Electrostatics: The Shocking Truth

Pre-Lab: The Van de Graaff Generator

A Bit of History

The Van de Graaff generator is an electrostatic generator, capable of producing constant electric potential differences reaching about 10 million volts. The models that you will use (thankfully) only achieve about 1% of that. The term *Van de Graaff electrostatic generator* may sound a little foreign, but there is one electrostatic generator that you are no doubt familiar with: earth's atmosphere. In fact, some of the most famous experiments in the history of electrostatics were done using the atmosphere. In May of 1752, Benjamin Franklin performed his well-known kite experiment, an experiment which strongly suggested that lightning might not be so different from the sparks he produced using silk and glass. Interestingly, not long after Franklin completed his experiment, he learned that he had been scooped by a group of Frenchmen who had read one of his recently published books. It turns out that both groups were lucky to survive the experiments, as a Swedish scientist died the next year while attempting to replicate them.[1]

The Van de Graaff generator itself has achieved great fame as a tool for demonstrating the principles of electrostatics to physics students in spectacular fashion. (The world's largest Van de Graaff generator, found at the Boston Museum of Science, exists solely for this purpose.) However, the Van de Graaff generator has also been used as a tool for doing real science ever since its invention by the American physicist Robert Van de Graaff around 1930. The high potential differences produced by large Van de Graaff generators are still used as particle accelerators around the world. While they can't accelerate particles to energies of a TeV (1 trillion electron volts) like the Large Hadron Collider at CERN, sometimes a few MeV's (millions of electron volts) is all a researcher needs. Among the many modern uses for the Van de Graaff generator are radiocarbon dating, x-ray imaging, and the production of particles for medical purposes.[2]

The Van de Graaff generator even played a role in a recent research project in which the Wash U physics department played a major part.[3] The *Stardust* mission sent a spacecraft through a comet tail, collected particles that had blown off the comet, and safely landed back on earth. In order to calibrate their collectors, scientists bombarded them with small grains accelerated to speeds up to 30 km/s. Such incredible speeds could most efficiently be produced using large Van de Graaff generators.

University of Virginia Van de Graaff Resource

The big piece of equipment in this week's experiment is a Van de Graaff generator powered by a hand crank. A Van de Graaff generator uses some clever tricks in order to charge a metal dome to a very high potential. (The Van de Graaff generator is described by Moore in Unit E, pages 15 and 102 and by Young & Freedman on page 857.)

The University of Virginia has an excellent virtual demonstration of the inner workings of the Van de Graaff generator. You can find a link to this demonstration on the Pre-Lab Links tab of the Electrostatics page of the lab website (you can also go to http://virlab.virginia.edu/VL/VDG.htm/state/0). Walk through the presentation (that is, watch the videos and read the slides) and answer the following questions.

PL1. What is the only quick way to discharge a fully charged Van de Graaff generator?

PL2. What is the function of the motor of the Van de Graaff generator?

PL3. Will a Van de Graaff generator work if the belt and the pulley are made of the same material? Explain briefly.

PL4. The outside of the belt carries electrons upward toward the dome. Where do these electrons come from? (You don't need to explain. We are just looking for an object.)

PL5. How can electrons jump from the outside of the belt onto the upper comb that is attached to the dome? Why aren't they repelled by the excess electrons that are already on the dome?

PL6. Is it possible to make a Van de Graaff generator with a positively charged dome? How?

Part I: Howdy Partner

The Story

What's the best way to get to know someone? We've always found that it's by delivering a mild electrical shock! Although, I suppose physicists aren't necessarily known for having the most highly developed social skills…

Equipment

- Van de Graaff generator
- Grounded wand (the wand with a wire connecting it to the base of the generator)
- Ungrounded wand (the wand with no wire connected to it)
- A New (soon to be old?) friend

1. Experiment

Read This: This procedure refers to Partner 1 and Partner 2. To make the flow more natural, the instructions will be written in the second person to Partner 1.

1.1. Record who is Partner 1 and who is Partner 2.

Do This: Place your left hand on the globe of the Van de Graaff generator and keep it there. Gently turn the crank **FIVE (5)** times with your right hand. Finally, touch the index finger on

Partner 2's right hand with the index finger on your right hand. After that, you can remove your hand from the dome.

1.2. What happened? Give a brief explanation of why this happened.

Do This: Touch the grounded wand to the dome of the Van de Graaff generator. This is called *grounding* the dome.

1.3. What happens to the excess charge on the dome when you ground it?

Do This: Place your left hand on the dome of the Van de Graaff generator and keep it there. Gently turn the crank **FIVE (5)** times with your right hand. This time, touch elbows with Partner 2 instead of fingers.

1.4. Was the experience any different? If so, do you have any guess as to why the experience was different?

Do This: Ground the dome again.

Do This: Place your left hand on the dome of the Van de Graaff generator and keep it there. Gently turn the crank **THREE (3)** times with your right hand. Have Partner 2 take the grounded wand by the plastic handle and touch it to your elbow. Then remove your hand from the dome.

1.5. What happened? Give a brief explanation of why this happened.

Do This: Place your left hand on the dome of the Van de Graaff generator and keep it there. Gently turn the crank **THREE (3)** times with your right hand. Have Partner 2 take the *un*grounded wand by the plastic handle and touch it to your elbow. Then remove your hand from the dome.

1.6. What happened? Give a brief explanation of why this happened.

Part II: Charging Up

The Story

There's a very funny scene in the film *Ghostbusters* where Dr. Vankman (played by Bill Murray) is testing out the effects of negative reinforcement on extrasensory perception (or ESP). A participant in the study tries to guess the shape on a card that Dr. Vankman is holding, receiving a mild shock if the guess is incorrect.

Having completed Part I of the lab, you should be an expert at shocking people. In Part II of today's lab, we'll be testing the effects of negative reinforcement on your ability to solve electrostatics problems. You'll be asked to make predictions as you work through today's experiment. (Be sure to read Appendix A about making predictions!) Every time you get a prediction wrong your partner gets to shock you.

(Plus you'll probably get shocked on accident a few dozen times.) Our preliminary findings indicate that you will indeed be more knowledgeable of electrostatics after completing this set of experiments.

Equipment

- Van de Graaff generator with grounded and ungrounded wands
- Tape
- Plastic fork
- Scissors

2. Are You the Positive or Negative Type?

You'll begin this experiment by determining the sign of the charge on the dome. After that, you can use this information to predict the outcome of various experiments.

Do This: Cut a strip of tape that is about 6 inches (~15 cm) long. Fold over about 1 cm of the tape onto itself in order to make a non-tacky handle. Label this handle with a *T*. This is *tape-T*. Stick tape-T to the table such that most of it is dangling down over the edge. Gently brush your fingers over the tape to remove any static electricity.

Do This: Repeat the previous **Do This** but label the tape with a *U*. This is *tape-U*.

Do This: You are about to stick these two strips of tape together in a very particular fashion. Stick them together such that the tacky side of tape-T is in contact with the un-tacky side of tape-U. Then pull the two strips of tape apart. Affix each strip of tape to a desk or table such that most of the strip is dangling over the edge. This time **do not** brush your fingers over the tape.

Read This: In the process of tearing the two strips of tape apart, you have given each a net charge! By conservation of charge, these two strips must be oppositely charged. You will figure out which one is negatively charged and which one is positively charged. This is where the plastic fork comes in handy. **FACT:** When you run a plastic comb through your hair, the comb becomes negatively charged. If you're a fan of Disney movies, you know that a fork works just as well as a comb.

2.1. Describe, perform, and analyze an experiment in order to determine which of the two strips of tape is negatively charged and which strip is positively charged.

Read This: Now that you know about the charges on each strip of tape, you will use them in tandem with the Van de Graaff generator in a series of experiments. You may recycle your fork.

Do This: Charge up the Van de Graaff generator. Grab tape-U at the folded end, remove it from the table and slowly bring it toward the dome of the generator. Make sure to start with the tape about 1 meter away from the generator.

2.2. What happens? What does this say about the charge on the dome of the generator?

Do This: Stick tape-U back on the table.

2.3. *Predict* what will happen if you remove tape-T from the table and slowly move it toward the charge dome as you did with tape-U. Again, make sure to start with the tape about 1 meter away from the generator. Explain your reasoning. (See Appendix A about making predictions.)

Do This: Put the prediction you made in Step 2.3 to the test.

2.4. Was your prediction correct? If not, explain where your reasoning failed. (And don't forget about negative reinforcement.)

Do This: Just to be safe, recharge your pieces of tape and stick them back on the table. Recharging the tape is an especially good idea if either strip touches the dome or the wands.

2.5. *Predict* the results (i.e. the behavior of the strips of tape) of the following experiment and explain your reasoning: After charging the Van de Graaff generator, you touch the *ungrounded* wand to the dome. Then you move this wand toward each of the two dangling strips of tape, one at a time.

Do This: Put the prediction you made in Step 2.5 to the test.

2.6. Was your prediction correct? If not, explain where your reasoning failed.

2.7. *Predict* the results (i.e. the behavior of the strips of tape) of the following experiment and explain your reasoning: After charging the Van de Graaff generator, you touch the *grounded* wand to the dome. Then you move this wand toward each of the two dangling strips of tape, one at a time.

Do This: Put the prediction you made in Step 2.7 to the test.

2.8. Was your prediction correct? If not, explain where your reasoning failed.

2.9. *Predict* the results (i.e. the behavior of the strips of tape) of the following experiment and explain your reasoning. This one's a little longer, so we'll give the steps letters:

a) Charge up the Van de Graaff generator.
b) Move the ungrounded wand to a distance of ten centimeters from the dome. Hold it there until (e).
c) Touch the ungrounded wand with the grounded wand. (If the Van de Graaff generator arcs to either wand at this point, ground everything and start from the beginning.)
d) Set the grounded wand down on the table, still holding the ungrounded wand 10 centimeters from the dome. (If the Van de Graaff generator arcs to either wand at this point, ground everything and start from the beginning.)
e) Pull the ungrounded wand away from the generator.
f) Bring the ungrounded wand toward each strip of tape, one at a time.

Do This: Put the prediction you made in Step 2.9 to the test.

2.10. Was your prediction correct? If not, explain where your reasoning failed.

Part III: Energy Considerations

There are many concepts that you learned last semester that are going to come back again and again during the spring. Energy is one such topic. There are all sorts of new places where we see energy changing from one form to another during second semester physics. The transformation of energy between different forms can be quite spectacular when using the Van de Graaff generator.

Equipment

- Van de Graaff generator with grounded and ungrounded wands
- Small fluorescent light bulb
- Test lead with banana plug on one end and alligator clip on the other end

3. Transferring Energy to the Generator

Do This: Charge the generator by turning the crank a few times. While doing, this try to be aware of the energy your arm is expending.

3.1. List the chain of the different forms that energy takes in the process of charging up the generator.

3.2. When you stop cranking and the generator dome is charged, where (in what form) is the energy?

Do This: Bring the grounded wand near the dome of the generator.

3.3. Describe what happens. (No explanations of "why" needed – just describe what you see, hear, etc.)

3.4. What happened to the energy stored in the generator when you brought the wand near the dome? If the energy has changed forms, which form(s) has it taken?

4. Fluorescent Light

Let's now consider how this room is lit. Looking upward you will notice that the light is coming from a series of fluorescent light bulbs. In these systems electrical energy (which originated in a power plant of some sort) has been converted into the light energy that eventually reaches your eye.

In order to light up a room, the two ends of a fluorescent bulb must be at different electrical potentials. This potential difference accelerates electrons, giving them kinetic energy that is used to create light.

(Light is produced through an interesting chain of events that you will investigate a little bit in this semester's Spectra lab.)

Do This: Connect one end of the test lead to the ground plug and connect the other end, via an alligator clip, to one end of your small fluorescent bulb. Holding it by the glass tube, place the unconnected end of the fluorescent bulb near (~5 mm) the dome of the Van de Graaff generator.

4.1. Describe what you observe when you crank the wheel of the generator.

4.2. Using energy considerations, explain the chain of events described in Step 4.1.

Do This: Now connect one end of the light bulb to the dome of the generator via the test lead and alligator clip (there is a receptacle for the banana plug on the top of the dome). Bring the unconnected end of the light bulb near the dome of the generator.

4.3. Describe what you observe when you crank the wheel of the generator.

4.4. Explain your observations (Step 4.3) in terms of potential energy (or electric potential).

4.5. Relate the experiments you have just done with the fluorescent light to birds standing on power lines.

Part IV: Dielectric Breakdown

Equipment

- Van de Graaff generator with grounded and ungrounded wands
- Test lead

5. Lil Lightnin'

You've probably seen some pretty fantastic little lightning bolts by now. In this Part, we'll investigate those in a little more detail. And you probably won't get shocked.

First, let's be clear about what happens when you see one of those sparks. It's the result of a phenomenon known as *dielectric breakdown*. When the electric field in air exceeds a value of about 3×10^6 V/m, air turns into a conductor as electrons are ripped from the air molecules by the strong electric field. (This critical electric field is called the *dielectric strength* of air.) We will learn more about why light is produced later in the semester.

Read This: Keep in mind during this section that as you turn the crank at a constant rate, new charge is added to the dome at an approximately constant rate.

Do This: Have one partner turn the crank at a gentle, constant rate. Have the other partner hold the grounded wand by the plastic handle. Slowly vary the distance between the wand and the dome of the Van de Graaff generator. Observe how the frequency of sparks changes as the position of the wand is varied.

5.1. Record your observations.

5.2. What is the equation for the electric field around a spherically symmetric charge distribution?

5.3. Explain the connection between your responses to Step 5.1 and Step 5.2.

Read This: If the critical electric field is exceeded in the entire region between two conductors, you have seen that a spark can jump between them. Sometimes, though, the critical electric field is reached only in a small region around a single conductor. When this happens, we get entirely different results.

Do This: Remove the grounded wand from the ground plug. Plug the long test lead in to the ground plug.

Do This: Have one partner turn the crank at a gentle, constant rate. Have the other partner hold the long test lead by part of it that's plastic. Slowly vary the distance between the tip of the test lead and the dome of the Van de Graaff generator. Observe what happens as the position of the test lead is varied.

5.4. Record your observations.

Read This: The observations you recorded in 5.1 and 5.4 are probably different. You might guess that this difference has something to do with the difference in geometry of the wand and the test lead, and you would be correct. As it turns out, electric field lines must intersect a conductor at a 90° angle. This fact means that the field lines can be more densely packed around a highly rounded object (such as the test lead) than they can around a less rounded object (such as the grounded wand) – this is another way of saying the electric field around a conductor is largest near points and other regions with a small radius of curvature. With this in mind, answer Head Scratchers 5.5 and 5.6.

5.5. The test lead has a smaller radius of curvature than the grounded wand, allowing the electric field lines around the test lead to be more densely packed than around the wand. As a consequence, if the grounded wand and the test lead are placed a few centimeters away from the charged dome (choose one and explain why you made your choice)…

A. the electric field around the test lead is not high enough to attain breakdown and no spark is observed.
B. the electric field around the test lead is so high that the breakdown happens so fast our eyes can't see it.
C. the electric field around the test lead is large enough to ionize the air around it, allowing excess charge to leave the test lead without producing an observable spark.
D. as Yoda would say, "the *Force* is with the test lead."

5.6. The electrical properties of that test lead are pretty cool. And these properties can be put to good use. What is a real world scenario where something like this test lead is exploited? (If you can think of more than one, feel free to show off.)

Head-Scratchers

Don't forget to complete the following problems. They should be at the end of your lab report. If you want to work on them during lab, start a new page in your lab notebook.

- 4.5
- 5.5
- 5.6

References

[1] Jonnes, Jill. (2003). *Empire of Light*. Random House, USA.

[2] Hinterberger, F. (2005). "Electrostatic Accelerators". CERN Accelerator School, The Netherlands.

[3]Posteberg, F., et al. (2011). "A New View on Interstellar Dust - High Fidelity Studies of Interstellar Dust Analogue Tracks in Stardust Flight Spare Aerogel". Lunar and Planetary Science Conference, Houston, TX.

Appendix A: Making Predictions

In this lab, you are asked to make many predictions, after which you test your predictions. It's okay if your predictions are wrong! Do not erase predictions that you discover were incorrect. Incorrect predictions will receive full credit as long as you "support your prediction with a sentence or two" as requested. On the other hand, correct predictions will receive little or no credit if you do not explain how you made your prediction.

After you test your predictions, you are asked whether or not you were correct. If your prediction was correct and complete, just draw a smiley face. If your prediction was incorrect or incomplete, you must explain where your reasoning failed. Make it clear that you understand what went wrong. Learning what your misconceptions are is the best way to fix them! As mentioned previously, do not erase incorrect predictions.