A study of the reported shortage phenomenon as a form of voltage reversal in microbial fuel cells

Stephen Taylor

sgtaylor@ucsc.edu

Abstract
Several different literature sources have reported a form of electrical shorting between microbial fuel cells stored in the same substrate, known as the shortage phenomenon. This presents some challenges to continued research of practical microbial fuel cell applications. If the reported shortage phenomenon actually exists, it would mean that microbial fuel cells cannot be placed in close proximity to one-another in the same substrate. We hypothesize however that the shortage phenomenon is a misdiagnosed form of voltage reversal, a common and well documented problem in microbial fuel cells. This research plan proposes incubating microbial fuel cells while carefully monitoring the potential of each electrode, in order to differentiate and identify voltage reversal vs the shortage phenomenon. The experiment shall observe three configurations: first shall be two cells connected in series but incubated in separate substrate, the next shall be another pair in series but incubated the same substrate, and finally the last configuration shall be two cells left unconnected and incubated the same substrate.

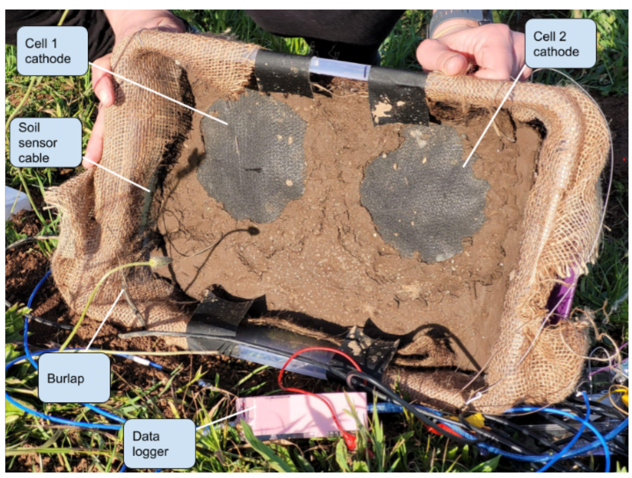

Figure 1: Two Soil Microbial Fuel Cells Deployed at Stanford University.

1 Introduction

As the demand for clean energy grows, continued research into microbial fuel cells (MFCs) has shown their value as a source of renewable energy for low power systems. MFCs are bioelectrocehmical systems that convert chemical energy to electrical energy. A unique family of bacteria known as exoelectrogens produce spare electrons as a natural byproduct of their respiration. In the wild, exoelctrogens offload these spare electrons to an external receptor, but if we put an anaerobic carbon-based electrode in the soil, and attach it to a resistive load and a cathode exposed to air, then the anode acts as an electron acceptor and a fuel cell is formed. MFCs could be an effective way to harvest energy for low-power applications where traditional techniques like solar may be difficult. Despite the potential wide-array of MFC applications, MFCs are still not widely adopted. This is in part due to the challenges presented by microbial fuel cell's low-power output. A microbial fuel cell's theoretical open-circuit voltage is 1.2V [6]. A potential solution to this challenge is to stack multiple MFCs in series or parallel to boost the total power. Unfortunately, there are two potential pitfalls to this approach: voltage reversal and shorting. Voltage reversal is when one under-performing microbial fuel cell in series reverses polarity, and the total voltage of the circuit decreases heavily as a result. Shorting is theorized to happen when two microbial fuel cells are connected in series in the same substrate, and the anode of one microbial fuel cell finds a current path along the electrolytes in the substrate to the cathode of another cell [6]. This would bring the potential difference between cells to zero.

However, the shortage phenomenon has not been adequately proven to be a short between the anode and the cathode of two cells. There have been several published papers discussing how when multiple microbial fuel cells were connected in series and stored in the same substrate, there was a significant decrease in the power output of each cell [7] . That does not prove a short occurred however, that simply proves that cells in series and in the same-substrate may under perform. This under-performance could just as easily be explained by voltage reversal, since the cells are in series.

The next step towards deploying microbial fuel cells in real-world applications is understanding their limitations. To that end, we need to determine whether or not the shortage phenomenon is actually occurring, and if so, successfully be able to diagnose when shortage is occurring and when voltage reversal is occurring.

We hypothesize that a number of the papers in the literature that discuss the shortage phenomenon may have conflated voltage reversal.

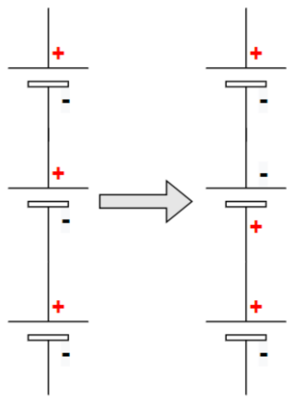

Figure 2: Voltage Reversal, the under-performing cell in the middle reverses polarity over time.

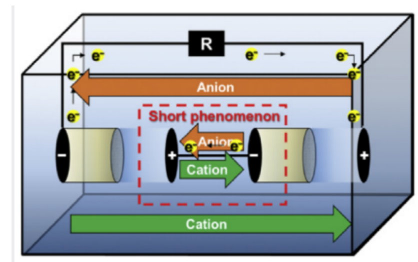

Figure 3: A diagram of two microbial fuel cells experiencing the Shortage Phenomenon as presented by Kim, Mohan, Fapyane and Chang. [6]

2 Background

Voltage reversal has been a recognized phenomenon since at least 2006, when Oh and Logan attribute the underperformance of a MFC stacked in series, and the cell's subsequent polarity reverse, to fuel starvation [11]. At it's core, voltage reversal arises from kinetic imbalances between the anode and the cathode of a particular cell stacked in series. In 2014, An and Lee identify that an overpotential across one cell, caused by a underperforming anode, will eventually result in voltage reversal [2][1]. It is important to keep in mind that voltage reversal can have severe consequences, such as bioanode corrosion [8] and can bring the stack voltage close to zero [2].

The shortage phenomenon on the other hand has been much less well documented. Some authors such as Ghadge and Ghangrekar [4] cite the shortage phenomenon as voltage reversal. Kim et. all on the other hand, identifies a decrease in stack voltage when the cells are connected by substrate and serial connection, and no potential drop when the stack is connected in series, or in the same substrate [7]. Other authors have undertaken similar experiments, and by mechanically connecting and disconnecting MFCs from each other in the same substrate and serial connections. Unfortunately this doesn't prove the existence of a phenomenon separate from voltage reversal, because under the same conditions voltage reversal could have occured. For the shortage phenomenon to be conclusively proven to be distinct from voltage reversal, it must occur under conditions in which voltage reversal could not, and must present electrical characteristics not yet documented in voltage reversal.

3 Hypothesis

Two microbial fuel cells placed in series can undergo voltage reversal regardless of whether they are in the same substrate. As postulated by Kim, Mohan, Fapyane and Chang [6], the shortage phenomenon occurs when the shared electrolytes in cells connected in series reduces the potential difference between the anode and the cathode to zero. We hypothesize the potential difference between the anodes and the cathodes connected in series will not go to zero, and is therefore not a short.

4 Methodology

The following steps will be repeated three times. This is because duplication of microbial fuel cells is necessary for accurate verification of results, and purchasing nine RocketLoggers is cost prohibitive. If running the experiment three times in a row turns out to be unfeasible in terms of time scale. Than 3 batches of microbial fuel cells will be prepared, and all batches will go through every step at the same time. With a RocketLogger being alternated between batch pairs. If full time monitoring is necessary, than the MFCs will be monitored using a Soil Power Sense Board[10] and ADC. *See Figure9*

Phase 1: Preparation and Incubation

1. Assemble 6 MFCs in their own individual substrate, roughly following jLabs MFC construction procedure [9]. Each group is further divided into pairs, such as pair AB. *See Figure 4*
   - All MFCs will be set in groups of two, and each MFC will be monitored by a RocketLogger
   - Each pair of MFCs will share a container, but not the same substrate. Each set of substrate will be separated by a sheet of acrylic
   - The substrate will consist of synthetic soil. Synthetic soil is soil mixed of exact percentages of lab grade sand, clay and silt in order to control for variables in the soil's properties, such as water

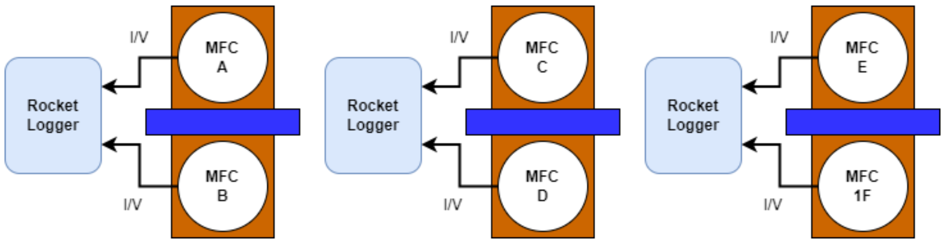

Figure 4: Six Microbial Fuel Cells Incubating, separated by a sheet of blue acrylic

retention. The substrate will be mixed with 30% clay, 30% sand and 40% silt to achieve clay loam [13]. Clay loam was chosen because of it's superior water retention to loamy, sandy and silty soils, and it's superior drainage to clay. Water will be added until the substrate reaches it's saturation point, which should be approximately 60% for clay loam [12].

- The containers will be covered with a plastic lid, but not sealed in order to retain moisture while still allowing some oxygen circulation.

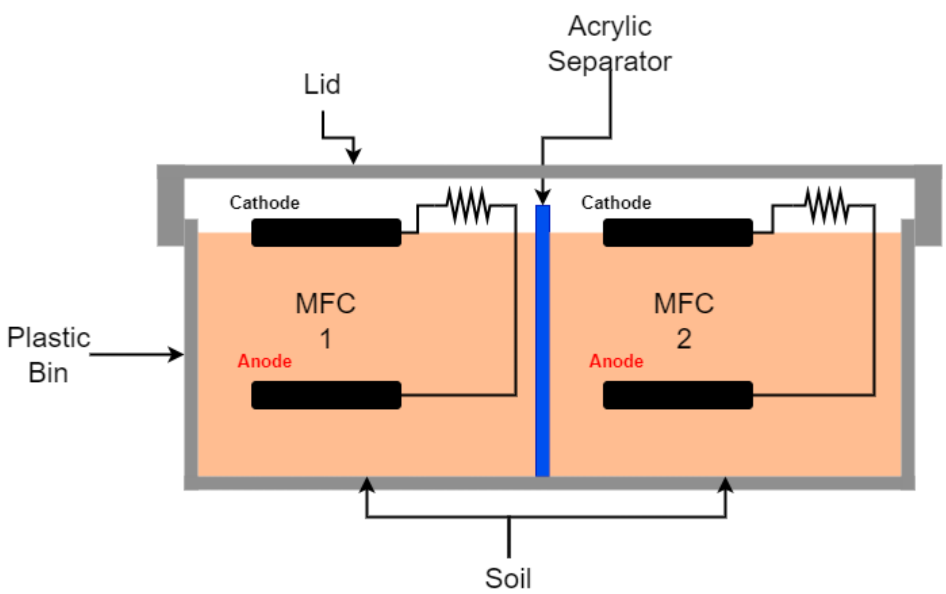

Figure 5: A set of two MFCs sharing a container. Each set of substrate will be separated by a removable acrylic plate.

2. Each MFC will be incubated for three weeks in it's own substrate
   - An MFC is considered "incubated" when it is producing an average of 150uW-hour of power over a 24 hour period, and does so consistently for at least a three day period.

Phase 2: Voltage Reversal and Shortage Phenomenon Detection

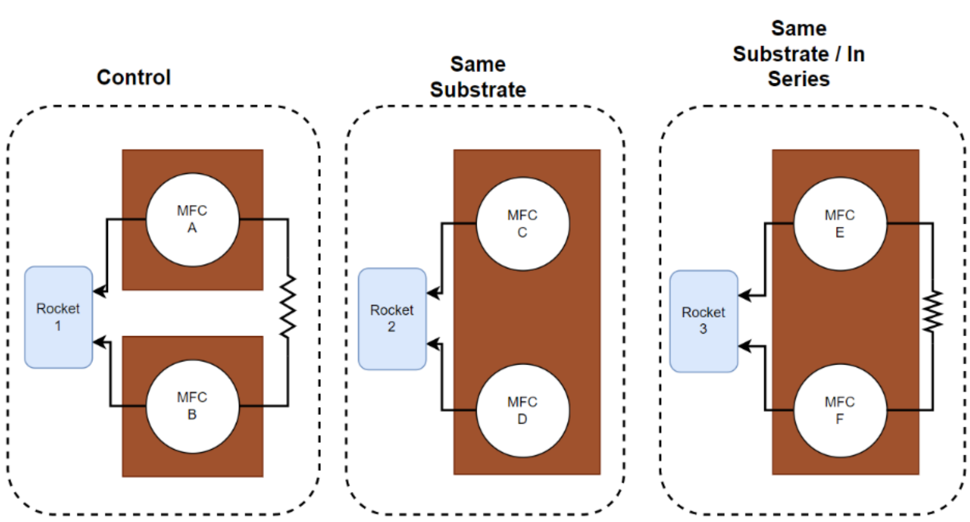

Figure 6: Microbial Fuel Cells Grouped for Testing, cells A and B are in series and separate substrates, B and C are in the same substrate and not in series and cells E and F are in series and the same substrate

1. Group the MFCs into sets of two for further testing *See Figure 6*
   - Connect A and B in series
   - Remove the acrylic separator between B and C

- Remove the acrylic separator between E and F[1] and connect them in series *See Figure 7*
- Reseal each container with it's plastic lid

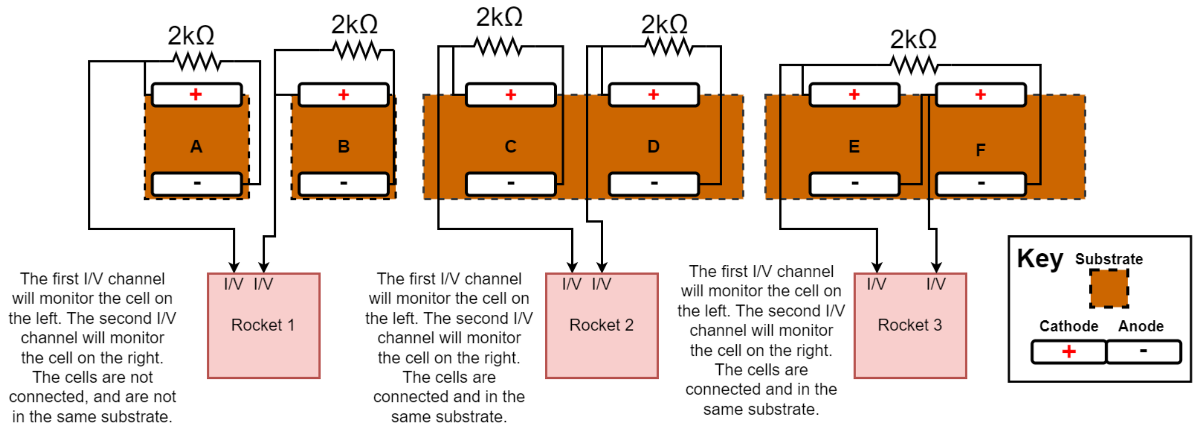

Figure 7: Testing Block Diagram

2. Every three days, to detect voltage reversal and or an instance of the shortage phenomenon each electrode will be measured against a BASi MF-2052 NaCl reference electrode, the procedure for using a reference electrode is detailed by Jaliff [5]. Reseal the cells with the plastic lid.

   - If there is a short, the potential difference between the anode and the cathode of the connected MFCs will go to zero
   - If there is voltage reversal, the electrode of one MFC will experience a large over-potential

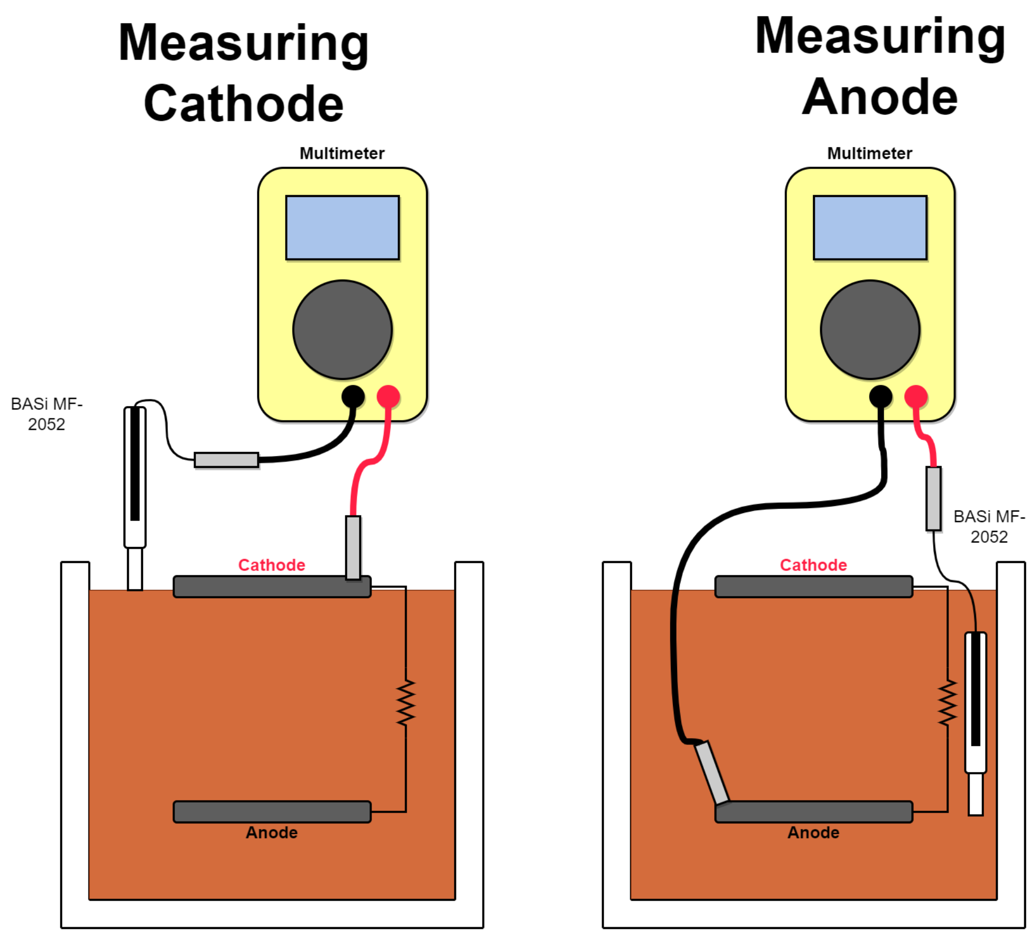

Figure 8: Reference Electrode Testing Setup

5 Timeline and Deliverables

Beginning March 10th, the MFCs will be assembled using synthetic soil. The cells will need to incubate for at least three weeks, or until we reach March 31st. During this incubation, the CSV files logged from the Rocketlogger will be stored on the team's shared google drive.

On April 3rd, the MFCs will be grouped as discussed in Phase 2, Step 1 at 9:00am. At 4:30pm, on the same day all electrodes will be tested using the NaCl reference electrodes. The results of said test will be stored on the team's google drive. The test will repeat twice a week in order to detect voltage reversal or the

[1]The removal of the acrylic may result in a rectangular hole in the soil, this will have to be manually filled in

shortage phenomenon. Preliminary dates are April 6th, April 10th, April 13th, April 17th and April 20th. If by March 30th no drop in stack voltage has occurred, or we have detected no shortage, we will attempt to induce voltage reversal by sabotaging a cell.

On April 28th, a 10 page research paper will be sent to the Journal of Power Sources and Journal of Power Sources Advances for publishing. It is estimated that it will take approximately 30 days, for the initial acceptance decision. In the interim period between we will be reviewing and editing the paper for submission into other conferences.

6 Potential Failure Points and Alternative Strategies

There are a few potential key points were the experimental plan could begin to breakdown, such as if a microbial fuel cell fails to incubate, or none of the microbial fuel cells undergo voltage reversal or the shortage phenomenon. In the case of a failed microbial fuel cell incubation, there are a few alternative strategies available, such as reusing a microbial fuel cell from an old experiment, or if the control group (cells A and B) successfully incubated, repurposing those cells for the same substrate or same substrate and in series groups.

If no cells experience any kind of drop in performance, voltage reversal could be attempted to be induced in a particular cell by removing a lid from a container to reduce moisture. Or a short could be induced by bringing the cells closer together within the same substrate.

Appendix

A NaCl Reference Electrode

An NaCl reference electrode is the most common type of reference electrode used, and the standard reference electrode used when measuring microbial fuel cells. A particular type of reference electrode may be used when it generates no potential in the system, and sodium chloride would not generate potential any within soil.

I intend to use the BASi MF-2052 NaCl reference electrode [3]. Along with the BASi CF-3000 NaCl solution and the MR-5275 storage vial. I will purchase three reference electrodes, two will be used for testing and the the third will be used for ensuring the integrity of the other two reference electrodes. This is because when using a reference electrode it is standard practice to verify it's continued functionality against a control electrode. This is because any contamination of a reference electrode will dramatically reduce it's accuracy. So before each measurement, the test electrode will be tested against the third control electrode.

B Synthetic Soil

The synthetic soil will consist of three different lab grades soil types, silt, clay and

C Alternative Monitoring Setups

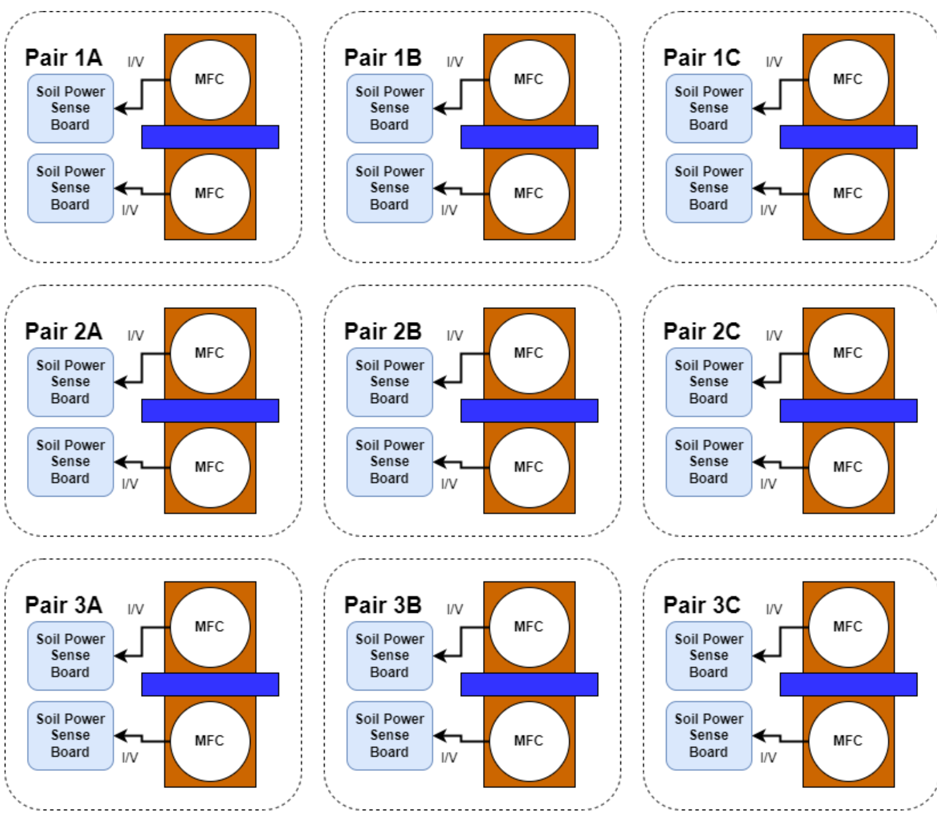

Figure 9: Eighteen Microbial Fuel Cells Incubating, separated by a sheet of blue acrylic

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