with a liquid anode flow field. Water is produced at the cathode and one third of this water plus all of the water arriving at the cathode due to Electro-Osmotic Drag (EOD) is sent back to the anode. In this way, enough water is available at the anode to support the anode reaction and provide for the ongoing EOD. Since water is only able to leave the cell as water vapour and the fraction of water in the vapour state is controlled by small adjustments to the fuel cell temperature. As the level of the low molarity re-circulation tank rises, the temperature is increased to compensate and vice versa.

Figure 3: Mechanism for Passive Water Recovery



A system schematic for the liquid anode concept is shown below in Figure 4.

Figure 4: Liquid Anode System Schematic



3.5 General System Description

The PolyFuel system has three fluid circuits that can be seen in the above diagram. The air is supplied to the fuel cell stack cathode by a pair of small fans after passing through an air filter as shown with blue lines in the figure. This air provides three functions for the fuel cell. Oxygen in the air is used as a reactant on the fuel cell cathode as shown in Equation #1 above. The channel geometry of the fuel cell stack cathode is a set of short straight passages that make the fuel cell look and act like an automotive radiator as shown in Figure 9 below. The air on the cathode is controlled to flow at a rate that will remove enough heat to control the temperature to the desired setpoint. The air flow required to cool the fuel cell is substantially more than the amount required to supply oxygen for the chemical reaction, so the cathode stoichiometry ranges from about 30 to about 200. The third function of the air on the cathode is to remove the product water. The MEA construction permits only vapor water to enter the fuel cell passages and the egress rate is controlled by the MEA geometry and the temperature of the stack.

The low concentration fuel loop is shown in Figure 4 in orange. To keep side reactions on the anode down to a minimum, to reduce the amount of fuel lost due to direct fuel crossover to the cathode, and to keep the membrane swelling to a reasonable level, the fuel entering the fuel cell cannot be pure methanol, but must be diluted with a significant amount of water. In fact, typical operation is much improved if the concentration of methanol is in the neighborhood of 3 wt% or 1 Molar. The water for the dilution and to participate in the anode reaction arrives from the cathode where excess amounts are produced. The fuel is re-circulated through the fuel cell where methanol is consumed and CO_2 is produced according to Equation #2. The two phase mixture is returned to the small re-circulation tank where the CO_2 bubbles are able to escape through the CO_2 separation membrane and are vented to atmosphere. A small fraction of the re-circulating liquid (about 3%) is diverted from the fuel cell and passed through a sensor to determine the methanol concentration in the liquid.

The pure fuel injection system is shown in red in the above figure. Pure fuel starts in the fuel tank and is pumped out of the fuel tank by a miniature pump through a filter and into the re-circulating low concentration fuel loop. A miniature valve is required to prevent the loss of methanol from the tank while the system is off. The fuel injection pump is operated in concert with the methanol sensor to keep the fuel concentration at the prescribed level.

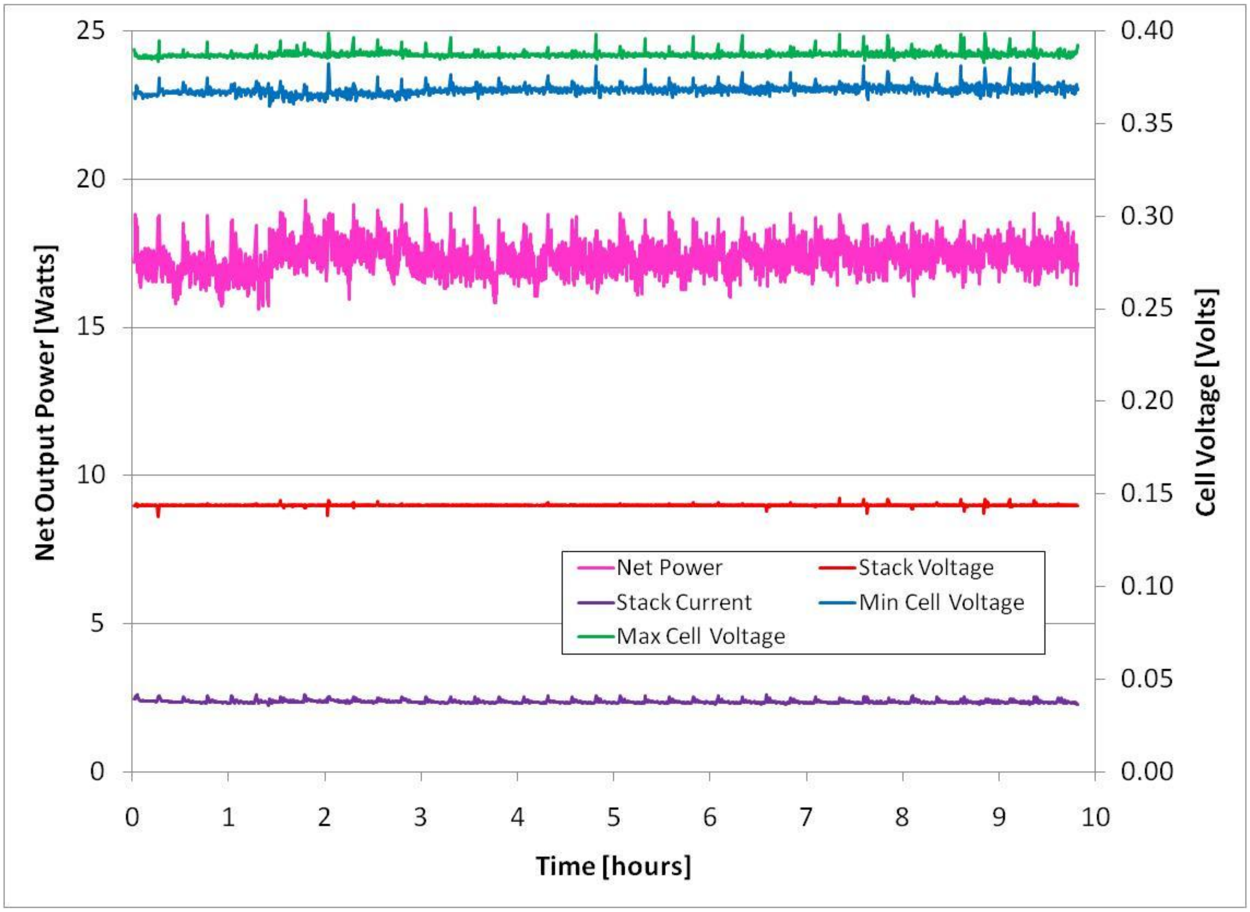
The system shown in the above schematic borrows ideas from both fully passive approaches that use no moving parts and from fully active approaches that use many components to regulate the fuel cell system. PolyFuel believes that this melding of approaches will yield designs that are suited to products in the range from 5 Watts up to 100 Watts. Devices requiring less than 5 Watts will need further simplification to achieve high power densities while devices over 100 Watts will benefit from the higher temperature operation that is possible with more conventional active systems.

3.6 System Operation

The fuel cell system is capable of excellent stable performance over long periods. The control system has to adjust the reactant flows in response to the current draw from the laptop computer and from the various sensors. Figure 5 shows the stable power output from the fuel cell system as well as the stable operation of the fuel cell stack. The individual cells are grouped quite tightly and the figure shows the spread between the lowest cell voltage and the highest among the 24 cell stack. PolyFuel typically sees a standard deviation of 10 mV for the 24 cell stacks during operation.

DMFC operation requires the use of periodic rests to rejuvenate the cells by removing contaminants from the catalyst surfaces. PolyFuel employs 20 second long rests every 10 to 15 minutes during which the fuel cell sees a sweep in potential. This rest regimen has proven to be sufficient to deliver steady performance, but PolyFuel believes there is room to optimize and improve on the exact algorithm. The figure below has had the potential sweeps during rests removed to provide greater clarity when viewing the graph.

Figure 5: System Stability During Single Cartridge Run



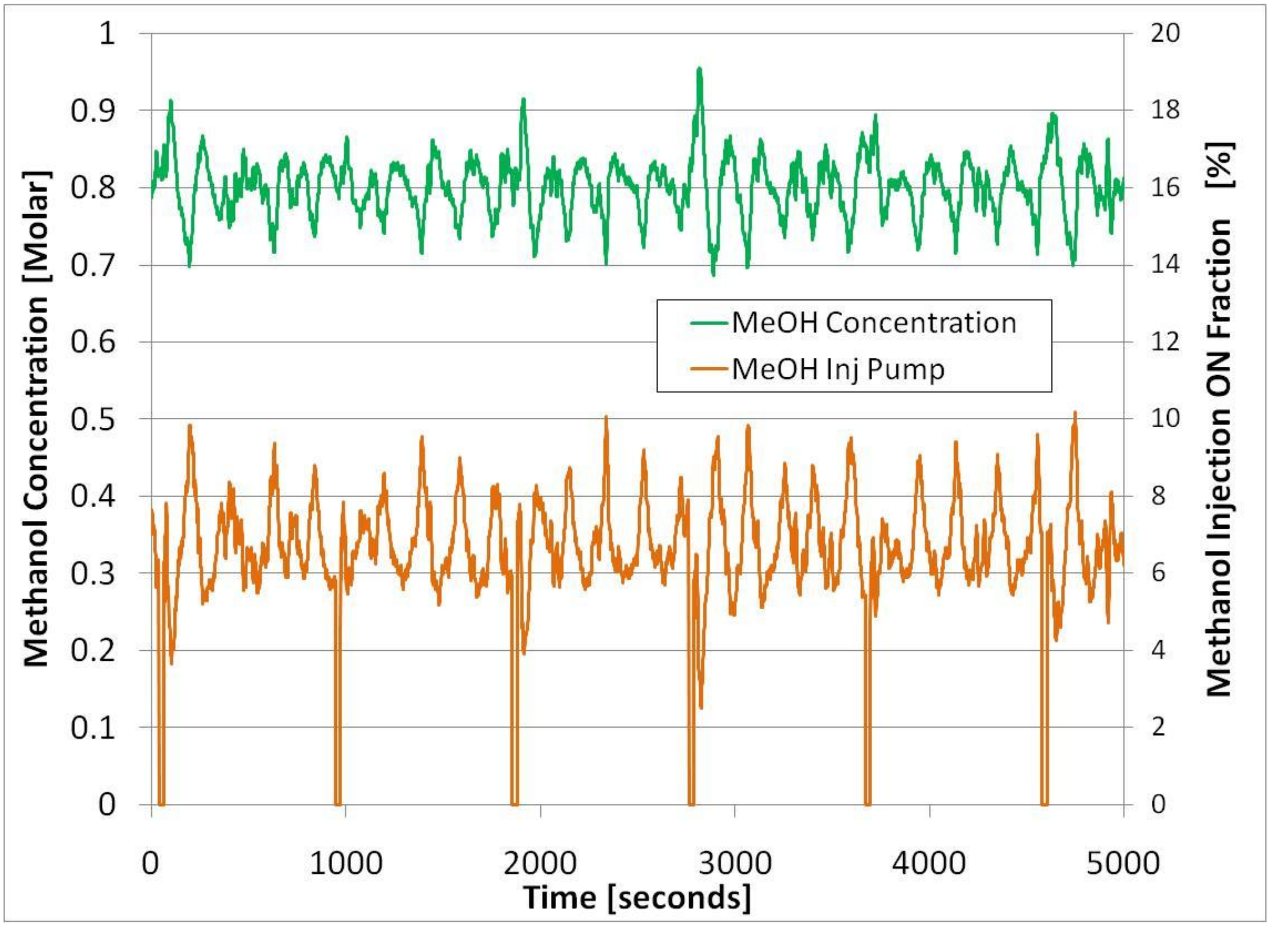
To run the fuel cell system, there are three simple control loops that adjust the system operation for steady performance. The three control loops are all PID based and control the following variables: methanol concentration, fuel cell stack temperature, and fuel cell voltage.

3.6.1 Methanol Concentration Control

The problem of methanol concentration control is miniature DMFC systems is difficult because the recirculation tank must be very small (holding about 10 cc). Without regular injections of pure methanol, the circulating fuel concentration would drop below usable levels in about 60 seconds. Fast sensor response and a well-tuned injection system are necessary for good control.

The fuel injection pump has a single fixed flow rate that is sized about ten times larger than required for normal operation. To control the fuel concentration, the pump is pulsed on and off with a period of ten seconds. Under typical operating conditions, the pump is on between 5% and 15% of the time. The controller uses a tuned PI type control with a feed forward term based on the fuel cell current. Since the fuel cell current is an excellent predictor for the usage of fuel, it works very well as a rough estimate for control with the proportional and integral terms used to fine tune the concentration. Figure 6 shows the fluctuations in methanol concentration as well as the duty cycle of the pump. During the test shown in the figure, the fuel cell was trying to maintain a concentration of 0.8 M. Fluctuations between 0.7 M and 0.9 M are observed and the long term average standard deviation in methanol concentration is about 0.035 M.

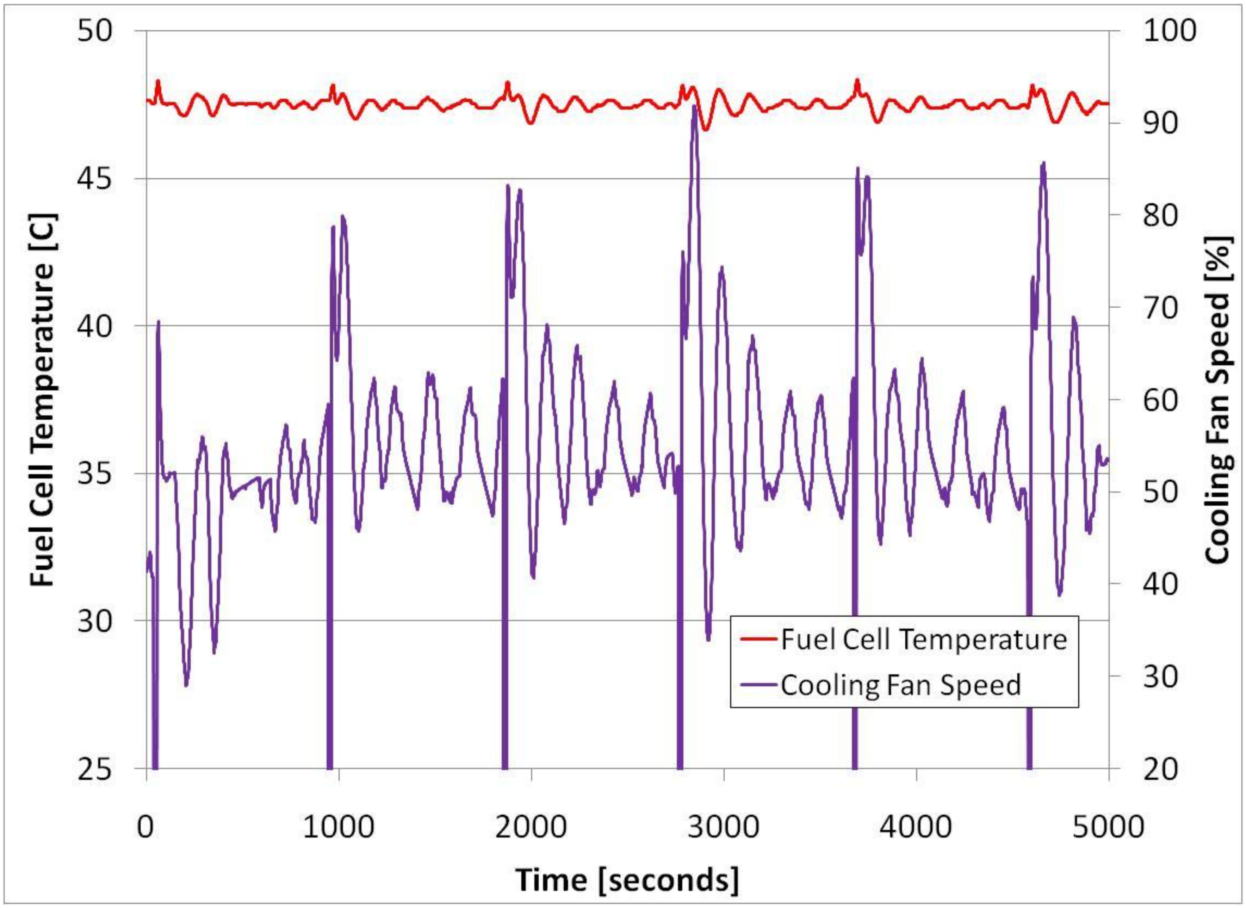
Figure 6: Methanol Concentration Control



3.6.2 Temperature Control

The fuel cell stack produces a substantial heat load (about 40 Watts) that must be removed while keeping the fuel cell stack at a temperature below that required for water neutrality. PolyFuel measures the fuel cell temperature with a thermistor and uses a pair of cooling fans to control the temperature. Temperature control to better than 1 ºC is important to maintain the water balance of the system. The cooling fans are speed controlled by adjusting the voltage applied to the fans using a simple PI control algorithm. The quality of the control is demonstrated in Figure 7. The periodic disruptions in the control that happen every 900 seconds are caused by the fuel cell rest periods.

Figure 7: Fuel Cell Temperature Control

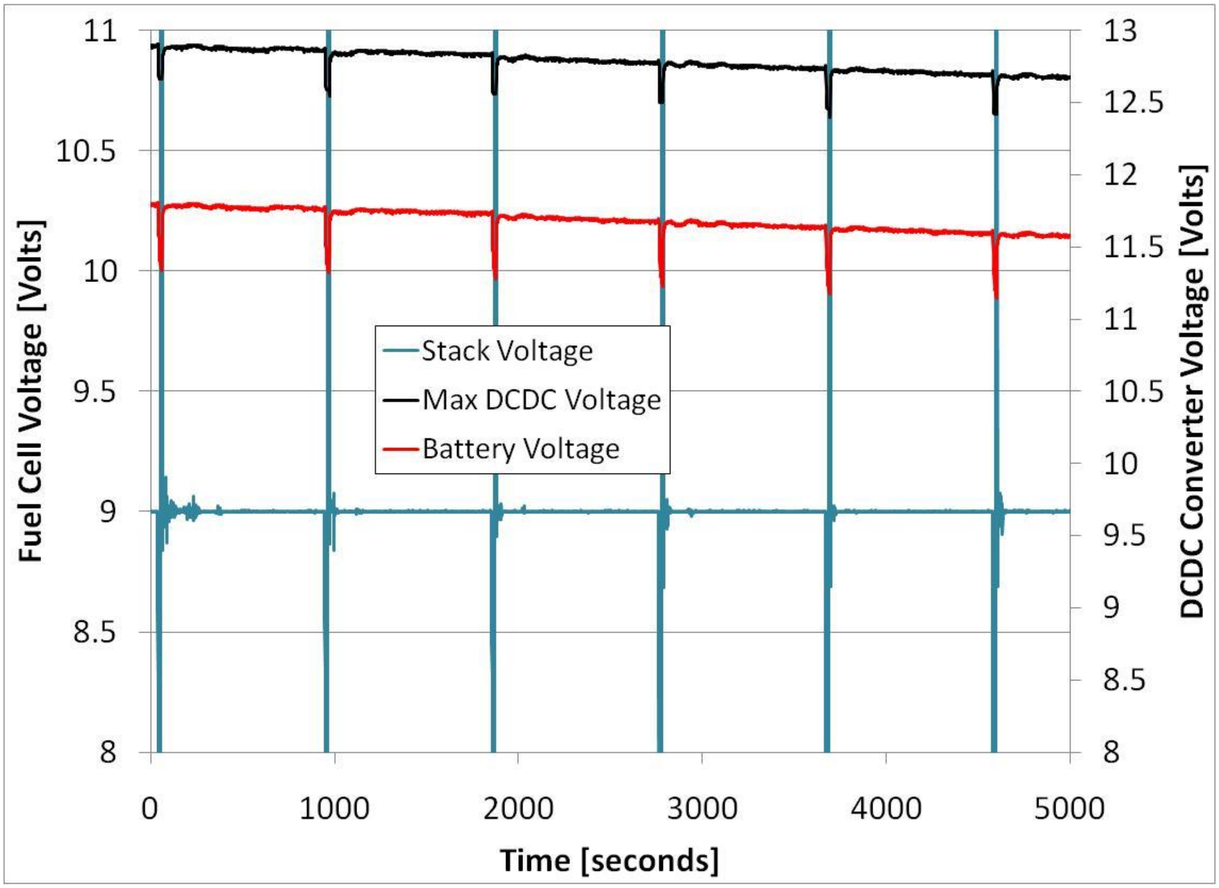


3.6.3 Fuel Cell Voltage Control

The fuel cell system is hybridized with a three cell lithium ion battery to provide power to the laptop computer. The fuel cell is intended to provide base load power with the battery providing startup power as well as peaking power during periods of high demand. During periods of low demand, the fuel cell recharges the battery. In order to limit the current out of the fuel cell and match the fuel cell system output voltage to the battery voltage, a current limited DCDC converter is used. As the fuel cell is capable of supplying more load, the current limit is increased and if the fuel cell has diminished capacity, the current limit is decreased.

In fact, since the important parameter in maintaining a healthy fuel cell stack is keeping the voltage from dropping too low, the control system limits the overall output current as a function of the fuel cell stack voltage. The current limit is adjusted with a PI controller to hold the fuel cell voltage constant. This is of particular importance during startup when the fuel cell is cold and has limited power availability, but it is desirable to warm the fuel cell stack as quickly as possible. See Figure 8 to see the operation of the voltage control algorithm. The periodic interruptions in the graphs occur during the fuel cell rest periods.

Figure 8: Fuel Cell Voltage Control

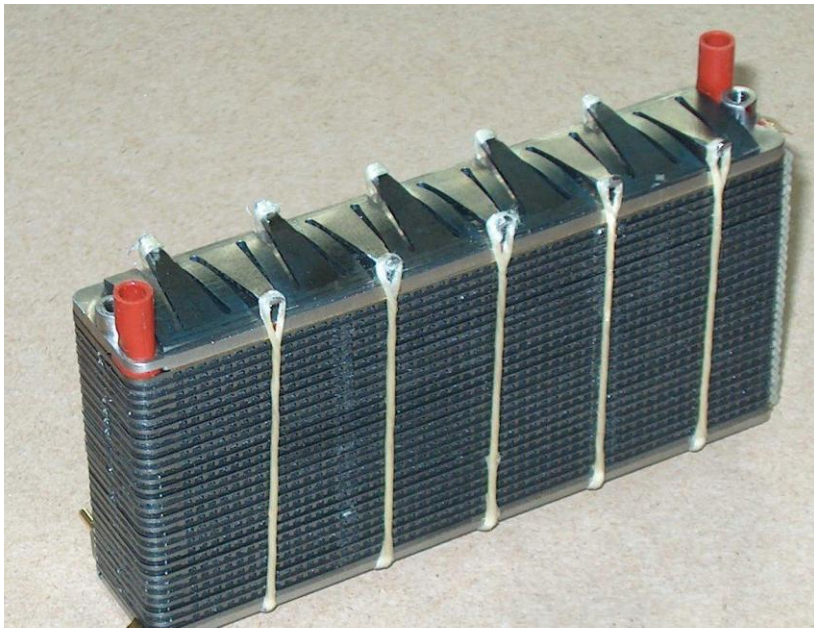


3.7 Detailed Description of System Components

3.7.1 Fuel Cell Stack

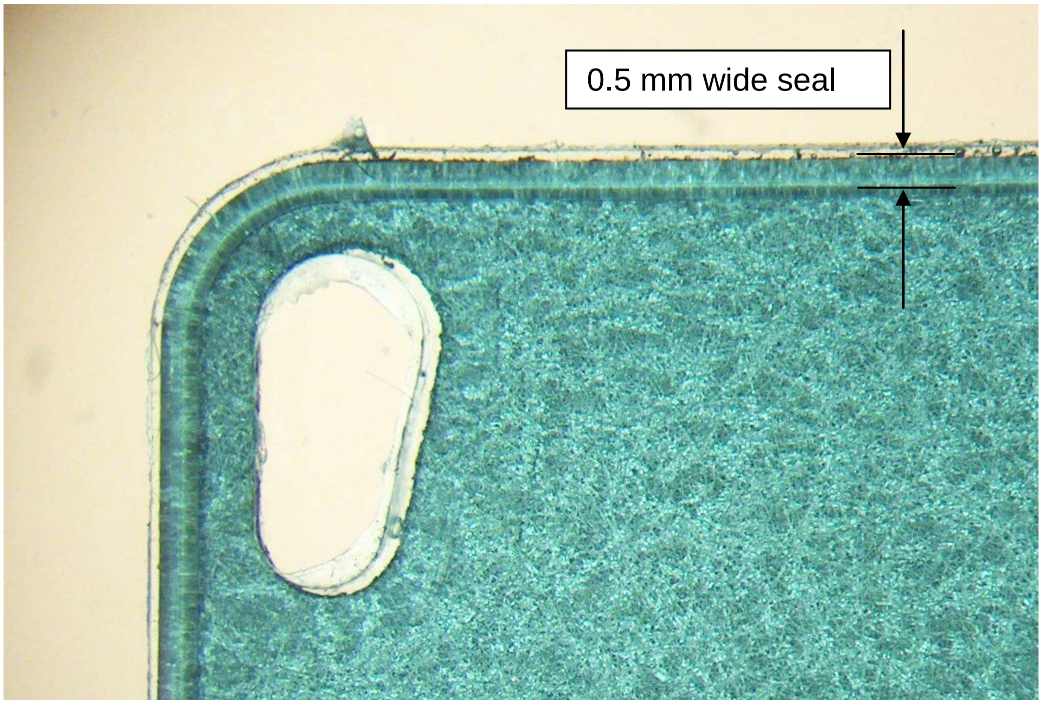
The fuel cell stack is a comprised of a set of alternating MEAs and bipolar plates sandwiched by corrosion protected steel endplates. The assembly is held together by a set of five thin straps which are in tension to hold the plates and MEAs in good compressive contact. A single custom spring is located on one end of the stack to apply the right compressive load. The spring and strap design was chosen to minimize the overall footprint of the compression system, leaving more room for the power generating portion. Two molded silicone tubes serve as the fuel inlet and outlet ports. See Figure 9 for a photo showing the fuel cell stack.

Figure 9: Fuel Cell Stack



In cells of this small size, seals around the perimeter must be as small as possible. PolyFuel has chosen a design that uses seals which are integrally molded onto the MEA so that seals with a width of only 0.5 mm are possible. The seal mates with a groove in the plate so that the seal compresses about 20% to 25%. The clear seal material is a liquid injection molding (LIM) compound that is injected into the seal mold at relatively low pressures. See Figure 10 for a close-up view of the seal design.

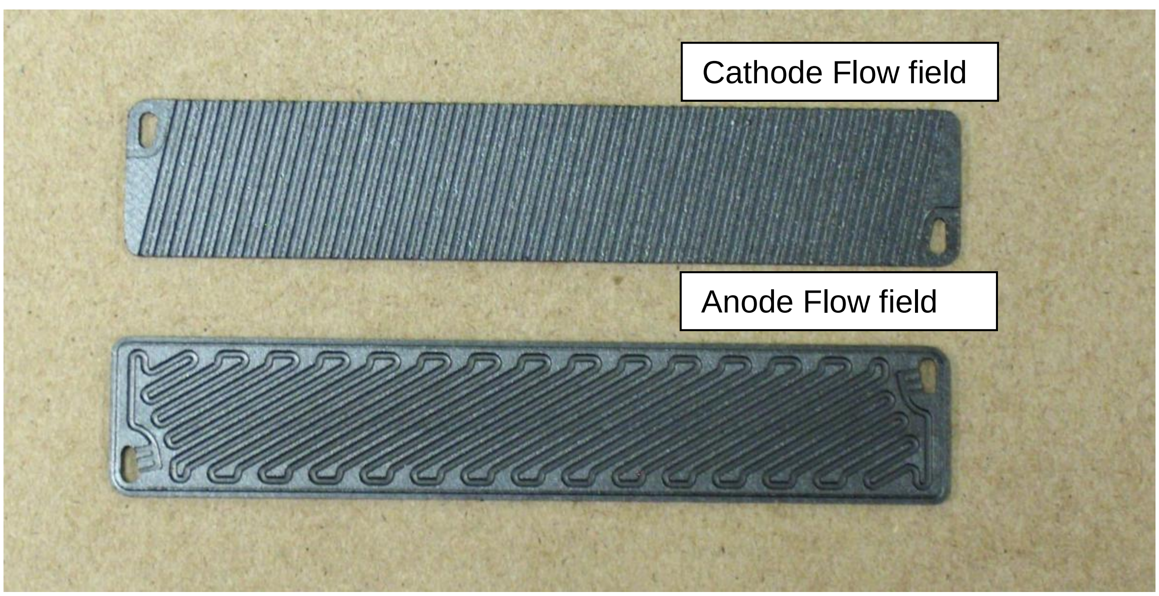
Figure 10: Close-Up of MEA Seal



The bipolar plates are machined from GraFoil material provided by GrafTech. A preliminary study indicates that with some small design changes the plates could be compression molded at high volume. The channels on the cathode side of the plate are chosen to provide adequate surface area for cooling while minimizing the required pressure losses from the cooling fan. The cathode channels behave very close to the predictions of the cooling model, including both the heat flux and the pressure drop.

The anode flow field is more difficult to predict analytically than the cathode because of the two phase nature of the flow. The fluid entering the anode is 100% liquid and transitions to two phase flow that becomes about 80% CO_2 by volume at the exit. The nature of the bubbles and the number of gas-liquid interfaces that develop in the channel dramatically affect the pressure-flow characteristics of the flow field. To build plates with the right flow characteristics, PolyFuel had to conduct tests on several candidate designs to complement the rough theoretical predictions. PolyFuel's tests indicate that a single serpentine channel on the anode has the best flow distribution, based on stoichiometry sensitivity tests. Single serpentine channels allow lower stoichiometry operation than other possible designs. See Figure 11 for a view of the final anode and cathode flow channel geometry.

Figure 11: Anode and Cathode Flow Channels



The two critical and innovative components for this fuel cell design are the hydrophobic, low porosity gas diffusion layer (GDL) and the membrane that permits reverse water transport. PolyFuel collaborated on the development of the gas diffusion layer with two companies: Ballard Material Products and SGL Carbon. Both understood the specification required by the design, however, for their own business reasons, neither was willing to commit resources to undertake the R&D required at this time. PolyFuel developed the ability to make prototype quantities of the coatings applied to commercial GDL substrates.

PolyFuel developed four quality control tests to make sure the mass transport properties were correct. These tests include the following:

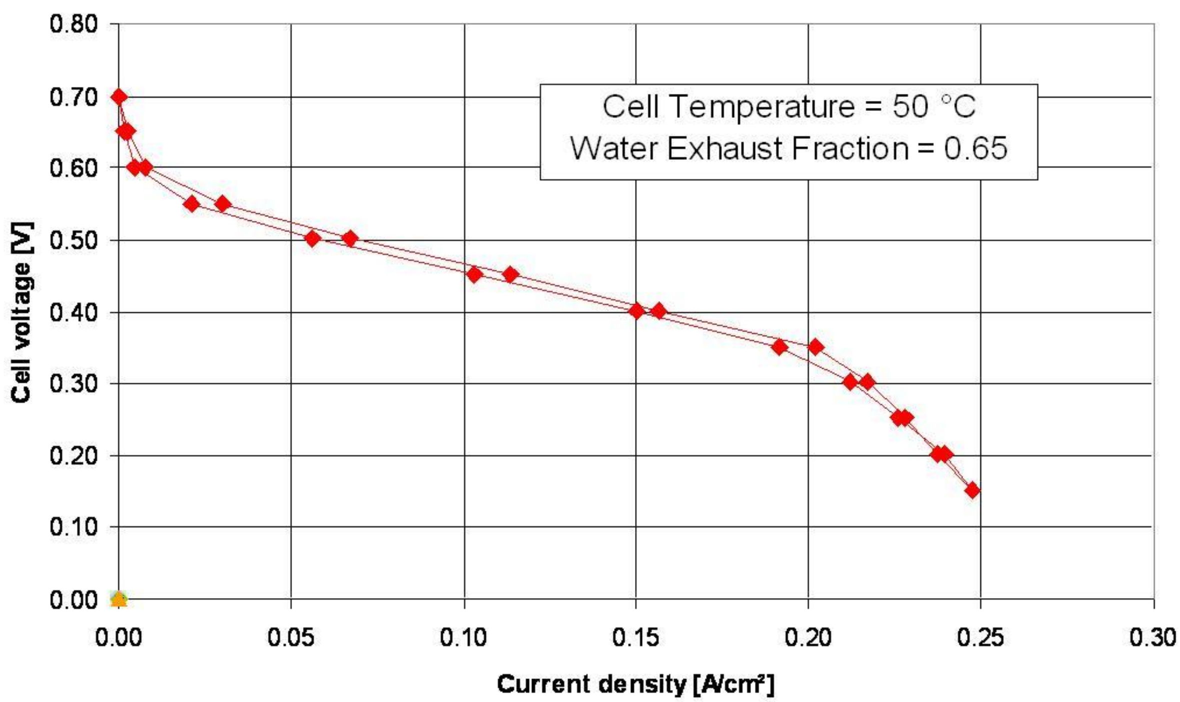
1. Water vapor diffusion rate measurement
2. Liquid water capillary pressure measurement
3. Qualitative measure of areal distribution of diffusion
4. Measurement of the degree of hydrophobicity

In addition to core fuel cell components, several system components were either purchased or designed by PolyFuel internally.

3.7.2 Fuel Cell Stack Performance

A typical polarization of the PolyFuel stack is shown in Figure 12 below.

Figure 12: Fuel Cell Polarization Curve



3.7.3 Recirculation Pump

PolyFuel examined and tested recirculation pumps from several different vendors using the following basic specifications:

1. Flow rate greater than 30 cc/min
2. Operating pressure greater than 2 psig (14 kPa)
3. Power consumption below 1.5 Watts
4. Physical size less than 15 cc

5. Able to quickly self prime with air

PolyFuel was unable to find liquid pumps that were small and efficient enough for use in the power supply. In fact, several of the 8 pumps that were evaluated were not able to effectively prime with liquid when initially full of air. None of the pumps came within a factor of two on either the size requirement or the power consumption requirement. PolyFuel made the decision to develop its own prototype pump to fill the gap in available parts.

The newly developed pump has a simple principle of operation and is sized for our application. Two coils of wire surround a magnet containing piston. The 3.8 mm diameter piston oscillates back and forth as the coils of wire are energized and de-energized in sequence. The overall stroke length of the piston is about 8 mm and the oscillating frequency is about 10 Hz. The pump uses two pairs of rubber valves to construct a double-acting pump. A drawing of the pump is shown in Figure 13 below. The pair of drive coils is not included in the figure to show the design in more clarity, but they would be wrapped around the piston sleeve. A photo of the pump is shown in Figure 14 with the green outer iron sleeve remove to expose the coil windings for viewing.

Figure 13: Drawing of the Fuel Re-Circulation Pump

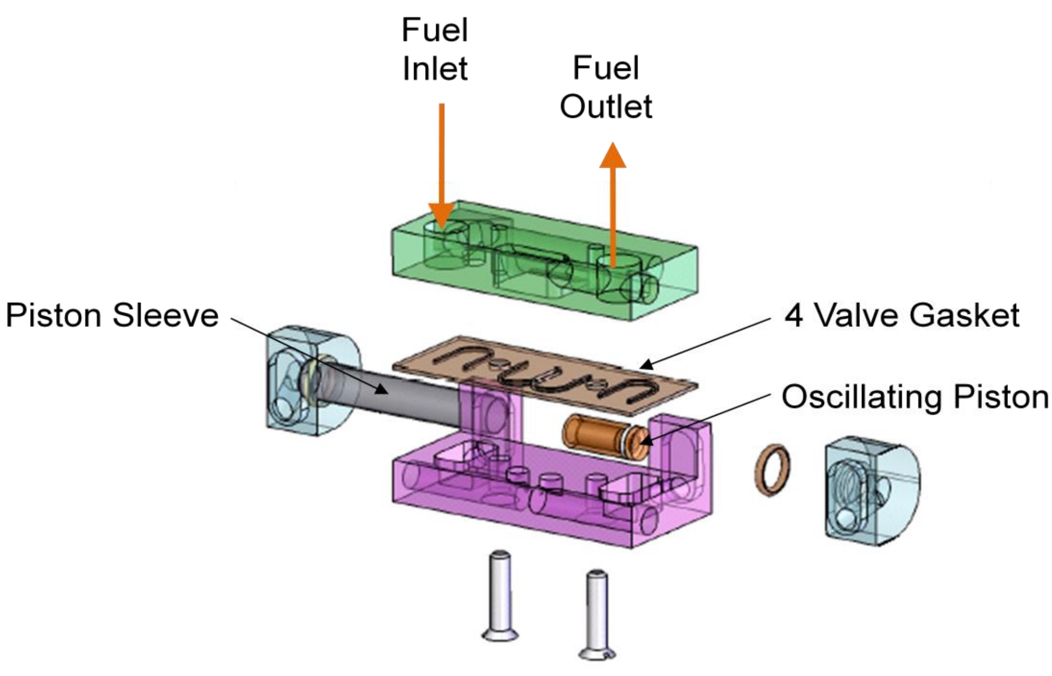
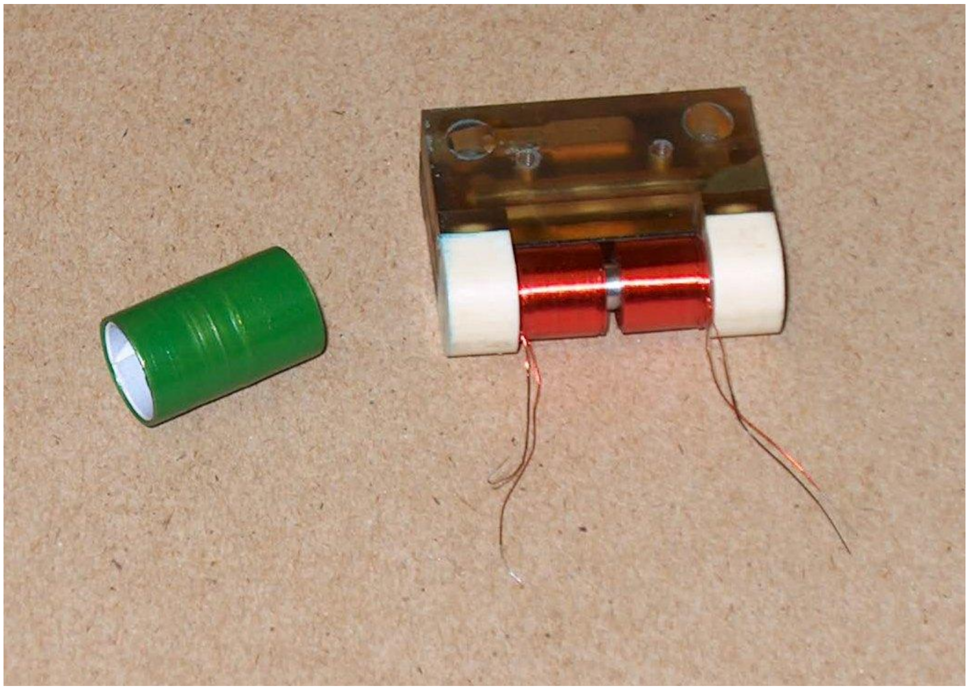
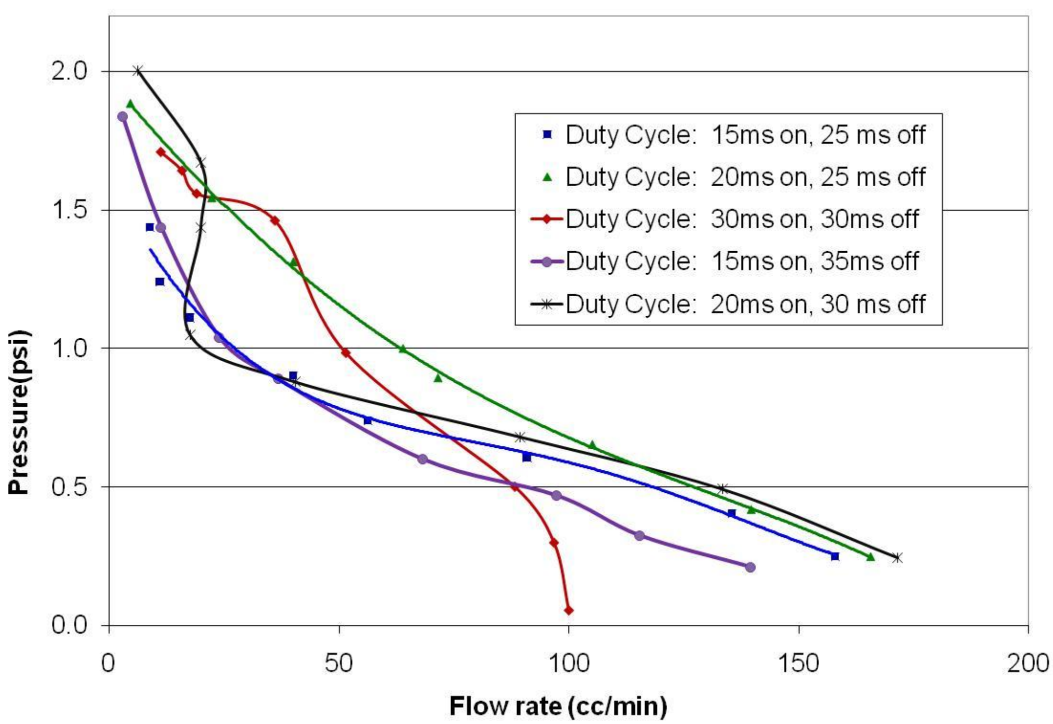


Figure 14: Photograph of the Re-circulation Pump



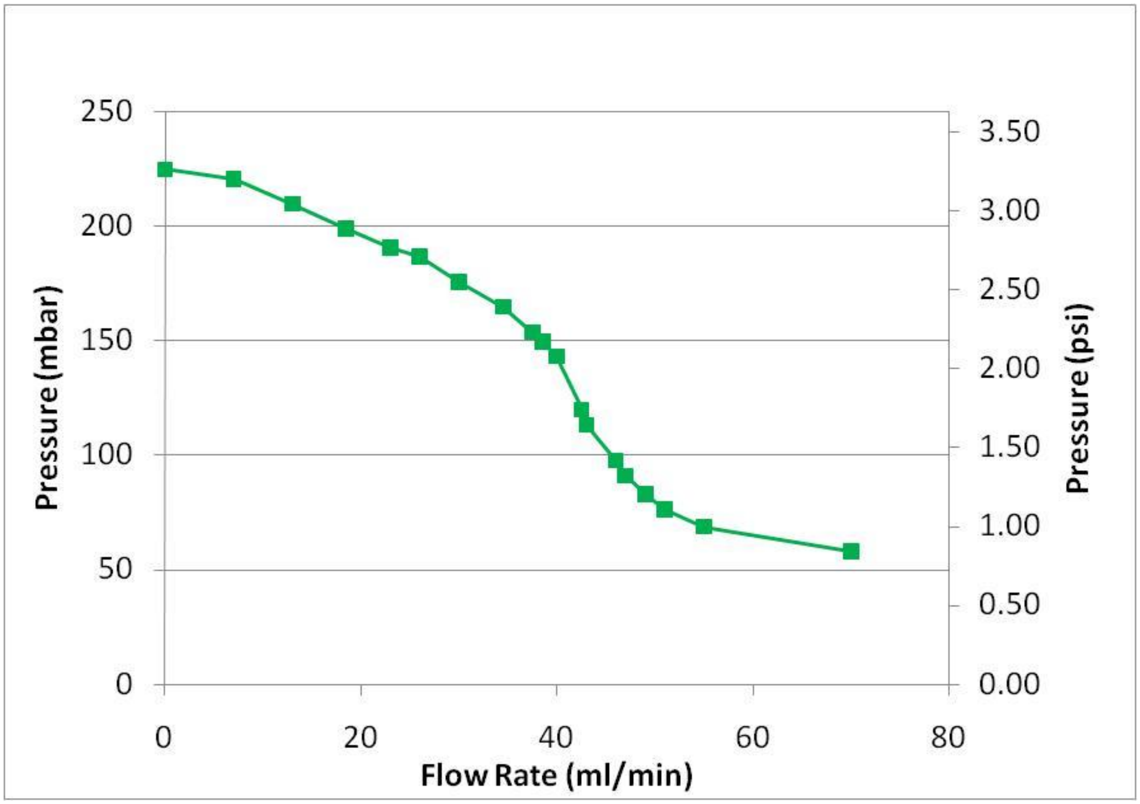
By changing the amount of time each of the coils is turned on, a performance versus efficiency trade-off was realized. In general, turning the coils on for a longer fraction of the period enabled a higher operating pressure, but consumed more power. A sample of data showing the effects of different pulse times is shown in Figure 15. This data is from a pump that provided higher flow and lower pressures than the targets.

Figure 15: Experiments Characterizing the Coil Energizing Times



The optimized PolyFuel pump is able to move 40 cc/min at 2 psi (14 kPa), occupies 7.5 cc of space and uses 750 mW to operate. A chart showing the optimized performance of the pump is shown in Figure 16.

Figure 16: Performance of Optimized PolyFuel Re-circulation Pump



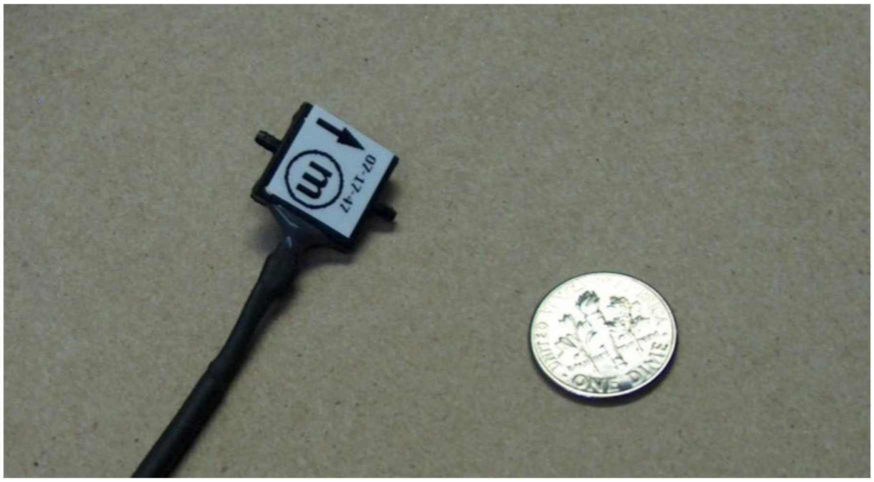
3.7.4 Fuel Injection Pump

The fuel injection pump is required to pump an absolute minimum of 250 µl/min at 2 psi in order to meet the fuel consumption of the fuel cell system under normal operating demands. A significant additional margin is required to be able to purge the fuel lines of air and get the initial burst of fuel into the fuel cell stack during the startup sequence. Three different candidates, all of which are piezoelectric devices, were tested for performance and ability to self prime from completely dry conditions. The most difficult test faced by the pumps was the self-priming test. Two of the pumps were able to deliver adequate or even exceptional performance when prefilled with liquid, but were not able to pull even a small vacuum to self prime when initially filled with air. The piezoelectric devices present a small challenge to power in that they require 200 V peak-to-peak at frequencies in the 50 to 100 Hz range. PolyFuel uses a standard electroluminescent display driver to produce a small amount of current at such voltages.

A pump from Bartels Microtechnik was selected as the best available candidate. It is capable of delivering 1.5 mL/min at 2 psi while using only 50 mW of power.

During longer term testing, the pump has had difficulty with self priming after being allowed to stand for several days. PolyFuel anticipates that the next generation of pump from Bartels Microtechnik, due to be released in early 2009, will address this outstanding issue. See Figure 17 for a photograph of the fuel injection pump. A dime is included in the photo for a sense of scale.

Figure 17: Fuel Injection Pump



3.7.5 Fuel Concentration Sensor

The fuel concentration sensor is a purchased part from ISSYS and is capable of measuring concentrations from pure water to pure methanol with an accuracy of about 0.1 Molar while consuming only 50 mW of power. The sensor is a MEMS device that measures the density of the fluid in the sensing element. The resonant frequency of a miniature vibrating tube is used to determine the fluid's density to a level better than 0.6 mg/cm^3. Complications arose during the initial integration of the sensor into the overall system as CO_2 bubbles produced on the fuel cell anode caused wild fluctuations in the density measurements as they passed through the sensor. Careful software filtering of the data from the sensor is used to eliminate data cofounded by bubble presence. The sensor is adequate for the purposes of this prototype, but the size and cost of the sensor will need to be reduced substantially to be used in a commercial product. See Figure 18 for a photo of the concentration sensor.

Figure 18: Photo of Fuel Concentration Sensor

3.7.6 Liquid Level Sensor

For the fuel cell to run for long periods, the amount of water in the liquid reservoir needs to be maintained. The control system generally tries to keep the reservoir about half full by adjusting the temperature of the fuel cell stack. As the temperature is raised, water will gradually leave the reservoir; when it is lowered, water will gradually accumulate in the reservoir. This very slow control loop requires a miniature level sensor with an accuracy of only about 10% or so.

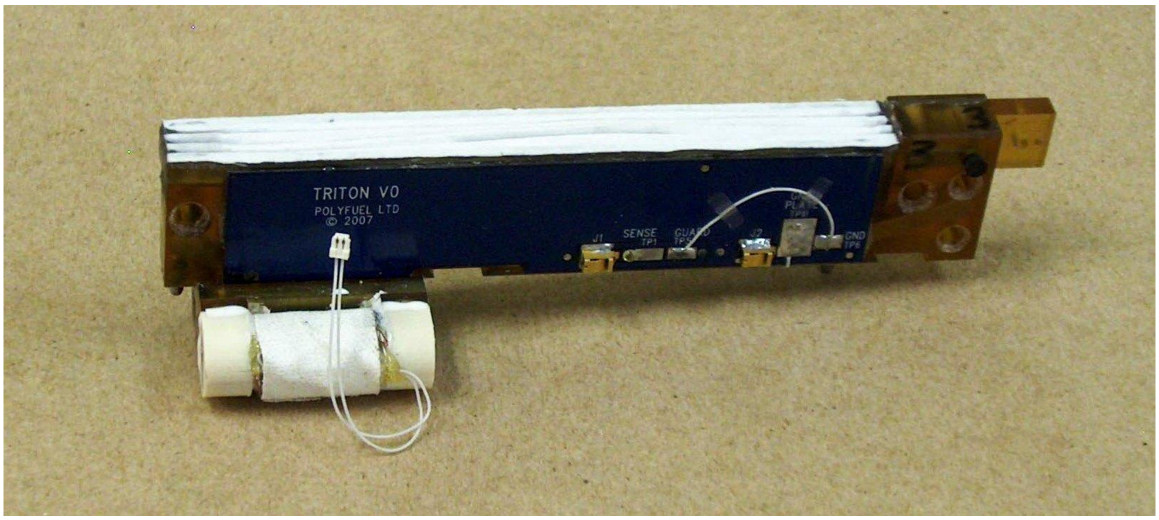
Two approaches were developed and prototyped during the project. The first was a simple capacitive sensor. Both sides of the liquid tank were covered in copper, forming a capacitor across the tank. More fluid in the tank increases the dielectric between the plates and increases the capacitance. A simple oscillator circuit was set up and the microprocessor measured the oscillation frequency to determine the capacitance. The base capacitance of an empty tank is about 6 pF while that of a full tank is about 12 pF. Measuring such low capacitances is tricky, but not impossible to do. A third conductive plate was required as a “driven shield” outside one of the capacitor plates. This plate acts to reduce noise from outside the system that can influence the capacitance measurement such as nearby components or other nearby objects such as fingers.

In general, this strategy works quite well, but had a significant problem with drift with both time and temperature. Relative measurements were good at any given time, but the drift over long periods caused measurement errors beyond the required specification for the sensor of +/-10%. Efforts were made to reduce the thermal effects, but a large amount of the temporal drift was not possible to eliminate.

The second sensor type operates on the principle that the low molarity solution in the tank conducts electricity significantly better than air. An electrified wire (5 Volts) is placed in contact with the solution at the bottom of the tank and a series of 30 pads at different heights up the side of the tank on the opposite side. Any of the pads that are submerged encourage a small current to flow from the electrified wire. The pads are connected to a comparator which digitally switches when the minute current is detected. The number of pads that are activated is a measurement of the level of liquid in the tank.

This second sensor type has been far more robust and stable due to its digital nature, but is more difficult to mass produce. The digital nature of the sensor also requires substantial filtering of the signals to produce a smooth, slowly varying measurement of the tank level. A photo of the capacitive sensor is shown in Figure 19.

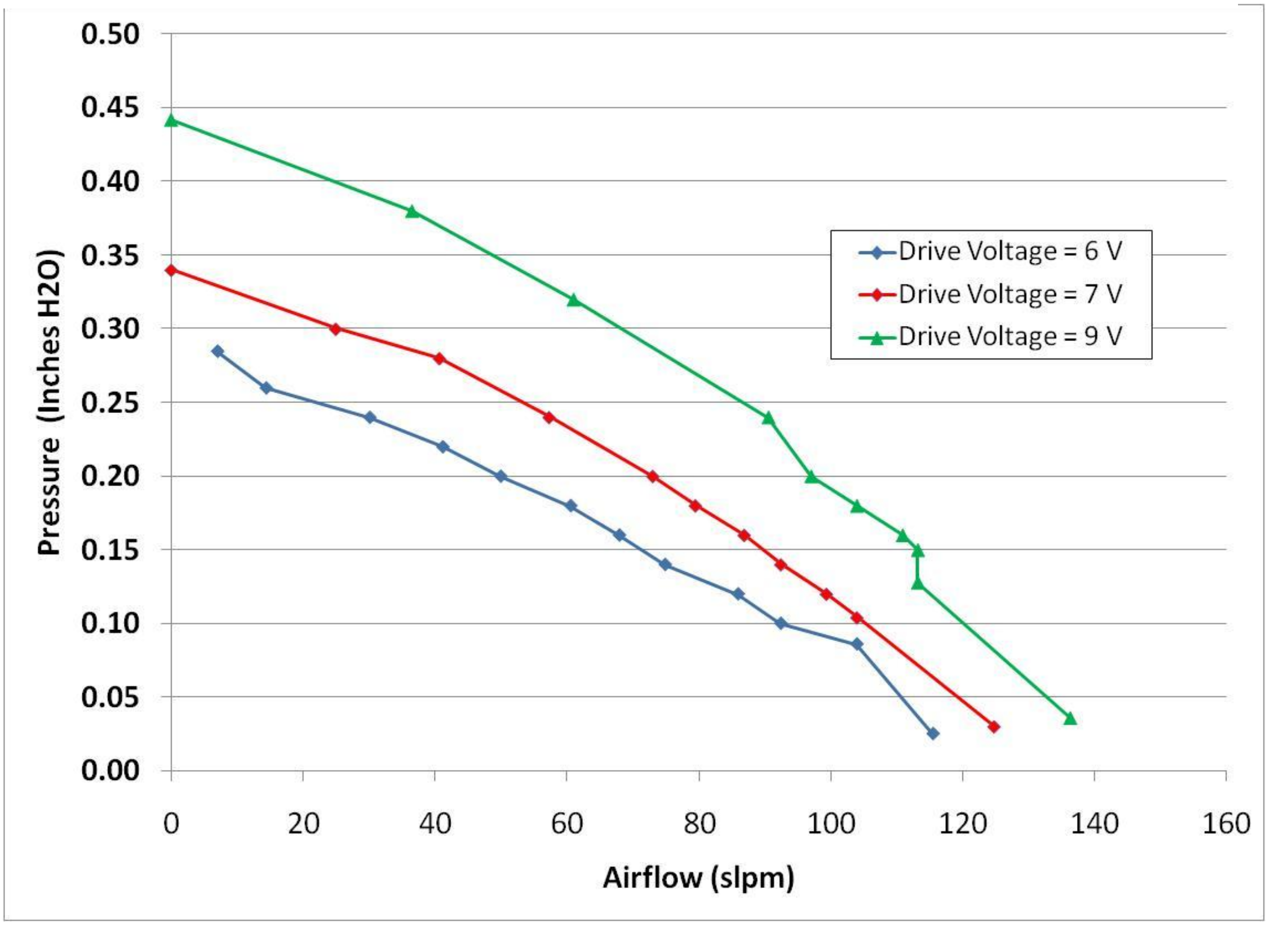
Figure 19: CO_2 Separator with Recirculation Pump and Level Sensor



3.7.7 Cooling Fans

The cooling fans are commercial laptop parts that are capable of 100 slpm at 0.2" H_2O. Using two of these fans, this air flow is adequate to cool the fuel cell to its operating temperature of 50 °C in an ambient environment up to 30 °C, the specification limit for most commercial laptop computers. It is desirable to improve the cooling system in future designs to reduce noise (the fans are the largest contributor) and expand the operating window. The challenge will be to improve the cooling while simultaneously decreasing the package size. Since good temperature control (to within 0.5 °C) is important in the PolyFuel design, the fan drive voltage is varied continuously using PID control to maintain the correct temperature. Figure 20 shows the characteristic fan curves for fans operating at different voltages. These characteristic curves are used in the thermal model to predict the thermal limits of the fuel cell system as well as assess the parasitic load of the fans.

Figure 20: Fan Characteristic Curves



3.7.8 CO_2 Separator

The CO_2 separator is a specialty membrane purchased from Donaldson that permits the release of the product CO_2 without the release of liquid solution. About 30 cm^2 of membrane is required to vent all of the CO_2 produced by the fuel cell.

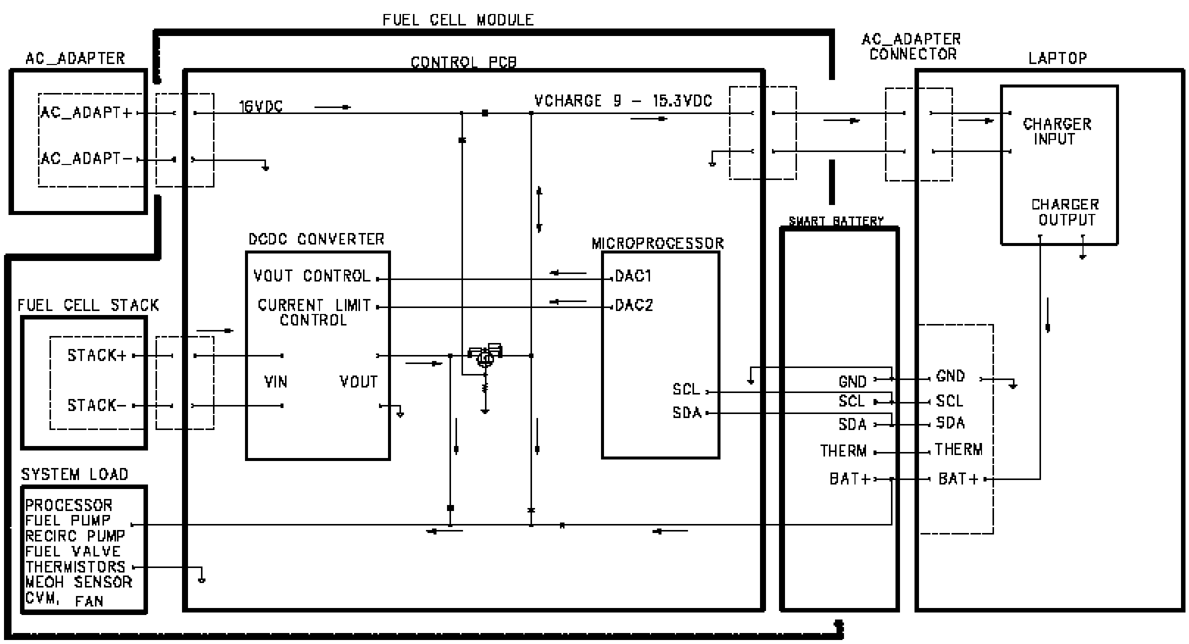
3.7.9 Controls

The control card is a custom circuit board developed by PolyFuel. The control card has two major power delivery functions: to co-ordinate the power flow from the battery and the fuel cell in a hybridized fashion and to condition the wide voltage range delivered by the fuel cell into the correct voltage required to power the computer.

During startup, the battery provides power to the computer so the user experiences no delay in starting that is required by the fuel cell. A small amount of power is diverted from the battery to inject fuel and air into the fuel cell to start the fuel cell system. The fuel cell is typically capable of delivering near full power within 2-3 minutes and takes over delivering the base load from the battery. Since large power spikes that are beyond the fuel cell's capability are possible in the computer, the battery is required fill the gap with short, quick discharges. During periods of low power usage, the fuel cell automatically recharges the battery. Once the battery is completely charged, the fuel cell is turned off for a period of time until the battery is discharged by 25% to 30% to allow space in the battery for excess fuel cell power.

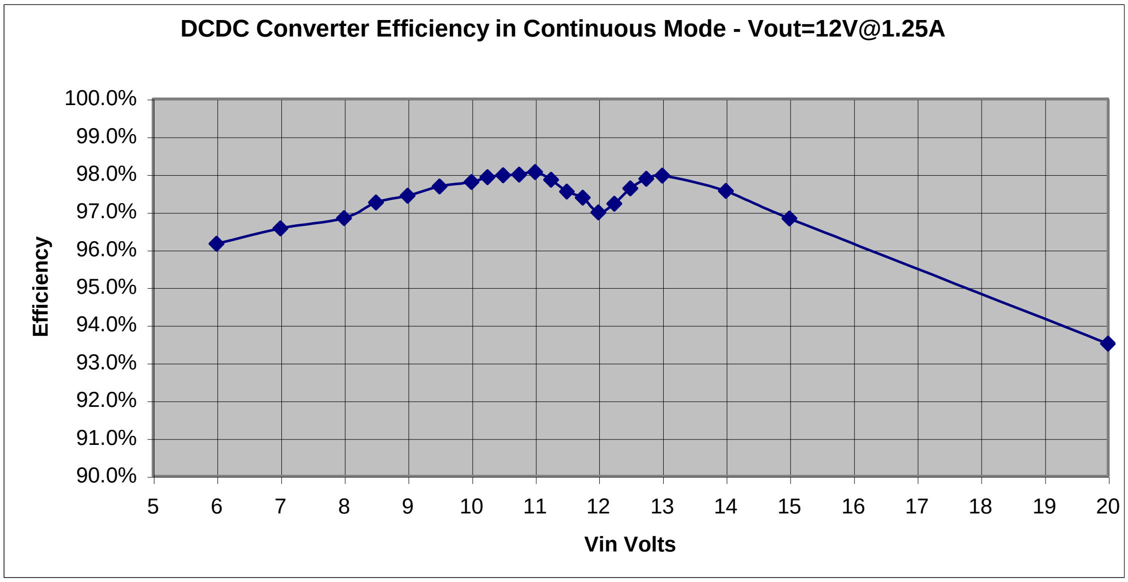
The second power function, to convert the wide voltage range from the fuel cell into a usable voltage range for the computer, is achieved with a high efficiency DC-DC converter with a wide input voltage range. The input window for the DC-DC converter is from 6 to 24 Volts and the output voltage range is from 8 to 12.6 Volts. The DC-DC converter also has an electronically adjustable voltage setpoint and an electronically adjustable current limit. The combination of these features permits automatic battery charging while making sure the fuel cell stack is never overloaded. Figure 21 shows the power flow and communications arrangement among the battery, fuel cell, and laptop.

Figure 21: Block Diagram Showing Power Flow



The DC-DC converter efficiency exceeded the ambitious goal of 95% at the nominal operating point at the start of the project. The final DC-DC converter configuration achieves an efficiency of over 97% in the output voltage range of use to the fuel cell system. See Figure 22 for test data showing the DC-DC converter efficiency over a wide range of input voltages. The efficiency is of high importance in the range between 8 and 11 Volts.

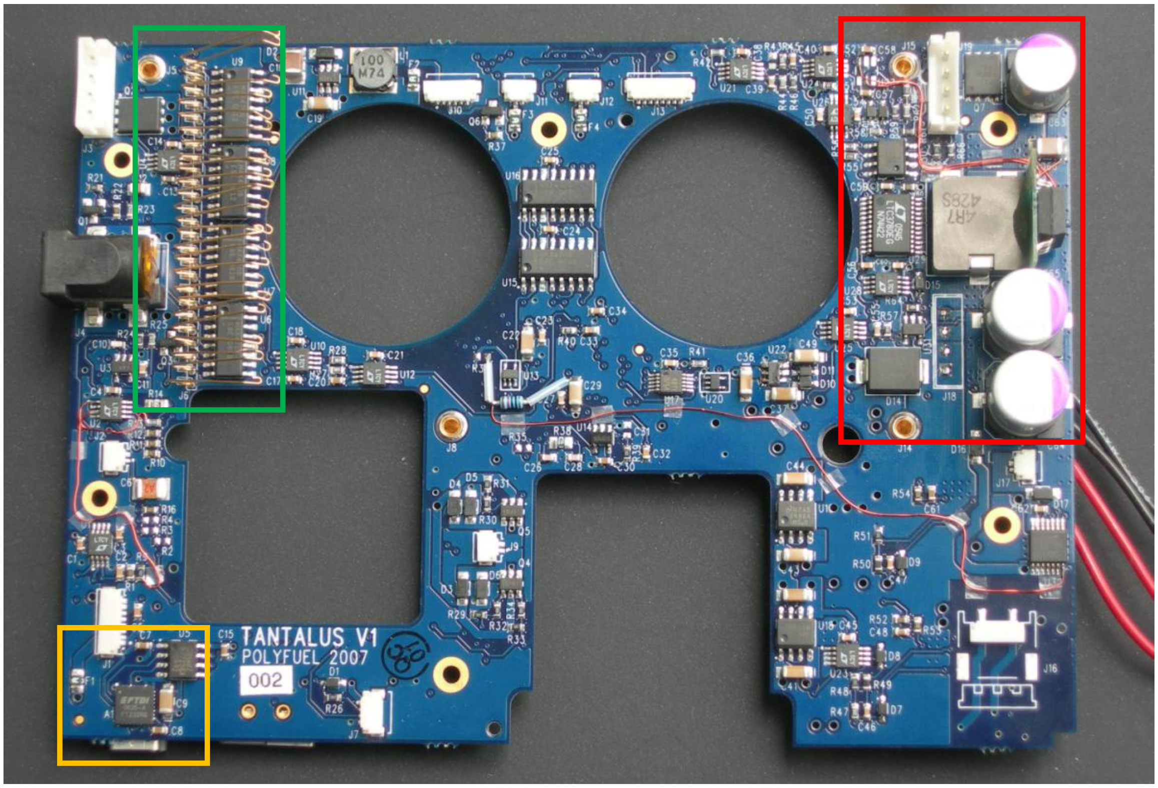
Figure 22: DC-DC Converter Efficiency Over a Range of Input Voltages



In addition to the power conditioning functions described above, the control card is responsible for controlling the fuel cell system. It has inputs to measure temperatures, voltages, currents, and methanol concentration and outputs to control fan speed, recirculation flow rate, methanol injection flow rate, and the rate of battery charging. The full Process and Instrumentation Diagram (P & ID) is shown in Figure 4.

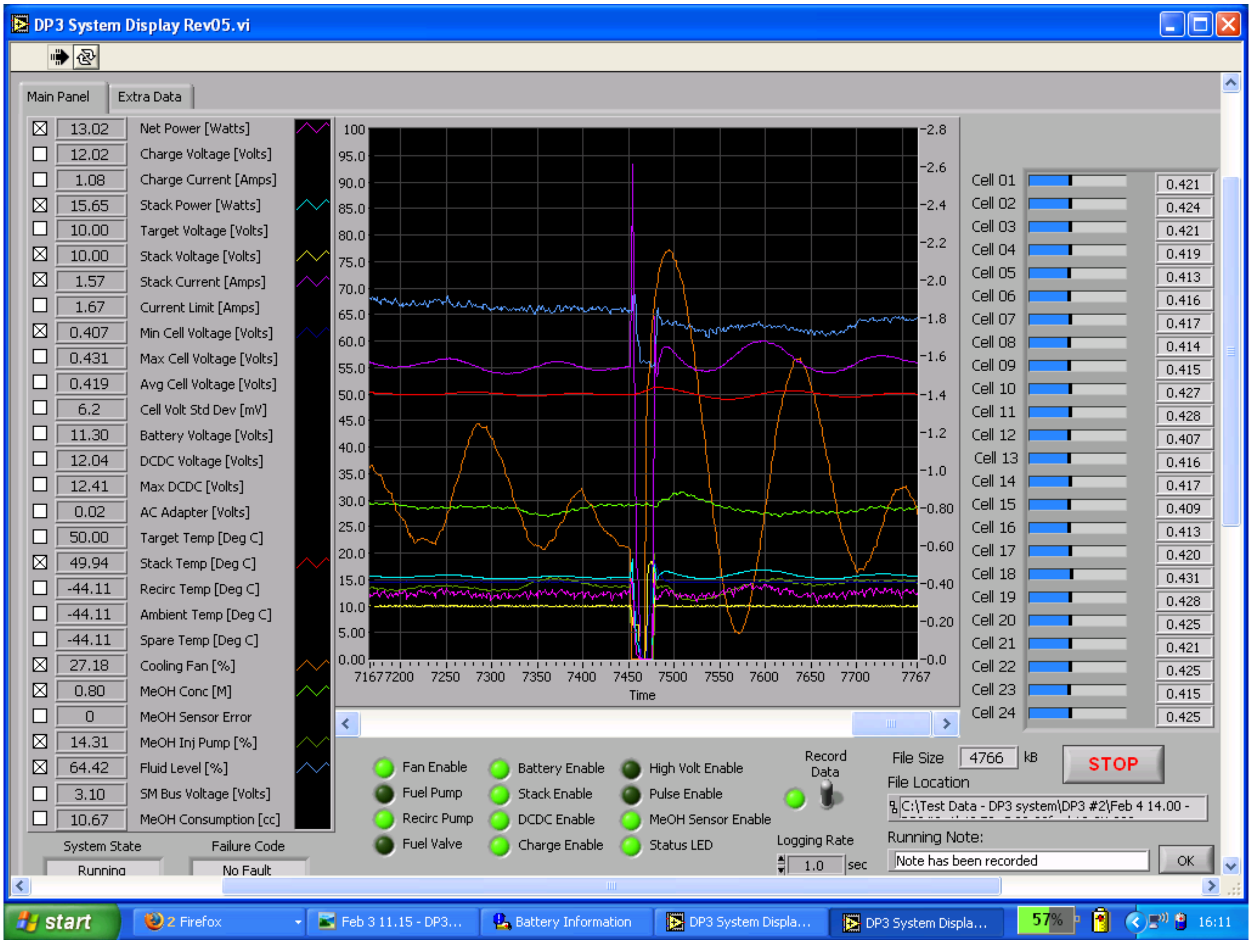
For the purposes of this project, the main goal was to develop the fuel cell system and gather as much data as possible. To that end, a few extra features were added to the control card to extract more information about the operation of the fuel cell system that are not necessary in a production unit. A compact monitoring system was included to measure individual cell voltages. The cells are contacted using a set of spring contacts that rest against the bipolar plates. Between each electrical contact is an extension of the fuel cell seal that prevents shorting between neighboring contacts. Figure 23 shows a photograph of the control card. The DC-DC converter is the largest section, has the highest components, and is highlighted in red in the photo. The cell voltage monitoring probes and associated circuitry is highlighted in green in the photo.

Figure 23: Photograph of the Custom Control Card



In order to record and analyze data collected by the control card, a USB port, highlighted in yellow in Figure 23 was included to communicate the instantaneous status of the fuel cell system to a nearby computer. The computer runs a custom piece of monitoring and logging software developed by PolyFuel to display and record the incoming data from the fuel cell system. The interface allows the test engineer to quickly see the performance of the fuel cell and determine the state of the various components in the system. A bar chart on the right hand side of the screen shows the individual cell voltages. Analog signals read by the control card are displayed on the left side of the screen. In the center of the screen is a large graph that will display any of the analog signals desired by the test engineer. Signals on the graph can be turned on and off in real time by toggling their controls. Lights indicating the status the status of the digital outputs of the system can be found at the bottom of the screen. See Figure 24 for a view of the data display and logging software.

Figure 24: Data Collection and Display Software



3.8 Energy Efficiency Analysis

The overall system efficiency is affected by most of the system components in one way or another, but there are four basic kinds of losses in a DMFC system.

The first is the efficiency with which the fuel cell can convert chemical energy in the fuel to electricity. This loss has several components including the effectiveness of the catalyst, the electrical resistance of the plate and GDL materials, the proton conductivity of the membrane, and the effectiveness with which reactants and products are able to diffuse into and away from the reaction sites. Several operational factors affect the fuel cell stack efficiency, particularly the operating temperature, the methanol concentration, and the fuel cell current. Higher temperature and lower fuel cell current lead to higher fuel cell stack efficiency, while there is an optimal methanol concentration for best efficiency. At the intended operating point for the fuel cell, 205 μL/min of fuel will be consumed electrochemically.

The second loss is called methanol crossover, a term used to describe the migration of fuel across the fuel cell membrane resulting in direct combustion of some of the fuel on the cathode without electricity generation. The crossover is affected by the resistance of the membrane to methanol migration, temperature, methanol concentration and the fuel cell current. Higher fuel concentration, higher temperature, and lower fuel cell current all lead to increased crossover. The fuel cell typically has a crossover current equivalent to 25 mA/cm^2 on average, but this value fluctuates significantly with different operating conditions. This corresponds to a loss of methanol for the entire stack of about 40 µL/min.

The fuel cell system has been tuned to produce maximum power with low fuel consumption while still operating in a widely stable regime. The table below shows the operating parameters currently used.

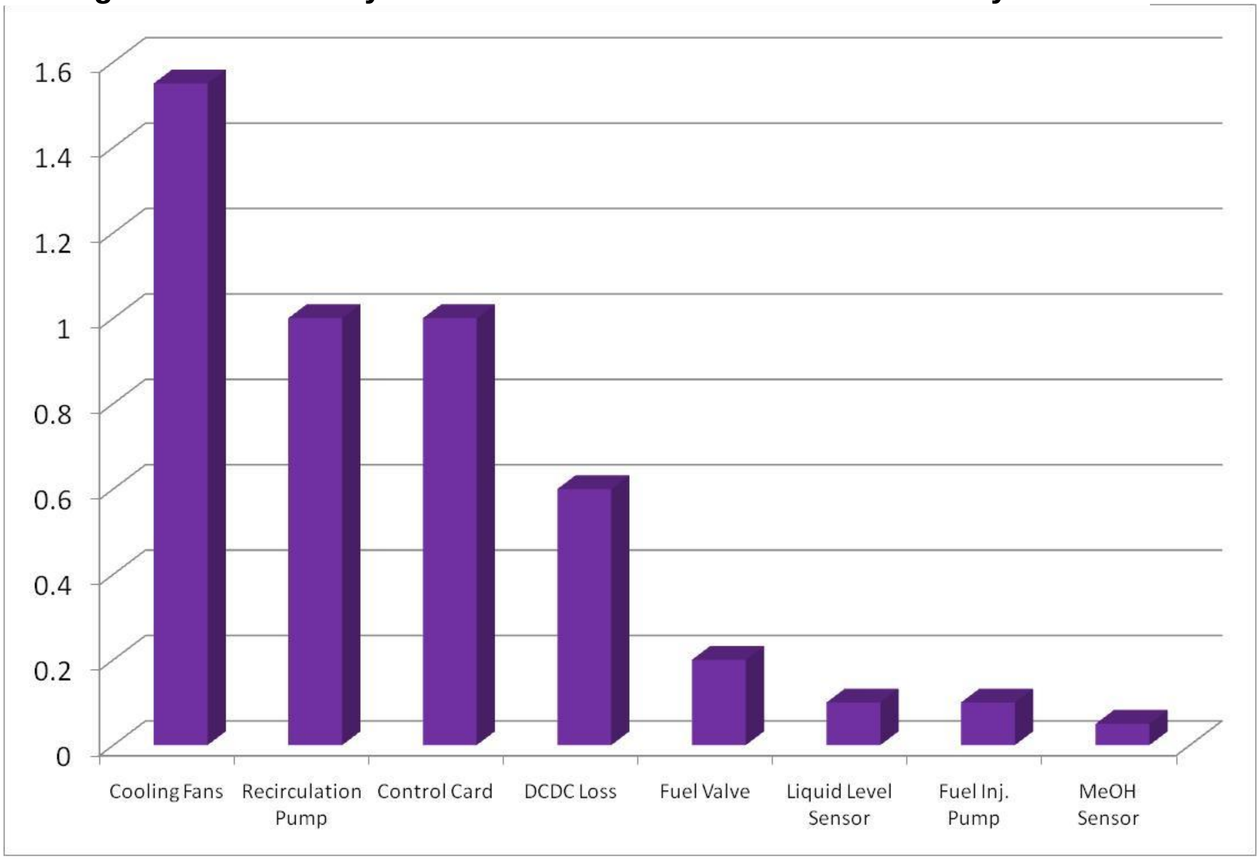
Parameter	Value
Fuel Cell Temperature	~ 50 C
Fuel Tank Concentration	100% MeOH
Dilute Fuel Concentration	0.8 M
Cell Current Density	150 mA/cm^2
Cell Voltage	380 to 430 mV

The third loss is the parasitic losses from the system components, whereby some of the electricity produced by the fuel cell is used to move reactants and coolant through the fuel cell stack and is not delivered to the user. The final loss is the electrical conversion loss in the DC-DC converter. A simplified accounting of all of these losses is shown in Figure 25 while a chart of the parasitic losses is given in Figure 26.

Figure 25: Fuel Cell System Energy Accounting

Description	**Power [Watts]**
Gross Fuel Cell Power	**+ 19.6**
Total Parasitic Losses	**- 4.6**
Cooling Fans	- 1.55
Recirculation Pump	- 1.0
Control Card	- 1.0
Power Conversion Loss in DC-DC Converter	- 0.6
Fuel Valve	- 0.2
Liquid Level Sensor	- 0.1
Fuel Injection Pump	- 0.1
Methanol Sensor	- 0.05
Net Power Delivered to Load	**+ 15.0**
Balance of Plant Efficiency (Gross Power / Net Power)	73.8%
Overall System Efficiency (Methanol to Net Power)	23.6%

Figure 26: Summary of the Parasitic Loads in the Fuel Cell System



3.9 Durability Testing

The fuel cell design has been durability tested at a variety of different scales. Single cells have been run for 1600 hours, stacks for 1800 hours, and full systems for 160 hours. Durability data for the single cell and stack are shown in Figure 27 and Figure 28. The single cell test was conducted at a constant current of 150 mA/cm^2 while the 24 cell stack test was conducted at a constant voltage of 0.35 Volts per cell. The grey trace at the beginning of the stack test had multiple problems with test station interruptions leading to a high degradation rate. The green trace portion of the test represents operation after the test station problems were resolved.

Figure 27: Single Cell Durability

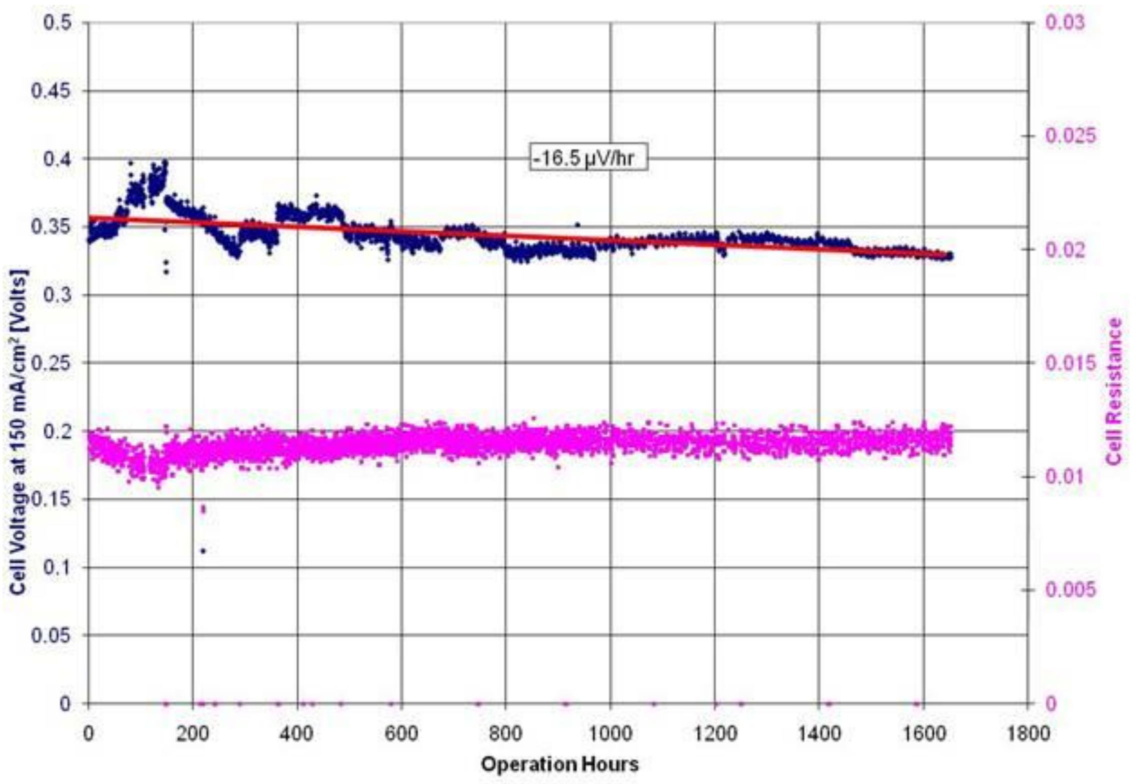
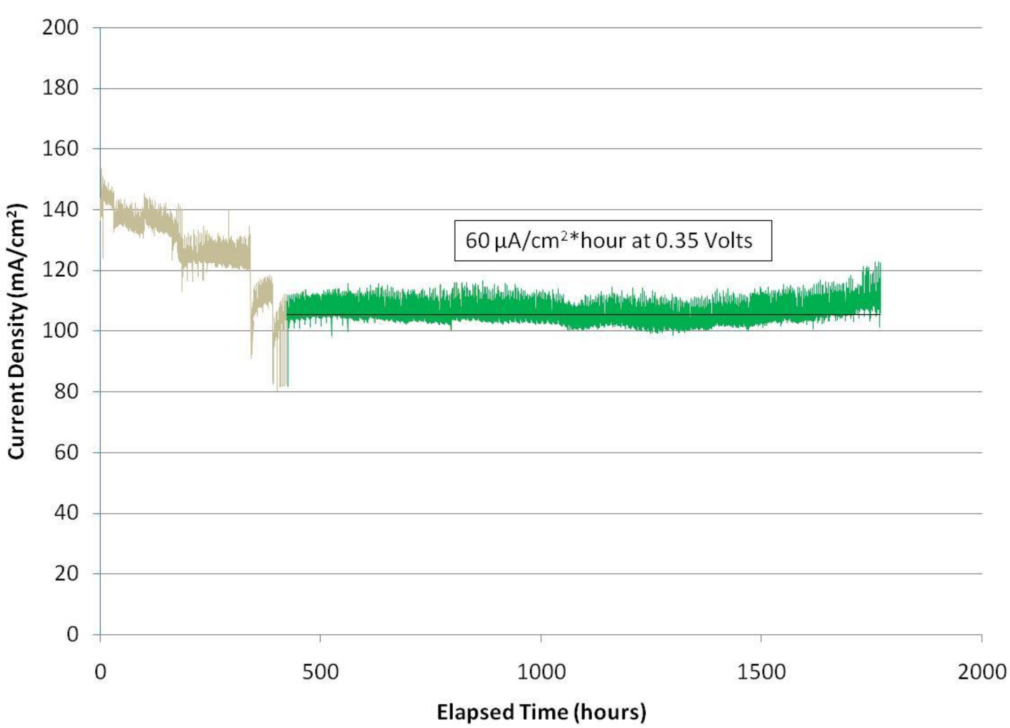


Figure 28: Fuel Cell Stack Durability



During the final months of the project, PolyFuel identified a large and unexpected problem with degradation in the off state. Systems, stacks, and cells left to sit non-operational on the shelf had a higher degradation rates than systems, cells, and stacks operated continuously. The longer a fuel cell was left non-operational, the worse the degradation. Preliminary tests indicate that the problem is catalyst related, but further work is necessary to better understand this problem. PolyFuel launched a significant effort to resolve this issue.

4 Future Plans & Commercialization

PolyFuel's goal is to accelerate the commercialization of DMFC based portable fuel cells by providing a reference design of this systems technology available to major consumer electronics OEMs. PolyFuel would derive its business profit from selling its specialized membrane to these customers. PolyFuel is currently in discussion with several potential partners to take the next steps towards commercialization.

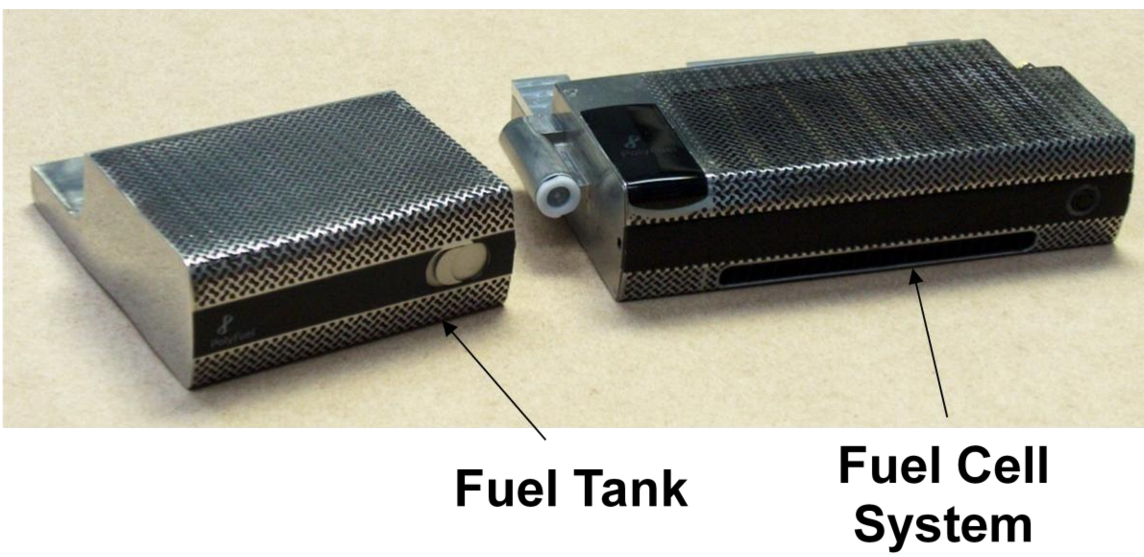
PolyFuel intends to work on further size and weight reductions of the system as well as increase the operating window and overall durability. Using these prototypes as a starting point, PolyFuel intends to explore their full potential. Projections at this time lead us to believe that a 30% reduction in size is possible within one year by further customization and optimization of the packaging. Another 30% size reduction following 2 years of R&D effort is also considered realizable. Combined, these two size reduction steps will result in a 25% to 30% reduction in weight as well.

5 Products Developed Under the Award

5.1 Prototypes Developed

The primary output of the project is a set of three direct methanol fuel cell power supplies that are fully integrated into commercially available laptop computers. The fuel cell works jointly with a modified three cell lithium ion battery in a hybridized fashion to deliver power to the computer. The fuel cell provides the average baseload power that the computer requires. During periods of high power demand, the battery discharges to handle the peaks while during periods of low demand, the fuel cell recharges the battery. Photos of the complete fuel cell system are shown in Figure 29.

Figure 29: Photographs of Complete Fuel Cell Systems



The fuel cell system power section has the following characteristics:

Length:	135 mm
Width:	100 mm
Height:	10 to 37 mm
Volume:	330 cc
Weight:	489 g
Power:	15 Watts

The fuel cartridges have the following characteristics:

Length:	82 mm
Width:	100 mm
Height:	10 to 37 mm
Volume:	170 cc
Weight:	245 g (full)
Weight:	125 g (empty)
Fuel in Tank:	150 cc or 120 g

Runtime on a single cartridge: 9 hours (demonstrated)
10 hours (projected with latest modifications)

<u>Demonstrated Energy Density</u>

Overall Energy Density: 270 Wh/L (one cartridge)
Overall Energy Density: 405 Wh/L (two cartridges)
Overall Energy Density: 184 Wh/kg (one cartridge)
Overall Energy Density: 276 Wh/kg (two cartridges)

<u>Projected Energy Density with Current Improvements</u>

Overall Energy Density: 300 Wh/L (one cartridge)
Overall Energy Density: 450 Wh/L (two cartridges)
Overall Energy Density: 200 Wh/kg (one cartridge)
Overall Energy Density: 300 Wh/kg (two cartridges)

Fuel cell stack operating hours: 1800 hours
Fuel cell stack degradation rate: 20 µW/h per cell
Fuel cell noise level: 43 dbA at 1 meter

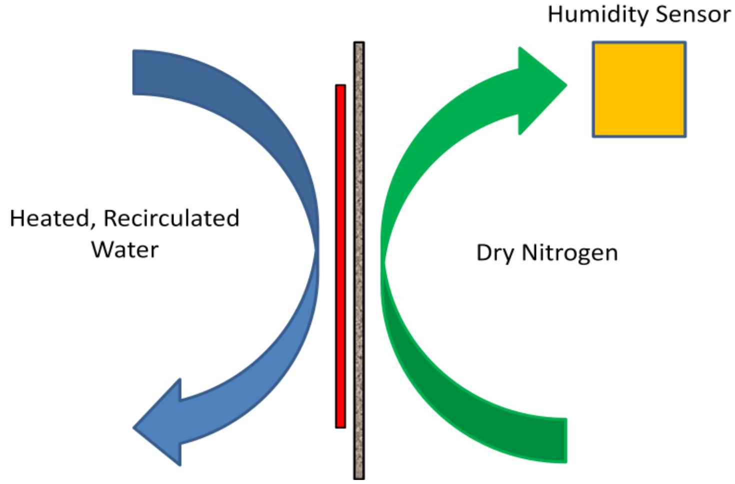
5.2 Techniques Developed

In order to develop the GDL coating, PolyFuel built up the capability to apply carbon/graphite/PTFE mixtures to porous substrates and sinter them in place. PolyFuel is now capable of making prototype quantities of GDLs with targeted diffusivities in the range of interest for DMFC power supplies. In addition to being able to make the material, PolyFuel developed specialized test techniques to measure the critical mass transport properties.

5.2.1 Water Diffusion Measurement

PolyFuel developed a custom apparatus to measure the rate of water vapor diffusion through the coating. The apparatus circulates a heated stream of water behind a sheet of expanded PTFE film on one side of the coating while passing a stream of dry nitrogen on the other. The heated water interface presents one well defined boundary condition to one side of the coating while the dry nitrogen presents other to the opposing side. By measuring the water content of the exit nitrogen stream, it is possible to determine the mass transport coefficient of the sample from a simple application of Fick's Law. The expanded PTFE sheet is included to eliminate convection through the porous substrate so that only the diffusivity is measured. See Figure 30 below for a sketch of the apparatus.

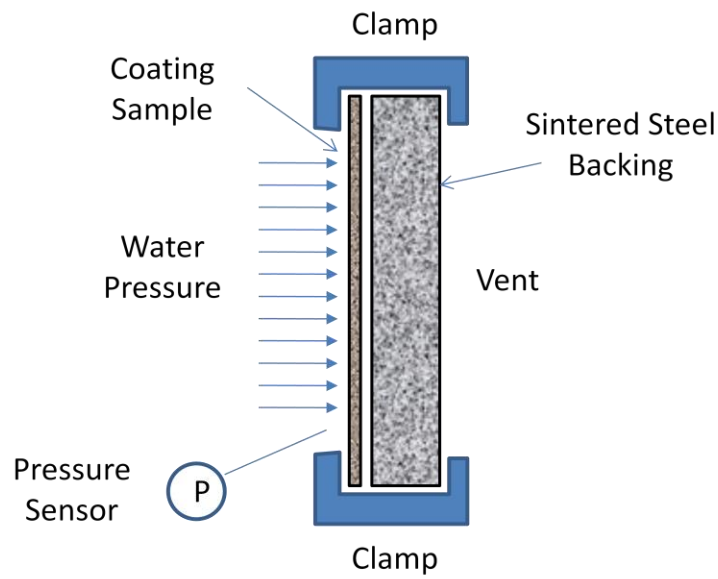
Figure 30: Schematic of Diffusivity Measurement Apparatus



5.2.2 Capillary Pressure Measurement

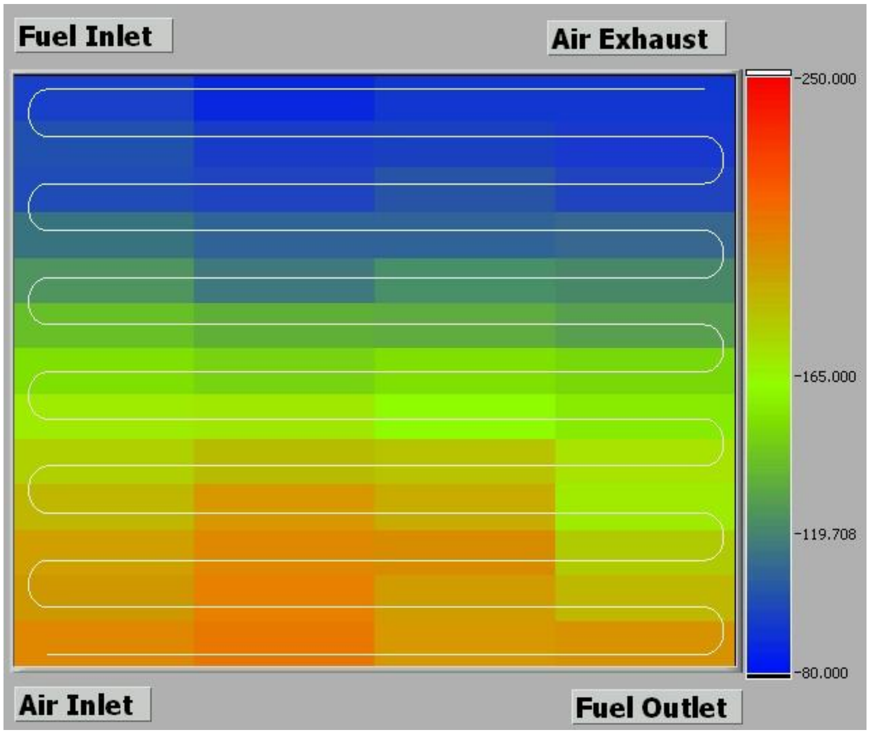
The second critical property of the GDLs is the capillary pressure, the liquid water pressure that the coating will sustain before allowing any liquid to pass through. This pressure is determined by the pore size distribution of the coating and its hydrophobicity. To measure the capillary pressure, the GDL is mounting in a very rigid fixture and a high water pressure is applied to one side of the coating. The other side of the coating is supported by sintered steel, but is able to communicate freely with the lab air. The pressurized water cavity is then isolated and the pressure is monitored. The decay rate of the water pressure is exponential and the asymptotic level is taken as the capillary pressure. See Figure 31 below for a sketch of the apparatus.

Figure 31: Sketch of Capillary Pressure Apparatus



In addition to the tools created to assist in the characterization of the special GDL materials, PolyFuel developed a moderate resolution current mapping plate. The plate is inserted into a cell or stack and measures the current density distribution flowing through it. There are 44 discrete measurements that are 0.5 cm^2 in area and have an accuracy of about 2 mA/cm^2. The tool gives very good insight into the operation of the fuel cell under different operating conditions. A very high performing cell has a uniform current density distribution while a low performing cell often has a very uneven current density distribution. The tool can show regions receiving insufficient reactants, inactive or damaged catalyst, damage to membrane integrity, and hot/cold zones in the cell. Figure 32 shows the operation of a cell with a deliberately reduced air flow. Notice the difference in current density from the cathode inlet to cathode outlet varies by a factor of two as the oxygen concentration drops.

Figure 32: Current Mapping Plate Data



5.3 Publications

In addition to annual presentations delivered at the DOE Hydrogen Program Review, PolyFuel has presented this work at the 2008 Fuel Cell Seminar:

2008 Fuel Cell Seminar, Henry Voss, GHT 41-1, "Passive Water Recycling Technology for Compact DMFC Power Supplies", October 30th, 2008.

5.4 Patent Applications filed during the project

Thus far PolyFuel has filed four provisional and two utility patent applications based upon research conducted on this project. Note that DOE funding for this project was suspended Dec 2005 and resumed April 2007. During this period the project was funded solely by PolyFuel with no assurances of resumed funding from DOE. These patent applications are:

Anisotropic Gas Diffusion Layer and Vapor Phase Fuel Cells (US Provisional)
Filed 5/5/2006 Application Number: 60/798,723

Vapor Phase Fuel Cells (US Provisional)
Filed 10/11/2006 Application Number: 60/851,182

Gas Phase Fuel Cells (US Utility Application based on some of the inventions contained in 60/798,723 and 60/851,182)

Filed 5/5/2007 Application Number: 11/745,341

Passive Recovery of Liquid Water Produced by Fuel Cells (US Provisional)
Filed 11/7/2006 Application Number: 60/864,767

Passive Recovery of Liquid Water Produced by Fuel Cells (US Provisional)
Filed 9/4/2007 Application Number: 60/969,890

Passive Recovery of Liquid Water Produced by Fuel Cells (US Utility)
Filed 11/6/2007 Application Number: 11/936,048

Fuel Cell Systems Using Passive Recovery of Liquid Water (US Provisional
Filed 2/14/2008 Application Number 60/040,539)