Leyden Jar

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The ancestor of modern day capacitors is the Leyden Jar, named after the city of Leiden in the country of the Netherlands in Europe (also known as Holland). The Leyden Jar was invented in the 1740s by a German named Ewald Georg von Kleist and independently by a man from Leiden in Holland named Pieter van Musschenbroek. The famous American, Benjamin Franklin, learned of the Leyden Jar in the decade of its invention and utilized it to collect electrical charge from clouds by flying a kite, which was connected electrically to a Leyden Jar. He was thereby able to demonstrate that lightning is actually electricity. You can read more about the Leyden Jar at this link:

http://en.wikipedia.org/wiki/Leyden_jar

You have already constructed a capacitor in a previous lesson. I thought it would be a good idea to learn more about the Leyden Jar, the precursor to the capacitor. In this lesson you will construct a Leyden Jar and use it to collect static electricity from a charged plastic pipe. You will then discharge the Leyden Jar, making an estimate of the voltage contained in the jar, by measuring the gap that a spark will jump. You will also calculate the theoretical capacitance of your Leyden Jar using a formula and confirm this calculation by measuring the capacitance with a meter.

There are design variations of the classic Leyden Jar, which I will not detail here. The one you will construct consists of a plastic container (jar), with a metal electrode inserted into the lid of the container. The container must be of insulating material, otherwise the jar will discharge immediately upon charging. If a metal lid is used, then insulation should be in place between the electrode and lid (an insulating lid is better and is the method you will use).

You will fill your jar about half-full with water so that the electrode is immersed in the water. The bottom-half of the outside of the container is wrapped in metal foil. When a negatively charged object is touched to the electrode, the excess electrons travel down the electrode, into the water, and then to the inside surface of the jar. At the same time, an equal number of electrons leave the foil on the outside, leaving an excess positive charge to balance the negative charge on the inside of the jar.

Constructing the Leyden Jar

1. Cut a strip of aluminum foil, long enough to make one wrap around the outside of the plastic container. The width of the foil should be such that it covers the bottom half of the container (about 28 to 30 mm wide).
2. Carefully wrap the foil around the bottom half of the container. Try to wrap the foil tightly, but be careful not to tear it. The foil should completely cover the bottom half.
3. Using a piece of bare wire, wrap it around the foil to hold it in place. Twist the ends of the wire together to tighten the wire around the jar. Later you will connect a wire jumper to this wire.
4. Fill the container half full with water and then attach the lid with electrode.

Calculating the capacitance of your jar

In the previous lesson on capacitors I gave you the formula for calculating capacitance:

$$C = (K)(Eo)(A/d)$$

In the above formula C is capacitance in Farads

For this lesson we will use a different unit for capacitance so that it will be easier to make your calculations.

$$C_{nf} = (K)(Eo)(A/d)$$

C_{nf} = capacitance in nanofarads (nF)   a nanofarad is one billionth of a Farad

K is the dielectric constant of the insulating material (the container), which for polyethylene is 2.2

Eo = 0.0000089, the permittivity of free space, when the capacitance is in nf and measurement of length in millimeters

A = area of the aluminum foil in square millimeters

d = thickness of the container in millimeters

Your assignment is now to calculate the capacitance of your Leyden Jar. The first step will be to calculate the surface area of the aluminum foil in square millimeters. Area is calculated by multiplying length by width. In this case the effective length of the aluminum foil is also the circumference of the jar. The circumference of a circle is calculated by multiplying the diameter of the circle by pi. The value of pi is 3.14. For example, the circumference of a circle that is 100 mm in diameter would be calculated as follows:

100 mm x 3.14 = 314 mm

Now calculate the circumference of your jar by first measuring the diameter with a ruler. Then complete the calculation below.

________________ mm diameter X 3.14 = ___________________ mm circumference

Once you have the circumference calculated, measure the width of the aluminum foil. Then you are ready to calculate the area of the foil in square millimeters:

___________ mm circumference X _______________ mm width = ______________ mm^2 area

Here is our formula again: C_{nf} = (K)(Eo)(A/d) You have just calculated the area, which is A in the formula. I have already measured the thickness of the jar for you using a micrometer. The thickness is 0.84 mm. Now you have all the information needed to solve for the capacitance of your Leyden Jar:

$$C_{nf} = (2.2)(\ 0.0000089)(A/0.84)$$

Let me do an example calculation assuming that the area is 100 square millimeters (much less than your actual jar)

$$C_{nf} = (2.2)(\ 0.0000089)(100/0.84)$$

So, how do we do the calculations?

Step one: divide the area by the thickness (A/d): 100/0.84 = 120

Step two: substitute the value of 120 for A/d:

$$C_{nf} = (2.2)(\ 0.0000089)(120)$$

Step three: multiply 0. 0000089 by 120 = 0.0011

Step four: multiply 0.0011 by 2.2 = 0.0024 OR **C_{nf} = 0.0024 nanofarads**

Now make your calculations:

1. Area of the foil (**A**) is: __________________ mm^2
2. Thickness **d** of container is: 0.84 mm
3. Calculate **A/d** (divide A by d): ____
4. C_{nf} = (K)(Eo)(A/d) or…
5. C_{nf} = (2.2)(0. 0000089)(A/d) or (2.2)(0.0000089)(___________) = _____________________

Measuring the capacitance of your Leyden Jar

You have just calculated the capacitance of your jar. Now it is time to compare the value you obtained by calculation to a measurement with a meter. You will use my meter (it has a gray colored case).

1. Set the meter selector to **CAP** and wait a few seconds until the reading on the meter stops changing or at least does not change very much.
2. Press the **REL** button on the meter to reset the reading on the meter to zero
3. Touch one of the meter probes to the Leyden Jar electrode
4. Touch the other probe to the wire wrapped around the foil
5. Record the reading on the meter _____________ nF

Compare your calculated and measured capacitance of the Leyden Jar

_______________ nF calculated _________________ nF measured

Your calculated and measured values will probably not be the same but they should not be greatly different. In other words, one value should not be twice or more than the other value. If this is not the case, you should recheck your calculations for the calculated value.

Charging your Leyden Jar to a high voltage

You may recall that capacitors have voltage ratings. The capacitors you have been using in the GEAR projects generally are rated below 100 volts. However, your Leyden Jar has a capacity of several thousand volts due to the high insulating value of the jar. Therefore, it can be used to store an electrical charge of thousands of volts. We can generate this high voltage in a static electricity experiment, which is what you will do now. While the voltage you will generate is high, the amount of charge the small Leyden Jar can hold is very limited. Therefore, the amount of current your body will experience if you accidentally get an electric shock is too small to harm you.

1. Place your Leyden Jar on your work table next to the wood frame containing the paper clip electrode. Slide the jar so that the tip of its electrode is close to the tip of the paper clip electrode. If the paper clip electrode is higher or lower than the jar electrode, then bend the paper clip so that its tip is at the same level above the table as the tip of the jar electrode.
2. Rub a plastic pipe with the cloth provided. Rub one end of the pipe about 20 times.
3. While holding the Leyden Jar by the foil, slide the rubbed end of the pipe along the electrode attached to the jar cap to transfer the charge to the jar. Make several passes, rotating the pipe between passes so that you transfer all the charge from the pipe to the jar. At no time should you touch the electrode of the jar with any part of your body, as this will discharge the jar and may give you a small electric shock (harmless).
4. Once you have the jar charged to a desired level, which may require several cycles of rubbing the pipe followed by a charge transfer, you will discharge the jar. It is important during this process that you never touch the electrode of the jar with any part of your body, as this will cause it to discharge (you may receive an unpleasant but harmless electric shock).
5. When the jar is charged, connect a jumper wire to the wire that is holding the foil in place. The other end of the jumper wire should be connected to the paper clip electrode on the wood frame.
6. With the jar sitting on your work table, slowly slide the jar toward the electrode of the wood frame. Your purpose here is to determine the maximum gap space between the jar electrode tip and the tip of the paper clip electrode of the wood frame when a spark will jump the gap. Slowly slide the jar, causing the two electrode tips to come closer together until you see or hear the spark caused when the jar discharges. At that point do not move the jar anymore.

7. Measure the spark gap in millimeters with a ruler. The spark gap is the distance between the tips of the electrodes and is an indication of the voltage contained in the charged jar.

You should repeat this experiment several times, entering your data in the table below for number of charges and spark gap. Start out by transferring only one charge to the jar. That is, rub the pipe 20 times and then transfer that charge to the jar. Then check to see if a spark will jump between the electrode tips. It is unlikely that you will observe a spark with only one charge collected in the jar. I would suggest that you then try transferring 3 charges to the jar (rub pipe 20 times, transfer to jar, then repeat another two times). Then you can try transferring 5 charges to the jar. With that much charge you should be able to get a spark if you are doing the experiment properly. You may also select additional numbers of charges if you wish to make your experiment more complete. After you are done you will calculate the voltage for each number of charges.

Number of charges in jar	Spark gap (mm)	Voltage

You can use a very simple formula to estimate the voltage of the charged jar:

Spark Gap in mm + 0.7 = Kv [1 Kv = 1,000 volts]

For example, suppose you charged your jar three times and found that a spark jumped across a gap of 2 millimeters. Then you could estimate the voltage in the jar like this:

2 mm + 0.7 = 2.7 Kv or 2,700 volts

If you found that you needed to set the electrode tips to a distance of 2mm from each other before the spark jumped the gap, then the voltage in the jar would have been about 2,700 volts.

Now calculate the voltage for each charge and complete the table above.

Paschen's Law

By experimenting with high voltage between metal plates, the German physicist Friedrich Paschen found a relationship between the air gap of the plates and the voltage required to cause a spark to jump across the gap. This relationship is known as Paschen's Law and is given by the formula on the next page.

$$V_B = apd/\ln(pd) + b$$

Where:

V_B is the breakdown voltage in volts (the voltage required to create a spark)

p is the pressure of the air in Atmospheres (the average pressure value for air on Earth at sea level is one Atmosphere)

d is the gap distance in meters

a and ***b*** are constants that have different values depending on the composition of the gas and here I will provide the values for the air on Earth, which is a mixture of primarily nitrogen and oxygen.

a = 4.36×10^7 V/(atm.m) or to make it simple just use this number: 43,600,000

b = 12.8

Example problem using Paschen's Law

Suppose we experimented with high voltage using two plates for electrodes. Furthermore, suppose the plates are separated by 2 millimeters. Then using Paschen's Law, we could calculate the voltage necessary to make a spark jump across the air gap between the plates. We will assume that the air pressure is one Atmosphere.

$$V_B = apd/\ln(pd) + b$$

$$V_B = (43{,}600{,}000)(1)(0.002)/\ln(1 \times 0.002) + 12.8$$

In the line above I have substituted all of the values into the formula. We have to convert the gap in millimeters to meters by dividing by 1,000 (*i.e.*, 2 mm = 0.002 meters). Now all we need to do is the calculations. In the numerator we must multiply the three numbers together. Since one of the numbers is a one, we can just ignore it and do this: 43,600,000 x 0.002 = 87,200.

Now we need to work on the denominator. What is that term **ln**? I am guessing that you have not learned about this yet in your math studies in school. It is called the natural logarithm. You don't need to understand it for now as long as you have a calculator that has the natural logarithm function. Look for a button that is labeled **ln**. In our case, we need to find the natural logarithm of 0.002. I enter 0.002 into the calculator and press the **ln** button to get the answer: -6.21, which is a negative number. To complete our calculation of the denominator we must add the negative number -6.21 to 12.8, which is the same as subtracting the positive number 6.21 from 12.8: 12.8 – 6.21 = 6.59. Now this is what we have so far:

$$V_B = 87{,}200/6.59$$

We divide 87,200 by 6.59 to get our answer: V_B = 13,200 volts

That amount of voltage is high compared to what you found in your Leyden Jar experiment. I gave you another formula for that experiment:

Spark Gap in mm + 0.7 = Kv

Using the above formula, the voltage required for a 2 mm gap should be 2,700 volts, not 13,200 volts. The difference is that you used POINTED ELECTRODES in your experiment, not flat plate electrodes. It takes less voltage for a spark to jump between pointed electrodes.

The formula I have given you for pointed electrodes is simplified and does not account for the atmospheric pressure or the composition of the gas in the gap between the electrodes. We are assuming that our experiment will be conducted at one Atmosphere of pressure in air.

Breakdown of an insulator

Various insulating materials will breakdown and conduct electricity if sufficient voltage is applied. Air is no exception to this rule. There are always a small number of free electrons in air due to cosmic rays and background radiation. When we apply a large voltage difference between two electrodes separated by air, it creates a very strong electrical field. The free electrons in that field are accelerated and in turn collide more readily with atoms of the air, knocking more electrons off the atoms in the air. In this process a channel of ionized air is created, which provides a conducting path for electric current through the air. These are the events that cause electrical sparks in air.