Development and Deployment of a Surface Based Benthic Micorbial Fuel Cell

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Abstract— Benthic microbial fuel cells (BMFCs) have the potential to provide long-term, sustainable power for undersea devices. BMFCs operate by harnessing organic matter in the sediment as a fuel source. Field systems have demonstrated power densities in the range of 5 to 20 mW/m^2 depending on size and operating conditions. Operation of anodes under anaerobic conditions is critical to the functionality of BMFCs because the presence of oxygen will negatively affect the microbiology and chemistry driving power production. In order to provide an anaerobic environment the BMFC anodes are usually buried at least 10 cm under the sediment which generally ensures a completely anaerobic environment in reducing coastal sediments. Furthermore, to increase a system's power output, large surface areas for the anode and cathodes are needed. Installation of these large-scale anodes is difficult, time consuming, and in the case of very deep water environments, almost impossible.

In order to solve the issue of complex burial techniques for large anodes, a unique design of BMFCs has been created which allows the anode to be placed on the sediment surface without being buried and still operate under anaerobic conditions. Carbon cloth anodes were covered on one side with metalized plastic film, specifically biaxially-oriented polyethylene terephthalate (BoPET), and sealed at the edges. This type of metal film has very low oxygen permeability which prevents oxygen in overlying water from diffusing through the film and interfering with current production at the surface of the anode. Weights were added to the perimeter of the film in order to ensure a seal between the anode edge and the sediment to prevent aerobic seawater from contacting the anode thus ensuring an anaerobic environment for the anode. The concept was tested at various scales in the lab environment and a prototype deployment system was developed and tested for future scale-up and field applications.

Keywords—Microbial fuel cell; benthic; sediment, deployment

I. INTRODUCTION

There exists a strong need for easily deployable, long-term power for undersea electronics. BMFCs present a viable solution to this need by converting chemical energy into electrical energy through the catalysis of microorganisms in the sediment. This process creates a natural potential difference between the anode and cathode [1,2]. In order for this process to occur the anode must be present in an anaerobic environment. To create this, the anodes of BMFCs are typically buried under the sediment surface. Bacteria present in the sediment then generate electron flow during their metabolism by oxidizing organic matter. If these bacteria are in close proximity with the anode, the electrons generated through their metabolism process may be transferred to the anode that is, in turn, electrically connected to a cathode in the overlying aerobic water where oxygen reduction occurs. The current generated from this process is able to sustain low-power electronics [3]. The fuel supply in the sediment is naturally replenished as organic matter settles on the sediment surface. This allows BMFCs to operate for extended periods of time as long as they are buried beneath the surface [4].

Previous studies have shown that the rate of electron production in BMFCs is strongly dependent on the electrode surface area [5]. Additional studies have shown that a correlation between surface area and power output exists however an increase in power output cannot be achieved by solely by increasing the active area [6,7]. In order to increase the power output of the BMFCs it is important to be able to increase the electrode's projected surface area. A great deal of effort has been put into increasing the surface area of the anodes in full-scale deployed systems for this reason. Initial efforts to deploy large scale buried anodes yielded successful results. Chadwick et al. successfully deployed large anodes based on carbon cloth but found that power output does not scale linearly with anode surface area [8]. Follow on studies from the same group produced deployments using a unique deployment sled which was capable of deploying two large anodes in the same deployment. This effectively doubled the anode surface area. Results showed that the BMFC was capable of sustaining 250mW over extended periods of time and was able to power remote undersea electronics [9].

The deployments referenced above require complex and cumbersome deployment techniques, often including a diver, that require burying the anodes under the sediment. As the deployments get larger and the depths increase these kinds of deployments will become almost impossible. An et. al. investigated the correlation between the depth of the anode in the sediment and power output and found that voltage and current output are improved with increasing anode embedding depth and that overall anode embedding depth is a factor in sediment based MFCs[10].

It is clear that a key limiting factor for the BMFCs used to power undersea electronics is not just the deployment mechanism but the concept of burial itself. A new concept of deployment based on the results of previous studies was created for this study, one which does not require burial. The objective of this study was to develop and test the feasibility of a surface based anode for microbial fuel cells that do not require burial under the sediment, and to evaluate prototype designs for the deployment of such as system to deep water.

II. METHOD

In order to first determine the feasibility of a surface based anode for BMFCs a number of laboratory experiments were conducted. Operation under anaerobic conditions is critical to the functionality of BMFCs because the presence of oxygen will negatively affect the microbiology and chemistry driving power production. The first experiment conducted was done in order to determine if the concept for the surface based BMFC would operate with power densities of the same order of magnitude as traditional buried systems. In order to solve the issue of preventing aerobic water from coming into contact with the anode which is on the surface sediment, a unique design of BMFCs was created which allows the anode to be placed on the sediment surface without being buried and still operate under anaerobic conditions. Carbon cloth anodes were covered on one side with metalized plastic film, biaxially-oriented polyethylene terephthalate (BoPET), and sealed at the edges.

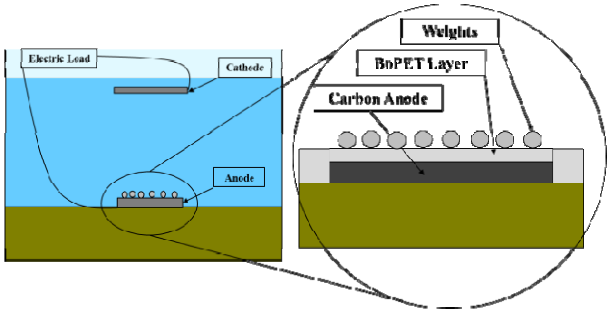

Fig. 1: Diagram of SBMFC (not to scale)

This type of metal film has very low oxygen permeability which prevents oxygen from overlying water from diffusing through the film and interfering with current production at the surface of the anode. Weights were added to the perimeter of the film in order to ensure a seal between the anode edge and the sediment to prevent aerobic seawater from contacting the anode, ensuring an anaerobic environment. Subsequent experiments were then conducted to directly compare traditional buried anodes to fully buried film-backed anodes, to evaluate the performance of larger scale surface anodes, and to evaluate the influence of adding a carbon source between the film backing and the anode. Finally, a prototype deployment system was developed and tested as a potential method to deliver the system to the deep sea environment.

A. *Small-Scale Laboratory Experiment*

Initial experiments were conducted using small scale anodes and cathodes (both 6in x 6in) in order to determine if the concept of the Surface Benthic Microbial Fuel Cell (SBMFC) was feasible. The anodes were made of carbon cloth and covered with BoPET material and sealed at the edges. Weights were then added to the edges of the material as well as the center of the anode in order to ensure no aerobic water would come into contact with the anode. Titanium wires were sewn into the anode carbon cloth for current collection and conduction. The cathode is made of the same carbon cloth material as the anode. The cathode also has a titanium wire for current collection and is allowed to float freely in the water to ensure it is fully submerged in aerobic conditions.

Fig. 2: Image of the surface anode after being placed on the sediment surface.

The experiments were conducted with two surface anodes for repeatability. In addition, two standard buried anodes of the same footprint were buried in the same tank. These anodes were buried approximately 3in under the sediment surface and act as the control for the experiment. The surface anodes were placed on the sediment. The anode and cathode current collecting wires were then run to the load and data acquisition system (DAQ).

Once the experiment was setup all BMFCs were brought to open circuit voltage (0.7-0.8 V). Once open circuit voltage was reached, the load was incrementally increased over a period of about 3 weeks until the target operating voltage of 400-450 mV was obtained. The load was then continuously adjusted in order to maintain the operating voltage in this range for all cells. The BMFCs were operated in this mode for approximately six months and the resistive load and voltage across the load were recorded in order to calculate the MFC current and power. In addition the voltages of the anode and cathode were measured separately against an Ag/AgCl reference electrode.

B. *Scale-up Laboratory Experiments*

Once the small scale experiments were completed a scale-up of the experiments was conducted. This was done to determine how larger area anodes would perform in terms of power production and also to determine if a more realistic scale, similar to what would be used in a deployment, would be viable. In addition to the surface anodes a variety of other anode types were setup in this experiment as well in order to further investigate the effects of BoPET and surface anode performance.

In this case a number of changes were made compared to the previous 6in x 6in experiments. In this set of experiments all of the anode surface areas were increased to 12in x 12in. In addition, rather than using weights, chain was placed around the outside edges of the surface anode. The chain serves the same purpose of the weights in the previous experiment, that is, to act as a sealing mechanism between the anode and the sediment in order to prevent aerobic water from coming into contact with the anode. In this case no chain was placed across the center of the anodes. This was because the design of this experiment was setup to more closely resemble how the anodes would be setup in a real world deployment.

Fig. 3: 12in x 12in surface anodes with chain around the edges for sealing to sediment. The anodes have some sediment which settled on top of the BoPET however they can be distinguished by the chain around the edges.

In addition to the standard surface anodes a number of other experiments were also included. Firstly, a second set of surface anodes were created however in this set chitin was placed in between the BoPET and the top of the carbon cloth anode. This was done to determine the effects of adding organic material as a method to increase the power output of the SBMFCs since the deep sea environment may be characterized by lower levels of natural organic matter. Next, another set of anodes was created with the BoPET layer, however, they were not set on the surface but rather were buried approximately 6in below the surface. This was done in order to compare to standard buried anodes determine if the BoPET renders one half of the carbon cloth anode surface inactive. Finally, carbon cloth anodes were buried similar to the previous experiment in order to act as a control group.

C. *Surface Anode Deployment Mechanism*

Once the concept of the surface anode proved feasible it was necessary to develop a deployment technique that was effective and simpler to use than current deployment techniques for the deep sea. This was done by creating a drop-in-place device which would automatically unfurl the surface anodes when it comes into contact with the sea floor. The device is designed to be dropped into the water and remained closed in a streamlined position until it comes into contact with the sediment surface, at which point the anodes unfurl. The cathodes are connected onto the device itself as well as all electronics.

Carbon cloth anodes were covered on one side with metalized plastic film and sealed at the edges. This type of metal film has very low oxygen permeability which prevents oxygen from overlying water from diffusing through the film and interfering with current production at the surface of the anode. Weights were added to the perimeter of the film in order to ensure a seal between the anode edge and the sediment to prevent aerobic seawater from contacting the anode, ensuring an anaerobic environment for the anode. In addition the weights allow the device to unfurl properly once it comes into contact with the sediment surface.

III. RESULTS AND DISCUSSION

In order to determine the feasibility of surface based BMFCs a number of laboratory experiments were conducted with a variety of design variables investigated. Results of these experiments are presented and discussed below.

A. *Small Scale Laboratory Experiments*

The first laboratory experiments consisted of two SBMFCs and two buried BMFCs. Since the overall objective in designing a SBMFC is to have a SBMFC which can be comparable in power output to the buried BMFC the buried BMFCs act as a control for the experiment since this design is known to function effectively. In order to make a direct comparison, all BMFCs were operated in a range of approximately 400-425mV.

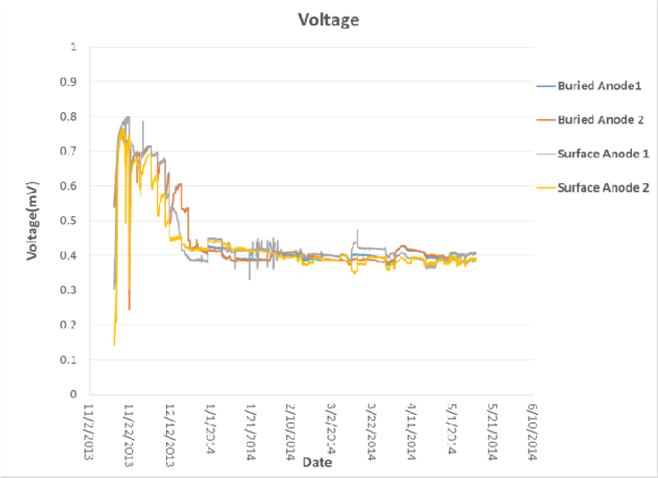

Fig. 4: Operating voltage of buried and surface BMFCs

Figure 4 shows the operating voltages of the BMFCs. All BMFCs were allowed to reach open circuit voltage and then the load was added in order to bring the voltage down to the 400mV range. After about three weeks, the cell potential stabilized at about 400 mV, and the load was varied in order to maintain this voltage. It can be seen from Figure 4 that the cell voltages were maintained in the range of 400mV for both surface and buried BMFCs for the remaining extent of the experiment. In addition to measuring overall voltage the individual anode and cathode voltages are measured against a Ag/AgCl reference electrode. This is done in order to determine if the anode or cathode are responsible for separate losses in the cell.

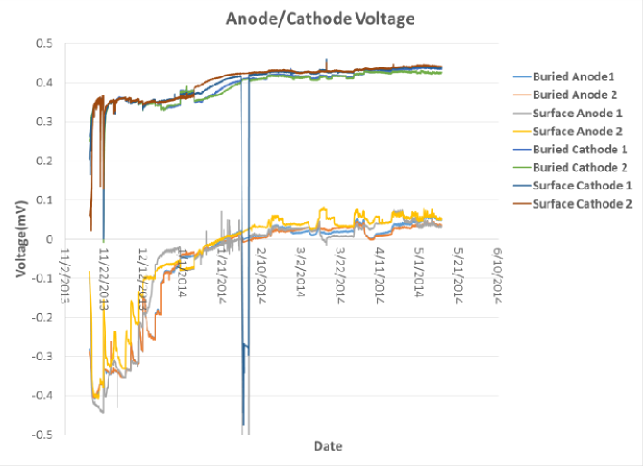

Fig. 5: Anode and cathode voltages against a reference electrode

Figure 5 shows the anode and cathode voltages of the 6in x 6in anodes. The drop off in data at about 2/1/2014 was due to an issue where the DAQ malfunctioned and is not representative of the data. As the MFC is loaded, the anode potentials comes up to a typical operating range of about -50 to +50 mV Ag/AgCl. This is characteristic of SMFC systems that are anode limited. After about three weeks it can also be seen that the cathode potentials increase from about +350 to +430 mV, a process that is believed to be associated with the formation of a biocathode. It can be seen from Figure 5 that the anode and cathode of both the surface and buried BMFCs were stable and performed well during the remainder of the experiment.

Finally the power and power density were calculated from the measured values. The power can be found in the figure below.

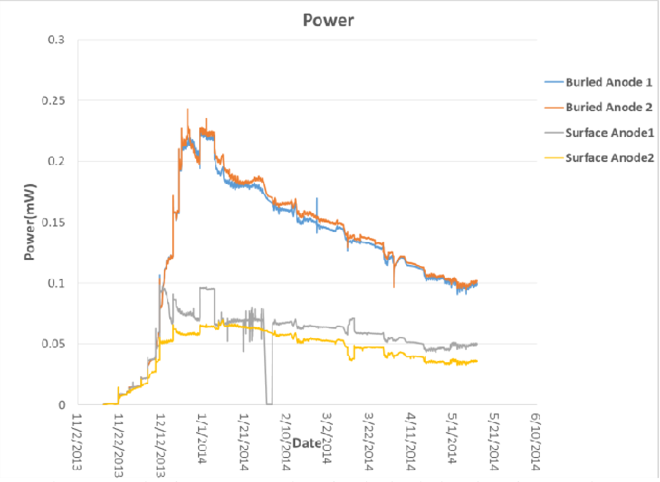

Fig. 6: Graph of power over time for the buried and surface anodes.

Figure 6 shows the power output of the BMFCs over time. It can be seen from the above figure that the buried anodes had a higher continuous power output than the surface anodes however, the power output from the buried anodes drops over time whereas the surface anodes remain more constant. One possibility is that the surface anode, because it is covered on one side in BoPET, may have less active surface area than the buried anode. Other explanations may include a reduced area for diffusion to the anode and trace oxygen penetration to the anode area.

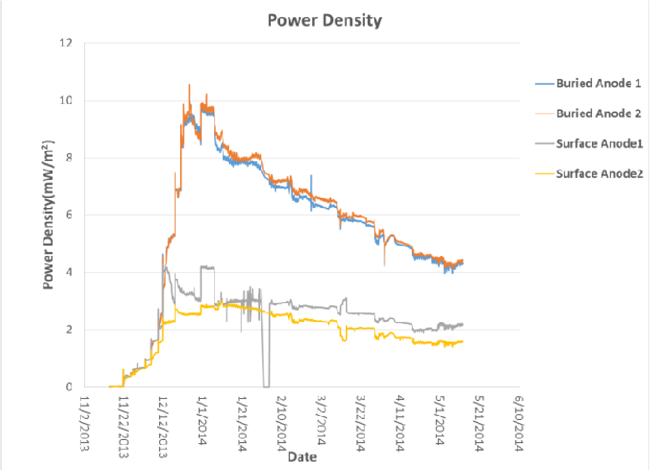

Fig. 7: Power density over time for surface and buried anodes

Figure 7 shows the power density for the different BMFCs. It can be seen from figure 7 that the power density of the buried anodes peaks early on and then levels off over time as they approach steady state operation at which point the power density of both buried anodes is approximately 4.5mW/m^2. The surface anodes remain fairly constant over time at a power density of approximately 2mW/m^2. One possible cause of the initial peak for the buried anodes if the abundance of organic material buried in the sediment, whereas there may be less on the surface based on higher rate of aerobic degradation. Once that organic material is consumed and metabolized the buried anode's power drops and approaches steady state. The steady state power for the buried anode compared to the surface anode is approximately double which implies that the difference may be due to the difference in active area. Additionally these systems are normally diffusion limited in the steady state, but not initially when organic material is still abundant near the anode.

B. Surface Anode Laboratory Scale-Up

The second set of experiments conducted in the lab was to determine the effects of increasing the area of the surface anode as well as to measure other effects such as the placement of chitin in the anode. In addition, based on the results of the previous experiment an additional set of anodes was used in this experiment which involved placing a BoPET layer on the anodes and then burying those anodes. If the part of the anode which is covered in BoPET is truly not active then the buried anode with BoPET would also perform approximately half as well as the buried anode without BoPET.

These BMFCs were run at 450mV. The voltage was controlled by adjusting the load resistors on the cells. Once OCV was reached the load was applied and the voltage was maintained in the same methodology that was used for the smaller systems. Small fluctuations in voltage were not considered significant.

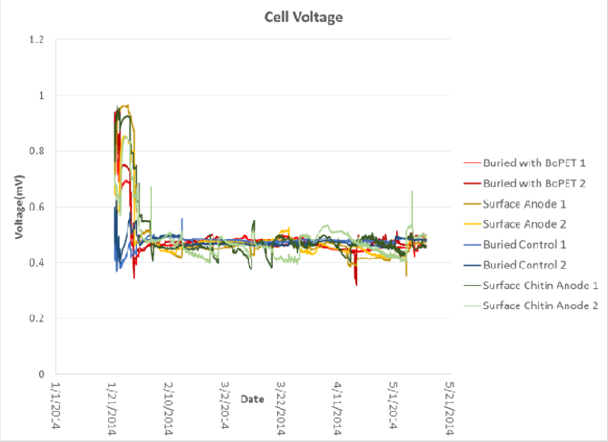

Fig. 8: Cell voltage over time for scaled up surface anode experiments.

Figure 8 shows the voltage over time for all of the 12in x 12in BMFC experiments. The voltage was maintained at approximately 450mV for all BMFCs.

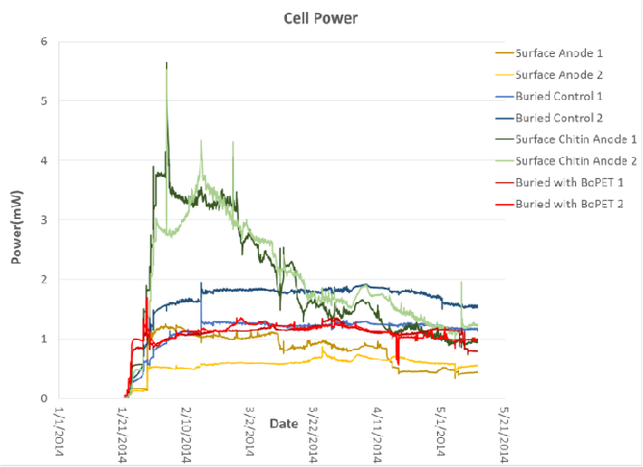

Fig. 9 BMFC power over time

Figure 9 displays the power output over time for all of the 12in x 12in BMFC experiments. Figure 9 shows that the anodes which had chitin in between the BoPET layer and the carbon cloth anode performed best initially however leveled off to a performance level similar to that of the buried anodes. This is most likely due to the fact that the chitin is consumed over time and after approximately two months of operation there is an extremely limited amount of chitin left.

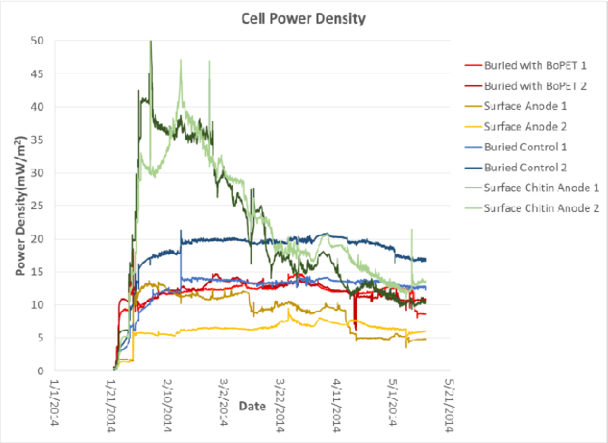

Fig. 10: Power density of BMFCs over time

Figure 10 displays the power density of all the scaled up BMFC laboratory experiments. From this graph it is clear that chitin poses a clear benefit, particularly in the first two months of operation where the power density nearly double that of the other anodes. Also clear from this graph is the fact that the buried anodes which have a BoPET layer on them are not half of the power density of those buried without the BoPET though they are lower in power output. This implies that the BoPET layer does have a negative effect on power however it is not the only thing affecting the power output of the surface anodes and further investigation is required. It is important to note that the overall performance of the SBMFCs, though lower than the buried ones, still maintain power output over an extended period of time. Both sizes of tested SMBFCs performed well and the ease of deployment gives them significant advantages over buried ones in certain applications.

C. *Surface Anode Deployment Device*

Though the SBMFCs showed a lower performance in the laboratory experiments compared to that of the buried anodes, the experiments were still considered successful, particularly due to the fact that the buried anodes are extremely complex to deploy in deep water. For this reason, the design and development of a surface anode deployment device was performed. Though field data was not collected for this device the design was completed and tested for deployment purposes and is described below.

The prototype system was designed and built to maintain a small profile while being deployed. It was designed to be able to be dropped from the surface and unfurl upon hitting the sediment surface. A unique design and method of deploying BMFCs was utilized that allows the anode to be placed on the sediment surface without being buried and still operate under anaerobic conditions without an extra burial process

Fig. 11: Prototype SBMFC deployment device being dropped into test pool

The device is designed to maintain a low profile while descending to the floor. It is also designed to ensure that it will stay upright while descending.

Fig. 12: Prototype SBMFC deployment device at bottom surface

Once the deployment device comes into contact with the sediment surface the system will unfurl and the surface anodes will come into contact with the sediment. The chain around the outside edge acts as a sealing mechanism between the sediment and the anode in order to ensure that no aerobic seawater will enter.

Fig. 13: Prototype surface anodes unfurling

Fig 14: Prototype surface anodes unfurled with BoPET layer on top.

Though power output data was not collected on the prototype device the system was designed and built with all actual BMFC components. The anodes and BoPET layer were the same as those used in the laboratory experiments and the system was successfully demonstrated for deployment and the next step is to deploy in San Diego Bay and begin collecting power production data.

IV. CONCLUSION

Previous works have shown that in order to get effective power output from BMFCs it is necessary to use large anodes. These anodes have, in the past, always needed to be buried in the sediment. The burial process is extremely difficult and complex and has not been done in very deep water due to the complexity of the process. In order to bypass this process of burying a surface based BMFC has been created and shown to produce effective power levels in the laboratory environment.

The following conclusions may be drawn from the experiments:

- Surface based BMFCs will produce an effective amount of power though that power will be lower than that of the buried anodes
- The BoPET layer is an effective method of preventing aerobic water from entering into the surface anode
- The use of chitin in between the BoPET layer is recommended for short term power production though for long term power production may make the system more cumbersome and will not increase power for long periods of time
- The BoPET layer is most likely not the only cause for the decreased power output in the SBMFCs

This method of SBMFC tested here does not require any burying or complex deployment mechanisms. Though the power output is less than that of a buried anode, due to the fact that it will require far less time and effort to deploy, the SBMFC is considered an effective method for long-term, low power production for undersea electronics.

ACKNOWLEDGMENT

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