Sensors and Acoustic Modems Powered by Benthic Microbial Fuel Cells at the MARS Observatory

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***Abstract*— The goals of this project were three-fold: 1) to power underwater instruments with energy harvested from deep sea, organic poor sediments using Benthic Microbial Fuel Cells (BMFCs); 2) to relay instrument data acoustically –and in near-real time- through a cabled seafloor observatory or surface vessel, as appropriate; and 3) to characterize the operational performance of these interactive systems during in situ deployments. Two BMFC- underwater sensing/communications packages were demonstrated near the Monterey Accelerated Research System (MARS) observatory in Monterey Bay, California. MARS is a cabled observatory that resides in deep water (~890 m), about 37 km (23 miles) seaward of the Monterey Bay Aquarium Research Institute (MBARI).**

The BMFCs were constructed using a cylindrical chamber design with a 0.28 m^2 footprint. Each BMFC was used to power an Aanderaa dissolved O_2/temperature or conductivity/temperature sensor, as well as a Teledyne Benthos compact acoustic modem which contained an integrated power management platform (PMP) for the complete system. The packages were deployed from a surface vessel and allowed to descend freely to the seafloor, at locations approximately 0. 5 km away from the MARS node, at depths of 863 and 895 m. The PMPs were programmed to record data from both the sensors and the BMFC (whole cell voltage, capacitor voltage, and battery voltage) on an hourly basis, and to monitor overall microbial fuel cell energy production on a daily basis. Post-deployment, BMFC 1 generated a net surplus of energy from days 98 through 166, and remained operational for 210 days. BMFC 2 began generating a surplus of energy on day 54 and remained operational for 158 days. Data recovered from the oceanographic sensors was transmitted acoustically over both the MARS node and to a research vessel, underscoring the utility of this technology.

***Keywords*— Benthic Microbial Fuel Cells (BMFCs), Monterey Accelerated Research System (MARS) observatory, deep water deployment, energy production**

I. Introduction

The first functional prototypes of benthic microbial fuel cells (BMFCs) were constructed just 12 years ago [1, 2]. BMFCs are bioelectrochemical devices driven by the naturally generated potential difference between anoxic sediment and oxic seawater. Electrons are delivered to the anode by microorganisms either directly from organic material or indirectly from inorganic products of organic matter degradation

[3].These electrons reduce dissolved oxygen to form water at the cathode. Microorganisms play several roles in these systems including: maintenance of the redox gradient, production of redox mediators, generation of electron-rich metabolites (e.g. sulfide ions), and in some cases, delivery of electrons to an electrode through direct electron transfer [4-7].

BMFCs are very promising power sources for a variety of marine sensors that have low power requirements [8-10]. Most oceanographic and surveillance instruments on the seafloor have no cable connection with the surface and therefore must store the information collected until the instrument can be recovered while utilizing batteries as their only energy source. The main drawbacks of batteries are limited lifetime and high cost of periodic replacement, particularly in deep water deployments.

In the past 10 years, the continuous generation of power densities ranging from 1 to 10 mW/m^2 (with areas representing chamber or simple plate electrode footprint) has been demonstrated in a wide variety of marine environments with peak power densities typically 10 - 30 mW/m^2 [2, 11-13]. Under unique operational conditions, when a chambered BMFC was deployed at a methane cold seep, peak power densities as high as 380 mW/m^2 have been observed [12, 14].

To date, BMFCs have only just begun to be applied to power a range of environmental sensors and thus to prove themselves as a viable means of providing long-term, uninterrupted power for submarine devices [11, 13, 15]. The objective of this study was to demonstrate benthic microbial fuel cell powered underwater sensing/acoustic communications in conjunction with the deep sea scientific research infrastructure at the Monterey Accelerated Research

System (MARS) observatory in Monterey Bay, California. The BMFC/sensor/acoustic modem packages were used to harvest energy, collect sensor and fuel cell performance data (i.e., power levels supplied), and to power an acoustic modem to transmit the data to either the MARS observatory or a surface vessel. Site characterization, including sediment properties, was performed in this deep-sea environment to determine the influence on energy harvesting as our previous studies have shown striking differences in performance among different locations.

II. Materials and Methods

A. BMFC, Acoustic Modem, Power Management Platform and Sensor System

Identical chambered BMFCs were fabricated in duplicate (Accelerate, INC, Upton, MA), one of which is shown in Figure 1 prior to a test deployment. The chamber was a cylindrical design constructed of PVC 0.5 m high, 0.3 m in diameter and consisting of an open bottom with a 0.28 m2 footprint. The chamber was designed such that the lower 60% of the volume could be submerged in the sediment while the upper volume, separated by a 0.6 cm thick perforated PVC disc, housed the electrode. The perforated disc allowed the electrode to be suspended above the sediment thereby minimizing negative impacts in performance due to bioturbation. The solid PVC top was bolted onto the chamber and sealed with a Viton rubber gasket. The top contained a one way check valve to prevent the buildup of pressure and allow water to exit the chamber. The anode and cathode electrodes were constructed using twisted #11 titanium stem wire and panex 35 carbon fiber fill brushes with 400,000 tips per inch (Mill-Rose Industrial, Mentor OH). Each electrode was 2 m in length.

Figure 1. Image of assembled BMFC chamber prior to test in Yaquina Bay, Oregon. The cathode is directly above the chamber. Above the cathode is the acoustic modem and PMP housing with an oxygen optode sensor attached to the side, all suspended by the foam float.

The energy harvested from the BMFC is typically at low voltage (<0.7 V). This energy was directed to a custom designed Power Management Platform (PMP) housed within the compact acoustic modem (both Teledyne-Benthos products, North Falmouth MA). The PMP consists of a multi-stage boost converter, 2 V super-capacitor for energy storage, 7.6 V stack of two Li-ion batteries, and a programmable microcontroller with a circuit to monitor and optimize energy storage and usage, and a circuit to monitor the energy state of the BMFC in real-time. The boost converter was designed to supply 5 V for the oxygen optode/temperature sensor or salinity/temperature sensor (Aanderaa models 4330 and 4120BIW respectively) and 7 V for the acoustic modems. The microcontroller managed scheduled potential sweeps, sensor readings and power for the acoustic modem.

Sensor data (temperature and dissolved oxygen or salinity), the voltage of the supercapacitor, and whole cell voltage (the voltage difference between the anode and cathode) were recorded on an hourly basis. A potential sweep was performed once every day over a range of resistances (5 – 10,000 ohms) to determine the current (I) – voltage (V) characteristics of the BMFC. The data collected was stored in a 14 day circular buffer memory in the modem. These data were transmitted acoustically after receiving an acoustic command from either the surface (on a nearby ship) or the Monterey Accelerated Research System (MARS) observatory in Monterey Bay, California.

B. MARS observatory, Equipment Deployment and Recovery

MARS is a cabled observatory that sits in deep water (~890 m) at the edge of Monterey Canyon (latitude 36.712508, longitude -122.186757) about 23 miles seaward of the Monterey Bay Aquarium Research Institute (MBARI) (Fig. 2) [16]. It provides a site for researchers to test ocean observing equipment and to design experiments dependent on a regional observing network. Science instruments can be attached to the observatory node using underwater data/power connectors and extension cords up to four kilometers long. The MARS node has electronic equipment that converts a 10,000 V power source supplied from the shore to 375 and 48 V (DC) outputs routed to eight science ports.

In this experiment, a *Teledyne Benthos* SM75 acoustic modem was attached on October 27, 2011 via Remote Operated Vehicle (ROV) to a 48 V port and configured to relay data received from remote modems back to scientists' computers on shore. Scientists, in turn were able to send commands out to request data transmissions. Grounding problems with the modem attached to the MARS node necessitated that initial data recovery efforts be performed on board a ship near the site using a Universal Deck Box and transducer (Teledyne-Benthos). Ultimately another high power modem (Teledyne-Benthos) was deployed on May 15, 2012 (latitude 36.712225, longitude -122.182826, 876 m depth) to serve as a relay between the compact modems on the BMFCs and the modem attached to the MARS node.

The modem/sensor/BMFC packages were dropped from a surface vessel on November 15, 2011 using a system of

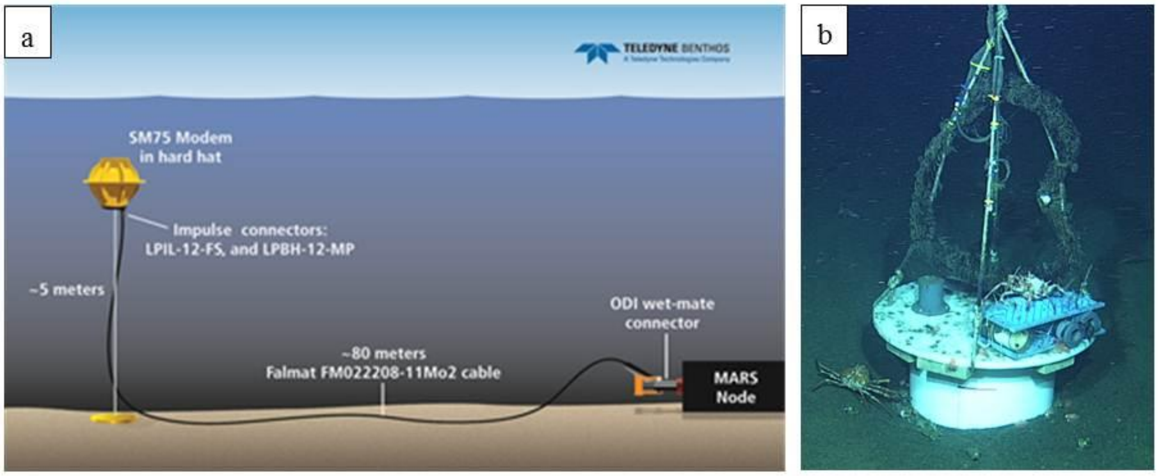

Figure 2. Illustration of the MARS observatory "science node" which has eight ports to supply data and power connections for a variety of scientific instruments as well as a cable to shore based facilities to allow scientists continuous access to their equipment and experiments (a). A BMFC deployed 0.5 km from the MARS observatory.

releasable "elevator" floats to slow descent to the seafloor at locations approximately 0. 5 km away from the MARS node (BMFC 1 latitude 36.715073 longitude -122.183237, BMFC 2 latitude 36.709230, longitude -122.182677), and at depths of 863 and 895 m. A ROV was used to release the elevator floats and to ensure BMFC chambers were inserted into the sediment.

The ROV also collected sediment core samples from each BMFC deployment site for characterization. Sediment cores were sectioned in 2 cm increments, placed in individual whirl pak bags, and frozen for future laboratory analysis. Subsamples were subsequently taken from each section, freeze dried, and analyzed for nitrogen and organic carbon content using an elemental analyzer.

The experiment was initially designed to be a 9 month deployment of the BMFCs. The decommissioning of one ship/ROV and problems associated with retrofitting equipment and instruments on the new ship forced the deployment to be extended to approximately 12 months. The BMFCs were recovered on November 13, 2012 by ROV.

C. *Energy Budget Calculations*

Following the approach of Gong et al., an energy budget was derived for each BMFC/sensor/modem package [17]. Accordingly, EBMFC is the energy harvested from the microbial fuel cell. This is calculated as the product of an average daily fuel cell potential (derived from hourly records), current and time. In this study, current estimates were interpolated from daily polarization curves.

$$\text{Euseful} = \eta 1 \eta 2 \ \text{EBMFC} \qquad (1)$$

Where $\eta 1$ is the efficiency of the primary charge pump converter on the power management board (estimated to be 85% in this study); $\eta 2$ is the efficiency of the boost converter (estimated to be 80% in this study).

$$\text{Econs} = \text{Emq} + \text{Ebq} + \text{Etrans} + \text{Eoptode} \qquad (2)$$

Where Econs is the energy consumption and is the summation of Emq, Ebq , Etrans, and Eoptode. Emq is the energy needed to maintain the acoustic modem in a quiescent state (at a constant power of 3 mW); Ebq is the minimum

energy required to maintain the duties of the power management platform including the internal clock (at a constant power of 45 μW); Etrans is the energy consumed when the stored data was remotely transmitted from the deployment site to shore by acoustic modem; and Eoptode is the energy consumed by the oxygen optode for hourly oxygen and temperature readings (each = 250 mW *3 s = 0.75 J). During this experiment, daily values of Etrans were dependent on how often data files were retrieved and thus the size of the recovered data file. One day's data equaled 1.1 KB and 40 J were consumed per KB.

Enet is the net daily energy saving and is defined as the difference of Euseful and Econs.

III. Results and Discussion

A. *BMFC deployment and site characterization*

Initial free-fall deployment of the BMFCs went smoothly as the fuel cells landed at their desired locations intact and in the proper orientation. However, they did not appear to be submerged very deeply into the sediment. All efforts by the ROV pilots to insert the fuel cells further into the sediment were.met with resistance and resulted in only modest gains with both being less than 10 cm deep (ideal depth ~20 cm). Sediment core samples collected from each site at the time of deployment revealed a compact clay deposit just centimeters below the sediment surface which likely impeded insertion of the BMFCs. This resulted in less sediment within the chamber and a greater than desired proportion of the chamber volume consisting initially of oxic seawater, requiring more time and microbial activity to create a favorable redox gradient for energy harvesting. Further analysis of the sediment core

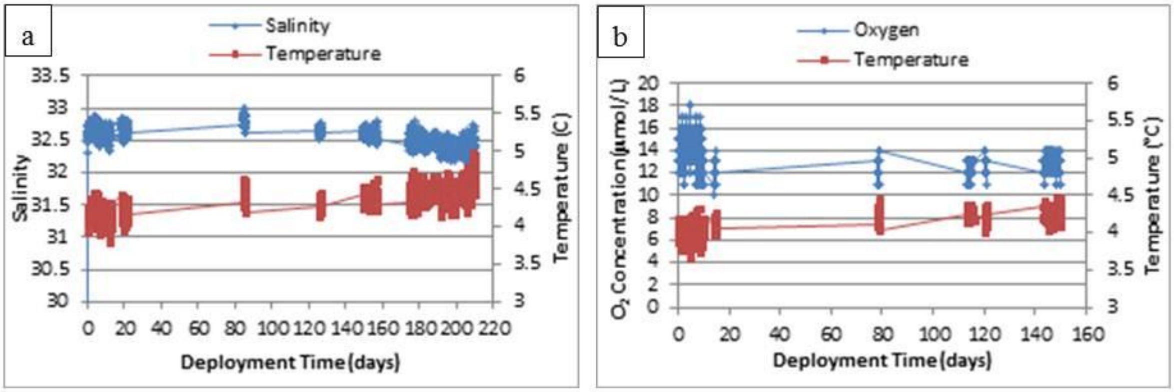

Figure 3. (a) Hourly oceanographic sensor readings of salinity and temperature from BMFC 1 and (b) oxygen concentration and temperature from BMFC 2. These records reflect the data that were collected by acoustic transmission. The sensors were operational throughout the deployments.

samples showed the sites to be organic-poor with total organic carbon content of ≤ 1%.

B. Modem communications

Following deployment, attempts at communicating with the BMFCs through the modem attached to the MARS node was problematic. It was evident that the fuel cells were receiving the query commands but the responses were unintelligible. Commands were sent to the compact modems to maximize the power of their transmissions but resulted in no improvement. An acoustic path refraction analysis was subsequently performed with models indicating only 1 m of bending given the recorded sound velocity profile over the 480 m distance between the MARS node and fuel cells thereby eliminating refraction as the problem. Communication with the BMFC compact modems and data recovery was initially established on a ship via surface hydrophone. This was fortuitous in so far as it both displayed the ability to communicate with the deep water fuel cells via surface vessel and indicated the problem was with the SM-75 modem attached to the MARS node. It was discovered that a seawater return for power was required for proper grounding but had not been established resulting in noisy data reception. Data continued to be collected intermittently via surface hydrophones from ships sent to the area until another high power modem was deployed at the site to strengthen the signal and act as a relay between the BMFCs and the MARS node. This solution resulted in good communications between MARS and the BMFCs for the remainder of the fuel cell systems' activities.

C. Data collection and energy production

The BMFCs were expected to be deployed for 9 months but remained in place for nearly 12 months, waiting for a ROV to become available for recovery. While the acoustic modems powered by the microbial fuel cells performed as expected, the consistent recovery of data collected throughout the first part of the project was impeded by the grounding problem at the MARS node. Acoustically transmitted data records, each of 1 to 8 days duration, show that the oceanographic sensors were powered throughout the operational life of each BMFC and performed well (Fig. 3).

Both BMFCs took longer than initially expected to begin generating significant power. The intermittent data collection leaves a range of time for this occurrence, between 28 and 90 days for BMFC 1 and 28 - 91 days for BMFC 2 (Fig. 4). This delay in the onset of significant power production can likely be

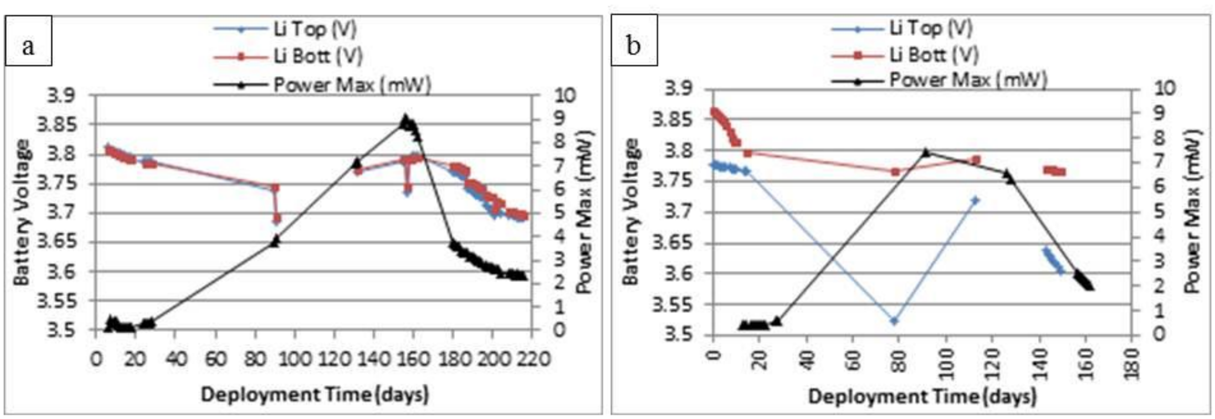

Figure 4. Maximum power generation and voltages of the Li-ion battery stack for BMFC 1 (a) and BMFC 2 (b).

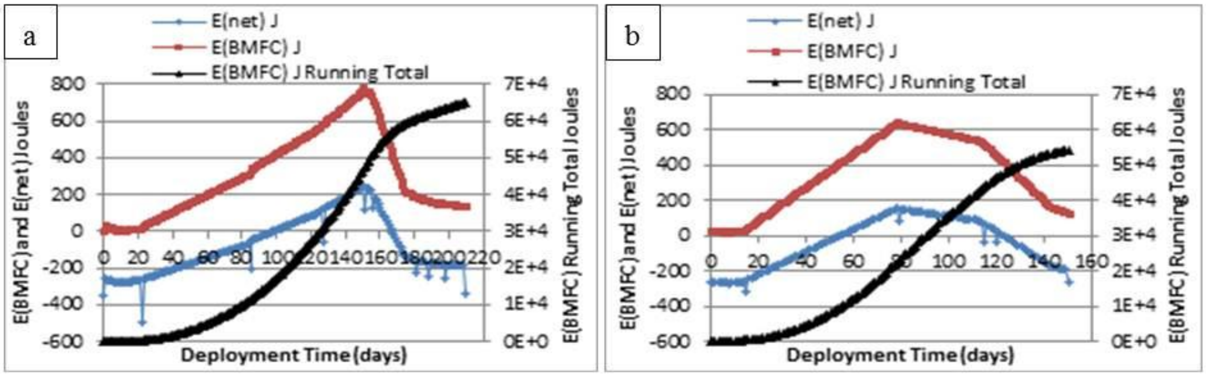

Figure 5. Energy budgets for BMFC 1 (a) and BMFC 2 (b) showing total energy produced, both daily and cumulative, and net energy produced daily after accounting for the energy consumed by the PMP, modem and sensor. Note that days with acoustic transmissions show dips in E(net).

attributed in large part to the increased chamber volume due to the compact clay deposit and the carbon poor sediments at the field sites. These poor site conditions also contributed to the shorter duration of maximum power production as power production tapered off significantly by day 180 for BMFC 1 and day 156 for BMFC 2. This level of energy generation was still sufficient to not only power the system and oceanographic sensors but to also maintain the voltage of the Li-ion battery stack in the PMP at or near a fully charged state of 3.8 V, the notable exception being the Top cell in BMFC 2 where the charge declined more rapidly. Post recovery analysis revealed that the Top Li-ion cell in BMFC 2 had failed.

The energy generated from each BMFC is plotted in Figure 5. E(BMFC) is the total energy produced, on either a daily or cumulative basis while E(net) is the energy remaining each day after factoring in efficiencies of the PMP, and energy requirements of the PMP, acoustic modem, sensors and monitoring. BMFC 1 began generating a net surplus of energy on day 98 continuing until day 166 and remained operational for 210 days. BMFC 2 yielded a net surplus more than a month earlier on day 54 and was operational for 158 days. The atypically long lag times are again attributed to the especially shallow penetration depth of the anode chamber and the carbon poor sediment, likely contributing to the shorter duration of BMFC operations as well.

While the total energy produced and the operational length of time were less than those from previous deployments of similar systems, the maximum power generated (<10 mW) yields a power density approaching 30 mW/m2 which is on the high end of values reported in the literature for typical deployments. These results are highly encouraging given the general inhospitable nature of the deployment site in terms of low temperatures, low bottom water oxygen concentrations (affecting BMFC cathode reactions), low organic carbon content, and the physical makeup of the sediment. Furthermore, the duration of the functional lifespan of the fuel cells may have been shortened artificially. BMFC 2 had a failing Li-ion cell in the PMP that may have terminated operations. Also, both systems, in an already low energy potential environment, had abnormally high energy burdens at times. The communication difficulties led to a greater number of attempts at data retrieval in short windows of time thereby depleting the available energy reserves of the PMP. It is possible that the PMP in each system was drained to a point where the system was forced to shut down even though energy was still being harvested by the fuel cells. Upon recovery, observations of the sediment layer within each BMFC showed it to be a dark brown/black color, significantly darker than the surrounding sediment. This is likely due to iron sulfide mineral precipitation under anoxic conditions indicating that the chamber maintained a reduced environment.

The PMP system will be overhauled and upgraded in future endeavors to improve efficiency, optimize data logging and include a fail safe mode to maintain operational viability in a low energy state or high energy demand situations. When future BMFC system demonstrations are planned, more attention will be given to predeployment site characterizations. Chambered BMFCs may also be preloaded with an internal layer of organic matter-enriched sediments to help prime and sustain environmental energy recovery.

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REFERENCES

[1] Reimers, C. E.; Tender, L. M.; Fertig, S.; Wang, W. Harvesting energy from the marine sediment-water interface. Environ. Sci. Technol. 2001, 35 (1), 192–195.

[2] Tender, L. M.; Reimers, C. E.; Stecher, H. A.; Holmes, D. E.; Bond, D. R.; Lowy, D. A.; Pilobello, K.; Fertig, S. J.; Lovley, D. R. Harnessing microbially generated power on the seafloor. Nat. Biotechnol. 2002, 20 (8), 821–825.

[3] Reimers, C. E.; Stecher, H. A., III; Westall, J. C.; Alleau, Y.; Howell, K. A.; Soule, L.; White, H. K.; Girguis, P. R. Substrate degradation kinetics, microbial diversity, and current efficiency of microbial fuel cells supplied with marine plankton. Appl. Environ. Microbiol. 2007, 73 (21), 7029–7040.

[4] D. R. Lovley, Bug juice: harvesting electricity with microorganismsl Nat. Rev. Microbiol., 2006, 4, 497–508.

[5] D. R. Bond and D. R. Lovley, Electricity production by Geobacter sulfurreducens attached to electrodes. Appl. Environ. Microbiol., 2003, 69, 1548–1555.

[6] D. E. Holmes, S. K. Chaudhuri, K. P. Nevin, T. Mehta, B. A. Methe, A. Liu, J. E. Ward, T. L. Woodard, J. Webster and D. R. Lovley, Microarray and genetic analysis of electron transfer to elecrodes in Geobacter sulfurreducens. Environ. Microbiol., 2006, 8, 1805–1815.

[7] G. Reguera, K. P. Nevin, J. S. Nicoll, S. F. Covalla, T. L. Woodard and D. R. Lovley, Biofilm and nanowire production leads to increased current in Geobacter sulfurreducens fuel cells. Appl. Environ. Microbiol., 2006, 72, 7345–7348.

[8] C. E. Reimers, L. M. Tender, S. Fertig and W. Wang, Harvesting energy from the marine sediment-water interface. Environ. Sci. Technol., 2001, 35, 192–195.

[9] L. M. Tender, C. E. Reimers, H. A. Stecher, D. E. Holmes, D. R. Bond, D. A. Lowy, K. Pilobello, S. J. Fertig and D. R. Lovley, Harvesting energy from the marine sediment-watre interface II Kinetic activity of anode materials. Nat. Biotechnol., 2002, 20, 821–825.

[10] D. R. Bond, D. E. Holmes, L. M. Tender and D. R. Lovley, Electrode-reducing microorganisms that harvest energy from marine sediments. Science, 2002, 295, 483–485.

[11] Tender, L.M.;Gray, S.A.;Groveman, E.; Lowy,D. A.; Kauffman, P.; Melhado, J.; Tyce, R. C.; Flynn, D.; Petrecca, R.; Dobarro, J. The first demonstration of a microbial fuel cell as a viable power supply: Powering a meteorological buoy. J. Power Sources 2008, 179 (2), 571–575.

[12] Nielsen, M. E.; Reimers, C. E.; Stecher, H. A. Enhanced power from chambered benthic microbial fuel cells. Environ. Sci. Technol. 2007, 41 (22), 7895–7900.

[13] Wotawa-Bergen, A. Q.; Chadwick, D. B.; Richter, K. E.; Tender, L. M.; Reimers, C. E.; Gong, Y. Operational testing of sediment-based microbial fuel cells in the San Diego Bay. In 2010 IEEE Oceans Conference Proceedings, 2010; pp 1_6.

[14] Nielsen, M. E.; Reimers, C. E.; White, H. K.; Sharma, S.; Girguis, P. R. Sustainable energy from deep ocean cold seeps. Energy Environ. Sci. 2008, 1 (5), 584–593.

[15] Donovan,C.;Dewan,A.;Heo,D.; Beyenal,H. Batteryless,wireless sensor powered by a sedimentmicrobial fuel cell. Environ. Sci.Technol. 2008, 42 (22), 8591–8596.

[16] http://www.mbari.org/mars/general/about_mars.html

[17] Gong, Y.; Radachowsky, S. E.; Wolf, M.; Neilsen, M. E.; Girguis, P. R.; Reimers, C. E. Benthic microbial fuel cell as direct power source for an acoustic modem and seawater oxygen/temperature sensor system. Environ. Sci.Technol. 2011, 45, 5047–5053.