

Capacitors

Introduction

When you need electricity, it is nice to be able to throw a switch and get it. If you have access to a generator, you can always insure that you have electricity whenever you throw the switch by keeping the generator moving by some means (steam driven turbine, windmill, etc.). However, if you do not have this, you will have to rely on some method of storing the electricity so that you can use it when you need it. There are two basic ways of storing electricity: chemically and mechanically.

The most common form of chemical storage is in batteries. Batteries store the charge by creating chemical compounds that will react in an acidic or basic solution to release electrons. Batteries have done a tremendous job over the years, but they have had problems. For one, they often use chemically toxic compounds like lead, mercury, and cadmium that are dangerous when the batteries are disposed of. For another, they can be problematic whenever there is a crack in their container or whenever they make a hole in their container. Anyone who has ever opened the back of a toy or appliance to find the innards eaten away by the acid or base by such a leak knows what kind of mess this can make.

Electricity can also be stored chemically in a fuel cell. This device does not require an acidic or basic solution, as the chemical species (hydrogen and oxygen are the optimal ones) react across a semipermeable membrane and release electrons in the process. The lone by-product from such a reaction is water if hydrogen and oxygen are used, which poses no problems to the environment. The biggest problem standing in the way of the widespread usage of fuel cells is size, as they are so large currently as to be limited to objects the size of small trucks and bigger.

Mechanical storage is achieved with the use of capacitors. Capacitors store the electricity without the need for chemical reactions, acids, or bases. They consist of two conductors that are placed near each other, but are not allowed to touch. As negative charge is placed on one of the conductors, positive charge begins to build up on the other, as electrostatic forces keep the unlike charges near each other. Whenever the electricity is needed, the electrons are allowed to flow to the positively-charged conductor through a circuit that connects both sides of the capacitor.



Fig 1: Capacitor in a circuit (NASA)

Capacitors are a mainstay in modern electrical circuits. The computer that you are using to read or print this file contains millions of them to perform various tasks that are required. But electrical instruments are not the only places that capacitors appear in your everyday life. Various parts of plant and animal bodies also act like capacitors. For example, the membrane of an cell keeps charge separated just like a capacitor. This occurs because the cell membrane contains channel proteins and ion pumps that maintain a different concentration of sodium, potassium, and chlorine ions on both sides. These different concentrations means that there is a charge difference (more negative ions inside of the cell than outside, normally), which results in a potential difference across the membrane. In nerve cells, this electric potential is about 70 millivolts. While this does not seem like a large potential difference, it must be remembered that is being maintained across a membrane that is only a couple of nanometers thick. This

corresponds to an electric field that is thousands of volts per meter, which is far greater than one finds in most electrical appliances.

All cells have some potential difference across the membrane due to ion concentration differences. This is important, as the electric field maintained by this "capacitor" membrane is very important for biological processes. It is responsible for driving amino acids and other molecules against the concentration gradients that exist to provide these nutrients to the inside of the cells. If the potential difference was not there, these nutrients would not be able to be "fed" to the cells, which would result in death. This potential difference is also important in the transmission of signals by nerve cells. When a portion of the nerve cell membrane is activated, channels open in the membrane and sodium ions are allowed to flow under the influence of the electric potential, causing an increase of positive ions in the cell and lowering the charge difference. This change in potential triggers the membrane closes to this section, causing it to undergo the same process. Thus, the signal will be sent down the cell membrane, as successive sections of the membrane are triggered. Before the nerve cell can "fire" again, the ions must be pumped out of the interior of the cell and the electric potential restored to its resting state.

In this week's lab, we are going to investigate some of the factors that affect how much electricity a capacitor can store.

Model

The capacitance of a parallel plate capacitor with no material between its plates is given by

$$C_o = \frac{\varepsilon_o A}{d}$$
 Equn. 1

where

C $_0$ is the capacitance without any material between its plates, ϵ_0 is the permittivity of free space (8.8542 x 10 -12 C2 /(N m2), A is the surface area of a plate of the capacitor, and d is the separation distance between the plates.

This equation is nice, but it neglects the fact that there is often material between the plates. The reason for this is that the plates are very close together, and there needs to be materials between them to make sure that they do not touch and discharge. Putting material between the plates, though, changes the capacitance. For a parallel plate capacitor with a dielectric material filling the region between its plates, the capacitance is given by

$$C = \kappa C_o = \kappa \frac{\varepsilon_o A}{d}$$
 Equn. 2

where

 κ is the dielectric constant for the material.

In this experiment, the plate area, A, is constant, while the plate separation distance, d, will be varied by inserting different thicknesses of dielectric material between the plates. A graph of capacitance, C, versus the reciprocal of the plate spacing, 1/d, should be a straight line. From equation 2, the slope of this straight line is

Using the measured value of the slope, the measured plate area and the known value of the permittivity of free space, ε_0 , the dielectric constant, κ , can be calculated.

Procedure

The equipment required for this activity is a multimeter that can measure capacitance, a ruler or precision calipers, two metal plates, and sheets of paper/index cards/thin plastic that are larger in area than the metal plates. For ease of use, it is best to use a commercially available variable capacitor (Fig. 2) that can be found from science equipment companies like Pasco Scientific. If you do not have such equipment, though, you can use thin aluminum or steel sheeting like that found in a hardware store for roofing flashing.

 Secure the necessary lab equipment: one set of parallel plates, sheets of dielectric material, a multimeter with capacitor settings, and ruler/calipers. Attach the wires from the parallel plates to the multimeter as shown in the picture to the right.



Fig. 2: Multimeter and variable capacitor

Measure the diameter of each plate, as well as the thickness of the edge of each plate of the capacitor, using the vernier calipers. Add these two values together and place this number on the activity sheet.

- 3. Place the plates together such that they are close to touching, but do not do so. You might try using a few rubber/plastic washers along the edge to keep them from touching if you do not already have some method for keeping them apart.
- 4. Measure the thickness from the outer edge of one of the plates to the outer edge of the other. Subtract the value found in step 2 from this number and place it on the activity sheet. Turn on the multimeter to the most sensitive capacitor setting and write the value on the activity sheet.
- 5. Move the plates further apart such that they are about 1 millimeter apart. Repeat step 4.
- 6. Continue moving the plates apart in millimeter increment, repeating step 4 at each setting, until the capacitor reading falls below .01 nF.
- 7. Place the plates back in their original space. Using several sheets of dielectric material, fill in the air gap between the plates. Make sure that the material is snugly held in place. Repeat step 4.
- 8. Add five sheets of the dielectric material between the plates and repeat step 4.
- 9. Repeat step 8 until you run out of dielectric material.
- 10. For both situations, plot the measured capacitance versus the inverse of the thickness.
- 11. Measure the slope of the line, and use this to calculate the dielectric constant κ for both air and the dielectric material. Compare this value to the stated value for both.
- 12. Answer the questions on the activity sheet.

Project IBEAM	Activity Sheet Capacitors									
Name:										
	2									
Plate area =	otal plate thickness = m									
Air										
Reading	1	2	3	4	5	6	7	8	9	10
Gap Thickness										
Capacitance										
Dielectric Material										
Reading	1	2	3	4	5	6	7	8	9	10
Gap Thickness										
Capacitance										
Create a plot of capacitance versus the inverse of the gap thickness for each. From the slope, calculate the dielectric constant Slope (air) = F m Slope (dielectric) = F m										
Air Experimental Dielectric Constant κ =					Theoretical Dielectric Constant κ =					
Dielectric Material Experimental Dielectric Constant κ =					Theoretical Dielectric Constant κ =					
Percent difference (air)=					Percent difference (dielectric)=					
1. What are some of the random errors in this experimental set-up? How have you accounted for them?										

- 2. What are some of the systematic errors in this experimental set-up?
- 3. How does your experimental results compare to the theoretical ones? Is this consistent with your systematic errors?