Dirt = Power: An Intro to Microbial Fuel Cells (*Advanced*)

Microbial fuel cells (MFCs) are bio-electrical devices that harness the natural metabolisms of microbes to produce electrical power. Within the MFC, microbes munch up the sugars and other nutrients in their surrounding environment and release a portion of the energy contained within that food in the form of electricity.

Techy Box 1
MFCs employ bacteria to convert chemical energy of soil molecules into electricity directly, whereas other technologies (such as biodigesters) rely on an intermediate step of heat or gas.

Microbes are ubiquitous throughout virtually all soils, sediments, and streams on the planet. Among the diverse communities of microbes are particular species with unique metabolic abilities that enable them to expel electrons onto oxidized metal compounds, such as rust. 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 with different amounts of oxygen (see Figure 1).

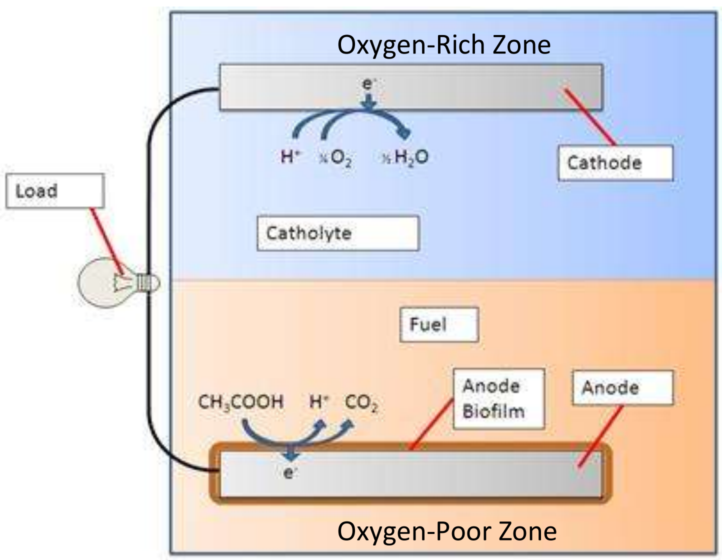
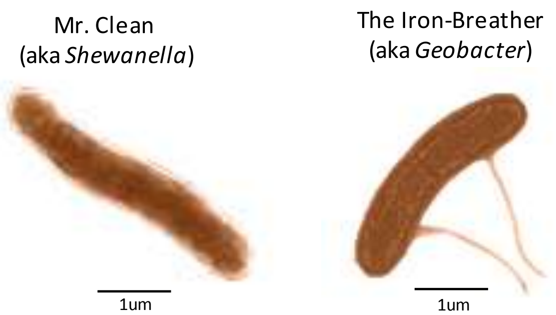


Figure 1. Basic MFC Composition

Techy Box 2
As described in the next Techy Box, the difference in oxygen concentration is what creates MFC's voltage, since the two electrodes are surrounded by environments with very different redox potentials.

Techy Box 3
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.

One electrode, called the anode, is placed in a nutrient-rich, but 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 (PEM), which is permeable to very small ions, such as protons, but not oxygen. If microbes are present within the anode chamber, a biofilm will spontaneously develop on the anode surface over time. Many MFC researchers inoculate this anodic media with pure cultures of particular species of electrogenic bacteria, such as *Shewanella* or *Geobacter*[i] which are described below in Figure 2. However, for MFCs utilizing natural media such as soils, sediments, or effluents, inoculation is not needed, since these electrogenic species are already abundantly present[ii].



Known for their versatility, *Shewanella* species can be found almost **everywhere** on earth, from mountain soils, to ocean sediments. They have an ability to metabolize a wide variety of elements that are toxic to humans, yet they don't cause disease in humans. They even have the ability to metabolize radioactive **Uranium**, precipitating it out of contaminated waters. These abilities make *Shewanella* an ideal bacterium for **bioremediation** processes.

Known as the **"iron-breather"**, *Geobacter* species have the ability to "inhale" iron compounds and use them in a way similar to the way humans use oxygen. In fact, they prefer to live in environments where there is no oxygen, such as deep underground or within ocean sediments. *Geobacter* species have the ability to consume many environmental pollutants, including **petroleum** and **Uranium**, and have been used in many soil and water **bioremediation** efforts.

Figure 2. Key Players in MFCs

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 (i.e. biomolecules with extra electrons attached to them). These biomolecules then donate their spare electrons to the anode in one of three ways, as diagramed below:

1) Direct transfer from the microbe's cell wall to the anode surface

2) Employing a secondary biomolecule to shuttle the electron to the anode

3) Transferring the electron through conductive appendages, termed "nanowires", grown by the microbe[iii]. These nanowires can form vast conductive networks, as is shown in Figure 4.

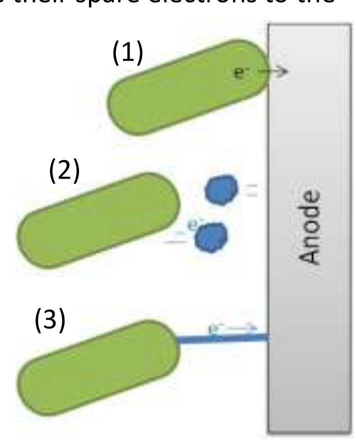


Figure 3 - Microbe-Anode Interaction

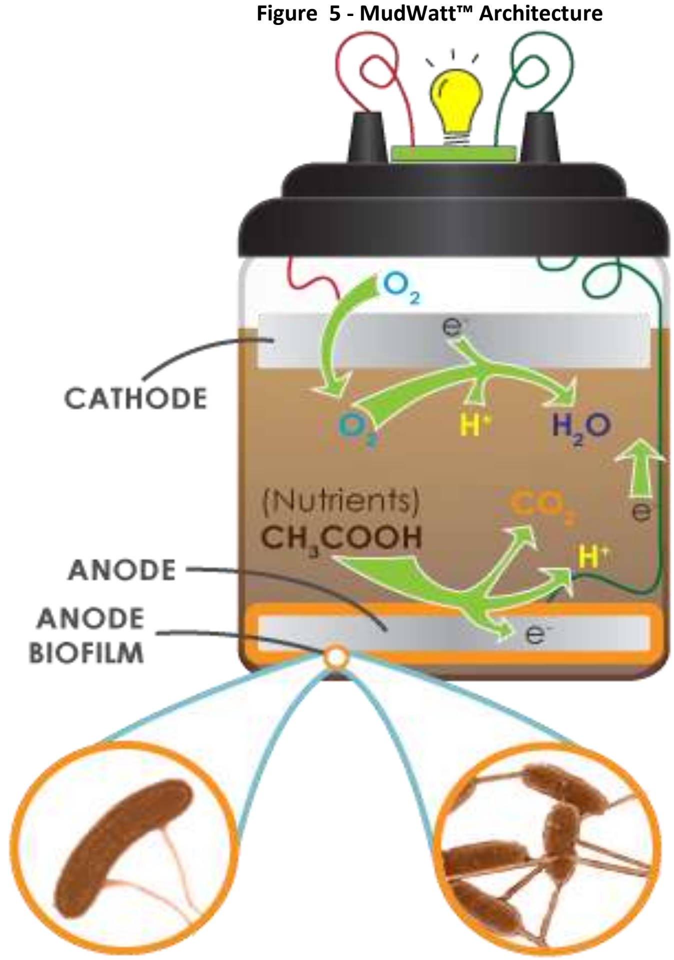
Figure 4 - A microbial community electrically connected by a vast network of nanowires

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 (as was seen in Figure 1). Thus electrical current is generated, from which one can extract power by simply placing a load (such as an LED light) between the two electrodes.

Power generation from an MFC is continuous so long as there are nutrients readily available within the anodic media. In open-system soil-based MFCs, nutrients are continuously replenished by the constant decay of fresh plant and animal material, which gives the MFC a theoretically indefinite lifespan.

MudWatt™ Microbial Fuel Cell Theory

Figure 5 - MudWatt™ Architecture



The MudWatt™ adheres to the same basic MFC principals as described above, whereby soil acts as the nutrient-rich anodic media, the inoculum, and the proton-exchange membrane (PEM). The anode is placed at a certain depth within the soil, while the cathode rests on top the soil and is exposed to the oxygen in the air above it (see Figure 5).

Soils are naturally teaming with a diverse consortium 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 plant and animal material decay. Moreover, the aerobic (oxygen consuming) microbes present in the soil act as an oxygen filter, much like the expensive PEM materials used in laboratory MFC systems, which cause the redox potential of the soil to decrease with greater depth. This is the cause of the voltage exhibited by the MudWatt™. The anode is placed at a depth at which this most negative redox potential exists, which varies depending on soil composition, but typically ranges from 2" to 6". The cathode, resting on top of the soil, is made of a porous carbon material which allows for the permeation of oxygen and enables the necessary chemical reaction to occur.

Techy Box 4
The redox potential of soils will typically level approximately -0.2V vs. SHE. Typical voltage potentials achieved in TMFCs are 0.2V to 0.6V vs. SHE for the cathode and -0.2V to 0.0V vs. SHE for the anode. The maximum recorded voltage from a MudWatt™ MFC has been 0. 92V from just soil.

Maximizing Performance: The Art of Potentiometry

MFCs generate maximum power when subjected to an external resistance that is equal to its own internal resistance. This internal resistance is a function of the ability of ions to diffuse through the MFC media from anode to cathode. The lower this internal resistance, the more power the MFC will produce. There are many ways to decrease this resistance, such as adding electrolytes (salts) to the media, and shortening the distance between the anode and cathode, while still ensuring that there is enough distance to achieve a suitable oxygen gradient. For more hints on how to minimize your internal resistance and maximize success with your MudWatt™ MFC, please visit our forum at www.keegotech.com/community.

To find the internal resistance of your MudWatt™, as well as its maximum power output, you will need to perform a technique called "potentiometry" (also referred to as a "sweep"). This involves reading the voltage output from your MFC over various resistances. For your convenience, your MudWatt™ electronics includes a series of 5 resistances that can be easily switched on and off. Instructions for performing a "sweep" are provided in your instruction pamphlet. Once you've performed a "sweep" on your MudWatt™ MFC, you will be able to generate a power curve, like the one shown to the right, by simply using Ohms law:

Figure 6 – Sample MFC Power Curve

$$P = \frac{V^2}{R}$$

P = Power (Watts)
V = Voltage (Volts)
R = Resistance (Ohms)

Experiment. Learn. Develop!

The MudWatt™ MFC was designed to give you free reign over what kind of fuel you use (though we recommend it be heavily soil-based for the reasons mentioned above) as well as the position of your electrodes. We encourage you to explore new ideas for minimizing the internal resistance and maximizing power of your MudWatt™ MFC. By sharing your construction information and power data with us, you will be taking your place in the Keego Community and taking part in a revolutionary international experiment run by citizen scientists like yourself from across the globe.

[i] Lovley, D.R. and Nevin, K.P. "Chapter 23: Electricity production with electricigens", In J. Wall et al. (ed.), Bioenergy, ASM Press, Washington, DC, 295-306 (2008).

[ii] White, H.K., Reimers, C.E., Cordes, E.E., Dilly, G.F., and Girguis, P.R., Quantitative population dynamics of microbial communities in plankton-fed microbial fuel cells: examining the relationship between power production, Geochem. and Microb. Ecol., International Society for Microbial Ecology, (2009).

[iii] Gorby, Y. A., Yanina, S., McLean, J. S., Rosso, K. M., Moyles, D., Dohnalkova, A., Beveridge, T. J., Chang, I. S., Kim, B. H., Kim, K. S., Culley, D. E., Reed, S. B., Romine, M. F., Saffarini, D. A., Hill, E. A., Shi, L., Elias, D. A., Kennedy, D. W., Pinchuk, G., Watanabe, K., Ishii, S., Logan, B., Nealson, K. H. and Fredrickson, J. K., "Electrically conductive bacterial nanowires produced by Shewanella oneidensis strain MR-1 and other microorganisms", Proceedings of the National Academy of Sciences of the United States of America 103(30), 11358-11363 (2006).