Using Microbial Fuel Cells in the High School Science Classroom

Lisa Swanson
Clarkston High School
Clarkston, WA

Jessica Schultz
Culdesac High School
Culdesac, ID

Washington State University Mentors
Dr. Haluk Beyenal
Chemical Engineering and Bioengineering
&
Hung Nguyen
Graduate Research Assistant

July, 2008
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project summary</td>
<td>3</td>
</tr>
<tr>
<td>Overview of project</td>
<td>3</td>
</tr>
<tr>
<td>Intended audience</td>
<td>3</td>
</tr>
<tr>
<td>Estimated duration</td>
<td>3</td>
</tr>
<tr>
<td>Introduction</td>
<td>4</td>
</tr>
<tr>
<td>Rationale for module</td>
<td>5</td>
</tr>
<tr>
<td>Science</td>
<td>5</td>
</tr>
<tr>
<td>Engineering</td>
<td>6</td>
</tr>
<tr>
<td>Goals</td>
<td>7</td>
</tr>
<tr>
<td>Activity #1</td>
<td>9</td>
</tr>
<tr>
<td>Activity #2</td>
<td>18</td>
</tr>
<tr>
<td>Activity #3</td>
<td>30</td>
</tr>
<tr>
<td>Activity #4</td>
<td>See separate file 31</td>
</tr>
<tr>
<td>Activity #5</td>
<td>38</td>
</tr>
<tr>
<td>Activity #6 (Final Project)</td>
<td>42</td>
</tr>
<tr>
<td>References</td>
<td>Appendix</td>
</tr>
</tbody>
</table>
PROJECT SUMMARY:

Overview of project

This module is designed to enhance interest in engineering amongst high school students through the design and experimentation of a microbial fuel cell (MFC). The reading material and lab activities provide opportunities to better understand microbiology, cellular respiration, material science, electricity and the principles of engineering. Further, the pre-project activities and the designing of a microbial fuel cell in the final project incorporate many of the essential academic learning requirements promoted by the Office of Superintendent of Public Instruction.

Intended audience.

Our intended audience is middle school and high school science students and teachers. Teachers and students with minimal background knowledge in microbiology, electricity and cellular respiration can perform these activities. The activities, and especially the design phase of this module can be modified to accommodate high school physics and vocational technology students. The background information and procedure contain all necessary information to teach this module. The equipment needed to conduct this module requires manufacturing prior to conducting the activity. Supplies will need to be ordered as some of the materials are not readily available.
**Estimated duration**

This module is intended to be completed in two weeks. This module is designed to build on each preceding activity beginning with an understanding of how cells undergo respiration and ending with how the energy potential of a cell can be utilized to operate an electrical device. The activity would culminate in the students constructing a MFC collecting data and analyzing data to determine which fuel cell generates the greatest amount of cell potential.

**Introduction**

This module is intended to engage students in hands on research endeavors surrounding microbial fuel cells and to promote enthusiasm and depth of content in high school science learning. As an introduction to microbial fuel cells and the ability of cells to produce electrical potential that can be used to power an electrical appliance, our module begins with an introduction to cellular respiration. Our module will build on the cellular processes and gives students the opportunity to test various materials and microorganisms for their ability to generate a cell potential. The materials that will be tested include the types of anodes and cathodes used, conductive wires, the type of yeast used as the microbe generating the cell potential and the nutrients provided to the yeast. The unit could be used in several different disciplines. The construction of the microbial fuel cell itself might be incorporated into a vocational classroom or a physics class. A biology class would use the MFC to supplement cellular metabolism and microbial functions. A physical science class or physics class could use the fuel cells to study materials and their ability to conduct cell potentials. A chemistry class would be able to use the
module to determine the chemical processes that are taking place within the yeast and the MFC. Each discipline would be able to manipulate the module to suit the needs of the particular class.

**Rational for Module**

The goal of this module is to increase student awareness to the field of engineering through the study of microbial fuel cells. This module will combine traditional content for many disciplines with cutting edge research to enhance student learning. The rationale for this module is to introduce students to the concept of cellular processes and how those processes can be used to build a structure that utilizes the cellular potential to operate an electrical devise that can conduct work. Cellular processes in themselves are not that exciting of a topic for most high school students. If the students can see that the processes cells us to make energy for themselves can actually be transferred to do work for us, the students may be more engaged in the learning of the topic. Students will be using engineering in that they will have various materials to use for the microbial fuels cells. They will need to determine which materials would work best and then apply scientific principles to determine if their predictions are correct. The beauty of this module is that it is flexible enough to allow for modifications to materials used and the number of experiments conducted. High school science classrooms need access to cutting edge research and the microbial fuel cell is that. Students will be able to learn about cellular processes, conductivity, cellular chemistry, material science, physics and engineering using this one module.
**Science**

The scientific basis for this module is the concept of capturing the electrons generated by microorganism and generating energy in a fuel cell. Microorganisms generate energy through different oxidation and reduction reactions. Chemical energy is converted to electrical energy during these reactions. By consuming organic substances, the microorganisms release electrons in the oxidation reactions. The idea behind the microbial fuel cell is to capture the free electrons on an anode and transfer the electron through a circuit to an electronic device, powering the device, and then onto the cathode side of the fuel cell. Oxygen is pumped into the cathode side of the fuel cell and accepts electrons. The protons generated from the oxidation reaction on the anode side of the fuel cell diffuse across a permeable membrane to the cathode side.

![Schematic diagram of MFC operation and components.](From Appendix 1)

**Figure 1.** Schematic diagram of MFC operation and components. (From Appendix 1)
Figure 2. Glucose oxidization by a microorganism in a MFC. (From Appendix 1)

Engineering

The idea for this module is to create an activity that compliments content already in the classroom while expanding students understanding of engineering. The final activity of this module is to design a microbial fuel cell that gives off the most cell potential for the greatest amount of time with available materials. This is essentially what engineers do on a daily basis. Take a simple concept and see what they can build out of it. In this module, the simple concept is cellular respiration. Students have to determine how they will construct a fuel cell that will provide the greatest amount of cell potential which in turn provides the greatest amount of electrical current.
Goals

By the end of this module the student will be able to:

- Construct a microbial fuel cell that generates a cell potential. (Application)
- Demonstrate and explain how various materials affect MFC performance. (Application)
- Define and understand redox reactions, the components of a MFC, current, cell potential, and other scientific terms. (Knowledge)
- Describe the impacts of nutrients on microorganism respiration. (Understanding)
- Students will compose a presentation to share their information and conclusions with an audience. (Synthesize)

Equipment

This information is contained within each activity.

Prerequisite student skills/knowledge

This information is contained within each activity of the module.

Procedure

This information is contained within each activity of the module.
Activity #1

(See Appendix 2)

Purpose/General Activity Information:

This activity is divided into two segments: how to use a multimeter and determining some good conducting and insulating materials. In the first part students are given a multimeter and some different batteries. Their objective is to learn how to measure current and voltage using a multimeter. In the second segment students use a battery connected to a multimeter and then measure the current by using different materials to connect the anode to the cathode of the battery; thereby, determining some good conductors/insulators.

Conclusions/Teacher Notes:

In Part 1 students should learn how to use a multimeter. They should learn the following:

- The black wire should ALWAYS be connected to the “COM”
- The other side of the black test probe should ALWAYS be connected to the negative (anode) side of the battery
- When measuring current:
  - The red wire should be connected to the “Ω”

Pencil, glass, aluminum foil, etc. will fill in the gap here
o The other side of the red test probe should be connected to the positive side of the battery (cathode). Students should be aware that they should only use the ones marked with == NOT ~

- When measuring voltage:
  o The red wire should be connected to the “V”
  o The other side of the red test probe should be connected to the positive side of the battery (cathode). Students should be aware that they should only use the ones marked with == NOT ~

In Part 2 students should learn about insulators and conductors. They should learn the following:

- Metals make better conductors than insulators
- Non-metals make better insulators than conductors
- Some metals are better conductors than others
- Some non-metals are better insulators than others

**Equipment:**

- Battery
- Multimeter
- Three wires with alligator clips
- Plastic pen
- Wood pencil
- Rubber eraser
- Graphite pencil lead
- Glass stirring rod
- Aluminum Wire
- Copper Wire
- Any other types of metal (copper strips, etc.)
- 12 V / 4 W light bulbs purchased at Home Depot (see picture)
**Prerequisite Skills:**

None

**Procedure:**

See activity handout

**Instructional Strategies:**

The teacher should observe students and help as needed keeping careful attention to student responses to the questions in the lab and that student duties are shared among group members.

**Data Collection:**

Students will fill in the questions as they follow the directions.

**Data Analysis:**

**Part 1 – How to use a multimeter:** Students will compare the voltage on the side of the battery with the voltage on their multimeter. They will then compare their current reading with the teacher’s result (can be shared on the overhead for each battery type).

**Part 2 – Conductors versus Insulators:** Students will utilize different materials and determine which materials are the best insulators and conductors.

**Evaluation Protocols:**

This is a formative assessment. The teacher should monitor student responses and help as needed. If vast issues arise then the teacher should model how to perform the sections where students are having issues. Students will not be able to understand later concepts if they are unable to use a multimeter or understand what good conductors and insulators are.

**Worksheet/Handout to be Given to Students:** (on next page)
ACTIVITY #1: USING A MULTIMETER

Purpose of Part 1:
To learn how to use a multimeter to measure things that a battery releases: voltage and current.

Materials/Equipment for Part 1:
- Multimeter
- 9 V battery
- Electrical tape (if needed)

Directions/Procedures for Part 1: How to use a multimeter

INSTRUCTIONS FOR MEASURING VOLTAGE:

1. **Black Test Probe:** Plug into the black terminal on multimeter marked “COM”
2. **Red Test Probe:** Plug the red probe into the red voltage socket marked “V” or “V/Ω”
3. Turn the dial to the V== segment. You may have several numbers to choose from (2, 20, or 200 for example). These are all voltage ranges. A maximum of 2 Volts, 20 volts, and 200 volts. Choose the one that fits the battery. Remember you are using a 9 Volt battery.
4. Take the black test probe and attach it to the negative (--) side of the battery

5. Take the red test probe and attach it to the positive (+) side of the battery

If you do not get a reading ask your teacher for help.

6. What voltage is the multimeter reading? ________________________________

7. Look at the voltage on the side of the battery. What is the voltage? ____________

8. What would cause the actual voltage to be less than the voltage reading on the side of the battery? ________________________________

9. If you were measuring the voltage of a AA battery what would you need to set the multimeter to? ________________________________

INSTRUCTIONS FOR MEASURING CURRENT

10. When you connect the probes do NOT leave them attached for more than 5 seconds. This draws energy from the battery.

11. Plug the **red test probe** into the Red “20A” socket. Current is measured in amps.

12. Turn the multimeter to the 20A == setting.
13. DO NOT turn to any of the amp setting that have this sign on it (~)

14. Take the black test probe and attach it to the negative (--) side of the battery

15. Take the red test probe and attach it to the positive (+) side of the battery.

16. What current are you reading on the multimeter? _____________________________

Check your answers with your teacher

17. _____True or False: To measure voltage of a battery the multimeter should be turned to V~.
   If false change the answer so it is true: _______________________________

18. _____True or False: To measure the current of a battery the multimeter should be turned to A~. If false change the answer so it is true: __________________________

19. Answer the following questions by checking the appropriate box:

<table>
<thead>
<tr>
<th></th>
<th>Black Test Probe</th>
<th>Red Test Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>This test probe plugs into the “V/Ω” socket.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>This test probe plugs into the A socket</td>
<td></td>
<td></td>
</tr>
<tr>
<td>This test probe is ALWAYS plugged into the “COM” socket</td>
<td></td>
<td></td>
</tr>
<tr>
<td>To measure voltage this test probe must be plugged into the V== socket</td>
<td></td>
<td></td>
</tr>
<tr>
<td>To measure current this test probe must be plugged into the 20A socket</td>
<td></td>
<td></td>
</tr>
<tr>
<td>This test probe touches the positive (+) side of the battery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>This test probe touches the negative (--) side of the battery</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Purpose for Part 2:

The purpose of this activity is to learn what good conductors are and what good insulators are. In addition, to give you some practice measuring voltage and current. Finally, to learn how to connect the wires from a battery to a light bulb (or other object) to power the devise.

Equipment/Materials for Part 2:

- Battery
- Multimeter
- Three wires with alligator clips
- Plastic pen
- Wood pencil
- Rubber eraser
- Graphite pencil lead
- Glass stirring rod
- Aluminum Wire
- Copper Wire
- Any other types of metal (copper strips, etc.)
- 12 V / 4 W light bulbs purchased at Home Depot (see picture)

Directions/Procedures for Part 2: Conductors versus Insulators:

A conductor allows energy to pass through it quickly. An insulator causes energy to pass through it slowly, if at all.

Construct a set-up like the diagram below:

Pencil, glass, aluminum foil, etc. will fill in the gap here
1. Put each item into the space between the battery and multimeter then fill in the table:

<table>
<thead>
<tr>
<th>Material</th>
<th>Description of Light Intensity</th>
<th>Voltage</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Wire</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper Wire</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass stirring rod</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graphite (pencil lead)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nail</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic Pen</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rubber eraser</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. What type of materials make good conductors? _________________________________

___________________________________________________________________________

___________________________________________________________________________

2. What type of materials make good insulators? ________________________________

___________________________________________________________________________

___________________________________________________________________________

3. Write the materials from your list in order from best conductor to best insulator in the space below:

Best Conductor:
Best Insulator:

4. Explain how you came up with the order for your “Best Conductor” – to – “Best Insulator” list: _______________________________________________________

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

5. Look at the intensity difference between the graphite and the nail.
   
   • Identify which object lights the object better
   • Explain why
Background Reading

Batteries are found nearly everywhere in our lives -- in our cars, our PCs, laptops, portable MP3 players and cell phones, to name a few uses. A battery is essentially a can full of chemicals that produce electrons. Chemical reactions that produce electrons are called electrochemical reactions. In this reading assignment, you'll learn all about batteries -- from the basic concept at work to the actual chemistry going on inside a battery to how they are used in our daily lives.

If you look at any battery, you'll notice that it has two terminals. One terminal is marked (+), or positive, while the other is marked (-), or negative. In an AA, C or D cell (normal flashlight batteries), the ends of the battery are the terminals. In a large car battery, there are two heavy lead posts that act as the terminals.
Electrons collect on the negative terminal of the battery. If you connect a wire between the negative and positive terminals, the electrons will flow from the negative to the positive terminal as fast as they can (and wear out the battery very quickly -- this also tends to be dangerous, especially with large batteries, so it is not something you want to be doing). Normally, you connect some type of load to the battery using the wire. The load might be something like a light bulb, a motor or an electronic circuit like a radio.

Inside the battery itself, a chemical reaction produces the electrons. The speed of electron production by this chemical reaction (the battery's internal resistance) controls how many electrons can flow between the terminals. Electrons flow from the battery into a wire, and must travel from the negative to the positive terminal for the chemical reaction to take place. That’s why a battery can sit on a shelf for a year and still have plenty of power -- unless electrons are flowing from the negative to the positive terminal, the chemical reaction does not take place. Once you connect a wire, the reaction starts.

Alessandro Volta developed the first battery in 1800. To create his battery, he made a stack by alternating layers of zinc, blotting paper soaked in salt water, and silver. This arrangement
was known as a **voltaic pile**. The top and bottom layers of the pile must be different metals, as shown. If you attach a wire to the top and bottom of the pile, you can measure a voltage and a current from the pile. The pile can be stacked as high as you like, and each layer will increase the voltage by a fixed amount.

The pile battery remained a laboratory curiosity for years, until the newly invented telegraph and telephone created a demand for reliable electrical power. After many years of experimentation, the "dry cell" battery was invented in the 1860s for use with the telegraph. The dry cell is not completely dry, however. It holds a moist paste inside a zinc container. The interaction of the paste and the zinc creates a source of electrons. A carbon rod is inserted into the paste and conducts electrons to the outside of the cell, where wires or metal contacts carry the electrons that power the device. A single dry cell produces about 1.5 volts.

**Experiments:**

If you want to learn about the electrochemical reactions used to create batteries, it is easy to do experiments at home to try out different combinations. To do these experiments accurately, you will want to purchase an inexpensive ($10 to $20) **volt-ohm meter** at the local electronics or hardware store. Make sure that the meter can read low **voltages** (in the 1-volt range) and low **currents** (in the 5- to 10-milliamp range). This way, you will be able to see exactly what your battery is doing.

You can **create your own voltaic pile** using coins and paper towels. Mix salt with water (as much salt as the water will hold) and soak the paper towel in this brine. Then create a pile by alternating pennies and nickels. See what kind of voltage and current the pile produces. Try a different number of layers and see what effect it has on voltage. Then try alternating pennies and
dimes and see what happens. Also try dimes and nickels. Other metals to try include aluminum foil and steel. Each metallic combination should produce a slightly different voltage.

Another simple experiment you can try involves a baby food jar (if you don't have a baby around the house, just purchase a few jars of baby food at the market and empty them out), a dilute acid, wire and nails. Fill the jar with lemon juice or vinegar (dilute acids) and place a nail and a piece of copper wire in the jar so that they are not touching. Try zinc-coated (galvanized) nails and plain iron nails. Then measure the voltage and current by attaching your voltmeter to the two pieces of metal. Replace the lemon juice with salt water, and try different coins and metals as well to see the effect on voltage and current.

Probably the simplest battery commercially made is called a **zinc/carbon battery**. By understanding the chemical reaction going on inside this battery, you can understand how batteries work in general.

Imagine that you have a jar of sulfuric acid (H2SO4). Stick a zinc rod in it, and the acid will immediately start to eat away at the zinc. You will see hydrogen gas bubbles forming on the zinc, and the rod and acid will start to heat up. Here's what is happening:

- The acid molecules break up into three ions: two H+ ions and one SO4-- ion.
- The zinc atoms on the surface of the zinc rod lose two electrons (2e-) to become Zn++ ions.
- The Zn++ ions combine with the SO4-- ion to create ZnSO4, which dissolves in the acid.
- Electrons from the zinc atoms combine with the hydrogen ions in the acid to create H2 molecules (hydrogen gas). We see the hydrogen gas as bubbles forming on the zinc rod.

**If you now stick a carbon rod in the acid, the acid does nothing to it. But if you connect a wire between the zinc rod and the carbon rod, two things change:**
• Electrons flow through the wire and combine with hydrogen on the carbon rod, so *hydrogen gas begins bubbling* off the carbon rod.

• Less energy is released as heat. You can power a light bulb or similar load using the electrons flowing through the wire, and you can measure a voltage and current in the wire. Some of the energy that was going into heat is now moving through the wire as electron flow.

  The electrons go to the trouble to move to the carbon rod because they find it easier to combine with hydrogen there. There is a characteristic voltage in the cell of 0.76 volts. Eventually, the zinc rod dissolves completely or the hydrogen ions in the acid get used up and the battery "dies."

**Battery Power and Uses:**

In any battery, the same sort of electrochemical reaction occurs so that electrons move from one pole to the other. The actual metals and electrolytes used control the *voltage* of the battery -- each different reaction has a characteristic voltage. For example, here's what happens in one cell of a car's *lead-acid battery*:

• The cell has one plate made of lead and another plate made of lead dioxide, with a strong sulfuric acid electrolyte in which the plates are immersed.

• Lead combines with SO₄ to create PbSO₄ plus one electron.

• Lead dioxide, hydrogen ions and SO₄ ions, plus electrons from the lead plate, create PbSO₄ and water on the lead dioxide plate.

• As the battery discharges, both plates build up PbSO₄ (lead sulfate), and water builds up in the acid. The characteristic voltage is about 2 volts per cell, so by combining six cells you get
a 12-volt battery.

A lead-acid battery has a nice feature -- the reaction is completely reversible. If you apply current to the battery at the right voltage, lead and lead dioxide form again on the plates so you can reuse the battery over and over. In a zinc-carbon battery, there is no easy way to reverse the reaction because there is no easy way to get hydrogen gas back into the electrolyte.

Modern batteries use a variety of chemicals to power their reactions. Typical battery chemistries include:

- **Zinc-carbon battery** - Also known as a standard carbon battery, zinc-carbon chemistry is used in all inexpensive AA, C and D dry-cell batteries. The electrodes are zinc and carbon, with an acidic paste between them that serves as the electrolyte.

- **Alkaline battery** - Used in common Duracell and Energizer batteries, the electrodes are zinc and manganese-oxide, with an alkaline electrolyte.

- **Lead-acid battery** - Used in automobiles, the electrodes are made of lead and lead-oxide with a strong acidic electrolyte (rechargeable).

- **Nickel-cadmium battery** - The electrodes are nickel-hydroxide and cadmium, with potassium-hydroxide as the electrolyte (rechargeable)

In almost any device that uses batteries, you do not use just one cell at a time. You normally group them together serially to form higher voltages, or in parallel to form higher currents. In a **serial arrangement**, the voltages add up. In a **parallel arrangement**, the currents add up. The following diagram shows these two arrangements:
The upper arrangement is called a parallel arrangement. If you assume that each cell produces 1.5 volts, then four batteries in parallel will also produce 1.5 volts, but the current supplied will be four times that of a single cell. The lower arrangement is called a serial arrangement. The four voltages add together to produce 6 volts.

Have you ever looked inside a normal 9-volt battery?
Manufacturers caution against disassembling batteries, to avoid personal injury. However, a partially disassembled 9-volt battery would look like this. It contains six, very small batteries producing 1.5 volts each in a **serial arrangement**!

Normally, when you buy a pack of batteries, the package will tell you the voltage and current rating for the battery. For example, a typical digital camera uses four nickel-cadmium batteries that are rated at 1.25 volts and 500 milliamp-hours for each cell. The milliamp-hour rating means, theoretically, that the cell can produce 500 milliamperes for one hour. You can slice and dice the milliamp-hour rating in lots of different ways. A 500 milliamp-hour battery could produce 5 milliamps for 100 hours, or 10 milliamps for 50 hours, or 25 milliamps for 20 hours, or (theoretically) 500 milliamps for 1 hour, or even 1,000 milliamps for 30 minutes.

However, batteries are not quite that linear. For one thing, all batteries have a **maximum current** they can produce -- a 500 milliamp-hour battery cannot produce 30,000 milliamps for 1 second, because there is no way for the battery's chemical reactions to happen that quickly. And at higher current levels, batteries can produce a lot of heat, which wastes some of their power. Also, many battery chemistries have longer or shorter than expected lives at very low current levels. But milliamp-hour ratings are somewhat linear over a normal range of use. Using the amp-hour rating, you can roughly estimate how long the battery will last under a given load.

If you arrange four of these 1.25-volt, 500 milliamp-hour batteries in a serial arrangement, you get 5 volts (1.25 x 4) at 500 milliamp-hours. If you arrange them in parallel, you get 1.25 volts at 2,000 (500 x 4) milliamp-hours.
Glossary:

- **Voltage**-
  - The difference in energy potential between two substances (i.e. zinc and copper) based on their ability to give up electrons.
  - The amount of electricity in the form of electrons passing through a substance (i.e. along a wire or cable). Measured in **volts**.

- **Current**- The rate of flow (speed) of electricity (electrons) through a substance (i.e. along a wire or cable). Measured in **amps**.

- **Ohm**- The measurement of **resistance** a substance has to electron (electricity) flow (insulators have greater resistance, higher ohms, to electron flow than conductors).

- **Conductivity**- How readily a material allows electrons (electricity) to pass through it.

- **Electrode**– Either of two posts by which electrons (electricity) enters or leaves a battery.

- **Anode**- Also known as the positive post. The post that, through chemical reactions, produces protons (H⁺). The protons will pass through the electrolyte to the negative post (opposites attract).

- **Cathode**- Also known as the negative post. The post where protons will combine with electrons.

- **Electrolyte**- The material the electrodes are contained in. The electrolyte allows the protons to pass to the cathode so as to complete the circuit.

- **Serial battery arrangement**- Connecting a series of batteries in such a way so as to increase the voltage output without increasing amperage. In a serial arrangement the negative post of one battery is connected to the positive post of the next battery.
• Parallel battery arrangement- Connecting a series of batteries in such a way so as to increase the amperage without increasing voltage. In a parallel arrangement the negative posts of the batteries are connected together as are the positive posts.

Key terms crossword follows as an assessment tool/review worksheet.
Across

2. measurement of resistance a substance has to electron (electricity) flow.
5. collect on this terminal of the battery.
8. difference in energy potential between two substances (i.e. zinc and copper) based on their ability to give up electrons.
10. that have a greater resistance.
15. material that allows the protons to pass to the cathode.
16. rate of flow (speed) of electricity (electrons) through a substance.

Down

1. stacks of zinc, saltwater soaked paper, and silver that generates a voltage.
3. type of battery arrangement the currents add up.
4. Speed of electron production by the chemical reaction within the battery.
6. that have a lower resistance.
7. type of battery arrangement the voltages add up.
9. like a flashlight, radio or cell phone that you connect to the battery.
11. of battery used in automobiles.
12. of battery like Duracell or Energizer, used in flashlights.
13. chemical reaction that produces electrons.
14. positive post on a battery.
Activity #3

Power point presentation introducing cellular respiration and microbial fuel cells

Purpose

The purpose of this activity is to introduce students to cellular respiration and how we use cellular respiration to generate energy in a microbial fuel cell.

Prerequisite Knowledge

Students should have an understanding of energy and how energy transfers through a system.

Instructional Strategies

The teacher should familiarize themselves with the background information in Appendix 1 in order to understand Microbial Fuel Cells and their operation. While presenting the PowerPoint Presentation, student should take notes on cellular respiration and MFCs.

See attached PowerPoint File
Activity #4 Assembling the MFC

(Adapted from Appendix 1)

Purpose

The purpose of this activity is to assemble the MFC.

Prerequisite Knowledge

Students should have a basic understanding of microbial fuel cells and their components.

Instructional Strategies:

The teacher should observe students and help as needed. Each member of the group should participate in the assembly of the MFC, whether it be handing various components to the assembler or reading the procedure to the assembler.

Data Collection:

None needed for this activity.

Data Analysis:

None

Evaluation Protocols:

The teacher should evaluate the group members on their cooperative efforts in assembling the fuel cell. The assembled fuel cell could also be an evaluation component. Questions regarding fuel cell components follow as a handout to students.

Worksheet/Handout to be Given to Students: (on next page)


**Equipment for MFC**

**Components of a MFC**

(a) **Anode and cathode compartments.** The holes at the top are used to insert electrodes or to make electrical connections to electrodes in addition to inserting a reference electrode.

(b) **Anode and cathode cover plates.** The anode and the cathode compartments and the cover plates are fabricated from polycarbonate. The working volume of each chamber is approximately 100 mL.

(c) **Cation exchange membrane (C-7000).** The anode and the cathode are separated by this cation exchange membrane.

(d) **Graphite electrode.** Graphite is used due to its inert structure. We use graphite as both anode and cathode.

(e) **Air electrode.** An air cathode composed of Pt wire mesh and coated with carbon powder is used. The choice of cathode material depends on the oxidizing agent used for the cathodic reaction. When oxygen is used as an electron acceptor, carbon materials are used with Pt or Ni catalysts because plain carbon gives a high kinetic limitation.

(f) **Rubber gasket.** A minimum of four gaskets are required for sealing one MFC.
(g) **Bolts and wing nuts.** Ensure that the structural hardware used to assemble the MFC is 316L stainless steel. We use 316L stainless steel due to its resistance to corrosion. During the experiments these parts will be wet. If we use a lower grade of stainless steel it corrodes easily.

(h) **Silicon adhesives.** Silicon adhesives are used to seal any unused ports on the MFC.

(i) **Conductive epoxy.** Conductive epoxy is used to secure electrical connections between wires and electrodes.

(j) **Fittings.** The fittings are used to connect silicon tubes to the inlet and outlet.

(k) **Barbed tube connectors.** These are used to connect two silicon tubes.

(l) **Saturated calomel electrode (SCE).** We use this as a reference electrode.

Figure 3 List of parts used to assemble a MFC  (From Appendix 1)
Equipment for operation and maintenance of MFC

(a) **Silicon tube.** Various lengths of tubing are used for the feed and waste streams.

(c) **Clamps.** These are used to close ports of inlets and outlets of the MFC.

(f) **Syringe:** The syringe is used to inject water into the MFC prior to autoclaving. It is also used to inoculate the MFC with yeast and feed the sterile growth medium into the MFC.

(h) **Flask with growth medium.** A growth medium suitable for the given microorganism is prepared. It is essential to properly mix the medium for optimum growth.

(i) **Tin foil for covering flasks**

(j) **Flask with inoculated yeast.** The yeast are nourished before the MFCs are started in order to decrease the lag phase.

Figure 4  Parts for operation and maintenance of MFCs. (From Appendix 1)
Electronic equipment

(a) Multimeter. The multimeter is used to measure the electrode potentials and current.

(b) Resistor. Resistors are connected between the anode and the cathode.

(c) Electrical wire and alligator clips. These are used for electrical connections.

Figure 5. Parts for electronic measurements and data acquisition. (From Appendix 1)

Procedure

*Students must familiarize themselves with the materials and equipment listed above before starting the assembly procedure.*

Preparing and operating a microbial fuel cell

Assembling a MFC.

a. The following parts are required to assemble a MFC
   1. Anode compartment
   2. Cathode compartment
   3. Two cover sheets
   4. Two electrodes (1 graphite, one air electrode)
   5. Membrane
   6. Four rubber gaskets
   7. Twenty-four nuts and 12 bolts
   8. Six connectors
   9. Two feet of silicon tube
   10. Silicon rubber
   11. Six clamps
b. Diagram that shows the dimensions and relative positions of the MFC parts

Figure 6 Microbial fuel cell. A) General view. B) Side plates. Port 1: outlet, port 2: air or nitrogen, port 3: media feed line. C) Growth chamber for anodic or cathodic compartment. D) Top view of the cell. Port 4 is for the salt bridge for the reference electrode, and ports 5 and 6 are for the electrical wires connected to the electrodes. E) Electrode configurations used in the compartments.

Make sure all parts are clean before starting the experiment

b. Cleaning the MFC parts
   1. Wash using glass cleaning detergent and tap water
   2. Rinse all the parts using tap water
Figure 7. Steps for assembling a MFC.

*Be certain to look at the figures to help you with this process

c. Assembling procedure

1. Insert a graphite electrode into the anode compartment, being careful not to disturb the connections (Figure a)
2. Insert an air electrode into the cathode compartment with the white side facing out, being careful not to disturb the connections (Figure a)
3. Ensure that the wires are routed through the appropriate ports at the top of the fuel cell (Figure a, b)
4. Place a rubber gasket on the inner side of the cathode compartment (Figure b)
5. Place the membrane after the gasket placed in step 4 (Figure c)
6. Place a rubber gasket on the other side of the membrane (Figure d)
7. Put the cathode and anode compartments together (Figure e)
8. Place rubber gaskets on the outsides of the anode and cathode compartments (Figure f)
9. Place the cover plates on the outside of the anode and cathode compartments, making sure the tube fittings are located in the appropriate location (Figure g, h)
10. Insert the ready-rod (including a washer on each end). Tighten (hand-tight is enough) using wing nuts. DO NOT overtighten, because you may break the polycarbonate. If the reactor leaks when filled with liquid, tighten it a ¼ turn (Figure h,i)
11. Attach silicon tubes (2-inch) to the connectors (Figure j) at the bottom of the cover plates
12. Close the inlets and outlets using clamp stoppers (Figure j)
13. Apply silicon rubber to close the openings of the compartments
14. Let the silicon rubber cure for 30 minutes.
**ACTIVITY #5 Loading the fuel cell**

*(Adapted from Appendix 1)*

**Purpose**

The purpose of this activity is to learn how to prepare growth mediums, inoculate microbes and load the fuel cells for electrical generation. Once the fuel cells are loaded, students will measure the cell potential.

**Prerequisite Knowledge**

Students will need to understand MFC and cellular respiration of microbes. Students will need to know how to properly use a scale for measuring chemicals, a graduated cylinder, syringe and a magnetic stirrer. Students will also need to know how to operate a multimeter and be able to plot data on a graph.

**Instructional Strategies**

The teacher should assist students in obtaining the chemicals, using the scales and magnetic stirrers (if available).

**Preparing inoculation and growth medium**

The MFC growth medium may be altered for different experiments. The nutrients and type of yeast can be altered depending on which variables you want to test. You need to determine the volume of your fuel cells and modify the medium amount accordingly.

**Standard growth medium for MFC inoculation and energy generation**

**Growth medium for *Saccharomyces bayanus***

1L Water
120 g light hopped Malt

1. Weigh the chemicals and put them inside a 1000-ml pyrex bottle. DO NOT mix the chemicals. After weighing each chemical clean your spatula so you won’t contaminate other chemicals.
2. Add 1L of water in the 1000-mL pyrex bottle
3. Mix until all the chemicals are dissolved well. You can do this by swilling the flask for several minutes.
4. Pour broth in a container that is heat resistant, cover loosely.
5. Bring broth to a boil for 10 minutes (either in a microwave or on the stovetop) allow to cool to room temperature. Make sure you stir so broth does not burn.
6. Divide the medium in half. One half will be used to inoculate the yeast and the other half will be used to load the fuel cell.
7. Cover the broth that you will use to load the cell with tinfoil. This is your growth medium for electricity generation.
8. Weigh out .13g of champagne yeast (Saccharomyces bayanus).
9. Add yeast to the remaining half of the cooled broth and swill to distribute yeast. This is your stock medium.
10. Cover yeast stock medium with tinfoil and allow to sit in a warm location, out of direct sunlight, for 30 minutes or overnight, whichever works best for your lab.

Cathode compartment

You need to determine the volume of your fuel cells and modify the buffer amount accordingly.

Fill with a buffer (pH = 7) of the composition shown below:

<table>
<thead>
<tr>
<th>Components</th>
<th>Formula</th>
<th>Composition (g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disodium phosphate</td>
<td>Na₂HPO₄</td>
<td>1.825</td>
</tr>
<tr>
<td>Monopotassium phosphate</td>
<td>KH₂PO₄</td>
<td>0.35</td>
</tr>
</tbody>
</table>

1. Weigh each chemical and put them inside a 1000-ml pyrex bottle.
2. Add 1L of water in the 1000-ml pyrex bottle containing the buffer chemicals.
3. Place a magnetic stirrer in the bottle and stir on a stir plate for 15 minutes. Make sure all chemicals are dissolved before continuing.

Starting the MFC

Make sure you have the following items ready:
1. Assembled MFC
2. Growth medium for electricity generation
3. Stock culture containing yeast
4. 20-ml syringe (2)
5. Buffer
6. Air pump and tubing
**Use the following procedure to start the MFC**

(All measurements are assuming the volume of the anode chamber is 100ml)

1. Obtain stock culture and growth medium
2. Remove the silicon rubber from the two inlets of the cathode at the top of the cathode compartment
3. Inoculate the MFC:
   a. Take a 20-mL syringe
   b. Open the stock culture vial
   c. Put 50ml of the stock culture inside the anode compartment through one of the tubes. *Take care to point the tube down towards the table as broth may expel out the tube during the filling process.*
4. Using the same syringe, fill the anode compartment with 50ml of growth medium for inoculation
5. Clamp tube after loading fuel cell
6. Immediately shake the MFC a little so that the culture is mixed well
7. Fill the cathode compartment with buffer using the second syringe.
8. Pump air into the cathode at a moderate rate through the bottom tube.
9. Remove the clamp from the upper tube on the anode chamber.
10. Pump air into the anode chamber through the bottom tube. Keep pumping air at the smallest rate possible. You may need to apply a clamp to keep the airflow to a minimum. The flow should be one bubble every few seconds. If too much oxygen is delivered, the electrons will not generate electricity but instead attach to the oxygen.

**Operation of the MFC in batch mode**

After starting the MFC the following steps are required for the operation of the MFC.

11. Maintain air flow to the anode compartment to reduce the pressure from the CO₂ generation.
12. Maintain air flow to the cathode compartment continuously
13. Maintain the fluid levels in the chambers by adding growth medium to the anode side as needed and buffer to the cathode side as needed. This will ensure that the entire electrode is available for electron and proton exchange.

**Monitoring the potentials of the anode, cathode and MFC and the current of the MFC**

We use a multimeter to monitor the electrode potentials and current.

14. Make sure the black wire on the multimeter is plugged into the black receptacle and the red wire is plugged into the red receptacle on the lower right corner of the multimeter.
15. Turn the multimeter on to the \( mV \) setting
16. Connect the red wire to the cathode
17. Connect the black wire to the anode
18. Record the volts for the anode and cathode, this is your cell potential
19. Cell potentials will be measured every hour for 3 days.
20. Prepare a graph of cell potential versus time in Excel.
Questions for MFC

1. Why is it important to handle the electrical components of the fuel cells with care?

2. What is the purpose of the membrane separating the two chambers?

3. Why should you point to filler tube down once you remove the syringe?

4. What is the charge on the anode?

5. What is the purpose of the wires that come out of the top of the fuel cell?

6. Why is it important to maintain the level of the fluids in the chambers?
ACTIVITY # 6 Effects of Various Nutrients on Cell Potential

Purpose:

The purpose of this activity is for students to design an experiment to determine if different types of nutrients affect cell potential in the microbial fuel cell. This activity is unguided inquiry where the students develop a problem, hypothesis, equipment list, procedure and data table. The students must then analyze the data and write up a conclusion of their findings.

Prerequisite Knowledge

Students will have learned how to use all materials and equipment in previous labs.

Equipment

See equipment lists for Activities #4 and #5.

Procedure

Part A: Predicting and Planning an Investigation

You are given the task of determining the effects of nutrients on cell potential in a Microbial Fuel Cell.

1. In your science notebook, state the problem you are trying to solve in this activity.

2. Develop a hypothesis that states what you predict the outcome of the experiment is and a reason for your prediction.

3. Work as a group to determine which materials you will need for this experiment. Keep in mind that you will only have 2 microbial fuel cells to use for your experiment.

4. Be sure to include a data table for recording your results.

5. Your problem, hypothesis, materials list, procedure and data table must be submitted for review and accepted by your teacher before beginning the investigation.
Part B: Conducting your investigation

After receiving your teacher’s approval for your experiment, conduct the investigation.

Conclusion

In your conclusion, Restate the problem you were trying to solve, whether or not the hypothesis was correct, and evidence from the experiment that supports your decision about the hypothesis. Explain any problems or issues you encountered while conducting the experiment and why or why not your hypothesis may have been correct/incorrect.
Appendix 1

MICROBIAL FUEL CELLS
EDUCATION MODULE

Washington State University, The School of Chemical Engineering and Bioengineering

Prepared by
Alim Dewan and Haluk Beyenal

Washington State University, The School of Chemical Engineering and Bioengineering

This module was tested for the first time in the 2007 Fall semester ChE 475, Bioprocess Engineering, class.

Copyright: Washington State University, The School of Chemical Engineering and Bioengineering, WA 99163, USA.
INTRODUCTION

This manual will guide you to run a microbial fuel cell (MFC) experiment in the laboratory. In the introduction, you will be introduced to the concepts of microbial fuel cells. “What is a microbial fuel cell?”, “How does it work?” and “What are the applications of microbial fuel cells?” are questions you have in your mind already. In the introduction we will try to find the answers to these questions. Important theories and definitions that are required for analyzing MFC experimental data will also be discussed in this section.

1.2. What is a Microbial Fuel Cell?
A microbial fuel cell is an electrochemical device that generates electricity directly from organic chemicals, using microorganisms to catalyze the redox reactions. First of all, it is a “fuel cell,” which is a device that uses electrochemical reactions to produce energy. In modern energy technology, fuel cells replace the conventional high-temperature combustion devices that generate energy from fossil fuels. Secondly, a fuel cell is composed of microorganisms which are used to produce electricity. In nontechnical terms the microorganisms consume organic chemicals to produce energy for their survival, and we collect electrons from the energy-producing pathway to produce electricity. Technically, the microorganisms act as catalysts that accelerate the redox reactions needed for the fuel cell. We can think of a MFC as a battery. The reaction mechanisms are similar. The difference is that in a MFC the fuel can be stored outside the cell and supplied continuously, while in a battery the fuel is limited and stored inside the cell.

Electrochemical cells are driven by redox reactions. A redox reaction is a combination of two half reactions: one, the oxidation half reaction, liberates electrons and the other, the reduction half reaction, consumes electrons. In a MFC the half reactions, oxidation and reduction, are separated by a cation exchange membrane. The electrode at which the oxidation reaction occurs is called the anode and the electrode at which the reduction reaction occur is called the cathode. Figure 1 shows a schematic diagram of a MFC and its components.
The main components of a microbial fuel cell are the anode, the cathode and the proton exchange membrane. In the anode, the microorganisms are grown anaerobically. Fuel, organic matter that can be oxidized anaerobically by microorganisms, is pumped into the anode compartment. The microorganisms oxidize the fuel and derive electrons from the oxidation of the fuel, then transfer them to the solid electrode. Then the electrons are transferred through an external circuit to the cathode. This electron transfer through an external circuit is used to power electronic devices. The protons that are produced during the oxidation of the fuel diffuse from the anode to the cathode through the proton exchange membrane to complete the circuit and balance the charge. An electron acceptor (usually oxygen) is pumped into the cathode compartment, where it accepts electrons from the anode through the external circuit while the protons diffuse through the membrane.

1.3. How does an MFC work?

Why did scientists, at the very beginning, think that microbes could be used in fuel cells? The answer to this question may help you to understand the idea behind the MFC. To find the answer let us examine the energy generation process of a single bacterial cell. The energy generation process involves many different reactions, but the overall reaction can be summed up as a redox reaction. In that redox reaction, one chemical is oxidized, liberating electrons, and another chemical is reduced by accepting the electrons. For example, Red 1 (reduced chemical 1) is a carbon source which is oxidized by microorganisms to form an oxidized species, liberating an electron. The reaction can be written as

\[ \text{Red 1} = \text{Ox 1} + e^- \]  

Eq 1

According to charge conservation, this electron must be accepted by an electron acceptor. As shown in Figure 2A, an electron acceptor, Ox 2 (oxidized chemical 2), is
reduced by the electron liberated by oxidation and is converted to Red 2 (reduced chemical 2).

\[ \text{Ox}_2 + e^- = \text{Red}_2 \quad \text{Eq 2} \]

Thus, the redox reaction comprises the oxidation of fuel and the reduction of an electron acceptor. The overall reaction can be written as

\[ \text{Red}_1 + \text{Ox}_2 = \text{Ox}_1 + \text{Red}_2 \quad \text{Eq 3} \]

Figure 2. Schematic diagram of how the microbial redox reaction is modified in MFCs. A) The microbial energy generation process involves a redox reaction. The idea of the MFC lies in separating the oxidation and reduction environments by membrane or salt bridge and transferring the electrons through an external circuit to maintain the charge balance. B) A schematic diagram of how the oxidation and reduction environments can be modified to make MFCs.

The idea behind microbial fuel cells is separating the oxidation and reduction environments in such a way that the electrons can be transferred through an external
circuit. The dashed line in Figure 2A is the position where, conceptually, we can separate the two environments. The separation is shown schematically in Figure 2B. The two environments are separated by a membrane (dashed line). The environment where the microorganisms grow and oxidize the fuel is called the anodic compartment, and the environment where the electron acceptor is reduced is called the cathodic compartment. Now the question may arise as to how microbes can produce energy if we do not allow them direct contact with a soluble electron acceptor. The answer is the solid electrode. Microbes can use a solid electrode to transfer the electrons that are liberated in the oxidation process. As depicted in Figure 2B, the electrode placed in the anodic compartment collects the electrons from the microbes and transfers them through the external circuits to the cathode where the electron acceptor (Ox 2) is reduced.

For example, if glucose is the reduced chemical that is metabolized by the microorganism, the overall reaction is written as (Please see glucose metabolism discussed later).

\[
C_6H_{12}O_6 + 6O_2 \leftrightarrow 6CO_2 + 6H_2O + 38ATP \tag{Eq 4}
\]

In this reaction, the oxidation of glucose is written as

\[
C_6H_{12}O_6 + 6H_2O \leftrightarrow 6CO_2 + 24H^+ + 24e^- \tag{Eq 5}
\]

and the reduction of oxygen is written as

\[
6O_2 + 24H^+ + 24e^- = 12H_2O \tag{Eq 6}
\]

If the anode and the cathode are separated by a membrane, we can draw the diagram of the MFC as in Figure . This diagram shows where the reactions occur and what the products in the anodic and cathodic compartments are.
How to calculate the number of electrons available to be transferred from the organic compound to the electron acceptor

The number of electrons that are available from the oxidation of an organic compound is calculated using the concept of degrees of reduction (Shuler and Kargi, Chapter 7, page 202-205). The degree of reduction of an organic compound (say glucose) is defined as the number of available electrons per gram-atom (similar to the number of gram-moles) of C. The total number of electrons available is calculated by multiplying the degree of reduction by the number of gram-atoms in the compound.
Example 1
The reduction number of an element is the same as the balance of that element. The reduction number of glucose (C$_6$H$_{12}$O$_6$) can be calculated as

$$\gamma = \frac{6 \times 4 + 12 \times 1 + 6 \times (-2)}{6} = 4$$

where the balance of C is 4, that of H is 1 and that of O is -2. The number of gram-atoms of carbon in one mole of glucose is 6. Thus, the total number of electrons available is 6 × 4 = 24. For lactic acid (C$_3$H$_{12}$O$_6$), the reduction number is again 4 ($\gamma = \frac{3 \times 4 + 6 \times 1 + 3 \times (-2)}{3} = 4$), and the number of gram-atoms in the lactate is 3. Therefore, the total number of electrons available from lactic acid is 4 × 3 = 12.

The concept of MFCs can be understood better if we study metabolic pathways. Let us examine the overall processes of aerobic and anaerobic respiration and the fermentation process.

**Aerobic respiration of Klebsiella pneumoniae**
Figure 4 is a schematic representation of the aerobic microbial respiration and fermentation of *Klebsiella pneumoniae*. Remember that *Klebsiella pneumoniae* is a facultative microorganism, which means it can also respire anaerobically. Here, aerobic respiration is chosen to explain the idea of MFCs. Later, the anaerobic respiration of *Shewanella oneidensis* (MR-1) will be discussed and compared with the aerobic respiration of *Klebsiella pneumoniae*. 
Figure 4. Schematic representation of the overall process of aerobic respiration and fermentation of *Klebsiella pneumoniae*. A single cell is mimicked and both processes are shown in the same figure, although in actuality the processes occur under different conditions. The fermentation does not require oxygen or the Krebs cycle. The fermentation process uses an organic electron acceptor. There are MFCs that use fermentation products to produce electricity. For simplicity, we do not discuss this kind of MFC.

The glycolysis process is common to respiration and fermentation. It produces adenosine 5'-triphosphate (ATP) and nicotinamide adenine dinucleotide (NADH) while producing pyruvic acids. In the fermentation process, the pyruvic acids and the electrons carried by the NADH form fermentation end products (detail is avoided for simplicity). In the respiration process, pyruvic acid is converted to Acetyl Co-A while producing carbon dioxide and NADH. The Acetyl CoA enters the TCA or Krebs cycle and produces carbon dioxide, ATP, NADH and FADH$_2$. The NADH and FADH2 are oxidized, to NAD+ and FAD, in the electron transport chain, and the electrons which are liberated are transferred through the transport chain by the cyclic oxidation and reduction of carrier molecules. While the electrons are transferred through the transport chain, the protons are pumped across the membrane by some carrier molecule, called a proton pump. A proton concentration gradient forms between the two sides of the cell membrane. Due
to that gradient, protons diffuse through ATP synthase. When this diffusion occurs, energy is released and is used by the enzyme to synthesize ATP from ADP and phosphorus.

**Anaerobic respiration of *Shewanella oneidensis***

\[
\begin{align*}
\text{Lactate} & \rightarrow \text{Pyruvate} \\
2 \text{ NADH} + 2 \text{H}^+ & \rightarrow 2 \text{ ATP} \\
2 \text{ NADH} + 2 \text{H}^+ & \rightarrow 2 \text{ CO}_2 \\
2 \text{ Acetyl CoA} & \rightarrow 2 \text{ ATP} \\
6 \text{ NADH} + 6 \text{H}^+ & \rightarrow 6 \text{ FADH}_2 \\
6 \text{ FADH}_2 & \rightarrow 6 \text{ ATP} \\
10 \text{ NADH} & \rightarrow 10 \text{ NAD}^+ \\
6 \text{ FADH}_2 & \rightarrow 6 \text{ FAD} \\
\end{align*}
\]

**Figure 5.** Anaerobic respiration of *Shewanella oneidensis* under a fumarate reduction condition. The pathway for fermentation is not shown here; it is the same as for *Klebsiella pneumoniae*.

In the anaerobic respiration of *Shewanella oneidensis* (MR-1) under a fumarate (electron acceptor) reduction condition, the lactate is converted to pyruvate and then to acetyl-coA. The Acetyl-CoA enters the TCA or Krebs cycle and produces carbon dioxide, ATP, NADH and FADH₂. In the electron transport chain, the NADH and FADH2 are oxidized to NAD⁺ and FAD, respectively, and the electrons are liberated. Then the electrons are transferred through the transport chain by the cyclic oxidation and reduction of the carrier proteins possessed in the chain. While the electrons are transferred through the transport chain, the protons are pumped across the membrane by proton pump. A proton concentration gradient forms between the two sides of the cell membrane. Because of this gradient, protons are diffused by ATP synthase. When this diffusion occurs, energy is released and is used by the enzyme to synthesize ATP from ADP and phosphorus. The electrons transferred through the electron transport chain reduce the fumerate to form formaldehyde. The whole respiration process can be summarized as Lactate→pyruvate→acetate→CO₂. When we use *Shewanella oneidensis* in our anodic
compartment, we don’t use fumerate because instead of fumerate, we want to transfer electrons to the solid electrode and generate current.

**Electron transport chain**
An electron transport chain consists of a sequence of carrier molecules that are capable of oxidation and reduction. The carrier molecules are flavoproteins, cytochromes and ubiquinones (Figure 6). The electron transport chain releases energy (ATP) as the electrons are transferred from higher-energy compounds to lower-energy compounds. Keep in mind that, according to the modern convention, electrons flow from a lower potential to a higher potential. If there are two compounds having different redox potentials, the electrons will flow from the compound with the lower redox potential to the compound with the higher redox potential.

![Electron transport chain diagram](image)

**Figure 6.** Electron transport chain. The electrons pass along the chain in a gradual and stepwise fashion through the oxidation and reduction of the flavoproteins (FMN), cytochromes (Cyt) and ubiquinones (Q). Here oxygen is the final electron acceptor, with a redox potential of +0.816 V\text{SHE}. NADH and FADH\textsubscript{2}, which are produced in glycolysis and the TCA cycle, have redox potentials of -0.32 V\text{SHE} and -0.22 V\text{SHE}, respectively. In a MFC the oxygen is replaced with a solid electrode which accepts electrons and delivers them to the cathode.
Remember that in a fuel cell the bacteria produce energy by anaerobic respiration. The mechanism of anaerobic respiration is the same as that of aerobic respiration, but the electron acceptor is different. In aerobic respiration, the final electron acceptor is oxygen, whereas in anaerobic respiration the final electron acceptor is a chemical other than oxygen. Some anaerobes (bacteria that can survive only in an anaerobic condition) and facultative anaerobes (bacteria that can survive in both aerobic and anaerobic conditions) can use nitrate, sulfate, carbonate and metals. A solid electrode which can accept electrons can be used for respiration, as happens in MFCs.

**How are electrons transferred from microorganisms to a solid electrode?**

So far we know MFCs can produce electricity using electrons released by microbial respiration through the production of NADH and FADH$_2$, which are oxidized in the electron transport chain. The electron transport chain carries the electrons to the final electron acceptor, which in the case of a MFC is a solid electrode. Now the question you may ask is “how are the electrons transferred from the electron transport chain to the electrode?” This question has not been answered yet. However, there are some hypotheses on electron transfer from the electron transport chain to the solid electrode. Keep in mind that researchers are still looking for experimental proof of the hypotheses. So come up with your own explanation that may be a breakthrough in MFC research. Figure 7 summarizes the hypotheses of the electron transport mechanism.

![Figure 7. Summary of hypothesized electron transfer mechanisms.](image)

A) Redox potentials inside the cell (E$_{cell}$), at the cell wall (E$_{cellW}$), in the medium (E$_{medium}$) and at the anode (E$_{anode}$). In an electrochemical system, the electrons move from lower redox potential to higher redox potential (see arrow in the figure). In this case, since the electrons are transferred from the cell to the anode, the potential inside the cell is the lowest and the anode potential is the highest. B) The electrons are transferred by a mediator. C) The electrons are transferred directly. There is evidence that certain microorganisms produce nanowires which transfer electrons directly to the
electrode. Some researchers also believe that cytochrome protein in the electron transport chain may transfer electrons directly to the anode.

We categorize electron transfer mechanisms into two groups: 1) mediated electron transfer and 2) direct electron transfer.

1) Mediated electron transfer
The mediators are redox species that can accept electrons from the electron transport chain and transfer them to the solid electrode. They are also called electron shuttles. The reduced metabolic products (for example hydrogen), and organic (for example, 2-hydroxy-naphthoquinone (HNQ) and organometallic compounds (for example iron-ethylenediamine-tetraacetic-acid (Fe-EDTA)) can be used as mediators. The mediators can also be produced by the cells; these are called microbially produced mediators. For example, the *Shewanella* species can produce an iron compound that acts as a mediator. The mediators can also be added externally, for example 2-hydroxy-naphthoquinone (HNQ), which is considered an artificial mediator. The mechanism of electron transfer is the same for artificial and microbially produced mediators.

2) Direct electron transfer
The cytochrome proteins in the electron transport chain may come in direct contact with the solid electrode and transfer the electrons directly. In addition, the recent discovery of bacterial nanowires leads some researchers to conclude that nanowires are used to transfer electrons directly. The researchers are still working to prove this kind of electron transfer mechanism experimentally. So, while running the experiments, keep your eyes open: you may discover something new about the electron transfer mechanism.

1.3 Concepts

**Electric potential**
Absolute electric potential cannot be defined for a single point in space: it must be determined with respect to the potential of another point in space. The electric potential at location A with respect to location B is defined as the work needed to bring one unit of positive electric charge from location B to location A. For example, an electric charge \( q_0 \) is transferred from A to B. Location A has electric potential energy \( E_{PEA} \), location B has electric potential energy \( E_{PEB} \), and the difference in electric potential energy between these locations is \( E_{PEB} - E_{PEA} = E_{PEAB} \). The numerical values of \( E_{PEA} \) and \( E_{PEB} \) are not known. Only the difference between them, \( E_{PEAB} \), is known: it is equal to the work needed to move the test electric charge from A to B. To make the result of the computation independent of the magnitude of the test electric charge, the energy change is computed per unit of the electric charge transferred.
\[
\frac{W_{AB}}{q_o} = \frac{(EPE_B - EPE_A)}{q_o} = \frac{EPE_{AB}}{q_o}
\]

Eq 7

The difference in electric potential energy of the unit positive electric charge between A and B is referred to as the electric potential difference between these two locations:

\[
\frac{EPE_{AB}}{q_o} = V_{AB} = V
\]

Eq 8

In an electrochemical system, the electric potential of an electrochemical cell is the work needed to move one unit of positive charge from a standard hydrogen electrode to the indicator electrode in the cell. The potential of the hydrogen electrode is zero by convention.

For example, using SI units, the work needed to take one unit charge from a hydrogen electrode to electrode ‘x’, the potential of electrode ‘x,’ is

\[
\frac{1 \text{ J}}{1 \text{ C}} = 1 \text{ V}
\]

Eq 9

**Electrode and cell potentials**

Redox reactions are composed of two half-reactions: one substance donates the electrons and the other substance accepts the electrons. The electrons have the tendency to move from one substance to the other because the substance that donates the electrons has a lower affinity for the electrons than the substance that accepts them. As a result of the electron transfer, the substance that donated the electrons is oxidized and the substance that accepted the electrons is reduced.

The affinity of a substance for electrons can be evaluated and cataloged for the standard conditions as the potential of the half-reaction in which this substance participates: the higher the potential of the half-reaction, the higher the affinity of the substance participating in that half-reaction for the electrons. As a result, substances can be compared by evaluating their affinity for electrons, and it can be predicted which substance will donate the electrons and which substance will accept the electrons, which substance will be oxidized and which will be reduced. Whether the actual transfer of the electrons occurs depends on kinetic limitations, and the kinetics of these reactions are determined experimentally. Technically, the difference between the potentials of the half reactions is called the cell potential, and it is proportional to the Gibbs free energy change resulting from transferring the electrons from one half-reaction to the other. In chemistry the tendency of a reaction to occur is quantified by computing the Gibbs free energy change. In electrochemistry this same tendency is quantified by computing the cell potential. The two computations are equivalent: the cell potential is the Gibbs free energy change expressed in electrical terms, and the Faraday constant is used as the conversion factor.
The Faraday constant (F = 96,485 C/mol) is equal to the electric charge of one mole of electrons, and it appears in many electrochemical equations. To compute the Faraday constant the electrical charge of a single electron, which is equal to \(1.602 \times 10^{-19}\) coulombs, is multiplied by the number of electrons in one mole of electrons, which is equal to Avogadro’s number, \(6.0238 \times 10^{23}\): the product of these numbers is the Faraday constant, 96,495 coulombs per mole of electrons.

The common expressions that use the Faraday constant are: (1) the Faraday constant multiplied by the number of moles of electrons (\(n\)) transferred between locations, \(nF\), which is equal to the charge transferred between these locations, and (2) the electric charge transferred between locations multiplied by the potential difference between these locations expressed in volts, \(nFE\), which is equal to the energy change. Actually, the latter expression should use \(\Delta E\) instead of \(E\), but it is customary to use \(E\) because potentials are always measured with respect to another potential, so \(E\) is always \(\Delta E\).

The electric charge transferred in a redox reaction, \(nF\), and the energy change, \(nFE\), are often used in electrochemical computations. From these relations, the Gibbs free energy change in an electrochemical reaction can be expressed as the equivalent of the potential difference:

\[
-\Delta G = nFE
\]

where \(\Delta G\) is the Gibbs free energy change associated with the electron transfer. The accepted sign convention is consistent with the convention used in chemical thermodynamics: the energy of the reactants is subtracted from the energy of the products.

Since the Gibbs free energy change for a simple electrochemical reaction can be computed from thermodynamics, and the free energy change in a redox reaction is equivalent to the potential difference, it is also possible to compute the equivalent potentials for these reactions. Such computations yield “half-cell potentials,” which have exactly the same use as the computations of Gibbs free energy change in these reactions, but the half-cell potentials are expressed in units used in electrochemistry, volts. Computing cell potentials from Gibbs free energy changes does not add any additional information: the cell potential is just the Gibbs free energy change divided by the electric charge transferred in that reaction (\(nF\)). The sign convention is such that reactions are spontaneous when their cell potentials are positive.

\[
E = -\frac{\Delta G}{nF}
\]

This sign convention is consistent with the discussion earlier: electrons tend to move from locations with lower potentials to locations with higher potentials. If we use the thermodynamic convention and subtract the potential of the final destination (the higher potential) from the potential of the initial location (the lower potential) the sign of the resulting change is positive,
which indicates that the transfer of electrons between these locations is spontaneous. A negative change of Gibbs free energy is equivalent to a positive potential.

Because the number of electrons transferred, \( n \), and the Faraday constant, \( F \), are constant for a given reaction, the cell potential, \( E \), is just another way of expressing the Gibbs free energy change for that reaction, \( \Delta G \). For the redox reaction described by the following stoichiometry:

\[
 r(\text{reactant}) + n e = p(\text{product}) \tag{Eq 12}
\]

\[
 \Delta G = \Delta G^\circ + RT \ln \left( \frac{\prod (\text{product})^p}{\prod (\text{reactant})^r} \right) \tag{Eq 13}
\]

where \( r \) and \( p \) stand for the stoichiometric coefficients associated with each of the reactants and products, introducing appropriate expressions for the relations quantifying the Gibbs free energy change yields:

\[
 \Delta G = -nFE \\
 \Delta G^\circ = -nFE^\circ
\]

This can be written as:

\[
 E = E^\circ - \frac{RT}{nF} \ln \left( \frac{\prod (\text{product})^p}{\prod (\text{reactant})^r} \right) \tag{Eq 14}
\]

This equation is called the Nernst equation. At 25°C (\( T = 298^\circ K \)), assuming \( F = 96,485 \) C/mol, \( R=8.314 \) J/mol.K,

\[
 E = E^\circ - \frac{0.059}{n} \ln \left( \frac{\prod (\text{product})^p}{\prod (\text{reactant})^r} \right) \tag{Eq 15}
\]

We measure the electrode potential as the difference between the electrical potential of an electrode and the electrical potential of a reference electrode.

**Potential described against reference electrodes**

The potentials of half-cells can be calculated with respect to reference electrodes other than SHE as distances between respective rungs on the potential ladder (Figure 8). For example, if an arbitrary half-reaction A has a half-cell potential with respect to SHE
equal to +0.362 V, then it has a half-cell potential of 0.362 V – 0.197 V = 0.165 V with respect to the saturated Ag/AgCl electrode. Similarly, if the half-cell potential of an arbitrary half-reaction B is –0.185 V with respect to SHE then its half-cell potential with respect to SCE is 0.241 V + 0.185 V = 0.426 V. As for the signs of the computed potentials: if the half-cell potential of the arbitrary half-reaction is above the potential of the selected reference electrode, the sign of the potential is positive, and vice versa. Consequently, the computed half-cell potential for half reaction A is +0.165 V, while the half-cell potential for half reaction B is -0.426 V. If the half-cell potential of an arbitrary half-reaction is between the potentials of SHE and, say, SCE, then it is positive with respect to SHE and negative with respect to SCE.

Figure 8. Relative positions of various reference electrodes.

MFC potential with mediated electron transfer
Let us consider a MFC in which the electron is transferred from the microorganism to the electrode by a mediator (M).

1) Calculation of anode potential. The mediator \((M_{\text{red}})\) that is reduced by accepting electrons from the microbial respiration system is oxidized at the anode according to the following reaction:

\[ M_{\text{red}} \leftrightarrow M_{\text{ox}} + e \quad \text{Eq 16} \]

\(M_{\text{red}}\) is the reduced form of the mediator and \(M_{\text{ox}}\) is the oxidized form of the mediator.

The anode potential \((E_A)\) is calculated using the Nernst equation:
where \((M)_{ox}\) and \((M)_{red}\) are the activities of the oxidized and reduced forms of the mediator, typically substituted for by the molar concentrations. \(E^o_m\) is the standard redox potential of the mediator. The challenge we have in this calculation is knowledge of the mediator. Generally we do not know the mediator; in this case we make an approximation and use artificial redox mediators for the calculation.

2) **Calculation of cathode potential.** If oxygen is reduced the cathode according to the following reaction

\[
O_2 + 4H^+ + 4e^- = 2H_2O
\]  

Eq 18

the cathode potential is

\[
E_C = E^o_{O_2} + \frac{0.059}{4} \log \left[ \frac{1}{p_{o_2} \left[H^+ \right]^4} \right]
\]  

Eq 19

3) **Calculation of the cell potential.** The cell potential of the MFC is determined by subtracting the anode potential from the cathode potential according to the following equation:

\[
E_{Cell} = E_C - E_A
\]  

Eq 20

This cell potential is called the open circuit potential (OCP) because no load is applied to the MFC (there is no current flow from anode to cathode) and the electrode reactions are in equilibrium. **Note:** \(E\) is used to denote the equilibrium potential and \(V\) is used for the actual potential (when there is a load or when a current flows from the anode to the cathode).

**Overpotentials and actual cell potential.** The potentials of an electrode at equilibrium and when a load is applied are different. An overpotential is defined as the difference between the equilibrium potential and the potential when a load is applied. Think about yourself as a student: you have homework with a deadline one month later. Generally you do not work on this homework although you have the energy (potential) to do. However, if the deadline is the next day, you start working on the homework and work
till late at night; at the end you become tired (your potential becomes low). Your equilibrium potential is your energy at the beginning when you are just starting to do your homework. Your overpotential is the difference between your potential at the beginning and your potential at the end: this is the driving force that makes your homework get done. Similarly, the overpotential in a MFC makes current flow. Because of losses of the equilibrium electrode potential or the overpotential, the actual cell potential of a MFC is always less than the open circuit potential. Here the word “loss” is used to show a negative sense, because when we apply a load to a MFC the electrode potential changes in a direction that is undesirable. The potential losses are actually called kinetic loss or overpotential. There are three types of potential losses or overpotentials: 1) activation overpotential, 2) ohmic overpotential and 3) concentration overpotential. Figure 9. is a theoretical plot of the change of an electrode potential with increase in current. The activation overpotential (Region I) is due to the activation energy needed for the oxidation/reduction reaction which occurs during the electron transfer from the compound to the solid electrode or from the electrode to the compound. The ohmic overpotential (Region II) includes the loss due to resistivity of the bulk electrolyte. The concentration overpotential (Region III) is due to the change in concentration of the electrolytes at the surface of the electrode during current flow; this is also referred to as diffusion loss.

**Figure 9.** Change of electrode potential with current. Region I: Activation overpotential, Region II: ohmic overpotential and Region III: concentration overpotential.

In an MFC, both electrodes may have all the losses described above. But remember, the directions of the potential changes of the anode and the cathode are opposite. When a load is applied to a MFC the anode potential changes towards the cathode and the cathode potential changes towards the anode. These changes can be depicted as shown in Figure 10. The cell potential ($V_{cell}$) is the difference between the equilibrium potential and the total overpotentials.
Figure 10. Change of anode and cathode potentials when a load is applied. $E_A$ and $E_C$ are the equilibrium potentials of the anode and the cathode, respectively. $V_{cell}$ is the cell potential at current $i$.

The actual cell potential can be written as

$$V_{cell} = (E_C - \eta_{l,c} - \eta_{III,c} - \eta_{III,c} - \eta_{II,c}) - (E_A + \eta_{l,A} + \eta_{III,A} + \eta_{III,A})$$

Eq 21

or

$$V_{cell} = V_C - V_A$$

Eq 22

where $V_{cell}$ is the actual cell potential, $E_C$ is the cathode potential at equilibrium, $E_A$ is the anode potential at equilibrium, $\eta_{l,c}$ is the activation overpotential at the cathode, $\eta_{l,A}$ is the activation overpotential at the anode, $\eta_{III,c}$ is the concentration overpotential at the cathode, $\eta_{III,A}$ is the concentration overpotential at the anode, and $\eta_{II,c}$ is the ohmic overpotential for both the anode and the cathode.

Now, if we make one electrode, say the cathode, very large compared to the other electrode, say the anode, the potential of the cathode may not be affected or the change will be very small (blue dashed line for cathode). In that case we can ignore the overpotential of the cathode. Then, the cell potential will be
\[ V_{\text{cell}} = (E_C) - (E_A + \eta_{\text{I,A}} + \eta_{\text{II,A}} + \eta_{\text{III,A}}) \]

Eq 23

or

\[ V_{\text{cell}} = E_C - V_A \]

Eq 24

Keep in mind that we also assumed that the cathodic current density is significantly higher than the anodic current density.

**Example 2**

If the anode potential of a MFC is changed as shown in Figure 11 and the cathode potential, \(E_C\), remains constant at 0.294 V, what are the overpotentials of the anode and the cathode at 1.5 mA? The equilibrium anode potential is -0.55 V. What is the cell potential at that current?

![Figure 11](image-url)

**Figure 11.** An experimental MFC result. At equilibrium the anode potential was 0.55 V. The external resistance between the anode and the cathode varied from 10 kΩ to 0.5 kΩ. The cathode potential was constant for the range of load applied.

Answer: Open circuit potential, \(E_{\text{cell}} = E_C - E_A = 0.294 - (-0.55) = 0.844\) V

Overpotentials: For this MFC experiment in which the cathode potential was constant: \(\eta_{\text{I,C}} = \eta_{\text{II,C}} = \eta_{\text{III,C}} = 0\). From Figure 11, \(\eta_{\text{I,A}} = 0.05\) V, \(\eta_{\text{II,A}} = 0.04\) V, \(\eta_{\text{III,A}} = 0.194\) V and \(E_A = -0.55\) V.

Cell potential: From equation 22, \(V_{\text{cell}} = 0.294 - (-0.55 + 0.05 + 0.04 + 0.194) = 0.56\) V
How to calculate current: electrode kinetics and the Butler-Volmer equation

When the current flows, and electrical charges are transferred between the electrodes and the dissolved species in the solution, the electrode acts as a chemical reactant and is subjected to the same rules of chemical kinetics as any other reactant. However, the existence of an electrical field in proximity to the surface of the electrode introduces additional factors that need to be taken into consideration in quantifying the kinetics of the reaction. The potential difference between the electrode and the solution generates an electric field. The electroactive species, the reactants in the redox reactions, are subjected to this electric field and behave differently than they behave in the absence of the field. Some electrically charged particles will find it easier to approach the surface of an electrode because they are electrostatically attracted to the surface, and other electroactive species in the solution will find it difficult to approach the surface of the electrode because they are repulsed by the electrical field.

In a reversible electrode reaction process at equilibrium, the current does not flow in the external circuit, and the fluxes of the electrical charges across the interface are equal in the two directions. The current measured in the external circuit is the result of the net difference between the flux of electric charges across the interface in one direction and that in the other direction. For the oxidation reaction of the mediator

$$M_{\text{red}} \leftrightarrow M_{\text{ox}} + e$$

Eq 25

the current can be measured using the Butler-Volmer equation, shown in equation 22.

$$i = i_0 \left[ \exp\left(\frac{-\alpha_c \eta F}{RT}\right) - \exp\left(\frac{\alpha_a \eta F}{RT}\right) \right]$$

Eq 26

where, \(i\) is the net current, \(i_0\) is the exchange current, \(\eta\) is the overpotential, \(F\) is the Faraday constant, \(R\) is the universal gas constant and \(T\) is the temperature in Kelvin, \(\alpha_c\) and \(\alpha_a\) are the transfer coefficients, and \(\alpha_c + \alpha_a = 1\). In most cases it is assumed that \(\alpha_c = \alpha_a = 0.5\), which indicates that the activation energy barriers of the oxidation and reduction reactions are the same.

The overpotential \(\eta\) is expressed as

$$\eta = \Delta E - \Delta E_{\text{eq}}$$

Eq 27
where $\Delta E$ is the potential difference between the electrode and the solution when the electrode is not in equilibrium and $\Delta E_{eq}$ is the potential difference between the electrode and the solution at equilibrium.

If the electrode is at equilibrium, $\eta = 0$, then the rate of the anodic reaction is equal to the rate of the cathodic reaction, and the anodic current density equals the cathodic current density. This special case of current density at equilibrium is called the exchange current density, $i_0$. It cannot be measured in the external circuit: at equilibrium the current in the external circuit is equal to zero.

**Example 3**
Compute the anodic, cathodic, and net current densities in the following system:

- $\alpha_a = \alpha_c = 0.5$
- $i_0 = 1 \text{ mA/cm}^2$
- Surface area of the electrode, $A = 1 \text{ cm}^2$

Use (1) cathodic polarization $\eta = -0.1 \text{ V}$ and (2) anodic polarization $\eta = +0.1 \text{ V}$.

To simplify computations note that $F/RT = 38.95 \text{ coulombs} \times J^{-1}$.

**For the cathodic polarization, $\eta = -0.1 \text{ V}$**

$$i_{net} = \exp\left[-0.5 \times (38.95) \times (-0.1)\right] - \exp\left[(0.5) \times (38.95) \times (-0.1)\right] = 7.01 - 0.14 = 6.86 \text{ mA/cm}^2$$

**For the anodic polarization, $\eta = +0.1 \text{ V}$**

$$i_{net} = \exp\left[-0.5 \times (38.95) \times (0.1)\right] - \exp\left[(0.5) \times (38.95) \times (0.1)\right] = 0.14 - 7.01 = -6.86 \text{ mA/cm}^2$$

**Current**
The current of a MFC is measured experimentally using an electrometer or calculated using the following equation when a load ($R$ in ohms) and a potential drop ($V_{cell}$ in volts) across the load are measured using an electrometer.

$$I = \frac{V_{cell}}{R_{ext}}$$

Eq 28

**Example 3**: Using equation 27, if the cell potential is $V_{cell} = 0.674 \text{ V}$ and load = 600 $\Omega$, the current is $I = 0.674/500 = 0.00112 \text{ A} = 1.12 \text{ mA}$.
**Power and power density**

The performance of a MFC is evaluated by calculating power generation. Power generation is calculated using the following equation:

\[ P = V_{\text{cell}} I = \frac{(V_{\text{cell}})^2}{R_{\text{ext}}} \]

**Eq 29**

**Figure 12.** A load is applied between the anode and the cathode. ‘Am’ is the ammeter connected in series and the ‘Vm’ is the voltmeter connected parallel with the load. If we know the load, \( R_{\text{ext}} \), and the \( V_{\text{cell}} \), we can calculate the power by calculating the current using equation 27. In that case we do not need to measure the current using an ammeter.

where \( P \) is the power (in watts); \( V_{\text{cell}} \) is the potential drop across the load (in volts), which is equal to the cell potential; \( I \) is the current flow; and \( R_{\text{ext}} \) is the external resistor applied between the anode and the cathode. Figure 12 shows how to connect the ammeter and voltmeter to the MFC to measure the potential and the current.

Power density, \( P_a = \frac{P}{A_e} \), where \( A_e \) is the geometric surface area of the electrode.

**Example 4**

If cell potential \( V_{\text{cell}} = 0.674 \) V, load \( R = 600 \) Ω, and electrode surface area \( A_e = 27 \) cm\(^2\). Calculate power density \( (P_a) \).

\[
I = \frac{0.674}{500} = 0.00134 A = 1.12 \text{ mA},
\]

Power = \( V_{\text{cell}} \times I = 0.674 \times 0.00134 = 0.00090 \) watts, and

Power density \( P_a = \frac{0.00090}{27} = 2.8 \times 10^{-5} \text{ watt/cm}^2 \).
**Faradic efficiency**

Faradic efficiency \( (\varepsilon_c) \) is defined as the total charge produced from a substrate divided by the maximum possible charge production from the same substrate.

\[
\varepsilon_c = \frac{\int_0^t I \, dt}{F \, n \, \frac{\Delta S}{M}} = \frac{\text{Actual charge production}}{\text{Theoretically available charge}}
\]

The total charge actually produced is calculated integrating the current over time. The maximum possible charge production is calculated multiplying the number of moles of substrate reacted \( (\frac{\Delta S}{M}) \) with the faraday constant \( (F) \), where \( \Delta S \) is the amount of substrate consumed during time 0 to t, M is the molecular weight of the substrate, and n is the number of moles of electrons involved in the redox reaction per mole of substrate. \( \varepsilon_c \) is the faradic efficiency. This is also called “coulumbic efficiency.”

**Example 5**

When a MFC using a mixed culture of bacteria was fed continuously with a medium of 1 g/L glucose and a load of 337 Ω was applied, the current generation was as shown in Figure 15. The feed rate was 0.05 L/day and the experiment was run for 48,000 sec. What was the coulombic efficiency if the glucose concentration in the effluent was 0.4 g/L?

![Figure 13](image)

**Figure 13.** Current vs. time profile when a 330-Ω resistor was applied.

\[
\int_0^t I \, dt = \text{actual charge production} = \text{area under the curve shown in Figure 13} = 239.7 \text{ coulombs. The area under the curve is calculated by a numerical method using MS Excel.}
\]
\[ F = \text{Faraday constant} = 96500 \text{ coulombs/mole of electrons} \]
\[ n = 24 \text{ for glucose oxidation} \]
\[ M = 180 \text{ g/mole of glucose} \]
\[ \Delta S = \text{amount of substrate consumed} = (1-0.4)g/L \times 0.1 \text{ L/day} \times 48000/86400 \text{ day} = 0.033 \text{ g} \]

\[
\begin{align*}
\text{and } F \times n & \quad \frac{\Delta S}{M} = 96500 \times 24 \times 0.033/180 = 424.6 \text{ coulombs} \\
\text{Thus, coulombic efficiency } \varepsilon_c &= \frac{\int_0^t I \, dt}{F \times n \times \frac{\Delta S}{M}} = 239.7/424.6 = 56.5 \% 
\end{align*}
\]

**Energy efficiency of the MFC**

Energy efficiency is defined as the ratio of the total energy that can actually be produced to the total energy that could be produced if the substrate were combusted. The heat of combustion is used as the denominator so that the efficiency of the MFC is comparable to the efficiency of energy generation by the thermal process.

\[
\varepsilon_E = \frac{\int_0^t V_{\text{cell}} \times I \, dt}{\int_0^t I^2 R_{\text{ext}} \, dt} = \frac{\text{Total energy production}}{\text{Theoretical available thermal energy}}
\]

Eq 30

where \( \varepsilon_E \) is the energy efficiency of a MFC, \( V_{\text{cell}} \) is the cell voltage, and \( I \) is the current flow. Thus, the integration of \( V_{\text{cell}} \times I \) over time 0 to \( t \) gives the total energy production. The term \( \Delta H_c \cdot m_{\text{in}} \) is the total energy that could be produced by combusting the same substrate. \( \Delta H_c \) is the heat of combustion (j/mole), and \( m_{\text{in}} \) is the total substrate used during time 0 to \( t \).
Example 6
In the experiment described in Example 4, what is the energy efficiency?

![Graph: I^2R vs. time](image)

**Figure 14.** $I^2R$ vs. time. The experimental conditions are the same as in Example 5.

Answer: Since the cell voltage profile is not given, we calculate energy efficiency using

$$\varepsilon_E = \frac{\int_0^t I^2R \, dt}{\Delta H_c \cdot m_{in}}$$

From the $I$ vs. $t$ data we can plot $I^2R$ vs. time as shown in **Figure 14**.

$$\int_0^t I^2R \, dt = 529.7 \text{ joules}$$

The heat of combustion of glucose at normal temperature and pressure is $\Delta H_c = 2830$ kJ/mole.

$$m_{in} = 1 \text{ g/L} \times 0.1 \text{ L/day} = 0.1 \text{ g/day} = 0.1 \text{ g/day ÷ 180 g/mole} = 0.00056 \text{ mol/day.}$$

Therefore, $\Delta H_c \cdot m_{in} = 0.00056 \text{ mole} \times 2830 \text{ kJ/mole} = 1584 \text{ joules.}$

Energy efficiency $\varepsilon_E = 529.7/1584 = 33\%$.

**Sustainability of MFC**
A MFC is sustainable if its electricity generation does not change over time. Since the purpose of running an MFC is to generate power for a long period continuously it is important that the MFC be sustainable; otherwise, application of the MFC would be difficult. For a sustainability test, a constant load is applied between the anode and the cathode and the current or the potential across the load is observed over time. If the MFC is sustainable, the current drops slowly and ultimately
reaches a steady state value, as shown in Figure 15 for 337 Ω. If the MFC is not sustainable the current decreases over time and does not reach a steady state value (Figure 15, for 10 Ω). Note that for these experiments the MFC was operated continuously.

Figure 15 also gives us another important message: If we consume natural energy at a rate faster than that it can be renewed (for example, by using a 10-Ω resistor) we will run out of energy very soon. However, if we consume the energy at a sustainable rate (the renewal of the energy is equal to the consumption rate) we can have energy for an unlimited time.

Figure 15. This MFC is sustainable at a low applied load (high resistor, 337 Ω) but not sustainable at a high load (low resistor, 10 Ω).
2. EQUIPMENT USED TO OPERATE MFCs and PERFORM MEASUREMENTS

This section introduces the equipment and tools required for running MFC experiments. A brief description and some tips for using the tools are given in the figure captions.

Figure 16. Flow diagram of a MFC system.

2.1 Components of a MFC

(a) Anode and cathode compartments. The holes at the top are used to insert electrodes or to make electrical connections to electrodes in addition to inserting a reference electrode.

(b) Anode and cathode cover plates. The anode and the cathode compartments and the cover plates are fabricated from polycarbonate. The working volume of each chamber is approximately 250 mL.
(c) **Cation exchange membrane (C-7000).** The anode and the cathode are separated by this cation exchange membrane.

(d) **Graphite electrode.** Graphite is used due to its inert structure. We use graphite as both anode and cathode.

(e) **Air electrode.** An air cathode composed of Pt wire mesh and coated with carbon powder is used. The choice of cathode material depends on the oxidizing agent used for the cathodic reaction. When oxygen is used as an electron acceptor, carbon materials are used with Pt or Ni catalysts because plain carbon gives a high kinetic limitation.

(f) **Rubber gasket.** A minimum of four gaskets are required for sealing one MFC.

(g) **Bolts and wing nuts.** Ensure that the structural hardware used to assemble the MFC is 316L stainless steel. We use 316L stainless steel due to its resistance to corrosion. During the experiments these parts will be wet. If we use a lower grade of stainless steel it corrodes easily.

(h) **Silicon adhesives.** Silicon adhesives are used to seal any unused ports on the MFC.

(i) **Conductive epoxy.** Conductive epoxy is used to secure electrical connections between wires and electrodes.

(j) **Fittings.** The fittings are used to connect silicon tubes to the inlet and outlet.
(k) **Barbed tube connectors.** These are used to connect two silicon tubes.

(l) **Saturated calomel electrode (SCE).** We use this as a reference electrode.

**Figure 17. List of parts used to assemble a MFC**

**2.2 Equipment for operation and maintenance**

(a) **Silicon tube.** Various lengths of tubing are used for the feed and waste streams.

(b) **Flow breaker.** This is used to prevent reverse contamination of the sterile growth medium.

(c) **Clamps.** These are used to close ports of inlets and outlets of the MFC.

(d) **Filter (0.2 μm).** Filters are used on the nutrient feed vessel in order to prevent contamination of the sterile growth medium.

(e) **Peristaltic pump and pump controller.** The pump is used to regulate the flow of sterile growth medium into the MFC.
(f) **Syringe and needle.** The syringe is used to inject water into the MFC prior to autoclaving. It is also used to inoculate the MFC with bacteria and feed the sterile growth medium into the MFC.

(g) **N₂ gas cylinder and regulator.** The nitrogen is pumped into the anode chamber to assure an anaerobic environment.

(h) **Carboy.** A carboy is used to collect MFC waste.

(i) **Flask with sterile growth medium.** A growth medium suitable for the given microorganism is prepared. It is essential to properly mix and sterilize the medium for optimum growth.

(j) **Flask with inoculated bacteria.** The bacteria are nourished before the MFCs are started in order to decrease the lag phase.

Figure 18. Parts for operation and maintenance of MFCs.

### 2.3 Electronic equipment

(a) **Multimeter.** The multimeter is used to measure the electrode potentials and current.

(b) **Resistor.** Resistors are connected between the anode and the cathode.
(c) **Electrical wire and alligator clips.** These are used for electrical connections.

(d) **Resistor box.** A resistor box is used to vary the external resistors used between the cathode and the anode.

(e) **Data logger.** We use a HP data logger which can record potentials and/or current values at preselected time intervals.

(f) **Potentiostat.** This device measures and controls the potentials of the electrodes in an electrochemical cell. We can run many electrochemical experiments using the potentiostat, including polarization, voltammetry, corrosion measurement, and electrochemical impedance spectroscopy. The device consists of an electric circuit which controls the potential across the cell by sensing changes in its resistance and varies the current accordingly.

**Figure 19.** Parts for electronic measurements and data acquisition.

### 3. PREPARING AND OPERATING A MICROBIAL FUEL CELL

#### 3.1. Assembling a MFC.

- The following parts are required to assemble a MFC
  1. Anode compartment
  2. Cathode compartment
  3. Two cover sheets
  4. Two graphite electrodes
  5. Membrane
  6. Four rubber gaskets
  7. Twenty-four nuts and 12 bolts
  8. Six connectors
  9. Two feet of silicon tube
  10. Silicon rubber
  11. Five clamps
b. Diagram that shows the dimensions and relative positions of the MFC parts

![Diagram of MFC parts]

Figure 20. Microbial fuel cell. A) General view. B) Side plates. Port 1: outlet, port 2: air or nitrogen, port 3: media feed line. C) Growth chamber for anodic or cathodic compartment. D) Top view of the cell. Port 4 is for the salt bridge for the reference electrode, and ports 5 and 6 are for the electrical wires connected to the electrodes. E) Electrode configurations used in the compartments.

c. Connecting electrical wires to the electrodes

To make sure of electrical connectivity we use two-point connections. In a two-point connection, two electrical wires are connected in each electrode at a distance of 2 cm. For the graphite plate electrode, the two holes are made 2 cm apart. The wire is inserted into the hole and filled with conductive epoxy. We use commercially available silver conductive epoxy (www.circuitspecialists.com) to connect the electrical wires with the electrodes. This conductive epoxy offers high electrical conductivity and strong conductive bonding. It is also good for long-term experiments in wet conditions. If we use two-point connections, we can check the connectivity of the wire with the electrodes while running the MFC; in addition, if one connection fails the other may work. The electrical connections are checked.
by measuring the resistance between the wires. We consider a resistance of less than 1 ohm between two wires acceptable for a good connection.

d. Cleaning the MFC parts
  1. Wash using glass cleaning detergent and tap water
  2. Rinse all the parts using tap water

Figure 21. Steps for assembling a MFC.

e. Assembling procedure

1. Insert a graphite electrode into the anode compartment (Figure a)
2. Insert a graphite electrode into the cathode compartment (Figure a)
3. Ensure that the wires are routed through the appropriate ports (Figure a, b)
4. Place a rubber gasket on the inner side of the cathode compartment (Figure b)
5. Place the membrane after the gasket placed in step 4 (Figure c)
6. Place a rubber gasket on the other side of the membrane (Figure d)
7. Put the cathode and anode compartments together (Figure e)
8. Place rubber gaskets on the outsides of the anode and cathode compartments (Figure f)
9. Place the cover plates on the outside of the anode and cathode compartments (Figure g)
10. Insert the ready-rod (including a washer on each end). Tighten (hand-tight is enough) using wing nuts. DO NOT overtighten, because you may break
the polycarbonate. If the reactor leaks when filled with liquid, tighten it a ¼ turn (Figure h, i)

11. Attach silicon tubes (2-inch) to the connectors (Figure j) at the bottom of the cover plates
12. Connect a flow breaker to a silicon tube (6-inch) and connect the tube to the connector at the top of the anodic compartment’s cover plate
13. Close the inlets and outlets using clamp stoppers (Figure j)
14. Apply silicon rubber to close the openings of the compartments
15. Let the silicon rubber cure overnight.

3.2. Sterilizing the MFC

1. Open two inlets in each compartment

![Figure 22](image-url) Filling the MFC with deionized water.

2. Fill both compartments with deionized (DI) water. Use a syringe (20-ml) to pour water inside. Keep a record of the liquid volume of the MFC.

![Figure 23](image-url) Clamps are used to close the inlets.

3. Close the inlets. Use the clamps shown in Figure 23.
Figure 24. MFC placed in an autoclavable tray.

4. Put the water-filled MFC in a tray (Figure 24). Be sure that the tray is autoclavable. Otherwise you may ruin the entire setup.
5. Put autoclave tape on it. After autoclaving the color of the tape is changed. The color change indicates that autoclaving is done.
6. Loosen (slightly) one clamp in each compartment (the clamp that is used to close the top inlet in each compartment). This step is important: otherwise the inside pressure may damage the silicon seal. When the autoclaving is done, close the feed lines keeping the tray inside the autoclave machine.

Figure 25. The tray with MFC placed inside the autoclave machine

7. Autoclave at 121°C for 15 mins. (We autoclave the MFC to kill all the bacteria present in the MFC, because later we will grow a single specific type of bacteria and we do not want any other bacteria to grow in the MFC.)
8. When autoclaving is done, close the inlets that were loosened to release the pressure. Take the tray out.
9. Cool the MFC down to atmospheric temperature.
10. Take the MFC out of the autoclave and cool it down to room temperature.

3.3. Growth medium composition
In this experiment we use two different mediums. The first medium is used to prepare the inoculum. The second medium is used to run the MFC for electricity generation. For inoculation we use LB broth (LB is an abbreviation for Lysogeny broth, a nutritionally rich medium. It is also known as Luria broth or Luria-Bertani broth.) The compositions of both types of growth medium for two different bacteria are shown below:
a. Growth medium composition for *Shewanella oneidensis* (MR-1)

**Table 2. Growth medium for *Shewanella oneidensis* (MR-1)**

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Formula</th>
<th>Composition (g/L)</th>
<th>Composition (g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tryptone</td>
<td>-</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Sodium chloride</td>
<td>NaCl</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Yeast extract</td>
<td>-</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Na-Lactate</td>
<td>C₃H₅O₃Na</td>
<td>-</td>
<td>11.23</td>
</tr>
<tr>
<td>Potassium phosphate</td>
<td>KH₂PO₄</td>
<td>-</td>
<td>0.77</td>
</tr>
<tr>
<td>Disodium phosphate</td>
<td>Na₂HPO₄</td>
<td>-</td>
<td>0.47</td>
</tr>
<tr>
<td>Ammonium chloride</td>
<td>NH₄Cl</td>
<td>-</td>
<td>1.5</td>
</tr>
<tr>
<td>Potassium chloride</td>
<td>KCl</td>
<td>-</td>
<td>0.1</td>
</tr>
</tbody>
</table>

b. Growth medium composition for *Klebsiella pneumoniae*

**Table 3. Growth medium for *Klebsiella pneumoniae***

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>Composition (g/L)</th>
<th>Composition (g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tryptone</td>
<td>-</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Sodium chloride</td>
<td>NaCl</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Yeast extract</td>
<td>-</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Disodium phosphate</td>
<td>Na₂HPO₄</td>
<td>-</td>
<td>1.825</td>
</tr>
<tr>
<td>Potassium phosphate</td>
<td>KH₂PO₄</td>
<td>-</td>
<td>0.35</td>
</tr>
<tr>
<td>Glucose</td>
<td>C₆H₁₂O₆</td>
<td>-</td>
<td>1</td>
</tr>
</tbody>
</table>

3.4. Preparing and sterilizing the growth medium

a. **Growth medium for MFC inoculation**

If there is ready growth medium for inoculation you can use it. However, you may need to go through the process with your TA.

1. Put about 400 ml of DI water in a 1000-mL pyrex bottle
2. Put the bottle on top of a magnetic stirrer controller
3. Put a magnetic stirrer inside the bottle
4. Start stirring
5. Weigh the chemicals (please see the composition in the table) and put them inside the bottle. DO NOT mix the chemicals. After weighing each chemical clean your spatula so you won't contaminate other chemicals. Be sure that your TA is watching you during this process.
6. Mix until all the chemicals are dissolved well
7. Add water to make up 500 ml of medium and mix well
8. Place the cap on the bottle and keep it a little bit loose. DON'T forget to do this: otherwise pressure will build up inside, which may cause damage when you take the bottle out.
9. Put the bottle in a tray
10. Autoclave at 121°C for 20 minutes
11. Close the cap
12. After the autoclaving is finished, cool the medium down to room temperature

b. Growth medium for electricity generation
1. Put approximately 400 ml of DI water in a 1000-mL pyrex bottle
2. Put the bottle on top of a magnetic stirrer controller
3. Put a magnetic stirrer inside the bottle
4. Start stirring
5. Weigh the chemicals (Please see the compositions in Table 2 and Table 3) and place them inside the bottle
6. Mix until all the chemicals are dissolved completely
7. Take 10 clean erlenmeyer flasks
8. Put 100 ml of medium in each of the flasks
9. Close the flasks using aluminium foil. See Figure 18j. Use two layers of aluminium foil for each flask to ensure there is no contamination.
10. Put the flasks in an autoclavable tray
11. Autoclave at 121°C for 15 mins
12. When the autoclaving is done, take the tray out and cool the medium down to room temperature.

3.5. Cathode compartment
Fill with a buffer (pH = 7) of the composition shown below:

<table>
<thead>
<tr>
<th>Components</th>
<th>Formula</th>
<th>Composition (g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disodium phosphate</td>
<td>Na₂HPO₄</td>
<td>1.825</td>
</tr>
<tr>
<td>Monopotassium phosphate</td>
<td>KH₂PO₄</td>
<td>0.35</td>
</tr>
</tbody>
</table>
3.6. Starting the MFC

Make sure you have the following items ready:
7. Assembled and sterilized MFC
8. Sterile growth medium for inoculation
9. Sterile growth medium for electricity generation
10. Disposable syringe and needle
11. Available laminar hood
12. Stock culture
13. 1-ml syringe, needle
14. Buffer
15. 70% alcohol
16. Air pump
17. Disposable syringe and needle

Use the following procedure to start the MFC
1. Clean and sterilize the laminar hood using 70% alcohol
2. Spray some alcohol on the MFC before putting it inside the hood
3. Take the sterilized MFC into the hood.
4. Take the sterile growth medium for inoculation, spray some alcohol on the bottle, and keep it inside the hood
5. Remove the DI water from both the anodic and cathodic compartments
6. Remove the silicon rubber from the two inlets of the cathode at the top of the cathode compartment
7. Fill the cathode compartment with buffer
8. Fill the anode compartment with growth medium for inoculation
9. Innoculate the MFC:
   a. Take stock culture from the freezer (kept at -85°C) to the hood and let the culture thaw. Do not wait for prolonged times because thawed cells may lose their activity. Generally it takes several minutes for thawing.
   b. Take one flask with sterile growth medium to the hood
   c. Take a 1-ml syringe and needle
   d. Open the stock culture vial
   e. Take the culture using the syringe
   f. Put the stock culture inside the anode compartment through one opening at the top. You do not need to remove the silicon rubber. Just insert the needle through the silicon rubber and push the syringe.
   g. Shake the MFC a little so that the culture is mixed well immediately
10. Take the MFC out from the hood
11. Please DO NOT forget to clean the hood using 70% alcohol and keep all tools where they belong
12. Pump air into the cathode at a moderate rate
13. Pump air into the anode chamber (for better growth and biofilm formation on the electrode surface). Keep pumping air only for 24 hrs. You need to
stop the air for electricity production: otherwise electrons will be delivered to the oxygen.

3.7. Operation of the MFC in batch mode
After starting the MFC the following steps are required for the operation of the MFC.
1. Maintain air flow to the anode compartment for 24 hrs
2. Maintain air flow to the cathode compartment continuously
3. Follow the fill and draw method: Draw 100 ml of cell culture from the anode side and fill with 100 ml of new medium. Consult with your TA during this fill and draw, because, depending on the experimental plan, you may need to change the fill and draw procedure.
   a. Put the MFC into the hood
   b. Remove 100 ml of cell culture from the anode by releasing the opening at the bottom
   c. Put the flask of growth medium (100 ml) for electricity generation into the hood
   d. Use a syringe to pump in 100 ml of new medium
4. Replace 100 ml of buffer from the cathode every day. You can do this outside the hood

4. Monitoring the potentials of the anode, cathode and MFC and the current of the MFC
We use a data logger to monitor the electrode potentials and current. Consult with your TA about connecting the electrodes to the data logger and computer system.

4.1. Connecting the MFC to the data logger
   1. Connect the data logger to the computer (ask TA for assistance)
   2. Connect the three electrodes to the three electrical wires
   3. Label the wires as anode, cathode and reference
   4. Connect the other end of the cable coming from the electrodes to data logger port #204 (anode), #205 (cathode) and ground (reference), respectively
   5. Verify the potentials read by the data logger using a multimeter reading data directly from the MFC ports
   6. A graphical representation may be observed on the computer screen if it is connected to the HP data logger.

4.2. Post processing
   1. Saving data: File-export data-tab delimited-channels-click start time-end time-Ok
   2. Open the file with ‘MS Excel ®
   3. Save as an ‘xls’ file. You are ready to analyze the data.
5. EXPERIMENTAL PLAN FOR CHE 475

We expect the students to spend a total of seven hours and follow the following steps in the lab.

**Day 1 (3 hrs): Make the MFC ready**
1. Clean the MFC parts
2. Measure and record the surface areas of the anode and cathode
3. Assemble the MFC
4. Prepare the growth medium for inoculation and inoculate it with the bacteria
5. Sterilize the MFC and medium

**Day 2. (1 hr): Start the MFC**
Inoculate the MFC and monitor the open circuit potentials
1. Start the MFC (see starting procedure)
2. Test the initial potential using a multimeter
3. Set the data acquisition system
4. Monitor the potentials continuously every 15 mins: Connect a 1000-Ω resistor between the anode and the cathode and monitor the anode and cathode potentials with respect to the reference electrode

**Day 3. (30 mins): Fill and draw**
5. Draw 100 ml of medium from the anode and feed in 100 ml of new sterile growth medium
6. Draw 100 ml of buffer from the cathode compartment and feed in 100 ml of fresh buffer

**Day 4 (30 mins): Fill and draw**
7. Draw 100 ml of medium from the anode and feed in 100 ml of new sterile growth medium
8. Draw 100 ml of buffer from the cathode compartment and feed in 100 ml of fresh buffer

**Day 5. Characterize the MFC (1 hr)**
9. Characterize the MFC using a polarization experiment (Your TA will help you to run this experiment)
   a. Change the setting to read data every 5 seconds
   b. Disconnect the resistor from the MFC
   c. Wait until the MFC has a cell potential of 500 mV
   d. Be sure the resistor box is ready
   e. Be sure that the resistor box has at least 0 to 10 kohms
f. Plan how you will change the resistor: advance planning is encouraged for a quick change of the resistor

g. Tips: The resistor box is operated manually, so be careful while changing the resistors. Practice this one with your TA.

h. Change the resistor every 30 sec. Start from 10K then 9k, 8k...1k, 900, 800...200, 100, 90, 80...20, 10, 9, 8...2, 1, done!!!

Day 6 (1 hr): Deassembling and cleaning

10. Stop the MFC and data acquisition system
11. Take the medium and buffer out of the MFC
12. Clean the parts with lots of hot water
13. Autoclave all MFC parts other than the membrane
14. Clean the membrane using hot water (don’t scratch with a sharp object) and keep it in a 0.1 M NaCl solution

Report:
For day-to-day operation and data acquisition:
1. Anode, cathode and cell potentials vs. time

For characterization experiments:
2. Cell potential vs. current density
3. Power density vs. current density
4. Answers to the test questions

6. SAMPLE EXPERIMENTAL RESULTS

Experiment 1
Applying a constant load and observing for a long time

Figure 26. A batch MFC run for a long time. The arrows show the fill and draw times (here fill and draw was done when the cell potential became very low (around 50-100 mV).
A 1000-ohm resistor was connected between the anode and the cathode and the cell potential was monitored overnight. The MFC was run using *Klebsiella pneumoniae* using the growth medium described above. The surface area of the electrode was 47 cm$^2$. The potentials of the electrodes were measured against SCE. Sample raw data are shown in Table 5.

**Table 5.** Sample raw data from the HP data logger. Potentials were read every 15 sec. VDC indicates DC voltage.

<table>
<thead>
<tr>
<th>Anode</th>
<th>204(Seconds)</th>
<th>204(VDC)</th>
<th>205(Seconds)</th>
<th>205(VDC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.018</td>
<td>-0.05693</td>
<td>0.018</td>
<td>1.47E-01</td>
<td></td>
</tr>
<tr>
<td>15.002</td>
<td>-0.05758</td>
<td>15.002</td>
<td>1.47E-01</td>
<td></td>
</tr>
<tr>
<td>30.002</td>
<td>-0.05824</td>
<td>30.002</td>
<td>1.47E-01</td>
<td></td>
</tr>
<tr>
<td>45.002</td>
<td>-0.05889</td>
<td>45.002</td>
<td>1.47E-01</td>
<td></td>
</tr>
<tr>
<td>60.002</td>
<td>-0.05954</td>
<td>60.002</td>
<td>1.47E-01</td>
<td></td>
</tr>
<tr>
<td>75.002</td>
<td>-0.06019</td>
<td>75.002</td>
<td>1.47E-01</td>
<td></td>
</tr>
<tr>
<td>90.002</td>
<td>-0.06084</td>
<td>90.002</td>
<td>1.47E-01</td>
<td></td>
</tr>
<tr>
<td>105.002</td>
<td>-0.0615</td>
<td>105.002</td>
<td>1.47E-01</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 27.** Power vs. time. This profile looks the same as that of cell potential vs. time. The power was calculated using $P = \frac{V_{Cell}^2}{R}$. The maximum power density was 254 µW/cm$^2$. 

86
Experiment 2
Polarization experiment

Figure 28. Experimental data. A. Current vs. time. B. Cell potential vs. time. The load was changed every 30 sec as described in Section 5.
Figure 29. Calculated data: cell potential vs. current density. These data are calculated from Figure 28.

Figure 30. Calculated data: power density vs. current density. This figure is used to characterize the MFC.
Figure 31. Anode and cathode and cell potentials vs. resistance. You can see that the anode potential changes with the resistor but the cathode potential is constant. This tells us that the anode electrode is the limiting electrode.

7. TEST QUESTIONS/ DISCUSSION OF THE CONCEPTS

1. Which bacterium is expected to produce more current?
2. What would you do to increase the power of the MFC?
3. How would you change the design of the MFC you used in this experiment if you were asked to power your house using a MFC?
4. Assume the oxidation of glucose at the anode and reduction of oxygen at the cathode follow these reactions:

   Anodic reaction: $C_6H_{12}O_6 + 6H_2O \rightleftharpoons 6CO_2 + 24H^+ + 24e^-$

   Cathodic reaction: $6O_2 + 24H^+ + 24e^- = 12H_2O$

   What will the current generation be if the glucose consumption is 1 kg/hr?

5. Calculate the energy efficiency in your experiment and compare it with Carnot efficiency assuming the same fuel cell is used for producing heat by combustion.
8. EXPERIMENTAL CONDITIONS FOR VARIOUS EXPERIMENTS

The following table demonstrates various experimental conditions. We plan to run experiments in groups. Each group will have an opponent group to make up a team. The groups in each team will run identical experiments except for one variable. Later there will be a debate in the class to discuss the experimental results and concepts.

Table 6. Planned group and team experimental conditions.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Conditions in the MFC</th>
<th>Concepts from this experiment</th>
<th>Chemical Engineering concepts</th>
</tr>
</thead>
</table>
2. Potential (Nernst equation), current, electrode kinetics (Butler-Volmer equation)  
3. MFC faradic efficiency  
4. Energy efficiency | Equilibrium  
Kinetics  
Energy conservation  
Mass conservation  
Sustainability |
| Electrode material  | 1. Graphite 2. Stainless steel                 | 1. Microbes-solids interaction  
2. Potential (Nernst equation), current, electrode kinetics (Butler-Volmer equation)  
3. Faradic efficiency (charge balance)  
4. Energy efficiency (Energy balance) | Equilibrium  
Kinetics  
Energy conservation  
Mass conservation  
Sustainability |
2. Potential (Nernst equation), current, electrode kinetics (Butler-Volmer equation)  
3. Faradic efficiency (charge balance)  
4. Energy efficiency (Energy balance) | Equilibrium  
Kinetics  
Energy conservation  
Mass conservation  
Sustainability |
| Membrane            | 1. Proton exchange membrane 2. Dialysis      | 1. Ion transport in membrane  
2. Potential (Nernst equation), current, electrode kinetics (Butler-Volmer equation)  
3. Faradic efficiency (charge balance)  
4. Energy efficiency (Energy balance) | Equilibrium  
Kinetics  
Energy conservation |


<table>
<thead>
<tr>
<th>Redox mediator</th>
<th>Membrane kinetics (Butler-Volmer equation)</th>
<th></th>
<th>Mass conservation Sustainability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. HNQ (external redox mediator)</td>
<td>1. Faradic efficiency (charge balance)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. No mediator</td>
<td>4. Energy efficiency (energy balance)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load</th>
<th>Membrane kinetics (Butler-Volmer equation)</th>
<th></th>
<th>Mass conservation Sustainability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Low resistor</td>
<td>1. Potential (Nernst equation), current, electrode kinetics (Butler-Volmer equation)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. High resistor</td>
<td>2. Faradic efficiency (charge balance)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Energy efficiency (Energy balance)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

REFERENCES

The Power of Fruit: A Study in Electrochemistry

Benjamin Morgan
Salk Middle School
Spokane, WA
&
Don Dotson
Charles Francis Adams High School
Clarkston, WA

Washington State University Advisors
Dr. Su Ha
Dept. of Chemical Engineering
&
Michael Fishback
Graduate Research Assistant
July 2006

The Project herein was supported by the National Science Foundation Grant No. EEC-0338868. Dr. Richard Zollars, Principle Investigator and Dr. Donald C. Orlich, co-PI. The module was developed by the authors and does not represent an official endorsement by the National Science Foundation.
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project summary</td>
<td>3</td>
</tr>
<tr>
<td>Overview of project</td>
<td>3</td>
</tr>
<tr>
<td>Intended audience</td>
<td>3</td>
</tr>
<tr>
<td>Estimated duration</td>
<td>3</td>
</tr>
<tr>
<td>Introduction</td>
<td>4</td>
</tr>
<tr>
<td>Rationale for module</td>
<td>5</td>
</tr>
<tr>
<td>Science</td>
<td>6</td>
</tr>
<tr>
<td>Engineering</td>
<td>6</td>
</tr>
<tr>
<td>Goals</td>
<td>7</td>
</tr>
<tr>
<td>Prerequisite student skills/knowledge</td>
<td>13</td>
</tr>
<tr>
<td>Procedures</td>
<td>13</td>
</tr>
<tr>
<td>Safety precautions</td>
<td>13</td>
</tr>
<tr>
<td>Lab Equipment</td>
<td>14</td>
</tr>
<tr>
<td>Lab activity #1</td>
<td>15</td>
</tr>
<tr>
<td>Lab activity #2</td>
<td>24</td>
</tr>
<tr>
<td>Lab activity #3</td>
<td>31</td>
</tr>
<tr>
<td>Lab activity #4</td>
<td>41</td>
</tr>
<tr>
<td>Lab activity #5</td>
<td>50</td>
</tr>
<tr>
<td>Lab activity #6</td>
<td>67</td>
</tr>
<tr>
<td>Lab activity #7 (Final Project)</td>
<td>73</td>
</tr>
<tr>
<td>References</td>
<td>83</td>
</tr>
</tbody>
</table>
PROJECT SUMMARY:

Overview of project

This module has been designed to enhance interest in engineering amongst middle school students through the design of batteries using fruit and common household items. The reading material and lab activities provide opportunities to better understand electricity, the chemistry involved in battery function, battery structure and the basic principles of engineering. Further, the pre-project activities and the designing of a multi-celled battery in the final project incorporate many of the essential academic learning requirements promoted by the Office of Superintendent of Public Instruction.

Intended audience

Our intended audience is middle school (sixth through ninth grade) students and teachers. Teachers and students with minimal background knowledge in chemistry, electricity and battery function can perform these activities. The activities, and especially the design phase of this module, can be modified to accommodate high school chemistry and physics students. Much effort was put into the data chart and teacher notes to give the instructor as much background information as possible so as to reduce teacher preparation time for this module. Most of the necessary materials are commonly found at the local grocery and/or hardware store.

Estimated duration

This module is designed to build on each preceding activity beginning with an understanding of how to measure electricity with a multi-meter through measuring electricity
flow produced in batteries and fruit to culminating in developing a fruit battery to power a simple electrical devise. Two weeks is the estimated time necessary to complete the entire module.

**INTRODUCTION:**

Electrochemistry can be a challenging subject to comprehend at any level but for middle school students, most getting their first introduction to the topic, electrochemistry can be quite overwhelming. Hands on activities and a very visual medium can help to alleviate some of the difficulties. Much about electrochemistry can be learned from activities involving simple batteries. From understanding how to use a multi-meter to developing a serial arrangement of fruit used to power a small electrical devise, the basics of electrochemistry are worked out by the students in this interactive learning module.

Many molecules readily give up electrons and/or protons to solution whereas others readily accept them. The “goal” of these molecules is to for electrical stability.

When a battery is in use, one post (termed the anode) readily gives up protons to the solution (electrolyte) it is bathed in. At the same time electrons will travel from this same post (to maintain stability) through a wire (or some other conductor) to the other post (cathode), which tends to collect the electrons. Here the electrons from the cathode and the protons released into the electrolyte combine. The electrons passing through the wire connecting the two posts constitute the battery’s electrical potential.

Any solution containing positively and negatively charged particles (this includes most fruits and vegetables) can be used as an electrolyte. Metals (such as copper and zinc) having differing levels of attraction for the electrons and protons that make them up serve as the sites for
the electrochemical reactions to take place. This knowledge forms the basis for our module in which students learn about the processes of electrochemistry through activities that combine the science and engineering behind batteries. The knowledge gained through these, inquiry-based, activities culminates in a competition to build the most economic fruit battery!

**RATIONALE:**

The goal of the originators of the grant funding this project is to increase middle and high school students’ exposure to and understanding of the various fields of engineering. A “best fit” for this introduction to engineering would seem to be in the science curriculum of middle and high schools. With this in mind the developers of this module strived to combine existing curriculum with new activities and a new angle so as to fulfill the goals of the project while at the same time avoiding the necessity of removing existing material from the science curriculum. The module introduces students to (or builds upon existing knowledge, depending at what level this module is used) key scientific principles such as atomic structure of matter, oxidation/reduction reactions, electricity, conductivity and pH, along with developing an engineering mindset in the students as they work through the difficult concept of “design within a budget”. Depending on the science background of the instructor and students, this module could easily be used at the introductory level in a middle school physical science course or with slight modification, in a high school physics or chemistry course.

**SCIENCE:**
The scientific basis of this module is the concept of electrochemistry; that bridge between the energy in the bonds of matter and “free” energy in the form of electricity used to power everyday items such as televisions and light bulbs. Electrochemistry cannot be discussed in any detail without including the concept of oxidation and reduction reactions, often the method by which chemical energy is changed to electrical energy. To the middle school student many new terms relating to the science of electricity and batteries are introduced. Terms such as; voltage, current, amperage, ohms, anode, cathode, and electrolyte, along with several others will, by design, become part of the students’ vocabulary during this module.

**ENGINEERING:**

Arguably the key to this module is the melding of engineering and science in such a way so as to not have to remove existing curriculum from the science course but rather to teach the same concepts from an engineering view. The culminating project involves the students competing to build the most powerful battery for the least cost (similar to what engineers are asked to do regularly). The hitch is they have to use the energy locked in the bonds of various common metals and the ions found in the juices of every day fruits. The idea is that each item they choose to use (galvanized nail, strip of copper, tomato etc) has a price attached to it which may or may not correlate to its value as part of the battery they design. To keep their costs as low as possible they must determine which items work best together to produce the greatest electrical potential. At the same time they will need to figure out how much energy (volts and amps) they will need to sound the alarm (a piezo buzzer). The engineering aspect becomes quite
evident when “best” doesn’t necessarily translate into most economical and a battery built in series might be a better battery, economically, than one built with the “best “ materials.

**GOALS:**

The goals of this project match the GLE’s. Bear in mind that you may focus on which GLE/EALR fits your needs.

**Grade Level Expectation: CH03 1.3.3 Conservation of Matter and Energy**

Understand that matter is conserved during physical and chemical changes. W

1. (7) Observe and describe evidences of physical and chemical changes of matter (e.g., change of state, size, shape, temperature, color, gas production, solid formation, light).

2. (7) Observe and describe that substances undergoing physical changes produce matter with the same chemical properties as the original substance and the same total mass (e.g., tearing paper, freezing water, breaking wood, sugar dissolving in water).

3. (7) Observe and describe that substances may react chemically to form new substances with different chemical properties and the same total mass (e.g., baking soda and vinegar, light stick mass before, during, and after reaction).

**Grade Level Expectation: PR04 1.1.4 Forms of Energy**

Understand that energy is a property of matter, objects, and systems and comes in many forms (i.e., heat [thermal] energy, sound energy, light energy, electrical energy, kinetic energy, potential energy, and chemical energy). W

1. (6) Describe the forms of energy present in matter, objects, and systems (i.e., heat [thermal] energy, sound energy, light energy, electrical energy, kinetic energy, potential energy, and chemical energy).

2. (6) Describe the form of energy stored in a part of a system (i.e., energy can be stored in many forms, “stored energy” is not a form of energy).

3. (8) Compare the potential and kinetic energy within a system at various locations or times (i.e., kinetic energy is an object’s energy of motion, potential energy is an object’s energy of position).
Grade Level Expectation: ST01 1.2.1 Systems Approach

Analyze how the parts of a system interconnect and influence each other. W

1. (6) Explain how the parts of a system interconnect and influence each other.

2. (7) Describe the flow of matter and energy through a system (i.e., energy and matter inputs, outputs, transfers, transformations).

3. (8) Describe the interactions and influences between two or more simple systems

Grade Level Expectation: ST02 1.2.2 Energy Transfer and Transformation

Understand how various factors affect energy transfers and that energy can be transformed from one form of energy to another. W

1. (6) Describe and determine the factors that affect heat energy transfer (e.g., properties of substances/materials [conductors, insulators], distance, direction, position).

2. (6) Describe how an increase in one type of energy of an object or system results in a decrease in other types of energy within that object or system (e.g., a falling object’s potential energy decreases while its kinetic energy increases).

3. (6) Describe how waves transfer energy (e.g., light waves transfer energy from sun to Earth, air transfers an object’s vibrations from one place to another as sound).

4. (8) Explain the transfer and transformations of energy within a system (e.g., conduction and convection of heat (thermal) energy).

Grade Level Expectation: DE01 3.1.1 Identifying Problems (continued)

Analyze common problems or challenges in which scientific design can be or has been used to design solutions. W

1. (6, 7, 8) Describe how science and technology could be used to solve all or part of a human problem and vice versa. (e.g., understanding erosion can be used to solve some flooding problems).

2. (6, 7, 8) Describe the scientific concept, principle, or process used in a solution to a human problem (e.g., understanding of the relationship between electricity and magnetism has been used to make electric motors and generators).
3. (6, 7, 8) Explain how to scientifically gather information to develop a solution (e.g. and collect data by measuring all the factors and establish which are the most important to solve the problem).

4. (6, 7, 8) Describe an appropriate question that could lead to a possible solution to a problem.

**Grade Level Expectation: DE02 3.1.2 Designing and Testing Solutions**
Apply the scientific design process to develop and implement solutions to problems or challenges. W

1. (6, 7, 8) Propose, implement, and document a scientific design process used to solve a problem or challenge by:
   - define the problem
   - scientifically gather information and collect measurable data
   - explore ideas
   - make a plan
   - list steps to do the plan
   - scientifically test solution
   - document the scientific design process

2. (6, 7, 8) Explain possible solutions to the problem (e.g., use pulleys instead of leavers to lift a heavy object).

3. (6, 7, 8) Explain the reason(s) for the effectiveness of a solution to a problem or challenge.

**Grade Level Expectation: DE03 3.1.3 Evaluating Potential Solutions**
Analyze multiple solutions to a problem or challenge. W

1. (6, 7, 8) Describe the criteria to evaluate an acceptable solution to the problem or challenge.

2. (6, 7, 8) Describe the reason(s) for the effectiveness of a solution to a problem or challenge using scientific concepts and principles.

3. (7, 8) Describe the consequences of the solution to the problem or challenge (e.g., using rocks on the edge of a stream to prevent erosion may destroy habitat).

4. (7, 8) Describe how to change a system to solve a problem or improve a solution to a problem.

5. (8) Compare the effectiveness of different solutions to a problem or challenge based on criteria, using scientific concepts and principles.

**Grade Level Expectation: DE04 3.2.1 All Peoples Contribute to Science and Technology**
Analyze how science and technology have been developed, used, and affected by many diverse individuals, cultures, and societies throughout human history.

1. (6, 7, 8) Explain how the contributions of diverse individuals have led to the development of science and technology.
2. (6, 7, 8) Explain how science and technology have affected individuals, cultures, and societies throughout human history.

**Grade Level Expectation: DE05 3.2.2 Relationship of Science and Technology**

Analyze scientific inquiry and scientific design and understand how science supports technological development and vice versa.

1. (7, 8) Describe how scientific investigations and scientific research support technology (e.g., investigation into materials led to Gortex and Kevlar).
2. (7, 8) Describe how technology supports scientific investigations and research (e.g., microscopes led to the discovery of unicellular organisms).
3. (7, 8) Describe how a scientifically designed solution to a human problem can lead to new tools that generate further inquiry (e.g. microscopes, telescopes, and computers).
4. (7, 8) Compare the processes of scientific inquiry and scientific design in terms of activities, results, and/or influence on individuals and/or society.

**Grade Level Expectation: DE06 3.2.3 Careers and Occupations Using Science, Mathematics, and Technology**

Analyze the use of science, mathematics, and technology within occupational/career areas of interest.

**Grade Level Expectation: IN01 2.1.1 Questioning**

Understand how to generate a question that can be answered through scientific investigation.

1. (6, 7, 8) Generate multiple questions based on observations.
2. (6, 7, 8) Generate a question that can be investigated scientifically.
3. (6, 7, 8) Generate a new question that can be investigated with the same materials and/or data as a given investigation.

**Grade Level Expectation: IN02 2.1.2 Planning and Conducting Safe Investigations**
Understand how to plan and conduct scientific investigations. W

- (6, 7, 8) Make predictions (hypothesize) and give reasons.
- (6, 7, 8) Generate a logical plan for, and conduct, a scientific controlled investigation with the following attributes:
  - prediction (hypothesis)
  - appropriate materials, tools, and available computer technology
  - controlled variables (kept the same)
  - one manipulated (changed) variable
  - responding (dependent) variable
  - gather, record, and organize data using appropriate units, charts, and/or graphs
  - multiple trials
- (6, 7, 8) Generate a logical plan for a simple field investigation with the following attributes:
  - Identify multiple variables
  - Select observable or measurable variables related to the investigative question
- (6, 7, 8) Identify and explain safety requirements that would be needed in the investigation.

**Grade Level Expectation: IN03 2.1.3 Explaining**
Apply understanding of how to construct a scientific explanation using evidence and inferential logic. W

1. (6, 7, 8) Generate a scientific conclusion including supporting data from an investigation using inferential logic (e.g. Chewing gum loses more mass than bubble gum after being chewed for 5 minutes. Chewing gum lost 2.00 grams while bubble gum only lost 1.47 grams).

2. (6, 7, 8) Describe a reason for a given conclusion using evidence from an investigation.

3. (6, 7, 8) Generate a scientific explanation of an observed phenomena using given data.

4. (6) Predict what logically might occur if an investigation lasted longer or changed.

5. (7, 8) Describe the difference between evidence (data) and conclusions.

**Grade Level Expectation: IN04 2.1.4 Modeling**
Analyze how models are used to investigate objects, events, systems, and processes. W
1. (6) Compare models or computer simulations of phenomena to the actual phenomena.

2. (6) Explain how models or computer simulations are used to investigate and predict the behavior of objects, events, systems, or processes.

3. (6, 7, 8) Create a model or computer simulation to investigate and predict the behavior of objects, events, systems, or processes. (e.g., phases of the moon using a solar system model).

4. (7) Explain the advantages and limitations of investigating with a model.

**Grade Level Expectation: IN05 2.1.5 Communicating**

Apply understanding of how to report investigations and explanations of objects, events, systems, and processes. W

1. (6, 7, 8) Report observations of scientific investigations without making inferences.

2. (6, 7, 8) Summarize an investigation by describing:
   - reasons for selecting the investigative plan
   - materials used in the investigation
   - observations, data, results
   - explanations and conclusions in written, mathematical, oral, and information technology presentation formats
   - ramifications of investigations
   - safety procedures used

3. (6, 7, 8) Describe the difference between an objective summary of data and an inference made from data.

**2.2 Nature of Science**

Understand the nature of scientific inquiry.

Apply curiosity, honesty, skepticism, and openness when considering explanations and conducting investigations.

**Grade Level Expectation: IN09 2.2.4 Evaluating Methods of Investigation**

Understand how to make the results of scientific investigations reliable and how to make the method of investigation valid. W

1. (6) Describe how the method of an investigation ensures reliable results (e.g., multiple trials ensure more reliable results).

2. (6, 7, 8) Describe how to increase the reliability of the results of an Investigation (e.g., repeating an investigation exactly the same way increases the reliability of the results).
3. (7, 8) Describe how the method of an investigation is valid (i.e., validity means that the investigation answered the investigative question with confidence; the manipulated variable caused the change in the responding or dependent variable).

4. (7, 8) Describe the purpose of the steps and materials of an investigation’s procedure in terms of the validity of the investigation.

5. (8) Modify an investigation to improve the validity of the investigation and explain how the modifications improved the validity (e.g., more controlled variables, more accurate measuring techniques, greater sample size).

**PREREQUISITE STUDENT SKILLS AND KNOWLEDGE:**

Students should have already studied atoms, molecules, bonding, and energy transformations. Ionic bonding should be specifically studied. During the course of this project we have focused the attention on the concepts of ions, electrons, chemical changes, and energy transformations (chemical-to-electric) is studied. You may also choose to delve into pH and many other variables.

**PROCEDURES:**

**Safety precautions:**

Though none of the activities carried out in this module pose any undo risk of injury, common laboratory safety practices should be observed. Protective eyewear should be worn at all times during the lab activities. Though unlikely, the possibility of eye damage due to contact with metal shavings, wires or liquids does exist and should be noted to the students. Due to the use of batteries and the generation of small electrical currents the possibility of minor electrical shock does exist. The metals used in this module are not highly reactive but caution should be given that chemical and physical reactions are taking place at the electrodes. Especially with the
magnesium but as well with all of the metals, gases are being released, some of which are flammable. In these activities the amounts of gasses are negligible but present. Finally, though some of the activities do involve the use of fruits and/or vegetables, these items should not be eaten before, during or after the completion of the labs.

**Necessary equipment:**

Each activity will have a detailed list of the necessary equipment and supplies. The following is a general list of the equipment and supplies needed to conduct all of the activities included in this module: Multi-meters able to measure in millivolts and milliamps, battery powered calculator, 1.5 volt LED diode, piezo buzzer (RadioShack), small beakers, AA batteries, copper and aluminum wire, wire cutters, galvanized nails, copper pennies, 1x5 cm strips of copper, aluminum and zinc, magnesium strips, various fruits and/or the juices of these fruits.

---

**Activity/Lab #1**

**Purpose/General Activity Information:**
This activity is divided into two segments: how to use a multimeter and determining some good conducting and insulating materials. In the first part students are given a multimeter and some different batteries. Their objective is to learn how to measure current and voltage using a multimeter. In the second segment students use a battery connected to a multimeter and then measure the current by using different materials to connect the anode to the cathode of the battery; thereby, determining some good conductors/insulators.

\[ \text{Battery} \quad \text{Multimeter} \]

Pencil, glass, aluminum foil, etc. will fill in the gap here

**Conclusions/Teacher Notes:**

In Part 1 students should learn how to use a multimeter. They should learn the following:

- The black wire should ALWAYS be connected to the “COM”
- The other side of the black test probe should ALWAYS be connected to the negative (anode) side of the battery
- When measuring current:
  - The red wire should be connected to the “Ω”
- The other side of the red test probe should be connected to the positive side of the battery (cathode). Students should be aware that they should only use the ones marked with ≠ NOT.

- When measuring voltage:
  - The red wire should be connected to the “V”
  - The other side of the red test probe should be connected to the positive side of the battery (cathode). Students should be aware that they should only use the ones marked with ≠ NOT.

In Part 2 students should learn about insulators and conductors. They should learn the following:

- Metals make better conductors than insulators
- Non-metals make better insulators than conductors
- Some metals are better conductors than others
- Some non-metals are better insulators than others

**Instructional Strategies:**

The teacher should observe students and help as needed keeping careful attention to student responses to the questions in the lab and that student duties are shared among group members.

**Data Collection:**

Students will fill in the questions as they follow the directions.
Data Analysis:

Part 1 – How to use a multimeter: Students will compare the voltage on the side of the battery with the voltage on their multimeter. They will then compare their current reading with the teacher’s result (can be shared on the overhead for each battery type).

Part 2 – Conductors versus Insulators: Students will utilize different materials and determine which materials are the best insulators and conductors.

Evaluation Protocols:

This is a formative assessment. The teacher should monitor student responses and help as needed. If vast issues arise then the teacher should model how to perform the sections where students are having issues. Students will not be able to understand later concepts if they are unable to use a multimeter or understand what good conductors and insulators are.

Worksheet/Handout to be Given to Students: (on next page)
ACTIVITY #1: USING A MULTIMETER

Purpose of Part 1:
To learn how to use a multimeter to measure things that a battery releases: voltage and current.

Materials/Equipment for Part 1:
- Multimeter
- 9 V battery
- Electrical tape (if needed)

Directions/Procedures for Part 1: How to use a multimeter

INSTRUCTIONS FOR MEASURING VOLTAGE:

20. **Black Test Probe:** Plug into the black terminal on multimeter marked “COM”

21. **Red Test Probe:** Plug the red probe into the red voltage socket marked “V” or “V/Ω”
22. Turn the dial to the V== segment. You may have several numbers to choose from (2, 20, or 200 for example). These are all voltage ranges. A maximum of 2 Volts, 20 volts, and 200 volts. Choose the one that fits the battery. Remember you are using a 9 Volt battery.

23. Take the black test probe and attach it to the negative (--) side of the battery.

24. Take the red test probe and attach it to the positive (+) side of the battery.

If you do not get a reading ask your teacher for help.

25. What voltage is the multimeter reading?

___________________________________

___________________________________________________________________

26. Look at the voltage on the side of the battery. What is the voltage?

_____________

___________________________________________________________________

27. What would cause the actual voltage to be less than the voltage reading on the side of the battery?

________________________________________________________

____________________________________________________________

___________________________________________________________________

__
28. If you were measuring the voltage of a AA battery what would you need to set the multimeter to?

________________________

________________________

INSTRUCTIONS FOR MEASURING CURRENT

29. When you connect the probes do NOT leave them attached for more than 5 seconds. This draws energy from the battery.

30. Plug the red test probe into the Red “20A” socket. Current is measured in amps.

31. Turn the multimeter to the 20A == setting.

32. DO NOT turn to any of the amp setting that have this sign on it (~)

33. Take the black test probe and attach it to the negative (--) side of the battery

34. Take the red test probe and attach it to the positive (+) side of the battery.

35. What current are you reading on the multimeter?

________________________________

________________________________

________________________________

________________________________

Check your answers with your teacher
36. _____ True or False: To measure voltage of a battery the multimeter should be turned to V~. If false change the answer so it is true:

_________________________________________________________________

_________________________________________________________________

_________________________________________________________________

37. _____ True or False: To measure the current of a battery the multimeter should be turned to A~. If false change the answer so it is true:

_________________________________________________________________

38. Answer the following questions by checking the appropriate box:

<table>
<thead>
<tr>
<th>Black Test Probe</th>
<th>Red Test Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>This test probe plugs into the “V/Ω” socket.</td>
<td></td>
</tr>
<tr>
<td>This test probe plugs into the A socket</td>
<td></td>
</tr>
<tr>
<td>This test probe is ALWAYS plugged into the “COM” socket</td>
<td></td>
</tr>
<tr>
<td>To measure voltage this test probe must be plugged into the V== socket</td>
<td></td>
</tr>
<tr>
<td>To measure current this test probe must be plugged into the 20A socket</td>
<td></td>
</tr>
<tr>
<td>This test probe touches the positive (+) side of the battery</td>
<td></td>
</tr>
<tr>
<td>This test probe touches the negative (--) side of the battery</td>
<td></td>
</tr>
</tbody>
</table>

**Purpose for Part 2:**
The purpose of this activity is to learn what good conductors are and what good insulators are. In addition, to give you some practice measuring voltage and current. Finally, to learn how to connect the wires from a battery to a light bulb (or other object) to power the devise.

**Equipment/Materials for Part 2:**

- Battery
- Multimeter
- Three wires with alligator clips
- Plastic pen
- Wood pencil
- Rubber eraser
- Graphite pencil lead
- Glass stirring rod
- Aluminum Wire
- Copper Wire
- Any other types of metal (copper strips, etc.)
- 12 V / 4 W light bulbs purchased at Home Depot (see picture)

**Directions/Procedures for Part 2: Conductors versus Insulators:**

A conductor allows energy to pass through it quickly. An insulator causes energy to pass through it slowly, if at all.

Construct a set-up like the diagram below:

```
Battery  -  +  Light
Pencil, glass, aluminum foil, etc. will fill in the gap here
```
6. Put each item into the space between the battery and multimeter then fill in the table:

<table>
<thead>
<tr>
<th>Material</th>
<th>Description of Light Intensity</th>
<th>Voltage</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Wire</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper Wire</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass stirring rod</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graphite (pencil lead)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nail</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic Pen</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rubber eraser</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7. What type of materials make good conductors?

______________________________

___________________________________________________________________

___________________________________________________________________

8. What type of materials make good insulators?

______________________________
9. Write the materials from your list in order from best conductor to best insulator in the space below:

Best Conductor:

Best Insulator:

10. Explain how you came up with the order for your “Best Conductor” – to – “Best Insulator” list:

___________________________________________________________________

___________________________________________________________________

___________________________________________________________________

___________________________________________________________________

11. Look at the intensity difference between the graphite and the nail.

- Identify which object lights the object better
- Explain why
Lab/Activity #2

Purpose/General Information:

This experiment builds off of the previous experiment (conductors vs. insulators). Students will design their own experiment that examines the effect that the amount of ions in water has on the conductibility of the water. Students will hook up a battery through distilled water like diagrammed:
They then measure the voltage and current. After this they add salt (NaCl) to the distilled water and measure the voltage and current again. They should find that the voltage remains the same, but the current increases. Thus, students are investigating the effect the amount of ions in water have on the conductivity of the water.

**Conclusions/Teacher Notes:**

Students should come up with the following results:

- **Conclusion:** The greater the amount of salt in water the greater the conductivity of the water.
- **Reason why:** there are more ions in water allowing electrons to pass through them more readily.
Equipment/Materials:

- Battery
- Distilled Water
- Table Salt
- Multimeter with chords
- Two electrodes of the same material (i.e. copper)

Instructional Strategies:

The teacher should observe students and help as needed. We suggest passing out the worksheet with 10-15 minutes left in class so that students may come to a consensus in their groups about what they will do in their experiment. They can then complete the experiment design section as homework.

Data Collection:

Students will design their own experiment given the experimental problem. Students will collect their data into a data table.

Data Analysis:

Students will take their data table and form a conclusion based off of their results.

Evaluation Protocols:
This is a formative assessment. The teacher should monitor student results and procedures. If issues arise then students may need to redo the experiment. Students should share their results with their teacher to get checked off.

**Worksheet/Handout to be Given to Students (next page)**

**Amount of Salt Experiment**

**Design an experiment to test the amount of salt.**

Be sure to include:
- Hypothesis (prediction) of the investigation results
- Materials that includes containers, all measurement devises, and anything else used
- Procedure that includes:
  - One manipulated (changed) variable
• One responding (dependent) variable
• One controlled (kept the same) variable
• Logical steps to do the investigation
• How often measurements are taken and recorded

**Question:** How does the amount of salt in water affect the conduction ability of the water?

<table>
<thead>
<tr>
<th>Question</th>
<th>Na</th>
<th>Cl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name of each atom?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of each atom in NaCl?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group Number each atom is in?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>What will each atom do: lose an electron or gain an electron?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge of ion?</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Hypothesis (Prediction):
Materials:

Use the space below to draw a labeled diagram to support your procedure:

Procedure:
Based on the data table from your experiment, write a conclusion that;
• Answers the investigative question
• Includes supporting data
• Explain how the data supports your conclusion

**Question:** How does the amount of salt in water affect the amount of electricity (voltage) that is made?

---

**Lab/Activity #3**

**Background Reading**

Battery Basics: How they work!

Batteries are found nearly everywhere in our lives -- in our cars, our PCs, laptops, portable MP3 players and cell phones, to name a few uses. A battery is essentially a can full of chemicals that produce electrons. Chemical reactions that produce electrons are called **electrochemical**
reactions. In this reading assignment, you'll learn all about batteries -- from the basic concept at work to the actual chemistry going on inside a battery to how they are used in our daily lives.

If you look at any battery, you'll notice that it has two terminals. One terminal is marked (+), or positive, while the other is marked (-), or negative. In an AA, C or D cell (normal flashlight batteries), the ends of the battery are the terminals. In a large car battery, there are two heavy lead posts that act as the terminals.

Electrons collect on the negative terminal of the battery. If you connect a wire between the negative and positive terminals, the electrons will flow from the negative to the positive terminal as fast as they can (and wear out the battery very quickly -- this also tends to be dangerous, especially with large batteries, so it is not something you want to be doing). Normally, you
connect some type of **load** to the battery using the wire. The load might be something like a light bulb, a motor or an electronic circuit like a radio.

Inside the battery itself, a chemical reaction produces the electrons. The speed of electron production by this chemical reaction (the battery's **internal resistance**) controls how many electrons can flow between the terminals. Electrons flow from the battery into a wire, and must travel from the negative to the positive terminal for the chemical reaction to take place. That’s why a battery can sit on a shelf for a year and still have plenty of power -- unless electrons are flowing from the negative to the positive terminal, the chemical reaction does not take place. Once you connect a wire, the reaction starts.

Alessandro Volta developed the first battery in 1800. To create his battery, he made a stack by alternating layers of zinc, blotting paper soaked in salt water, and silver. This arrangement was known as a **voltiac pile**. The top and bottom layers of the pile must be different metals, as shown. If you attach a wire to the top and bottom of the pile, you can measure a voltage and a current from the pile. The pile can be stacked as high as you like, and each layer will increase the voltage by a fixed amount.

The pile battery remained a laboratory curiosity for years, until the newly invented telegraph and telephone created a demand for reliable electrical power. After many years of experimentation, the "dry cell" battery was invented in the 1860s for use with the telegraph. The dry cell is not completely dry, however. It holds a moist paste inside a zinc container. The interaction of the paste and the zinc creates a source of electrons. A carbon rod is inserted into the paste and conducts electrons to the outside of the cell, where wires or metal contacts carry the electrons that power the device. A single dry cell produces about 1.5 volts.
Experiments:

If you want to learn about the electrochemical reactions used to create batteries, it is easy to do experiments at home to try out different combinations. To do these experiments accurately, you will want to purchase an inexpensive ($10 to $20) volt-ohm meter at the local electronics or hardware store. Make sure that the meter can read low voltages (in the 1-volt range) and low currents (in the 5- to 10-milliamp range). This way, you will be able to see exactly what your battery is doing.

You can create your own voltaic pile using coins and paper towels. Mix salt with water (as much salt as the water will hold) and soak the paper towel in this brine. Then create a pile by alternating pennies and nickels. See what kind of voltage and current the pile produces. Try a different number of layers and see what effect it has on voltage. Then try alternating pennies and dimes and see what happens. Also try dimes and nickels. Other metals to try include aluminum foil and steel. Each metallic combination should produce a slightly different voltage.

Another simple experiment you can try involves a baby food jar (if you don't have a baby around the house, just purchase a few jars of baby food at the market and empty them out), a dilute acid, wire and nails. Fill the jar with lemon juice or vinegar (dilute acids) and place a nail and a piece of copper wire in the jar so that they are not touching. Try zinc-coated (galvanized) nails and plain iron nails. Then measure the voltage and current by attaching your voltmeter to the two pieces of metal. Replace the lemon juice with salt water, and try different coins and metals as well to see the effect on voltage and current.

Probably the simplest battery commercially made is called a zinc/carbon battery. By understanding the chemical reaction going on inside this battery, you can understand how
batteries work in general.

Imagine that you have a jar of sulfuric acid (H2SO4). Stick a zinc rod in it, and the acid will immediately start to eat away at the zinc. You will see hydrogen gas bubbles forming on the zinc, and the rod and acid will start to heat up. Here's what is happening:

- The acid molecules break up into three ions: two H+ ions and one SO4-- ion.
- The zinc atoms on the surface of the zinc rod lose two electrons (2e-) to become Zn++ ions.
- The Zn++ ions combine with the SO4-- ion to create ZnSO4, which dissolves in the acid.
- Electrons from the zinc atoms combine with the hydrogen ions in the acid to create H2 molecules (hydrogen gas). We see the hydrogen gas as bubbles forming on the zinc rod.

If you now stick a carbon rod in the acid, the acid does nothing to it. But if you connect a wire between the zinc rod and the carbon rod, two things change:

- Electrons flow through the wire and combine with hydrogen on the carbon rod, so hydrogen gas begins bubbling off the carbon rod.
- Less energy is released as heat. You can power a light bulb or similar load using the electrons flowing through the wire, and you can measure a voltage and current in the wire. Some of the energy that was going into heat is now moving through the wire as electron flow.

The electrons go to the trouble to move to the carbon rod because they find it easier to combine with hydrogen there. There is a characteristic voltage in the cell of 0.76 volts. Eventually, the zinc rod dissolves completely or the hydrogen ions in the acid get used up and the battery "dies."
Battery Power and Uses:

In any battery, the same sort of electrochemical reaction occurs so that electrons move from one pole to the other. The actual metals and electrolytes used control the voltage of the battery -- each different reaction has a characteristic voltage. For example, here's what happens in one cell of a car's lead-acid battery:

• The cell has one plate made of lead and another plate made of lead dioxide, with a strong sulfuric acid electrolyte in which the plates are immersed.

• Lead combines with SO4 to create PbSO4 plus one electron.

• Lead dioxide, hydrogen ions and SO4 ions, plus electrons from the lead plate, create PbSO4 and water on the lead dioxide plate.

• As the battery discharges, both plates build up PbSO4 (lead sulfate), and water builds up in the acid. The characteristic voltage is about 2 volts per cell, so by combining six cells you get a 12-volt battery.

A lead-acid battery has a nice feature -- the reaction is completely reversible. If you apply current to the battery at the right voltage, lead and lead dioxide form again on the plates so you can reuse the battery over and over. In a zinc-carbon battery, there is no easy way to reverse the reaction because there is no easy way to get hydrogen gas back into the electrolyte.

Modern batteries use a variety of chemicals to power their reactions. Typical battery chemistries include:

• **Zinc-carbon battery** - Also known as a standard carbon battery, zinc-carbon chemistry is used in all inexpensive AA, C and D dry-cell batteries. The electrodes are zinc and carbon,
with an acidic paste between them that serves as the electrolyte.

- **Alkaline battery** - Used in common Duracell and Energizer batteries, the electrodes are zinc and manganese-oxide, with an alkaline electrolyte.

- **Lead-acid battery** - Used in automobiles, the electrodes are made of lead and lead-oxide with a strong acidic electrolyte (rechargeable).

- **Nickel-cadmium battery** - The electrodes are nickel-hydroxide and cadmium, with potassium-hydroxide as the electrolyte (rechargeable)

In almost any device that uses batteries, you do not use just one cell at a time. You normally group them together serially to form higher voltages, or in parallel to form higher currents. In a **serial arrangement**, the voltages add up. In a **parallel arrangement**, the currents add up. The following diagram shows these two arrangements:

The upper arrangement is called a **parallel** arrangement. If you assume that each cell produces
1.5 volts, then four batteries in parallel will also produce 1.5 volts, but the current supplied will be four times that of a single cell. The lower arrangement is called a serial arrangement. The four voltages add together to produce 6 volts.

Have you ever looked inside a normal 9-volt battery?

Manufacturers caution against disassembling batteries, to avoid personal injury. However, a partially disassembled 9-volt battery would look like this. It contains six, very small batteries producing 1.5 volts each in a serial arrangement!

Normally, when you buy a pack of batteries, the package will tell you the voltage and current rating for the battery. For example, a typical digital camera uses four nickel-cadmium batteries that are rated at 1.25 volts and 500 milliamp-hours for each cell. The milliamp-hour rating means, theoretically, that the cell can produce 500 milliamps for one hour. You can slice and dice the milliamp-hour rating in lots of different ways. A 500 milliamp-hour battery could produce 5 milliamps for 100 hours, or 10 milliamps for 50 hours, or 25 milliamps for 20 hours, or (theoretically) 500 milliamps for 1 hour, or even 1,000 milliamps for 30 minutes.

However, batteries are not quite that linear. For one thing, all batteries have a maximum
current they can produce -- a 500 milliamp-hour battery cannot produce 30,000 milliamps for 1 second, because there is no way for the battery's chemical reactions to happen that quickly. And at higher current levels, batteries can produce a lot of heat, which wastes some of their power. Also, many battery chemistries have longer or shorter than expected lives at very low current levels. But milliamp-hour ratings are somewhat linear over a normal range of use. Using the amp-hour rating, you can roughly estimate how long the battery will last under a given load.

If you arrange four of these 1.25-volt, 500 milliamp-hour batteries in a serial arrangement, you get 5 volts (1.25 x 4) at 500 milliamp-hours. If you arrange them in parallel, you get 1.25 volts at 2,000 (500 x 4) milliamp-hours.

**Glossary:**

- **Voltage**
  - The difference in energy potential between two substances (i.e. zinc and copper) based on their ability to give up electrons.
  - The amount of electricity in the form of electrons passing through a substance (i.e. along a wire or cable). Measured in volts.

- **Current**-The rate of flow (speed) of electricity (electrons) through a substance (i.e. along a wire or cable). Measured in amps.

- **Ohm**- The measurement of resistance a substance has to electron (electricity) flow (insulators have greater resistance, higher ohms, to electron flow than conductors).

- **Conductivity**- How readily a material allows electrons (electricity) to pass through it.

- **Electrode** – Either of two posts by which electrons (electricity) enters or leaves a battery.
• Anode- Also known as the positive post. The post that, through chemical reactions, produces protons (H⁺). The protons will pass through the electrolyte to the negative post (opposites attract).

• Cathode- Also known as the negative post. The post where protons will combine with electrons.

• Electrolyte- The material the electrodes are contained in. The electrolyte allows the protons to pass to the cathode so as to complete the circuit.

• Serial battery arrangement- Connecting a series of batteries in such a way so as to increase the voltage output without increasing amperage. In a serial arrangement the negative post of one battery is connected to the positive post of the next battery.

• Parallel battery arrangement- Connecting a series of batteries in such a way so as to increase the amperage without increasing voltage. In a parallel arrangement the negative posts of the batteries are connected together as are the positive posts.
Activity/Lab #4

Transfer of Energy: The Lemon Battery

Purpose:

To help students learn more about electrochemistry by helping them increase their understanding of electron transfer and its role in chemical changes.

Teacher notes:

By the end of elementary school, students should know several points about energy transformation. Students should know that when warmer objects are put with cooler ones (at a distance or next to each other), the warmer objects transfer internal energy (emitted as heat) to the cooler ones until they all reach the same temperature. They should understand things that give off heat can also give off other sorts of energy, including light. Students should also know that some materials transmit energy much better than others (materials that are poor conductors can reduce the transmission of energy from one object to another).

This prerequisite knowledge helps middle-school students learn the following three points about energy transformation:

- Energy cannot be created or destroyed, but only changed from one form into another (ex. Chemical to electrical as in a fuel cell or battery).
- Most of what goes on in the universe—from exploding stars and biological growth to the
operation of machines and the motion of people—involves some form of energy being
transformed into another (ex. Chemical energy in food to mechanical energy moving
muscles).

- Energy in the form of heat is almost always one of the products of an energy
  transformation.

At this early stage, there may be some confusion in students' minds between energy and
energy sources. Focusing on energy transformations may alleviate this confusion. Food,
gasoline, and batteries obviously get used up. But the energy they contain does not disappear; it
is changed into other forms of energy through physical or chemical processes.

As a starting point to help overcome some of these misconceptions, ask students these
questions.

1. In a light bulb, for example, how does electrical energy become light? (Electrical
   energy excites the atoms in the filament, which in turn radiate excess energy as light.)

2. Compared to the amount of electrical energy that goes into the light bulb, how much is
   actually emitted as light; more than, less than, or equal to the initial quantity? (Less, because
   while energy cannot be created or destroyed, some energy is also radiated as heat.)

**Instructional Strategies:**

Initial discussion/ question and answer session should review basic concepts of energy
transformations and electron flow in relationship to electrical potential along with review of how
a battery works. While the students are answering the pre-lab questions, the teacher should
observe student involvement in the groups and verbally check for comprehension. During the lab activity the teacher should observe construction of the lemon battery and monitor for comprehension while students are testing the battery with the voltmeter (multi-meter) and answering the post-lab questions.

**Data Collection:**

Students will record voltage and amperage readings gathered during the activity.

**Data Analysis:**

Students will make assumptions and compare results gathered from a single lemon to the results of two lemons connected in series and in parallel. They will also compare these results to results gathered in activity 2 (voltage and amperage of a battery).

**Conclusions:**

Students should make the prediction that two lemons will result in twice or near twice the voltage but that the amperage (rate of e-flow) will not change when in series whereas parallel connections will increase amperage but not voltage. They should be able form reasonable conclusions as to why actual results are slightly less than double due to resistance to ion flow in the lemons and wire. They should also conclude that a standard AA battery, because it allows for greater flow of electrons, produces greater voltage and amperage.
Evaluation Protocols:

This is a formative assessment. The teacher will monitor student responses and assist as needed.

Materials List

For each student group:
- 1 large, fresh lemon with slits cut into it as shown in the photo. (pg 4).
- 2 galvanized nails (preferably untarnished)
- 2 pennies (preferably untarnished)
- A copper wire with alligator clips at each end
- A voltmeter able to measure millivolts and milliamps

Procedures:

Using the Lemon Battery student Sheet to guide them, students will perform the Lemon Battery experiment. Instruct students to follow the directions on the sheet to make their own lemon batteries.

Students should work in pairs to make a single lemon battery. Then, the student pairs should form teams to test batteries comprised of two lemons. After students have conducted the activity, review the questions on the student sheet with the class.
Post-Activity Assessment:

Ask the students these questions about the Lemon Battery experiment:

1. What role does the lemon itself play in the battery? (The lemon is the electrolyte, which transfers electrons from the nail to the penny.)

2. Which of the following fruits would make good electrolytes, and which would not: bananas, limes, tomatoes? (Bananas would make poor electrolytes due to lower acidity. Tomatoes and limes would make good electrolytes due to high acid contents.)

3. Ask students to write down what they felt was the main point of this lesson. Ask students to share. (The purpose of this lesson is to increase students' understanding of electrochemistry by helping them to better understand electron transfer and its role in chemical changes.)

Extensions:
Experiments in Electrochemistry on the Fun Science Gallery site contains other activities that can be used to reinforce or further develop the ideas in this lesson.

**Student Activity/Lab #4**

**Student Answer**

**Sheet**

**Transfer of Energy: The Lemon Battery**

Name(s)________________________  Class Period____________

______________________________  Date___________________

**Lemon Battery**

Conduct the Lemon Battery experiment and then answer the questions that follow.
Lemon Battery Activity:

• Insert a copper penny into one of the precut slits in your lemon.

• Insert a galvanized nail near the other end of the lemon. Make sure the nail and the penny do not touch.

• Attach the alligator clip of the positive (red) wire to the penny, and insert the other end into the positive terminal of the voltmeter.

• Attach the alligator clip of the negative (black) wire to the nail, and insert the other end into the negative terminal of the voltmeter.

• Record the voltage observed using a voltmeter. Next check the milliamps. Your teacher should have one or more voltmeters (multi-meters) that you can use.

• Join with a student team to combine your lemon batteries. Hook up two or more lemon batteries in series to the same voltmeter. That is, rather than attaching the negative (nail) wire into the voltmeter, attach it to the positive electrode (penny) of another lemon, and connect the negative end of this second lemon into the voltmeter. Record the volts and milliamps.

• Finally, reconnect your two lemons in parallel by connecting the nail (-) of the first lemon to the nail of the second lemon. Do the same (+ to +) with the pennies). Record the volts and amps.

Now answer the questions on the following page and be prepared to discuss your answers with the class:
Transfer of Energy: The Lemon Battery

1. What voltage did you record with a single lemon? ______ milliamps? ______
2. What voltage did you record with the two lemons connected in series? ______ milliamps? ______
3. What voltage and amperage did you record with the lemons in parallel? ______ milliamps?_______
4. The movement of ___________ from the zinc nail through the wire accounted for the voltage displayed on the voltmeter.
5. Protons (H⁺) moved from the nail to the ______________ through the lemon juice. This suggests that the lemon juice acted as a(n) _________________.
6. In terms of electron flow, explain how two lemons connected in series increased the voltage of your battery. How was the amperage (the rate of flow) affected?
7. What changes to the lemon, nail, and penny might decrease the voltage?
8. Could a lemon battery power a light bulb?
Student Activity/Lab #4

Transfer of Energy: The Lemon Battery

1. What voltage did you record? Amps? About 0.9 volts, but this will vary. About 5mv.

2. What voltage did you record with the two lemons connected in series? The voltage will approximately double. The amperage will not change.

3. What voltage and amperage did you record with the lemons in parallel? The voltage will not change but the amperage will approximately double.

4. The movement of electrons from the zinc nail through the wire accounted for the voltage displayed on the voltmeter.

5. Protons (H+) moved from the nail to the penny through the lemon juice. This suggests that the lemon juice acted as an electrolyte.

6. In terms of electron flow, explain how two lemons increased the voltage of your battery. Two lemons had a greater electron flow than one lemon. The rate of electron flow (amperage) did not change.
7. What changes to the lemon, nail, and penny might decrease the voltage? A less acidic lemon, a tarnished nail and a tarnished penny could all decrease the voltage.

8. Could a lemon battery power a light bulb? Only a very small light bulb. But theoretically, enough lemons connected in series could power a light bulb.

Activity/Lab #5

Purpose/General Activity Information:
This activity is the final activity students do prior to doing their final engineering project. Students are introduced to the final two project questions:

1. Design three ways of powering a calculator using the same electrolyte
2. Design the cheapest, most powerful (most efficient) method to power a piezo buzzer

Students are given the materials they can choose from and told that each will have a cost. Students are not told the cost of each item. They then are given one to two class days to experiment on different variables. Each of these variables is recorded into a data table. In addition, students will perform one lab write-up for a question that they want to solve surrounding the projects final question.

Conclusion/Teacher Notes:
Students can look at the following variables (and probably many more). Bear in mind that students may bring an electrolyte of their choice to test on since they will have this freedom in their final project.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Material used for the anode</td>
<td>• The magnesium strips are the most reactive; therefore, giving the highest current and voltage. This has to do with the energy potential of each material.</td>
</tr>
<tr>
<td></td>
<td>• Voltage and current are affected</td>
</tr>
<tr>
<td>• Material used for the cathode</td>
<td>• The copper will have the highest affinity for electrons.</td>
</tr>
<tr>
<td></td>
<td>• Voltage and current are affected</td>
</tr>
<tr>
<td>• Distance between anode and cathode when using a lemon/fruit</td>
<td>• When the distance between the anode and cathode is decreased then the voltage and current increases because there are fewer pulp types of materials getting in the way.</td>
</tr>
<tr>
<td>• Size (width/length) of cathode</td>
<td>• The greater the surface area the current (this may not show due to the membranes in the lemon/fruit.)</td>
</tr>
<tr>
<td></td>
<td>• Voltage is NOT effected</td>
</tr>
<tr>
<td></td>
<td>• The material used for the electrolyte, anode, and cathode are the only things that affect voltage</td>
</tr>
<tr>
<td>• Size of anode (width/length)</td>
<td>• Students should find the greater the surface area the higher the current</td>
</tr>
<tr>
<td></td>
<td>• Voltage is NOT affected</td>
</tr>
<tr>
<td></td>
<td>• The material used for the electrolyte, anode, and cathode are the only things that affect voltage</td>
</tr>
<tr>
<td>• Type of electrolyte</td>
<td>• Students will have a choice of any fruit/vegetable (no juices are allowed). In general the more acidic/basic the greater the voltage</td>
</tr>
<tr>
<td></td>
<td>• Voltage and current are affected</td>
</tr>
<tr>
<td>• Type of wire</td>
<td>• Students will find no major difference between the two</td>
</tr>
<tr>
<td></td>
<td>• With much, much larger batteries the copper will work out better, but the current is too low here</td>
</tr>
<tr>
<td></td>
<td>• The type of wire will not effect the voltage</td>
</tr>
<tr>
<td>• Connecting in Series</td>
<td>• The voltage will increase (hopefully double)</td>
</tr>
<tr>
<td>• Connecting in Parallel</td>
<td>• The current will increase (hopefully double)</td>
</tr>
</tbody>
</table>

The following data table is included for your reference. Students should not see this table.
<table>
<thead>
<tr>
<th>#</th>
<th>Connection (Series or Parallel)</th>
<th>Wire Type</th>
<th>Electrolyte</th>
<th>Anode (-)</th>
<th>Cathode (+)</th>
<th>Voltage</th>
<th>Current</th>
</tr>
</thead>
</table>
| #1 | ---                             | Copper    | Vinegar (50 mL in a 100 mL beaker) | Galvanized Nail 3mm diameter | Copper Wire (1 mm diameter) | T1 = .90 V  
T2 = .96 V  
T3 = .99 V | T1 = 1.1 mA  
T2 = .9 mA  
T3 = 1.02 mA |
| #2 | ---                             | Copper    | Vinegar (50 mL in a 100 mL beaker) | Galvanized Nail 3mm diameter | Copper Stip 1 cm x 5 cm | T1 = .95 V  
T2 = .94 V  
T3 = .95 V | T1 = 2.03 mA  
T2 = 1.4 mA  
T3 = 1.6 mA |
| #3 | Copper                          | (50 mL in a 100 mL beaker) | Zinc Strip 1 x 5 cm | Copper Stip 1 cm x 5 cm | 1.2 V  
1.4  
1.6 | about equal to current with galvanized nail |
| #4 | ---                             | Copper    | Vinegar (50 mL in a 100 mL beaker) | Galvanized Nail 3mm diameter | Aluminum Wire 1mm diameter | T1 = .340 V  
T2 = .487 V  
T3 = .466 V | T1 = .025 mA  
T2 = .022 mA  
T3 = .023 mA |
| #5 | ---                             | Copper    | Vinegar (50 mL in a 100 mL beaker) | Galvanized Nail 3mm diameter | Penny shiny | T1 = .96 V  
T2 = .96 V  
T3 = .95 V | T1 = 2.04 mA  
T2 = 1.5 mA  
T3 = 1.8 mA |
| #6 | ---                             | Copper    | Vinegar (50 mL in a 100 mL beaker) | Aluminum Wire 1mm diameter | Penny shiny | T1 = .42 V  
T2 = .45 V  
T3 = .44 V | T1 = .07 mA  
T2 = .04 mA  
T3 = .03 mA |
| #7 | ---                             | Copper    | Vinegar (50 mL in a 100 mL beaker) | Aluminum Strip 1.4 cm width | Penny shiny | T1 = .55V  
T2 = .53 V  
T3 = .53 V | T1 = .06 mA  
T2 = .06 mA  
T3 = .05 mA |
| #8 | ---                             | Copper    | Vinegar (50 mL in a 100 mL beaker) | Copper Strip 1 cm x 5 cm | Copper Stip 1 cm x 5 cm | T1 = 17.3 mV  
T2 = 15.1 mV  
T3 = 11 mV | T1 = .003 mA  
T2 = .006 mA  
T3 = .005 mA |
<table>
<thead>
<tr>
<th>#</th>
<th>---</th>
<th>Copper</th>
<th>Vinegar (50 mL in a 100 mL beaker)</th>
<th>Copper Strip 1 cm x 5 cm</th>
<th>Galvanized Nail 3 mm diameter</th>
<th>V (−.89 V)</th>
<th>V (−.89 V)</th>
<th>V (−.74 V)</th>
<th>mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>#9</td>
<td>---</td>
<td>Copper</td>
<td>Vinegar (50 mL in a 100 mL beaker)</td>
<td>Copper Strip 1 cm x 5 cm</td>
<td>Galvanized Nail 3 mm diameter</td>
<td>(−1.6 mA)</td>
<td>(−1.3 mA)</td>
<td>(−1.5 mA)</td>
<td></td>
</tr>
<tr>
<td>#10</td>
<td>---</td>
<td>Copper</td>
<td>Lemon Juice (plastic squeeze bottle)</td>
<td>Galvanized Nail 3 mm diameter</td>
<td>Aluminum Strip 1x5 cm width</td>
<td>.43 V</td>
<td>.44 V</td>
<td>.45 V</td>
<td></td>
</tr>
<tr>
<td>#11</td>
<td>---</td>
<td>Copper</td>
<td>Vinegar (50 mL in a 100 mL beaker)</td>
<td>Galvanized Nail 3 mm diameter</td>
<td>Old Penny (dull)</td>
<td>.99 V</td>
<td>.98 V</td>
<td>.99 V</td>
<td>2.9 mA</td>
</tr>
<tr>
<td>#12</td>
<td>---</td>
<td>Copper</td>
<td>Lemon (not mashed/rolled)</td>
<td>Galvanized Nail 3 mm diameter</td>
<td>Penny shiny</td>
<td>.93 V</td>
<td>.93 V</td>
<td>.92 V</td>
<td>.18 mA</td>
</tr>
<tr>
<td>#13</td>
<td>----</td>
<td>Copper</td>
<td>Lemon (not mashed/rolled)</td>
<td>Galvanized Nail 3 mm diameter</td>
<td>Copper Strip 1 cm x 5 cm</td>
<td>.95 V</td>
<td>.94 V</td>
<td>.93 V</td>
<td>.29 mA</td>
</tr>
<tr>
<td>#14</td>
<td>----</td>
<td>Copper</td>
<td>Vinegar (50 mL in a 100 mL beaker)</td>
<td>Galvanized Nail 3 mm diameter</td>
<td>Aluminum Strip 1x5 cm width</td>
<td>.43 V</td>
<td>.38 V</td>
<td>.42 V</td>
<td>.066 mA</td>
</tr>
<tr>
<td>#15</td>
<td>----</td>
<td>Copper</td>
<td>Lemon (not mashed/rolled)</td>
<td>Galvanized Nail 3 mm diameter</td>
<td>Aluminum Wire 1 mm diameter</td>
<td>.37 V</td>
<td>.39 V</td>
<td>.34 V</td>
<td>.018 mA</td>
</tr>
<tr>
<td>#16</td>
<td>----</td>
<td>Copper</td>
<td>Lemon (not mashed/rolled)</td>
<td>Galvanized Nail 3 mm diameter</td>
<td>Copper Strip 1 cm x 5 cm</td>
<td>.9 V</td>
<td>.87 V</td>
<td>.87 V</td>
<td>.2 mA</td>
</tr>
<tr>
<td>#17</td>
<td>----</td>
<td>Copper</td>
<td>Lemon (not mashed/rolled)</td>
<td>Galvanized Nail 3 mm diameter</td>
<td>Copper Strip 1 cm x 5 cm</td>
<td>.87 V</td>
<td>.85 V</td>
<td>.86 V</td>
<td>.14 mA</td>
</tr>
<tr>
<td>#18</td>
<td>----</td>
<td>Copper</td>
<td>Lemon (mashed/rolled)</td>
<td>Galvanized Nail 3 mm diameter</td>
<td>Copper Strip 1 cm x 5 cm</td>
<td>.79 V</td>
<td>.81 V</td>
<td>.79 V</td>
<td>.55 mA</td>
</tr>
<tr>
<td>#19</td>
<td>----</td>
<td>Copper</td>
<td>Vinegar (25 mL in a 100 mL beaker)</td>
<td>Galvanized Nail 3 mm diameter</td>
<td>Copper Strip 1 cm x 5 cm</td>
<td>.98 V</td>
<td>.96 V</td>
<td>.96 V</td>
<td>1.02 mA</td>
</tr>
<tr>
<td>#20</td>
<td>----</td>
<td>Copper</td>
<td>Vinegar (15 mL in a 100 mL beaker)</td>
<td>Galvanized Nail 3 mm diameter</td>
<td>Copper Strip 1 cm x 5 cm</td>
<td>.91 V</td>
<td>.92 V</td>
<td>.9 V</td>
<td>.3 mA</td>
</tr>
</tbody>
</table>

#20
<p>| #21 | ---- | Copper | Lemon Juice (plastic squeeze bottle) | Galvanized Nail 3mm diameter | Copper Stip 1 cm x 5 cm | .95 V | .94 V | 5 mA | 4.7 mA | 4.5 mA |
| #22 | Copper | Lemon Juice (plastic squeeze bottle) | Zinc Strip 1 x 5 cm | Copper Stip 1 cm x 5 cm | 1.06 | 1.02 | 7 mA |
| #23 | ---- | Copper | Lemon Juice (plastic squeeze bottle) | Aluminum Strip 1.4 cm width | Copper Stip 1 cm x 5 cm | .45 V | .42 V | .025 mA | .023 mA | .029 mA |
| #24 | ---- | Copper | Lemon Juice (plastic squeeze bottle) | Galvanized Nail 3mm diameter | Aluminum Rod .7 cm diameter | .47 | .47 | .099 mA | .099 mA | .1 mA |
| #25 | ---- | Copper | Lemon Juice (plastic squeeze bottle) | Galvanized Nail 3mm diameter | Galvanized Nail 3mm diameter | .023 | .026 | .027 | .023 | .023 |
| #26 | ---- | Copper | Lemon Juice (plastic squeeze bottle) | Galvanized Nail 3mm diameter | Penny shiny | .99 | .96 | .99 | 5.2 mA | 5.2 mA | 4.5 mA |
| #27 | ---- | Copper | Lemon Juice (plastic squeeze bottle) | Galvanized Nail 3mm diameter | Copper Wire (1 mm diameter) | .95 | .95 | .92 | 4.2 mA | 3.3 mA | 3.3 mA |
| #28 | ---- | Copper | Lemon Juice (plastic squeeze bottle) | Galvanized Nail 3mm diameter | Aluminum Wire 1 mm diameter | .57 V | .57 | .58 | .021 mA | .023 mA | .021 mA |
| #29 | ---- | Copper | Orange Juice | Galvanized Nail 3mm diameter | Copper Stip 1 cm x 5 cm | .94 | .93 | .94 | 2.4 mA | 2.9 mA | 2.3 mA |
| #30 | ---- | Copper | Orange Juice | Galvanized Nail 3mm diameter | Penny shiny | .99 | .97 | .96 | 1.8 mA | 2 mA | 1.6 mA |
| #31 | ---- | Copper | Lemonade Frozen Concentrate 15% lemon juice | Galvanized Nail 3mm diameter | Copper Stip 1 cm x 5 cm | .93 V | .93 V | .93 V | .3 mA | .4 mA | .3 mA |</p>
<table>
<thead>
<tr>
<th>#</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>#32</td>
<td>----</td>
<td>Aluminum</td>
<td>Lemon Juice (plastic squeeze bottle)</td>
<td>Galvanized Nail 3mm diameter</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>.95 V .97 V .93 V</td>
</tr>
<tr>
<td>#33</td>
<td>2 in series</td>
<td>Copper</td>
<td>Lemon Juice (plastic squeeze bottle)</td>
<td>Galvanized Nail 3mm diameter</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>1.9 V 1.9 V 1.9 V</td>
</tr>
<tr>
<td>#34</td>
<td>3 in series</td>
<td>Copper</td>
<td>Lemon Juice (plastic squeeze bottle)</td>
<td>Galvanized Nail 3mm diameter</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>2.3 2.3 2.4 V</td>
</tr>
<tr>
<td>#35</td>
<td>2 in Parallel</td>
<td>Copper</td>
<td>Lemon Juice (plastic squeeze bottle)</td>
<td>Galvanized Nail 3mm diameter</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>.89 .9 .89</td>
</tr>
<tr>
<td>#36</td>
<td>3 in Parallel</td>
<td>Copper</td>
<td>Lemon Juice (plastic squeeze bottle)</td>
<td>Galvanized Nail 3mm diameter</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>.89 V .9 .9</td>
</tr>
<tr>
<td>#37</td>
<td>----</td>
<td>Copper</td>
<td>Lemon Juice (plastic squeeze bottle)</td>
<td>Magnesium Stip .4 cm x 5 cm</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>1.9 V 1.9 V 1.9 V</td>
</tr>
<tr>
<td>#38</td>
<td>----</td>
<td>Copper</td>
<td>Vinegar (15 mL in a 100 mL beaker)</td>
<td>Magnesium Stip .4 cm x 5 cm</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>1.7 V 1.6 V 1.7 V</td>
</tr>
<tr>
<td>#39</td>
<td>----</td>
<td>Copper</td>
<td>Vinegar (15 mL in a 100 mL beaker)</td>
<td>2 Magnesium Strips .4 cm x 5 cm</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>1.7 V 1.6 V 1.7 V</td>
</tr>
<tr>
<td>#40</td>
<td>----</td>
<td>Copper</td>
<td>Lemon Juice (plastic squeeze bottle)</td>
<td>3 Magnesium Strips .4 cm x 5 cm</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>1.7 1.7 1.7</td>
</tr>
<tr>
<td>#41</td>
<td>----</td>
<td>Copper</td>
<td>Apple Juice</td>
<td>Galvanized Nail 3mm diameter</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>1.0 1.0 1.01</td>
</tr>
<tr>
<td>#42</td>
<td>----</td>
<td>Copper</td>
<td>Apple Juice</td>
<td>1 Magnesium Strip</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>1.6 1.6 1.67</td>
</tr>
<tr>
<td>#43</td>
<td>Copper</td>
<td>Apple Juice</td>
<td>Galvanized Nail 3mm diameter</td>
<td>Aluminum Strip 1x5 cm width</td>
<td></td>
<td>0.42 .46 .46</td>
</tr>
<tr>
<td>#</td>
<td>Material</td>
<td>Color</td>
<td>Metal</td>
<td>Length</td>
<td>Width</td>
<td>Voltage</td>
</tr>
<tr>
<td>-----</td>
<td>----------</td>
<td>---------</td>
<td>-------</td>
<td>--------</td>
<td>-------</td>
<td>---------</td>
</tr>
<tr>
<td>#44</td>
<td>Copper</td>
<td>Diet Coke</td>
<td>Galvanized Nail</td>
<td>3mm diameter</td>
<td>Copper Stip</td>
<td>1 cm x 5 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#45</td>
<td>Copper</td>
<td>Tomato</td>
<td>Galvanized Nail</td>
<td>3mm diameter</td>
<td>Copper Stip</td>
<td>1 cm x 5 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#46</td>
<td>Copper</td>
<td>Tomato</td>
<td>Magnesium Strip</td>
<td>1 cm x 5 cm</td>
<td>Copper Stip</td>
<td>1 cm x 5 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#47</td>
<td>Copper</td>
<td>Tomato</td>
<td>Galvanized Nail</td>
<td>3mm diameter</td>
<td>Aluminum Strip</td>
<td>1x5 cm width</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#48</td>
<td>Copper</td>
<td>Tomato</td>
<td>Magnesium Strip</td>
<td>1 cm x 5 cm</td>
<td>Aluminum Strip</td>
<td>1x5 cm width</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#49</td>
<td>Copper</td>
<td>Peach</td>
<td>Galvanized Nail</td>
<td>3mm diameter</td>
<td>Copper Stip</td>
<td>1 cm x 5 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#50</td>
<td>Copper</td>
<td>Peach</td>
<td>Magnesium Strip</td>
<td>1 cm x 5 cm</td>
<td>Copper Stip</td>
<td>1 cm x 5 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#51</td>
<td>Copper</td>
<td>Peach</td>
<td>Galvanized Nail</td>
<td>3mm diameter</td>
<td>Aluminum Strip</td>
<td>1x5 cm width</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#52</td>
<td>Copper</td>
<td>Peach</td>
<td>Magnesium Strip</td>
<td>1 cm x 5 cm</td>
<td>Aluminum Strip</td>
<td>1x5 cm width</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#53</td>
<td>Copper</td>
<td>Lime</td>
<td>Galvanized Nail</td>
<td>3mm diameter</td>
<td>Copper Stip</td>
<td>1 cm x 5 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#54</td>
<td>Copper</td>
<td>Lime</td>
<td>Magnesium Strip</td>
<td>1 cm x 5 cm</td>
<td>Copper Stip</td>
<td>1 cm x 5 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#55</td>
<td>Copper</td>
<td>Lime</td>
<td>Galvanized Nail</td>
<td>3mm diameter</td>
<td>Aluminum Strip</td>
<td>1x5 cm width</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#56</td>
<td>Copper</td>
<td>Lime</td>
<td>Magnesium Strip</td>
<td>1 cm x 5 cm</td>
<td>Aluminum Strip</td>
<td>1x5 cm width</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#57</td>
<td>Copper</td>
<td>Orange</td>
<td>Galvanized Nail</td>
<td>3mm diameter</td>
<td>Copper Stip</td>
<td>1 cm x 5 cm</td>
</tr>
<tr>
<td>#58</td>
<td>Copper</td>
<td>Orange</td>
<td>1 Magnesium Strip</td>
<td>Copper Strip</td>
<td>1 cm x 5 cm</td>
<td>1.5 V</td>
</tr>
<tr>
<td>-----</td>
<td>--------</td>
<td>--------</td>
<td>-------------------</td>
<td>--------------</td>
<td>-------------</td>
<td>-------</td>
</tr>
<tr>
<td>#59</td>
<td>Copper</td>
<td>Orange</td>
<td>1 Magnesium Strip</td>
<td>Aluminum Strip</td>
<td>1x5 cm width</td>
<td>.97 V</td>
</tr>
<tr>
<td>#60</td>
<td>Copper</td>
<td>Orange</td>
<td>Galvanized Nail 3mm diameter</td>
<td>Aluminum Strip</td>
<td>1x5 cm width</td>
<td>0.42</td>
</tr>
</tbody>
</table>

**Instructional Strategies:**

The teacher should observe and help student as needed making sure students are filling out there data table and that students are examining one variable at a time.

**Data Collection:**

- Students will fill in their data table as they work through the questions/variables they are testing
- Students will perform one experiment design of their own from one of the questions/variables they feel might affect the lemon batteries power.

**Data Analysis:**

- Students will decide on what variables to test, test this variable using the multimeter, and record their findings into a data table.
• Students will decide on what one variable they want to perform an experiment write-up on and then perform that experiment recording their data into a data table and then writing a conclusion based on their experimental results.

Evaluation Protocols:

• Formative assessment: The teacher will monitor student variables and make sure that students are finding the correct conclusions. If not, the teacher needs to determine what went wrong and have students redo the experiment.

• Summative assessment: Students will be asked to come up with their own variables, plan their own investigations, record their experimental data, and come up with a conclusion based on their data. They will then take this data to solve the final engineering project:

• Design the cheapest (most efficient) way to power a calculator using a lemon battery.

Worksheet/Handout to be given to Students: (next page)
Variables in Batteries

Purpose:
In this activity you will perform a series of experiments to determine how different variables effect either the voltage or the current. You will record this data into a data table and use the information in the final two projects:

1. Design three ways of powering a calculator using the same electrolyte
2. Design the cheapest, most powerful (most efficient) method to power a piezo buzzer

These two engineering problems should focus what experiments you decide to perform. Keep these in questions in mind as you do the experiments so you can relate your results to the two engineering issues above.

Also, keep in mind the final projects rules:

1. You may bring any fruit/vegetable you want to use from home/the store.
2. Each fruit/vegetable you use has a cost
3. Bring fruits/vegetables to test. All other materials will be given for you to use. If you decide not to then you may only use the potatoes.
4. Each material you use will have a cost
5. You may alter the fruit/vegetable as you see fit
6. All other materials used in your battery are provided at your table:

Directions:
Using only solid fruits and/or vegetables you are to:

1. Decide on what manipulated variable to test
2. Test the effect that variable has on voltage and current
3. Perform at least two trials per group
4. Record your data into the data table given to you
5. Write a conclusion based on the experimental results.

You also need to come up with one question (manipulated variable) to design an experiment around. The question will not be given to you. You and your partner need to decide on a question and then scientifically answer the question through an investigation.

Materials:
- magnesium strips
- copper strips
- aluminum strips
- zinc strips
- copper penny
- zinc nail
- Copper wire
- Aluminum wire
- Graphite
- Vinegar
- Aluminum wire
- Copper wire
- Potatoes
- Apples
- Electrolytes (fruits/vegetables) of your choice from home
- Multimeter

<table>
<thead>
<tr>
<th>Manipulated Variable Tested?</th>
<th>Voltage</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manipulated Variable Tested?</th>
<th>Voltage</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manipulated Variable Tested?</th>
<th>Voltage</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manipulated Variable Tested?</td>
<td>Voltage</td>
<td>Current</td>
</tr>
<tr>
<td>------------------------------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manipulated Variable Tested?</td>
<td>Voltage</td>
<td>Current</td>
</tr>
<tr>
<td>------------------------------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manipulated Variable Tested?</th>
<th>Voltage</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manipulated Variable Tested?</th>
<th>Voltage</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manipulated Variable Tested?</td>
<td>Voltage</td>
<td>Current</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manipulated Variable Tested?</td>
<td>Voltage</td>
<td>Current</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manipulated Variable Tested?</td>
<td>Voltage</td>
<td>Current</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
List four controlled variables in your experiments:

1. _____________________________________________________________________
   _____________________________________________________________________
   _____________________________________________________________________
   _____________________________________________________________________

Experiment Design Format:

Name: ____________________________ Assignment #: ____________________________
Period: ______ 

**Design your own experiment**

Be sure to include:
- Hypothesis (prediction) of the investigation results
- Materials that includes containers, all measurement devises, and anything else used
- Procedure that includes:
  - One manipulated (changed) variable
  - One responding (dependent) variable
  - One controlled (kept the same) variable
  - Logical steps to do the investigation
  - How often measurements are taken and recorded
<table>
<thead>
<tr>
<th>Question:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hypothesis (Prediction):</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Materials:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Use the space below to draw a labeled diagram to support your procedure:
Procedure:

Data:
Based on the data table from your experiment, write a conclusion that;
- Answers the investigative question
- Includes supporting data
- Explain how the data supports your conclusion

Question:

Activity/Lab #6

Purpose/General Activity Information:
This is the first engineering task students need to solve. They must design three methods of powering the calculator using the same electrolyte in all three solutions. This will take one class day to complete. All materials are supplied for this activity including the electrolyte. Students may choose to bring their own if you want.

Conclusion/Teacher Notes:
Students will need to connect their battery in series to get enough voltage to power the calculator. We suggest using the TI 30xA calculator. The Sunway electric calculator proved to be too easy. Also, to power the calculator the screen must be easily read (not faint). We suggest using a standard electrolyte and allowing students to alter the electrodes and any other variables.

<table>
<thead>
<tr>
<th>Material</th>
<th>Series</th>
<th>Parallel</th>
<th>Electrolyte</th>
<th>Wire Type</th>
<th>Anode (-)</th>
<th>Cathode (+)</th>
<th>Power/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunway Electric Calculator</td>
<td></td>
<td></td>
<td>Lemon Juice 40 mL in a 100 mL beaker</td>
<td>Copper</td>
<td>2 magnesium strips</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power</td>
</tr>
<tr>
<td>- (SK - 8819B)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 1.5 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 1.6 mA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sunway Electric Calculator</td>
<td></td>
<td></td>
<td>Lemon Juice 40 mL in a 100 mL beaker</td>
<td>Copper</td>
<td>1 magnesium strip</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power</td>
</tr>
<tr>
<td>- (SK - 8819B)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 1.5 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 1.6 mA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sunway Electric Calculator</td>
<td>2</td>
<td></td>
<td>Lemon Juice 40 mL in a 100 mL beaker</td>
<td>Copper</td>
<td>Galvanized Nail 3mm diameter</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power</td>
</tr>
<tr>
<td>- (SK - 8819B)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 1.5 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 1.6 mA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sunway Electric Calculator</td>
<td>2</td>
<td></td>
<td>Vinegar 40 mL in a 100 mL beaker</td>
<td>Copper</td>
<td>Galvanized Nail 3mm diameter</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power</td>
</tr>
<tr>
<td>- (SK - 8819B)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 1.5 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 1.6 mA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TI 30xA Calculator</td>
<td></td>
<td></td>
<td>Lemon Juice 40 mL in a 100 mL beaker</td>
<td>Copper</td>
<td>2 magnesium strips</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power, but very faint numbers (will do calculations)</td>
</tr>
<tr>
<td>~ 3 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TI 30xA Calculator</td>
<td></td>
<td></td>
<td>Lemon Juice 40 mL in a 100 mL beaker</td>
<td>Copper</td>
<td>1 magnesium strip</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power, but very faint numbers (will do calculations)</td>
</tr>
<tr>
<td>~ 3 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TI 30xA Calculator</td>
<td></td>
<td></td>
<td>Vinegar 40 mL in a 100 mL beaker</td>
<td>Copper</td>
<td>1 magnesium strip</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power, but very faint numbers (will do calculations)</td>
</tr>
<tr>
<td>~ 3 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TI 30xA Calculator</td>
<td></td>
<td></td>
<td>Vinegar 40 mL in a 100 mL beaker</td>
<td>Copper</td>
<td>1 magnesium strip</td>
<td>Penny</td>
<td>Power, but very faint numbers (will do calculations)</td>
</tr>
<tr>
<td>~ 3 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TI 30xA Calculator ~ 3 V</td>
<td>Vinegar 40 mL in a 100 mL beaker</td>
<td>Copper</td>
<td>2 magnesium strips</td>
<td>aluminum strip</td>
<td>No power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------</td>
<td>---------------------------------</td>
<td>--------</td>
<td>--------------------</td>
<td>----------------</td>
<td>----------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TI 30xA Calculator ~ 3 V</td>
<td>Lemon Juice 40 mL in a 100 mL beaker</td>
<td>Copper</td>
<td>2 magnesium strips</td>
<td>copper wire only</td>
<td>No power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TI 30xA Calculator ~ 3 V</td>
<td>Lemon Juice 40 mL in a 100 mL beaker</td>
<td>Copper</td>
<td>1 magnesium strip</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TI 30xA Calculator ~ 3 V</td>
<td>Lemon Juice 40 mL in a 100 mL beaker</td>
<td>Copper</td>
<td>1 magnesium strip</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power, very faint numbers and won't calculate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TI 30xA Calculator ~ 3 V</td>
<td>Lemon Juice 40 mL in a 100 mL beaker</td>
<td>Copper</td>
<td>1 magnesium strip</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TI 30xA Calculator ~ 3 V</td>
<td>Lemon Juice 40 mL in a 100 mL beaker</td>
<td>Copper</td>
<td>1 magnesium strip</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power, very faint numbers and won't calculate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TI 30xA Calculator ~ 3 V</td>
<td>Salt Water</td>
<td>Copper</td>
<td>1 magnesium strip</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TI 30xA Calculator ~ 3 V</td>
<td>Apple Juice 40 mL in 100 mL beaker</td>
<td>Copper</td>
<td>Galvanized Nail 3mm diameter</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power, but very faint numbers (will do calculations)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TI 30xA Calculator ~ 3 V</td>
<td>Apple Juice 40 mL in 100 mL beaker</td>
<td>Copper</td>
<td>1 magnesium strip</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TI 30xA Calculator ~ 3 V</td>
<td>Apple Juice 40 mL in 100 mL beaker</td>
<td>Copper</td>
<td>2 magnesium strips</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>No power to a very faint number that won't calculate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TI 30xA Calculator ~ 3 V</td>
<td>Apple Juice 40 mL in 100 mL beaker</td>
<td>Copper</td>
<td>1 magnesium strip</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power, but very faint numbers (will do calculations)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TI 30xA Calculator ~ 3 V</td>
<td>Diet Coke 40 mL in 100 mL beaker</td>
<td>Copper</td>
<td>1 magnesium strip</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Instructional Strategies:

Students will have free reign to work on their own solutions. They should use the data table they put together to guide their thinking. The teacher needs to monitor and help as needed.

### Data Collection:

Students will draw a labeled diagram of their three answers.

<table>
<thead>
<tr>
<th>TI 30xA Calculator ~ 3 V</th>
<th>2</th>
<th>Diet Coke 40 mL in 100 mL beaker</th>
<th>Copper</th>
<th>1 magnesium strip</th>
<th>Copper Stip 1 cm x 5 cm</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>TI 30xA Calculator ~ 3 V</td>
<td></td>
<td>Tomato</td>
<td>Copper</td>
<td>1 magnesium strip</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power, but very faint numbers (will do calculations)</td>
</tr>
<tr>
<td>TI 30xA Calculator ~ 3 V</td>
<td>3</td>
<td>Lime - tomato - peach</td>
<td>Copper</td>
<td>Galvanized Nail 3 mm diameter</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Power</td>
</tr>
</tbody>
</table>

### Data Analysis:

Students will utilize their data sheet from the previous activity to test different solutions for powering the calculator. They will then draw a diagram of their three solutions labeling the different materials they used.

### Evaluation Protocols:
This is a formative assessment. The teacher should monitor student interactions and help where needed.

**Worksheet/Handout to be given to Students: (see next page)**

Name: ______________________________

Period: _____

**SPUD POWERED CALCULATOR**

**Purpose/Problem:** You need to devise three different methods to power the calculator using potato(es).
Rules:

1. You may not alter the potato in any way except to put your electrodes into the potato.
2. You may use only the potato as the electrolyte.
3. The only source of power for the calculator is the potato.

Materials:
- Potatoes
- TI 30xA calculator
- Copper Wires
- Potatoes
- Magnesium strips
- Galvanized Nails (Zinc coated)
- Zinc Strips (3 x 5 cm)
- Aluminum strips
- Aluminum wires
- Copper wires
- Copper strips
- Penny

Question: Answer the following questions.
Draw a diagram of each of your three solutions.
- Label each part:
  - What did you use for the wire?
  - What length of wire did you use?
  - What did you use as the cathode?
  - What is the length and width of the cathode?
What did you use as the anode?
What is the length and width of the anode?
What is your electrolyte?
How much electrolyte did you use?
Label any other important features

- Label the direction of electrons as it flows through your circuit.

Labeled diagram of solution #1:

Labeled diagram of solution #2:

Labeled diagram of solution #3:

Activity/Lab #7

Purpose/General Activity Information:
This activity is the final culminating engineering project. Students were introduced to this problem in the last activity/lab. Students will most likely need two class days to complete; although, some students may finish on the first day. The culminating engineering question is:

Design the cheapest, most powerful (most efficient) method to power a piezo buzzer

**Conclusion/Teacher Notes:**

There are a variety of correct answers students could come up with. Students need to follow the rules and are allowed to bring an electrolyte of their choice. They should use their data table to help them devise their solution. Following is a table that may help you:

<table>
<thead>
<tr>
<th>Material</th>
<th>Series</th>
<th>Parallel</th>
<th>Electrolyte</th>
<th>Wire Type</th>
<th>Anode (-)</th>
<th>Cathode (+)</th>
<th>Power/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezo Buzzer</td>
<td></td>
<td></td>
<td>Lemon Juice 40 mL in a 100 mL beaker</td>
<td>Copper</td>
<td>1 magnesium strip</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Buzzed</td>
</tr>
<tr>
<td>- (Radio Shack)</td>
<td>- 3V - 28 V - 5 mA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piezo Buzzer</td>
<td></td>
<td></td>
<td>Lemon Juice 40 mL in a 100 mL beaker</td>
<td>Copper</td>
<td>Galvanized Nail 3 mm diameter</td>
<td>Copper Stip 1 cm x 5 cm</td>
<td>Low Buzzer</td>
</tr>
<tr>
<td>- (Radio Shack)</td>
<td>- 3V - 28 V - 5 mA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piezo Buzzer</td>
<td></td>
<td></td>
<td>Lemon Juice 40 mL in a 100 mL beaker</td>
<td>Copper</td>
<td>Galvanized Nail 3 mm diameter</td>
<td>aluminum strip</td>
<td>No buzz</td>
</tr>
<tr>
<td>- (Radio Shack)</td>
<td>- 3V - 28 V - 5 mA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Equipment/Materials:
- Potatoes (for students that do not bring their own electrolyte)
- Piezo buzzer
- Copper Wires
- Magnesium strips
- Galvanized Nails (Zinc coated)
- Zinc Strips (3 x 5 cm)
- Aluminum strips
- Aluminum wires
- Copper wires
- Copper strips
- Pennies

### Instructional Strategies:
The teacher should observe student interactions and let students solve the question with minimal teacher involvement.

### Data Collection:

<table>
<thead>
<tr>
<th>Piezo Buzzer - (Radio Shack)</th>
<th>Lemon Juice 40 mL in a 100 mL beaker</th>
<th>Copper 1 magnesium strip</th>
<th>aluminum strip</th>
<th>Buzzer Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Buzz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>High Buzz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very low buzz</td>
<td>Low Buzz</td>
<td>Galvanized Nail 3mm diameter</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Piezo Buzzer - (Radio Shack)</th>
<th>Lemon Juice 40 mL in a 100 mL beaker</th>
<th>Copper 1 magnesium strip</th>
<th>aluminum strip</th>
<th>Buzzer Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Buzz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>High Buzz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very low buzz</td>
<td>Low Buzz</td>
<td>Galvanized Nail 3mm diameter</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Students will diagram out their final solution and give reasons for each choice they made. This handout is provided to the student.

**Data Analysis:**

Students will share this information and the reasons behind their decisions in a post-project write-up.

**Evaluation Protocols:**

This is a formative assessment. Students should have a basic understanding learned through experimentation. They now apply what they learned to solve the engineering problem.

**Worksheet/Handout to be given to Students: (see next page)**

Name: ____________________________

Period: _____
FRUIT POWER!!

Purpose:
Design the cheapest, most powerful (most efficient) method to power a piezo buzzer

Rules:
1. You want a loud buzzer, but you also want it to be cheap. Just because your solution is the loudest does NOT mean that your solution will be the winner of the competition.
2. You may not remove the piezo buzzer or the wires from their location on the wood board.
3. You may not use any other materials besides what is provided at your table and the fruit(s) you bring.
4. You may provide your own solid fruit/vegetable from home, or use the potatoes provided.
5. You may modify the fruit/vegetable in any way you choose.

Materials/Cost:

<table>
<thead>
<tr>
<th>Material</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Strip</td>
<td>$1.50 / 5 cm</td>
</tr>
<tr>
<td>Aluminum Wire</td>
<td>$1.00 / 5 cm</td>
</tr>
<tr>
<td>Copper Strip</td>
<td>$2.50 / 5 cm</td>
</tr>
<tr>
<td>Copper Wire</td>
<td>$2.00 / 5 cm</td>
</tr>
<tr>
<td>Electrolyte/Fruit or Vegetable</td>
<td>$2.50 / fruit or vegetable</td>
</tr>
<tr>
<td>Galvanized Nail</td>
<td>$1.75 each</td>
</tr>
</tbody>
</table>
Pre-Project Question:

What is the voltage of the Piezo buzzer:

_______________________________________

What is the current of the Piezo buzzer:

_______________________________________

Final Plan: (answer on next page)

- Draw a diagram of your final solution
- Label each part:
  - What did you use for the wire?
  - What length of wire did you use?
  - What did you use as the cathode?
  - What is the length and width of the cathode?
  - What did you use as the anode?
  - What is the length and width of the anode?
  - What is your electrolyte?
  - How much electrolyte did you use?
  - Label any other important features
- Label the direction of electrons as it flows through your circuit

Draw labeled diagram here:
Explanations of Final Plan:

1. Wire:
   - Identify what type of wire you chose to use. Explain why you chose to use this for wire.
   - Identify the length of wire you chose to use. Explain why you chose to use this length.

2. Cathode:
   - Identify the material you built your cathode out of. Explain why you chose this material.
   - Identify the width and length of your cathode. Explain why you chose this width and length.
3. Anode:
   - Identify the material you built your anode out of. Explain why you chose this material.
   - Identify the width and length of your anode. Explain why you chose this width and length.

4. Electrolyte:
   - Identify what you used as your electrolyte. Explain why you chose to use this for your electrolyte.
   - How much electrolyte did you use. Explain why.

5. Series:
   - Identify if you connected your battery in series.
   - If you connected your battery in series identify how many series you used
   - Explain why you did this.
6. Parallel:
   - Identify if you connected your battery in parallel.
   - If you connected your battery in parallel identify how many parallels you used.
   - Explain why you did this.

<table>
<thead>
<tr>
<th>Description</th>
<th>Increased Voltage</th>
<th>Increased Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
References:


http://home/howstuffworks.com/battery.htm


http://www.funsci.com/fun3_en/electro/electro.htm


Introduction to Electricity and Batteries. Retrieved July 25, 2006, from


http://faraday.physics.uiowa.edu/em/5E40.25.htm


Potato Battery. Retrieved July 25, 2006, from


www.qrg.northwestern.edu/projects/vss/docs/power/2-how-do-batteries-work.html