Microbial Fuel Cell
Using Inexpensive Materials

Group #4
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Abstract
We built and tested a microbial fuel cell using low-cost materials. Our intention is to test the use of two new materials: Gore-Tex as a proton exchange membrane and loose-weave carbon fiber cloth as the anode. While the cell functioned it produced disappointingly low power densities due to slow diffusion through the Gore-Tex. Its price per watt of power produced compared unfavorably to Nafion.

Introduction
Conventional PEMFC design focuses on achieving high power densities for weight-critical applications such as transportation. Microbial fuel cells cannot achieve comparable power densities due to their inherent limitations. Microbes produce hydrogen at a much slower rate than fuel delivery systems in conventional fuel cells and demand much more space than is typically available. To maintain an anaerobic environment at the anode we need to maintain a gap of several centimeters from the membrane and the oxygen at the cathode, further slowing hydrogen diffusion. Thus microbial fuel cells must be much larger and are not suitable for weight- and space-critical applications.

Instead, a typical installation would be as a cogeneration unit at a wastewater treatment plant or other biomass site such as a paper mill or brewery. The unit is stationary and quite a lot of space is available. The critical measurement is, instead, cost. Several components of a PEMFC fuel cell are very expensive; the Nafion membrane is costly and
the electrodes contain precious metal catalysts such as platinum. Logan and others (documented in his book *Microbial Fuel Cells*) have thus focused on finding alternative, inexpensive replacement materials. 

In this spirit we have built a microbial fuel cell using materials as inexpensive as possible. We intend to study the use of two replacement materials. Standard carbon cloth electrodes often become clogged in microbial fuel cells because the pore sizes are comparable to the dimensions of the microbes themselves. Dead microbes often fill these pores and reduce the effective surface area of the electrode. Since other researchers have found that the microbes do not need a platinum catalyst at the anode, we will build ours using a different type of carbon fiber material. While it is also a cloth, ours was designed for use in composite materials. Having a much looser weave it should provide larger spaces for microbial colonies. It is also much less expensive than conventional electrodes.

The second material is a new membrane. Nafion, the standard material, is polytetrafluoroethylene (a.k.a. Teflon) with added sulfonic acid functional groups. Those groups provide gateways for the transport of cations, including $\text{H}^+$, across the membrane. Since the current densities are much lower in microbial cells, though, we will explore the use of Teflon without any added sulfonic acid groups. Marketed under the name Gore-Tex, it is currently used as a semi-porous cloth in high performance winter outerwear. It is of interest because of its dramatically lower price. While Nafion can cost as much as $1,500 per square yard Gore-Tex can be purchased for $19 per yard, two orders of
magnitude less. We hope that this difference will compensate for any loss in current density.

Materials

Less than three hundred dollars was spent to obtain the materials for the cell. Three materials were ordered by mail and represent most of the cost:

- Carbon cloth impregnated with platinum 1 mg/cm² (XC-72, 17 cm x 17 cm), $149.99
- Gore-Tex fabric, $18.49/yard
- Plain Weave Carbon Fiber Fabric (5.7 Oz/Sq Yd, 50" Wide, .012" Thick, 12.5 x 12.5 Plain Weave), $59.99/yard

While we ordered a yard of each fabric to meet the minimum order size this was far more than we needed to build one cell. Other materials were obtained at a local hardware store:

- Two one-liter bottles of soda pop
- Plastic Tubing
- Roll of aluminum screening (36” x 84”)
- Two aluminum hose clamps
- Tube of silicone caulk
- Recycled plastic milk jug
- Box of probiotic septic system treatment, Rid-X brand
- 1 lb. Bag of Table Sugar

Design of the Fuel Cell

The fuel cell is single chambered with an open air cathode. Its form is cylindrical, with the anode placed along the axis and the cathode wrapped around the outside of the chamber. This is very different from traditional fuel cell geometry but provides some unique benefits for microbial cells. Since the anode interacts with colonies of the
microbes it must provide a hospitable environment; shelter, in other words. Electrolyte flow is necessary to keep the microbes supplied with nutrients but can also disrupt and move the colonies themselves if it is too forceful. This cylindrical layout allows us to design a cathode with a three dimensional structure – a series of folded sheets, in our case – that provides the nooks and crannies necessary to promote stable microbe colonies. Testing of this geometry, however, is not our primary focus.

The apparatus consisted of four containers connected with clear plastic tubing. Besides the reaction vessel, we stored electrolyte in a recycled milk jug that was raised above the top of the vessel to provide a gravity-driven drip feed. Next to this was a bottle filled with water used as a gas trap. Any gasses building up within the reactor (say, air leakage or carbon dioxide produced by the microbes) would rise through a tube into this bottle and bubble through the water to the surface. This tube was also occasionally used to drain the reactor. Finally, a plastic catch basin was placed beneath the reactor to contain leakage and depleted electrolyte solution.
Coffee filter holds solids

Electrolyte Reservoir

Water

Plastic Tubing

Anode

Cathode wrapped around bottle circumference

Excess gas from bottle can bubble to surface

Catch Basin
A one liter polycarbonate soda pop bottle was used as the reaction vessel. Its overall dimensions were standard; 12 inches in height and 4.5 inches (11 centimeters) in diameter. The circumference is 34 centimeters. The anode was inserted into the middle axis of this bottle and emerged through the neck opening; two tubes were also threaded through the neck, one leading to the electrolyte reservoir and one to the gas trap.

The cathode was wrapped around the middle of the bottle. Windows were cut through the plastic to allow contact with the electrolyte. The most expensive component – carbon cloth impregnated with platinum catalyst – dictated the cathode dimensions. We purchased a 17cm by 17cm square of the material; this was cut in half lengthwise. The two pieces were then wrapped around the middle of the bottle. The windows were cut to
be slightly smaller than the carbon cloth. They were laid out manually using quarter inch masking tape. First two pieces were wrapped around the diameter, separated by 8 centimeters; then the tape was applied in a zig-zag pattern between the two edges. The plastic under these pieces was left to connect and support the top and bottom of the bottle. They were applied at roughly a 50 degree angle and formed three V-shapes:

![Pattern of windows, unrolled, ¼ scale](image)

Unfortunately the layout lacked precision but we can estimate the total area:
6 triangles with 10 cm base x 7 cm altitude: $6 \times \frac{1}{2} \times 10 \text{ cm} \times 7 \text{ cm} = 210 \text{ cm}^2$

These windows were overlain with three layers of material. First, a strip of Gore-Tex about six inches wide was applied with the membrane side down. The edges of the fabric were sealed with silicone caulking applied to the plastic of the bottle along all of the cut edges (including the V-shaped connections) and along the vertical seam at the end of the fabric. Next the two pieces of carbon fabric electrode were placed over the area of the windows. Last, a strip of aluminum mesh screen material was wrapped around the outside; the excess was folded together and rolled down flat against the bottle. The layers were then secured to the bottle using a pair of aluminum hose clamps at the top and bottom edges.
The anode consisted of a different type of carbon fiber cloth. This loose-woven material is manufactured for reinforcement of composites rather than use as an electrode. It is not coated with any catalyst. We cut a 6” by 50” strip of the cloth and applied tape to the edges to prevent unraveling. We then folded and stacked the cloth into a two-inch wide fanfold. This was slipped inside a strip of sheet aluminum. Half an inch wide and a yard long, we bent the aluminum 180 degrees at its midpoint until it folded back upon itself using hand tools. The carbon cloth was forced up against the fold. To insure good physical and thus electrical contact the loose ends of the aluminum were bound closed with rubber bands. The finished anode had a diameter of approximately two inches, leaving about an inch gap between the outer electrode and the membrane. This gap is within the 1 – 4 cm range tested in air cathode cube reactors by Logan et al (p.87) and near their observed maximum at 2cm.

**Construction**

Some deficiencies in the design became evident during the construction. We had difficulty making the reaction vessel waterproof. As the silicone caulk cured the membrane edges wrinkled, creating gaps where leaks developed. This was repaired by sewing the lower portion of the Gore-Tex seam with needle and thread to take up the tension, followed by liberal application of more caulk. If we built another fuel cell of this design we would sew the entire seam closed in this manner.
Initial testing of electrical continuity across the aluminum mesh and hose clamps on the cathode indicated problems; this was alleviated by adding several rubber bands to apply pressure around the middle of the cathode.

Once the leaks were reduced to a slow trickle we inoculated the cell and began testing. The electrolyte was de-ionized water with sucrose and salt added. Because the microbes are biological creatures and require a variety of nutrients – not just the sugar we used as fuel – we initially added a variety of items to a coffee filter placed in the fluid reservoir:

1 cup of table sugar
1 teaspoon of iodized salt
2 tablespoons of probiotic septic system treatment powder (Rid-X brand)
1 multivitamin and mineral tablet
1 tablet of chelated potassium (99 mg)
1 tablespoon of coffee grounds
1 rusty screw (for iron)

Once the system was filled we applied a voltage across the terminals to encourage bacteria to colonize the anode and establish nanowire connections. This was done by turning our multimeter to the resistance measuring position and leaving the apparatus to culture overnight. In that time the measured resistance from anode to cathode reduced from a large value to 30 kOhms.

**Testing and Results**

We had great difficulty maintaining a consistent open cell voltage. Our first measurement was 360 millivolts. We then connected a 5 kOhm potentiometer as a load resistance and took a series of voltage and current measurements. As part of that series
the open cell voltage was measured as 343 mV. We then paused to add an additional resistor to the circuit so we could take more measurements at lower currents. At the conclusion of that second series we re-measured the open cell voltage. It had reduced to 215 mV. Suspecting that the cathode had dried out, we tried pouring liquid over the outside of the reactor vessel. This temporarily depressed the voltage (due to dilution of the reactants); when it had returned to equilibrium, though, we did not observe any improvement. We also dipped the reactor in a pitcher of water, yielding the same results.

Variations that large interfered with our ability to take meaningful measurements, so we decided to stop and regroup on a later day. When we returned, seven days later, the voltage had sunk to 128 mV. We then tried several interventions, one at a time, to see which might improve the voltage. First we added half a liter of de-ionized water to the electrolyte reservoir; then we raised the reservoir several inches to increase the pressure. These had a small effect on the voltage. Next we emptied half the contents of the reactor (about half a liter,) allowing it to re-fill with fresh fluid. This had a dramatic effect on the voltage; it spiked to 580 mV, our highest reading. The withdrawn fluid was recycled with added sugar. The voltage then started to ramp down slowly.

As we started to take our third set of data the open cell voltage was 434 mV. After five readings it sank to 411 mV. Acting on a hunch, we paused to lift the reaction vessel and give it a vigorous shake. This improved the voltage immediately; it peaked at 500 mV. After six more measurements we repeated the shaking and it improved the voltage to 506
mV. This procedure allowed us to maintain the voltage in the range 411-506 mV during the gathering of the third data series.

As you can see, the data does not conform well to any reasonable curve. The fluctuations in the open cell voltage during testing had a proportional effect on the measured voltage. Below is a second chart with the voltages normalized by dividing them by the observed open cell voltage at the time of each measurement:
This is close to a straight line for the second and third datasets. The first dataset also gives a straight line, inexplicably at a higher total current (short circuit i=16.3 rather than 11.5 microamps.) The reason for this is undetermined but may be due to higher salinity of the electrolyte during the test. Note that the data is linear right down to zero volts; there is no visible depletion region.
The load resistance at peak output power gives us the internal resistance: 58 kOhms. The peak current density, from the first data series, was: $16.3 \, \mu A / 210 \, cm^2 = 0.342 \, \mu A/cm^2$.

**Directions for Future Research**

Time limitations prevented us from completely characterizing the fuel cell behavior, optimizing the design, or stabilizing the open cell voltages. Profitable topics for further research include:

- Find the optimal level of salinity. The one inch gap between anode and cathode is typical of microbial fuel cells but is exceptionally large by other standards. The electrical resistance of pure deionized water could substantially contribute to the
overall ohmic resistance. For that reason some salts (potassium and sodium chloride) were included in the initial inoculation. However the amounts used were guesses; we are not sure they were adequate or optimal. We did not conduct this experiment because of the risk; a high level of sodium could alter the ecology of the cell or possibly kill all of the microbes.

- Improve circulation through the cell by increasing the flow rate of the electrolyte. We originally intended to puncture the bottom of the cell to provide an exit drip and keep the fluid circulating. However, leaks around the cathode provided the slight drip that we needed. A faster rate of drip would probably stabilize the variations in open cell voltage that we observed. We could not allow the cell to run dry, though; it would jeopardize the survival of the microbes. Since we did not have 24-hour access to the cell this meant we had to keep the drip rate slow enough that the cell could go several days without refilling. Our gravity feed design could support a much faster rate, though, if the apparatus is tended constantly. Circulation rate could be increased even more using a small pump, such as those built for use in fish tanks.

- The rate of sugar consumption could be studied using a hydrometer or refractometer. We did not attempt this due to the difficulty of verifying our measurements without proper equipment. The concentration of sugar in a pure solution can be measured easily by taking readings of the specific gravity of the liquid. Unfortunately the electrolyte in an MFC is a very impure mixture of many compounds. Hydrometer measurements would need to be confirmed against an independent standard or another method of measurement.
• Performance of the Gore-Tex might be improved if a thinner variety is used or if
  the membrane were hot-fused to the cathode. Also, a cell with the same geometry
could be constructed using Nafion to provide baseline data for comparison and to
evaluate the geometry of the design in comparison to traditional flat cells.
• Characterization of the fuel cell could be completed using impedance
  spectroscopy and cyclic voltammetry.

Conclusions

The open cell voltages produced by our cell compare favorably to those reported by
Logan. When the cell is tended and shaken frequently it can consistently produce
voltages from 0.4 – 0.5 volts; in a batch-fed MFC he reports voltages between 0.5-0.6
volts (p.83.) Given the lack of precision in our measurements, though, we did not detect
any handicap generated by our use of nontraditional carbon cloth in the anode.

Our results indicate a need for faster and better circulation of the electrolyte. This should
alleviate our problems with open-cell voltage consistency. It is notable that they
manifested as a reduction in voltage, probably due to dips in reactant concentration, but
no depletion region was seen on the current-voltage graph. It was linear throughout the
voltage range, the ohmic region extending all the way to zero voltage. This tells us that
the cell’s bottleneck was in cation transport.
This verdict is not favorable for our other innovation. The Gore-Tex membrane gave us very high internal resistance. Our measured resistance of 58 kOhms is orders of magnitude higher than Logan’s values; with Nafion he reports 1.3 kOhms in a bottle reactor and 84 ohms in a cubic reactor (p.69) This difference accounts for our dramatically lower power density of 48 microwatts per square meter. The chart below compares the important metrics (data is from Logan):

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Our Cell</th>
<th>Nafion Bottle Cell</th>
<th>Nafion Cubic Cell</th>
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</thead>
<tbody>
<tr>
<td>Internal Resistance (ohms)</td>
<td>58,000</td>
<td>1272</td>
<td>84</td>
</tr>
<tr>
<td>Max Power Density (μW/m²)</td>
<td>48</td>
<td>38,000</td>
<td>514,000</td>
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<tr>
<td>Membrane Cost ($/m²)</td>
<td>13.97</td>
<td>1400</td>
<td>1400</td>
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<tr>
<td>Power per Dollar (μW/$)</td>
<td>3.4</td>
<td>27</td>
<td>367</td>
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</tbody>
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Though Nafion is one hundred times as expensive as Gore-Tex, it still produces more power per dollar spent by a dramatic margin (one or two orders of magnitude.) Thus it cannot serve as a cost-effective alternative.

**Bibliography**