I. Introduction

In 1910, M. C. Potter first observed the ability of *E. coli* to produce electricity [1]. Ever since, scientists have studied the ability of microbes to produce electric potentials in depth, and have incorporated this phenomenon into the design of microbial fuel cells (MFCs), which take advantage of natural biological processes in the microbes to catalyze the conversion of chemical energy in organic fuels into electrical energy. Recently, the search for alternative forms of energy has brought renewed interest to MFCs.

A. *Benefits of MFCs*

MFCs offer many potential advantages over other means of localized power generation. In general, since fuel cells do not use combustion, their efficiencies are not limited by the Carnot cycle. The microorganisms in MFCs can derive energy from many different types of fuels [1], making them convenient for situations where refined fuels are not available. While the substrate molecules are oxidized via microbe metabolism as opposed to combustion, there are no harmful, partially oxidized byproducts such as carbon monoxide. Although different types of MFCs have been designed for various operating conditions, MFCs are generally operated at room temperature and neutral pH, so they can be employed where maintaining harsh conditions is impractical or undesirable, unlike many other types of fuel cells.

B. *Applications*

Many potential applications for microbial fuel cells have been described, and some have been implemented with varying degrees of success. Among these applications, methods of wastewater treatment have proven the most successful [1–3], and a small industry of startup companies has already begun efforts to scale up MFC wastewater management processes to municipal levels. MFCs have also been used to power networks of low-power sensors [1, 4]. In at least one case [3], a robot was powered by an MFC. This so-called *gastrobot* was fueled by sugar cubes fed to the MFC anode compartment.

Other attractive applications which have been proposed include MFCs for off-grid power, particularly for use in poor, rural communities. For example, researchers in India have developed an MFC for less than $1, made from commercially available, locally produced earthen pots, for use as a wastewater treatment and local power generation device [5]. The MFC gave a maximum power output of 70 W/m^3, and a Coulombic efficiency of 64.5%.

Groups have also begun proof-of-concept studies on the use of MFCs *in vivo* to power implanted medical devices such as pacemakers [6, 7]. While many types of bacteria can also produce

useful chemicals such as methane and hydrogen, the use of MFCs as sources of these chemicals has also been proposed [2].

C. Limitations, and how they may be addressed by students

There are still many limitations that impede MFC development for widespread, practical use. Many materials used in state-of-the-art MFCs can be costly, such as custom electrodes and proton exchange membranes. However, some researchers have shown that cheaper alternatives exist, depending on the applications [4, 5].

The types of microbes capable of generating a potential in an MFC are extremely diverse, and each has its own electrical and metabolic properties; full understanding of the electricity-generating processes for most microbial species is far away, and optimizing these processes is even further [8]. Most research has been focused on experimenting with different bacteria, mediator molecules, and electrode materials instead of looking directly to applications. A lack of standards between labs hinders their ability to compare results. While the highest power densities are around 4 W/m^2 [9], this remains too low to be a cost effective means of power generation for most applications. Although there has been success for some applications in the lab, no one has demonstrated scalability in any practical sense.

While the challenges are daunting, the possibilities for MFC technology are seemingly endless. Preliminary research has shown the potential of MFCs for multiple applications; the field now needs massive, parallelized streams of research to explore the possibilities of MFCs of different constructions and for different uses.

In the meantime, MFCs have already been used as fun, educational tools for young students and scientists. MFCs make good teaching tools because they can be approached from many angles; as an extremely interdisciplinary subject, the MFC provides strong lessons about many subjects and how they interface in one system. MFCs have been used by both hobbyists and research scientists. We should take advantage of this relationship, and mobilize students and hobbyists to help conquer challenges through parallel experimentation and development to solve the world's problems of waste management, localized power production, and so on.

In the following sections, we follow an outline of the operational principles of MFCs with discussion of a specific educational MFC lesson for high school students. We then discuss the application of concepts involved in this lesson to implantable MFC devices in order to translate the theory from the classroom into meaningful perspectives on applications research.

II. How MFCs work

MFCs use naturally occurring biological processes to convert the chemical energy in organic fuels into electrical energy. While the term *metabolism* is defined as the totality of an organism's chemical reactions [10], this term is widely used to refer specifically to an organism's accumulation and use of energy. Conceptually, metabolism can be divided into *catabolism*, the breakdown of complex chemicals to simpler ones in order to release energy, and *anabolism*, the formation of complex chemicals from simpler ones in order to store energy. Since fuel cells operate by breaking down fuel chemicals to release energy, we are concerned here with catabolism.

A general MFC schematic is shown in Fig. 1.

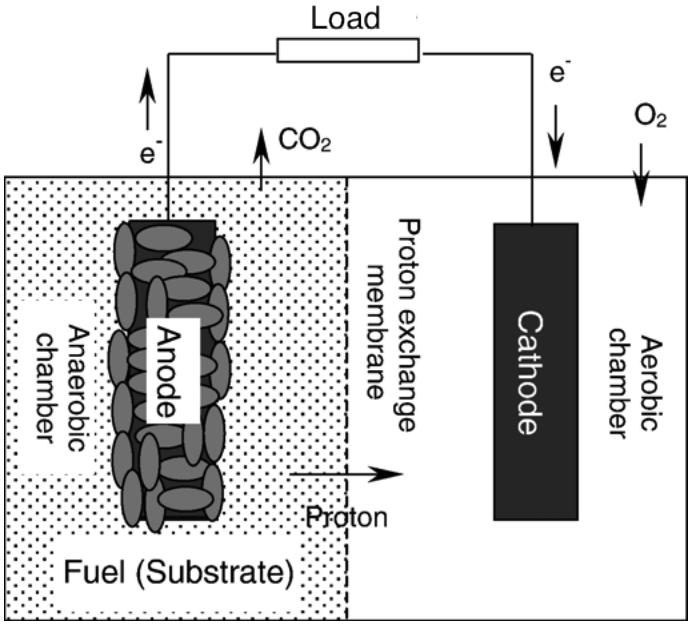

Figure 1: Schematic diagram of a typical two-chamber microbial fuel cell, adapted from [3]

In overview, microbes in MFCs break down fuel molecules via their natural catabolic chemical reaction pathways. While some of the energy released from these reactions is used by the organism to power its own functions, some of the energy can be harnessed by introducing electron-mediating chemicals into the culture. These electron-mediating chemicals reduce chemicals in the catabolic pathways, then diffuse from the cells and deliver electrons to the anode. Meanwhile, protons, another catabolic product, are released and diffuse through a cation-specific exchange membrane to react with electrons and oxygen to form water at the cathode. This ion separation gives rise to an electric potential across the anode and cathode, which is used to power a load.

The following subsections describe each of these steps in closer detail. The relevant project work uses *Saccharomyces cerevisiae*, a common species of yeast, as the microbe, methylene blue

as the electron mediator, potassium ferricyanide as a cathode catalyst, and glucose as the fuel. Therefore, MFC operation with these components will be explicitly outlined as an example.

A. Catabolism and electron transfer

The biological breakdown of complex chemicals in order to release energy is referred to as *catabolism*. During these reactions, the energy-rich fuel molecules are oxidized to simpler molecules. Oxygen has a high reduction potential of 0.82 V, so *aerobic* reactions, or those which require oxygen, tend to be highly favored during catabolism over *anaerobic* reactions, which can proceed without oxygen [11].

In order for power to be transferred to the fuel cell circuit, an intermediate oxidizing agent must be substituted in the anode chamber for oxygen. While oxygen acts as a final oxidizing agent in the cathode chamber, inserting an intermediate step into the overall oxidation of the fuel allows for some of the redox potential to be developed across the MFC electrodes. Many chemicals are capable of serving as this redox intermediate, and some are naturally produced by different kinds of bacteria when oxygen is not present [11]. Fig. 2 shows some of these chemicals in their oxidized and reduced forms, and where they fall in order of reduction potential; such a list of redox couples,

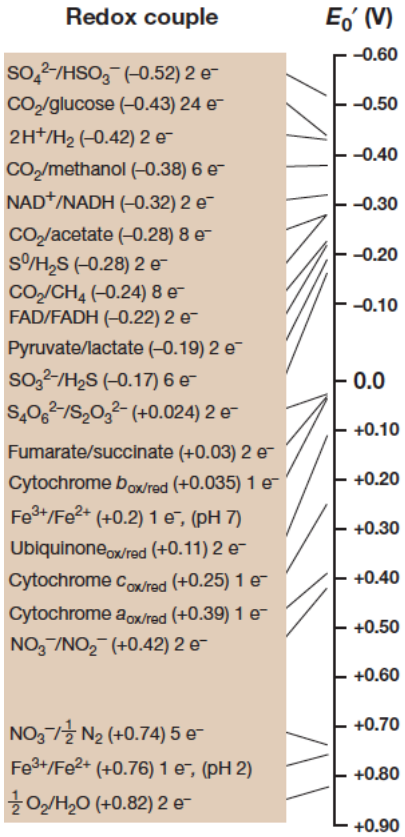

Figure 2: A redox tower lists redox couples in order of reduction potential [11].

ordered by reduction potential, is often referred to as a *redox tower*, and is analogous to vertical steps on a potential energy graph.

Canonically, the example fuel molecule most often discussed is glucose; glucose is a highly prevalent and important molecule, and many larger molecules, such as starches, are first broken down to glucose before they are degraded further. While catabolism of other types of food molecules may follow slightly different pathways, most catabolic pathways have highly conserved motifs. Conveniently, glucose also serves as the fuel molecule used in the relevant project work, which will be discussed later.

In *S. cerevisiae*, our example microbe, anaerobic catabolism of glucose proceeds according to the pathway shown in Fig. 3.

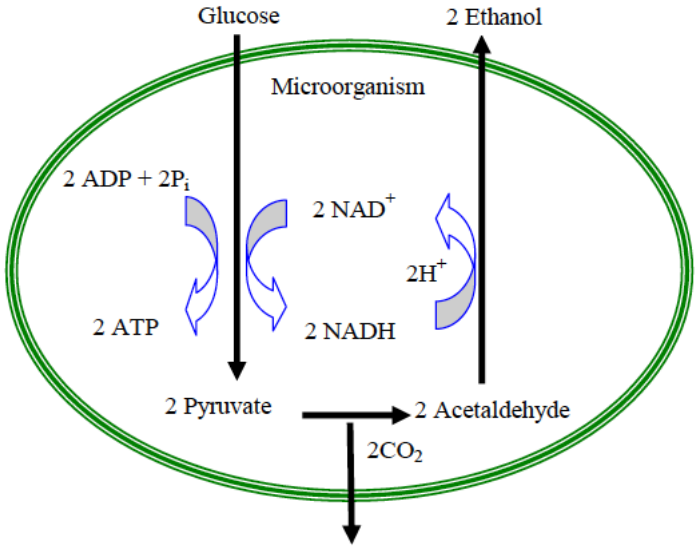

Figure 3: A simplified flow chart of anaerobic glucose catabolism in *S. cerevisiae* via fermentation [12].

Before catabolism begins, glucose diffuses into the cell. This transport is enabled by passive transport proteins, which specifically pass glucose through the cell membrane with a set permeability. In the first step of glucose catabolism, each glucose molecule undergoes *glycolysis*, or breakdown to two molecules of pyruvate while two molecules of adenosine diphosphate (ADP) are converted to two molecules of adenosine triphosphate (ATP), an energy storage molecule, and two molecules of nicotinamide adenine dinucleotide (NAD^+) are reduced to two molecules of NADH (simply referred to as reduced nicotinamide adenine dinucleotide), a different energy storage molecule. One molecule of carbon dioxide then separates from each molecule of pyruvate, forming acetaldehyde. While ATP is recycled to ADP when it is used to power the organism's other functions, NAD^+ is also required for glycolysis and must be recycled by a redox reaction. Therefore, NADH is oxidized by acetaldehyde to NAD^+, and acetaldehyde is reduced to ethanol.

When methylene blue is introduced to the *S. cerevisiae* culture, it plays the role of NADH oxidizer, obtaining two electrons as NADH is converted to NAD^+. Although it seems that this leaves acetaldehyde to accumulate, these reactions are very tightly regulated by other metabolic players, particularly with respect to NAD^+/NADH [13]. Since methylene blue presence inhibits the reduction of acetaldehyde to ethanol, pyruvate is processed along an alternate metabolic pathway. For example, pyruvate can react to form any of a large number of other molecules, such as alanine, aspartate, isoleucine, phenylpyruvate, or valine. The degree and timescale of waste molecule buildup, as well as the identity of any waste molecules, is an ongoing topic of research.

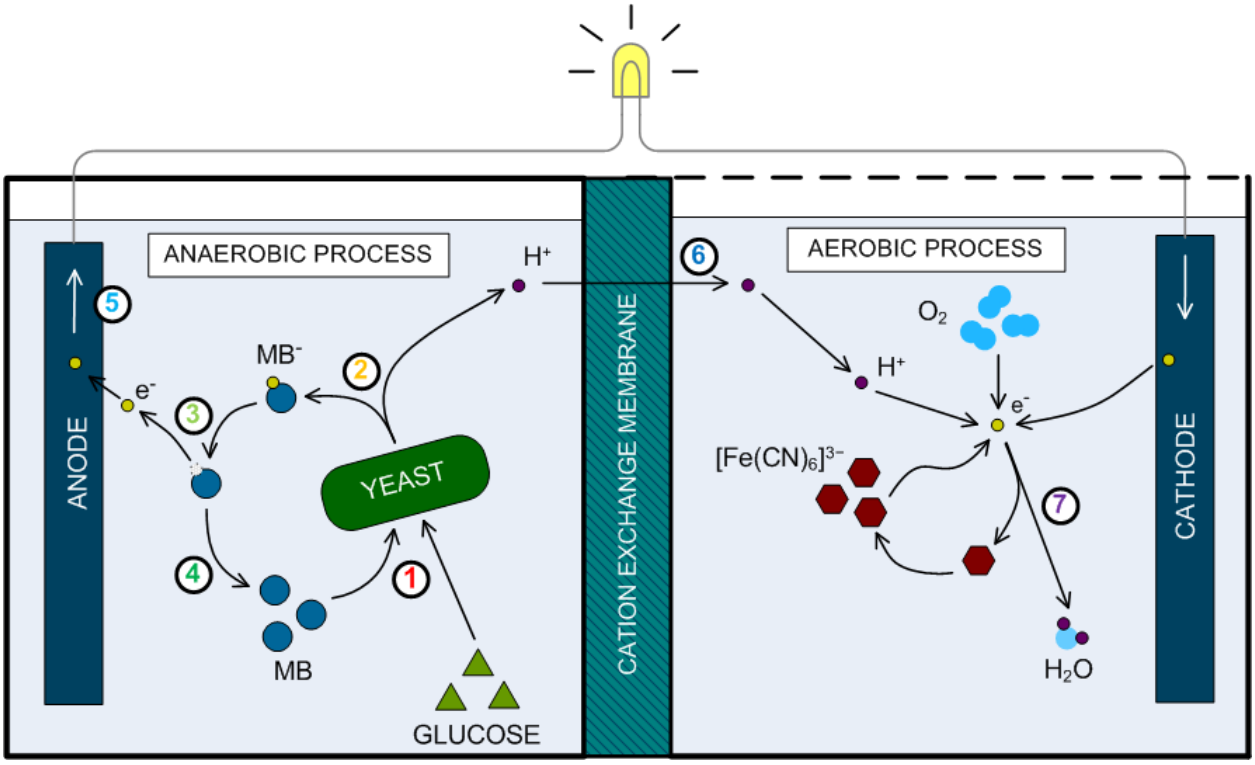

Figure 4: Diagram of MFC Processes. 1. The microbe takes in fuel (glucose) and the mediator molecule (methylene blue, MB), and digests the glucose. During this process, an electron (e^-) binds to the mediator molecule. 2. The microbe excretes the negatively-charged MB^- and a proton (H^+) into the surrounding fluid. 3. An electron is transfered from MB^- to the anode. 4. MB is recycled. 5. The electron traveles from the anode to the cathode across a load. 6. Meanwhile, a proton diffuses across the cation exchange memebrane to the cathode chamber. 7. The proton, oxygen, electron and ferricyanide ($[Fe(CN)_6]^{3+}$) react to form water. The ferricyanide is recycled.

B. Electron transfer

Much current research on MFCs focuses on determining more effective means of transferring electrons from within microbes to the anode [1–4,8,14]. While *S. cerevisiae* requires the addition of an electron-mediator molecule, certain strains of bacteria called *exoelectrogens* are capable of attaching directly to the anode and depositing electrons on the anode directly. While exoelectrogens have been shown to produce much higher power densities in MFCs than non-exoelectrogenic microbes,

we limit our discussion to the simple case of *S. cerevisiae* due to safety and cost restrictions for the applications to be discussed.

While the exact mechanisms of electron delivery by the reduced form of methylene blue onto different anode materials are unknown, the reactions incur measurable activation loss. While this loss is important, it is heavily outweighed by ohmic loss [13].

C. Proton exchange and cathode reactions

Protons, another catabolic product, are secreted by the microbes during MFC operation. The protons diffuse across a cation-specific membrane to the cathode chamber, where they react with oxygen and electrons to form water, completing the circuit.

Different types of materials may be used for the cation exchange membrane, though the most successful ones tend to be porous polymers with complex structure and charged functional groups, such as sulfate. Positive ions diffuse through the pores, finding local potential energy minima at the charged functional groups. In order to achieve efficient transport through the membrane, it must be well hydrated before hand.

Often, potassium ferricyanide is added to the cathode as a catalyst to prevent the partial reduction of oxygen to peroxide, which results in dramatic voltage loss [13].

D. Summary

To reiterate, we are focusing on a MFC with a *Saccharomyces cerevisiae*/methylene blue anode and a potassium ferricyanide/oxygen cathode. Fig. 4 concisely illustrates this model.

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