Ecowatt

PROJECT PROPOSAL AND FEASIBILITY STUDY

Calvin College ENGR 339

December 10, 2007

Team 10 Members

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Abstract

The Ecowatt Biobattery is a feasible and attractive prospect for a Calvin College Engineering Senior Design Project with great promise for a marketable and worthwhile product. The research shows that Microbial Fuel Cells have been implemented in previous studies at the university level, but no viable products have come to fruition. Ecowatt testing proves the MFC concept – achieving an average closed circuit voltage output of 0.3V for over a week without feeding. An assortment of sources indicates that more power can be achieved with a more efficient proton-exchange membrane. Possible electrode arrangements and membrane options are slated for testing in January 2008. The Biobattery fits in perfectly with the Fundamental Ecowatt Values of Stewardship, Trust, and Justice, and a business plan clearly demonstrates the economic worth of the project. Finally, the preliminary design is progressing strongly. The MFC block diagram is completed, and a bacterium has been selected. The regulating circuit method has been specified, and the monitoring system and feeding / waste system has advanced significantly based on research and group discussions. The Ecowatt Biobattery is an unmistakably feasible project that, given another semester for development, will produce an impressive prototype and demonstrate its own success with electrifying results.
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1. Introduction

1.1. Problem Statement

Conventional batteries seem to work pretty well, and the consumer can buy them for a reasonably low price. These batteries can power electronics for a couple of weeks up to a year, and they are thrown away. Some batteries are even rechargeable and last longer but with decreased performance for every charge over time.

Unfortunately, conventional batteries are not as low cost as they seem. The materials used in most batteries are toxic and harmful to the environment; these materials are not recyclable. In an attempt to minimize their impact, battery processing centers have been implemented, but the process is expensive and time-consuming, and the vast majority of batteries are simply discarded into the “trash.”

Ecowatt is a team that is called to answer the problems caused by conventional batteries by developing a power source that is portable, consistent, and reliable. The power source must last longer and should be more easily disposed than conventional batteries. It must also be easy to operate and provide a reasonable amount of stable power at 1.5 volts, without requiring frequent or expensive maintenance.

1.2. Project Objectives

For this project, Ecowatt will design and create a prototype for a microbial fuel cell aka "Biobattery." The term “Biobattery,” for the purposes of this project, refers to a device which generates power by Geobacter, a type of microbial organism. The Biobattery designed by Ecowatt will consist of a Microbial Fuel Cell (MFC) system comprising a Feed and Water System, an Output Regulator, and a MFC Monitoring System.

All features of the case design must be reasonably robust and leak-resistant. The case must be easy to carry and intuitive to use. The Biobattery should be contained in an attractive package that appeals to the target market.

Each MFC contains two compartments separated by a proton exchange membrane that generate an electric charge as a result of the eating behavior of the microbes. MFC design will also include specifications for the appropriate electrodes and a proton exchange membrane between the two solutions.

The Feed and Water System will manage the flow of feed solution into the MFC as well as the flow of water solution out of the MFC. The Feed and Water System also includes design of the MFC chambers and a Tank Refilling Station.
The Output Regulator will ensure a stable power output at standard battery voltage and consistent current whenever the MFC is functioning.

A MFC Monitoring System will communicate to a user by relaying important information such as the voltage level of the MFC and feeding time for Geobacter.

Safety and Environmental Impact

There are consequences to our actions that impact environment, sometimes negative even when we do not intend to do so. Many products in the market claim to be green but are produced in not so green environment. So not only a product should be environmentally friendly but it is also preferable that the environment itself where the product is made be green. So the other aspect of our design is to ensure that the process used for making MFC itself does not impact the environment in negative ways. This means that the methodology used also must have minimal and positive effects on the environment.

Equally important is the safety of the device and anyone who is operating the device. One way to ensure safety is providing appropriate labels for caution and warning. However the more effective way is to educate a user about the correct usage of product. Safety must also be practiced while producing the product itself. Still the safety of the MFC must also be considered so that foreign objects do not intrude into the system causing inadvertent effects.

1.3. Project Requirement and Criteria

There are minimum requirements that must be fulfilled in order to meet the objectives of the project. So the design must meet following criteria for this project to be successful.

- The microbial fuel cell array must provide at least 1.5 volts.
- The user must be able to feed the Geobacter without any unreasonable difficulty.
- There must be a feed indicator for letting the user know that it is time to feed Geobacter.
- The circuit implemented for monitoring and regulating the voltage must use minimum possible power from the MFCs.
- In case the circuit fails, the Biobattery should still provide a voltage output and also let user know about the failure.
- The Biobattery case must protect the Biobattery contents from the outside world and protect the outside world from the Biobattery contents.
- The terminals from the Biobattery must be easily accessible for a user to power a device.
- The circuit must protect itself and the connected device from any voltage spikes, so it must provide a stable voltage and not cause any damage to connected device when
functioning properly. The circuit must also ensure that it does not inadvertently damage the MFC itself.

- Geobacter should not outgrow its living environment nor die off when operated under standard conditions.
- Finally, the system must be portable, appealing, and user-friendly.

2. Research

2.1. Microbial Fuel Cell

Microbial fuel cells (MFC) have been in research papers since the early 1970s. Three main types have received the most attention in the last 15 years: heterotropic, photoheterotropic and sediment cells. Heterotropic and photoheterotropic cells use suspended bacterial cultures to produce current. Sediment cells are historically made with sediment found from the local body of water, using an electrode and cathode (electrically conductive metals) placed in the sediment and water above the sediment. Heterotropic cells have consistently provided higher power to surface area ratios which allow for smaller electrode areas.

2.2. MFC Power Generation

Many different possibilities for electron generation from biological species and sources have been developed. Bacteria that can produce free electrons on the outside of their cell membrane are called exoelectrogenic bacteria. The two main groups researched are mixed and pure cultures for microbial fuel cells.

The term mixed culture demotes that the culture of bacteria has more than one species. The mixed cultures composition (ratio of one species to another) changes with each generation depending on what species survives the best in the current environment. Mixed cultures are typically found in nature usually from streambeds and sediment. The sediment battery’s generation of electricity is due to mixed cultures of bacteria found in the sediment.

One of the problems with using mixed cultures in a microbial fuel cell is that a symbiotic relationship has been shown to form in certain examples, where one species creates free electrons and one species captures the energy from the free electron. This relationship is not conducive to electricity generation in a microbial fuel cell because the more free electrons in the media then consumed by the second species of bacteria.

Another problem with mixed cultures is that attaining a culture that is efficient in free electron production is challenging to achieve. Many mixed cultures only have a small portion of
bacteria that are free electron generators, with the majority simply consuming the organic feed in the media. There have been some cases in the research where mixed cultures have produced a higher power density (Fabaey 2004). One of these cases, using glucose as a carbon source, yielded a power density of 3.6 W m⁻² (Rabaey 2003).

Isolated pure cultures are more readily analyzable and reliably attainable. The pure cultures refer to the cultures (or growth of bacteria) having only one species present. These pure cultures have been gained by selectively growing a certain species from a mixed culture and testing only that one species. Many environments support these free electron producing bacteria. In fresh water environments, the bacteria Geothrix contributes to electricity production. Desulfobulbus produces free electrons in the presence of sulfur. Rhodospirillum rubrum generates electricity when exposed to ultraviolet light in an anaerobic environment. Many iron reducing bacteria have been discovered. These include “Geobacter hydrogenophilus," Geobacter sulfurreducens, Geobacter chapelleii, Geobacter Metallireducens, and others. This species of free electron producing bacteria are commonly referred to as the Geobacter. Geobacter was first described by Lovely et, al. on November 19, 1987. Geobacter Metallireducens was the first bacterium that was discovered to completely oxidize multi-carbon organic compounds with the reduction of iron (Lovely 1987).

The typical medium used for the Geobacter species includes ferric citrate as the electron acceptor and sodium acetate as the general organic feed. These chemicals are, for the purpose of this project, obtained from the biology department at Calvin College.

American Type Culture Collection (ATCC) is a non-profit organization that collects, preserves, and distributes pure cultures of living organisms. The ATCC provides a specific medium for each organism where they guarantee the continued living of the organism. The medium is ATCC #1768 Broth: Medium for Geobacter metallireducens. This ATCC medium production procedure is located in the Appendix III. The species is anaerobic and produce more electricity when in an anaerobic environment. The gas environment is highly recommended to be 80% Nitrogen and 20% Carbon Dioxide. Geobacter metallireducens also requires Wolf’s Vitamin and Mineral solutions.

2.3. Power Management

Power management is crucial in today’s technological applications. It is especially true for the systems that use batteries as the source of power. However a power management circuit itself uses power from the source so the design of such a system must be careful not to tax the source with power management circuit. The concept behind power management is to use the minimum possible power from the source to monitor and regulate the output. Power management can be divided into two sub-systems: monitor and regulator.
2.3.1. MFC system monitors research:

The first system of the power management is the monitor. The monitoring circuit oversees the voltage output from the MFC as well as the power used by the load connected to the MFC terminals. The monitor measures the current and voltage generated by the MFC, and displays the MFC’s status. MFC voltage decays over time, and current generated changes according to the power supplied to a load. Both of these variables need to be constantly monitored and make a user aware of MFC status.

A simple circuit like an analog voltmeter and ammeter can measure the output voltage and current of a MFC, which can display the voltage level. An analog multimeter must be calibrated against a standard voltage before it can be implemented to a MFC system. Although this type of multimeter is basic to implement, it has two major disadvantages. First, it does not provide precision readings. Second, it is inflexible. On the other hand, a digital monitoring system is more accurate, especially for reading small voltages.

Digital monitoring circuit is sensitive even to a slight change of voltage. A digital monitor will also be capable of providing other MFC status information than just a voltage reading for a user. The voltage may be low because the MFC is generating less power or the load is withdrawing too much current from the system. An analog multimeter will not communicate the difference between the two so a user won’t know if it is time to feed or the load is consuming the MFC power. An analog multimeter will have a limited range of voltages to compare against the voltage generated by the MFC. But a digital system can be implemented to display a vast array of specific voltages.

Digital systems are also more efficient than its analog counterparts. Most of the today’s technological applications make use of the digital monitoring system, for instance a cell phone. A digital system is much more robust. There are microchips available which can monitor the battery. The microchips are cheap and are also very small which can be easily integrated to a MFC system. These devices can be customized to system-specific application.

2.3.2. Regulator Circuit Design

The typical cell output is 0.5V; the ability for one cell to produce the desired output is not feasible. A minimum voltage of 3.0V is needed for reliability. Hence, a minimum of six cells are necessary to keep the battery, the regulating circuit, and the measuring circuit working at optimum performance.

The battery’s circuit design yielded three options. Each design carefully considered the needs of the circuit and the needs of the battery. The needs of the circuit included minimum voltage, current, and power to enable the circuit to operate correctly. Beyond this point, the circuit needed adjustment to make sure that the voltage level of 1.5V came from the voltage
regulator’s output. In addition, measurement of the circuit is essential, so that the measuring devices needed calibration as well. The generation portion needs the circuit to not harm or kill the bacteria inside the battery. Therefore, a way to make sure that the bacteria lived long, healthy lives, while outputting the maximum voltage with minimum feeding became another criterion.

The first design is simple, using a voltage regulator and measurement devices to regulate and monitor the voltage. The measurement devices also measure the pH and the bacteria’s feeding times. The use of an LED system makes it possible to measure when the bacteria in the battery need food.

The second design would use more specialized parts, such as a low input linear voltage regulator and a low input voltage bipolar junction transistor (BJT). While this design basically included the same parts as the first design, the second design concentrated more on lowering the demand required of the bacteria’s voltage output. If the output of the bacteria dipped, the resulting voltage will not affect the output voltage and the circuit’s functionality. Another change includes the concept of making the voltage measurement passive, meaning that the circuit loses no further energy.

The third design would use a switching voltage regulator in a configuration with a diode, four resistors, and four capacitors. This design requires more power than the second design, but this design is more efficient than the second design simultaneously. The difference is about 30% efficiency in the second design while the third design has about 70% efficiency.

The third design was chosen as the best choice. Given that each biobattery cell outputs about 0.5V, the design requires six cells for safe operation but will require significantly less power than the first design. This design also ensures that the circuit does not consume as much electricity for proper function. Furthermore, this design will measure the circuit without having to worry about failure.

2.5. Feeding Process

Microbial fuel cells contain bacteria that must have a sufficient supply of “food” to survive. In fact, the power generation performance of a microbial fuel cell is dependent on food supply. Since the bacteria must live in an anaerobic environment, the method of adding the food to the cell solution requires finesse.

The food supply can be added to the cell solution periodically in controlled amounts through a process called batch feeding. At feeding time, the solution must be maintained while the food supply is added and the waste solution is simultaneously removed. Unfortunately,
batch feeding must be done at relatively frequent intervals, and the power output can drop significantly starting about one week after last feeding.

To solve the problems associated with batch feeding, researchers have employed continuous feeding. Continuous feeding maintains a steady flow of food supply into the cell and waste solution out of the microbial fuel cell. Requiring little maintenance or upkeep. On the other hand, continuous feeding systems are complicated and expensive to implement. Pumps would be necessary to continually draw the food supply into the microbial fuel cell; the power for such pumps would use more energy than the Biobattery could possibly generate, rendering them unfeasible.

To optimize the benefits and overcome the drawbacks to both batch and continuous feeding processes, a combination of the two methods is implemented in the design. The batch-fed continuous feeding process will be discussed in detail in the Design section.

3. Design

3.1. Preliminary Design

The MFC system can be divided into three sub-systems namely the fuel cell, MFC monitor and Output Regulator. The figure below is a basic block diagram of the overall system. The figure 1 shows the interaction between the MFC and the power management systems.

![Block Diagram of Overall System](image)

*Figure 1: Block Diagram of Overall System*

3.1.1. Case Design

The Biobattery case for Ecowatt will house the various solution tanks, electronic circuitry, microbial fuel cells, and the user interface for monitoring the Biobattery. It will also
protect the solutions from contamination and leaking, and it will be aesthetically appealing as well as easy to carry. The complete Biobattery should weigh less than 40 lbs. The case should be made out of a low cost, low density, and sufficiently strong plastic such as HDPE or PET; it should fit into a one meter cube.

3.1.2. Microbial Fuel Cells

![Figure 2: Schematic of Microbial Fuel Cell](image)

A microbial fuel cell (figure 2, Derek R. Lovely, 2006) uses the electro-chemical potential difference between a donor bacterium and the final acceptor free atmospheric oxygen. The bacterium gains metabolic energy by transferring electrons from an electron donor, which could be any organic molecule, to an electron donor. A bacterium, in a microbial fuel cell, does not directly transfer the produced electrons to the terminal electron acceptor but are redirected to an electrode. The electrode that is in contact with the bacterium is the anode. The electrons are then conducted over a wire and are directly converted into electrical energy. (Rao et Al., 1976) The electrons finish at the cathode where they are combined with protons that travel through the proton membrane and oxygen in the solution to form water.

**Electrodes:**

The MFC will include two electrodes, anode and cathode, for transferring electrons. The anode is the negative terminal where the electrons are deposited and transferred by Geobacter as electrons gets generated. The cathode is the positive terminal where the electrons will ultimately be transferred from the anode. The buildup of electrons in anode causes the
potential difference between the two electrodes so the electrons flow from anode to cathode generating electricity.

The two electrodes are made from the same material. Copper electrodes are unsuitable for this design since copper has detrimental effect upon Geobacter. Any non corrosive metal will work for the use of electrodes. Porous graphite electrodes will be used for this particular design. Electrodes can be made in different shapes and sizes. For the use of this design, electrodes will have a bar shape. The potential of the electrode increases with the surface area of the electrodes so a porous electrode is preferred since it has larger surface area. With a greater number of pores, there is a larger surface area available for electron collection. The greater number of pores also helps prevent clogging. In the anode compartment, Geobacter transfer the electrons to the electrode. Pili, also known as nanowires, are the appendages of Geobacter, the electrons produced are carried to the electrode via these pili as these Geobacter cling on the surface of the electrodes. The cathode, which is also the graphite electrode, collects the electrons which flow from the anode. In the cathode compartment, oxygen acts as the final electrons acceptor. The chemical reactions that take place in the cathode compartment are written below.

\[ \text{O}_2 + 2e^- \rightarrow 2\text{O}^- \]  \hspace{1cm} \text{(Eq. 1)}

\[ 2\text{O}^- + 4\text{H}^+ \rightarrow 2\text{H}_2\text{O} \]  \hspace{1cm} \text{(Eq. 2)}

Oxygen is suitable since it has high oxidation potential, it is freely available and it combines with hydrogen ions coming via membrane to form water, so there is no harmful waste.

3.1.3. Fuel Cell Arrangement

Two options exist for the fuel cell arrangement. Like with a circuit, the arrangement has the potential to be in series or in parallel. Despite the continuing research, prior knowledge concerning the arrangement gives weight to each of the possibilities.

If the fuel cells are in series, the voltages of each cell will add together. However, a problem exists for serial connection. If one of the cell’s output becomes unusable, it will short the circuit between the rest of the cells. In the final design, this has the potential to become difficult to repair. As a result, the entire battery can become crippled by one small malfunction, such as the death of the bacteria in one of the cells.

On the other hand, one can wire the fuel cells in parallel. While this option can possibly suffer from lower output, it has a higher guarantee for success. That is, it is less likely to short
out from the failure of one fuel cell. The difference here is akin to how a string of lights works. If one goes out, they all go out versus having one go out while the others still work properly.

For the purpose of having a reliable current and voltage, the fuel cell arrangement decision needs careful consideration. A plan for deciding which of these is optimal is currently in effect. Hopefully, evidence will allow for this decision to manifest soon.

3.1.4. Feeding

The Biobattery incorporates a batch-fed continuous feeding process to provide a steady food supply to the microbial fuel cells with minimal upkeep while requiring no additional power. First of all, the Food Supply Tank contains a food solution for the microbial fuel cells in a pressurized nitrogen and carbon dioxide environment, and the Waste Tank contains water and air. As time passes, the pressure gradient draws the food supply from the Food Supply Tank into the microbial fuel cells and the waste from the microbial fuel cells into the Waste Tank.

As the Solution Monitoring System indicates in section 3.1.5, the user will empty the waste tank and refill the Food Supply Tank. The Food Supply Tank must be removed and refilled at a separate Refill Station. The user will empty the previous contents of the Food Supply Tank and install it into the Refill Station. The user will then add water to the Refill Station and pour the contents of the Food Packets into the solution. At this point, a pressurized gas tank containing nitrogen and carbon dioxide is implemented to condition the environment in the Food Supply Tank. Reinstalling the Food Supply Tank into the Biobattery case will immediately begin a controlled and continuous feeding process again. It is important to note that the Refill Station design is dependent on the final Case Design, and is likely to change with the final design.

3.1.5. Power Management

3.1.5.1. Monitoring

The objective of an MFC system monitor is to monitor the system status. MFC is a dynamic system and requires the voltage output to be monitored. When a load is connected to the MFC, it is also essential to monitor the power consumption by the load. The basic concept behind the monitoring system is to measure voltage and/or current and display the status of the MFC system. Figure 3 represents the block diagram of the monitoring system. The design involves an analog-to-digital converter, a micro-controller and an output driver.
ADC:

The ADC, analog-to-digital converter, takes the measured voltage or current, which are analog signals, and converts the signal into stream of bits. These bits are the digital form of voltage/current measurements.

Micro-controller:

The micro-controller basically is a CPU which will process the bits converted by ADC. The micro-controller takes the converted bits and performs mathematical manipulations and operations. After processing the bits, depending upon the instructions, it will send an appropriate signal to the output driver circuit.

Output driver:

An output driver is a circuit to run an output such as LED/LCD display for a user to inform about MFC system status. The micro-controller sends signal to output driver to perform a specific task. Then output driver circuit activates the output device.

3.1.5.2. Regulation

Because the circuit requires low power usage, one specialty circuit component is important. In particular, the TPS62100 will become a major component in the regulator’s design. This part is a multimode low-power buck converter that will adjust the voltage at a frequency of 300 kHz. This will satisfy the design requirements substantially because test results have shown that the rate of decay in voltage for the biobattery takes several days. This part consumes little power while maintaining stable performance. No other parts were available on the market for use that fit the requirements of the circuit design.

As for the other parts necessary in the circuit, the only resistors and capacitors are needed. These parts are available in the Calvin College Electrical Engineering Lab.
3.1.5.3. Power Conditioning

The voltage produced by a single microbial fuel cell is not constant enough for consideration as a reliable power source; it is imperative to regulate the changes in voltage and condition the battery's output for a given application. Theoretically, the voltage regulator adjusts the input voltage to a set reference voltage, but it does not serve to adjust the voltage to just any voltage desired. The voltage regulator, in conceptual design thus far, is only capable of leveling relatively small changes in fuel cell output. Experimentation has not matured to the stage of determining the precise variations in voltage levels. If the variations are too great some sort of temporary storage solution may become necessary.

Currently, the plans to implement the circuit described above are in place. However, several problems must receive attention before proceeding further. The circuit design depends greatly on the output of the bacteria. No final circuit realization can occur until after the microbial fuel cell’s output becomes known. A voltage of 1.5V is required for the output coming directly from the bacteria into the voltage regulator. The current must be at least large enough to power the circuit. For this reason, parts that use little voltage and current are critical to the circuit's design. In the meantime, simulation of the circuit must assume the worst case scenario that the bacteria produces little voltage and current. Research of what these parts are and how they interact is ongoing. Similarly, the method for balancing large spikes at feeding time and dips in power towards the end of a batch needs further study. Hopefully, the voltage regulator will assist in this process, as well as extending the period between feedings. To fulfill these needs, the time spent meeting between members of the team recently increased.

A figure of the third design alternative is available online at http://www.datasheetcatalog.com/datasheets_pdf/T/P/S/6/TPS62100.html and in Figure 4. This design requires at least 2.5V for the input to output 1.8V at a variable current of 0mA to 500mA. The design uses a setup called an Output Automatic-Mode Switching Converter Application Circuit. This circuit fits the specifications for the project’s design norms; nonetheless, further modeling and testing of the circuit is needed.
3.2. Method of Approach

This project uses the basic approach of researching, designing and implementing for a successful completion of the project. Although there are three distinct phases in the project, they overlap with each other over the course of the project.

Research

The first phase of the approach is research. Research is of utmost importance to our project. Microbial fuel cell is a recent technology and there is a lot of research going on in this field. We have been able to get a lot of information about MFCs.

Design

The next phase of the approach is design. After researching necessary materials, the next step to do is develop a design of the product that we will build. The design is mostly done on paper and computer. The design itself is divided into other steps. The first design is just the block diagram of each component in the system so there is a basic understanding of how the system should function. Then next step is to take each component of the system and blow it into each individual sub-system. Each sub-system has a block diagram of its own to show how it functions. Then each components of the sub-system is designed according to the required specification.
Implementation

The last phase of the approach is implementation, or prototyping. Each component of the sub-system is implemented either with computer model/simulation or a prototype. Without implementation there is no way to know if the design actually works.

Although the approach seems linear, the phases overlap. The implementation will not always work as designed or planned, so we need to go back to our design and readjust the changes. Sometimes we might even have to go back to our research and find out what we overlooked. Many times design has to be revised based on new findings and researching, so we are constantly changing design for improvement. So the approach is more cyclic as seen in figure 5 above.
4. Feasibility study

Preliminary design verification is needed to show the feasibility of the project at technical level. Experiments for microbial fuel cells were conducted to find the voltage and power output from the system.

4.1. Preliminary Testing of MFC

There were two similar experimental setups for testing of microbial fuel cell. The major difference between the two designs is the length of the salt bridge. The first was the U-shaped salt bridge between the test tubes. The second was a vertical salt bridge with the anode compartment upside down and the cathode compartment was a beaker instead of a test tube. The setup for both the experiments is shown in figure 6. The data were collected over one week for first test setup and ten days period each second test setup. The first setup was on 100 ohm loads and the second setup was on 1 kilo-ohm load. The second setup used the media that was already made for the first setup, so the media was a week old and the Geobacter had not been fed for a week.

Figure 6: First setup (left) and second setup (right)
4.1.1 Electrode Potential:

The main variable that needs to be measured in the MFC system is voltage. Individual electrode potential can be measured to a reference electrode. Silver chloride is usually used as a reference electrode. The actual cell voltage, or Electromotive Force, EMF is the difference between the individual electrodes potential. However cell EMF is close to the open circuit voltage (OCV) of the two terminals, so for the practical reasons cell EMF will be considered equal to open circuit voltage. The voltage produced is the potential difference between two electrodes. The potential difference remains virtually constant over the course of the electricity generation period and starts dropping when there is inadequate media for Geobacter to feed on.

\[ \text{EMF} = V_{\text{anode}} - V_{\text{cathode}} \]  

The voltage was measured periodically during the length of the experiment. For the first setup, the initial voltage measured was 0.63V, however the voltage dropped by half the next day. The voltage relatively stayed stable, dropping just a little bit each day. Figure 7 shows the voltage behavior for the first setup.

![First setup voltage measurement](image)

For the second setup, the measured voltage for the first time was 0.2V which is less than for the first setup. This is because Geobacter had been without media for a week and it takes time for it to show activity once again. As predicted the voltage increased next day and the voltage stayed stable over the course of the experiment. The peak voltage was 0.335V. Figure 8 shows a very similar voltage pattern to the first one except for the first measured voltage.
4.1. 2. Polarization Curve:

Current is measured under a load. Ohm's law is used for calculating the current where different values of resistors are used as loads to measure the current drawn from the system. So current is a function of electrons released by Geobacter while feeding on media. Equation (ii) gives the current flowing in the circuit.

\[ I = \frac{V}{R} \]  

The maximum current generated from the MFC was 0.023mA for the first setup and 0.03mA for the second setup. The maximum current produced for a given load was in the range of 100-1000 ohms.

The polarization curve (Bruce E. Loagn, 2006) reflects a better picture of current behavior in the system. The polarization curves in Figure 9 and Figure 10 show the voltage as the function of current. The polarization curve was created by measuring current values with increasing resistor values in a pseudo-steady state. There are three zones in this curve. The first zone starts at open circuit voltage at zero current where there is activation loss because Geobacter are trying to output current to a load. In the second zone, voltage steadily falls because of the internal resistance of the system. The third zone shows a dramatic fall in voltage because of the concentration losses. The 11/27/07 labeled curve in the second setup is the ideal polarization curve. However due to the high inefficiency of the salt bridge, the voltage drops dramatically with little increase of current.
Figure 9: Polarization Curves for Various Resistors (First Setup)

Figure 10: Polarization Curves for Various Resistors (Second Setup)
4.1.3. Power Curve:

The power output of the system determines its performance. Power can be calculated using equation (iii).

\[ P = VI \]  

(iii)

However power itself is not a good measure for the performance. Power density, which is power with respect to the anode surface area, gives better picture of its performance. The first setup gave a better performance than the second setup. The power curve (Bruce E. Loagn, 2006) portrays the power (density) with respect to current. At zero current there is no power output. The power increases until it reaches its maximum output then there is a fall in power after that point. Figure 11 and Figure 12 are the power curves for the first and second setup respectively.

![Power curve for first setup](image)

*Figure 11: Power Curve for First Setup*
4.1. 4. Ohmic Loss:

There is loss of electrical potential due to internal resistance of salt bridge and MFC system. The internal resistance for the salt bridge prohibits the smooth flow of hydrogen ions from anode to cathode. This is evident there was little change in the water level in the cathode compartment. The open circuit voltage is less than the actual cell EMF. Ohmic losses (Bruce E. Loagn, 2006) are proportional to the current produced and ohmic resistance. The internal resistance of the MFC is calculated with equation (iv).

\[
\text{EMF} = I(R_{\text{int}} + R_{\text{ext}}) \tag{iv}
\]

In above equation (iv), cell EMF, current following in the circuit and external resistor values are known. Using the equation, the internal resistance for the first setup was approximately 18Kohm while for the second setup, it was approximately 42Kohm. (Appendix II) The internal resistance of the system is very high compared to the load used which uses all the current produced by the MFC.

4.2. MFC Monitoring Circuit Simulation

A monitoring circuit is required to know the exact status of the MFC system. The circuit relays important information to a user about the MFC condition including power output and Geobacter feeding time based on the voltage output from the MFC. A simulation of monitor circuit was performed for preliminary testing of the circuit function. The first thing done for im-
implementing a monitoring circuit was creating a micro-controller using SOPC builder in Quartus II program. SOPC builder (Appendix IV) generates all the required components for a micro-controller. It utilizes a FPGA, Cyclone II, processor onboard, an on-chip memory, an external ADC component (VHDL code for ADC interface was provided by Professor Brouwer, Appendix VI), a LCD and a timer interrupt. After compiling the system generated by SOPC builder, the program was loaded into the DE2 board. Then an assembly language code was written for processing the signal and driving the output to LCD (see Appendix V for assembly code).

A Hewlett-Packard 6205C Dual DC Power Supply was used for sending test analog signal. The voltage was varied from 0 – 3.3 V. An ADC component, TLC 549, converted the analog signal to digital signal. Altera DE2 board was used as the micro-controller for processing the signal and finally the processed signal was sent to LCD on the board to display the voltage. Table 1 shows the values used for comparing the voltage and displaying the status.

<table>
<thead>
<tr>
<th>Voltage Range</th>
<th>ADC Value Range</th>
<th>Message Displayed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 &lt; V &lt;= 3.3</td>
<td>155 to 255</td>
<td>Good</td>
</tr>
<tr>
<td>1.0 &lt; V &lt;= 2.0</td>
<td>78 to 154</td>
<td>Low</td>
</tr>
<tr>
<td>0 &lt; V &lt;= 1.0</td>
<td>1 to 77</td>
<td>DANGER!</td>
</tr>
<tr>
<td>V = 0</td>
<td>0</td>
<td>ERROR!</td>
</tr>
</tbody>
</table>

The timer interrupted as expected; however the display did not change as voltage was varied. It would only change the value occasionally. It was determined that the maximum time for LCD to execute all its instructions was less than 200ms and timer was interrupted every 500ms which is more than enough time for the LCD to complete the instructions before the timer interrupts. But it seemed the timer was not interrupting fast enough so the timer interrupt period was changed to 200ms but it still behaved same as before. Then the ADC was changed to make sure it was not the problem, but still the problem persisted. An oscilloscope was then connected to the ADC to see what exactly was coming out of it. The ADC was functioning as it should. So it was not obvious what was causing the problem. There was not enough time to make other changes and further test it. However the concept was proven to work.

4.3. Intellectual Property Issues

When beginning the design work, the team sought existing patents on the subject of MFCs; to have some previous work to start from often can shorten the design stage and
improve the efficiency of the entire process. Glenn Remelts, Hekman Library Director, offered his expert research assistance on the matter, but no applicable patents were available. Instead, the team focused research time on studies and experiments on MFCs conducted by other universities such as University of Massachusetts-Amherst and Michigan State University. For reference information on the research and papers that apply most directly to the Biobattery, see the References section.

4.4. Regulating Organizations

The Biobattery is intended to be feasible as a product that can be sold in the United States, so the team is investigating certain regulating organizations to ensure the feasibility of certification.

4.4.1. Underwriters Laboratories Inc.

Underwriters Laboratories Inc. (UL) provides a service for certification of products before introduction to the market. It evaluates products based on a set of specifications; products that pass are permitted to carry the UL Certification Mark (UL.com). Many retailers, such as Walmart, Best Buy, and Target, will refuse to carry products that have not been through UL’s testing process.

For UL certification, the manufacturer must list all parts for individual component certification. Biobatteries include the use of chemicals and biological hazards, additional considerations are necessary for UL certification. Also, a UL engineer must investigate the product for full certification. The UL engineer will inspect each component, exhaust system, fault, fuel or fluid handling system, manufacturer data, photograph, printed circuit board, product information, rating, and system diagram. These constraints apply for any fuel cell that needs UL approval.

4.4.2. Case Design Regulations

UL specifications for consumer electronics for the case design are not prohibitively restrictive due to the low power of the MFC. However, the lack of previous similar products tested for UL certification could result in an extensive testing process. The main concerns seem to be regarding products that use over 40V or AC line power.

Two possible safety concerns for the Biobattery are the autonomous operation and the proximity of water tanks to a power source. To run autonomously and safely, the product has been designed with no moving parts and no automated feeding systems. For safe operation with water tanks near a power source, the tanks seal tightly with the case. Also, the power supplied is relatively low and cannot cause personal bodily injury even if contacted.
4.4.3. Circuit Design Regulations

Ecowatt wishes to comply with all electrical standards concerning bio-batteries. If this is not possible, then Ecowatt will take all measures necessary to make consumers aware of any potential hazards that the electrical components cause.

While a biobattery does not need to have Reduction of Hazardous Substances (RoHS) compliance, Ecowatt will make all parts hazard-free in terms of chemical hazards. This includes lead-free wires and any other components in the electrical design. Any parts found that do not comply with this standard will not become a component in the biobattery.

4.4.4. Bacteria Regulations

International Organization for Standards (ISO) is the world’s largest developer and publisher of standards. This organization has support in both governing bodies and business consensus. Conforming to these standards allows Ecowatt to be environmentally and ethically responsible to society and government. Standards are available for bacterial regulation for products intended for human consumption. Standards for batteries include hybrid safety features, wheelchair requirements and backup safety batteries. No regulations have been published concerning bacteria contained in a battery. The technology in a biobattery is new to industry and no regulations have been written for Ecowatt to adhere. Ecowatt will continue to investigate throughout this project looking for standards in this area.

5. Christian Perspective on the Project

The ministry of Jesus Christ is critical to the Ecowatt team as an inspiration for change. Ecowatt is making its way into an industry that, for the most part, seems concerned only with the design factors of low cost and high performance. Seeking to make a change, the design team is dedicated to three values based primarily on the example of love shown in the life Jesus Christ.

Any project from Ecowatt must adhere to the Fundamental Ecowatt Values of Stewardship, Trust, and Justice. For viability’s sake, each project must use global resources responsibly; the Biobattery project will provide an option for portable power that does not use corrosive chemicals. In addition, dependability and reliability are a must. The Biobattery project will provide a stable power supply in a convenient, easy-to-use package. Ecowatt will publicly disclose any issues of general public or environmental safety. Finally, the Biobattery project is an expression of Justice; the rights of non-users and users are a critical consideration in the design process. When considering materials, environmental and health impacts are separately weighted. Even in production, the effect on every person is the subject of careful deliberation.
6. Task Breakdown and Time Schedule

6.1. Team Member Bios

6.1.1. Brianna Bultema, BSE+CHEM

Brianna is a fourth-year senior engineering student with a chemical concentration and additional course work in biology. She grew up in the shadow of the Rocky Mountains in Colorado Springs, CO where she learned to appreciate and cherish nature. Her biology course work and independent laboratory knowledge make her an invaluable resource for Ecowatt. She has worked at DC Cook Nuclear Power Plant in Bridgman, MI and for a company that specializes in sensors for space, Blue Line Engineering in Colorado Springs, CO. Her passion for renewable and alternative energy sources has stemmed from her internship in the nuclear field and grown through her research and further study on the Biobattery. She is enjoying seeing her contributions become actualized in a final product or prototype.

6.1.2. Jared Huffman, BSE+MECH/ELEC, BA-PHIL

Jared is a fifth-year senior engineering student (BSE) with a split concentration between the electrical and computer concentration and the mechanical concentration at Calvin College. He will also be achieving a BA in Philosophy from Calvin College at the same time. He has held a couple of different internships over the years, with the most recent opportunity being a position at Kellogg Company in Grand Rapids, MI; he has worked full time during the summer months and part time during the school year. His favorite Engineering subjects are Industrial Processes and Technical Writing; his course work in the Philosophy department has enabled him to develop a keen analytical sense as well as creative problem solving skills. He grew up mostly in Lowell, MI in a family of seven with two brothers and two sisters; his passion for Project Management originated with the large family unit and extended into frequent leadership positions in various clubs and projects throughout his high school and college education.

6.1.3. Christopher Michaels, BSE+EE

Christopher Michaels is a fifth-year Engineering student with an Electrical and Computer Concentration. This past summer he held an internship at the Holland Board of Public Works. He is from Mackinaw City, Michigan. He wishes to design high fidelity audio equipment after graduation, which reflects his musical interests. Also, he would like to utilize his Japanese language skills.

6.1.4. Achyut Shrestha, BSE+ELEC

Achyut Shrestha is a senior engineering student with an electrical concentration. He comes from a small town called Damauli in Nepal, home of the Himalayas. His first name
literally means “man of integrity” and he gives his best to portray it. He grew up in family where principles are highly valued. He is currently working as a software programmer in Calvin's IT department. His affinity to learn new things, both educational and social, makes him very adaptable. He excels on pressure and the engineering program in his school has provided ample opportunities. His passion is in cutting edge technology however he wants to use his engineering knowledge and skill to help people from his country where basic necessity is more important than high tech gadgets.
6.2. Organization Chart

- **Project Leader**
  - Jared Huffman

- **Team Advisor**
  - Prof J Aubrey Sykes
  - Calvin College

- **Biological Components**
  - Brianna Bultema

- **Output Regulation**
  - Chris Michaels

- **MFC monitor / Web Designer**
  - Achyut Shrestha

- **Tank / Case Design**
  - Jared Huffman

- **Microbiologist**
  - Prof John Wertz
  - Calvin College

- **Microbiologist**
  - Gemma Reguera
  - Michigan State University
6.3. Team Member Roles Description

The project has been evenly divided for the four members of the team. Contribution from each team member is essential for the successful completion of the project. Each team member is responsible for completing their assigned sections as well as helping the other members finish their part. Although the divided section is complete in itself, it is of little use without the integration so the integration of the project will require the expertise from the each member in their assigned sections. The role of each member has been properly defined and designated (Table 2).

Jared Huffman is the leader of the project. He is responsible for overseeing that the project is completed in a timely manner. As a designer, his primary responsibility is to design a case for the system and integrate the different parts together. His job is to make the product user friendly to the extent possible.

Brianna Bultema is primarily responsible for the biochemical part of the project. Her job description includes, but not limited to, overseeing welfare of the Geobacter and help setup a proper environment for the microbial fuel cell. Her work is closely related to the biology and chemistry aspect of the project.

Chris Michaels is responsible for designing an output regulator circuit. His work is to devise a circuit that will take the voltage from the MFC and stabilize it before optimizing the voltage to a specified output level. He will also be testing the working of a final prototype.

Achyut Shrestha is responsible for designing MFC system monitor. His job is to design a circuit that will oversee the system status and communicate the information to a user in an appropriate way. He is also responsible for testing the initial experimental setup. He also maintains the website for his team project.

Table 2: Team Member Responsibilities

<table>
<thead>
<tr>
<th>Brianna Bultema – Biological Components</th>
<th>Achyut Shrestha – MFC Monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Biological Research</td>
<td>• Electrical research</td>
</tr>
<tr>
<td>• Bacteria Management</td>
<td>• MFC monitoring design</td>
</tr>
<tr>
<td>• MFC inner workings</td>
<td>• Testing experimental setup</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chris Michaels – Output Regulation</th>
<th>Jared Huffman - Tank / Case Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Electrical research</td>
<td>• System Integration</td>
</tr>
<tr>
<td>• Regulator circuit design</td>
<td>• User Interface</td>
</tr>
<tr>
<td>• Testing prototype</td>
<td>• Tank Design</td>
</tr>
</tbody>
</table>
6.3.1. Contingency Plan for Individual Failure/Absence

As a product, the Biobattery is only viable with all of its features. New products in this field cannot afford superfluous features. Unfortunately, a product with no superfluous features with any unsuccessful or non-functioning parts simply cannot function as a product. Unsuccessful as a product, the Biobattery can still function as a proof of concept demonstration of the functioning features.

6.3.1.1. MFC Contingency

In the event of failure of the MFC aspect of the project, Ecowatt plans to demonstrate the viability of the power regulation system through controlled input voltage. A similar controlled input voltage test will verify the proper operation of the monitoring system design, and the feeding system will demonstrate proper feeding and waste removal on a non-functional dummy MFC.

6.3.1.2. Monitoring System Contingency

In the event of failure of the Monitoring System aspect of the project, Ecowatt plans to demonstrate the viability of the Biobattery MFCs, power regulation system, and feeding and waste removal system. The feeding times and other monitoring functions can be determined with a handheld digital multimeter setup to indicate power status.

6.3.1.3. Power Regulation Contingency

In the event of failure of the Power Regulation aspect of the project, Ecowatt plans to demonstrate the viability of the Biobattery as a power supply with the MFCs, monitoring system, and feeding and waste removal system fully functioning. An unregulated output has limited but undeniable uses, such as powering an LED.

6.3.1.4. Feeding and Waste Removal Contingency

In the event of failure of the Feeding and Waste Removal aspect of the project, Ecowatt plans to demonstrate the viability of the Biobattery MFCs, power regulation system, and monitoring system. The Biobattery prototype can be constructed within a week of the demonstration to show full functionality of the concept. Unfortunately, the power will begin to decrease irreparably after about a week. Each prototype setup would have a limited but fully functioning life.
6.4. Gantt Charts

At the start of the Fall 2007 Semester, Ecowatt met to determine a schedule for the Fall Semester. The schedule was determined based on each member’s individual schedule as well as a list of project due dates provided by the Professors of Senior Design. The task list for Senior Design was supplemented with other important tasks the team deemed important and relevant to the schedule. The team estimated how many days or weeks each task was expected to require and assembled a Gantt Chart of the results (Figure 13).

Throughout the Fall 2007 Semester, Ecowatt met regularly to discuss important matters about the project. The schedule was frequently discussed; the team changed the schedule as appropriate to meet more specific or changing deadlines for Senior Design as well as to compensate for unforeseen scheduling conflicts and lead times for ordering materials.

Towards the end of the Fall 2007 Semester, Ecowatt met to again to analyze the team’s adherence to the predetermined schedule. The team updated and discussed an “Actual” Gantt Chart for the Fall 2007 Semester (Figure 14). The research portions of the project, originally perceived as preceding all other testing and prototyping, continued throughout the entire semester. The lead-time for ordering bacteria was not accounted for and thus required an adjustment to the schedule as well. However, the team stayed on schedule within reason, keeping each of the Senior Design deadlines as well as many of the team’s own additional tasks.

For the Spring 2008 Semester, Ecowatt plans to follow the schedule as well as it did during the Fall, and the goal was to plan for the rest of the year before the end of the Fall Semester. However, the Spring 2008 Senior Design Schedule has not yet been confirmed. Prof Wunder was able to provide the Spring 2007 Senior Design Schedule as a starting point. From each individual team member’s own schedule and the Spring 2007 Semester Schedule, the team derived a preliminary schedule for next semester, represented with a Gantt Chart (Figure 15).
6.4.1 Fall Semester - Plan

Figure 13: Gantt Chart of Fall Semester Plan
6.4.1 Fall Semester – Actual

![Gantt Chart of Fall Semester Actual](image)

*Figure 14: Gantt Chart of Fall Semester Actual*
6.4.2 Spring Semester – Plan

Figure 15: Gantt Chart of Spring Semester Plan
6.5. Project Milestones

In the beginning of the semester, there were few milestones identified that would keep on track the scope and the schedule of the project. The time-line for the fall semester schedule was used to identify these milestones. The milestones that would be achieved by the end of this semester were oral presentations, industrial consultant brief, poster design, website design and PPFS report (Table 3). These were the concrete milestones that were given in course requirements. We were able to accomplish all of the mentioned milestones on or before deadline.

<table>
<thead>
<tr>
<th>Table 3: Major Milestones and Dates Accomplished</th>
</tr>
</thead>
<tbody>
<tr>
<td>Presentation 1</td>
</tr>
<tr>
<td>Poster, Website 1</td>
</tr>
<tr>
<td>Project Brief for Consultant</td>
</tr>
<tr>
<td>Poster, Website 2</td>
</tr>
<tr>
<td>Final PPFS</td>
</tr>
</tbody>
</table>

In addition to class milestones, soft milestones were created for our specific project. As the semester progressed, these milestones shaped the project’s future direction. These milestones included purchasing Geobacter, creating a working MFC, and testing.

Geobacter, the workhorse of our MFC, was purchased. Getting the right species of bacteria was important because these are expensive and must be handled with great care. After receiving the Geobacter, they are being cultured and reproduced in biology lab. Geobacter will last the life of this project.

One of the defining milestones during the course of the project was being able to successfully test experimental setup of the microbial fuel cell. This was very important because it proved that the project was feasible, at least technically.

The other major milestone was recognizing that the voltage output from the single MFC is too little to power up anything and would have no commercial value. So a multiple MFCs configured in a certain arrangement to generate a standard voltage was proposed and decided. Getting a standard voltage from the cell would make it commercially viable.

Similarly there will be milestones for the next phase of the project. Identified milestones for next semester include deciding on the nominal voltage output from the MFC, testing the MFC with membrane, and deciding on layout of MFCs.
7. Cost Estimates for Building Prototype

7.1. Electrical

The only two parts needed that require purchase are the AT-41533 General Purpose, Low Noise NPN Silicon Bipolar Transistor from Avago Technologies and the LP38841-ADJ 0.8A Ultra Low Dropout Adjustable Linear Regulator from National Semiconductor. The voltage regulator is $2.08/unit, and the transistor is $0.39/unit. Therefore, the cost per unit not including special parts and other costs is $2.47. All other parts needed for production are accessible through Calvin College’s Electrical Engineering Lab.

7.2. Case

The cost of the case is largely dependent on undetermined factors. The number of MFCs and their arrangement affects the size and shape of the case. The type of feeding method is also dependent on the MFC arrangement and determines certain aspects of the case design. The team anticipates the implementation of some type of plastic, but the specific design is not completed. Furthermore, the Refill Station design is not complete. Overall, Ecowatt plans to maintain a Case Cost of approximately $50 with a 100% contingency.

7.3. Biology Materials

The bacteria, Geobacter metallireducens, ATCC 53774, will cost $175 for a single investment because the bacteria can reproduce without having to buy more. Wolfe’s Vitamin Solution, Vitamin Supplement MD-VS and Wolfe’s Mineral Solution, Trace Mineral Supplement MD-TMS are valuable solutions for keeping the bacteria alive and healthy. These cost $40/5L of media. The sales order for these materials is SO807459 with the bacteria lot number being 7405983, the vitamin lot number being 57954988, and the mineral lot number being 57954994. These materials came on November 5, 2007, which is 13 days after ordering. The individual battery cost for bacteria will be highly dependent on the final number of MFCs produced.

8. Business Plan for Full Scale Production of Product

8.1. Marketing

Because the resulting cost of each unit will go beyond the means of what most consumers will want for a battery, the bio-battery will sell strongest among those concerned about the environment. Therefore, marketing will focus on those willing to pay the price in their cause of good stewardship of the environment. In addition, marketing will show that this device will demonstrate that the bio-battery is a viable alternative fuel to regular lead acid
batteries. As such, a push for the scientific community in general to use and research further on bio-batteries is a must.

8.2. Basic Production Process

A facility interested in manufacturing Biobatteries on full scale level needs to account for certain intricacies of the product. Either the unit must be shipped with the bacteria frozen, or the Biobattery must be fed every 7 days, even during shipment. If the unit is shipped frozen, it will require assembly upon reception. The assembly would be somewhat complex – requiring individual assembly and pressurization of each MFC and then incorporation into the full Biobattery case. Based on this difficulty, the recommended method of shipment is as a fully functioning, non-frozen unit. At certain stages of the assembly, a MFC is sensitive to other bacteria, so some sterile processes are required. Packets of the ingredients for the Feed Solution must be included with the product, and refills will need to be sold separately to keep the Biobattery functioning. Finally, a Refill Station must be included; the Refill Station operates on a pressurized nitrogen and carbon dioxide gas mixture that must be included as well as sold separately to allow for feeding of the Biobattery. For more details on Biobattery assembly, see the Biobattery Assembly Instructions section in Appendix I.

8.3. Budget

The current estimate for the cost of each Biobattery is $300. While the electrical parts will cost less than $10 per unit the rest of the unit will cost substantially more. These costs include the bacteria, the container, the feeding solution, and for the rest of the expenses involved for the actual manufacturing of the battery. The cost of labor and any other costs not listed above are not part of the estimate for the construction of the Bio-battery prototype.

9. Conclusions

The Ecowatt Biobattery is a feasible and attractive prospect for a Calvin College Engineering Senior Design Project with great promise for a marketable and worthwhile product. The team thoroughly investigated the feasibility of the Biobattery through research, testing, preliminary design, and a business plan.

The team successfully researched the many aspects of the project over the course of a semester. The team determined that the Biobattery has not been completed previously as a whole project, but MFCs have been tested. University researchers have conducted experiments proving the concept of MFCs, providing inspiration for the current design. By spending a semester researching MFCs in different implementations and their relative limitations, the team gained a context for the Biobattery design that is absolutely necessary for the success of the project.
Based on previous implementations and helpful guides available online, the team constructed a test setup that successfully demonstrates the functionality of an MFC. The salt bridge membrane MFC with test tubes for the anode and cathode chambers achieved an average closed circuit voltage output of 0.3 that it maintained for at least a week without feeding. The setup is less than ideal, and the power output has not yet been optimized, but the test data proves the concept. Future testing is planned for Interim 2008, including possible electrode arrangements and membrane options.

The Biobattery project meets the Fundamental Ecowatt Values, and a business plan has been constructed. The market research reveals that early adopters of this new technology would be consumers with a desire for a stable, environmentally friendly power supply. As the product and market mature, more applications will arise. The product is designed with manufacturing in mind. Clearly, the Biobattery is a feasible business product.

While the MFC testing was being conducted, the team worked diligently on preliminary designs. The team has completed preliminary design by specifying the bacteria and creating a block diagram of an MFC. A switching regulator is being implemented in the regulating circuit, and monitoring systems have been prototyped. The feeding system and case design have progressed to the point where the team can confidently assert the feasibility of the Biobattery.
References


Logan, Bruce E., Bert Hamelers, Rene Rozendal, and Uwe Schroder. Microbial fuel cell: Methodology and technology. n.d.

Lovely, D. R., Microbial Energizers: Fuel cells that keep on going. Microbe (Volume 1, Number 7), 2006


STMicroelectronics. 6 Dec. 2007
Acknowledgements

We would like to acknowledge the following people for their support throughout the duration of this project. Without their assistance and support we would not be able to undertake such a multi-disciplinary process.

- Professor Randall Brouwer, Engineering Department, for supplying VHDL code for ADC interface.
- Sam Brower, for various visual design and photographic assistance.
- Bob DeKraker, Engineering Department, for logistical support with procurement of circuit components.
- Rich Huisman, Chemistry Department, for assistance with salt bridge supplies.
- Lori Keen, Biology Department, for assistance in biological procurement and lab support.
- Professor Walter Rawle, Engineering Department and Senior Design Team Mentor, for meeting with our team and assisting us with the in progress reviews.
- Professor Gemma Reguera, Michigan State University, for providing technical information and expertise.
- Professor J. Aubrey Sykes, Engineering Department, for his ongoing role as the senior design advisor and for all of this feedback about our project.
- John Wertz, Biology Department, for assistance in Microbiology growth and experimentation.
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Appendix I - Biobattery Assembly Instructions
50mL Test Tubes with Salt Bridge, No Autoclave – Not Final Design

Note: Prepared Bacteria Test Tubes from this procedure expire in about a week, but steps 1-3 do not expire and can be completed in large quantities in advance.

Testing instruments:
- Multimeter
- Resistors
- Cables
- wires
- alligator clips
- Oscilloscope
- Data logger

Procedure:
1. Prepare the wire and electrode. \(5 \text{ min} / \text{tube} + \text{Epoxy Curing Time}\)
   a. Obtain a 10” wire with good conductivity (non-copper).
   b. Using a box cutter, cut a portion of electrode that will fit into the test tube (about 1cm X 0.5cm X 3cm, larger electrodes should result in higher power output).
   c. Attach the electrode to the end of the wire using a conductive epoxy or cement.

2. Prepare the cap (One for each desired bacteria-filled test tube, up to 16). \(20 \text{ min} + 5 \text{ mins} / \text{tube}, \text{Requires Rich Huisman}\)
   a. Obtain a rubber stopper of size 4.
   b. Insert a custom bent glass tube.
      i. Ask Rich to bend a glass tube (~18”) into three sides of a square.
      ii. Ask Rich to help create a hole in the rubber stopper for the custom bent glass tube.
   c. Insert the wire into the cap.
      i. Pierce the cap with a 16 gauge needle.
      ii. Thread the wire through the needle, leaving enough wire for the electrode to hang suspended just above the bottom of the test tube.
iii. Remove the needle, leaving the wire in the cap.

3. Prepare the Salt Bridge (Repeat for each desired bacteria-filled test tube). \( 20 \text{ mins} + 5 \text{ mins / tube} \)
   a. Boil 30mL de-ionized water in a 100mL beaker with a stir-bar.
   b. Stir the solution and add ingredients.
      i. Add 1.5g KCl.
      ii. Add 2.5g Ultra-Pure Agar.
   c. Using a 16 gauge needle and a 10mL syringe, quickly add the Agar solution to the custom bent glass tube (from part 2) with as few bubbles as possible. The Agar solution will cool quickly and solidify.

4. Prepare Media Solution (No Autoclave). \( 45 \text{ mins} \)
   a. Boil 100mL de-ionized water in a 250mL Erlenmeyer Flask.
   b. Add 3.425g Sodium citrate (13.7g/L).
   c. Cool to room temp using ice bath.
   d. Adjust the pH to 6.0 using 10M NaOH.
   e. Add to the solution.
      i. Add 150mL de-ionized water.
      ii. Add 0.625g NaHCO3.
      iii. Add 0.0625g Ammonium Chloride.
      iv. Add 0.15g NaH2PO4H2O.
      v. Add 0.025g KCl.
      vi. Add 1.7g Sodium Acetate.
   f. Degas the media in a 1L Erlenmeyer Flask with Side Arm

5. Prepare the test tubes (Repeat for each desired bacteria-filled test tube). \( 5 \text{ mins / tube} \)
a. Using the nitrogen tank, blow the air out of a test tube.

b. Using an automatic pipette, transfer 15mL of prepared Media Solution to the test tube by quickly removing the cap and transferring the Media Solution.

c. Continue to blow the air out of the tube with the nitrogen tank and immediately close the cap again.

d. Add 7mL carbon dioxide.

e. Mix the gasses by shaking the test tube.

f. De-pressurize the test tube by quickly penetrating the cap with a needle. Remove the needle as soon as the tube audibly de-pressurizes.

6. Add the Vitamin and Mineral Solution (Repeat for each desired bacteria-filled test tube). \(5 \text{ mins}\)

   a. Using a syringe and needle, add 0.16mL Wolfe’s Vitamin Solution.

   b. Using a syringe and needle, add 0.16mL Wolfe’s Mineral Solution.

7. Add the bacteria (Geobacter Metallireducens) (Repeat for each desired bacteria-filled test tube). \(10 \text{ mins/tube}\)

   a. Select a healthy culture (light greenish brown).

   b. Sterilize the top of the culture.

      i. Using a cotton swab, apply a layer of 95% ethanol to the top of the cap on the culture solution test tube.

      ii. Using a Bunsen burner, ignite the entire top of the cap, burning off all of the ethanol.

   c. Using a sterile needle, pierce the cap of the culture solution test tube.

   d. Withdraw about 2mL culture solution.

   e. Add the culture solution to the media solution test tube by piercing the cap and injecting the culture.

8. Place each Prepared Bacteria/Media Solution in a 30°C Agitator Bath. \(1 \text{ min}\)
Appendix II – MFC Testing Data

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Appendix III – Product Information Sheet of ATCC® 53774

ATCC ® NUMBER:  53774

ORGANISM:  *Geobacter metallireducens*
Type strain GS-15. This material is cited in a U.S. and/or other Patent Application and may not be used to infringe the patent claims.

CITATION STRAIN:
If use of this strain results in a scientific publication it should be cited in that manuscript in the following manner: *Geobacter metallireducens* ATCC® 53774.

ATCC ® MEDIUM:
#1768 Broth: Medium for *Geobacter metallireducens*

Milli Q H₂O, 800mL
Ferric citrate (Sigma F-6129), 13.70 g
Vitamins (see below), 10mL
Minerals (see below), 10mL
NaHCO₃, 2.50g
NH₄Cl, 0.25g
NaH₂PO₄•H₂O, 0.60 g
KCl, 0.1 g
Sodium acetate, 6.8 g

*Heat about 400 ml of Milli Q H₂O on a hot/stir plate to near boiling. Add ferric citrate, allow to dissolve then cool to room temperature in a slurry of ice, bring the volume of Milli Q H₂O up to 800 ml by adding 400 ml Milli Q (this quickly cools the media to room temp). Adjust the pH to 6.0 using 10N NaOH (When the pH approaches 5.0 add the NaOH drop wise.). The approximate volume of 10N NaOH per liter is 6 ml.*

Add the remaining ingredients and bring the final volume up to one liter with Milli Q H₂O.
Bubble the medium with 80% N₂ and 20% CO₂. The final pH should be around 6.8-7.0.
This medium should not be exposed to light.

CONDITIONS:
Temperature: 30°C
Atmosphere: Anaerobic (80% N₂, 20% CO₂)

BIOSAFETY LEVEL: 1
Appendix IV – SOPC Builder for Voltage Monitoring

Screenshot of SOPC builder for project Ecowatt
Appendix V – Assembly Code for Voltage Monitor

/*****************************/
/* Name: Achyut Shrestha, Jared Huffman & Chris Michaels */
/* Course: Engr 325A       Lab #: 5 (project) */
/* Date: 11/20/07          */
/*****************************/
.include "nios_macros.s"
/* Define your reset and exception vector addresses here. The values come */
/* from your cpu configuration in SOPC builder. Should be word aligned. */
.equ RESET_VECTOR, 0x00
.equ EXCEPTION_VECTOR, 0x20
/* comment out the next line if not using interrupts */
#ifdefine USING_INTR 1
/* Define mask values for setting interrupt enable bits */
.equ PIE_MASK, 0x01
.equ TIMER_INTR_NUM, 0
.equ TIMER_MASK, (0x01 << TIMER_INTR_NUM) /* set to interrupt #0 */
/* I/O Definitions go here */
/* Define the base address for the IO devices. Use "movia ri, xxx_BASE" */
/* to load the base address into a register (e.g. register i). Then you */
/* can use ldwio and stwio instructions to read/write to the device. */
.equ TIMER, 0x11000 /* base location of TIMER register for timer device */
.equ LCD, 0x11020 /* base location of LCD */
.equ ADC, 0x11028 /* base location of ADC */
.equ TIMERSTAT, 0x00 /* base location of TIMER register for timer device */
.equ TIMERCTRL, 0x4
.equ DATAOFFSET, 0x0
.equ LCDINSTR, 0x0
.equ LCDDATA, 0x4
.text
.org RESET_VECTOR /* Place the main routine at the reset address */
.global _start
_start: /* Program start location must be identified */
/* ... enable interrupts code */
br MAIN_PROG_INIT
/*****************************/
/*#define USING_INTR 1
/*****************************/
.org EXCEPTION_VECTOR
#elseifdef USING_INTR
ISR:
rdctl et, ctrl4 /* Check if an external (hardware) interrupt has occurred */
beq ea, ea, 4 /* If yes, decrement ea to re-execute interrupted instruction */
br END_ISR
TIMER_BR:
movia gp, ADC
EXCEPTION_ACTION:
/* The interrupt-service/exception-handler routine: After determining the source */
/* of the interrupt, the interrupt condition must be cleared. */
/* check for interrupt, if interrupt is 0 go to timer branch else goto direction*/
andi r6, et, 0x1 /* check to see if there was an pending bit */
bne r6, r0, TIMER_BR /* go to direction branch if r6 not equal to 0 */
br END_ISR
TIMER_BR:
movia gp, ADC
ldw r12, 0x0(gp) /* load bit value from ADC */

andi r12, r12, 0xff /* masks the important bits to the register */

END_ISR:

/* The cpu does the following when you return from the interrupt:
1. Copies the contents of estatus (ctl1) to status (ctl0)
2. Transfers program execution to the address in the ea register (r29)
*/

movia gp, TIMER
stwio r0, TIMERSTAT(gp)
eret /* Return from exception */

/* end of exception handler routine */
#endif

/****************************MAIN******
***********************************************************************/

/* the main program startup code goes here */
MAIN_PROG_INIT:
/* initialize variables if needed */
movi r10, 154 /* Branch Value for Good */
movi r11, 77 /* Branch Value for Danger */
movi r12, 250 /* Junk */
Value to start r12 before it gets interrupted */
mov r8, r0

/* Initialize the timer */
movia gp, TIMER
movi r20, 0b11
stwio r20, TIMERCTRL(gp)

/* Turn on the LCD */
movi r9, 0b1100
movia gp, LCD
stwio r9, LCDINSTR(gp)

#endif USING_INTR

/* now enable the cpu interrupts */
rdctl et, ct1 /* Read the interrupt enable register */
ori et, et, 0x1 /* set the TIMER interrupt enable bit high */
wrctl ct1, et
rdctl et, ct0 /* Read the status register */
ori et, et, 0x1 /* set the PIE bit high to enable all interrupts */
wrtcl ct0, et
#endif

MAIN_PROG:

movia gp, ADC
ldw r12, 0x0(gp)
/* load bit value from ADC */
andi r12, r12, 0xff /* masks the important bits to the register */

beq r12, r8, MAIN_PROG /* If no new value, no new display. */
mov r8, r12 /* Set the new value to work from for the display. */

DisplayChooser:

movia gp, LCD
movi r9, 0x1
stwio r9, LCDINSTR(gp)
bgt r8, r10, VoltGood
bgt r8, r11, VoltLow
bgt r8, r0, VoltDanger

VoltError:

movi r9, 0x45
call BUSYFLAG
stwio r9, LCDDATA(gp)
movi r9, 0x52
call BUSYFLAG
stwio r9, LCDDATA(gp)
movi r9, 0x52
call BUSYFLAG
stwio r9, LCDDATA(gp)
movi r9, 0x4f
call BUSYFLAG
stwio r9, LCDDATA(gp)
movi r9, 0x52
call BUSYFLAG
stwio r9, LCDDATA(gp)
movi r9, 0x21
call BUSYFLAG
stwio r9, LCDDATA(gp)
br MAIN_PROG

VoltDanger:
movi r9, 0x44
call BUSYFLAG
stwio r9, LCDDATA(gp)
movi r9, 0x41
call BUSYFLAG
stwio r9, LCDDATA(gp)
movi r9, 0x4e
call BUSYFLAG
stwio r9, LCDDATA(gp)
movi r9, 0x47
call BUSYFLAG
stwio r9, LCDDATA(gp)
movi r9, 0x45
call BUSYFLAG
stwio r9, LCDDATA(gp)
movi r9, 0x52
call BUSYFLAG
stwio r9, LCDDATA(gp)
movi r9, 0x21
call BUSYFLAG
stwio r9, LCDDATA(gp)
br MAIN_PROG

VoltLow:
movi r9, 0x4c
call BUSYFLAG
stwio r9, LCDDATA(gp)
movi r9, 0x6f
call BUSYFLAG
stwio r9, LCDDATA(gp)
movi r9, 0x6f
call BUSYFLAG
stwio r9, LCDDATA(gp)
movi r9, 0x6d
call BUSYFLAG
stwio r9, LCDDATA(gp)
br MAIN_PROG

VoltGood:
movi r9, 0x47
call BUSYFLAG
stwio r9, LCDDATA(gp)
movi r9, 0x6f
call BUSYFLAG
stwio r9, LCDDATA(gp)
movi r9, 0x6f
call BUSYFLAG
stwio r9, LCDDATA(gp)
movi r9, 0x6f
call BUSYFLAG
stwio r9, LCDDATA(gp)
br MAIN_PROG

BUSYFLAG:
    /* Waits until the Busy Flag is unset before moving on */
movia gp, LCD
ldwio r18, LCDINSTR(gp)
andi r18, r18, 0b1    /* Masks the first bit for the busy flag. */
nop  /* Troubleshooting nops */
nop
nop
bne r18, r0, BUSYFLAG
ret

ProgEnd:
    /* end of program code goes here */
.end
Appendix VI - VHDL Code for ADC Interface (Courtesy of Professor Brouwer)

-- Simple Interface between NIOS II and an 8-bit serial ADC
-- Engineering 325
-- Calvin College, Grand Rapids, MI 49546
-- Prof. R. Brouwer
-- November 2007

library ieee;
use ieee.std_logic_1164.all;
-- since incrementing a std_logic_vector, need the math library
use ieee.std_logic_unsigned.all;

-- This component provides an interface between the NIOS avalon
-- fabric and a TI tlc549 8-bit serial ADC. The ADC requires:
--   - I/O clock with max freq of 1.1 MHz (Period~900ns)
--   - CS active low for 8*I/Oclk_period+1.7us ~ 9 us
--   - CS inactive (high) for at least 17 us
--   - CS period of 17+9 us ~ 26 us
--   - data read (MSbit first) on each rising edge of I/O clock during
--     the CS active period
--   - I/O clock low during first 1.4us of CS active

entity Ext_ADC is
  port (clk : IN STD_LOGIC;
         reset_n : IN STD_LOGIC;
         chipselect : IN STD_LOGIC;
         read : IN STD_LOGIC;
         readdata : OUT STD_LOGIC_VECTOR(7 downto 0);
         IO_CLK : OUT STD_LOGIC;
         ADC_CS : OUT STD_LOGIC;
         ADC_DATA : IN STD_LOGIC);
end entity Ext_ADC;

architecture my_rtl of Ext_ADC is
  signal intern_ioclk : STD_LOGIC;
  signal intern_cs : STD_LOGIC;
  signal data_reg : STD_LOGIC_VECTOR(7 downto 0);
  signal shift_reg : STD_LOGIC_VECTOR(7 downto 0);

-- This design takes the 50 MHz clock and divides it down by 32 to generate
-- each phase of the IO clock. The IO clock runs
-- 8 cycles during which the clock signal is sent to the ADC. After that, no
-- clock signal is sent to the ADC for 56 IO clock cycles. During the last of
-- the 56 (delay) cycles, the CS is driven low.

architecture my_rtl of Ext_ADC is
  signal intern_ioclk : STD_LOGIC;
  signal intern_cs : STD_LOGIC;
  signal data_reg : STD_LOGIC_VECTOR(7 downto 0);
  signal shift_reg : STD_LOGIC_VECTOR(7 downto 0);
-- need a free-running counter for ~ 40 us in length (20ns*2^11)
signal clk_counter : STD_LOGIC_VECTOR(10 downto 0);
signal valid_ser_data : STD_LOGIC;
begin
-- This process creates an 11-bit counter that overflows after approx
-- 40 us.
--------------------------------------------------------------------------------
clk_gen: process(clk, reset_n)
begin
if (reset_n = '0') then
  clk_counter <= (others => '0');
else
  if (clk'event and clk = '0') then -- falling edge
    clk_counter <= clk_counter + 1; -- ignore overflows
  end if;
end if; -- else
end process;
-- the sixth bit is the right freq for the io clk to give it a period of ~ 1.28 us
intern_ioclk <= clk_counter(5);
-- activate this flag for approx 10.2 us - IO clock will be active during that time
valid_ser_data <= '1' when (clk_counter(10 downto 8) = "001" or clk_counter(10 downto 8) = "010") else '0';
-- only drive the IO clock when we will be looking for serial data. There needs
-- to be a delay after CS is activated.
IO_CLK <= intern_ioclk and valid_ser_data;
--------------------------------------------------------------------------------
-- This process drives the CS signal low at a certain point in time and
-- holds it at that state with a latch. After a delay period, the latch is
-- (p)reset and the CS signal returns high.
--------------------------------------------------------------------------------
cs_control_proc: process (clk, reset_n)
begin
if (reset_n = '0') then
  intern_cs <= '1'; -- '1' is not active
else
  if (clk'event and clk = '0') then -- falling edge
    -- 000100xxxxx occurs at T=2.56 us (after the counter resets)
    if (clk_counter(10 downto 5) = "000100") then
      intern_cs <= '0'; -- force active late in first sequence
    end if;
    -- 011000xxxxx occurs at T=15.340 us -> CS active for 12.8us
    elsif (clk_counter(10 downto 5) = "011000") then
      intern_cs <= '1'; -- clear cs after second sequence
    else
      intern_cs <= intern_cs; -- explicit latch/register
  end if;
end if; -- else
end process;
end if;
end if;
end if; -- else
end process;
-- use the internal cs signal to drive the output port
ADC_CS <= intern_cs;

-- This process reads the adc_data port on the rising edge of the IO
-- clock signal. It also takes care of shifting the prev bits left.
shift_reg_proc: process (clk, reset_n)
begin
if (reset_n = '0') then
    shift_reg <= (others => '0');
else
    if (clk'event and clk = '0') then -- falling edge
        -- only read data near the rising edge of the IO_CLK signal
        if ((valid_ser_data = '1') and (clk_counter(5 downto 0) = "011111")) then
            shift_reg(7 downto 1) <= shift_reg(6 downto 0); -- shift bits toward MSbit
            shift_reg(0) <= ADC_DATA; -- read into the LSB the new data
            end if;
        end if;
    end if;
end if;
end process;

-- This process transfers the shift register bit pattern to a data
-- register that can be read by the avalon fabric interface. The
-- transfer takes place at T=20.5 us.
data_reg_proc: process (clk, reset_n)
begin
if (reset_n = '0') then
    data_reg <= (others => '0');
else
    if (clk'event and clk = '0') then -- falling edge
        if (clk_counter(10 downto 0) = "10000000000") then
            -- transfer data to data reg after read/shift is complete
            data_reg <= shift_reg;
            end if;
        end if;
    end if;
end if;
end process;
-- only drive the data port when a read is requested from the avalon fabric
readdata <= data_reg when (chipselect = '1' and read = '1') else
    "ZZZZZZZZ";
end architecture;