Fall Final Report

Team 16

Design and development of optimized flow channels for an alkaline membrane fuel cell (AMFC) educational kit

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Date Submitted

12/06/16

Team Bios

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Terry is a senior in mechanical engineering and has been selected as the team leader to organize and move the team forward. He wants to be an energy engineer with a focus in renewable or sustainable sources of energy, including biofuels, hydro, wind and solar power. He is from Haiti and wants to develop sustainable products for his country. Aside from engineering, he enjoys working on his car during his free time.

Tristan Walter – Design Engineer

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Tristan Walter has been selected as the design engineer for team 16 due to his passion in 3D modeling. Tristan is a senior in mechanical engineering at Florida State University. His job experience with Siemens has helped him develop helpful strategies to complete this project. Tristan is currently perusing the thermal fluids track which has also helped with research and interest in studying fuel cells. Apart from engineering, Tristan enjoys extreme sports and being with his dog.

Trevor Gwisz – Research/Development Engineer

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Trevor Gwisz is the research and development engineer for team 16. Trevor is a senior in the Mechanical Engineering at Florida State University. He is a member of the American Society of Mechanical Engineers as well as the Florida Engineering Society. He has a passion for getting involved with sustainable and renewable energy sources. Outside of engineering, Trevor enjoys outdoor activities such as camping and fishing.

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Oluwafemi Ojo is on an exchange program at the FAMU-FSU College of Engineering from The Federal University technology, Akure, Nigeria, and is expected to graduate with his B.S. in Mechanical Engineering in May 2017. He had an internship in Blackhorse Plastic Limited, Nigeria and he specializes in material processing and materials selection. He also intends to pursue his master’s degree in mechanical engineering after his undergraduate. He enjoys playing saxophone in his free time.

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ABSTRACT

The goal of the fuel cell project is to investigate the performance of a proposed alkaline fuel cell membrane (AMFC) and find the effects of different flow configurations on the fuel cell's performance. The fuel cell is used as an educational kit for high school and college level laboratories to spark interest in fuel cell's and how they can be optimized by focusing on different flow configurations. This investigation involves learning from the flaws of the current fuel cell kit and finding new ways of improving the performance of the fuel cell. New flow configurations plates will be added to the kit enabling the user to interchange plates and record respected power outputs. These experimental outputs will then be correlated with back up research on flow configurations of what characteristics affect the fuel cells performance. It has been determined that pressure drop and thermal behavior within the plate affect the fuel cell's output for different reasons. The parallel, serpentine, and interdigitated designs all carry positive and negative responses to these affects. Research has been conducted to learn from these previous configurations responses in order to design a new flow configuration that optimizes all these traits. Learning experimental procedures and safety have been included in the kit to ensure that this product can be developed for commercialization and be successful on the market in the future.

1.0 Introduction

Advancements in the development of fuel cells have been slow relative to other power generation systems like combustion engines, wind power, and solar energy. The high demand of more clean, and sustainable power generation has brought a new focus to the development of fuel cells. In practical application, fuel cells operate at lower efficiencies than the expected value. Therefore, most researchers are dedicated to improving their performance. With the development of computer based software and knowledge in fluid dynamics, a previously developed filter paper AMFC prototype flow configurations will be studied and modified.

2.0 Project Definition

2.1 Background Research

The fuel cell was invented in 1839 by a British professor William Grove. His fuel cell was constructed of a series of cells containing a dilute solution of sulphuric acid, and pairs of test tubes filled with hydrogen and oxygen. Grove observed that the ratio of consumption of the hydrogen to oxygen was 2:1. The volume ratio is an agreement with the simple reaction equation of hydrogen and oxygen to produce water. Since the invention of the first fuel cell, other types of cells have emerged including:

1) Proton Exchange Membrane (PEM)
2) Phosphoric Acid Fuel Cell
3) Alkaline Fuel Cell (AFC)
4) Direct Methanol Fuel Cell

2.2 Fuel Cell Application

Fuel cells have been used for power generation for over two decades, and are an attractive alternative source of energy due to their high efficiencies and non-polluting operation. They have been used to power automobiles, space crafts, and even been used in large scale power plants. Portable fuel cells have also been developed for use in the powering of electronic devices for camping, yachting, traffic monitoring, medical treatment, and warfare. [1] In general, fuel cells produce electricity and can power any device or equipment that runs on electricity. Once again, the main advantage of fuel cell application is that it does not emit pollutants and other greenhouse gasses that are harmful to the environment.

2.3 Fuel Cell Operation

The purpose of a fuel cell is to convert chemical energy into electrical energy. The fuel cell provides an electrical current to an external circuit, providing on-demand power while requiring no moving parts. This is achieved by taking advantage of oxidation and reduction reactions, which release and capture electrons, respectively. The diagram of a standard alkaline fuel cell can be found below in figure 1. [2]

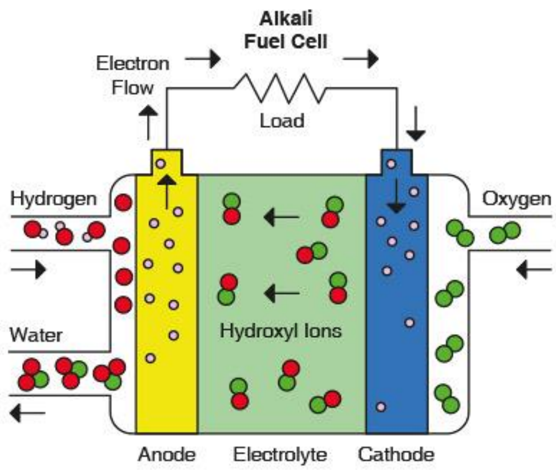


Figure 1: A diagram depicting an alkaline fuel cell [3]

The diagram above shows how the alkaline fuel cell functions. On the left side of figure one, hydrogen gas is supplied into the fuel cell. Once hydrogen gas enters the fuel cell, it begins to diffuse into the anode, which is highlighted in yellow. The anode is an electrical conductor which allows for a flow of electrons. The anode must not only conduct electrons, but must also contain a catalyst to speed up the oxidation reaction. The anode in an alkaline fuel cell is usually made of porous carbon coated with either platinum or nickel. These two metal have a high electrical conductivity, and act as a catalyst for the oxidation and reduction reactions. This is due to the high porosity of the metals microstructure, which allows for efficient diffusion of hydrogen and oxygen into the microstructure. The faster this diffusion process can occur, the more current the fuel cell can produce. To the right of the anode is the electrolyte soaked membrane (seen in green). From this membrane, hydroxyl ions supplied from the electrolyte solution diffuse into the anode. The hydroxyl ions react with the hydrogen gas. This reaction is the oxidation reaction, and its balanced chemical equation can be found below in equation 1. [4]

$$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^- \quad (1)$$

From equation 1 seen above, we can see the how the first half of the process works. As the hydrogen gas (H_2) diffuses through the anode, the two hydrogen atoms which make up the hydrogen gas, break apart. One of these atoms bonds with one hydroxyl ion. This reaction results in one water molecule and one excess electron. The water is expelled out of the anode, and eventually out of the fuel cell, and the electron flows out of the anode and through the external circuit. This electron flows from the anode to the cathode (seen above in figure 1 in blue) because of electric potential. The anode is electropositive, and the cathode is electronegative. This simply means there is an excess of electrons at the anode, and a shortage of electrons at the cathode. This creates an electrical potential, or voltage, which ultimately drives the flow of electrons. The cathode is constructed the same as the anode. Oxygen gas supplied into the fuel cell (which can be seen on the right side of figure 1), diffuses into the cathode, and a reduction reaction occurs. The balanced reduction reaction that occurs at the cathode can be seen below in equation 2. [4]

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad (2)$$

The hydroxyl ions (OH^-) produced in equation 2 then flow through the membrane from the cathode to the anode, effectively completing the circuit of electrons and ions. Currently, two possible configurations of membranes exist. One is the static electrolyte configuration. In this configuration, the membrane is usually either asbestos or the more complex Alkaline Anion Exchange Membrane (AAEM) which is ammonium based. These membranes are soaked in a highly-concentrated electrolyte solution such as potassium hydroxide (KOH). This electrolyte solution is responsible for the flow of ions. In the flowing configuration, the membrane consists of some form of a matrix microstructure which allows the electrolyte to circulate freely. The static configuration is generally safer in vehicular applications. However, these materials tend to be more toxic. More specifically, ammonia can cause acute toxicity when inhaled or digested, and asbestos is a well-known carcinogen. Research is still attempting to develop a safe and efficient membrane. One possibility that is still being tested is a cellulose based membrane. [4]

One important aspect governing fuel cell efficiency are the flow channels which provide fuel to the anode and the oxidizer to the cathode. Very little actual research has been done to test the best way to supply these gasses to the fuel cell. Ideally, the flow channels will be designed to produce maximum diffusion of both hydrogen and oxygen through the corresponding electrodes. The flow channels must also be designed to facilitate the removal of water vapor from the surface of the anode, which is the byproduct of the oxidation reaction occurring within the anode. Theoretically, a perfectly designed flow channel would be able to supply equally concentrated gas over the entire surface of the electrode, while maintaining a small pressure drop. If the gas is not equally concentrated over the entire surface of the electrode, the current density will be uneven within the electrode, and will not produce optimal results. One consequence of having an uneven distribution of current within the electrode is uneven heat distribution. This could potentially affect the longevity of certain components in the fuel cell. This could also lead to a poor evacuation of water vapor. Likewise, if the head loss is too significant due to the complexity of the design, diffusion through the electrode will be slowed drastically. High pressure drops caused by head loss could also result in stagnation within the flow channels, potentially leading to similar results previously mentioned.

2.4 Advantages and Drawbacks

There are several advantages to using alkaline fuel cells. Generally, fuel cells only emit pure water. If contained and managed properly, the fuel cell can also prove to be a source of clean water in addition to providing clean energy. Another advantage is that fuel cells are quiet during operation. This can be attributed to a lack of moving parts. Also, when compared to other types of fuel cells, alkaline fuel cells offer relatively high current density. This is due to the fact that the alkaline solution allows for quicker chemical reactions than acidic membrane fuel cells. From a safety aspect, alkaline membrane fuel cells only operate at about 100 degrees Celsius. While still hot enough to burn, this temperature poses little challenges in terms of materials selection. [3]

The main drawback to using an alkaline fuel cell is a phenomenon known as carbon dioxide poisoning. This occurs when the fuel being used is not pure. An example would be using air instead of pure oxygen. When carbon dioxide enters the fuel cell, carbonates form. These carbonates block and clog the pores within the anode and cathode. This blocking slows the rate at which diffusion occurs until it eventually stops the process altogether. The chemical reaction which causes this phenomenon at the anode and cathode can be seen below in equations 3 and 4, respectively. [4]

$$CO_2 + 2KOH \rightarrow K_2CO_3 + H_2O \quad (3)$$

$$2OH^- + CO_2 \rightarrow CO_3^{-2} + H_2O \quad (4)$$

The formation of these carbonates, potassium carbonate (K_2CO_3) and carbon trioxide (CO_3^{-2}), create a need for pure oxygen gas and pure hydrogen gas to allow the fuel cell to remain efficient for long periods of time without maintenance. Purifying and collecting these gasses is a relatively complicated and sometimes expensive process. The best way to obtain pure oxygen is to use cryogenics. If air is cooled to -183°C, pure oxygen will liquefy, and it can then be collected and returned to a gaseous state. This method, however, is expensive and complicated. A simpler method to collect pure hydrogen is to use electrolysis to separate water into pure hydrogen and pure oxygen. A diagram of this process, as well as the chemical reactions involved, can be found below in figure 2. [6]

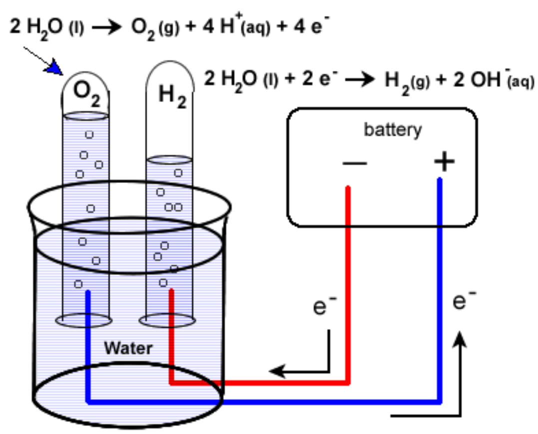


Figure 2: A diagram showing the electrolysis of water into hydrogen gas and oxygen gas [6]

The figure above shows a relatively safe and inexpensive way to produce pure fuel for an alkaline fuel cell. This method is one that could be easily used to power an at home fuel cell kit. As seen in the diagram, electrons leaving the battery from the negative terminal create a negative electrode in the water. This causes a reduction reaction (electrons gained) of H_2O, and hydrogen gas bubbles upwards where it is collected. The blue wire then becomes an effective positive electrode or cathode, and H_2O is oxidized. This releases pure oxygen gas which can also be collected. It is important to note that pure water is a very poor conductor. This is because pure water molecules have no free electrons to transfer electrical current. This slows down the process of electrolysis. To speed up this process, salt or any other common water soluble electrolytes can be added to the water. [6]

2.5 Need Statement

The project is being sponsored and advised by Florida State Professor Dr. Juan Ordonez. The project will include and demonstrate various experiments of testing different flow diagrams to show students the correlation between flow systems and efficiency in AMFC single cell. The fuel cell and all necessary parts will be in one portable kit that can be easily transportable. A previous educational fuel cell kit has been made and is located at the CAPS lab at Florida State University. This project will take this fuel kit and redesign it with the addition of exchangeable flow channel plates that contain different flow configurations. The team eventually plans to deliver a fully functioning AMFC educational kit that will be commercialized as a marketable product.

"The current AMFC setup does not effectively allow students to test the effects of flow configurations on fuel cell performance."

2.6 Goal Statement and Objectives

"Deliver a functioning educational alkaline membrane fuel cell kit that demonstrates the effects of flow configurations on the fuel cell's performance by the end of spring 2017 semester."

The main objectives that have been addressed from assessing the need statement are listed below.

- Improve the design of an alkaline membrane fuel cell (AMFC) educational kit for high school and college level laboratory demonstration

- Improve the overall safety of the kit as well as the fuel cells operation
- Include multiple flow configurations to compare performance
- Conduct a thermal fluids systems analysis to correlate with fuel cell performance
- A standard operation procedure and a product specification sheet included in the kit
- Design experimental procedures for optimal learning experience
- Develop a model for commercialization of the kit.

2.7 Constraints

The proposed project was given several constraints by the advisor and sponsor Dr. Juan Ordonez. To start, the kit needs to be fully automated. One way to ensure automation is that the kit must deliver pure oxygen and hydrogen to the system. As mentioned in the background research a method of electrolysis will be used to create pure oxygen and hydrogen. This method requires an outside power source to power the process. It has been decided that a plug-in power supply will be used to supply a steady supply of current. It has been concluded through testing that a battery won’t produce enough fuel for extended testing periods.

Another constraint of the project was for the entire kit to remain transportable. Currently, the kit has been designed so that all necessary components fit inside the carrying case. The current case is a black hard case constructed with an aluminum alloy frame and steel corners. The case is approximately 18 x 6.5 x 13 in. The constructed house of quality in Table 1 shows that size and weight are a major constraint based on the need statement to deliver a mobile kit. Any part of the system that requires extra parts or components will create problems of keeping this desire satisfied.

Table 1: House of quality used to rank fuel cell kit characteristics of importance

		Engineering Characterisitcs					
Improvement Direction		↓	↓	↑	↓	↑	↑
Customer Requirements	Importance Weight Factor	Weight	Leaking Probability	Material Strength	Time to Set up	Accuracy of Volt Meter	Weather Resistance
Contains all Parts	5	9	0	1	8	0	0
Five-Year Lifetime	3	2	3	9	2	4	9
Test effects of flow structures	5	0	7	2	0	9	2
Portable	4	9	4	5	5	0	0
Tool-less installation	2	4	7	4	8	0	0
Efficient	4	1	9	7	2	9	0
Raw Score (527)		99	110	98	90	93	37
Relative Weight		18.8	20.9	18.6	17.1	17.6	7.0
Rank Order		2	1	3	5	4	6

Safety is another constraint based on the initial needs assessment. The fuel kit product will be used as a learning tool to fuel students. The system will deal with purified gases and electrical components being used in a classroom setting putting safety at a high priority. Additionally, the fuel cell will operate at a maximum temperature of 100 degrees Celsius. This ultimately affects materials selection as well as the overall design to ensure users can safely operate and experiment with the design. A large portion of current design improvements have been made with safety in mind. This includes a baseplate to provide stability to the fuel cell during operation, as well as insulate against heat and electricity. Finally, the improved design will take advantage of a system of Teflon gaskets sandwiched between the anode and cathode as well as a large silicon gasket between the two endplates. These gaskets will prevent gas from leaking from onside the fuel cell, as well as ensure no KOH leaks from the membrane of the fuel cell.

The last constraint for the design is to ensure durability. A large portion of the current kit is being reused from the previous years (2015) senior design team. New parts to be ordered currently total in at around $575. To make the kit a feasible purchase for a consumer, it must be a durable kit which can be reused many times. This has ultimately affected material selection as well as some important design aspects. Specifically, it has been decided that the flow configurations will be constructed of stainless steel 304. This will prevent the endplates from corroding. The use of Teflon and silicon gaskets will prevent any potassium hydroxide from leaking onto the endplates. Potassium hydroxide is mildly corrosive and could directly cause corrosion.

3.0 Design and Analysis

3.1 Design Components

3.1.1 Fuel Cell Components

The alkaline membrane fuel cell kit will contain all necessary components required to assemble the fuel cell. The previous design required bolts, nuts, and washers to assemble the fuel cell. While this design is sturdy, as well as cheap, it requires the use of multiple wrenches to tighten. This would ultimately add to the number of required components in the kit, increasing weight and decreasing transportability. To combat this, the bolts, nuts, and washers will be replaced with quick release bicycle skewers. A simple modification will be made to the acrylic housing, allowing for the skewers to be loosened, and then slid off. This will also decrease assembly time because it reduces the need to completely unscrew the fasteners. A modeled image of this design can be seen below in Figure 3.

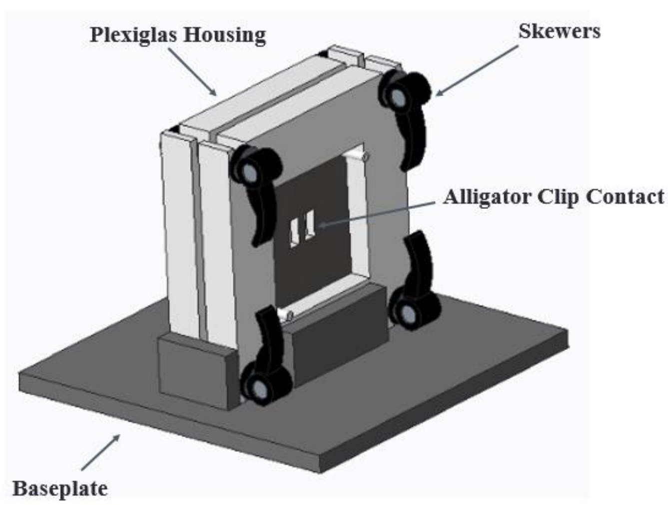


Figure 3: Updated design of the Fuel Cell with added components

The kit will also contain a total of six endplates which will contain specific flow configurations. These endplates will be interchangeable to compare different performances in fuel cell operation. In addition, the kit will contain electrodes made of 40% platinum on carbon paper. The kit will include multiple membranes made of filter paper, allowing the operator to test several different times before purchasing any replacements. A controlled amount of 40% concentrate KOH will also be included in the kit, which will be used as the alkaline electrolyte. Finally, the kit will contain a plastic baseplate that will house the fuel cell during operation. The baseplate will serve to stabilize the fuel cell, as well as insulate against electricity and heat.

3.1.2 Electrolysis Components

Compressed hydrogen and oxygen are extremely dangerous and expensive. Because of this, keeping these gases within the fuel cell kit is impractical. The kit will instead contain a kit for producing, capturing, and delivering these gases to the fuel cell. This will make the kit safer and cheaper. The method being used is known as electrolysis. Electricity will be used to separate the water molecule into pure hydrogen and oxygen gas. The gas will then flow from the water source to the inside of the fuel cell flow configuration. This will be done using a DC power supply, two flasks, two collection cups, and gas lines. An adjustable DC power supply will convert 110V AC power from the wall into a safe and useable power that can power electrolysis. It was decided that using a battery to complete this task would make the kit too heavy and expensive. The flasks, collection cups, and gas lines will then be used to hold the water, trap the gas produced by electrolysis, and finally move the gases from the flasks to the fuel cell. The gases will be driven to the fuel cell by pressure which will build up as the electrolysis process takes place. Gas lines must be tight fitting to prevent leaking.

3.1.3 Kit Components

The final design of this project will include everything needed to assemble and test a working alkaline membrane fuel cell. This will allow users of the kit to gain hands on experience and learn the fundamentals about how a fuel cell operates and what aspects influence their performance. The kit will include an instruction manual that will list the steps required to assemble the fuel cell, as well as different experiments that can be conducted by the user. The current design will require no tools to assemble. This will eliminate unnecessary components contained in the kit. The kit will also contain a Fluke 116 digital multimeter. The multimeter has a DC voltage resolution of 0.1mV, and DC microamp resolution of 0.1 microamps. It is also capable of tracking minimum and maximum values, as well as calculating an average reading. This will ensure that the user can take very precise, and accurate measurements. Furthermore, the multimeter is capable of using a thermocouple. A Fluke 80BK-A Thermocouple will also be included in the kit, allowing the user to take temperature readings at various places on the endplate. Finally, alligator leads will replace the multimeters standard leads, which will ensure safe and steady electrical measurements during operation.

3.2 Effects of Different Configurations on Cell

Ultimately, the main idea behind testing different flow configurations is the optimization of diffusion. Diffusion is the driving force in producing power and maximizing efficiency in a fuel cell. Diffusion takes place at the anode and cathode, and allows the reduction and oxidation reactions to take place, respectively. This process is effected by three different factors. These factors include gas distribution, pressure, and waste water management.

Gas distribution is important for several reasons. To start, evenly distributed gas will ensure that diffusion is occurring at an even rate across the entire anode/cathode. If the gas is not evenly distributed, diffusion will occur faster in some spots than others. This causes an uneven current density which reduces overall power output. Additionally, this will cause uneven heating of the fuel cell. In extreme cases, poor thermal management can lead to warping and degradation of the fuel cell.

Pressure drop is also an important factor when studying diffusion within a fuel cell. A flow configuration that contains complicated flow regimes could potentially result in high minor losses. Minor losses in fluid dynamics are caused by physical traits such as sharp edges, bends, entrances, and decreasing diameter in the flow regime. These minor losses cause a pressure drop. Pressure is important in diffusion because as pressure becomes higher, gas molecules tend to become more excited. This type of behavior maximizes the molecules contact with the fuel cell. This inevitably increases diffusion. If pressure drop is too high, the gases will not flow autonomously through the flow channels, meaning poor diffusion rates.

Waste water management is another aspect which effects diffusion rates in a fuel cell. As the fuel cell operates, hydrogen and hydroxyl ions undergo an oxidation reaction which leads to the formation of water and extra electrons. This water vapor must be effectively removed from the flow channels to prevent the buildup of condensed water. If water begins to condense inside the fuel cell, it will prevent gas from contacting the surface of the anode. This would result in an obvious reduction of diffusion. It is for this reason that the flow channels be designed to facilitate the removal of water vapor from the fuel cell.

3.3 Design Concepts

This fuel cell kit will not only provide a hands-on learning experience behind the construction of a fuel cell, but it will also offer an insight into the aspects which effect fuel cell performance. More specifically, diffusion. This will be done by containing at least three different fuel cell flow configurations, for a total of six end plates. The three configurations that are currently being analyzed are the parallel, serpentine, and interdigitated flows. Users can configure the fuel cell, allow it to run, and measure the fuel cells performance using the multimeter. Then, the user can disassemble the fuel cell, and reconstruct using a different flow configuration. This enables the user to run the fuel cell and compare the results. Each configuration has different positive and negative aspects on the efficiency of the fuel cell. For example, a serpentine style flow configuration is shown in Figure 4.

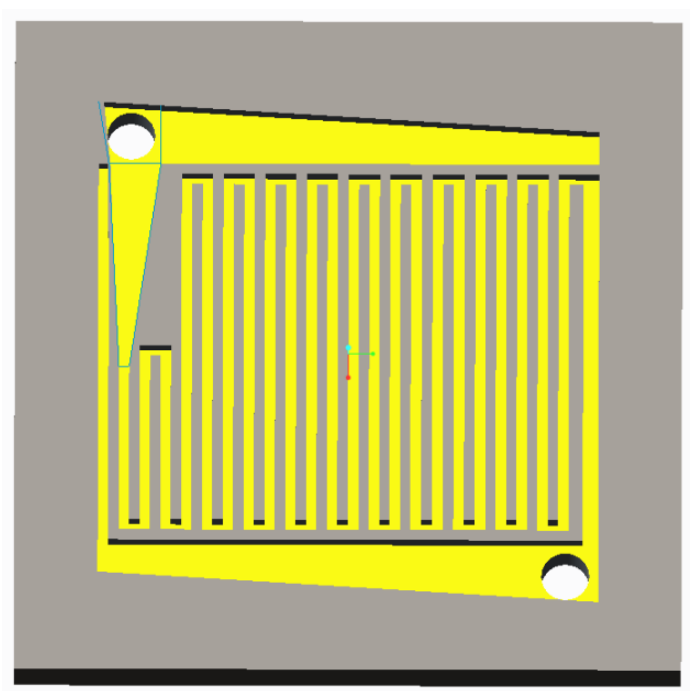


Figure 4: Team 16 3D model of serpentine flow configuration

The model above has the same dimensions to fit in the housing of the current fuel cell (drawings can be found in Appendix A). By observing the flow configuration, some assumptions have been made from the flow path of the fluid. The fluid flows through one path and is continuous, along the path the gas becomes less concentrated as it diffuses through the electrode. This can cause a reduction in current density, and a reduction in fuel cell efficiency. One benefit of this design is that if pressure drop can be overcome, there is little to know room for stagnation [7].

The interdigitated flow configuration is the other alternate plate that will be used to compare for testing as shown in Figure 5.

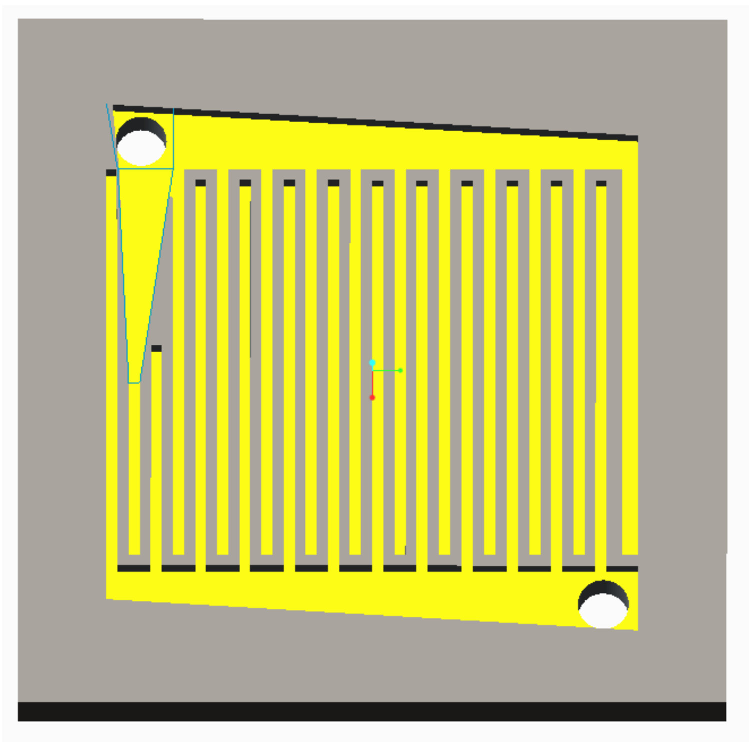


Figure 5**:** Team 16 3D model of interdigitated flow configuration

The interdigitated configuration flow path is not continuous as seen above. Fluid may flow through multiple paths which allows for a more evenly distributed spread of gas within the fuel cell. The inlet and outlet channels are not connected which forces the flow to laterally diffuse over the ribs through the electrode. This can cause forced convection which results in a higher heat transfer rate and a higher fuel cell efficiency [7]. The pressure drop may be higher in this configuration due to the non-continuous flow, the fluid needs to be pushed over the ribs resulting in the higher energy losses through the configuration.

The parallel configuration is already included in the current kit and can be seen in Figure 6.

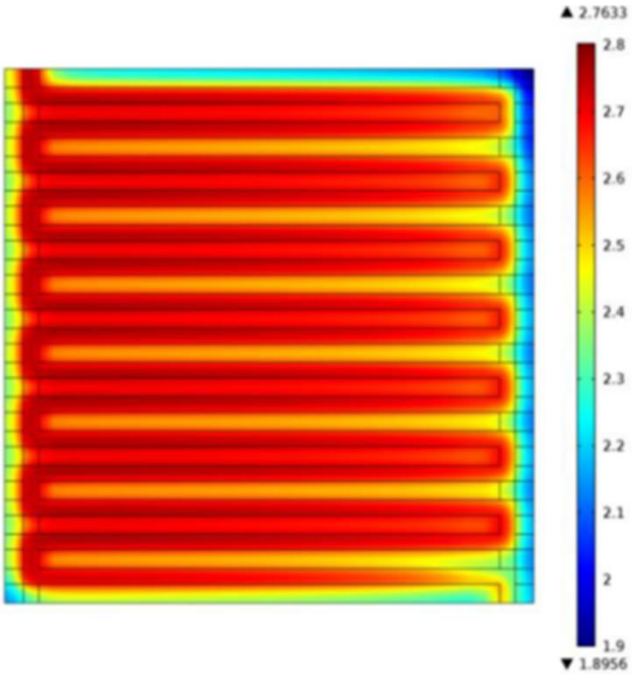
Figure 6: Current parallel flow configuration

The flow can flow through multiple paths allowing for a lower pressure drop flow is not being forced into one specific channel. One potential drawback of this design is the likelihood for stagnation points in certain regions of the flow channels.

4.0 Outcomes and Discussions

4.1 Evaluations of Configurations

Before machining of the serpentine and interdigitated configurations Team 16 has taken the steps to research and analyze the configurations. Thermal imaging has been a helpful tool to see the behavior of what is taking place internally during operation. By observing the heat distribution between the different configurations, it is possible to make some assumptions based off research. Thermal imaging of the interdigitated and serpentine flow configurations can be seen below in Figure 7.



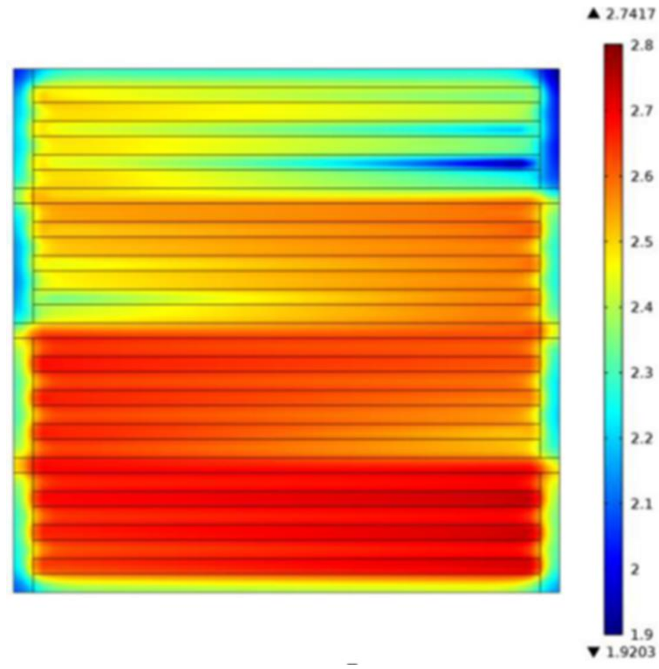


Figure 7: Thermal Imaging Interdigitated (left) Serpentine (Right) label with current density (A/cm^2)

Temperature values found using thermal imaging were correlated and converted to a respective current density. Current density is the amount of current per unit of area. From Figure 7, it can be concluded that the current density in the interdigitated design is more evenly distribute and is higher overall. Higher temperatures are correlated with how fast diffusion is occurring, and ultimately current density. Higher rates of diffusion and a more uniform current density is desired to optimize for the fuel cell's efficiency. When gas enters the flow channels, it diffuses through the electrode, and initiates half reactions which create power. In the serpentine configuration, the gas is initially at a higher concentration. This results in a higher current density at the begging of the flow configuration. Current density decreases as the gas travels through the flow channel, becoming less concentrated as it flows through the plate. Figure 7 verifies that in the serpentine configuration only the first four channels reach an ideal operating temperature. As for the rest of the serpentine plate, the temperature decreases drastically, meaning current density is uneven throughout the flow channel. This leaves the performance of the cell at a disadvantage because diffusion is not being utilized through the entire space resulting in a lower expected performance when compared to the interdigitated design.

Pressure drop has also been an important aspect when considering the different flow configuration designs. The interdigitated design has the highest pressure drop due to the forced flow of the fluid over the ribs at the dead ends. High pressure drop can result in poor water management and can also lead to possible flooding of the fuel cell. As water forms on the anode due to the half reaction which occurs, the water vapor and condensed water vapor must be removed from the flow channels to ensure that diffusion still takes place. This can only take place if there is enough pressure to force the water vapor from the flow channel. High pressure drop can also lead to poor thermal management. If the fluid experiences too high of a pressure drop, it will become stagnant within the fuel cell.

The power output of the cell is the most important aspect when comparing the different designs. To calculate power, the general equation can be used as seen below in Equation 5.

$$P = IV \qquad (5)$$

Current density is simply the current, I as a unit per area, and voltage, V in volts. Figure 8 below shows theoretical values of output voltage based on current density

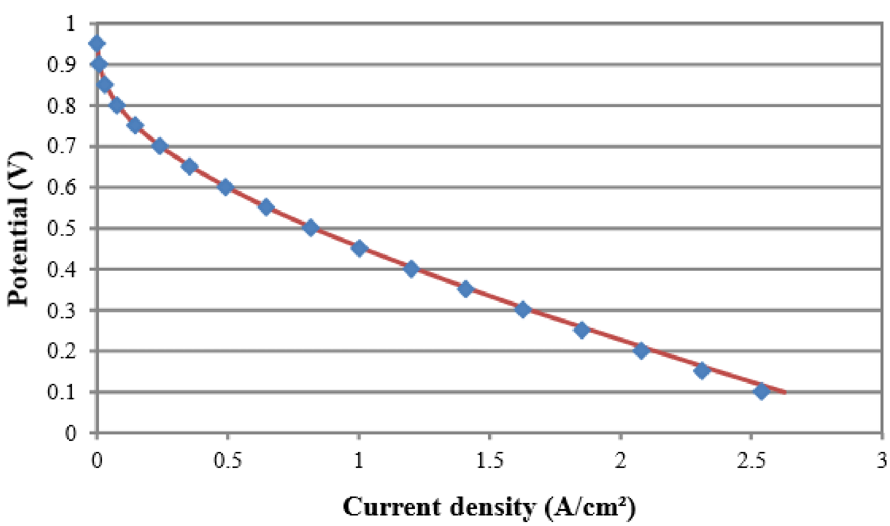


Figure 8: Theoretical values for Voltage vs. Current Density (Blue dots: Serpentine, Red line: Interdigitated)

It can be concluded that the output voltage of an associated current density will produce the same amount of voltage regardless of design. What is important to consider is the overall current density of the whole cell. When power is considered, the behavior of the power curve over the voltage curve can be seen in Figure 9.

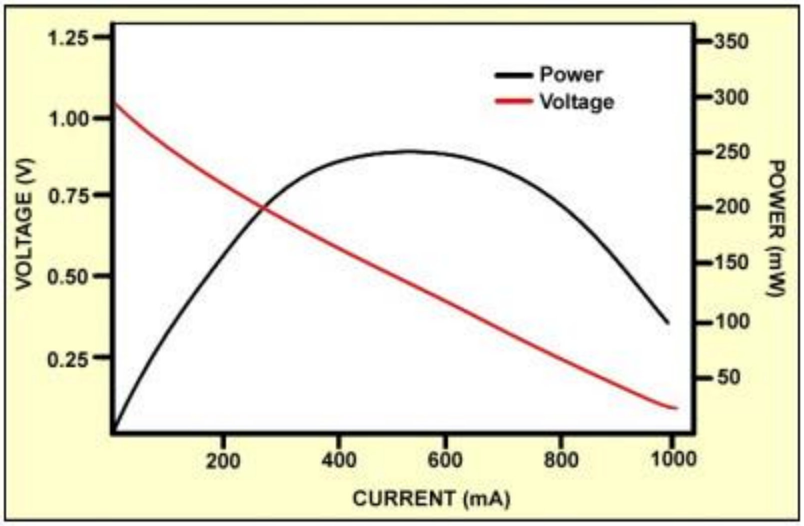


Figure 9- Voltage and Power vs. Current curve behaviors

When comparing output voltage with current density, as current density increases the associated output voltage decreases exponentially. The shape of this graph can be summarized into four major sections, each defined by a specific irreversibility. These irreversibilities include activation losses, fuel crossover and internal currents, Ohmic losses, and mass transport or concentration losses. Activation losses are due to the speed of the reactions taking place on the surface of the electrodes [8]. Fuel crossover and internal currents are energy losses that are a result of fuel passing through the electrolyte. Since the membrane within the cell is porous it is possible for a small amount of diffusion to occur through membrane itself. This essentially means fuel is wasted instead of contributing to the circuit. Ohmic losses are caused by the resistance of the flow of electrons when flowing through the material of the electrodes and other connections. Mass transport or concentration losses are a result of the change in concentration of the reactants at the surface of the electrodes as the fuel is used [8]. As mentioned earlier the concentration losses can be observed in Figure 7, in the serpentine design.

To further conclude on the behaviors of the curves in Figure 10, it can be stated that the cell's performance is not purely based on output voltage. Maximum power output is desired from the cell with a sufficient amount of voltage and current output to power the external circuit effectively. The current of the system outweighs the voltage drop and therefore defends that a higher uniform current density is a positive aspect for power output.

4.2 Pressure Drop Conclusions

The electrolysis method has been utilized in the design to create pure hydrogen and oxygen gas for the fuel cell. Two, 200 ml cylinders with 1/8 in diameter inlet tubes will be connected to the fuel cell plates to supply the hydrogen and oxygen. An adjustable power supply will be attached to leads and placed in the cylinders to start the electrolysis reaction. The current set up is producing a flow rate of 0.2678 L/hr which results in a fluid velocity of 0.036 m/s with the previously mentioned inlet tube geometry. This fluid velocity produces a very slow feeding pressure that is not desired when considering a thermal fluid system. As mentioned in research the distribution of the reactant throughout the cell is extremely important when considering performance of the cell. By relating this back to the current flow rate that is producing a poor feeding flow rate, it is possible that the fluid will not overcome the losses associated with the serpentine and interdigitated configurations. The current configuration, parallel has the lowest pressure drop and therefore the cell can function with this setup. However, when considering the serpentine and interdigitated flow channels, it is possible that the current setup may not be able to overcome this pressure drop. The forced flow over the dead ends of the interdigitated and the single path flow of the serpentine requires a higher driving flow rate. A numerical analysis of pressure drop has been performed on the serpentine design. The serpentine design is the only design that can be calculated by using the modified Bernoulli's equation. The one path continuous flow makes it possible to analyze each minor loss to calculate a pressure drop.

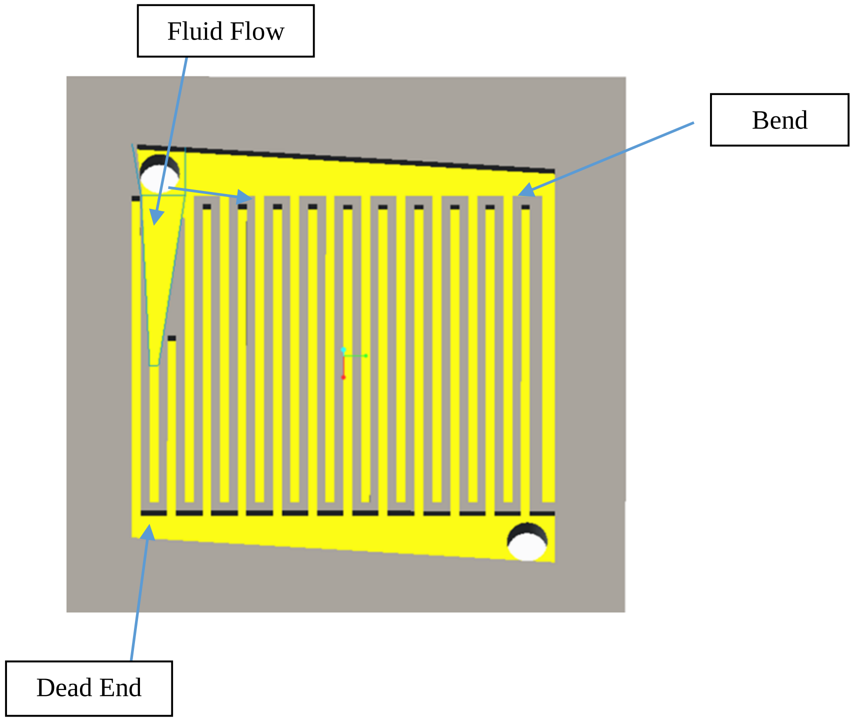


Figure 10- Interdigitated Design demonstrating minor losses

Figure 10 demonstrates the minor losses that affect the pressure drop throughout the system. The interdigitated design holds two key minor losses that affect the system, bends and the dead ends. The dead ends require a forced flow over the ribs to enhance the diffusion rates. Bernoulli's equation was used to determine the pressure difference, and can be found in Equation 6 below.

$$P_1 + \frac{1}{2}\rho {V_1}^2 + \rho g z_1 = P_2 + \frac{1}{2}\rho {V_2}^2 + \rho g z_2 + \frac{fL}{D}\frac{\rho V^2}{2} + \Sigma K \frac{\rho V^2}{2} \qquad (6)$$

The first step in producing the pressure drop from the equation above is to find the value of the Reynolds number. The Reynolds number is a dimensionless value that is the ratio of the inertial forces over the viscous forces. This value determines whether the flow is laminar (low Reynolds numbers) or turbulent (high Reynolds numbers) and can be determine by using Equation 7 on the next page.

$$Re = \frac{\rho V D}{\mu} \qquad (7)$$

The current set up has produced a Reynolds number of 0.42. In Equation 6 the friction factor f, is found by using correlations of the Reynolds number. This calculated Reynolds value is too small to find a friction factor value of the system. Research has been conducted to find the behaviors of extremely low Reynolds numbers and it has been determined that the current feeding pressure is too low to analyze the system. To receive a numerical value of pressure drop for the serpentine design a new selected fluid velocity has been chosen to carry out necessary calculations. The velocity of 6 m/s. The velocity has been increased to produce a Reynolds number that is relevant to further carry out pressure drop calculations. This value has also been carefully selected to ensure that the flow is still in the laminar region. If the flow rate and feeding pressure is too high other problems can occur such as flooding within the cell. The current setups geometries and dimensions have been kept constant to see if the end pressure result is possible. Using equation 7 above to calculate Reynolds number, a new value of 56.45 was found. This value was then used to calculate the pressure drop at velocity flow rate of 6 m/s. The total minor loss values have been calculated by summing the total amount of bends in the system where one bend value of K has been determined by interpolating in Table 2 [8].

Table 2- : Geankoplis table of friction losses for non-turbulent flow

Re	50	100	200	400	1000	Turbulent
K_f	17	7	2.5	1.2	0.85	0.75

Table 2 shows the correlated minor loss coefficient for 90º bends in a fuel cell system. It has been assumed that for the 180º bends the associated K value has been doubled. By using the modified Bernoulli's equation, a pressure drop of 0.1663 psi has been calculated. The feeding pressure from the electrolysis set up must overcome this pressure to drive the fluid throughout the system efficiently.

It has been determined that the feeding pressure is too low with the current electrolysis set up to feed the cell efficiently and to overcome the pressure drop associated with the new configurations. There are some methods to increase the feeding pressure which will result in a faster flow rate. By speeding up the electrolysis reaction, the system will split the hydrogen and oxygen molecules at a faster rate, therefore increasing pressure within the cylinder and forcing the gas through the inlet tubes to the cell at a faster rate. There are some factors that can speed up the electrolysis reaction process. The voltage potential and current used to initiate the electrolysis process is directly proportional to the reaction time. To increase the voltage and current to the cylinders, an adjustable DC power supply will be used instead of the 9 Volt battery. The power supply will allow the user to change the current and voltage as necessary to achieve a usable flow rate. The adjustable power supply allows for the team to speed up the reaction and pumping to the system to overcome the energy losses within the system.

5.0 Potential Experiments for an Educational Kit

Ultimately, the goal of the educational alkaline membrane fuel cell kit is to encourage and facilitate learning. The kit provides an opportunity for hands on experience with a technology that is still on the forefront of research and development. There is currently an endless supply of fuel cells available on the market today that provide a working fuel cell. What separates this kit is that it provides an opportunity for users to experiment with different factors which affect the performance of a fuel cell.

The main idea is to provide a kit which allows the user to assemble the fuel cell with a matching pair of endplates. These endplates will have a specific flow configuration which determines how hydrogen and oxygen are distributed onto the surface of the electrodes. The operator will run the fuel cell, and record the results. This includes current and voltage output which can then be used to calculate power output. Measurements will be taken using a Fluke 116 digital multimeter. This multimeter will allow the user to take measurements at a very high resolution so that users can develop a very thorough understanding of the fuel cells performance. The multimeter can record minimum and maximum values during operation, and can also produce a bar graph of measured values. Once the user has taken measurements for one set of endplates, the fuel cell can be turned off by disconnecting the gas delivery lines. Then the fuel cell can be allowed to cool down so that it can be disassembled. The fuel cell will then be reassembled with a different pair of endplates. Measurements can then be taken, and then compared with the previous results. Furthermore, the Fluke 116 is compatible with a thermocouple attachment. Users can allow the fuel cell to reach a steady state of operation, and then they can record temperature readings at different locations on the endplates. This will allow the user to determine how evenly the current density is distributed throughout the fuel cell. This can be concluded based off the idea that a higher current density is correlated with higher temperatures. Finally, the DC power supply which will be used to power electrolysis will have an adjustable current and voltage output. The rate at which electrolysis occurs is directly dependent on current. The adjustable power supply will allow the user to increase current, in turn increases flowing rate. This will allow the operator to see how the fuel cells performance increases with a higher flow rate.

Once completed, the fuel cell kit will contain all the components necessary to assemble, operate, and experiment with a fully functioning fuel cell. Along with a user’s manual, which will be included to prevent injury or damage to the fuel cell, the kit will also include guidelines and examples of experiments that the user can conduct. These components combined will provide the user with a means to gain an in-depth understanding of fuel cell operation.

6.0 Safety

As mentioned, the alkaline membrane fuel cell kit is designed to be an educational kit. Because of this, safety is a major concern in the design and selection of different components within the kit. As with any fuel cell, there are going to be several inherent safety risks due to the manner of their operation. These safety risks pose a risk both towards the integrity of the fuel cells operation, as well as the user of the fuel cell. These safety risks include electrical hazards, temperature hazards, and toxicity hazards. These hazards and respective measures taken to prevent injuries and failures within the design will be discussed further below.

The first and most obvious safety concern for the kit is electrical shock. Although the fuel cells current and voltage output will operate at safe levels, it is important to eliminate any risk of shock. Within the fuel cell, it is very important to prevent a short between the two end plates as well as the anode and cathode. To prevent this, polymer gaskets will be placed between the electrolyte impregnated membrane and each electrode. This will prevent an internal short which could cause extreme local heat generation at the location of the short, potentially damaging the membrane causing gas crossover. Ultimately this would lead to failed operation of the fuel cell. Additionally, to combat shorting between the two end plates, an external gasket will be used to separate the edges of the endplates. As for minimizing electrical hazards to the user, the design will facilitate a hands-off testing approach. Once fully assembled, the fuel cell will remain stationary, and won't require any contact to measure voltage and current output of the fuel cell during operation. To ensure of this, a baseplate has been designed which will hold the fuel cell in place while testing. This base plate can be seen below in Figure 11, and will prevent the need for the user to reposition or stabilize the fuel cell during operation.

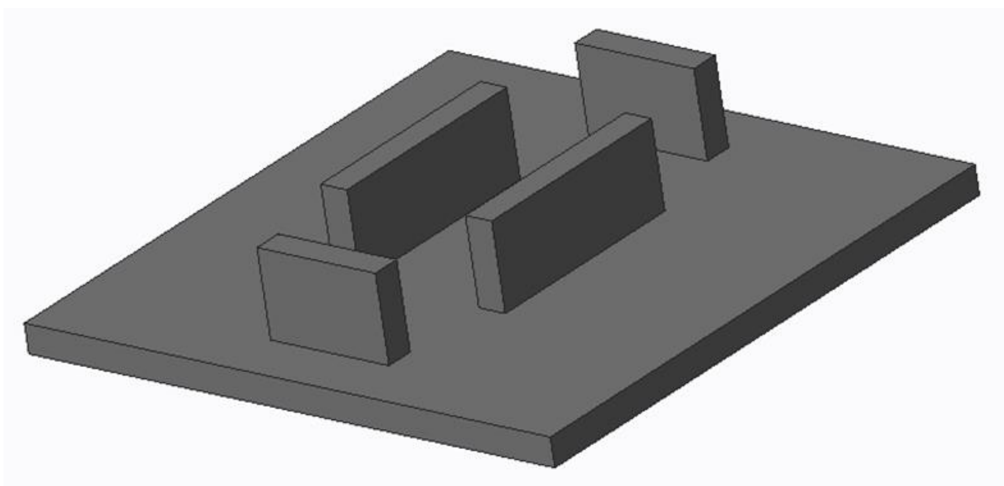


Figure 11- Base plate (5 X 5 X 0.25 in)

The baseplate will be constructed of FR-4 laminate which is an excellent insulator of electricity. Additionally, each endplate will have built in notches in which the user can then attach the leads of the digital multimeter with insulated alligator clips prior to operation. This will ensure that the user won't have to adjust any electrical connections during operation and risk electrical shock.

Another safety hazard which has been analyzed is the risk of high operating temperatures. The main preventative measure for preventing burns will be to avoid touching the fuel cell during operation. As with anything, there is no way to make the design 100% safe. High operating temperatures, while less extreme than in other types of fuel cells, are unavoidable in an alkaline membrane fuel cell. Many of the same features used to prevent electrical shock will also serve to prevent burns. The baseplate will keep the fuel cell stationary to prevent the user from reaching out and grabbing or touching the fuel cell. FR-4 laminate has a maximum recommended operating temperature of 285 degrees Fahrenheit. Alkaline membrane fuel cells have a maximum operating temperature of around 212 degrees Fahrenheit. This ensures that the baseplate can withstand the fuel cells maximum operating temperature. Additionally, secure electrical connections will reduce the need for adjustment during testing. If adjustment is needed, large insulated alligator clips will provide a safe means to do so. The design intends for the user to be able to take endplate temperature readings using a thermocouple, which makes it important to leave the fuel cell uncovered. Because of this it is important for the user to use utmost caution during use.

The last safety hazard present in the kit is the risk of acute toxicity and/or irritation caused by the alkaline solution. The alkaline solution will consist of potassium hydroxide at a concentration of 40%. This solution will saturate the membrane, and will require handling by the user. The kit will require but not include the user to wear standard laboratory protective gear. This includes but is not limited to lab goggles and chemical resistant gloves. To prevent unintentional spillage of the solution from within the fuel cell, a silicon gasket will be used to seal the entire fuel cell.

Safety is extremely important in the design of the educational alkaline fuel cell kit. However, to keep the kit hands on, and to allow the kit to facilitate learning, it is impossible to eliminate all safety hazards entirely. To prevent any injury, the kit will require the user to thoroughly understand all risks associated with operating the kit. This includes taking all listed safety precautions, and being aware of said risks. This means the operation of the kit will likely require supervision by an experienced laboratory instructor depending on the age and experience of the operator.

7.0 Project Management

As with any project, it is important to organize each step of the project into different sections with specific goals. Having goals helps the project maintain a linear path towards completion, and helps ensure completion of important tasks necessary to complete the project.

This has been and continues to be an important part of Team 16's design process. Initially, the most important tasks were to recognize the needs of the customer, as well research the science and fundamentals behind how a fuel cell operates. Background research was conducted, and a HOQ was completed. Once the team had the knowledge necessary to understand the task at hand, the design and planning process was begun. The team members used their knowledge in engineering, coupled with the needs of the customer to begin improving the old fuel cell kit, and ultimately designing the new fuel cell kit. An FMEA was conducted to provide a thorough evaluation of potential design flaws. Constraints were used to help guide the team along the way. Additionally, Team 16 periodically communicated with Dr. Juan Ordonez to receive advising on the project.

7.1 Budget and Parts List

This projected was allocated a budget of $2000. The goal is to keep the cost of the design and manufacturing to a minimum while maintaining integrity, durability, and safety of the kit. Currently none of the budget has been spent on the project. Planning and attention to detail has been placed on materials and parts selection to avoid unnecessary spending. A table of parts to be ordered at the beginning of Spring 2017 can be found below in Table 3. The first four parts account for the digital multimeter and the components required for the measuring of the performance of the fuel cell during operation. A Fluke Multimeter was chosen to be included in the kit for measuring Ohmic outputs. Fluke has a reputation for reliability, accuracy, and affordability in the market of digital multimeters. The Fluke 116 model allows for the use of a thermocouple for temperature testing, as well as a relatively high resolution in voltage and amperage readings. Additionally, Fluke components were chosen to pair with the Fluke Multimeter to ensure compatibility. Part number 5 includes the material in which the new flow configurations will be machined out of. 304 stainless steel was chosen to maximize thermal and electrical conductivity, while also minimizing the risk of corrosion. Part number 8 accounts for the material in which the baseplate will be constructed. The baseplate will secure the fuel cell during operation. FR-4 laminate was chosen due to its high maximum operating temperature of 285 degrees Fahrenheit, as well its ability to insulate against heat and electricity. Finally, part number 9 is the power supply which be used to power the electrolysis process. The power supply is a variable linear single-output DC power supply. It allows for an adjustable output of up to 30 volts and 5 amps to allow for an increase in electrolysis rates. As of now, the parts list totals to $586.56 not including sales tax and shipping. This accounts for about 30% of the allocated budget, and leaves a substantial amount of money for additional purchases of materials and manufacturing costs.

Table 3: Table of parts to be ordered

Item Number	Component Name	Quantity	Source	Price
1	Fluke 116 Multimeter	1	amazon.com	$147.95
2	Fluke 80BK-A Temperature Probe	1	amazon.com	$44.99
3	Fluke 80AK-A Thermocouple Adapter	1	amazon.com	$31.94
4	Fluke X-Large Banana Clip Leads	1	amazon.com	$69.00
5	12"x36"x0.1875" 304 Stainless Steel Sheet	1	OnlineMetals.com	$118.69
6	12"x12" Teflon Gasketing Sheet	1	fuelcellstore.com	$13.00
7	12"x12" EPDM Rubber Sheet	1	fuelcellstore.com	$23.00
8	12"x12"x0.25" FR-4 Laminate Sheet	1	professionalplastics.com	$29.00
9	HY3005D DC Power Supply	1	amazon.com	$108.99
Total				$586.56

7.2 Schedule

As our project stands, we have completed our research, and the analysis of our design. All our research and information has been organized, and a parts list to be ordered has been put together. Additionally, we have talked to the machine shop concerning getting our materials machined and finished. As a team, our main priority is starting out the Spring Semester strong. This means that we must have all parts ordered within two weeks of the start of the semester. This will allow us to have the necessary time to machine and test our new parts. Once we can confirm that our fuel cell is operational, we can begin commercializing our kit. This will include organizing all necessary components within the kit in an attractive, and marketable fashion. This also means producing a user manual with safety warnings, operational instructions, and troubleshooting. Additionally, it will include a series of experiments for the user to conduct. These plans ensure that the initial goal statement of our project can be successfully completed by the end of the Spring Semester, and can be seen in a Gantt below in Figure 12.

Figure 12: Team 16 Gantt Chart

8.0 Marketing

Part of the sponsor's goal for the project is to develop commercialization of the fuel cell kit. The kit has demonstrated an opportunity for Team 16 as entrepreneurs. Developing the educational fuel cell kit has been determined to be an exceptional opportunity for eventual manufacturing and introduction to the market. Alternative energy is a high interest in today's society due to global warming. The targeted consumers of Team 16's fuel cell kit have been high schools, university labs, and science centers. Since the kit will include demonstrational experiments it is a good learning tool. The kit will engage students on a hands-on level about learning about renewable energy sources. More specifically, the science behind fuel cells. When people are engaged in learning, they retain information more efficiently. The kit will include all necessary parts and be easily assembled and portable. The case will be relatively lightweight and compactable resulting in a simplistic learning tool. Team 16 is passionate about spreading knowledge about clean energy sources, all the while doing it in a manner that can be fun and interesting.

9.0 Conclusion

The objective of this project is to test different flow configurations of an alkaline membrane fuel cell (AMFC) and determine all components of the configuration that effects the overall efficiency. The fuel cell will be used for an educational tool for high school and college level laboratory demonstrations. The kit will contain 4 different flow configurations, the parallel, serpentine, interdigitated, and Team 16's own configuration. By acknowledging the effects of different configurations on the fuel cell's efficiency, the team will develop their own configuration. The goal in optimizing the fuel cell is to reduce the pressure drop to allow for easy fluid flow through the system while simultaneously keeping diffusion rates high. The team has noted these characteristics, and conducted research and testing to produce a fully optimized channel. The team will eventually develop a model for commercialization of the kit to sell on the market to STEM institutions. Team 16 is currently in the process of finalizing the design of the overall kit. Moving forward, the team plans to have all necessary materials and parts ordered by the beginning of

Spring 2017. This will allow enough time for testing of the new fuel cell components, and completion of the finalized prototype.

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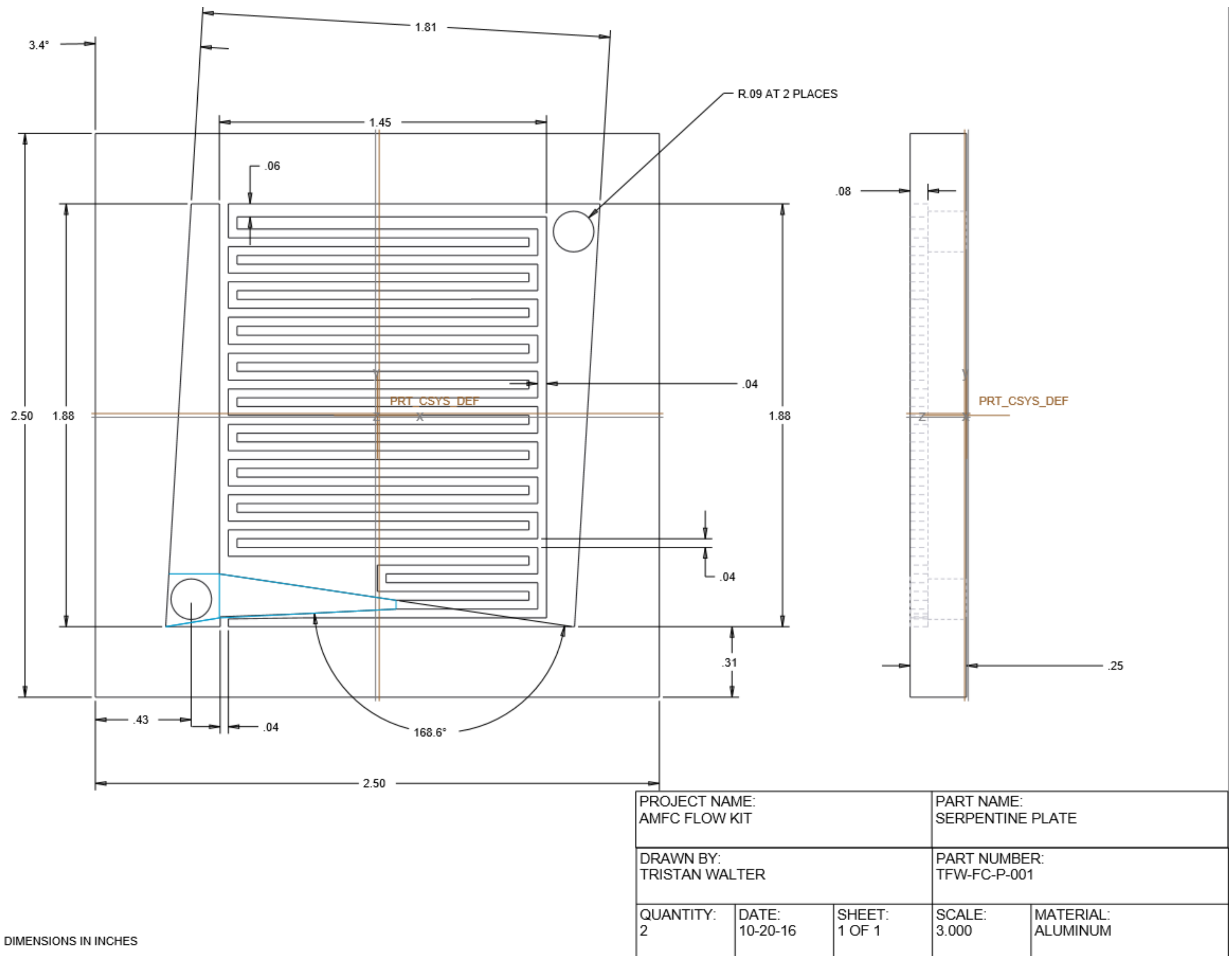
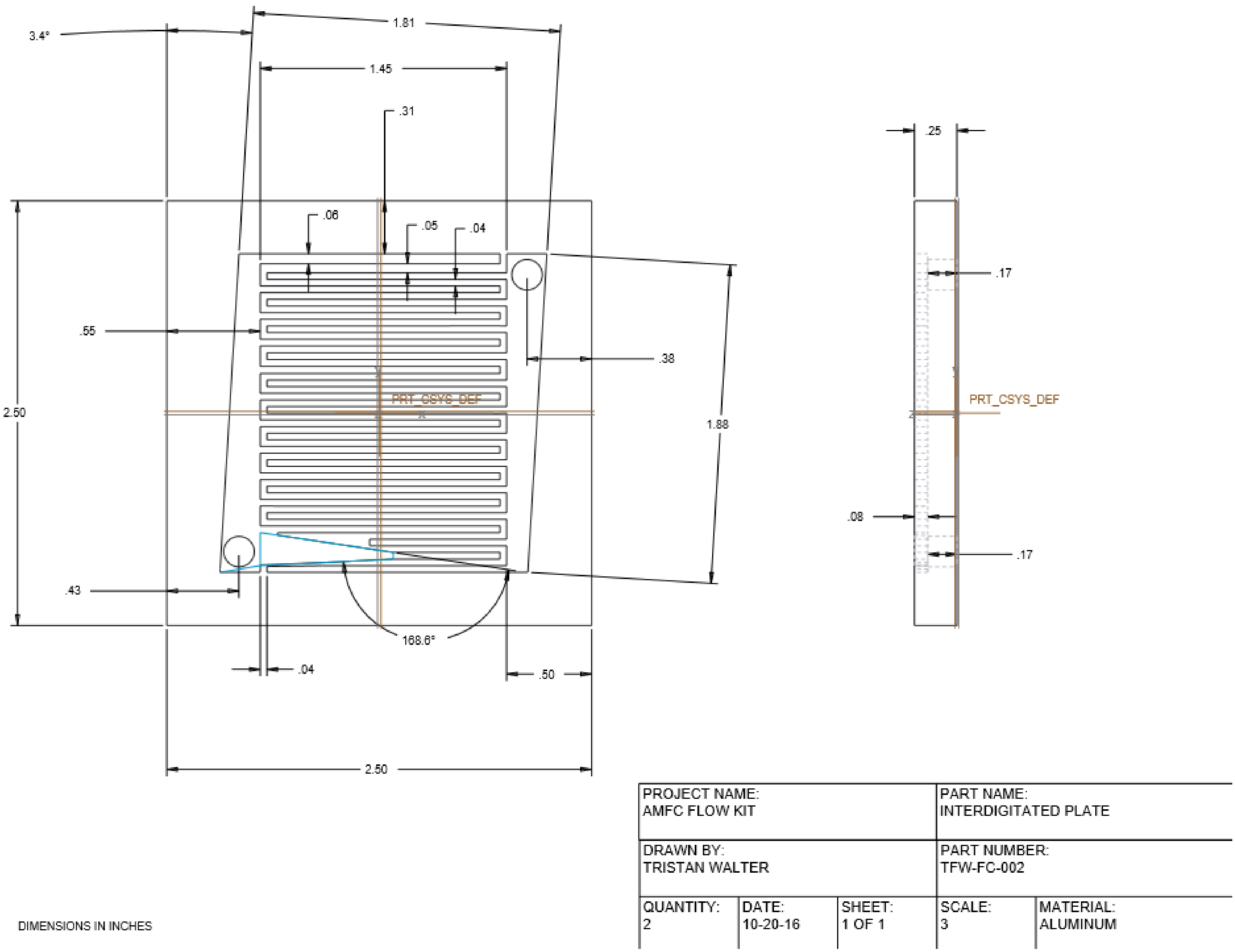
Appendix



CAD of Serpentine Design



CAD of Interdigitated Design