Anode Effects On Microbial Fuel Cell Efficiency

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Abstract— *The use of microbial fuel cells to detect anaerobes and power experiments in remote extreme environments is examined by a team of scientists and student teachers in a joint venture of the California State University system and NASA Ames. The economic viability of carbon fiber electrodes is tested by comparing their performance to graphite rods, which are commonly used. A connection between concentration of life and voltage output is indicated, which provides a potentially easy and powerful test for the presence of life in extreme environments such as found on Mars. Pollution free but low power density microbial fuel cells are shown to demonstrate viability as a power source for sensing applications.*

Keywords: Life in extreme environments, microbial fuel cell, life on Mars

1. Introduction

Two great questions confront scientists working in astrobiology and extreme environments. The first is how to detect life outside our planet, and the second is how to power equipment in extreme environments. In this paper we suggest a potential solution to both problems.

1.1 Detecting Life in Extreme Off-world Environments

Recent studies, see [4], have cast doubts on the interpretation of the 1976 experiments conducted by Viking, which indicate no life in the soil samples analyzed. The basic problem with Viking was that its experiments were destructive to organics, and required chlorine to be in a chloride salt form, when it turns out from Mars Phoenix Lander that chlorine is in perchlorate form. The new Mars Science Lab to be launched soon will hopefully clarify some of the results, but still the question remains as to what is a good way to detect life on another planet that has an extreme environment.

Ideally, we would like to submit the samples to a wide range of tests, but this is economically not viable. Detection of life is dependent on the form the life takes, so to detect life with a minimum of equipment requires some assumptions to be made. We postulate a few simple ones.

- First, if Mars had life, it was carbon based. Other elements like silicon has been suggested but we have no idea exactly what such a life would look like and thus it would be very hard to detect, and harder to prove.
- Second, if Mars had carbon-based life, it likely had microbial life somewhat similar to earth. This is reasonable for a variety of reasons, including ease of formation, durability, necessity in an ecosystem, possibility of cross-fertilization from impacts, and if not true it is unlikely we could guess the exact nature of life on Mars.
- Third, if Mars had microbial life, it likely had a range of anaerobes, as the atmosphere likely had higher carbon dioxide and less free oxygen than Earth.
- Finally, if Mars had anaerobes, metal reducing ones similar to Geobacter sulfurreducens were likely to exist, as they are widely dispersed on earth, and would fit the Mars well.

Metal reducing anaerobes could be present in the ground of Mars, and could even still be alive in Martian lava tubes, which would provide a viable system for them to still survive. Testing for the presence of metal reducing anaerobes, is thus a logical step to verifying if Mars has or had life.

1.2 Powering Equipment in Extreme Environments

One of the greatest challenges of exploring extreme environments is the difficulty of finding long-term, self-sustaining, and indefinitely sustainable power sources for the kinds of equipment that may need to remain in place for extended periods under incredibly inhospitable conditions. In the case of a Mars rover, for example, scientists and engineers can leverage the power of the sun using solar panels to charge and recharge on-board batteries. In other situations anchored to the ground, wind can be harnessed to provide a renewable energy source. Underwater, near the deep ocean thermal vents, engineers and scientists can access the heat rising from the Earth's core to power sensors or equipment for exploration within a certain range. As scientists and engineers begin to explore more and more extreme and remote regions that are lacking in these more obvious energy sources, a new question arises: specifically, what types of practical, cost-effective, self-sustaining power sources can we tap into in regions like the bottom of Earth's oceans - the kinds of places where sunlight does not reach, pressure is unbearable, oxygen is scarcely available, and our ability to fix or replace parts is extremely limited?

One of the most promising energy sources for this kind of exploration is so simple and omnipresent it might easily be overlooked: namely, the energy generated by the microbial life forms that can be found anywhere from the deepest reaches of the ocean to the shallowest mud puddle in a suburban back garden. If we could design and engineer a fuel cell that harnesses the energy of microbes in the deep ocean - or anywhere else in the Universe where they might be found - we could conceivably develop simple power cells fueled by microbes going about their daily business of metabolizing glucose, acetate, other organic materials, or even metals. And we could potentially do so for extended periods - for as long as a power source is needed.

1.3 Science Education

This paper presents the preliminary results of the work carried out by a group of science and math oriented student teachers under the supervision of scientists from several universities and two NASA labs, as part of the NASA/CSU Spaceward Bound Project funded by the California State University's Mathematics and Science Teacher Initiative Program. A major subgoal of this paper is to demonstrate how actual science can be performed in classrooms, and to instigate further classroom projects in this vein.

2. Experimental Setup

The purpose of this experiment was to test the viability of detecting low density anaerobes as well as to compare the potential energy yields and cost-benefit models that could be achieved using different forms of carbon anodes - in this case, comparing the efficacy of four one-half inch diameter graphite rods and six yards of six-inch woven carbon fiber tape. By deliberately starting from materials that are both abundant and inexpensive, our goal was to refine the design parameters for this new type of microbial fuel cell so that it could be more quickly, easily, and cheaply manufactured and deployed to remote locations anywhere they might be useful, from the deep mud of Earth's ocean floor to the potential use on Mars, Europa, or anywhere else.

The basic design of a battery is elegantly simple. It has two key parts: the anode and the cathode. In a bacterial battery, microbes attach to the anode. As they metabolize food, they create energy which wants to be released in oxygen. Since there is no oxygen at the anode, the energy transfers to the cathode through a wire. The movement of energy along the wire from the anode to the cathode creates a current which can be harnessed as usable energy. The use of microbes in this situation utilizes the chemical energy produced by the microbes and converts it directly into electricity as well as converting substrate into a source of electrons to complete the battery circuit. The bacteria are kept on the anode along with their food source. They convert their food source (often glucose) into CO_2, protons and electrons. The protons and electrons are then used for energy for the battery. Several different food sources have been tested including waste water, organic waste stream, and recycling waste water. All of these are rich in nutrients and provide amiable conditions for bacterial growth.

Although the concept of a microbe powered battery is wonderful in theory, in practice we needed to focus on inexpensive, widely available materials that could be used to amplify the amount of power being created. Typically, researchers have used graphite to make these batteries. For this experiment, four graphite rods were used ($1/18$ m^2) on one battery and 6' of carbon fiber (2 m^2) on the second battery. It is expected that the graphite rods generate more current energy per unit area but the expected increased area of carbon fiber will make a more cost efficient product. The carbon fiber is expected to have a lower cost per V-A than the graphite rods.

One very promising design has been researched and prototyped by a research group at The Pennsylvania State University. They have done work using both one and two chambered microbial fuel cell batteries as well as flat plate and salt bridge designs. All designs are tested and compared by the researchers in an effort to discover the most reliable design for production of energy with microbes. The microbes they use come from waste water, air, or soil. All bacteria are grown on graphite rods, or plates that provide a food source for the microbes.

Another design with great potential has been developed by the Geobacter Project, based at the University of Massachusetts, Amherst. Their design emphasizes their discovery of a strain of Geobacter with increased capacity for power production in microbial fuel cells which can be utilized in fuel cells as well as give insight for the mechanisms by which long range electron transfer operate in biofilm. Dr. Lovely and his fellow researchers hold that Geobacter sulfurreducens is a good choice to study electron transfer and power production under high pressure. They are working toward creating selective pressures to drive the new strain of bacteria to evolve that prefers to grow on the anodes of the batteries so that they can be more efficiently utilized in fuel cell design.

If it can be proven cost-effective and energy-efficient, this new energy source could be even more promising than its predecessors. Our research is meant to help advance the conversation about these new energy sources and to demonstrate the ability [viability] of such energy sources and materials to support deep sea mud batteries as an energy source for exploration in extreme, remote, and muddy places.

2.1 Graphite Rods

In this experiment, we used a battery constructed of graphite rods instead of fabric as a control, since batteries of this type have been constructed before. We used a series of four graphite rods, available at most home improvement stores, as electron sources. When placed in anoxic mud, anaerobic bacteria will grow on these rods, producing free electrons as byproducts of their metabolism.

Each rod has a cylindrical shape and is about 30.5 cm long and 1.27 cm in diameter. The surface area of each rod, excluding the tops, is equal to $2\pi rh$ where r is the radius and h is the height. Since we know the diameter, d, the surface area is given by πdh. Therefore, surface area = $30.5 * 1.27\pi = 38.74\pi$ cm squared. Graphite is the same material the lead of your pencil is made of. We chose graphite, because it is a good conductor of electricity and is relatively soft and therefore easy to drill into.

Holes were carefully and gently drilled into the tops of the rods. The holes were approximately 0.238 cm in diameter and 7 cm in depth. The hole in each rod was just wide enough to allow a small amount of 'breathing room' for the wire (i.e. it wasn't a tight fit). In order to not damage the rods when drilling, each rod was wrapped at the tip with electrical tape. Copper house wire about 15 cm long was inserted into each hole and sealed in with a combination of solder material and hot glue. The hot glue will act as a sealant to prevent the bacteria from eating away at the rods. The rods were divided into two pairs and each pair of copper wires was connected to twist-on wire connectors (wire nuts). A fifth wire was then added to each wire connector that connected the two pairs and a sixth wire led from one of the wire connectors to the rest of the battery circuit. It was expected that the graphite rods would prove to be more durable than the graphite fabric, because the rods are much thicker and more sturdy.

Although graphite rods provide less overall voltage and current as compared to the carbon fiber sheets (due to less surface area), it is a great conductor of heat and electricity. It also has excellent corrosion resistance as well as a high resistance to fracture. This will provide us with more consistency for an extended period of time when returning to the site to retrieve data.

2.2 Carbon Fiber

Two types of Microbial fuel cells are considered, a traditional graphite-rod based battery and a new carbon fiber based battery. Neither of these use a proton-exchange membrane and both only utilize inexpensive materials, with the intent to optimize the cost to electricity produced ratio.

The carbon fiber based battery is set up with two sheets of fiber: a long piece placed approximately one meter underground in anaerobic conditions, and a short piece placed so that it is exposed to oxygen (either above ground or in water). The long piece will act as the anode, through which electrons generated from cyanobacteria will enter the system. The short piece will act as the cathode, towards which the electricity will flow. The testing box, with the resistors, will be placed between the two sheets.

The purpose of the long carbon fiber sheet is to act as a host for the cyanobacteria. As the microbacteria undergo bioelectrogenesis, the released electrons travel through the carbon fibers, which offer the path of least resistance, towards the cathode. Since the carbon fibers are unidirectional along the length of the sheet, three additional bare copper wires were interwoven and soldered, with tin, perpendicular to the fibers. This will allow the electricity in the fibers to be directed towards a main wire which is attached to the ends of the three copper wires. This main wire will lead directly to the test box. All exposed wires that will be in the anaerobic conditions are covered with hot glue in order to prevent bacteria from using the copper as a food source.

The long sheet was placed in a 'lasagna' shape, and local mud was placed between each layer. The carbon fiber sheet acting as the cathode does not necessarily have to be of this material, but any excellent conducting material may be used. The only purpose for this sheet is to create a potential difference for the electrons to flow through the circuit, thus creating a current. Anaerobic bacteria use a final electron acceptor other than oxygen to complete their electron transport chain. For this test location, the final electron acceptor may be sulfur, as it is abundantly found around the area.

Compared to the graphite rod battery, the surface area of the fiber buried in the ground is much larger for the same cost and can thus accept more electrons from the microbacteria.

2.3 Test Box

To verify electrical production from the mud battery, there needs to be means of measuring the current and voltage. We built a switched testing circuit to simplify these measurements and enclosed it in a waterproof "test box." The test box is controlled by an simple switch to open the circuit through a pair of testing leads, or close the circuit through the battery in default use. The test box has a dial which can be turned from the off position to one of five other positions which passes the current through resistors of various strength as described in Section 2.4.

Following a circuit diagram, we constructed the inner workings of the test box by soldering to the connection endpoints of a 6-way rotary switch and soldering the contact points to secure them. The output wires from the dial lead were attached to test leads which can be probed by a multimeter to get a reading of the electrical yield of the mud battery. The circuit continues through slide switches and to additional wires that lead outside the box to the main battery.

2.4 Current and Voltage Measurement Setup

We wanted to be able to test the battery at different levels of resistance. Using a small circuit board from Radio Shack, some resistors ranging from 10Ω to $100,000\Omega$, a soldering iron, and some soldering material we soldered the resistors to the circuit board. Altogether we soldered 4 rows of 5 resistors each to the board. Each row had a 10, 100, 1,000, 10,000 and a 100,000 ohm resistor. You can determine the rating of a resistor by using the established color code. The body of each resistor contains a band of three or four colors that indicate the rating. In some cases there is an extra band on the body that indicates the resistor's tolerance or accuracy rated as a percentage. The tolerance is typically 1%, 2%, 5% or 10%.

According to Ohm's law the current flowing through a resistor is directly proportional to the voltage. In other words $V = IR$, where V is voltage, R is resistance and I is current. The bacteria in the mud and the oxygen in the air create a flow of electrons through the circuit. Each of the five resistors is connected to an independent circuit that can activated with the turn of a circular switch. Since the switch has five different settings and each setting is connected to only one circuit the circular switch is called a six pole two throw switch. We can control how much current flows though the battery just by turning the switch to a different setting. For a fixed voltage V the larger the resistance the smaller the current and vice versa.

The only difficulty we encountered with constructing the resistor pack was in the soldering. We had to be very precise to make sure only the exposed wire of the resistor was soldered to the board and that the board itself did not come into contact with soldering iron. This required a lot of patience!

3. Data Analysis

In our first experiment, rich, dark anaerobic mud with a strong associated odor was used to verify the operation of the fuel cell. Open circuit voltages of 0.6 volts were measured immediately on graphite rods, and served as a baseline for comparing the main experiment.

For our main experiment, we used a grey mud, which did not have a strong odor. There were two benefits of this selection. First it allowed us to verify if measurements of life could be taken of a sample that was not as rich to begin with. Several samples were also collected for lab testing. Second, this allowed us to examine the viability of a microbial fuel cell in sub-optimal soil conditions.

For the first several days, only open circuit voltages could be measured, so only open circuit measurements will be discussed in this paper. On the morning of the first day, the voltage on the graphite rods were measured to be 55mV and the voltage on the carbon fiber was 110 mV. As expected the carbon fiber, performed significantly (two times) better in the same soil conditions. Eight hours later, the voltage on both anodes had risen: the graphite measured 64mV and the carbon fiber measured 130mV. The voltages were checked repeatedly over the next 20 minutes and the voltage never varied more than a few mV.

The circuit was then closed to allow easy flow of electrons, and presumably the maximum growth of the microbes. The voltage on the graphite rods was measured one day later to be 117mV, no measurement of the carbon fiber was taken at this time. The carbon fiber was measured the next morning and found to be 236mV. A wire on the graphite rods had come loose in the mean time and was detected and fixed at this point, but the two systems were no longer both in identical states so exact comparison was no longer possible. While the measurements were not taken at the same time, the general trend of the carbon fiber having twice the voltage was continued.

The circuit was closed again and left alone for a month. At this point the carbon fiber had risen to 0.36V. A new soil sample was taken and the mud was both noticeably darker and had a much stronger smell.

4. Conclusions

The results are very preliminary, but several things seem likely. First, carbon fiber provided a superior performance to graphite rods, for a comparable price, suggesting it is a viable candidate for future power generation techniques. Second, even in a soil sample with likely a low concentration of microbes, an easily measurable voltage was obtained, verifying that it can be used to measure life. Third, the voltage grew simultaneous with the increase in other indicator of life, verifying that even in extremely low concentrations, a small probe could be left behind in a "grow" state (closed circuit), and returned to later to be measured for any increase. The preliminary results thus indicate that carbon fiber microbial fuel cells are a potentially viable source of power in remote, extreme environments, and that the fuel cell life detector is a reasonable candidate for detecting life on other planets.

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