Autonomous Device for Evaluating the Field Performance of Microbial Fuel Cells in Remote Areas

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The performance of sediment microbial fuel cells (SMFCs) in the field must be evaluated prior to their being relied on as a power source for sensor networks. Currently, the ability to perform such evaluation is limited. The goal of this work was to develop an autonomous, battery-powered, low-cost device (a remote sediment microbial fuel cell tester, or RSMFCT) that can evaluate the field performance of SMFCs charging capacitors in remote areas. The developed RSMFCT allows an SMFC to charge a capacitor between preset charge and discharge potentials and monitors anode and cathode potentials, capacitor potential, and temperature. The RSMFCT was tested at a remote location in the Hot Lake Research Natural Area, near Oroville, WA, USA and used to evaluate the optimum conditions for operating an SMFC. Using the recorded data, the average power and frequency of cycle were determined. We found that SMFCs deployed in Hot Lake operated optimally when charging a 5-F capacitor from 300 mV to 400 mV. Under these conditions, the SMFCs produced an average daily power of 10.28 μW and required an average capacitor charging time of 3.08 hours. We conclude that the RSMFCT is practical for: 1) determining the optimum operation parameters, those that maximize the power output of SMFCs in field operation, and 2) reliably incorporating individual SMFCs as power sources for remote sensor networks by allowing the prediction of their power output and frequency of charge cycles.

The work described by Dewan et al. required a set of experiments that took place over the course of several days. In addition, a computer was needed to control the charge and discharge potentials, and for data acquisition. This work was possible because the experiments were carried out in the Palouse River, which is located within the power grid of the city of Pullman, Washington, which allowed the researchers to run a computer for several days. In addition, the

Several studies have demonstrated that sediment microbial fuel cells (SMFCs) can be used to operate remote sensors in the field. 1–6 SMFCs provide cost-effective, long-term power for sensor networks monitoring changes in environmental conditions. SMFCs utilize natural microorganisms and in situ nutrients to convert chemical energy in organic compounds into useful electrical energy.7–9 Accordingly, SMFCs are especially attractive for long-term use because natural organic compounds are continuously renewed by natural processes and inert electrodes and electronic components have a long operation life. The drawback of using SMFCs is that the power generated using SMFCs is relatively low and cannot be used to power most electronic devices continuously.10,11 The power generated by an SMFC powering sensors varies between 3.4 and 36 mW.10 However, it is possible to obtain power on the order of hundreds of milliwatts by using large SMFC systems with footprint more than decades of square meters.12 Because of the limitations on SMFC scale-up, directly increasing the size of SMFC electrodes does not result in significant increases in power production.13,14 On the other hand, the power requirements for remote sensors vary between 10 μW and 85 W, and the sensors most commonly used for environmental monitoring require upwards of 50 mW.10,15 For example, Diamond et al. reported the power required for operating an electrochemical pH electrode is 50 mW.15 Moreover, a viable deployment strategy for environmental sensor networks requires using wireless communication devices to transmit data to a central network gateway, which increases the power requirement of the sensor networks.2,6 As a result, it is not currently feasible to use SMFCs to provide enough energy to power remote sensor networks continuously.

To alleviate these limitations, researchers have developed systems in which low continuous power from SMFCs is stored in a primary storage device, such as a capacitor or a rechargeable battery.16–19 The stored energy can then be discharged to provide short bursts of high power that is used to power sensors intermittently.20–22 In this scheme, an individual SMFC is allowed to charge a capacitor until a certain potential is reached (charge potential), and then the capacitor is discharged to a lower potential (discharge potential). The amount of power delivered when the capacitor is discharged and the frequency of the charging-discharging cycle depend on the SMFC power output, the capacitance, and the charge and discharge potential values selected by the user. To obtain higher power outputs, intermittent power can be scaled up by using several independent SMFCs. In one example, capacitors were connected in parallel while being charged using SMFCs and then were discharged in series to provide higher power.23 Alternatively, the energy output of electrically isolated SMFCs can be used to charge a secondary capacitor at a higher voltage using a DC/DC converter.24 The latter approach has been demonstrated to scale up the power output linearly as a function of the number of independent SMFCs used.24

Regardless of the strategy used for harvesting energy from SMFCs, successful implementation of SMFC-powered remote sensors requires the delivery of reliable and predictable power. Accordingly, designing reliable energy-harvesting circuitry will require prior knowledge of the performance parameters of the SMFCs. These parameters include which electrode (cathode or anode) is current-limiting, the optimum capacitance, the charge and discharge potentials that allow harvesting the maximum power from the SMFC, and the average frequency of a charge-discharge cycle under optimum conditions. Dewan et al. previously demonstrated that these parameters can be obtained by performing a series of charging-discharging experiments using a variety of capacitors, with a range of charge and discharge potentials for each capacitor value.25 They built a device in which the circuit logic control and data acquisition were performed using a computer and evaluated it in the laboratory and in the field.

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Sediment microbial fuel cell.—A schematic diagram of the SMFC deployment is shown in Figure 1A. The anodes were made of 4 inch × 4 inch carbon fabric (Panex 30 PW-06, Zoltek Companies Inc., St. Louis, MO) with a titanium wire (0.025-inch diameter, grade 2 annealed ASTM B863, Malin Co., Cleveland, OH) woven into the electrodes and soldered to an insulated copper wire. The cathodes were made of 11 inch × 9 inch × 0.25 inch graphite felt (HP Materials Solutions, Woodland Hills, CA) with a titanium wire woven through the graphite felt and soldered to an insulated copper wire. The graphite felt was wrapped around a plastic bottle (9-inch height, 3.5-inch diameter) partially filled with sand in order to keep it floating near the surface of the water. All soldered connections were thoroughly covered with marine sealant (5200, 3M, Maplewood, MN). The reference electrodes were Ag/AgCl manufactured in our laboratory according to previously published experimental protocols. The anode, cathode, and reference electrode were fixed into a PVC anchor that was driven into the sediment at the bottom of the lake for approximately 2 feet. Finally, the insulated copper wires (42 feet long) were used to connect the SMFC to the RSMFCT deployed on the shore of Hot Lake. The RSMFCT was placed in a sealed water resistant case to protect the circuitry against changes in environmental conditions (S1072, MTM Molded Products Company, Dayton, OH). Figure 1B shows the location of deployment of SMFCs 1–5 in Hot Lake and their connection to RSMFCTs 1–5 on the shore. Five SMFCs were deployed using different capacitor values (1, 5, 5, 10, and 350 F for SMFCs 1-5, respectively). All SMFCs were operated with a charge potential \( V_{c} = 500 \text{ mV} \) and a discharge potential \( V_{d} = 300 \text{ mV} \), with the exception of SMFC2 \( V_{c} = 400 \text{ mV} \), SMFC3 \( V_{c} = 500 \text{ mV} \), and SMFC4 \( V_{c} = 400 \text{ mV} \). These conditions were tested in order to demonstrate the utility of the RSMFCT for comparing the effects of different experimental conditions on the performance of SMFCs (i.e., capacitor value, charge, and discharge potentials). Since our goal was to develop the RSMFCT and test its utility, we limited the number of conditions tested. When needed, more RSMFCTs can be used for more sensitive optimization. The charge/discharge potentials and capacitor sizes were selected based on our previous experience in the field.

Remote sediment microbial fuel cell tester.—The RSMFCT consisted of a custom-designed electronic circuit, a capacitor, a microcontroller interfaced with configurable analog inputs and digital outputs, a temperature controller, a real-time clock, and a data logger. A block diagram illustrating the components of the RSMFCT is provided in Figure 2. The RSMFCT connected an SMFC to a capacitor through a custom-designed electronic circuit utilizing two n-channel metal oxide semiconductor field effect transistors (MOSFETs). This circuit
Figure 3. Complete circuit diagram of the RSMFCT and the power circuits connected to the MFC. The basic components are: 1) power supply board, 2) MFC connected through MFC connector, 3) temperature sensor, 4) two n-channel MOSFETS, 5) microcontroller board, 6) capacitor, 7) SD card data logger, and 8) real-time clock.

was functionally equivalent to the custom-designed circuit reported by Dewan et al.,25 with additional components added for power management and data collection to allow for remote operation. Briefly, the two MOSFETs acted as switches, allowing the SMFC to charge the capacitor until the charging potential was reached. Once the capacitor potential reached the charging potential, the MOSFET switches were activated, which isolated the SMFC from the capacitor and allowed the capacitor to be discharged through a load. The discharging stopped when the capacitor potential dropped to the discharge potential, which deactivated the MOSFETs and allowed the SMFC to charge the capacitor again. The MOSFETs used in RSMFCT have a source-drain resistance less than 115 mOhm (Fairchild semiconductors, FDN339AN and FDN338P). Thus, the effect of MOSFETs on power measurements is negligible. The full circuitry of the RSMFCT is shown in Figure 3.

The charge and discharge cycle was controlled through a programmable microcontroller interfaced with configurable analog inputs and digital outputs (Cypress Programmable System on Chip CY8C29466). The functions of the microcontroller were 1) to monitor the potentials of the anode and cathode compared to a reference electrode, 2) to monitor the potential across the capacitor, 3) to control the charge and discharge cycle by comparing the potential across the capacitor to preset charge potential and discharge potential values and activating or deactivating the MOSFET switches accordingly, and 4) to monitor the temperature reading from the temperature sensor. In order to reduce the power consumption, the microcontroller was set to sleep mode by default and was activated periodically based on a signal from a real-time clock (Maxim DS1337) and a preset data acquisition rate. The microcontroller was set to activate and record data once every 60 seconds. The data acquisition rate could be adjusted by the user to suit the requirements of the experiment. When the recorded capacitor potential increased above the preset charging potential value, the analog output of the microcontroller was used to activate the MOSFET switch, allowing the isolation of the SMFC from the capacitor and a discharge through the external load. The microcontroller was used similarly to reconnect the SMFC to the capacitor once the capacitor was discharged to below the preset discharge potential. The microcontroller sent the recorded data (time, anode and cathode potentials, capacitor potential, temperature, and number of discharge cycles) to a data logger (SparkFun OpenLog DEV-09530) which recorded the data on a secure digital (microSD) card. The RSMFCT was powered using four LR20 (alkaline D-cell) batteries.

Calculations of the average power, total energy harvested, and frequency of charging cycle.—The RSMFCT recorded the capacitor potential (V_{cap}) as a function of time. The power while the capacitor was charged was then calculated using Equation 1. The 1st order forward finite difference method was used to compute the derivative of capacitor potential as a function of time. The derivative of capacitor potential multiplied by the capacitance is equal to current. Large positive currents (above 1 mA) were filtered because they represent outliers of unrealistically high currents, and cause an overestimate
in the power calculations. In addition, large negative currents were filtered out because they represent the intermittent discharging of the capacitor through a load after reaching $V_c$. Large negative currents were defined as the current required for decreasing the capacitor potential more than twice the voltage resolution of the analog inputs (2 mV). Large positive and negative currents are filtered because these currents cannot be attributed to microbial respiration.

$$P = IV = CV_{cap} \frac{dV_{cap}}{dt}$$  \[1\]

The power is reported as the average power per cycle and the average daily power. The average power was calculated by averaging the power calculated using Equation 1 for each respective time period. Finally, the total energy harvested from the SMFC was calculated by numerically integrating the power calculated in Equation 1 with respect to time.

**Results and Discussion**

The deployed RSMFCTs were operated for 20 days, from August 20$^{th}$, 2013 to September 9$^{th}$, 2013. After the RSMFCTs were recovered, the data were used to compare the anode and cathode potentials, average power output and frequency of the charge cycle under the conditions tested. Example results for SMFC1 (a 5-F capacitor with a charge potential of 300 mV and a discharge potential of 400 mV) are provided in Figure 4, Figure 5, and Figure 6. A summary of the data comparing the performance of the five SMFCs is presented in Table I.

The anode, cathode, and capacitor potentials during a typical charging/discharging cycle are shown in Figure 4. The SMFCs started charging the capacitor immediately after deployment, which indicates the presence of anodic electroactive microorganisms in Hot Lake sediment. Initially, the SMFC was allowed to charge the capacitor until it reached the charge potential (400 mV). Once the charge capacitor reached the charge potential, the microprocessor activated the MOSFET circuit, which discharged the capacitor to the discharge potential (300 mV). The discharging of a 5-F capacitor from 400 mV to 300 mV releases 0.175 joules, which simulates the use of the energy stored in the capacitor to power a sensor or to charge a secondary energy storage unit. The energy produced during each charge cycle is theoretically sufficient to power a sensor requiring 11 mW and a telemetry unit [such as those used in Ref. 2] for a period of 7 seconds.

Figure 5 shows the average power generated during each charging cycle and the average daily power. The SMFC provided an average daily power of 10.28 μW, which remained relatively constant throughout the period of SMFC operation. The power generation of the SMFC followed a typical diel cycle oscillating between 5 and 17 μW. The oscillation of power generated by the SMFC is expected, because the metabolic activity of the microorganisms at the anode is dependent on the daily variations in natural parameters such as temperature, light, and substrate availability. Previous reports documented that Hot Lake conditions undergo daily cycles in redox potential caused by variations in light energy input and metabolic interactions among the microbial species associated with a well-developed benthic phototrophic mat. The large magnitude of daily oscillations of SMFC power suggests that the power generated is directly or indirectly coupled to the photosynthesis in the Hot Lake microbial mat or photosynthetic organisms in the overlying water column. The data set provided in Figure 5 illustrates that the RSMFCT provides enough temporal resolution for monitoring the transient daily changes in SMFC behavior, which are an important design parameter for the reliable use of SMFCs as a power source.

Figure 6 shows the data directly recorded using the RSMFCT over the period of SMFC1 operation. Figure 6A shows the anode and cathode potentials. The average cathode potential was $-15 \pm 12$ mV vs. Ag/AgCl, while the average anode potential was $-394 \pm 11$ mV vs. Ag/AgCl. The potentials of both anode and cathode varied during the charge cycle, indicating that either the anode or the cathode could be the current-limiting electrode. This observation is consistent across all five SMFCs tested. This result is unexpected, considering that the cathodes had significantly larger surface areas than the anodes. However, our results are consistent with the observation reported in a previous study that a 316L stainless steel cathode surface was current-limiting even though its surface area exceeded that of the graphite anode by more than 10-fold. In MFC systems, the cathodic oxygen reduction reaction is catalyzed by cathodic biofilms. The cathode limitation in this work could be attributed to a lack of cathodic microorganisms catalyzing the oxygen reduction reaction and to slow oxygen reduction kinetics on bare graphite electrodes. Alternatively, the reduced efficiency of SMFC cathodes could be due to the
presence of competing reactions on the cathode, such as the reduction of sulfate to sulfite. Indeed, the concentration of sulfate ions in Hot Lake increases significantly during the dry season, during which the RSMFTCs were deployed, for example, reaching approximately 1.8 mM on September 1 and October 20 of 2011. The presence of competing reactions on the cathode (such as sulfate reduction, which has a standard reduction potential of $-39 \text{ mV vs. Ag/AgCl}$) could also explain the relatively low cathode potential compared to similar SMFCs deployed in freshwater and ocean water sediments. We should note that sulfate reduction is possible in the presence of a thick biofilm in which the top layers consume oxygen and generate anoxic conditions for the sulfate reducers at the bottom of the biofilm.

Figure 6B shows the capacitor potential recorded using an RSMFCT with a 5-F capacitor which was charged between 300 and 400 mV. The average capacitor charging time was 3.08 hours. This period represents how often a sensor can be powered if the capacitor is used to power the sensor directly, without further power conditioning. When the capacitor was discharged, an event logger recorded a time stamp indicating the time at which the MOSFET circuit was activated. The cumulative number of discharge events is displayed in Figure 6C. This was used as a verification of the number of discharge events, to prevent false discharge counts if the potential of the capacitor dropped for reasons other than programmed discharge. The number of discharge events based on the capacitor potential data gave the same number of discharge events, which means that drops in capacitor potential happened only through activation of the discharging circuit. This agreement confirms the RSMFCT operated according to the design specification. Figure 6D shows the temperature recorded for the RSMFCT; it shows that the operation of the RSMFCT was not disturbed by changes in temperature (between 7°C and 44°C).

| Capacitor (F) | $V_c$ (mV) | $V_d$ (mV) | Cathode potential (mV vs. Ag/AgCl) | Anode potential (mV vs. Ag/AgCl) | Number of charge cycles | Average power ($\mu$W) | Average charge cycle time (hours) |
|--------------|------------|------------|-----------------------------------|----------------------------------|-----------------------|------------------------|-----------------------------|
| SMFC1        | 5          | 400        | 300                               | $-15 \pm 12$                     | $-394 \pm 11$         | 151                    | 10.28                       | 3.08                        |
| SMFC2        | 5          | 500        | 400                               | $61 \pm 15$                      | $-416 \pm 11$         | 18                     | 1.71                        | 25.67                       |
| SMFC3        | 1          | 500        | 300                               | $41 \pm 15$                      | $-429 \pm 19$         | 134                    | 4.22                        | 3.46                        |
| SMFC4        | 10         | 500        | 300                               | $60 \pm 35$                      | $-401 \pm 43$         | 9                      | 4.36                        | 50.78                       |
| SMFC5        | 350        | 500        | 300                               | $-10 \pm 41$                     | $-373 \pm 57$         | 0*                     | N/A                         | N/A                         |

*The MFC charged the capacitor from 0 to 459 mV, accumulating about 36.9 joules. The capacitor was not discharged because the capacitor potential did not reach the preset charging potential (500 mV).
Practical Application of the Remote Microbial Fuel Cell Tester

The performance of SMFCs in the field must be evaluated prior to using them as a reliable power source for sensor networks. While standard methods have been established for evaluating the performance of SMFCs in the laboratory, their implementation in remote areas off the grid is still a cumbersome and challenging task. Hence, there is a need for an autonomous, cost-effective, battery-powered device that can be used for evaluating the performance of SMFCs in the field without intervention from an operator.

If SMFCs are to be used as a power source at a remote location, two challenges must be overcome: 1) optimizing the power output of the SMFCs and 2) predicting the performance of the SMFCs over time. The first challenge, optimizing SMFC design to produce maximum power, involves performing a set of experiments in which the power output is measured as a function of controlled experimental parameters, such as electrode size and material. When intermittent energy harvesting is used, both capacitor size as well as charge and discharge potentials need to be optimized. Determining the optimum SMFC design parameters allows for utilizing the maximum power from the SMFCs. The second challenge is predicting the long-term behavior of SMFCs under optimized conditions. This must include evaluation of the range of power output and the frequency of charge-discharge cycles. Accurate characterization of this behavior will allow the design and reliable operation of sensor networks in which both the sensor power input and the operation frequency requirements are satisfied.

The purpose of the RSFMCT is to provide a solution to both challenges. When deploying a sensor network at a remote location, the RSFMCT can be used to evaluate the behavior of SMFCs at that location prior to the installation of the sensor network. In this initial phase, multiple SMFCs can be tested in order to determine the optimum operating conditions. Because of the low-cost, simple operation and short deployment time, a large number of SMFCs can be tested in a single deployment. After a period of time (e.g., a few months), the RMFCs can be recovered and the data analyzed. The optimum operating conditions can then be directly calculated by comparing the data from the RSFMCTs. In addition, the behavior of SMFCs under optimum conditions over that period of time can be characterized. With these data in hand, it will be feasible to deploy a sensor network in which both the power and operation frequency requirements are met using SMFCs.

The challenges of field experiments must be considered when RSFMCTs are used to evaluate the performance of SMFCs at remote locations. For example, two replicate SMFCs deployed in proximity to one another might not yield the same results because of the heterogeneity of sediment. Since deployment location affects SMFC performance, a researcher must run replicates of each condition and use the average performance to determine the optimum operating conditions of the SMFCs. Similarly, if access to the deployment site is limited or if the deployment site exhibits large seasonal fluctuations, it may be necessary to run all test conditions and replicates at the same time. In addition, testing the SMFCs must be performed for a long period of time to study the effect of seasonal variations on the power output. Depending on the range of conditions tested, running all experiments simultaneously might become cost-prohibitive. Hence, the uniqueness of each deployment site must be considered when SMFCs are considered as a power source at that site.

Conclusions

We developed and demonstrated the operation of an autonomous battery-powered device for testing the performance of sediment microbial fuel cells in the field. The device works by allowing a sediment microbial fuel cell to charge a capacitor until a preset charge potential is reached and then discharging the capacitor to a preset discharge potential. The device monitors and records the capacitor, anode and cathode potentials, as well as temperature with respect to time. Running a series of experiments under a range of conditions allows the user to determine the optimum conditions for harvesting power from sediment microbial fuel cells in the field. Once the optimum operation conditions are determined, the device can be used to evaluate the behavior of sediment microbial fuel cells under optimum conditions prior to their utilization as part of a reliable power source at a remote location. We conclude that:

- Under the conditions tested in this research, Hot Lake SMFCs produced a maximum power of 10.28 μW when charging a 5-F capacitor from 300 mV to 400 mV.
- It is feasible to use the data recorded to evaluate the average power and the frequency of the charge cycle. For example, a sediment microbial fuel cell charging a 5-F capacitor from 300 mV to 400 mV required an average capacitor charging time of 3.08 hours and produced an average power of 10.28 μW.

This device allows the optimization of sediment microbial fuel cells to produce the maximum power output in the field. The optimization process requires operating several sediment microbial fuel cells under a range of experimental conditions (e.g., electrode sizes, capacitor values, and charge and discharge potentials). For example, under the conditions tested in this work, a sediment microbial fuel cell charging a 5-F capacitor from 300 mV to 400 mV both produced the maximum average power and provided the highest charge cycle frequency.

List of Symbols

- C: Capacitance
- SMFC: Sediment microbial fuel cell
- V_{cap}: Capacitor potential
- V_c: Charge potential
- V_d: Discharge potential
- MOSFET: Metal oxide semiconductor field effect transistor
- RSMFC: Remote microbial fuel cell tester
- PMS: Power management system
- P: Power
- I: Current
- t: Time

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