Appendix A: Winter 1997 Recommendation Report

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Appendix B: Data from Experiments 1a & 1b

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Appendix C: Surface Membrane Spectra

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Appendix D: Engineering Drawings of Final Prototype

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33

Fuel Cell Locomotive
Fuel Cell "Stack"

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35

Abstract

In June of 1996 an interdisciplinary project was organized with the goal of designing a fuel cell powered locomotive. The objective of this team of students is to design a fuel cell "stack" which is capable of producing a minimum power output of 5 kW. The fall 1996 fuel cell "stack" team examined conceptual and operational fuel cell stack designs, as well as heat and water management issues, and came up with a new method for fuel cell arrangement. This quarters team took the new fuel cell stack arrangement and considered its feasibility. Tests were conducted that suggested the need for a prototype. A design for the prototype was completed and manufacturing was started. In addition, calculations were completed that specify the amount of heat and water that must be removed. These removal processes will be examined in further detail next quarter.

Table of Contents

List of Figures

List of Tables

39

Glossary of Terms

- Hydronium- a H_3O^+ ion. H^+ will not exist in the fuel cell by itself so it attaches to a water molecule.

- Membrane- a semi-permeable material which allows the hydronium ion to pass through, but not the oxygen molecule.

- Mesh- a wire or graphite mesh which supplies an ellectrical path between the patch and the external electrical contact.

- Nafion- the brand name of the proton exchange membrane.

- Pads- the patch and the mesh

- Patch- platinum catalyst emulsified in a carbon ink that is applied to the surface of the membrane.

- SMMP- single membrane multiple pad. The new concept of a fuel cell stack by the authors of this report.

- SMSP- single membrane single pad. The common fuel cell design.

40

Introduction

Project Origin

The fuel cell locomotive is a senior design project created to incorporate different engineering disciplines into one project. "The project is a unique combination of the new and promising technology of fuel cells with the long standing tradition of rail transportation." (1) The project is supported by a group of about 20 students from various disciplines including: Chemical Engineering, Mechanical Engineering, and Electrical Engineering. The project is broken down into five smaller groups: Single Cell - Fuel Cell, Fuel Cell Stack, Chassis/Shell, Drive Train/Brakes and the electric motor group at Penn State University. This report describes the work of the fuel cell stack team which consists of two chemical and two mechanical engineering students.

Background of the Fuel Cell

Fuel cells operate in a manner similar to storage batteries in which a chemical reactions occurs causing a flow of electrons through an external circuit. As shown in Figure 1, an external supply of fuel and oxygen gas are supplied such that the reaction can occur for very long periods of time. Here, the fuel is hydrogen gas which is exposed to an electrode. The electrode is a platinum catalyst emulsified in carbon ink that is painted onto both sides of the electrolyte. The electrolyte used is a Nafion membrane or a proton exchange membrane (PEM) which allows hydronium ions and water
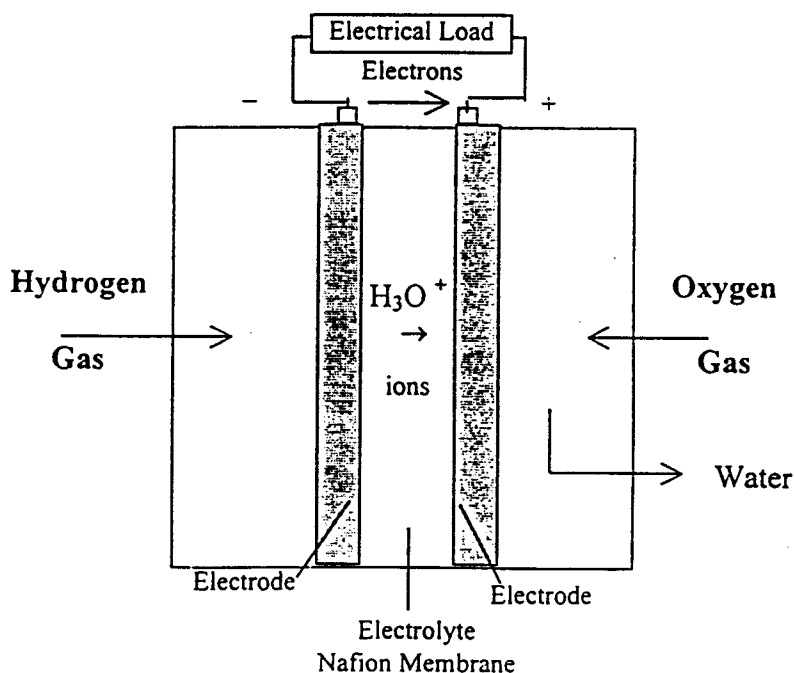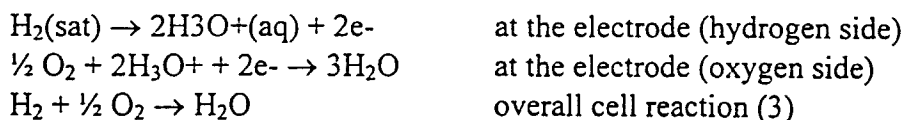

Figure 1. Schematic diagram of a hydrogen-oxygen fuel cell.

molecules to pass through the membrane, but does not allow the passage of oxygen molecules. Hydrogen molecules exposed to the electrode lose electrons forming two hydronium ions that pass through the water-saturated Nafion membrane. The electrons that were lost pass through an external circuit to the electrode on the other side. Here they recombine with the hydronium ions that passed through the Nafion and an external supply of oxygen to form water molecules. The electrode and overall cell reaction equations are:

$$H_2(sat) \rightarrow 2H3O+(aq) + 2e-$$ at the electrode (hydrogen side)
$$\tfrac{1}{2} O_2 + 2H_3O+ + 2e- \rightarrow 3H_2O$$ at the electrode (oxygen side)
$$H_2 + \tfrac{1}{2} O_2 \rightarrow H_2O$$ overall cell reaction (3)

Each of the fuel cells has an open-circuit voltage of around .7 to 1 volts and a current of one ampere per square centimeter. Therefore the desired power output is obtained by combining many fuel cells. Previous designs generally accomplish this by stacking the cells on top of each other, thus the term fuel cell stack. It is the objective of this team to combine a set of single fuel cells in such a manner that a desired output of 5 kW is obtained.

Design Requirements Identified Fall Quarter

As described in the fall quarter progress report (2), the fuel cell stack requires a cooling system, consisting of a heat exchanger within the stack, a pump, and a radiator outside of the stack in order to maintain the fuel cell stack at the optimum operating temperature. (See Figure 1, Appendix A) The tanks for the H^2 and O^2 must be easily refillable and of an appropriate size to be carried on the locomotive. Humidification tanks for each of the gasses are also needed in order to maintain the proper humidity within the fuel cells.

Requirements for the power were also determined fall quarter. The initial working power specifications were set at 5 kW output from the fuel cell stack for operation of the required motors. If 1 ampere is produced per square centimeter of reaction area, a minimum reaction area of 7000 cm^2 is required.

In addition to system requirements and power requirements, heat and water management were additional constraints considered both fall and winter quarters. In order to keep the cell from flooding, all of the water produced as a result of the chemical reaction must be removed. This is critical because the Nafion membrane must remain completely saturated to maintain the desired reaction rates. Flooding or dehydration of the membrane reduces the rate of reaction and thus the power output. For these same reasons, the heat within the reaction area must be controlled. It was estimated by Dr. Gottesfled that the optimal operating temperature of the fuel cell is 80°C. It was estimated in the fall quarter progress report that the heat that must be removed is about 106 W per 100 cm^2. Given a reaction area of 7000 cm^2, a total of 3200 W must be removed for the entire fuel cell stack. (2)

42

Fall Quarter Design Concepts

The initial design concept was based on the Ballard fuel cell stack patents (4) (patent # 5260143). In this design, the membrane is sandwiched between two graphite coated aluminum plates. The gasses pass through a serpentine pattern that is etched into the plates such that the gasses have turbulent flow while exposed to the membrane, which increases the rate of reaction. Thirty-six such cells, each with a reaction area of 100 cm^2 would need to be connected in series to form one stack. Two such stacks would be needed to produce the required power output based on a one ampere per square centimeter. The fuel cell plates contain two inlets and two outlets each for the gasses and the cooling water (See Figure 2, Appendix A). With this design, seals are required for each plate at every gas or cooling water inlet and outlet, between each plate. This amounts to more than 8000 seals which induces a large probability of leaks. Therefore a new design was considered. (2)

The objective's of the new design are to reduce the number of seals required and increase the output voltage. This concept uses only one membrane with multiple reaction pads (See Figure 3, Appendix A). This requires only one seal around all of the pads and gives a potential between each of the smaller pads. This new design is described in further detail in the following section. (2)

Winter Quarter Goals

The goal of the fuel cell stack team for winter quarter is to determine the feasibility of the new concept, design, build and test a prototype of the new concept for fuel cell arrangement. This quarters goals also include doing calculations related to heat and water management.

Current Leakage Experiment

Results and Discussion

The new concept originated from the need to minimizing the number of o-rings required to seal the fuel cell system. The fuel cell stack team brainstormed a new concept fall quarter which consisted of a single membrane with multiple reaction pads (SMMP), such that the reaction areas were located in the same plane. The membrane would essentially serve as a barrier between the two gasses eliminating the need for seals between gasses, and therefore the fuel cell system would only require one o-ring around the outside of all the reaction pads.

It was determined at the end of fall quarter that the concept would only work if the membrane was electrically non-conductive between the catalyst pads on the single membrane. Conductivity between the pads would result in a short circuit and thus producing no power. Therefore, at the beginning of winter quarter, the following experiment was designed to test the SMMP arrangement.

Objective

The objective of this experiment was to determine if current would travel between two pads of different voltage potential and separated by a specified distance. If current did travel between two of these pads, the objective was to find the minimum distance allowable between pads.

Procedures

Two plates of 3 x 3 inch square Plexiglas 1/8 inch thick were assembled by four #8 x 2" zinc plated screws. The screws were separated by nylon spacers, that were 1" x 0.125" ID x 0.375" OD. Seven #8 screws were assembled with nuts threaded to the head and then screwed into the seven holes located in the top plate. (Figure 2) The following procedures were followed in conducting the current leakage experiment.

1. Create a template of desired pattern (Figure 3) for platinum/carbon ink overlay.
2. Have single cell group prepare Nafion with the template as shown in Figure 3.
3. Soak Nafion test pattern in de-ionized water; maximum water absorption is preferred.
4. Place Nafion test Pattern in test stand on top of the bottom plate shown in Figure 2. Tighten the screws onto the pads.
5. Fill large beaker with de-ionized waster and heat to 80°C. Maintain temperature at a constant 80°C.
6. Run tubing from H_2 gas supply to beaker and bubble slowly into the de-ionized water.
7. Wire test stand as shown in schematic (Figure 4)
8. Measure the current between the hot wire (black) and each of the other wires. Record the current measurement at each wire.

Top View

8 screws

Side View

1 inch long
0.375 in O.D. x 0.1875 in I.D.
nylon spacer.

Figure 2. Test Stand for Current Leakage Experiment.

Carbon ink pads
indicated by
shaded area.
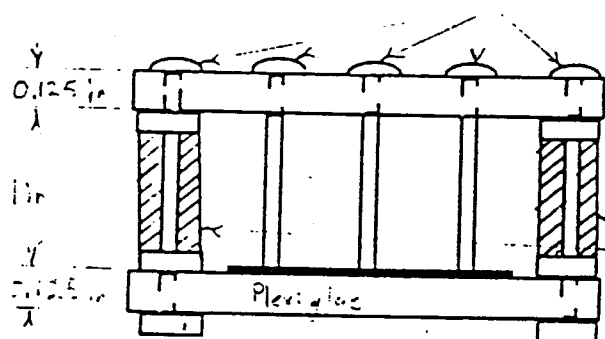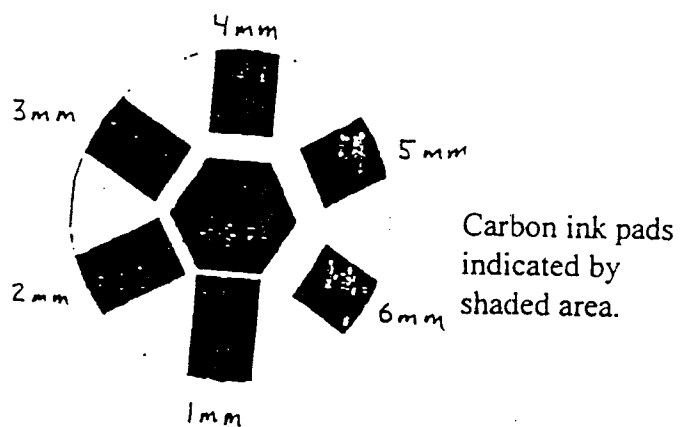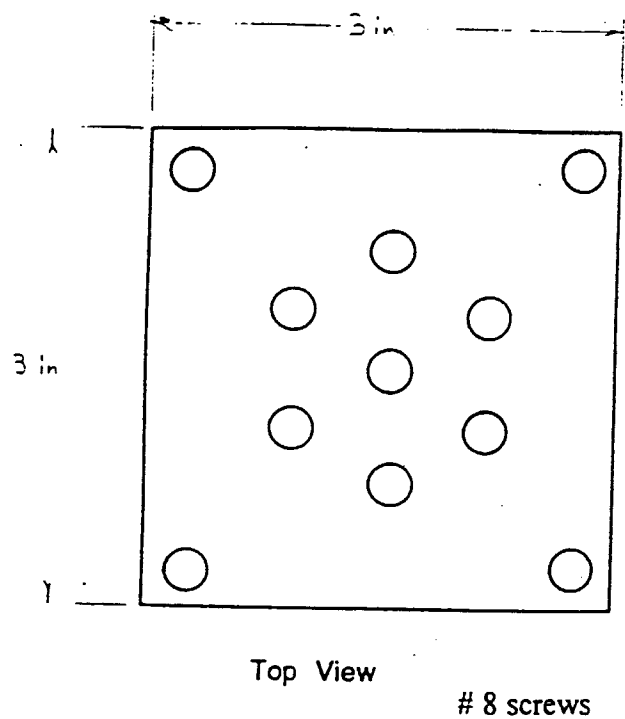
Figure 3.

Test Pattern for Current Leakage Experiment.

gap on Nafion
6mm 5mm 4mm 3mm 2mm 1mm
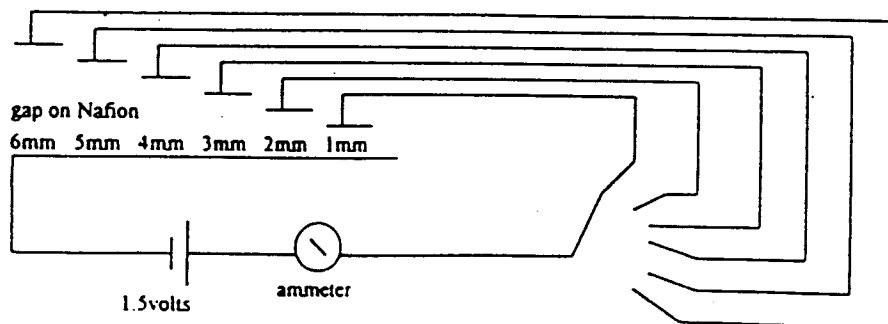
1.5volts   ammeter

Figure 4. Schematic for Test Stand.

Conclusions and Recommendations

The results of the experiment are shown in Table 1. The results did not show a pattern relating current produced to the distance between pads. These results were discussed with Professor Eric Stuve and produced the following conclusions:

Table 1. Current Leakage Experiment Results

Run #1 - Ran Experiment as Described	
Distance Between Pads (mm)	Current (milliamps)
1	0.14
2	1.75
3	0.48
4	0.72
5	1.62
6	1.25

Run #2 - Checked Connections	
Distance Between Pads (mm)	Current (milliamps)
1	0.44
2	1.48
3	0.77
4	0.73
5	0.61
6	0.9
Wire lead in water	0.03

Run #3 - Conducted Experiment in Air	
Distance Between Pads (mm)	Current (milliamps)
1	0.08
2	0.50
3	0.15
4	0.45
5	0.08
6	0.22
Wire lead in air	0.00

- The metal screws in the water bath may have produced an electrochemical reaction that may have increased the conductivity of the water.
- It is unlikely that $H+$ ions were released since there was not an oxidized component in the experiment. Therefore no hydronium ions were released into the membrane and there was not an increase in conductivity.
- Very small currents were detected. We assumed that the current observed was the upper limit of the current which may occur between pads in the working stack.

- The conclusion reached was to proceed with the prototype because a prototype would be the best way to simulate the actual environment of the fuel cell. Therefore, the prototype would be the best way to test for current leakage.

Prototype Design

Results and Discussion

Results from the current leakage test indicated the most efficient method to test for current leakage was to build a prototype. A prototype would also be the most efficient way to characterize heat and water management issues along with test various types of meshes. The fuel cell stack group discussed various elements that should be included in the prototype design. The prototype should contain four cells. At least two cells are needed in order to determine if there is current leakage however, four cells would allow different parallel/series wiring arrangements and comparison experiments of different meshes. The total surface area would be about 56 cm^2 in order to achieve the most accurate results from heat and water management experiments. The significant elements that make up the prototype are:

- *Plates* - The plates should be made out of a non-conductive material. They must be able to withstand a continuous temperature of 80°C and a maximum pressure of 75 psi. They must be easy to manufacture in the University machine shops, affordable, and readily available. In addition, each plate should have recessed areas of approximately 14 cm^2.
- *Filler and Adhesives* – Fillers and adhesives must be available for replaceing material lost in the milling process.
- *Membrane* - The proton exchange membrane (PEM) should have four pads (standard process for pads as provided by single cell group). The pads should be separated by a gap of not more than 10 mm and not less than 3 mm based on the discussion with Professor Stuve regarding the current leakage experiment.
- *Meshes* - Various meshes should be tested that provide turbulent gas flow and that act as an electrode for the pads.
- *Tabs* - Metal tabs should be present for conduction between the mesh and the external electrical connection.
- *Fittings* - Standard fittings (English Units) should be used to connect to the O$_2$/H$_2$ supply lines.
- *Seals* - The prototype should have a single seal around all of the reaction pads.
- *Clamping* - A clamping method must be designed for easy assembly and disassembly of the stack.

The first prototype design shown in Figure 5 incorporated all of these elements. The prototype is 127 mm x 127 mm and the plates are 12.7 mm thick. The four cells each measure 18 mm x 18 mm, and they are separated by a distance of 5 mm. The resulting total reaction area is 5544 mm^2. The seal is an o-ring in a groove around the outside of all the reaction pads.

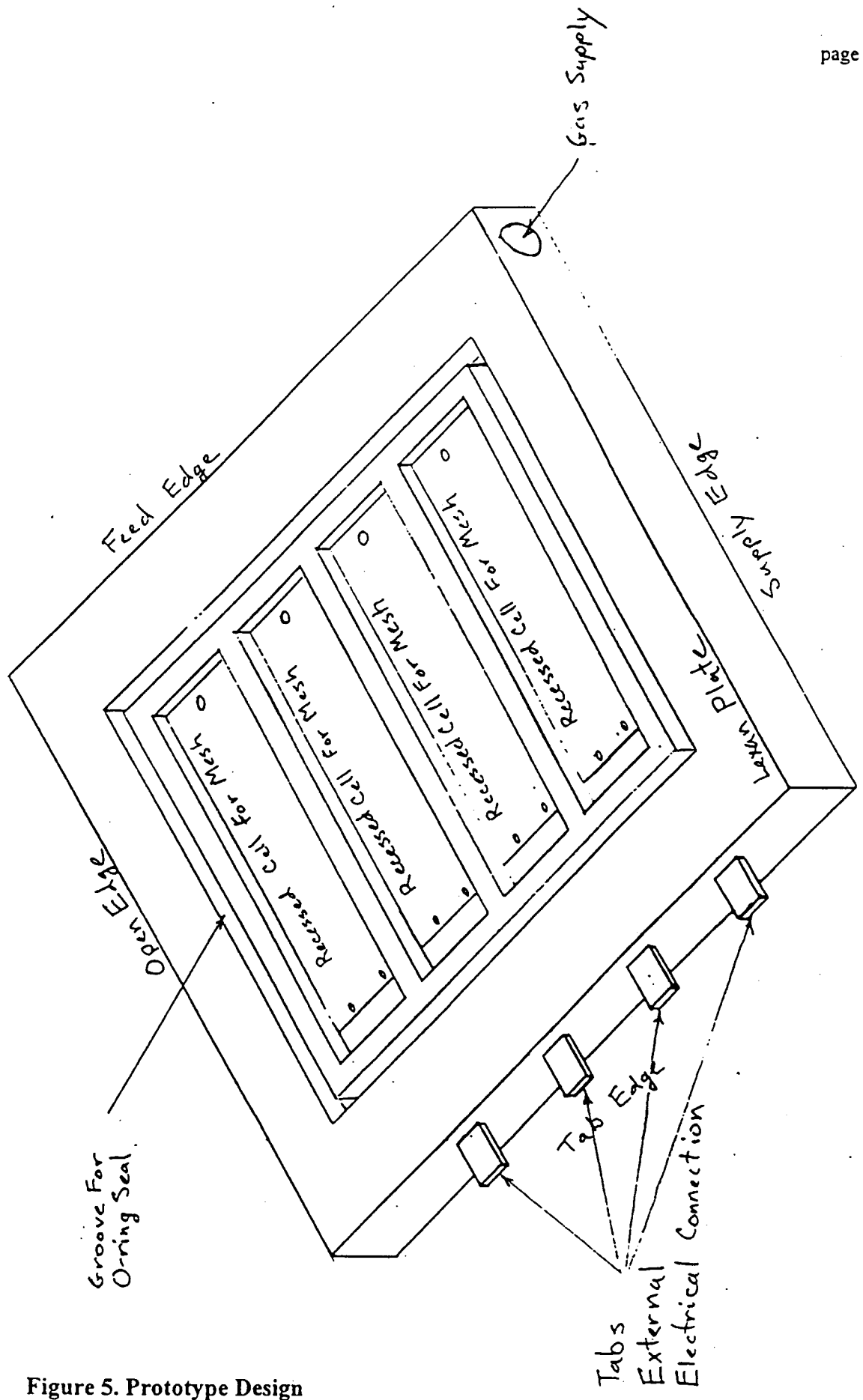Figure 5. Prototype Design

Gas Supply

Feed Edge

Open Edge

Groove For
O-ring Seal.

Recessed Cell For Mesh

Recessed Cell For Mesh

Recessed Cell For Mesh

Recessed Cell For Mesh

Supply Edge

Lexan Plate

Tab Edge

Tabs
External
Electrical Connection

The following sections explain the significant elements of the prototype in further detail.

Plates

Two materials for the plates were compared: Acrylic (Plexiglas) and polycarbonate (Lexan). Both are electrically non-conductive, readily available, and easily machined. Table 2 compares important properties of Plexiglas and Lexan. (5) (6)

Table 2: Comparison of Plexiglas MI-7 and Lexan

Property	Test Method	Plexiglas MI-7	Lexan
Specific Gravity	ASTM-D792	1.17	1.2
Hardness, Rockwell	ASTM-D785	M 68	M 70
Resistance to heat	(continuous) C	74-85	121
Heat Distortion °C (Pa)	ASTM-D648	85(1.8e6)	135(2.5e6)
Water Absorption %	ASTM-D570	0.3	0.15

The plate contains four recessed areas that are 18 mm x 77 mm and 2.54 mm deep, to hold the meshes. The recessed areas are separated by 5 mm. A groove that is 6mm from the recessed area measures 3.175 mm wide and 3.05 mm deep, and is milled for a 0.125 in diameter o-ring seal.

The plates shown in Figure 6 are constructed in the following manner:

1. The material in the recessed cell areas and the groove for the tabs is removed by milling. (Detailed milling instructions found in Appendix x)
2. The tabs are placed in the groove with adhesives and the remainder of the groove is filled in with a filler and adhesive. (The filler and adhesive is discussed below.)
3. The filler and adhesive is allowed to harden and a groove for the o-ring is cut.
4. The supply line is made on the drill press. Drilling will begin from the supply edge of the plate.
5. From the feed edge of the plates, a feed hole is drilled through the supply line to a point just below each recessed area.
6. The hole from the feed edge to the supply line is plugged with the filler/adhesive and allowed to harden. The supply line is re-drilled to clean out residue.
7. The inlet port is drilled from the bottom of the recessed area to the feed line.
8. Two holes for the outlet ports are drilled from the rescued areas to the exterior face next to the contact area of the tab.
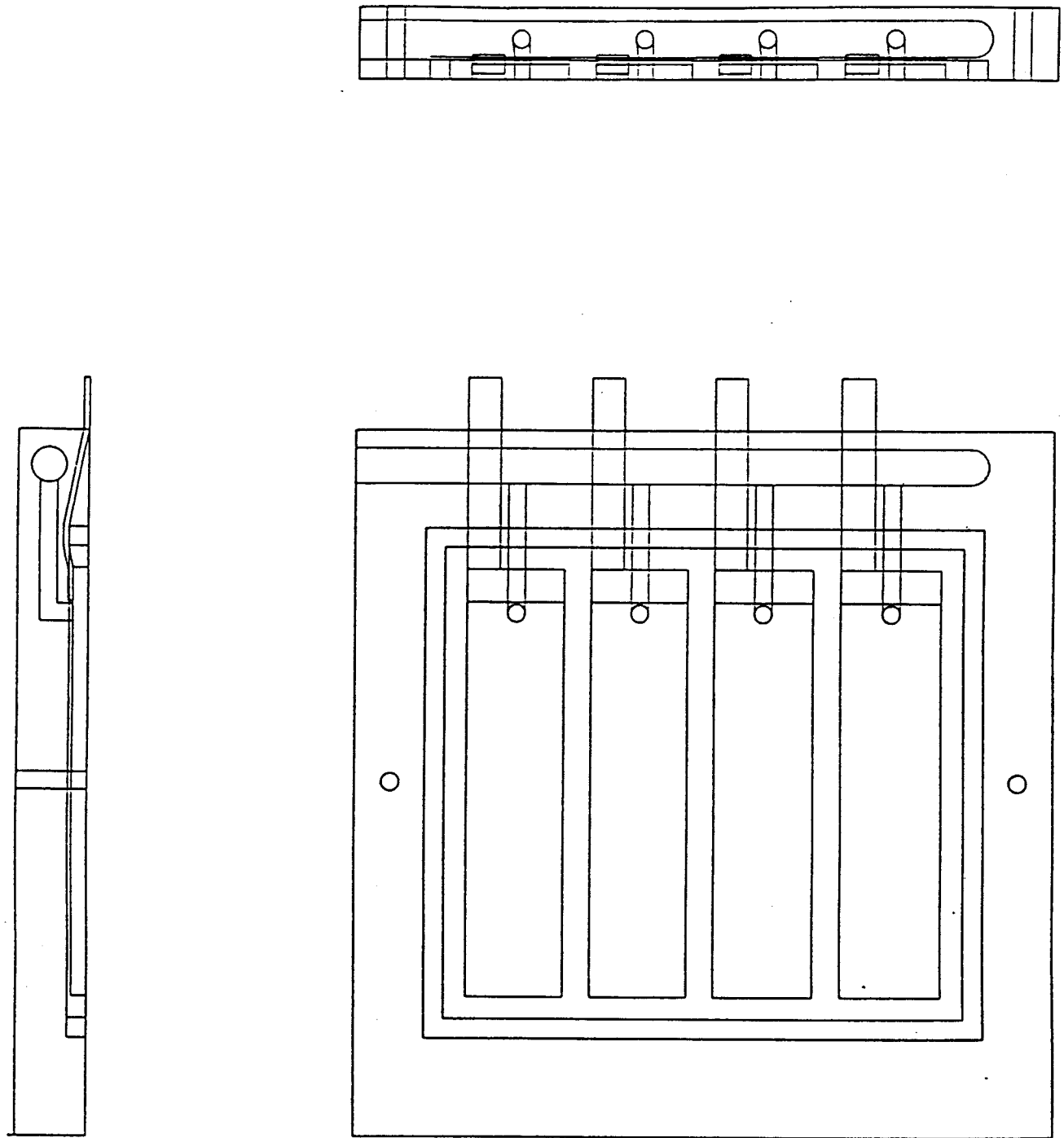
49

Figure 6. Configuration of Prototype Plates

Filler and Adhesives

Fillers and adhesives are needed to fill in grooves in the Lexan plates that are made during milling. There are few adhesives that adhere to polycarbonates and still withstand the pressure and temperature that will be experienced by the prototype. Some solvents would work except that the conditions under which they are applied are too hazardous. Therefore, two adhesives will be tried: Weld-on 16 (IPS Corp.) and Araldite 2042 (Ciba-Giegy).

Filler materials are necessary to replace the material lost during milling. The filler material will be made from strips of Lexan cut to fit and/or Lexan shavings mixed with the adhesive.

Over spring break, the team will conduct a test for the adhesives on an extra piece of Lexan. (Figure 7) A groove 0.25 in wide and 0.1 in deep will be cut one inch from the edge of the plate. A hole will then be drilled from the edge to just below the groove. Another hole will be drilled from the bottom of the groove to meet the first hole drilled. The groove will then be filled in with filler and adhesive and allowed to harden. From the edge of the plate a groove 0.125 in wide and 0.125 deep is cut across the filled in groove near the hole. This will test the machinability of the filler and adhesive. The first hole will be tapped and fitted with a 0.25 in compression - 0.0625 in NPT brass fitting. The plate will then be submerged in a tank of 80°C water and air at 75 psi will be applied to the fitting. Observations will be made and the test piece will be checked for leaks (indicated by bubbles) or catastrophic failure.
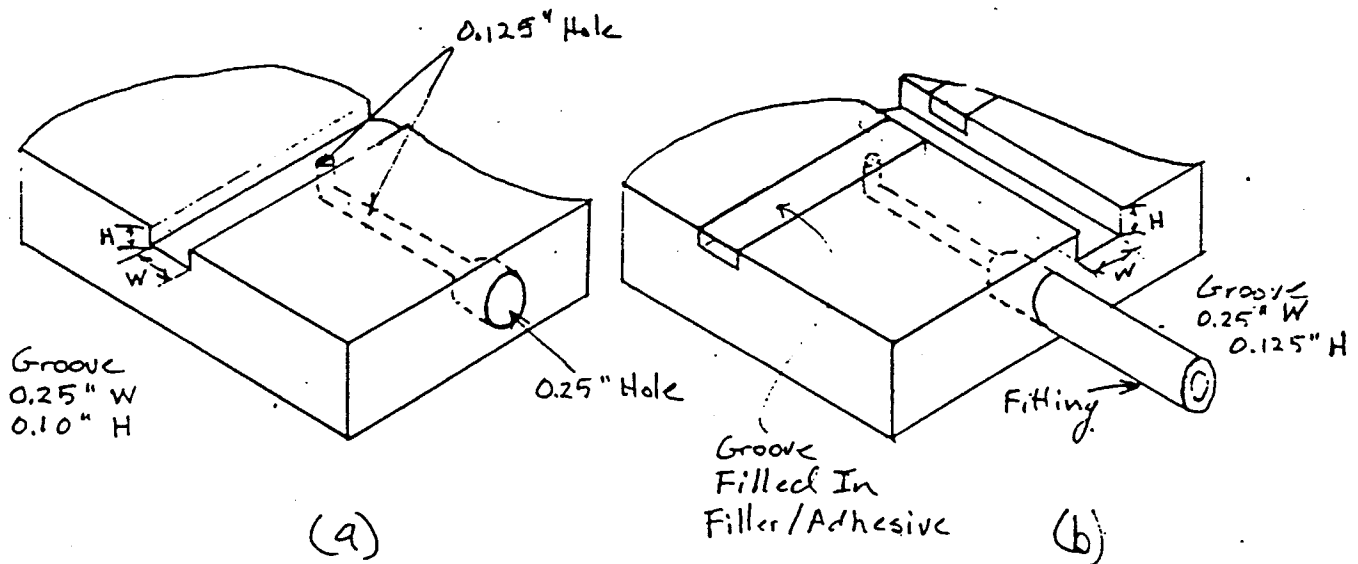

Figure 7. Filler and Adhesive Test

The first adhesive being tested will be Weldon 16. The machinability will be tested and the pressure test will occur first week of April.

Membrane

The PEM will be 127 mm x 127 mm and will have four pads that will align with the recessed areas in the plates. The membrane preparation will be done by the single cell group with aid from the stack group

Meshes

Background

The stack group will be using stainless steel mesh screens coated with graphite as a gas diffusion device and as an electrode for collecting the voltage. The reason for using the graphite coating is that it is the same material as the carbon filter paper that is used as the catalyst. One major issue confronted by the single cell group was corrosion of a graphite disk. In a sample fuel cell, a graphite coated gas diffusion disk was corroded after long periods of operation. This corrosion was due to the fact that the graphite coating was peeling or chipping away from the base material. It was therefore necessary to determine a graphite coating method that would minimize the possibility of the base material becoming exposed.

Purpose

The purpose of this study was to determine the most efficient way of graphite coating the stainless steel screens. The methods investigated for the graphite coating were:

1. Graphite vaporization with a graphite coated string.
2. Graphite vaporization with a pure graphite rod.
3. Polymer coating
4. Graphite coating with method 2 then Electrodag
5. Graphite coating with Electrodag and Aerodag.

Methods

Graphite Vaporization The vaporization was conducted in an evacuated environment. Electrical current was sent through a graphite coated filament, where the filament was heated and the graphite evaporated onto the screens. Method 1 used a graphite coated string about one inch long for the filament; method 2 used about a 4 inch long graphite rod.

Regular Graphite Coating The regular coating was conducted with Electrodag and Aerodag. Electrodag is a graphite solution that is mixed with an isopropanol solvent at a volumetric ratio of three parts isopropanol to one part Electrodag solution. Aerodag is a prepared graphite solution in an aerosol can that can be directly applied. Both methods were

baked in a furnace for about 10 minutes at a temperature of about 75°C after the graphite was applied. The purpose for the baking was to evaporate the solvents.

Results

Method 1. This method required a long setup time to evacuate the coating chamber, and we were only able coat one screen at a time. The coat was very thin and flaky, and required several applications. This method was eliminated due to the poor graphite and the long application time.

Method 2. This method also required a long setup time to evacuate the coating chamber. In addition, the setup for the graphite rod was long due to the fact that the rod had to be sharpen. The graphite rod was very brittle which caused a lot of downtime. The final coat was cleaner and thicker than method 1, but not thick enough. At least two applications were needed to coat both sides of the screen. In addition, only one screen could be coated at a time.

Method 3. The mesh screen was coated with a polymer. The coated screen was place in a furnace that used argon instead of oxygen; oxygen would have converted the carbon into carbon dioxide. The furnace was held at 400 °C for 1.5 hours, until the polymer was reduced to carbon. Only one screen could be process each time. The coating was poor and left clumps.

Method 4. This method took the graphite coated screen from method 2 and then coated it with Electrodag to provide the desired coating. The final coat was very desirable but the application time was long.

Method 5. In the final method, the screen was initially coated with Electrodag to provide a rough coat and then it was baked at 75°C. Next, Aerodag was applied and baked. The Aerodag application was conducted a second time. Finally, a final coat using the Electrodag was applied. The result was a desirable coating that was thick enough for application. Furthermore, four screens could be coated during this proceed instead of one. The time consumed in coating was considerably less.

Tabs

The tabs will be made from 18 Ga. stainless steel sheet metal. (Figure 8) The long leg of the tab will be folded across the short side as shown in the figure. The short side of the leg will fit into the end of a recessed cell. The tab will then be glued in place and the tab groove filled. The exposed surface of the tab will be coated with graphite to prevent corrosion.
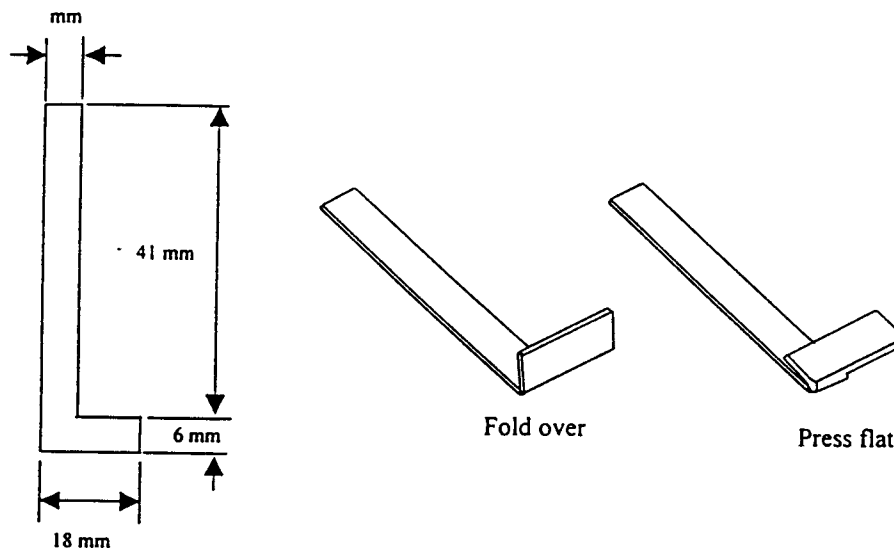
Figure 8. Tab Configuration

Fittings

The prototype includes areas where connections need to be made. These connections will be made by using fittings. The following are the two types of fittings that will be tried:

- First is a brass fitting ¼ in compression- 1/16 NPT . The supply line will be tapped for NPT and the fitting installed. If the fitting leaks when tested with compressed air (75 psi) then silicone sealant will be used on the threads.
- Second, a heavy walled (0.065 in thick) copper tube will be threaded with standard ¼ NC. The supply line will be tapped with ¼ NC threads. The tube will be screwed in and tested with compressed air (75 psi) for leaks. Silicone sealant may be used to stop small leaks.

Seals

An o-ring seal will be placed in a 0.125 wide x 0.12 deep groove cut into the plate around all of the recessed cell areas. The o-ring seal will be tested to 75 psi and may hold up 45 psi under normal fuel cell operations. The o-ring will be made from nitrile or silicone bulk o-ring seal cord. The joint is held by RTV silicone adhesive. The length of the o-ring is measured from the centerline length of the groove.

Clamping

The clamp to hold the assembly together will be made from two ¼ in thick aluminum plates. Each plate will be 4 in wide and 6 in long. One half inch will extend over the supply

and open edge of the plates. Four bolts through holes in the overhang will hold the assembly together. See Figure 9.
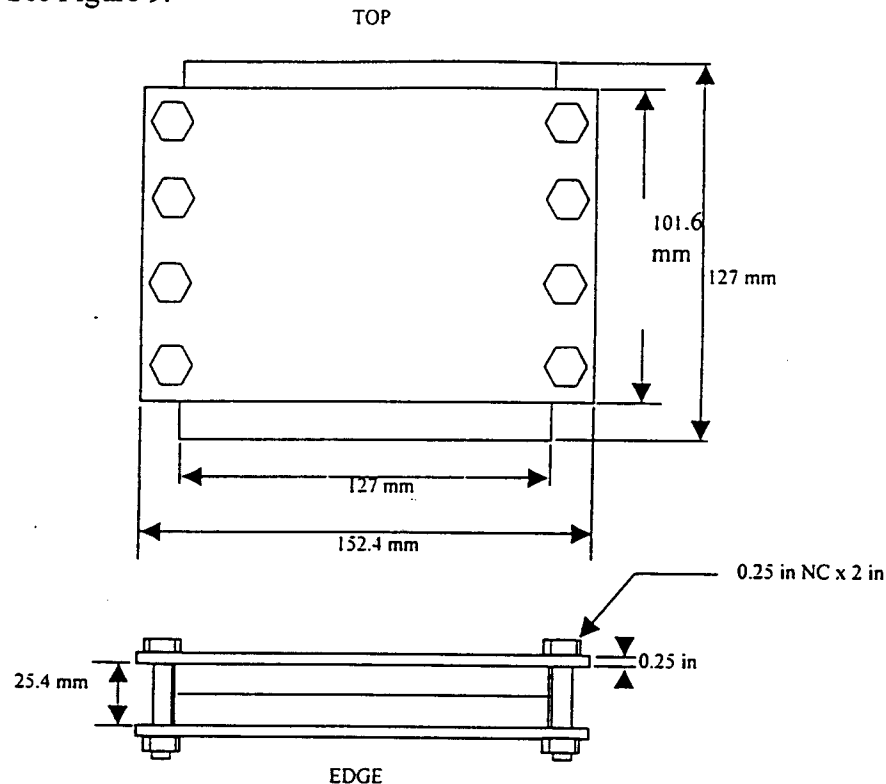
TOP

101.6 mm

127 mm

127 mm

152.4 mm

0.25 in NC x 2 in

0.25 in

25.4 mm

EDGE

Figure 9. Clamping of the Fuel Cell Assembly

Conclusions and Recommendations

The plates for the prototype have been milled for recessed cell area and tabs. The supply, feed, and exhaust holes have been drilled. The adhesive tests still need to be completed; the Weld-on 16 appears to be okay but the pressure test will be completed the first week of April 1997. When the results from the adhesive test are in the tabs will be glued into place and the tab groove filled with the filler/adhesive. The final operation to the plate is to make sure the surface is smooth and mill the groove for the o-ring.

The development of a process for coating the stainless steel screen with graphite is complete. Methods 1, 3, and 4 were too time intensive and methods 1 and 2 could only process one screen at a time. Methods 1, 2, and 3 had poor graphite coating. Method 5 will be the method used to prepare the meshes for the prototype; all of the stainless steel screens can be processed at the same time with a very good graphite coat.

In April the following items need to be completed for the prototype: the tabs need to be formed into their final configuration; different types of fittings will be tested; make the o-rings; complete final design and make the clamp.

Project Constraints

Results and Discussion

As mentioned in the beginning of this report, there are three primary project constraints. They are: power requirements, water management and heat management. These constraints are discussed here in detail.

Power Requirements

The total power of the plant (as previously stated) is 5 kW. The fuel cell will be producing 1 Amp/cm^2 reaction area. The voltage per cell was specified to be 0.7 Volts/cell. Once the overall voltage is specified the following relationship can be employed to determine the number of fuel cells required in the plant and the size of the cells (See Equation 1).

$$\textbf{Total Voltage from Plant = 0.7 V/Cell * \# cell/plant} \qquad (1)$$

In a similar manner, the size of each cell can be found by using the following relationships (See Equations 2).

$$\textbf{Total Power = 5 kW = Total Current * Total Voltage} \qquad (2)$$

Penn State required a total potential of 300+ Volts. To provide this with a margin of error, 500 cells will be implemented. This will create a potential of 350 Volts.

Using this potential, the power requirement, and the 500 cells, it can be deduced that the cell size must be 14 cm^2. This amount to cells which provide 10 kW of power each for the new concept.

It is necessary to determine the amount of inlet gas stoichiometrically required and to feed that amount of gas to insure the specified power requirements are met. This can be performed using simple electrochemical equations (see Appendix C, page 1). The stoichiometric requirement for power production are outlined in Table 3.

Table 3. Stoichiometric Requirement for Power Production

	Required Fuel	
Oxygen Gas	2.6E-6 [moles/(cm^2*s)]	0.083 [mg/(cm^2*s)]
Hydrogen Gas	5.19E-6 [moles/(cm^2*s)]	0.01083 [mg/(cm^2*s)]

Water Management

As previously stated, all of the water taken into the stack and all of the water produce by the reaction in the stack must be removed to keep from flooding the Nafion. On the other

end of the spectrum, if too much water is removed the cell will dehydrate. Both flooding and dehydration must be prevented in order to maintain the desired reaction rate.

Nafion is a biphasic material, which simply means that a portion of the cell is hydrophilic, and a portion of the cell is hydrophobic. In this membrane, the internal portion of the sheet is hydrophilic, absorbing water to remain saturated. The exterior of this cell is hydrophobic, driving water from the surface of the membrane. If too much water collects on the surface, it will create a barrier, preventing the reaction from taking place. If there is not enough water present, water will glean out of the center of the cell, reducing the internal conductivity of the cell, and inhibiting hydronium ion transport across the membrane.

To transport the necessary fuel across the cell, there must be water present. There is an osmotic drag associated with the transport of 1.1 moles water/moles H_2 to 2 moles water/moles H_2 (4). This translates to a need to greatly humidify the hydrogen inlet fuel gas. The oxygen gas should not be humidified as removing water introduced with the hydrogen gas will be difficult on its own, and because it is desire to create an osmotic driving force to carry hydronium ion across the membrane thereby improving the reaction rate.

Based on the hydrogen gas requirements of 5.19E-6 mole/(cm^2*s), the moles of water introduced can be found. Assuming 1.445 moles of water for every mole of hydrogen, the inlet hydrogen gas must be humidified at 84°C to provided the required moisture (see Appendix C, page 3 for further details of calculations).

Humidification is just one method by which water is introduced to the cell. Water is also produced within the cell via the reaction. This produced water amount to 0.0932 mg/(cm^2*s). The sum of the total water introduced by humidification and production then are known and a method for removing it must be found.

A straight-forward way to remove the water is to transport it out of the stack in excess oxygen gas as a vapor. The cell will be operated at 80°C, so the excess oxygen exiting the stack can be assumed to be at this temperature. The humidity of water in oxygen at 80°C is calculated via partial pressure s and the ideal gas law and found to be 0.6042 lb., water per lb. O_2 (See Appendix C, page 2). The total water to be removed equals the water introduced with the humidified hydrogen gas and the water produced by the reaction. With the use of the humidity, the oxygen required to transport it out of the cell can be calculate. Five and seven-tenths times the stoichiometric requirement of oxygen must be used to remove all of the water (Appendix C, page 4). All water management issues have been addressed and have initial with them. Now, physical tests must be performed to determine how accurate the calculated values are.

Heat Management

When a heat balance is performed on the stack, it can be concluded that all of the heat introduced via inlet gases plus all the heat produced must be removed. Some of this heat is going to leave the stack with the outlet gases, and a bit more by natural convection through the walls but the remainder must be removed with some sort of a cooling system.

The total heat introduced into the system by a 24°C oxygen stream and an 84°C stream of humidified hydrogen amount to approximately 0.53 W/cm^2. The heat produced by the reaction is calculated to be 1.03 W/cm^2. The total heat lost via gases leaving the stack is approximated as 0.73 W/cm^2 (see Appendix C, page 5). To determine the heat lost to natural convection, a cavity calculation must be performed. All of the previous calculations are

based on a reaction area, which is not possible for a cavity calculation. It is calculated based on the size and materials of the prototype, and found to be 5.27 W (see Appendix C, page 6). The prototype has a reaction area of four 14cm² pads, or 56 cm². Now, all the calculations can be standardized on a basis of the prototype. The following relation is used to predict the heat which must be removed by the cooling system (See Equation 3):

Heat of cooling = Heat [produced + introduced − removed (walls & gases)] (3)

This yields a required heat removal of 41.7 W for the prototype.

Conclusions and Recommendations

The calculations for the water and heat produced and removed have been completed, and the following conclusions were reached:
- With the use of the humidity, the oxygen required to transport it out of the cell can be calculated. Five and seven-tenths times the stoichiometric requirement of oxygen must be used to remove all of the water (Appendix C, page 4).
- The total amount of heat that needs to be removed from the prototype is 41.7 W.

Based on these conclusions, a cooling system must be examined that will remove the 41.7 W remaining. Once this is completed, the prototype can be used to test our calculations and adjustments to humidification and cooling can be made.

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