Benthic Microbial Fuel Cells: Long-Term Power Sources for Wireless Marine Sensor Networks

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ABSTRACT

Wireless marine sensor networks support an assortment of services in industries ranging from national security and defense to communications and environmental stewardship. Expansion of marine sensor networks has been inhibited by the limited availability and high cost of long-term power sources. Benthic Microbial Fuel Cells (BMFCs) are a novel form of energy harvesting for marine environments. Through research conducted in-lab and by academic collaborators, Trophos Energy has developed a series of novel BMFC architectures to improve power generation capability and overall system robustness. When integrated with Trophos' power management electronics, BMFCs offer a robust, long-term power solution for a variety of remote marine applications. The discussions provided in this paper outline the architectural evolution of BMFC technology to date, recent experimental results that will govern future BMFC designs, and the present and future applicability of BMFC systems as power sources for wireless marine sensor networks.

Keywords: Benthic microbial fuel cell, remote power source, marine power, marine sensor network, remote sensor network, environmental fuel cell

1. INTRODUCTION

Wireless marine sensor networks have proven to be highly valuable in a wide range of applications from providing enhanced intelligence for naval operations to producing high-density data to track the effects of global climate change. These sensor networks, however, have still not been widely used within the naval or scientific community due to a variety of technical challenges that have been faced. Many of these challenges, relating to aquatic wireless transmission hardware, have been overcome in the last decade; a wide variety of robust subsea sensor and communications hardware is easily accessible today. However, the key component that continues to limit the expansion of wireless sensor networks is the availability of a reliable, long-term power source.

While many forms of energy harvesting technology are currently being investigated, power supplies for marine sensor networks almost solely come in the form of one or many batteries. While the upfront cost of batteries is relatively minimal, it is their necessary pressure housings and their finite lifetime (typically less than 3 years) that yield them to be so costly. For sensors deployed in the deep sea, the cost of hiring a boat and crew to replace batteries can exceed \$500k per node. Replacing batteries leads to high operational costs and jeopardizes the security of the network in circumstances where node covertness is essential. Additionally, there are limitations relating to the transportation of batteries including regional borders and maximum mass[i]. Finally, batteries placed in extreme environments require capital intensive housings, particularly when deployed in high-pressure locations such as the sea floor.

Microbial fuel cells (MFCs) have shown great promise as a novel energy harvesting technology that can provide consistent, maintenance-free power for long periods of time, well beyond the lifetimes of sensor and communication hardware. MFCs were first deployed in marine sediments about ten years ago[ii,iii]. In 2007, these MFCs (hereafter referred to as benthic MFCs or BMFCs), were first demonstrated to be viable power sources for undersea sensor and communications systems[iv]. Trophos Energy has developed and deployed a number of these aquatic systems in the field for both demonstration and research purposes. This paper will outline the progress that Trophos has made in the

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development of BMFC technology and the steps that are being taken currently to enhance power generation capability and robustness of this novel and promising power source.

2. MFC BACKGROUND

Microbial fuel cells (MFCs) are bio-electrical devices that harness the natural metabolism of microbes to directly produce electrical power. Within the MFC, microbes act as a catalyst to break down sugars and other nutrients in their surrounding environment and release a portion of the energy contained within those molecules as electrical current. MFCs were a laboratory curiosity for nearly a century before the major advances in biochemistry and microbiology in the last decade stimulated significant interest in their commercial potential. This interest has led to the development of environmental MFCs that harness the energy contained within substrates of the natural world, such as terrestrial soils and marine sediments. Over the last five years, the scientific understanding of various MFC mechanisms has been greatly enhanced and power generation capability of MFCs, both in the lab and in the field, has risen steadily[v,vi]. Sediment-based MFCs were first explored in 2001, and it was demonstrated that power could be generated from the microbes and the nutrients found within the sediment alone[ii]. The first field application of an environmental MFC was demonstrated in 2007 by Leonard Tender et al. of the Naval Research Laboratory (NRL), in which an ocean sediment-based MFC was used to power a meteorological buoy[iv]. As will be discussed in greater detail in later sections, Trophos Energy, in collaboration with key researchers in the field of environmental MFCs, has advanced BMFC design and developed it into an integrated platform with a suite of sensing and communications hardware.

2.1 Microbial Fuel Cell Theory

Microbes are ubiquitous in our biosphere, and exist in virtually all habitable soils, sediments, streams, and effluents. Among this diverse assemblage of microbes are particular species with unique metabolic pathways that enable them to reduce (or transfer electrons to) oxidized metals such as iron oxide to support respiration. In a sense, these so-called "electrogenic" microbes are able to "breathe" metal compounds much like humans and other organisms breathe oxygen. MFCs employ these unique metabolisms by providing electrogenic microbes with a certain configuration of two inert, carbon-based electrodes placed in environments exhibiting different redox potentials (see Figure 1).

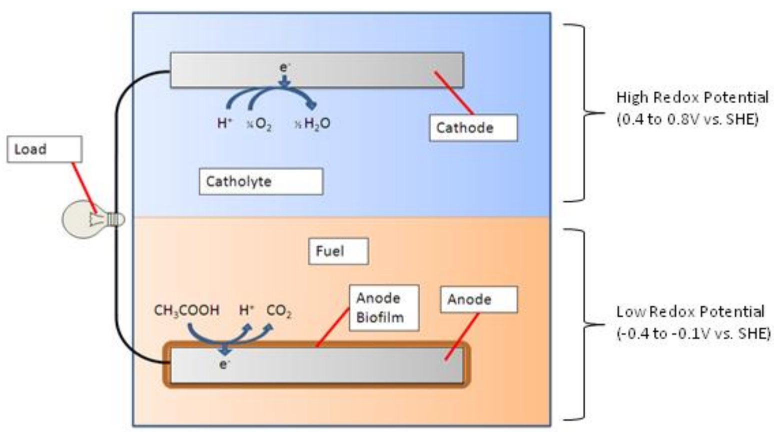

Figure 1. Graphical representation of a microbial fuel cell. Electrical energy is harvested from electrodes located in spacially separated Reduction/Oxidation reactions.

One electrode, called the anode, is placed in a nutrient-rich, oxygen-poor environment, while the other electrode, the cathode, is placed within an oxygen-rich environment. These two media are typically separated by a proton-exchange membrane that is permeable to protons, but impermeable to oxygen. If microbes are present within the anodic media, a biofilm will spontaneously develop on the anode surface. Many MFC researchers inoculate this anodic media with particular species of electrogenic bacteria, such as *Shewanella* or *Geobacter*[vii]. However, for MFCs utilizing natural media such as sediments, soils, or effluents, such as those that Trophos Energy utilizes, inoculation is not needed since these electrogenic species are already abundantly present[viii].

Once a microbial community forms on the anode, its natural metabolic pathways begin to break down the nutrients within the surrounding media, generating highly reduced biomolecules, such as NADH. These biomolecules then donate electrons to the anode in one of three ways: 1) directly transferring from the molecule to the anode surface, 2) employing a secondary biomolecule to shuttle the electron to the anode, or 3) transferring the electron through conductive appendages, termed "nanowires", propagated by the microbe[ix]. Once the electron has been transferred to the anode, it then travels to the cathode, where it reacts with an oxygen molecule and a proton, a byproduct of electrogenic metabolism, to form water. Thus electrical current is generated, from which one can extract power by simply placing a load between the two electrodes.

The voltage of the MFC is determined by the difference in redox potential between the two distinct electrode environments. When a microbial community forms and begins to respire at the anode surface, the highly reduced biomolecules mentioned above start to accumulate around the anode. This build-up of metabolic byproducts causes the electrical potential of the anode to decrease, typically settling between -0.1V and -0.4V vs SHE (standard hydrogen electrode). The second electrode, the cathode, is placed in a more oxic environment, such as aerated water. The presence of dissolved oxygen gives the cathode a higher electrical potential, typically from 0.4V to 0.8V vs SHE. The working voltage of the MFC is merely the potential of the anode subtracted from the potential of the cathode. It should be noted that MFCs have a theoretical maximum voltage that can be achieved between the two electrodes – approximately 1.2V – since the redox potential of reduced biomolecules has a minimum of -0.4V vs. SHE and the redox potential of oxygen is 0.8V vs. SHE. In order to employ MFCs to power commercially available sensor and communications hardware, Trophos Energy has developed proprietary power conversion electronics which up-convert this voltage to the conventional 3.5V to 12V, depending on the application.

Power generation from an MFC is continuous, but is limited by the availability of nutrients within the anodic media. In environmental MFCs, such as sediment-based BMFCs, nutrients are continuously replenished by the constant decay of fresh microbe and animal material, which gives the BMFC a theoretically indefinite lifespan. This will be discussed in more detail in the next section.

2.2 Benthic Microbial Fuel Cell Theory

The BMFC adheres to the same basic MFC principals as described above, whereby ocean sediment acts as the nutrient-rich anodic media, the inoculum, and the proton-exchange membrane (PEM). Sediments are naturally teaming with a complex community of microbes, including the electrogenic microbes needed for MFCs, and are full of complex sugars and other nutrients that have accumulated over millions of years of microbe and animal material decay. Moreover, the aerobic (oxygen consuming) microbes present in the top few centimeters of the sediment act as an oxygen filter, comparable to the costly PEM materials used in laboratory MFC systems, and cause the redox potential of the sediment to decrease with greater depth, typically leveling at approximately -0.4V vs. SHE. While the level of dissolved oxygen within a body of water does generally decrease with greater depth, continuous water circulation ensures that water above the seafloor retains a high enough level of dissolved oxygen to maintain proper cathode function even at extreme depths. It has been shown that cathodes may still exhibit potentials of 0.4V vs. SHE at depths in excess of 950 meters[x].

Early BMFC prototypes employed the simple architecture of having a graphite-based anode plate buried within the ocean sediment, while a graphite-based cathode lay stationary in the overlying water. In this architecture, new nutrients reach the anode via simple diffusion through the sediment pore water. This diffusion, while sometimes aided by natural seafloor seepage, is a slow process and limits power production. BMFCs of this design have typically exhibited power densities of 30mW/m^2 of footprint continuously, depending on sediment conditions[xi].

In 2006, investigators at Oregon State University developed a novel BMFC architecture called a Benthic Chamber Microbial Fuel Cell (BC-MFC) designed to address the limitations of nutrient diffusion[xii]. Outlined in Figure 2, the BC-MFC employs a large semi-enclosed chamber that rests securely on the seafloor. Through the use of a one-way check valve, the chamber utilizes the tidal fluctuations in water pressure to passively pump pore water from the underlying sediment into the chamber. This water is not only nutrient-rich, but also depleted of oxygen due to the rich consortium of aerobic microbes present within the sediment. These microbes, in effect, "filter" oxygen from the water before it reaches the chamber. The inside of this chamber houses the carbon fiber brushes that are arranged inside to serve as anodes. The nutrient-rich water flows through the brushes, and comes into contact with the thick films of electrogenic microbes that develop on their surface, before exiting the chamber. The one-way check valve located at the top of the chamber allows only outflow from the chamber, preventing the overlying, oxygen-laden water from reaching the anode. The cathode, also composed of carbon fiber brush, is attached to the top of the chamber and floats freely in the water with the use of syntactic foam floats. With this novel architecture, the detrimental effect of diffusion limitation on power generation is negated, enabling power densities to reach reported peaks of 380 mW/m^2 of footprint[x].

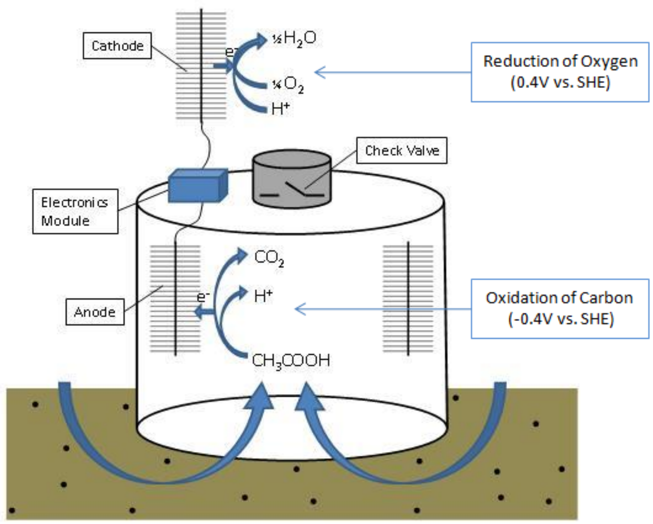

Figure 2. Benthic Chamber MFC Architecture

Researchers of BMFC technology have both modeled and demonstrated long-term (multi-year) power generation. In addition to the abundance of academic literature identifying the persistent nature of environmental MFC systems, Trophos Energy has developed a mass/energy balance model for BMFC systems. Using environmental data of substrate chemistry and biogeochemical cycling, we have determined that with appropriate power management technologies, field-deployed BMFCs, differentiated from laboratory closed-cell systems, can last multiple decades. As our fundamental understanding of environmental MFCs continues to develop, and power generation capability continues to improve through technical innovation, BMFCs show great promise as robust power solutions for remote marine sensing applications[xiii].

3. FIELD DEPLOYMENTS

Trophos Energy has devoted its efforts to the development of MFC technology in both sediment and soil environments. Trophos has delved into a number of research areas found to crucially affect MFC performance: electrode materials and architecture, power management strategies and related electronics, and biological manipulation. In conjunction with in-lab experimentation using several generations of bench-scale BMFC systems, Trophos developed and deployed three generations of field-type BMFCs since June of 2009.

Leveraging support from key academic advisors, Trophos Energy has investigated a range of MFC architectures to evaluate improvements to system performance and long-term power density. Iteration between both laboratory and field testing of BMFCs has enabled advances in system design. Trophos Energy's current BFMC research supports the development and integration of small, modular BMFCs that enable more efficient energy harvesting per unit area in addition to maximizing system performance through isolation and control of each discreet fuel cell. Leveraging this in-lab research effort along with practical field consideration, Trophos Energy has developed and deployed an advanced BMFC design, the outer housing of which is shown below in Figure 3. With this architecture, BMFCs can be deployed without significant excavation of the underlying sediment, while protecting the anode chamber from potential oxygen poisoning through scouring of the sediments and / or bioturbation.

Figure 3. Photographic images of Trophos Gen. 3 BMFC in the laboratory and during field deployment.

Currently, Trophos Energy has deployed this third generation BMFC in an experimental pilot-study in Boston Harbor, MA. The primary purpose of this field deployment is to support the advancement of the MFC power management platform (PMP) and integrated sensor/communication hardware. While these two topics will be discussed later, the reader should note that Figure 4 (a recent data set from Gen 3 BMFC deployments) clearly shows the system's sustainable power density above 10mW/m^2 and steady increasing trend. As such, 10mW/m^2 will be the baseline against which further development should be measured. The variations in power density throughout the day clearly demonstrate the dynamic nature of the power system.

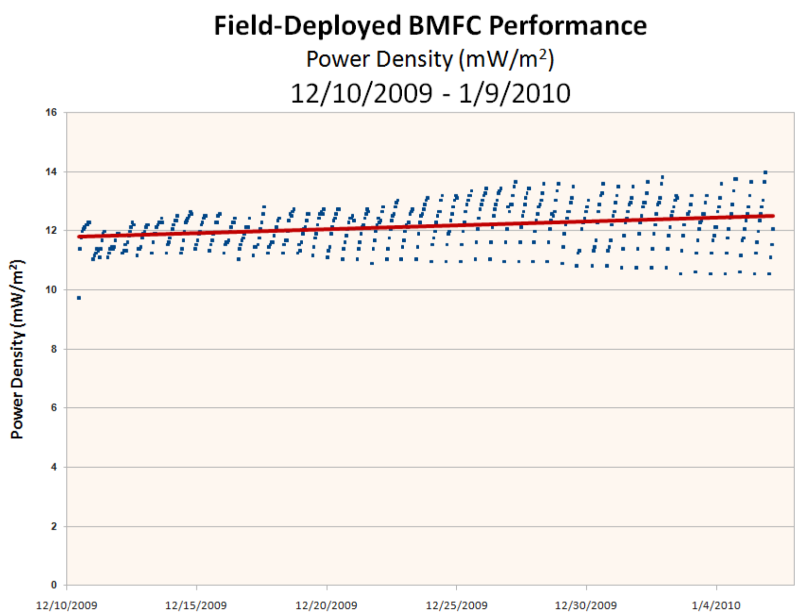

Figure 4. Data from the deployment of Gen 3 BMFC in Boston Harbor, MA.

While a number of endeavors are underway to improve the power production of MFCs, Trophos Energy believes that improvements will only be made through development activities focused on increasing the electrically active surface area within the chamber and optimizing the control strategies for extracting power from these dynamic biological systems. However, mechanical design of the MFC may help stabilize the chemical potentials observed at each electrode, but outside of introducing new (artificial) chemistry into the system, it is not possible to increase the voltage above that of the naturally occurring RedOx reactions. As such, increases in power have to be associated with increases in current. Thus, technology and operational techniques that increase current density will subsequently enhance power density.

4. RESEARCH APPLIED TO BMFC DEPLOYMENTS

The research executed at Trophos Energy is performed with the goal of producing improvements in the BMFC systems deployed in the field. Our experiments are performed in-house on lab-scale systems using proprietary materials and testing architectures designed to facilitate the transition between bench and pilot scale systems. Each experiment is executed with the intent of directly applying the result to a deployable system. Several key parameters which will improve the operation of BMFCs have been identified and quantified. The following sections showcase some of the most critical research applied to BMFCs based on experiments, literature, and applied theory.

4.1 Diffusion Limitations

The current state of research, both performed at Trophos and in academic settings, shows that MFCs are highly limited by mass transfer - principally diffusion of nutrients to the electrogenic biofilm located on the anode. In order to address this limitation, Trophos performed diffusion limitation experiments by mixing the anode headspace to ensure no nutrient concentration gradients existed. The results for this experiment are shown in Figure 5, and show that BMFCs are particularly affected by diffusion limitations. The experiment tested three flow rates. The optimal power densities were achieved at our intermediate flow rate, with significant decrease in performance once the flow rate increased. This result implies that extremes in flow rate are problematic, and that an ideal flow rate may exist between those which were experienced, which will possibly result in higher power densities. This experiment gave credibility to utilizing flows through the BMFC to increase power production.

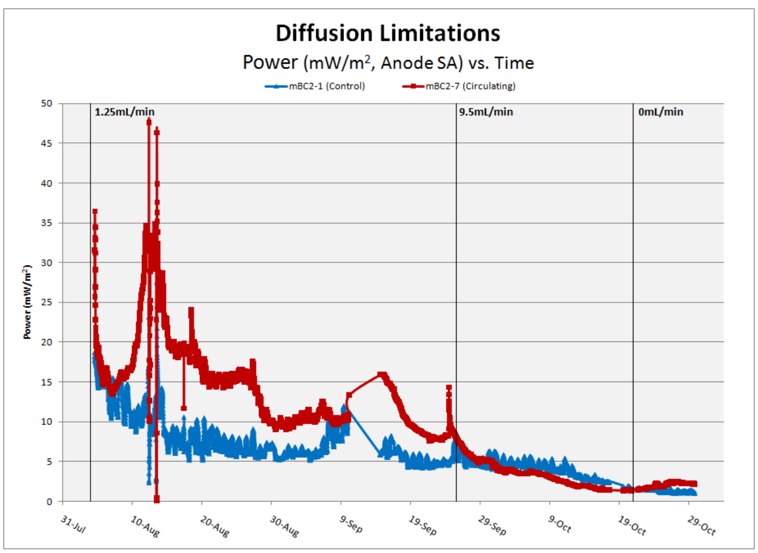

Figure 5. Mixing BMFC headspace to eliminate diffusion limitiations

4.2 Nutrient Additions

MFC current production is highly dependent on the concentration of nutrients present. Nutrient additions have been the sole feed source for laboratory MFCs used in academia. In the case of deployed BMFCs, nutrient additions can be utilized for a number of uses, most importantly to shorten the transient period required for these systems to reach anaerobic conditions, but also to measure performance and to jumpstart ailing systems. Figure 6 shows the results of an experiment in which varying amounts of nutrients were added to BMFC systems to observe the effect on the power's step response. In this scenario, it is evident that the addition of the nutrients produced significantly higher power. It is also evident that there is an upper threshold for the maximum nutrient consumption in BMFCs, which will be further investigated to determine the proper range.

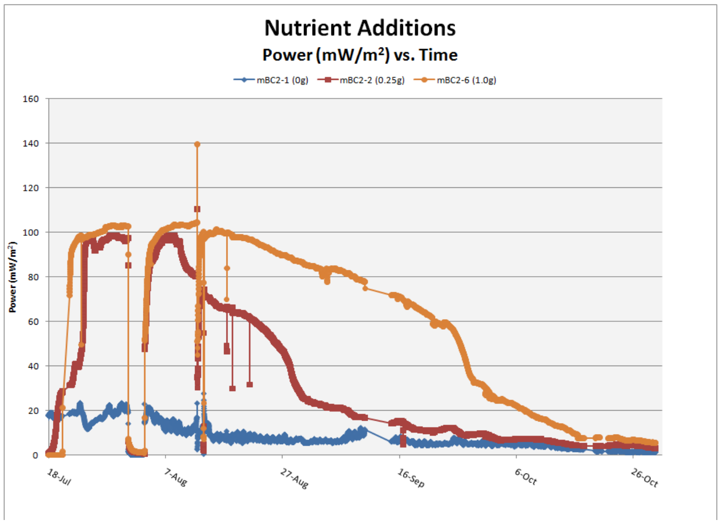

Figure 6. Effect of nutrient additions on BMFCs

4.3 Advective Flow

Advective flow through the BMFC also proved to be beneficial to increase power production by introducing nutrient-rich streams. While continuous pumping could be performed in the lab, a self-sustaining method for implementing advective flow was sought. Tidal pumping, imposing a flow utilizing the changes in tidal pressure, was deemed a reliable method. To simulate tidal pumping in the lab, different volumes of porewater were extracted periodically. The results, shown in Figure 6, illustrate the marked difference in performance between the control and any of the BMFCs which experienced tidal pumping. This experiment was performed over a nine month period. Unfortunately, tidal pumping did not help to improve the performance of BMFCs when their output was significantly declining due to nutrient depletion.

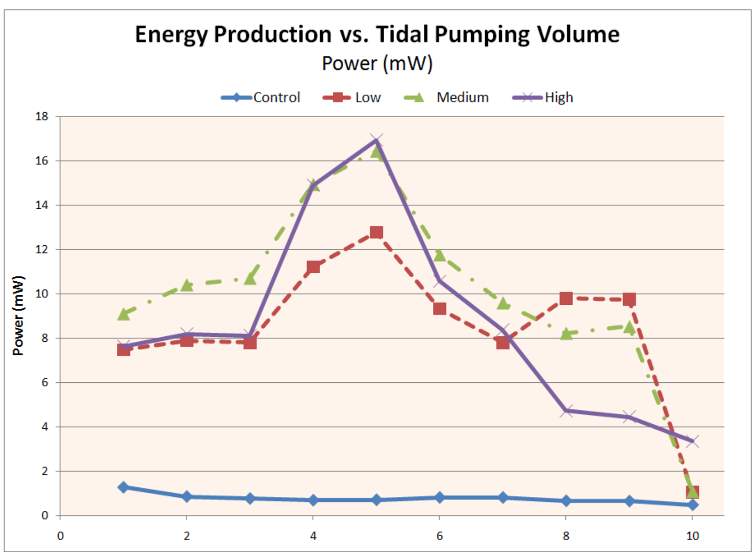

Figure 7. Tidal pumping through BMFCs

4.4 BioCathode

All MFCs that are developed and deployed by Trophos naturally develop biofilms on all of the surfaces of the electrodes. It has been shown in research that MFCs featuring cathodes covered in biofilm, termed "biocathodes", instead of cathodes impregnated with precious metals on their surface can produce higher currents while having lower capital costs[xiv]. Trophos has experienced this phenomenon with all aquatic MFCs, has concluded that this feature is beneficial, and has utilized cathode materials that facilitate biofilm growth.. In a recent experimental deployment in the Boston Harbor, a clean, biofilm-free cathode was connected in parallel with the fully developed biocathode of a mature BMFC that had already been deployed for several months. In this apparatus, the open circuit voltage exhibited between each cathode and their shared anode could be measured and compared, as shown below in Figure 8.

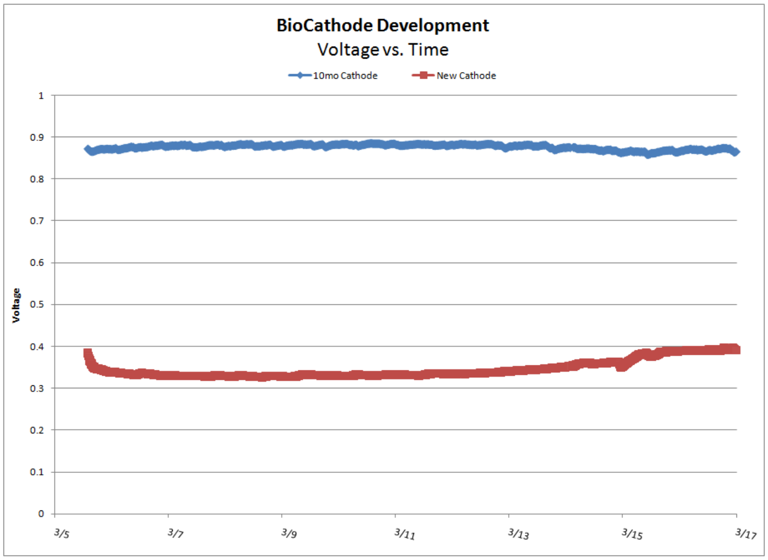

Figure 8. Performance comparison between a biocathode and a biofilm-free cathode.

As you can see in the above figure, the newly installed cathode exhibited a significantly lower voltage than the established biocathode. It should also be noted that the fresh cathode showed a 25% increase in voltage over a span of 12 days. Recent site visits and dives have shown that a biofilm, along with considerable growth of larger marine-life, has begun to develop on the new cathode, but with no decrease in performance. The fact that the clean cathode has performed so poorly in comparison to the old is evidence that aging in the water results in higher performance - which is most likely due to biofilm development over time.

4.4 Advanced Power Management Strategies

As shown earlier in Figure 4, and further supported below in Figure 9, BMFCs are biological systems that exhibit a certain dynamic nature. As a result of natural biogeochemical fluctuations and other dynamic environmental variables, the optimal load point for pulling power from a BMFC often varies over time. As such, advanced power management systems are needed to track the maximum power point (MPPT) demonstrated as the ridgeline on the 3D potentiometry graphic in Figure 9 below.

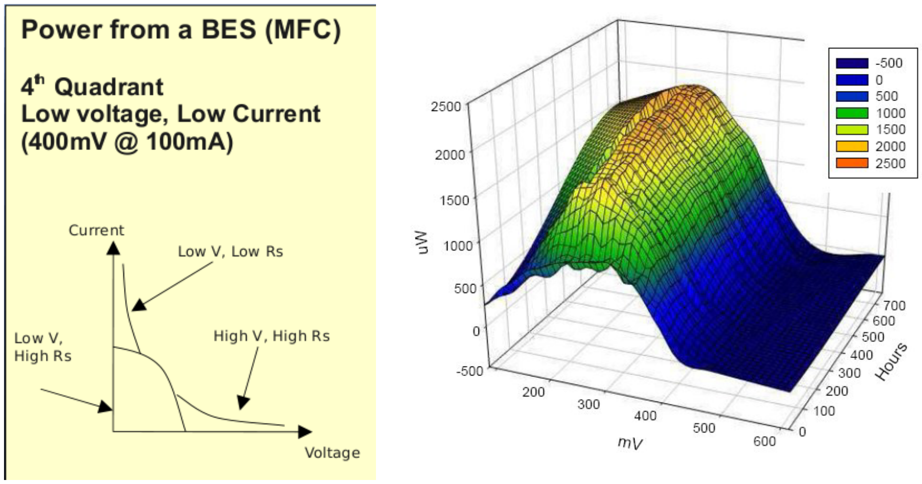

Figure 9. Graphical representation of MFC power quality

In addition to this dynamic behavior, the 'quality' of the MFC electrical power is unique, in that it is a low-current, high-impedance power source, preventing the use of standard off-the-shelf electronic systems.

5. APPLICATION

Microbial fuel cells are a nascent technology with the potential for pervasive applications ranging from providing electricity as power sources, remediating wastewater and soil, to acting as biosensors. While exploring these markets, Trophos Energy has focused on developing MFCs as an energy source for low power devices. The technical feasibility of this work has been proven through a pilot project called BackyardNet™. While BMFCs can be deployed in a wide range of aquatic environments, they are particularly beneficial in deepwater locations: those where devices need to be deployed for extended lengths of time with intermittent power draw, and where battery replacement and regular servicing are problematic.

BMFCs produce power in ranges incompatible with commercial devices, requiring power conversion electronics. Trophos has been developing these electronics, and believes that BMFCs will only be useful when integrated with appropriate power management, as described in the following section.

5.1 BMFC Electronics Package

The BMFCs developed at Trophos Energy have essential capabilities operating as a power source for a variety of commercially available devices, but this work also involves development of electronics equipment for power management. A critical activity at Trophos has been to develop the appropriate technologies to allow MFCs to interface with commercial products. Figure 10 shows the layout for Trophos' power management platform (PMP) that contains sub-components able to boost the incoming electrical potential to a usable voltage, to provide energy storage for use in the application, and to provide power management to optimize the extraction of power from the MFC, all while accounting for lifetime considerations and biological upkeep.

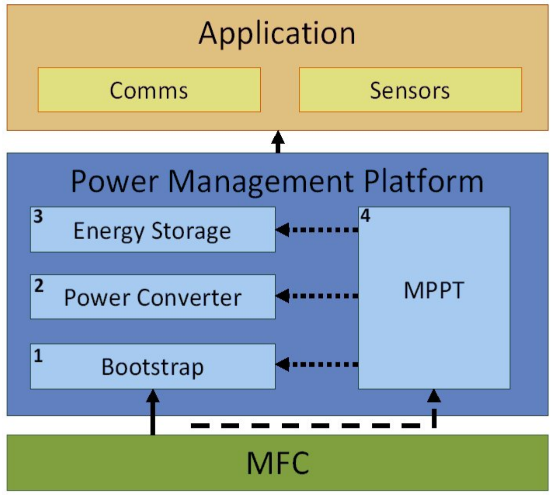

Figure 10. Block diagram of MFC power management platform

Trophos has developed ultra-low power electronics to address the need to convert the power produced by the MFC to be compatible with current commercial, off-the-shelf devices. These power management electronics were developed in-house, since there were no commercial solutions available for this type of power conversion. These electronics have been optimized for either terrestrial or benthic MFCs, and are purpose built, taking into account the power requirements of the intended application. In addition to the converting electronics, Trophos has focused development on adaptive algorithms designed to match the power-converter operation with the MFC performance to ensure that power is extracted from the MFC at the peak efficiency. A component of the PMP development work will focus on advancing the firmware designed for this purpose, thus increasing its efficiency through advanced power management algorithms.

6. CONCLUSION

Wireless sensor networks are a growing necessity in today's information-driven world. The collection and propagation of pervasive data in difficult operating environments such as on the ocean floor is becoming increasingly critical for a range of services, from monitoring ship traffic and environmental conditions, to enhancing communications. The devices used for these tasks have a critical limitation due to the lack of a robust, long-term power source. Wired connections, batteries, solar panels, and ROV services are all impractical for long-term deployments of field instrumentation due to their operational costs and poor reliability. The capital and maintenance savings, long-lifetime, redundancy features, and covert installment, make BMFCs a promising technology for a wide variety of remote marine applications.

Trophos Energy has developed the technologies necessary to achieve application of BMFCs as a ubiquitous, reliable, and long-term power source for wireless marine sensor networks. With deployed BMFC units producing sustained power of $30mW/m^2$ and peak power above $380mW/m^2$, it has been shown that BMFC technology can be a viable long-term power source in places where batteries and other energy harvesting technologies cannot. As mentioned previously in Section 2.2, BMFCs can withstand the extreme pressures of the deep ocean and are constructed from non-corroding, biologically inert materials to ensure long lifetimes. This makes BMFCs particularly suited for nearly any marine environment, especially considering the versatility of the highly adaptable power management electronics, which enables the BMFC to be successfully integrated with numerous off-the-shelf sensor and communication packages.

Academic research of MFCs has proven that BMFCs are complicated systems involving a considerable amount of environmental and engineering variables. Through in-lab and field-based experimentation, and with heavy collaboration with university researchers, Trophos has been able to further the understanding of some fundamental processes in BMFC function. This has enabled Trophos to continuously innovate new BMFC architectures, design new BMFC operational strategies, and play a critical role in developing the technology to be applicable for powering marine sensor devices. To date, BMFCs have been shown to be reliable, long-term power sources suitable for many marine applications. As further improvements are made to this still nascent technology, and power generation capability continues to climb, further market opportunities will undoubtedly present themselves.

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