Design of a single chamber Microbial Fuel Cell

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Abstract

Microbial fuel cells (MFCs) are devices that use bacteria to generate electricity from organic matter. Most of the current research performed on MFCs is concerned with increasing the power density of the system with respect to the peripheral anode surface area; little research has been done on determining the effects of voltage output in comparison to varying fuel cell components. A research grant of $100 was awarded to obtain materials needed to fabricate 7 single chamber MFCs. A permit from the City of Arcata was used to obtain sample primary effluent domestic wastewater. Investigation concluded that a proper biofilm is needed to obtain desirable voltage results, voltage generation is not dependent on volume, an exessive amount of substrate introduced to a minimal amount of biofilm will obtain unwanted voltage results, a capacitance issue was exhibited in a MFC inoculated with DI water and further research will be needed to fully understand the results obtained from this study.

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1 Introduction

Renewable energy will one day be a large portion of global energy production and usage. Microbial fuel cell (MFC) technology represents a new form of renewable energy by generating electricity from what would otherwise be considered waste. According to the Logan Group of Pennsylvania State University (PSU), this technology can use bacterium already present in wastewater as catalysts to generating electricity while simultaneously treating wastewater (Lui et al., 2004; Min and Logan, 2004). Although MFCs generate a lower amount of power than hydrogen fuel cells, a combination of both electricity production and wastewater treatment could reduce the cost of treating primary effluent wastewater. Currently, most of the research performed on MFCs is concerned with increasing the power density of the system with respect to the peripheral anode surface area, while little research has been done on determining the effects of voltage output in comparison to varying fuel cell components.

A research grant of $100 was awarded from the Friends of the Arcata Marsh (FOAM) in support of developing a better knowledge base and skills associated with MFC technology. With this award, and donations from the Schatz Energy Research Center (SERC), E-TEK and Ballard Power Systems; materials were obtained to build 7 different single chamber MFCs. The single chamber MFCs were modeled after one developed at PSU. These MFCs were tested with domestic primary effluent wastewater as the inoculate from the Arcata Wastewater Treatment Facility. The domestic wastewater was obtained by use of a Nature Area Use permit granted by the City of Arcata.

2 Problem Formulation

The objective of this study is to design and assess a single chamber MFC. Analysis will include: building 7 single chamber MFCs with dimensions of 25 m^2 of anode peripheral surface area to 1 m^3 of inoculate volume (Figure 10), inoculating each MFC repeatedly at varying conditions, logging voltage data from each MFC, and developing an I-V curve from one MFC. From this analysis, further investigation can be conducted on the biological and electrochemical mechanism involved with a MFC.

3 Literature Review

The purpose of this literature review is to organize relevant information to use as a reference when applying principles of research and experimentation to MFC technology. This section contains an overview of the biological mechanism of a MFC and the current design structures of MFCs.

3.1 Biological Mechanism

According to Bennetto, normal microbial catabolism consists of a substrate initially oxidized anaerobically when its electrons are released by enzymatic reactions (Bennetto 1990). Bennetto suggests that the electrons are stored as intermediates (e.g. Nicotinamide adenine dinucleotide - NADH, quinones) which become reduced and are then used to provide the living cell with energy (Bennetto 1990). Bennetto states that the ending location for the electrons is molecular oxygen or dioxygen at the end of the respiratory chain (Bennetto 1990).

According to the Logan Group, a MFC uses bacteria to catalyze the conversion of organic matter into electricity by transferring electrons to a developed circuit (Bond et al. 2002). The Logan Group suggests that microorganisms can transfer electrons to the anode electrode in three ways: exogeneous mediators (ones external to the cell) such as potassium ferricyanide, thionine, or nuetral red; using mediators produced by the bacteria; or by direct transfer of electrons from the respiratory enzymes (i.e., cytochromes) to the electrode (Bond et al. 2003, Min 2004). Bennetto suggests that these mediators can divert electrons from the respiratory chain by entering the outer cell membrane, becoming reduced, and then leaving in a reduced state to shuttle the electron to the electrode (Bennetto 1990).

Bond suggests that the bacteria *Shewanella putrefaciens, Geobacter sulfurreducens, Geobacter metallireducens* and *Rhodoferax ferrireducens* are able to generate electricity in a mediatorless MFC (Bond et al. 2003). Oh suggests that bacteria present in mediatorless MFCs have electrochemically active redox enzymes on their outer membranes that transfer the electrons to external materials and therefore, do not require exogeneous chemicals to accomplish electron transfer to the electrode (Oh et al. 2004). Both Bond and the Logan Group specify when these bacteria oxidize the organic matter present in the wastewater, the electron is shuttled to the electrode and the protons produced diffuse through the water to the counter electrode (cathode) giving this particular electrode a positive characteristic

(Bond and Lovely 2003, Bond et al. 2002, Lui et al. 2004). Oxygen, the hydrogen protons, and the electron that is connected by a circuit from the anode to the cathode, are then catalytically combined with a platinum catalyst to form water at the cathode in the inside chamber of a single chamber MFC (Bond and Lovely 2003, Bond et al. 2002, Lui et al. 2004). A simple representation of the biological mechanism previously mentioned is shown within a single chamber MFC (Figure 1).

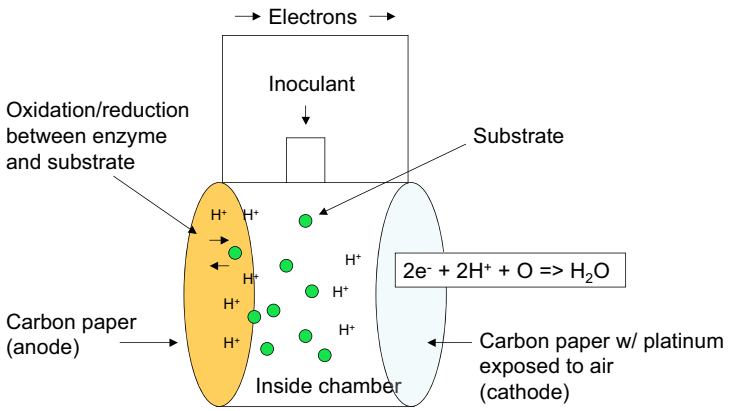


Figure 1: Representation of Anaerobic (anode portion) and Aerobic (cathode portion) Biological Degradation Simultaneous to Electricity Generation in a single chamber Microbial Fuel Cell

Note that the mechanism of MFC technology is still in research stages and many possible reasons for electricity generation cannot be answered without a better understanding of the characteristics of the electricity generating bacteria in MFCs (Min 2004).

3.2 Design Structures

Typical MFCs consists of two separate chambers which can be inoculated with any type of liquid. The Logan Group suggest that these two chambers, an anaerobic anode chamber and an aerobic cathode chamber, are generally separated by a Proton Exchange Membrane (PEM) such as Nafion (Oh and Logan 2004). Both Bond and the Logan Group specified that a MFC such as this can be classified into two types (Bond and Lovely 2003, Chundhuri and

Lovely 2003, Lui et al. 2004). One type generates electricity from the addition of artificial electron shuttles (mediators) to accomplish electron transfer to the electrode, whereas the other type does not require these additions of exogenous chemicals and can be defined as a mediatorless MFC (Bond and Lovely 2003, Chundhuri and Lovely 2003, Lui et al. 2004).

According to Bond, mediatorless MFCs can be considered to have more commercial potential then MFCs that require mediators because the typical mediators are expensive and toxic to the microorganisms (Bond et al. 2003). However, the Logan Group suggests that one major disadvantage of the two chamber system is that the cathode chamber needs to be filled with a solution and aerated to provide oxygen to the cathode (Lui and Logan 2004).

Lui states that hydrogen fuel cells consist of a cathode directly bonded to a PEM which allows for oxygen from the air to directly react at the electrode (Lui and Logan 2004; Gottesfeld 1997). The Logan Group suggest that this same principle can be used to design a single chamber MFC where the anode chamber is separated from the air-cathode chamber by a gas diffusion layer (GDL) allowing for a passive oxygen transfer to the cathode, eliminating the need for energy intensive aeration of the liquid (Figure 2).

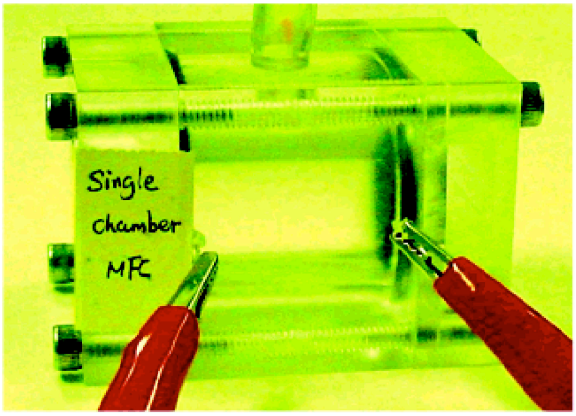


Figure 2: Representation of a single chamber Microbial Fuel Cell designed at Penn. State University (Lui and Logan 2004)

Studies have shown that MFCs typically use expensive solid graphite electrodes, but the Logan Group suggests that less expensive graphite felt and carbon cloth, can also be used (Bond and Lovely 2003, Tender et al. 2002, Chundhuri and Lovely 2003, Lui et al. 2004). Lui states that PEMs such as Nafion are also expensive and if removed, can substantially reduce the overall cost of the MFC (Lui and Logan 2004). Oh specified that platinum is a critical catalyst at the cathode and no alternative metal has been proven to catalyze the combination of oxygen, the hydrogen proton, and the electron in a more efficient manner

(Oh et al. 2004). These design parameters set a limit on the overall cost reduction of the MFC (Lui and Logan 2004).

4 Methods and Materials

This section details the methods and materials pertaining to this particular design and experimentation. Included within this section is: the MFC materials and the dimensions used in fabricating the MFCs.

4.1 Materials

The majority of cost in a MFC is attributed to the platinum catalyzed carbon paper used as the cathode component. Other materials include the non-catalyzed carbon paper (for use as the anode), polycarbonate material and nuts and bolts for fastening the fuel cell together (Table 1).

Table 1: Table of Material Costs

Material	Manufacturer/Distributer	Unit/Dimension	Cost ($US)
Toray carbon paper, standard 0.35mg/cm2 Pt	E-TEK	10cm x 10cm	192.18*
Carbon cloth, 2mg/cm2 Pt	SERC	scrap material	unknown*
Carbon paper, AvCarb P50	fuelcellstore	20cm x 25cm	9.25
Carbon paper, AvCarb P50T	Ballard	20cm x 25cm	no cost
Carbon paper, AvCarb P75T	Ballard	20cm x 25cm	no cost
Toray carbon paper, standard Wet Proofing	E-TEK	10cm x 10cm	16.50*
Polycabonate, hollow rod	McMaster-Carr	0.5in x 0.25in x 12in	1.48
Polycabonate, hollow rod	McMaster-Carr	1.25in x 1.0in x 12in	4.32
Polycabonate, sheet	McMaster-Carr	6.0in x 6.0in x 0.25in	2.27
Nuts and Bolts	Ace Hardware	ea.	0.32
* donated portions			

All carbon based materials used in this project were of hydrophobic characteristic less the AvCarb P50 material. The hydrophobic characteristic allowed for the inoculate to detain within the MFC.

4.2 Dimensions

The single chamber MFC developed at PSU exhibited length dimensions of 3 cm diameter and 4 cm long corresponding to 7.068 cm^2 area and 28.27 cm^3 volume. This is equivalent to dimensions of 25m^2 of anode surface area to 1 m^2 of inoculate volume (Figure 2). A simple calculation yields,

$$\frac{7.068 \times 10^{-4}}{2.827 \times 10^{-5}} = 25$$

and since,

$$\text{Area } (A) = \pi r^2$$

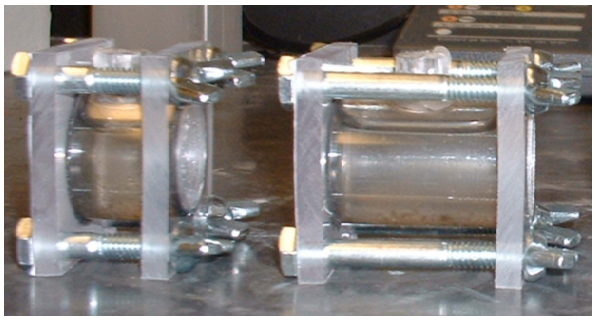
and,

$$\text{Volume } (V) = A \times \text{Length } (L)$$

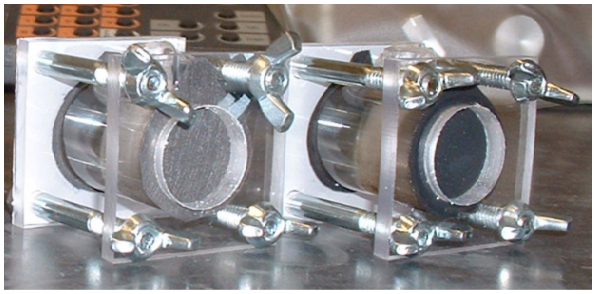
then

$$\frac{A}{V} = \frac{A}{AL} = \frac{1}{L}$$

showing that the ratio of peripheral anode surface area to inoculate volume is not dependent on the area. With the dimensions of a one inch diameter constraint of materials, the same length of 4 cm (1.575 in) could be used for fabrication of the 7 MFCs to obtain 25 m^2/m^3 ratios. The volume of the MFCs developed at Humboldt State University less one are 20 cm^3 or 20 mL. One MFC cell exhibited a 50 m^2/m^3 ratio by decreasing the volume to half the size of the other MFCs (Figure 3; a).



(a)



(b)

Figure 3: Single chamber MFCs developed at Humboldt State University. (a) exhibits of MFCs at a 50 m^2/m^3 and 25 m^2/m^3 ratio; (b) view of cathode portion.

5 Application

This section details the procedure applied to each MFC and the conditions under which the experiments took place.

5.1 Procedure

Each MFC was inoculated with primary effluent (about 20ml) after a transfer bottle was washed thoroughly using domestic city water and conditioned by filling and refilling the bottle a few times with the sample. This was done on a routine basis of either every day or every other day until a biofilm developed on both the anode and cathode portion (Appendix). Voltage was inspected by use of a Fluke 73-III multimeter after each re-inoculation.

5.2 MFC Conditions

Each MFC was inoculated with primary effluent domestic wastewater at various temperature conditions (Table 2).

Table 2: Table of MFC Conditions

Number	Size	Anode (carbon)	Cathode (carbon)	Temperature
1	$25m^2/m^3$	cloth (SERC)	2mg/cm2 Pt (SERC)	outdoor ambient
2	$25m^2/m^3$	cloth (SERC)	2mg/cm2 Pt (SERC)	20 C
3	$50m^2/m^3$	cloth (SERC)	2mg/cm2 Pt (SERC)	20 C
4	$25m^2/m^3$	paper P75T (Ballard)	0.35mg/cm2 Pt (E-TEK)	20 C
5	$25m^2/m^3$	paper P50 (fuelcellstore)	0.35mg/cm2 Pt (E-TEK)	20 C
6	$25m^2/m^3$	paper P75T(Ballard)	0.35mg/cm2 Pt (E-TEK)	37 C
7	$25m^2/m^3$	paper P50T(Ballard)	0.35mg/cm2 Pt (E-TEK)	37 C

Two control MFCs were used to investigate the affects that DI water may have in a MFC (Table 3).

Table 3: Table of control MFC Conditions

MFC number	Size	Anode (carbon)	Cathode (carbon)	Temperature
control 1	$25m^2/m^3$	cloth (SERC)	2mg/cm2 Pt (SERC)	indoor ambient
control 2	$25m^2/m^3$	paper P75T (Ballard)	0.35mg/cm2 Pt (E-TEK)	indoor ambient

6 Results and Discussion

This section details the results obtained from each MFC and the two control MFCs. A small discussion is integrated with each subsection.

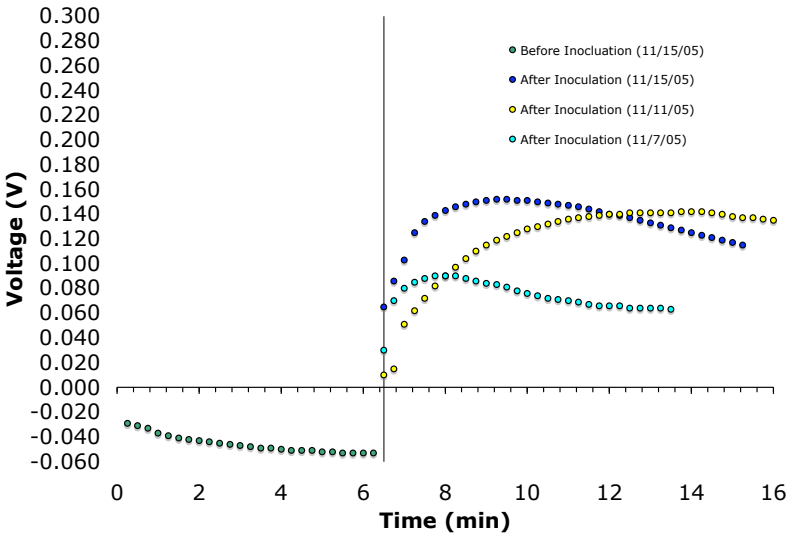
6.1 MFC number 1

MFC number 1 of a 25 m^2/m^3 ratio with anode and cathode materials supplied by SERC was stationed at the Arcata Wastewater Treatment Center at ambient conditions. The MFC re-inoculation procedure occured for the longest amount of time in comparison to the other MFCs. This would allow for a larger amount of biofilm to develop in comparison to other MFCs. The inoculation data taken during the experiment indicates voltage readings after 2

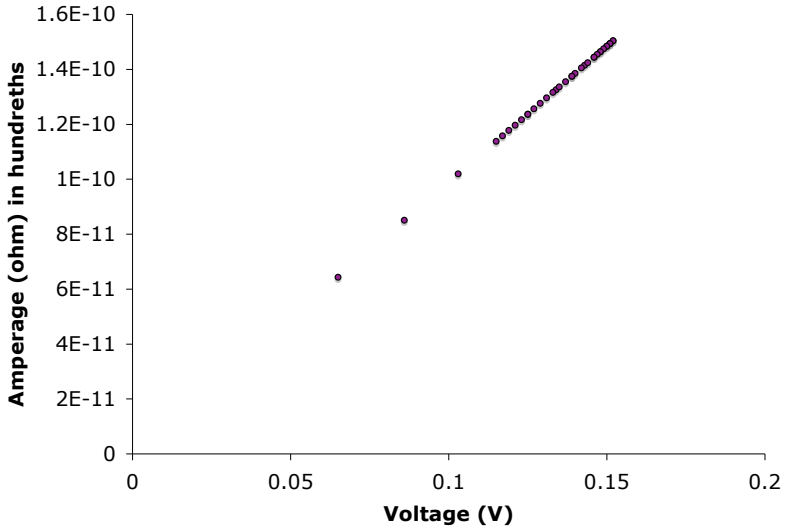
and one half weeks (Appendix A). This may be indicative of a less accurate multimeter. After one month time, logged data of voltage readings were take (Figure 4; a). With this data, an I-V curve was developed under the assumption of the Fluke 73-III multimeter possessing an internal resistance of 10.11 MΩ, R (Figure 4; b). A simple calculation for each data point of voltage, V, can be expressed as,

$$I = \frac{V}{R}$$

There appears to be a maximum voltage of 180 mV by this MFC at these conditions. The I-V curve is not representative of a typical hydrogen fuel cell.



(a)



(b)

Figure 4: Logged data of MFC number 1; (a) voltage readings over time in seconds (b) corresponding I-V curve

6.2 MFC number 2

This MFC used the same materials that of the MFC located at the Arcata Wastewater Treatment Facility, but was located in an incubator at 20 degrees celsius. Voltage readings began instantly after re-inoculation (Appendix B). Logged data readings were taken after one week of re-inoculation of everyday (Figure 5). A maximum voltage of roughly 280 mV was obtained.

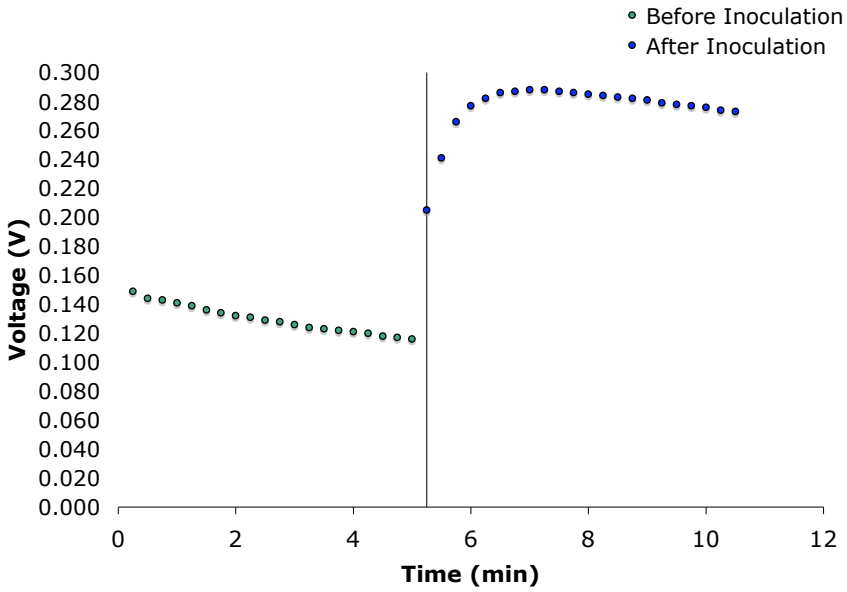


Figure 5: MFC number 2 voltage readings over time in seconds

6.3 MFC number 3

MFC number 3 was sized to $50m^2/m^3$ or exactly half the volume of the other MFCs. It utilized materials of MFC number 2 and exhibited very similar results of MFC number 2 (Figure 6). This suggests that voltage generation is not dependent on volume, i.e. if a system were to increase the size of the anode with respect to volume, voltage generation may be expected to stay the same. A data log of re-inoculation shows a similar procedure to that

of MFC number 2 (Appendix C).

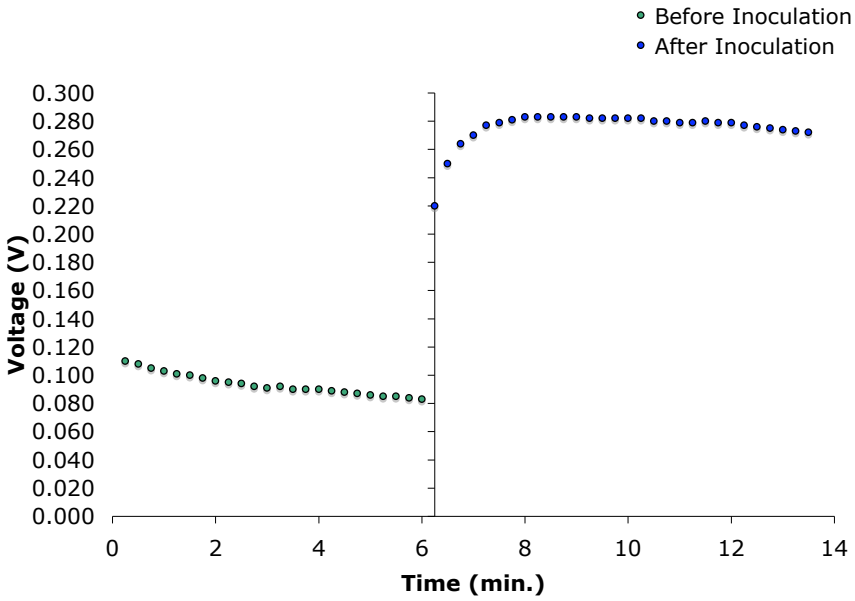


Figure 6: MFC number 3 voltage readings over time in seconds

6.4 MFC number 4

The fourth MFC contained materials from Ballard and E-TEK. The procedure of experimentation was similar to that of MFC number 2 and number 3 (Appendix D). The voltage readings show a dramatic decrease immediately after re-inoculation (FIgure 7). This might suggest that there was insufficient biofilm present and the amount of substrate within the wastewater was overbearing to the small amount of biofilm that might have been present.

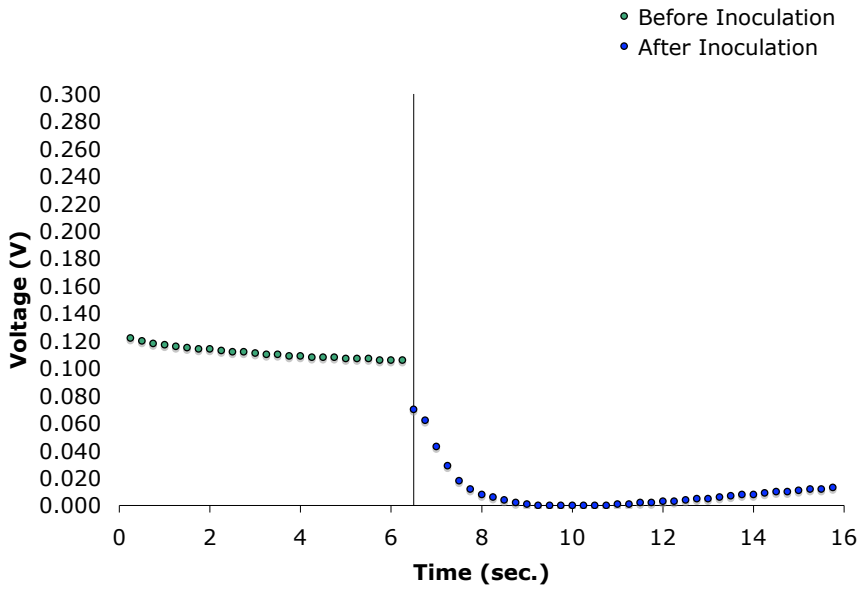


Figure 7: MFC number 4 voltage readings over time in seconds

6.5 MFC number 5

The fifth MFC was the only MFC with a hydrophilic characteristic anode. When securely fastened, water was able to be detained sufficiently in the MFC. The procedure of re-inoculation was the same as previous re-inoculation procedures (Appendix E). The voltage readings were similar to that of MFC number 4 suggesting again that there was not a sufficient amount of biofilm present to utilize the amount of substrate present in the wastewater (Figure 8).

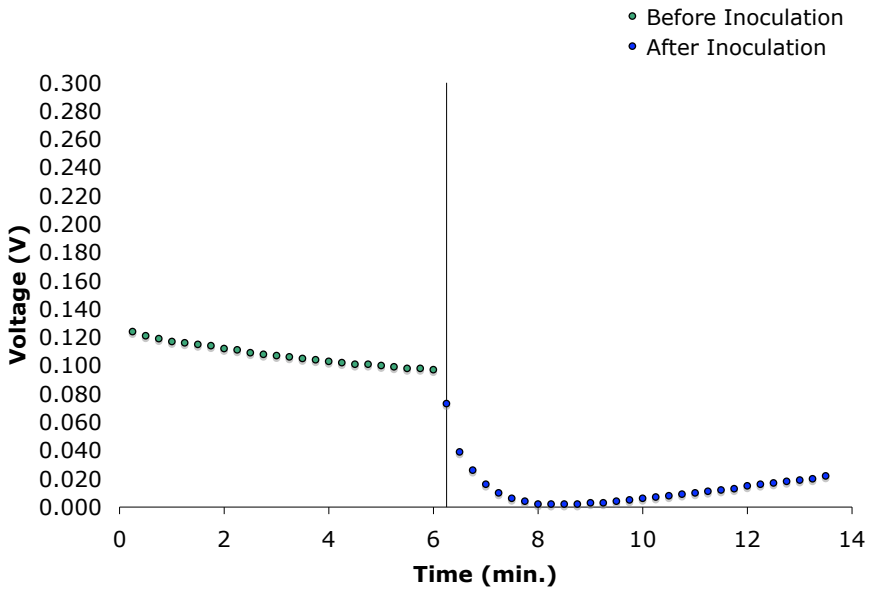


Figure 8: MFC number 5 voltage readings over time in seconds

6.6 MFC number 6

This MFC was kept at 37 degrees celsius and had a similar re-inoculation procedure to that of previous procedures (Appendix F). After re-inoculation, there was a sudden jump in voltage for a very short while before the voltage decreased to the original magnitude (Figure 9). This may also suggest that the amount of substrate in the wastewater was overbearing to the amount of biofilm that may have been present, or it may suggest that there was some sort of capacitance associated with the inoculate to introduce the jump in voltage where the minimal amount of internal resistance in the Fluke 73-III pulled all the current available.

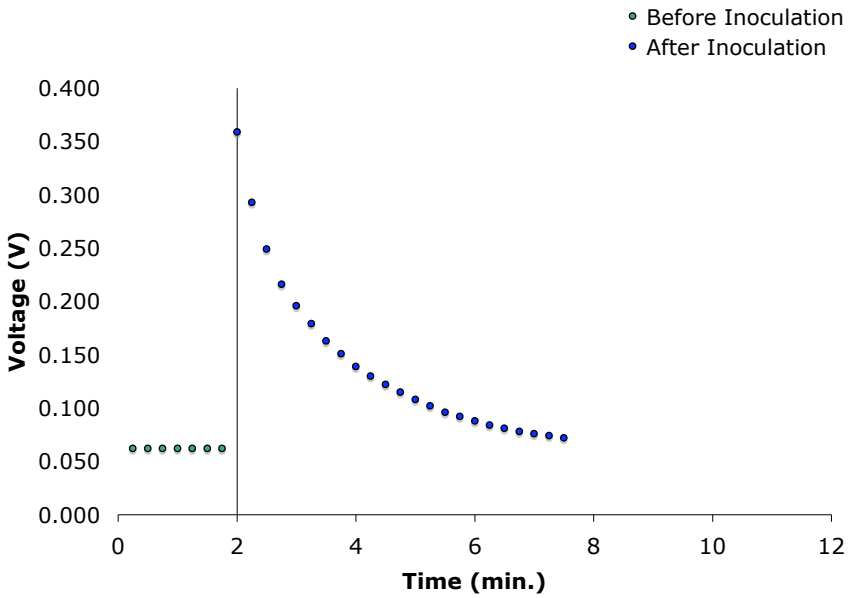


Figure 9: MFC number 6 voltage readings over time in seconds

6.7 MFC number 7

This MFC was kept at 37 degrees celcius and used the same procedure as the previous MFCs (Appendix G). Voltage readings of this MFC were more representative of what might be expected such as what was seen in MFC number 1, number 2 and number 3 (Figure 10). A maximum voltage reading of roughly 110 mV was recorded.

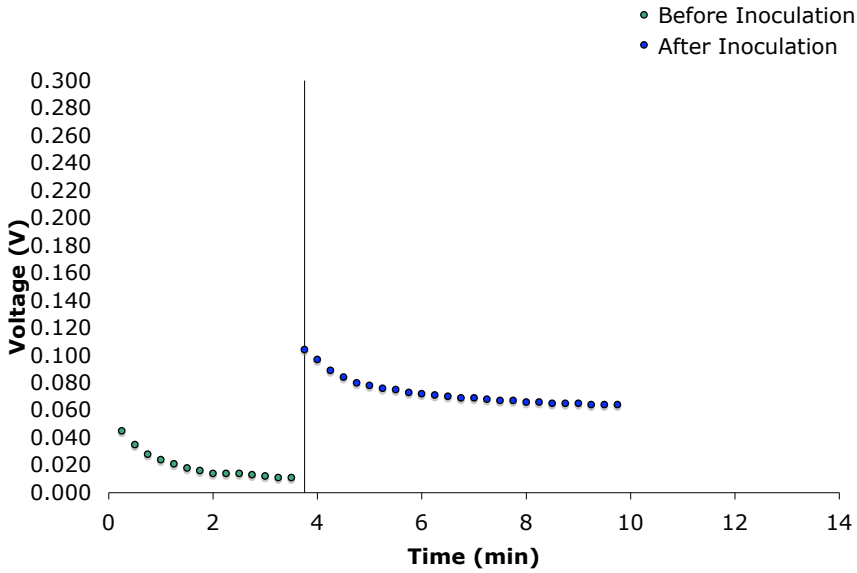


Figure 10: MFC number 7 voltage readings over time in seconds

6.8 MFC control number 1

The first control exhibited a very large jump in a voltage reading upon the initial inoculation of DI water, while the second inoculation exhibited a smaller jump; both decreasing rapidly (Figure 11). This suggests a capacitance attribute associated with the DI water used to inoculate the MFC.

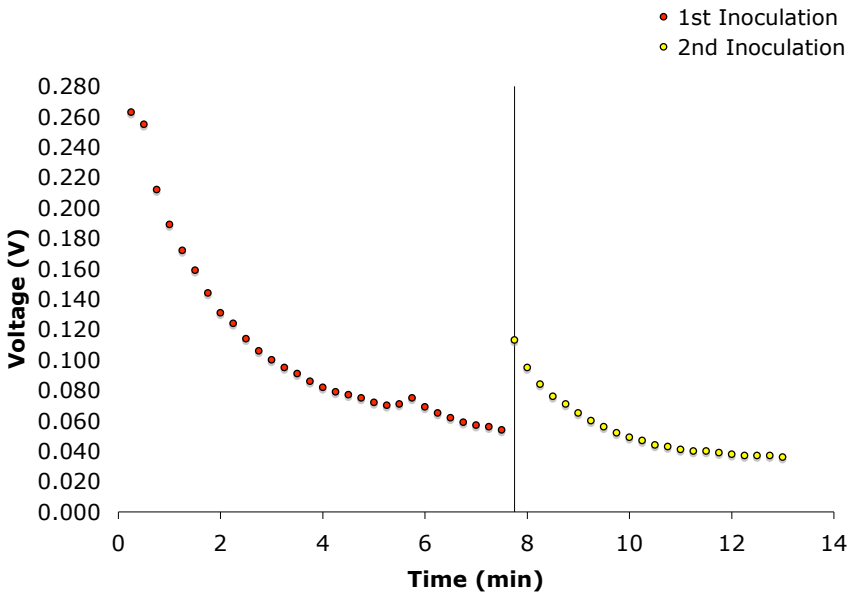


Figure 11: MFC control 1 voltage readings over time in seconds

6.9 MFC control number 2

As anticipated, the second control exhibited hardly any voltage reading at all (Figure 12). However, the little amount of voltage that was read exhibited an increasing attribute.

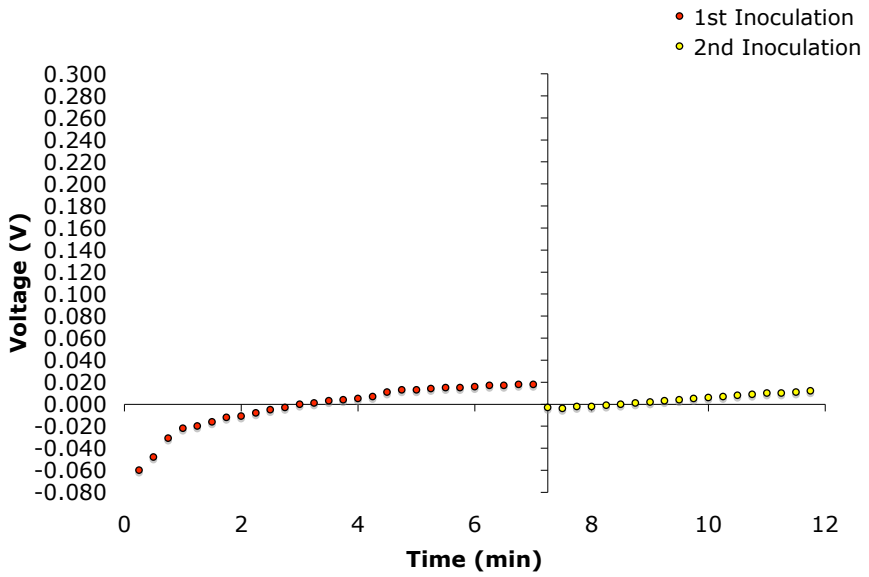


Figure 12: MFC control 2 voltage readings over time in seconds

7 Conclusion

The results of this design demonstrate that electricity generation can be obtained by use of a single chamber Microbial Fuel Cell. Specifically, the investigation shows the following:

- A proper amount of biofilm is needed to exist on the anode portion of the MFC to produce desirable voltage results.
- Voltage generation is not dependent on volume.
- An excessive amount of substrate introduced to a minimal amount of biofilm obtains unwanted voltage results.
- A capacitance issue is exhibited within DI water when used in a MFC.
- Further research is needed.

8 Further Investigation

This study was preliminary with an objective to indulge upon researching a new form of renewable energy. The results obtained were not similar to other studies, so further research is needed to understand the reasons for the obtained results.

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10 Appendix

10.1 Appendix A

Eric Zielke
MFC data log
at varying temp

Date	Time	Description	Environment
09/28/05	08:30 AM	inoculated fuel cell with primary effluent (about 20ml) after the bottle was washed thoroughly and conditioned by filling and refilling the bottle a few times with the sample	roughly 50 degrees F, kept in an abandoned refrigerator for minor climate control
09/28/05	08:30 AM	re-inoculated (same procedure)	roughly 50 degrees F, kept in an abandoned refrigerator for minor climate control
09/30/05	08:30 AM	re-inoculated (same procedure)	roughly 50 degrees F, kept in an abandoned refrigerator for minor climate control
10/03/05	09:00 AM	re-inoculated (same procedure), checked voltage with analog voltmeter and it registered zero	roughly 50 degrees F, kept in an abandoned refrigerator for minor climate control
10/07/05	08:00 AM	re-inoculated (same procedure), checked voltage with analog voltmeter and it registered zero	roughly 50 degrees F, kept in an abandoned refrigerator for minor climate control
10/10/2005	08:30 AM	re-inoculated (same procedure), checked voltage with analog voltmeter and it registered zero	roughly 50 degrees F, kept in an abandoned refrigerator for minor climate control
10/14/2005	08:10 AM	re-inoculated (same procedure), checked voltage with Fluke multimeter, 0.108V before inoculation, 0.140V after inoculation, previous multimeter would still not register	roughly 50 degrees F, kept in an abandoned refrigerator for minor climate control
10/14/05 (same day)	11:20 AM	checked voltage at 0.152V, but then carbon tab broke off of cathode and voltage would not register higher then 0.138V, but consistent (steady voltage)	roughly 50 degrees F, kept in an abandoned refrigerator for minor climate control
10/21/2005	10:20 AM	checked voltage before inoculation 0.150V-0.090V quickly decreasing, after inoculation, 0.210V-0.190V quickly decreasing and at 0.175V decreasing 0.001V every 15 seconds. 2600 ohms. Checked voltage again and started at 0.270V-0.200V quickly decreasing.	roughly 50 degrees F, kept in an abandoned refrigerator for minor climate control
10/28/2005	04:30 PM	checked voltage before inoculation 0.160V-unknownV quickly decreasing, after inoculation, 0.215V-0.100V quickly decreasing.	roughly 50 degrees F, kept in an abandoned refrigerator for minor climate control
10/31/2005	07:00 AM	checked voltage before inoculation 0.160V-unknownV quickly decreasing, after inoculation, 0.210V-unknownV quickly decreasing.	roughly 50 degrees F, kept in an abandoned refrigerator for minor climate control
11/01/2005	06:30 AM	checked voltage before inoculation 0.160V-unknownV quickly decreasing, after inoculation, 0.210V-unknownV quickly decreasing.	roughly 50 degrees F, kept in an abandoned refrigerator for minor climate control
11/02/2005	06:30 AM	checked voltage before inoculation 0.150V-unknownV quickly decreasing, after inoculation, 0.168V-unknownV decreasing by 0.001V every 30 sec.	roughly 50 degrees F
11/03/2005	07:00 AM	checked voltage before inoculation 0.150V-unknownV quickly decreasing, after inoculation, 0.150V increasing to 0.164V, then decreasing	roughly 50 degrees F
11/04/2005	07:30 AM	checked voltage before inoculation 0.095V-unknownV quickly decreasing, after inoculation, 0.0.075V increasing, checked voltage with 50ohm resis., and voltage would increase by 0.002V with every check	roughly 50 degrees F
11/07/2005	08:30 AM	checked voltage before inoculation: ~0.041V after inoculation: refer to graphs	roughly 50 degrees F
11/11/2005	04:00 PM	checked voltage before inoculation: ~0.041V after inoculation: refer to graphs	roughly 50 degrees F
11/15/2005	01:30 PM	checked voltage before and after inoculation: refer to graphs	roughly 50 degrees F

10.2 Appendix B

MFC_SERC_ _20C

MFC (25m^2/m^3) @20C
Anode: Carbon paper seemingly very hydrophobic and it may be catalyzed supplied by SERC
Cathode: 2mg/cm^2 Pt catalyzed (hydrophobic) supplied by SERC

Date	Time	Description	Environment	Voltage Before	Voltage After
10/28/2005	04:00 PM	inoculated fuel cell with primary effluent (about 20ml) after the bottle was washed thoroughly and conditioned by filling and refilling the bottle a few times with the sample	20 degrees C	N/A	N/A
10/31/2005	07:00 AM	inoculated fuel cell with primary effluent	20 degrees C	N/A	N/A
11/01/2005	07:00 AM	inoculated fuel cell with primary effluent	20 degrees C	0.090V (decreasing)	0.175V (decreasing)
11/02/2005	07:00 AM	inoculated fuel cell with primary effluent	20 degrees C	0.087V (decreasing)	0.168V (decreasing)
11/03/2005	07:30 AM	inoculated fuel cell with primary effluent	20 degrees C	0.099V (decreasing)	0.175V (decreasing 0.001V every 15sec)
11/04/2005	08:30 AM	inoculated fuel cell with primary effluent, checked voltage with 50ohm resistor, but nothing was affected. The amps were checked, but resistered nothing	20 degrees C	0.150V (decreasing)	0.175V (decreasing)
11/07/2005	07:30 AM	inoculated fuel cell with primary effluent	20 degrees C	0.101V (decreasing)	0.115V (decreasing)
11/11/2005	11:00 PM	inoculated fuel cell with primary effluent	20 degrees C	No Reading	No Reading
11/15/2005	02:00 PM	inoculated fuel cell with primary effluent	20 degrees C	refer to graph	refer to graph

10.3 Appendix C

0_5MFC_SERC_ _20C

MFC (50m^2/m^3) @20C
Anode: Carbon paper seemingly very hydrophobic and it may be catalyzed supplied by SERC
Cathode: 2mg/cm^2 Pt catalyzed (hydrophobic) supplied by SERC

Date	Time	Description	Environment	Voltage Before	Voltage After
10/28/2005	04:00 PM	inoculated fuel cell with primary effluent (about 20ml) after the bottle was washed thoroughly and conditioned by filling and refilling the bottle a few times with the sample	20 degrees C	N/A	N/A
10/31/2005	07:00 AM	inoculated fuel cell with primary effluent	20 degrees C	N/A	N/A
11/01/2005	07:00 AM	inoculated fuel cell with primary effluent	20 degrees C	0.135V (decreasing)	0.220V (decreasing)
11/02/2005	07:00 AM	inoculated fuel cell with primary effluent	20 degrees C	0.140V (decreasing)	0.220V (decreasing)
11/03/2005	07:30 AM	inoculated fuel cell with primary effluent	20 degrees C	0.140V (decreasing)	0.223V (decreasing)
11/04/2005	08:30 AM	inoculated fuel cell with primary effluent	20 degrees C	0.85V (increasing)	0.210V (decreasing)
11/07/2005	07:30 AM	inoculated fuel cell with primary effluent	20 degrees C	0.138V	0.205V (increasing)
11/11/2005	11:00 PM	inoculated fuel cell with primary effluent	20 degrees C	No Reading	No Reading
11/15/2005	02:00 PM	inoculated fuel cell with primary effluent	20 degrees C	refer to graph	refer to graph

10.4 Appendix D

MFC (25m^2/m^3) @20C
Anode: Carbon paper P75T
Cathode: 0.35mg/cm^2 Pt catalyzed

Date	Time	Description	Environment	Voltage Before	Voltage After
10/28/2005	04:00 PM	inoculated fuel cell with primary effluent (about 20ml) after the bottle was washed thoroughly and conditioned by filling and refilling the bottle a few times with the sample	20 degrees C	N/A	N/A
10/31/2005	07:00 AM	inoculated fuel cell with primary effluent	20 degrees C	N/A	N/A
11/01/2005	07:00 AM	inoculated fuel cell with primary effluent	20 degrees C	N/A	0.128V (steady state for 1 minute)
11/02/2005	07:00 AM	inoculated fuel cell with primary effluent	20 degrees C	0.175V (decreasing)	0.120V (decreasing)
11/03/2005	07:30 AM	inoculated fuel cell with primary effluent	20 degrees C	0.195V (decreasing)	0.130V (decreasing)
11/04/2005	11:00 AM	inoculated fuel cell with primary effluent	20 degrees C	0.185V (decreasing)	0.150V (decreasing)
11/07/2005	07:30 AM	inoculated fuel cell with primary effluent	20 degrees C	0.215V	0.200V (decreasing)
11/11/2005	11:00 PM	inoculated fuel cell with primary effluent	20 degrees C	No Reading	No Reading
11/15/2005	02:00 PM	inoculated fuel cell with primary effluent	20 degrees C	refer to graph	refer to graph

10.5 Appendix E

MFC (25m^2/m^3) @20C
Anode: Carbon paper P50
Cathode: 0.35mg/cm^2 Pt catalyzed

Date	Time	Description	Environment	Voltage Before	Voltage After
10/28/2005	04:00 PM	inoculated fuel cell with primary effluent (about 20ml) after the bottle was washed thoroughly and conditioned by filling and refilling the bottle a few times with the sample	20 degrees C	N/A	N/A
10/31/2005	07:00 AM	inoculated fuel cell with primary effluent	20 degrees C	N/A	N/A
11/01/2005	07:00 AM	inoculated fuel cell with primary effluent	20 degrees C	0.120V (decreasing)	0.030V (increasing)
11/02/2005	07:00 AM	inoculated fuel cell with primary effluent	20 degrees C	0.120V (decreasing)	0.035V (increasing)
11/03/2005	07:30 AM	inoculated fuel cell with primary effluent	20 degrees C	0.094V (decreasing)	0.018V (increasing)
11/04/2005	11:00 AM	inoculated fuel cell with primary effluent	20 degrees C	0.030V (increasing)	0.020V (increasing)
11/07/2005	07:30 AM	inoculated fuel cell with primary effluent	20 degrees C	0.088V	0.075 (decreasing)
11/11/2005	11:00 PM	inoculated fuel cell with primary effluent	20 degrees C	Refer to Graph	Refer to Graph
11/15/2005	02:00 PM	inoculated fuel cell with primary effluent	20 degrees C	refer to graph	refer to graph

10.6 Appendix F

MFC (25m^2/m^3) @37C
Anode: Carbon paper P75T
Cathode: 0.35mg/cm^2 Pt catalyzed

Date	Time	Description	Environment	Voltage Before	Voltage After
10/28/2005	04:00 PM	inoculated fuel cell with primary effluent (about 20ml) after the bottle was washed thoroughly and conditioned by filling and refilling the bottle a few times with the sample	37 degrees C	N/A	N/A
10/31/2005	07:00 AM	inoculated fuel cell with primary effluent	37 degrees C	N/A	N/A
11/01/2005	07:00 AM	inoculated fuel cell with primary effluent	37 degrees C	0.168V (appeared steady)	0.118 (appeared steady)
11/02/2005	07:00 AM	inoculated fuel cell with primary effluent	37 degrees C	0.165V (decreasing)	0.120 (decreasing)
11/03/2005	07:30 AM	inoculated fuel cell with primary effluent	37 degrees C	0.160V (decreasing every 10sec.)	0.115V (decreasing)
11/04/2005	11:00 AM	inoculated fuel cell with primary effluent	37 degrees C	0.130V (increasing)	0.130V (decreasing)
11/07/2005	07:30 PM	inoculated fuel cell with primary effluent	37 degrees C	0.098V	0.105V
11/11/2005	11:00 PM	inoculated fuel cell with primary effluent	37 degrees C	No Reading	No Reading
11/15/2005	02:00 PM	inoculated fuel cell with primary effluent	37 degrees C	refer to graph	refer to graph

10.7 Appendix G

MFC (25m^2/m^3) @37C
Anode: Carbon paper P50T
Cathode: 0.35mg/cm^2 Pt catalyzed

Date	Time	Description	Environment	Voltage Before	Voltage After
10/28/2005	04:00 PM	inoculated fuel cell with primary effluent (about 20ml) after the bottle was washed thoroughly and conditioned by filling and refilling the bottle a few times with the sample	37 degrees C	N/A	N/A
10/31/2005	07:00 AM	inoculated fuel cell with primary effluent	37 degrees C	N/A	N/A
11/01/2005	07:00 AM	inoculated fuel cell with primary effluent	37 degrees C	0.060V (decreasing)	0.075V (decreasing)
11/02/2005	07:00 AM	inoculated fuel cell with primary effluent	37 degrees C	0.050V (decreasing)	0.075V (decreasing)
11/03/2005	07:30 AM	inoculated fuel cell with primary effluent	37 degrees C	0.045V (decreasing)	0.075V (decreasing)
11/04/2005	11:00:00 AM	inoculated fuel cell with primary effluent	37 degrees C	0.055V (decreasing)	0.075V (decreasing)
11/07/2005	07:30:00 AM	inoculated fuel cell with primary effluent	37 degrees C	0.070V (decreasing)	0.125V (decreasing)
11/11/2005	11:00 PM	inoculated fuel cell with primary effluent	37 degrees C	No Reading	No Reading
11/15/2005	02:00 PM	inoculated fuel cell with primary effluent	37 degrees C	refer to graph	refer to graph