

Optimization of Sediment Microbial Fuel Cell for Power Generation

Jack Lehman¹, Hongjian Lin¹, Bo Hu¹

¹ *Department of Bioproducts & Biosystems Engineering, University of Minnesota – Twin Cities, St. Paul, MN, USA*

Abstract

Microbes are able to create an electric potential as they undergo oxidation and reduction reactions. The optimal configuration that a Sediment Microbial Fuel Cell may be arranged in is therefore desirable. Three Sediment Microbial Fuel Cells were built in order to determine the ideal configuration for power generation. The configurations all consisted of: sediment contained within a reactor at a depth of 6 cm, a carbon cloth anode buried 1.5 cm beneath the sediment and a medium consisting of water for an overall reactor depth of 17.7 cm. Configurations differed in that: one reactor utilized a floating cathode coated in an activated carbon, isopropyl and nafion solution on the side in contact with water and polyvinylidene fluoride (PVDF) on the surface in contact with air, while the remaining reactors consisted of submerged cathodes coated in the same activated carbon, isopropyl and nafion solution on each side. These two reactors had their cathodes located at different depths in order to monitor how factors such as internal resistance and dissolved oxygen levels would affect power output. After monitoring the three reactors for two months it was seen that the two reactors with submerged cathodes consistently generated more power than the reactor with a floating cathode; furthermore there was not a significant difference in the power generated by the reactors with submerged cathodes regardless of the distance of the cathode in relation to the anode. From the results seen in this study the superior configuration of a Sediment Microbial Fuel Cell is one in which the cathode is completely submerged in the medium, but the depth of the cathode in the medium makes no substantial difference to power generation.

Introduction

Microbial Fuel Cells have been in existence since the early 20th century, although widespread utilization has not occurred. This is in large part due to applications that a fuel cell of this type may have. One use currently being researched is in the field of bioremediation where a Microbial Fuel Cell is used to expel a material such as phosphorus from a solution or soil sample. Microbial Fuel Cells also have the capacity to replace batteries that currently exist in low power applications without the need to replace them frequently or ever if an adequate organic supply is given.

A Sediment Microbial Fuel Cell (SMFC) is a variation in which microbes present in sediment are able to use the organic matter present in the sediment to undergo oxidation and reduction reactions. A cathode and anode are

then placed within the fuel cell in order to generate power due to the electric potential that the oxidation and reduction reactions create. Optimization of a fuel cell would enable a SMFC to have more widespread use as it could replace current applications of batteries in scenarios where the replacement of the battery would be both expensive and time-consuming.

To approach the problem of optimizing the power generated by a SMFC, multiple commonly used configurations were built side by side in order to determine if the difference in power output was due to the configuration itself. To quantify this data, measurements were taken on all fuel cells over a period of roughly 60 days to identify differences between the systems.

This research was able to identify that a SMFC utilizing a submerged cathode is capable of producing and sustaining more power than a

cathode in contact with air on one side and a medium on the other. It furthermore provides a basis upon which future hypothesis about sediment composition, anode and cathode surface area, dissolved oxygen levels and materials and medium chosen might be varied in order to monitor how each may or may not play a role in generating power in a SMFC.

Methods

The research started with the creation of four SMFC's, three of which contained electrodes as well as a fourth control cell containing sediment not in the presence of an electrode.

Fuel Cell Creation

All fuel cells were manufactured in the same way with the exception of the electrode of each cell.

Physical Characteristics

All fuel cells were created in 17.7 cm tall plastic cylinders. The radius of each cylinder was approximately 2.5 cm. Each fuel cell was first filled with between 6-6.1 cm of lake sediment gathered prior to the experiment from Lake Como located in St. Paul, MN. Afterwards sediment was placed in the reactors the reactors were filled with tap water to an overall reactor depth of ~16 cm each. Periodically tap water was added to each reactor to counteract evaporation.

Electrode Construction

Anodes were constructed in the same manner in all three fuel cells with electrodes. They consisted of plain carbon cloth cut into 25 cm² squares which were then placed ~1.5 cm below the sediment surface. An aluminum wire was also attached with epoxy glue to each anode to serve as the connection point during monitoring of the fuel cell.

Reactor #3's cathode was made by coating a plain carbon cloth with an area of 19.6

cm². A solution comprised of activated carbon, isopropyl and nafion solution was spread evenly onto the side of the cloth that was in contact with water. This solution contained activated carbon in a 20 mg/cm² ratio with the surface area of the carbon cloth. To the activated carbon, nafion was added in a 6.67 μL/mg activated carbon ratio and isopropyl in a 3.33 μL/mg activated carbon ratio. To the side of carbon cloth in contact with air, 10% polyvinylidene fluoride (PVDF) solution was coated on it in a 0.07 g/cm² of carbon cloth ratio. Additionally an aluminum wire was attached to the PVDF side of the carbon cloth with epoxy glue and foam was attached (with a hot glue gun) around the rim of the carbon cloth to aid in flotation and to prevent water from leaking onto the PVDF coated side of the cathode.

Reactor #1 and Reactor #2 had their cathodes made in the same way. They were each comprised of plain carbon cloth with an area of 19.6 cm². These cathodes were coated on both sides in the same activated carbon, nafion and isopropyl solution as the underside of Reactor #3's cathode; the solution was prepared in the same way, but in a quantity twice as large as in Reactor #3 to account for both sides of the cathodes being coated. To each cathode an aluminum wire was attached with epoxy glue.

Electrode Configuration

Reactor #1 consisted of an anode buried ~1.5 cm below the sediment layer and a cathode submerged underwater. The overall distance between the anode and cathode in this configuration was ~3 cm.

Reactor #2 consisted of an anode buried ~1.5 cm below the sediment layer and a cathode submerged underwater. The overall distance between the anode and cathode in this configuration was ~10.5 cm.

Reactor #3 consisted of an anode buried ~1.5 cm below the sediment layer and a cathode floating on the surface of the water. The overall

distance between the anode and cathode in this configuration was ~12 cm.

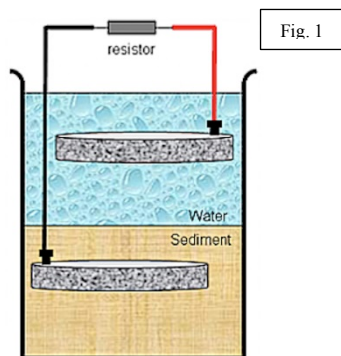


Figure 1 demonstrates the general setup of Reactor's #1 and #2

Monitoring Reactors

Collection of data for all reactors took place over a period of approximately 60 days. Data was taken on maximum voltage output, maximum current density, power generation vs. resistance, internal resistance, chemical oxygen demand, total organic carbon, reactive phosphorus and total phosphorus.

Maximum Voltage, Maximum Current Density and Power Generation vs. Resistance

Voltage and current density were measured frequently over the course of 60 days by way of a voltmeter.

Power generation was determined by varying the strength of an external resistor connected to the anode and cathode of each reactor and monitoring the voltage generated; with the voltage output known, power can be calculated at each given resistance in accordance with Ohm's law in the form of $P = I^2 * R$. After each voltage was recorded, the external resistor was changed and the reactor was allowed 10 minutes to equilibrate between measurements. Furthermore, maximum power given by each reactor was calculated through the use of a linear regression using the data collected.

Once a large enough resistance to begin to reduce power was attached, the maximum voltage was gathered by taking the voltage of the system after the circuit had been open for a period of 10 minutes.

Maximum current density was recorded by closing the system with no external resistor attached and taking a reading after 10 minutes had elapsed.

Additional measurements of power generation, maximum voltage and maximum current density were taken in which the configuration of Reactor #1 and #2 were switched (i.e. Reactor #1's cathode was raised a depth of 1.5 cm below the surface of the water and Reactor #2's cathode was lowered to a depth of 1.5 cm above the sediment layer). These measurements were taken as verification of a reactors effectiveness resulting from the configuration measurements were taken in rather than any physical variance found between Reactors #1 and #2.

Internal Resistance

The internal resistance of each reactor was monitored at two points in time. Once when the reactors had been operable for a period of a week and once again upon the completion of the experiment in order to determine any degree of change of internal resistance in the reactors.

Internal resistance was gathered through the use of Gamry Instruments software. A potentiostatic EIS test was performed at varying external voltages to determine the internal resistance of each resistor.

Chemical Oxygen Demand

Chemical oxygen demand (COD) of each reactor was measured multiple times in accordance with Hach Company's COD test kit.

Results

Results for all data given below were collected between June 11th, 2015 and August 6th, 2015. Charts and figures for pertinent measurements are shown below and are labeled to give explanation of the data exhibited.

Power Generation

Data regarding power generation of the three reactors containing electrodes was extensive and lasted for a period of just under 60 days. Maximum power data points were pinpointed after performing a linear regression of the data given by recording the voltage output of each resistor at varying external resistances. In some cases data could not be gathered on a specific day due to the short-circuiting of a reactor or maintenance of the electrode being needed to make it operational.

Fig. 2 demonstrates Reactor #1's power generation vs. time

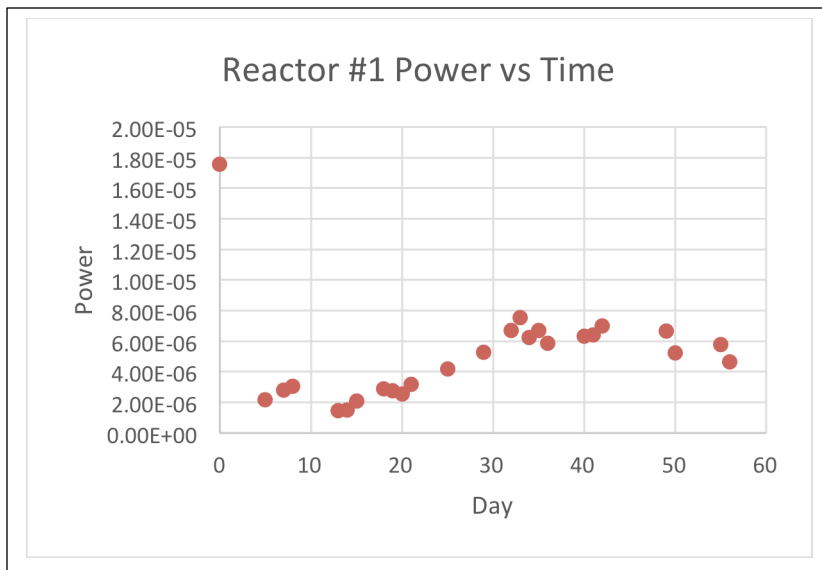
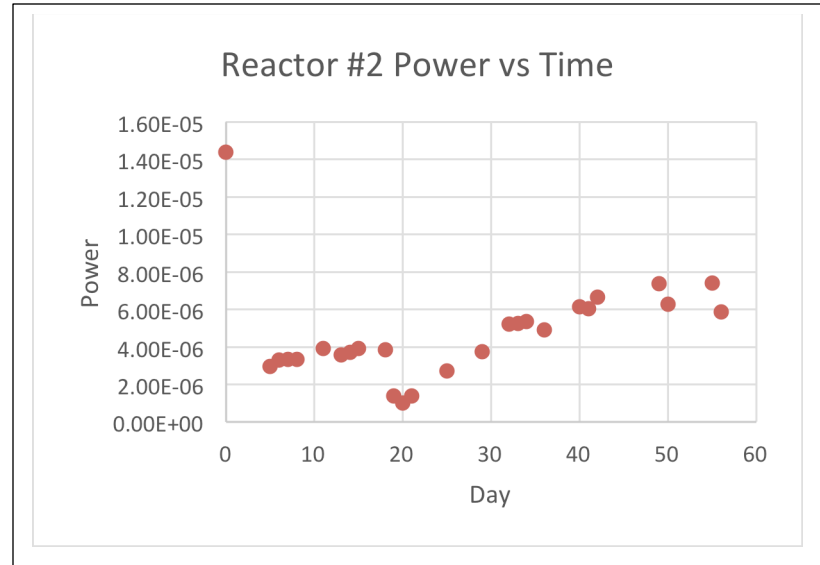


Fig. 3 shows Reactor #2's power generation vs. time



The graph displaying Reactor #3's power generation as well as a side by side comparison of all reactors power outputs is attached on the next page.

The data points plotted on graphs for Reactors #1 and #2 show a large initial power output which sharply declines within the first week followed by an overall increase in power output over the remaining 60 days of the experiment.

Fig. 4 gives Reactor #3's power over time

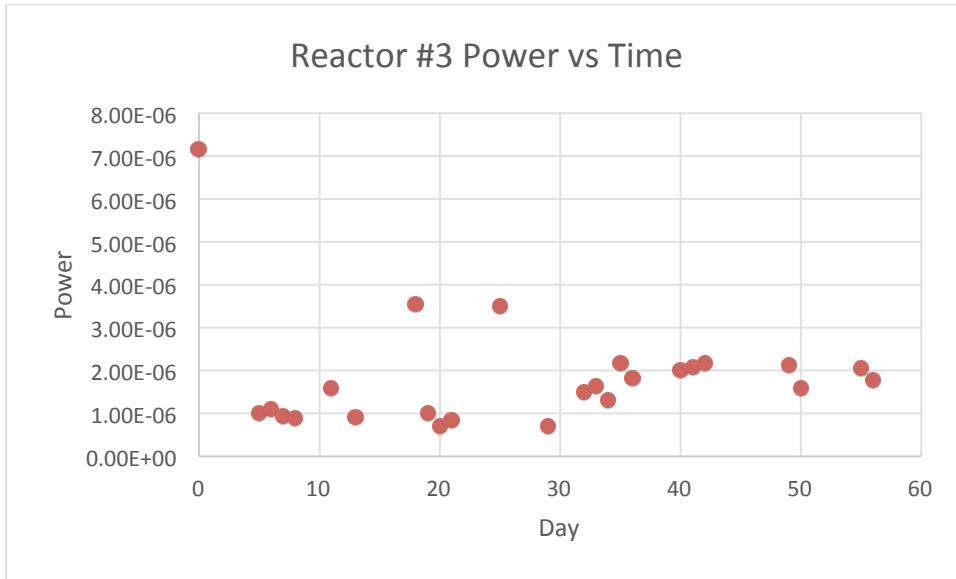
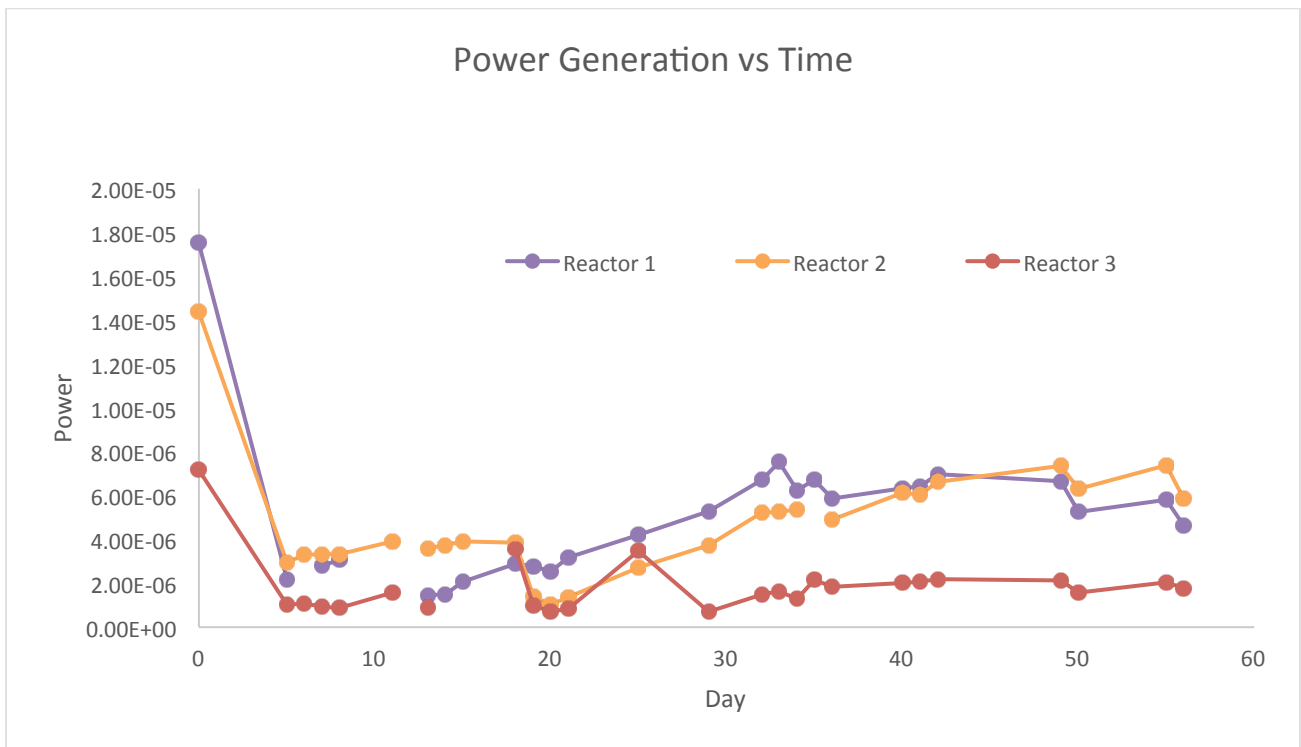


Fig. 5 shows all SMFC's power output over the course of the experiment



Examination of data points reveals that Reactor #1 output the most power initially, before being overtaken by Reactor #2 upon day 5 of data collection. From day 5 to day 18 Reactor #2 generated the most power. From day 19 to day 49 Reactor #1 generated the most power. Aside from two spikes in power generation, Reactor #3 exhibited the lowest power output of all reactors.

Modified Configuration Power Generation

As stated in “Methods” additional data for power output was gathered when the location of the cathodes in Reactors #1 and 2 had been switched.

Fig. 6 shows Reactor #1’s power output when the cathode was 10.5 cm away from the anode vs. normal location

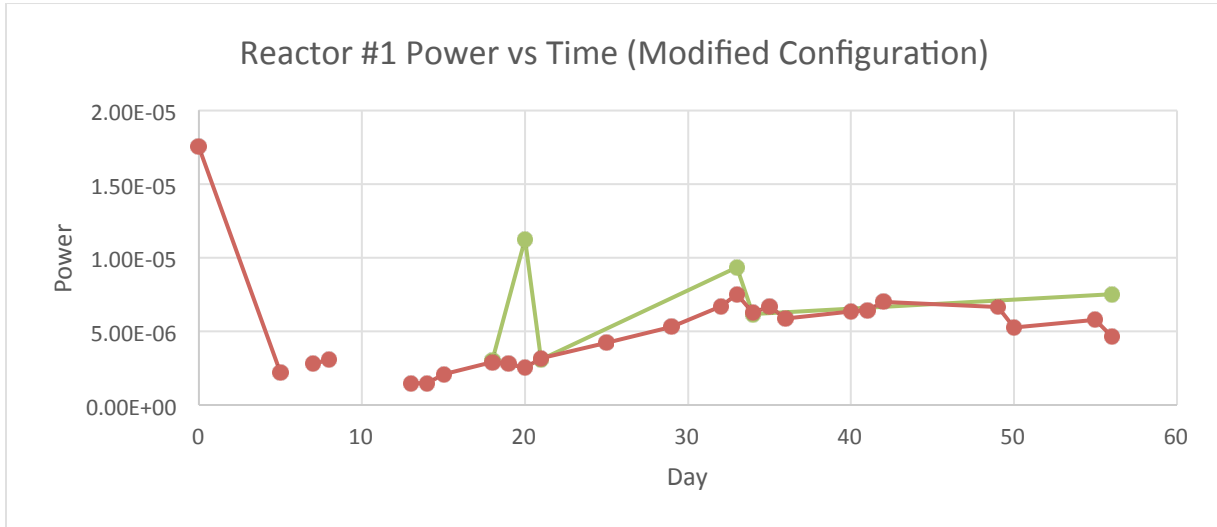
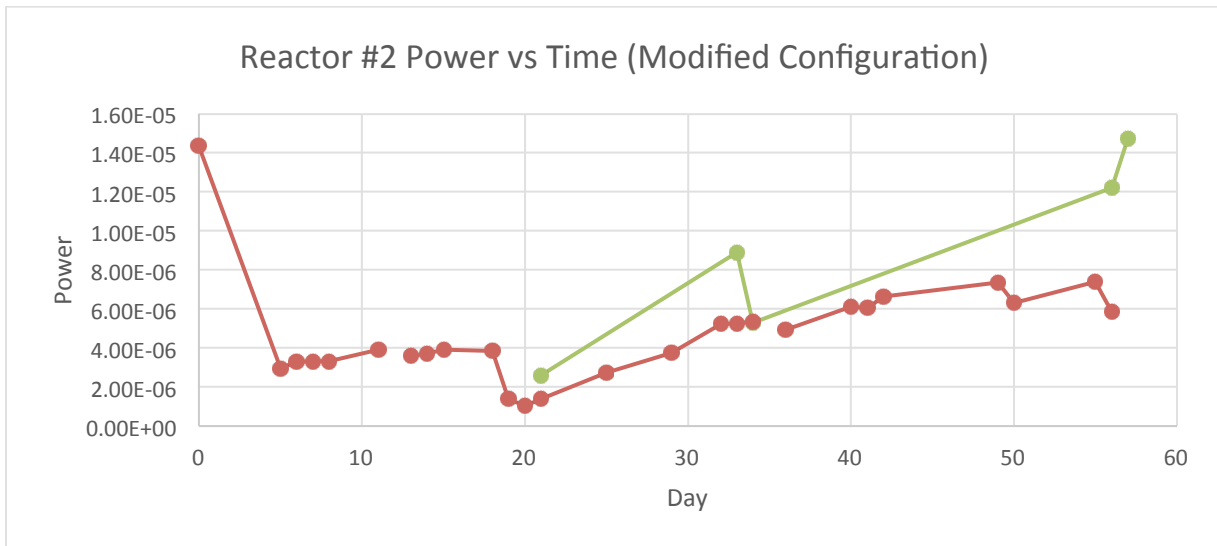


Fig. 7 shows Reactor #2’s power output when the cathode was 3 cm away from the anode vs. normal location



Maximum Current Density

Maximum current density was not initially recorded. It was recorded at the time corresponding to day 7 of collection of power generation data.

Fig. 8 shows Reactor #1's maximum current density over time

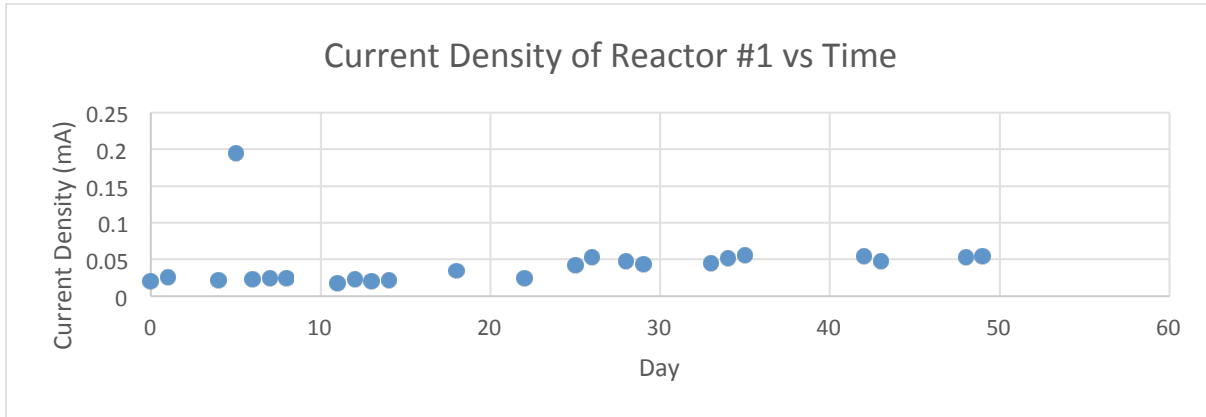


Fig. 9 shows Reactor #2's maximum current density over time

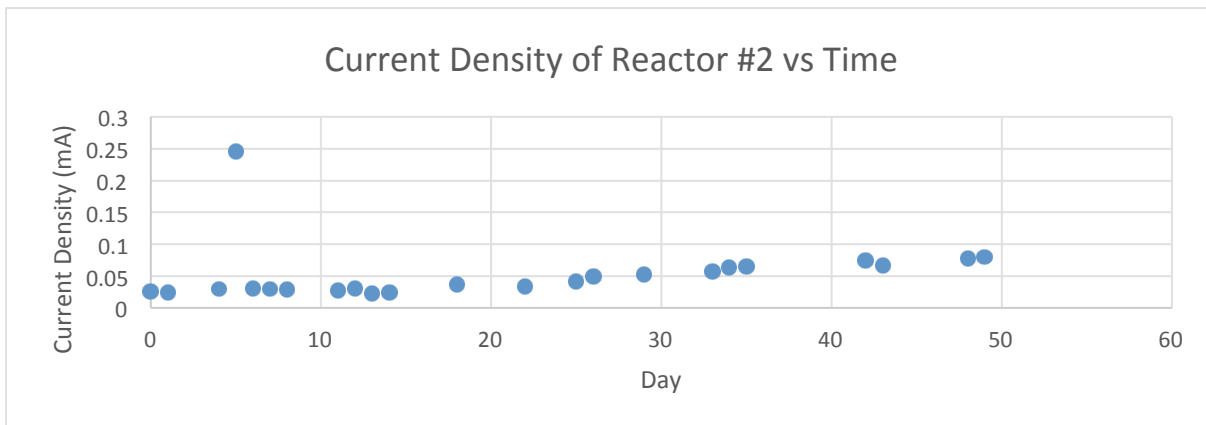


Fig. 10 shows Reactos #3's maximum current density over time

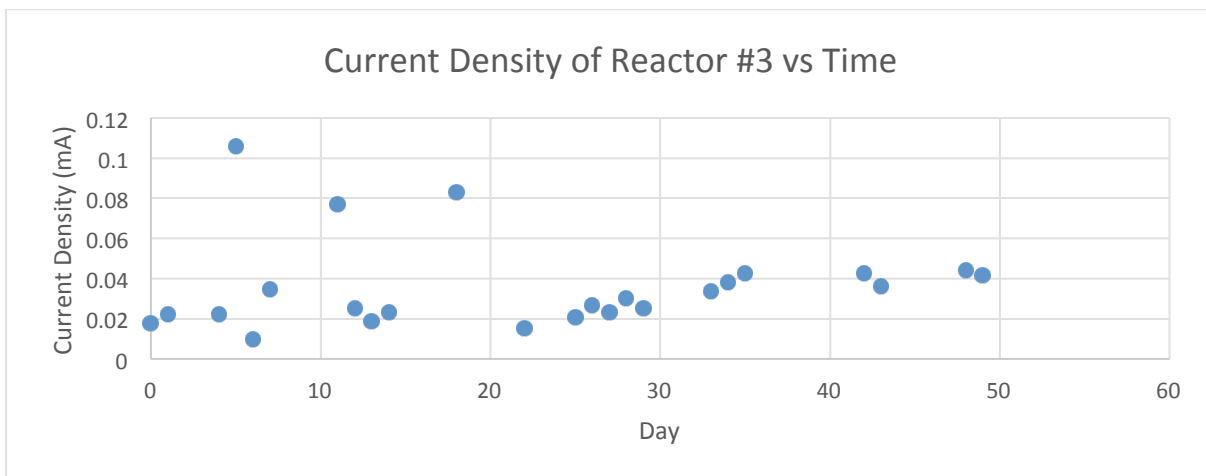
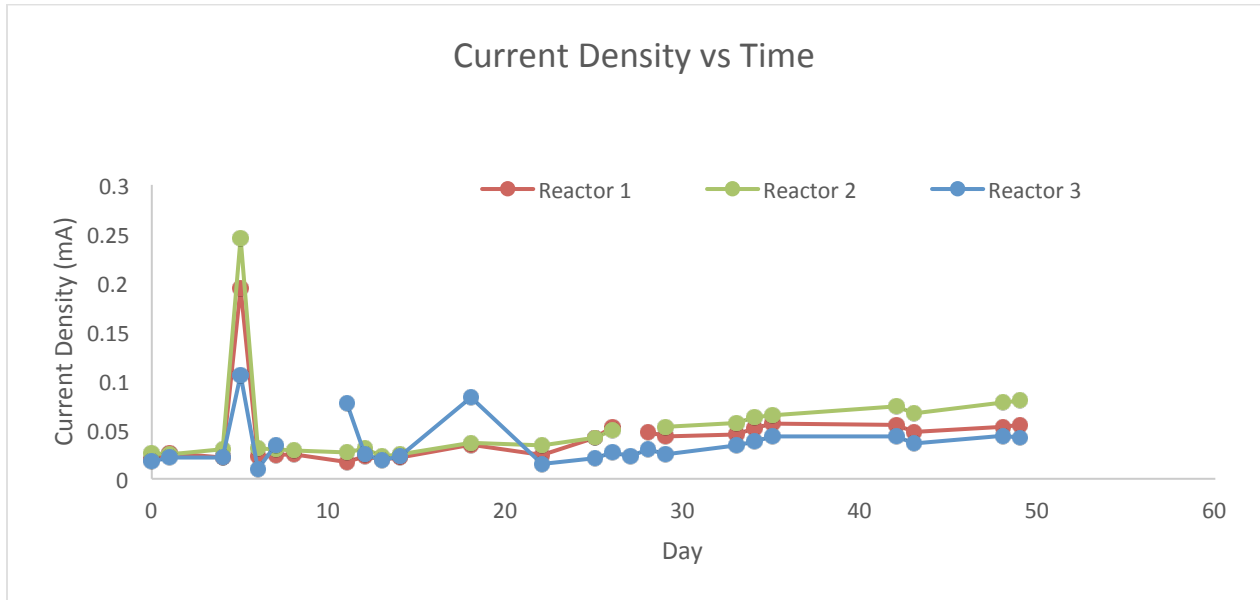


Fig. 11 shows a side by side comparison of all reactor's maximum current density over time



Current density is seen to spike on day 6 in all reactors, followed by all reactors current density trending upwards throughout the remainder of the experiment with the exception of two single day spikes from Reactor #3. A similar trend to power generation is seen in which Reactor #2 maintains the largest value for current density over the last two weeks of data collection.

Maximum Voltage

Maximum voltage was not initially recorded. It was recorded at the time corresponding to day 7 of collection of power generation data.

Fig. 12 shows maximum voltage vs. time for Reactor #1

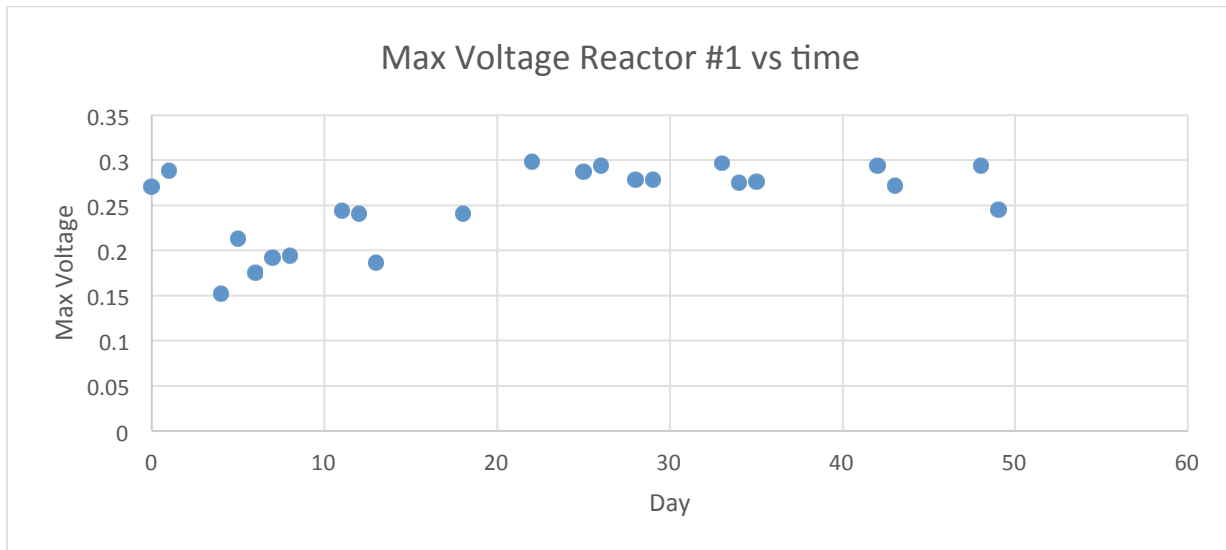


Fig. 13 shows maximum voltage vs. time for Reactor #2

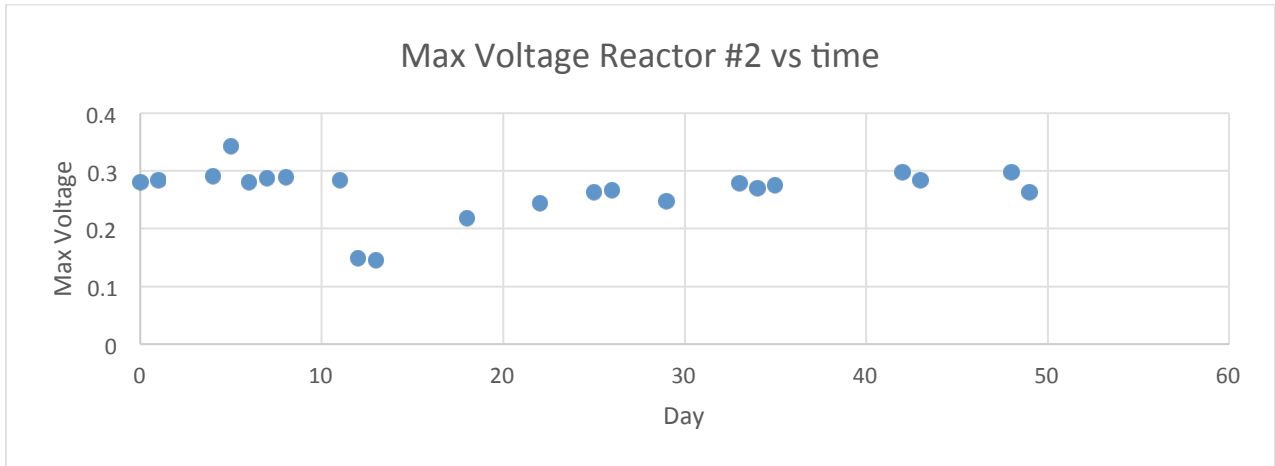


Fig. 14 shows maximum voltage vs. time for Reactor #3

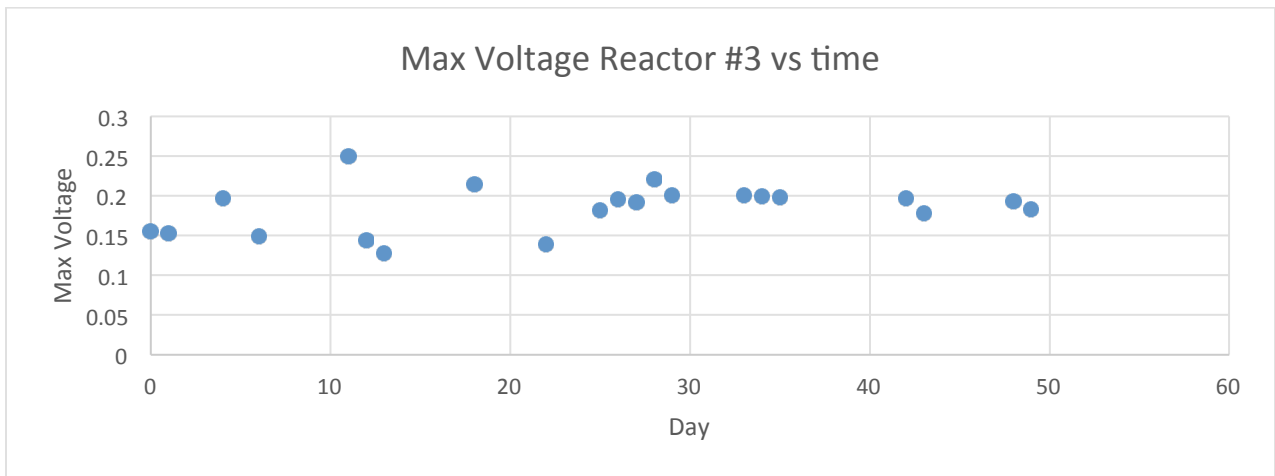
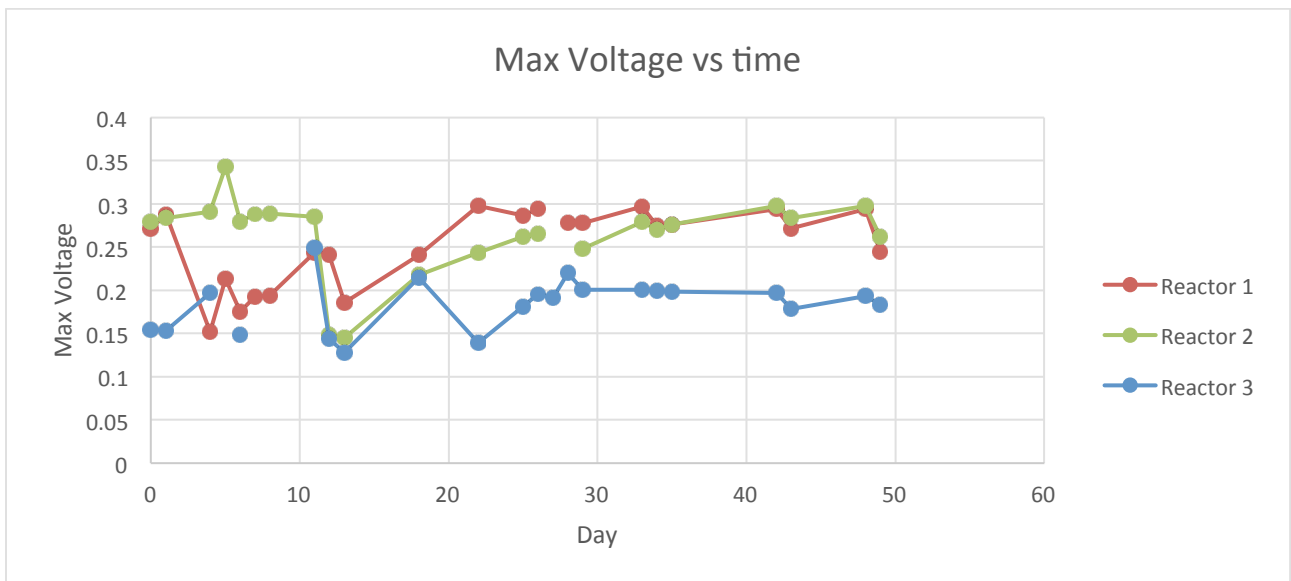


Fig. 15 shows maximum voltage of all reactors over time



The maximum voltage data gathered from the reactors nearly mimics the activity seen in power generation of the reactors. Reactor #2 maintains the highest voltage early on in the experiment. Later on, Reactor #1 consistently gives higher readings than Reactor #2, but over the final days of data collection Reactor #2 once again exhibits the largest values for maximum voltage.

Internal Resistance

Internal resistance data was gathered once on June 10th, 2015 and again on July 17th, 2015 in order to monitor any change in internal resistance over the course of the experiment.

Table 1 shows the change in internal resistance of all reactors over time

Date	Value	Reactor #1 (in Ohms)	Reactor #2 (in Ohms)	Reactor #3 (in Ohms)
June 10 th , 2015				
	Avg. Ohmic Resistance	129.7	276.1	283.4
	Avg. Activation Resistance	N/A	N/A	N/A
	Avg. Mass Transfer Resistance	480.4	836.8	702.1
	Avg. Total Resistance	610.1	1112.9	985.5
July 17 th , 2015				
	Avg. Ohmic Resistance	436.1	697.8	342.3
	Avg. Activation Resistance	N/A	209.2	441.1
	Avg. Mass Transfer Resistance	101.2	56.2	111.9
	Avg. Total Resistance	537.3	963.2	895.3

Chemical Oxygen Demand

Chemical Oxygen Demand was measured on June 15th, 2015 and again on July 6th, 2015. The difference in measured COD is shown in figures below.

Fig. 16 shows the change in COD of the Control reactor

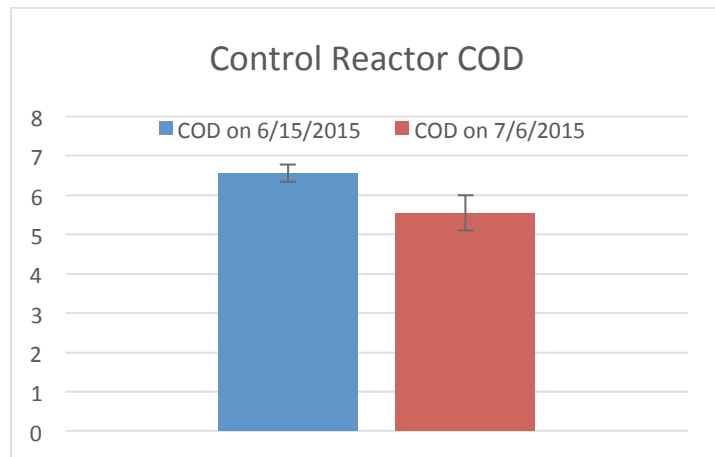


Fig. 17 shows the change in COD of Reactor #1

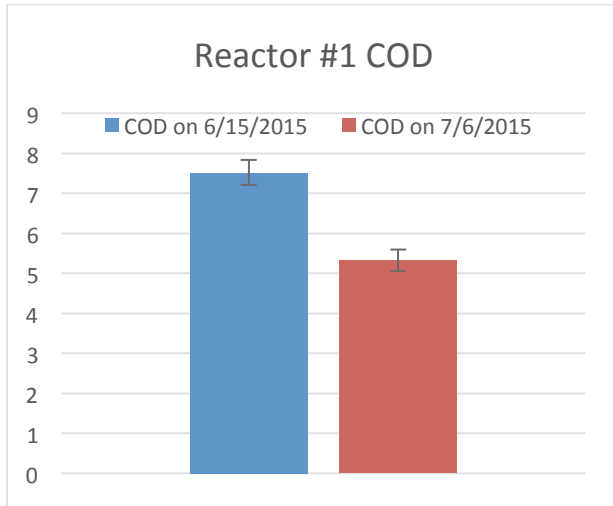


Fig. 18 shows the change in COD of Reactor #2

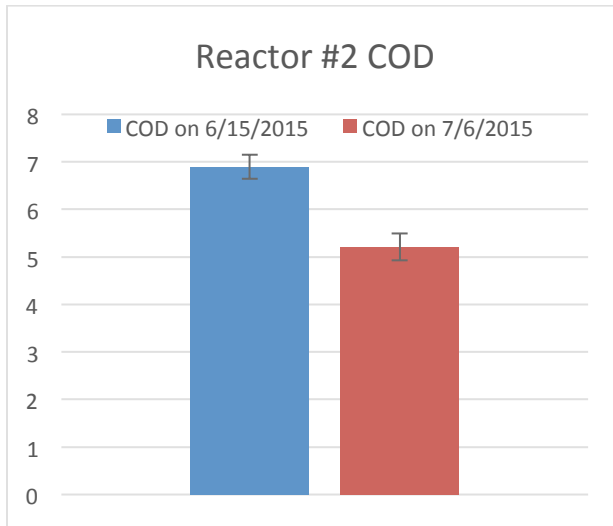
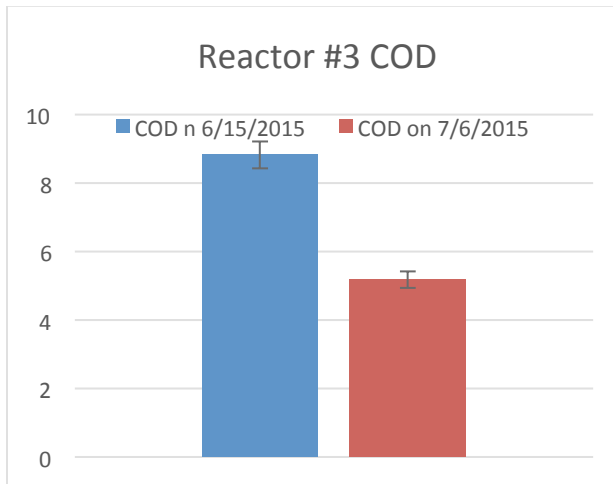


Fig. 19 shows the change in COD of Reactor #3



Discussion

Prior to this experiment, it was known that a SMFC could be constructed to produce sustained power. However it was not known if the power output would increase, decrease or remain stable over time.

After analyzing the results from the power generation segment located in "Results" we can see that over a period a two months, power does not in fact degrade but rather increases in a relatively linear manner. The reason that the initial values for power generation were likely seen is that the external resistance connected was large enough to the point where relatively no current was able to flow. One hypothesis entering the experiment is that over the course of two months there would be a general decline in power output from the reactors due to the organic matter in the sediment being consumed by the microbes. This was not the case and it is possible that the organic matter present in the system is not the limiting factor in power generation of a SMFC.

By examining the power generation charts when the configuration was switched in Reactors #1 and 2, the likely cause of the slight increase in power was not the configuration of these reactors but the disturbance to the system. Disturbing the system through adjusting the configuration of the electrode or by adding water to the system could be the starting point of a future study to see if any effect of power generation is due to system disturbance.

Another conclusion drawn through the data supplied in this experiment is that a reactor utilizing an electrode with a submerged cathode will generate more power than a reactor using an electrode with a cathode located at the surface of the water. This result would be the expected outcome of additional studies, although the effect that materials would have upon power generation could either reaffirm or contradict the outcome seen in this study.

The relationship between power, current density and voltage is also clearly evident through comparison of their charts. The same overall differences between reactors are discernable in figures examining power, maximum current density and maximum voltage.

Table 1 compares the internal resistance of reactors near the outset of the experiment as well as close to the conclusion of the study. It was believed that the internal resistance of the reactors would decrease over time as the sediment, microbes and medium were subject to a stable environment for a sustained period of time. This hypothesis is supported by the data located in Table 1 as the overall resistance and the mass transfer resistances each fell. This supports the hypothesis because over time smaller amounts of mass transfer were occurring due to the stabilization of the environment of the reactors. This result is one reason why the increase of power generation over the course of the study was unexpected.

Conclusions drawn from the COD data is more theoretical than anything, as the standard deviation of the control reactor on the dates indicated do not overlap. Meaning that there is a statistically significant difference in the COD levels present in a reactor in which no electrode is present, a result that we should not see. However, larger differences than the one found in the control reactor are seen in all additional reactors tested. This data suggests that the COD present after over a month of subjection to an electrode has decreased. This result is expected to be seen as the microbes present in the reactors consume organic matter.

Conclusion

This study has advanced our knowledge of Sediment Microbial Fuel Cell's by examining the capability of various configurations to generate power. It was seen that a submerged cathode was able to generate more power than a floating cathode over a period of nearly two

months. Additionally the data points to the fact that over a period of nearly two months, power generation does not decline in the manner of which we would expect. Rather the overall power that was output by all reactors tested was seen to increase.

It was further demonstrated that the internal resistance of a reactor will decline over time, a result that was anticipated but confirmed due to this study.

COD levels were observed to have fallen over the course of the experiment as we would expect due to the consumption of organic matter by microbes present in the reactors. However it is not possible to say with certainty that the microbe's creation of power was the reason for declining COD values due to the deviation found in the Control reactor's COD levels.

Future research that could result from the findings of this study could come from many different areas. The further optimization of power output is certainly possible through adjustment of parameters such as cathode and anode surface area, the identity of the medium used, the location of the electrode within a reactor, the materials used to construct the reactor and more. Research could also use a similar configuration to the one(s) used in this study in an effort to extract chemicals from a medium in the process known as bioremediation.

References

Zhang, Fei, Lei Tian, and Zhen He. *Powering a Wireless Temperature Sensor Using Sediment Microbial Fuel Cells with Vertical Arrangement of Electrodes* (2011): n. pag. 19 July 2011. Web. 18 Feb. 2015.

Lin, Hongjian. "ELECTRICITY GENERATION WITH ORGANIC MATTER AND AMMONIUM REMOVAL FROM SWINE WASTEWATER VIA MICROBIAL FUEL CELLS." Diss. U of Minnesota, 2013. Print.