Power Storage and Conversion from an Ocean Microbial Energy Source

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***Abstract*-Long term microbial energy is readily available in the ocean, both in sediment and the water column. Making this energy accessible in a useful way for modern electronics requires efficient power conversion and significant bulk energy storage. This paper describes methods based on both direct DC-DC conversion and bulk storage in capacitor banks before conversion.**

I. INTRODUCTION

Seafloor microbial fuel cells are devices designed to harness the energy of microbial metabolism in marine sediments. [4] [2] In principal, seafloor microbial fuel cells are a nearly infinite power source, as they rely on the oceanic carbon cycle to provide substrates for microbial metabolism. Microbial energy sources offer a distinct long-term advantage over galvanic sea-water batteries in that they are not consumed in the process of generating electricity. In addition to the aforementioned longevity, microbial fuel cells are likely to be more environmentally friendly, as they are typically constructed from inert materials such as graphite.

In marine sediments, microbial metabolic activity, namely respiration, produces a potential difference between the sediments and the overlying water, typically between 0.7Vdc and 0.8Vdc at open circuit. While the resulting potential affords one the opportunity to harness the energy from microbial metabolism with fuel cell electrodes, this potential is extremely low, and without further power management may not be as useful. Increasing the voltage by placing fuel cells in series (as is done with traditional alkaline batteries) is impractical because cells can not be isolated due to seawater's conductivity. To overcome the limitations inherent to seawater microbial fuel cells, we designed and developed several versions of low power DC-DC converters to boost voltage for use by more conventional devices.

In addition, we developed a system that is designed to collate the energy delivered by a microbial fuel cell for conversion to higher voltage. This second system was also designed to uncouple power delivery to DC-DC converters (and downstream devices) from microbial fuel cell energy production. This enables the system to be used as an intermediate energy source, e.g. to supply energy to a battery trickle-charging station.

We have demonstrated powering LEDs, buzzers and low-power optical detectors directly from these devices driven by seafloor microbial fuel cells. Applications for this technology include long-term low-power sensors as well as auxiliary energy supplied to various platforms, including cabled observatories, buoys and autonomous vehicles. The realms of applications of a power-managed microbial fuel cell range from basic oceanography to homeland security to land-based and emergency energy harvesting.

This paper presents a suite of methods for optimally extracting the energy from the microbial fuel cells based on experiments with laboratory systems. We discuss the development of voltage converters, present the measured efficiency of these converters and discuss how to optimize the efficiency for use with a microbial fuel cell. We discuss how a saltwater sediment system may be scaled to provide more power for more demanding applications.

II. MEASURING WHOLE CELL POTENTIAL UNDER LOAD

Using a dynamic load board and a suite of test instrumentation, it was possible to directly measure the whole cell voltage (WCV), the anode and cathode potentials relative to seawater as well as the current delivered under a constant load condition. This can be seen in Figure 1. By multiplying the WCV by the current delivered, it is possible to calculate the power delivered to a load.

$$P = VI \qquad \text{(Watts)} \qquad (1)$$

Integrating the delivered power over time calculates the energy extracted from the cell.

$$E = \int_0^t P\delta t \qquad \text{(Joules)} \qquad (2)$$

These calculations are shown graphically in Figures 2-4.

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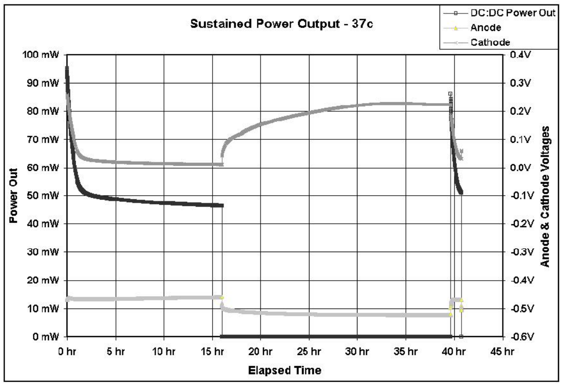

Fig. 1. The results of a sustained power output test, at room temperature, showing the sustainable power output, cathode limitation and required recovery time for the cell.

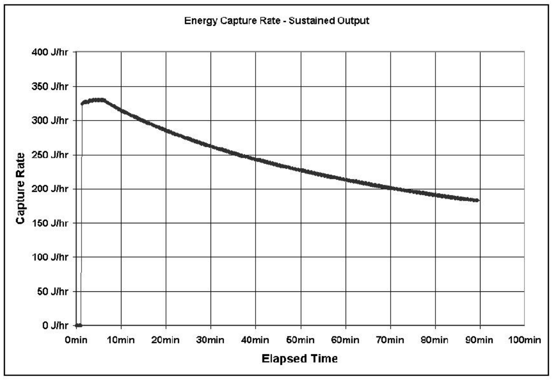

Fig. 3. The energy capture rate shows an upward trend over the first few minutes of the capture. This needs more investigation to determine why the rate increases before it decreases.

Several tests were conducted to ascertain the best electrical conditions under which to run the cell. The microbial fuel cell under test was constructed from four 48.3cm diameter by 1.3cm thick graphite plates wired in parallel and buried in marine sediment to act as the anode. The cathode floating in the water column above the sediment was composed of graphite fibers densely wrapped on a 2-m long titanium wire as has been described for seawater batteries. [11] The entire assembly was housed in a mobile plastic container so that it could be moved in and out of a chilled room at will. The test unit was supplied with a continuous supply of fresh seawater and an oxygen bubbler. The output of the fuel cell was connected to a dynamic load, and a data logger (Agilent 34970A; Agilent Technologies, Palo Alto, CA) logged the anode and cathode voltages relative to a silver-silver chloride electrode as well as the current. Tests were initially conducted over a period of hours.

Fig. 1. shows the results of a test conducted at room temperature. The changes in potential at both anode and cathode indicate that this particular fuel cell was cathode limited, and the sustainable power output was about 45mW. It is worth noting that the WCV under load was about $0.5V_{DC}$. One of the problems with running the cell in this sustained power output mode is the cell's recovery time. While the anode recovered fairly quickly, the cathode took over 10 hours to recover.

Further testing of the fuel cell involved repeated shorting of the cell into a large 60F supercapacitor followed by a recovery period and analyzing the charge curve (Figs. 2-4). Fig. 2 shows it was possible to deliver over 1W for a few seconds at about $0.5V_{DC}$. This testing also demonstrated that the cell could deliver over 90J in less than 3 minutes. Repeated testing under varying load conditions showed that power was maximized if the cell was run at a potential of $0.5V_{DC}$. One other interesting observation from these tests is that the energy delivery from the cell increased before decreasing (Fig. 3). We have no definite explanation for this behavior currently, but suspect electrode reaction kinetics are at play.

III. LOW-POWER DC-DC CONVERTER

Because the majority of modern electronics will not run at voltages less than 3.3Vdc, and many oceanic sensors are designed to run on voltages greater than 5Vdc, we developed a switching boost DC-DC converter that works at the low input voltage potential generated by the sediment fuel cells, ca. $0.5V_{DC}$. To optimize key components, several versions of this DC-DC converter were developed to run directly from the microbial cell. The primary DC-DC converter developed (Fig.

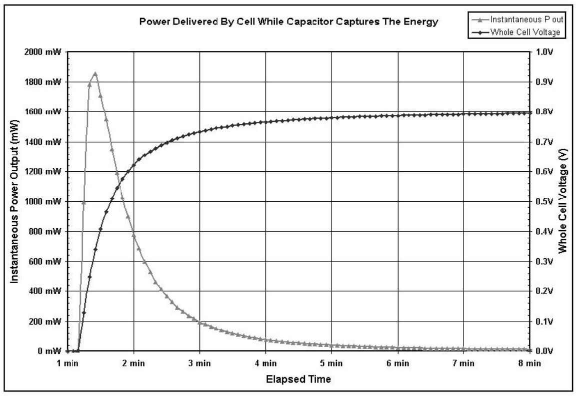

Fig. 2. The results of a test to capture energy from the cell directly by shorting a large capacitor directly across the cell's anode and cathode. It is possible to capture 90J from the cell within 3 minutes. This test was conducted with the cell at room temperature.

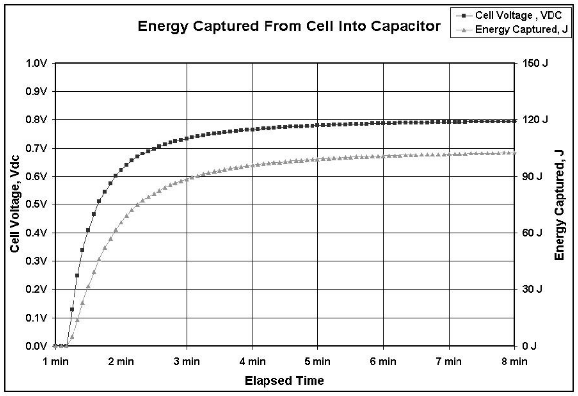

Fig. 4. Shows the power delivered by the cell during the same energy capture test. Note that it is possible to deliver over 1W momentarily while maintaining a whole-cell voltage of 0.5Vdc.

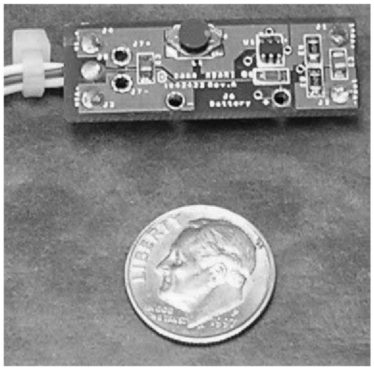

Fig. 5. The 1.5-5V DC-DC converter used to harvest power from a microbial cell.

5) can deliver between 1.5V and $5V_{DC}$ and another self-contained DC-DC converter, in a 9V battery form factor, can deliver $9V_{DC}$ (Fig. 8).

The first step in harnessing the energy generated from microbial fuel cells is basic voltage conversion of the output. After a survey of commercial datasheets, the first DC-DC converter built for this project was based on a Linear Technologies LTC3429 micropower boost converter. This MOSFET technology part was designed to run from a minimum voltage source of as low as 0.5V. Unfortunately, the efficiency of the power conversion suffers from running at such a low extreme, as shown in Fig. 7. The maximum measured efficiency while running at such a low input voltage was 55%. This converter was able to power a low-current LED directly from the laboratory sediment fuel cell.

IV. FUEL CELL TESTING AND SYSTEM OPTIMIZATION

It became apparent from the first testing with the DC-DC converter that the fuel cell, and overall system, would need to be optimized for use with such a converter. The least complicated way to increase the efficiency of the system was to boost the input voltage to the converter.

Fig. 6. A prototype supercapacitor array that can be charged by microbial fuel cells optimizes the energy conversion to a load.

Since the system's energy capacity could not be increased by creating a series string, we considered a parallel architecture. The parallel approach allows the system to increase its energy production by adding the current from the individual electrodes together but it does not raise the voltage.

Testing also indicated that the fuel cell output could be optimized by extracting the energy in short bursts that would allow the fuel cell to recover more quickly than a sustained energy draw. The extracted energy could be stored and delivered to a load via a system that would isolate the instantaneous needs of the load from the fuel cell.

V. ENERGY STORAGE AND DELIVERY BANK

In order to achieve an optimized system, a prototype switched storage bank was developed to store the generated energy. This prototype also isolated the fuel cell from the system load. It utilizes a method that allows a capacitor bank to charge in parallel then switch to a series configuration to provide a higher input voltage to the DC-DC converter.

The prototype contains two banks of 12 60F super capacitors. While one bank is being charged in parallel by the microbial fuel cell, the other bank has been switched in series and delivers the energy to the load. The two banks switch back and forth every few minutes. The output of the series bank is connected to the input of a DC-DC converter that can currently deliver power to a load at a potential of up to 9V.

VI. SECOND CELL CONSTRUCTION

A second laboratory fuel cell was constructed for demonstration purposes at the DARPATech conference in southern California. The system was designed to be self-contained, since there was no supply of fresh seawater

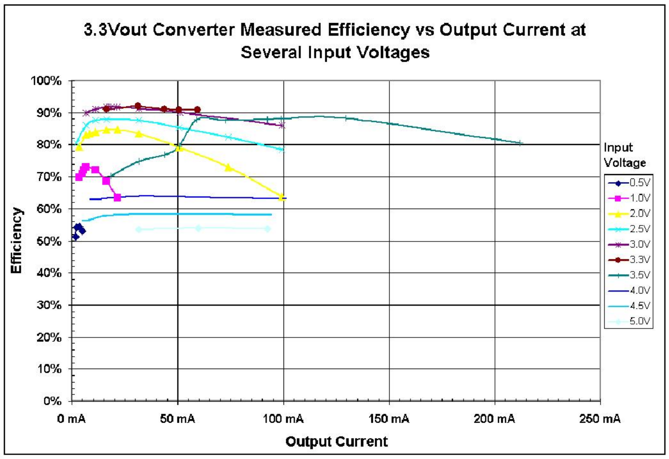

Fig. 7. This graph shows the measured efficiency of a 3.3Vconverter over a range of input voltages. The efficiency is inversely propotional to the output voltage, so a 5V converter would have a lower efficiency set of curves.

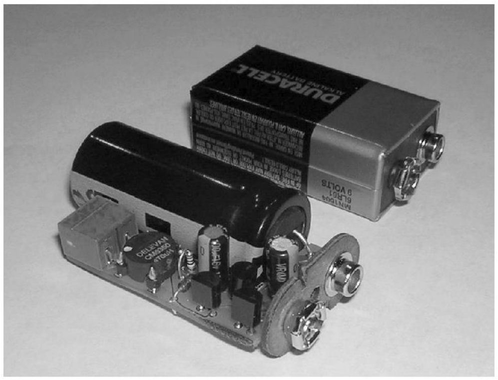

Fig. 8. A prototype supercapacitor based "battery" that can be charged directly from a microbial fuel cell.

available at the conference. Anoxic sediments were collected from a local estuary (Elkhorn Slough, Monterey County, CA). Both the anode and cathode were composed of four one meter-long titanium wire electrodes interwoven with graphite strands. The entire assembly was housed in a 100 liter acrylic aquarium. This cell is shown in Fig. 9.

VII. LABORATORY TESTING CHALLENGES

Building a microbial fuel cell of this nature that would work reliably in a non-seawater laboratory was a challenge. The fuel cell requires a separation of anoxic sediments from aerated seawater to function. The first unit was built in a seawater lab, and had ready access to a constant supply of cold oxygenated seawater. As such, we were able to maintain an anoxic sediment bed and oxygenated seawater by continuously flushing the microbial fuel cell with fresh seawater.

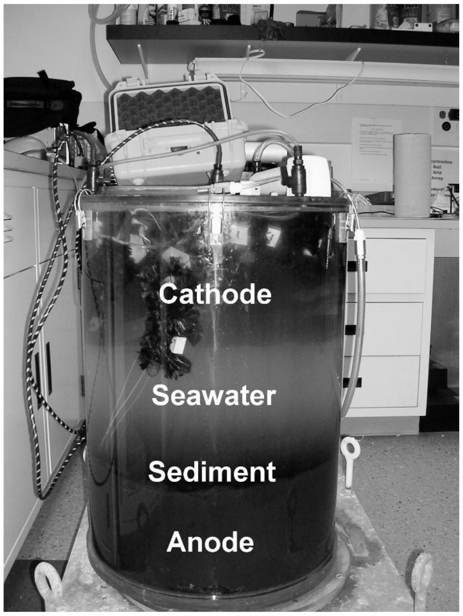

Fig. 9. The second microbial fuel cell being tested in the lab prior to being demonstrated at DARPATech

In the case of the second system, which was operated in a laboratory without flowing seawater, the aquarium water had to be reoxygenated using an aquarium bubbler. At first, the sediment released a significant amount of hydrogen sulfide, and it was difficult to keep the overlying water aerated (and as such the voltage potential between the electrodes fell). After several attempts to supply additional oxygen to counteract the effects of the sulfide, the system did stabilize and provide energy. However, its performance was noticeably degraded due to the lack of fresh seawater.

VIII. SELF-CONTAINED ENERGY STORAGE (9V DESIGN)

An application that quickly became apparent as a result of testing was the direct storage of generated energy into a portable energy source. The fuel cell is capable of directly charging a super capacitor, and the super capacitor can directly run a DC-DC converter. To test this concept, a 9V unit was built, shown in Fig. 8, based on an existing design, in the form of a 9V battery. [1] This integrated unit contained one 60F super capacitor and a simple integrated 9V DC-DC boost converter. While this form factor would allow the user to use microbially-generated energy to power commonly available devices, the form factor does not allow significant energy storage and would only be practical for extremely low-power applications.

IX. SCALABLE SOLUTION

The system is scalable by adding additional graphite cathodes and anodes in parallel. This parallel architecture increases the overall geometric surface area and current output of the system, but it does not increase the potential difference between the cathode and anode. Testing performed using the graphite-titanium electrodes showed that the electrodes could have just as well have been the shape of the outer dimensions of the electrodes and that higher small scale surface area, formed from the individual strands, didn't add to the overall

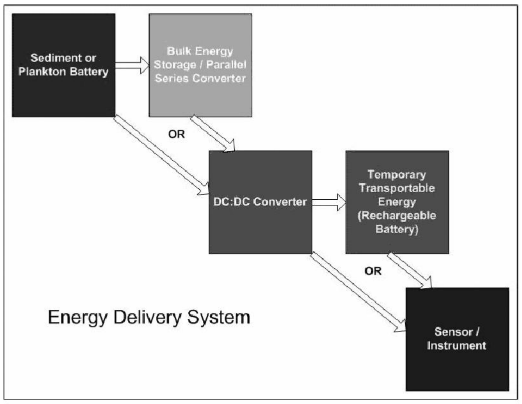

Fig. 10. Block diagram of the energy delivery system

energy output.

By adding parallel banks of capacitors to the energy storage system, shown in Fig. 10, it is possible to increase the intermediate energy storage capacity of the conversion system as well. It is possible to increase the voltage output of the capacitor storage bank by adding more capacitors to the series string. Adding more parallel banks of electrodes and capacitors would reduce the required sustained power delivery and allow the system to remain at a higher efficiency state since the recovery time for an individual electrode pair would be reduced.

X. IMMEDIATE APPLICATIONS

The seafloor fuel cells in this study powered several applications that were developed for use in the lab. They include an LED based illumination system, a binary light detector, and an acoustic buzzer. The system can also be scaled and packaged to deliver power to most any standard ocean sensor such as a CTD and low-power data logger without the addition of depletable metal anodes. Similar power conversion design efforts and applications were recently reported by Shantaram et. al. [10].

XI. CONCLUSIONS

Long term microbial energy is available in the ocean, both in sediment and the water column. The devices presented can be used to readily harvest that energy and apply it to sensor networks and communication devices. Microbial fuel cells are also under development that draw power from waste water and agricultural wastes. [13] Thus, there should be wide application for low voltage DC-DC power conversion technologies.

In our experimental fuel cells, sulfide was enriched in the sediments that came from a local eutrophic estuary. However, sediment microbial fuel cells deployed in nearly any marine sediment will generate power that can be harnessed and managed by the storage bank and power converters described here. It is also possible to scale such systems up (i.e. an array of microbial fuel cell over a larger footprint on the seafloor) to provide additional current for storage and conversion by these systems. Because microbial fuel cells may produce power for years - possibly decades- an integrated microbial fuel cell/power storage and management system may provide users an opportunity to deploy instruments in extremely remote locations (such as under polar ice caps) for remote sensing and monitoring, without the need for frequent servicing.

XII. ACKNOWLEDGEMENTS

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