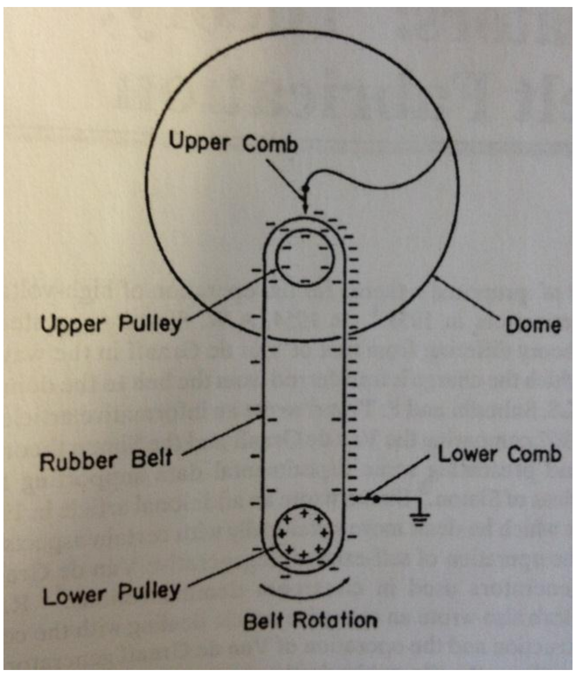
The Van de Graaff Generator

By: Lindsey Rasmussen

Lab: H001

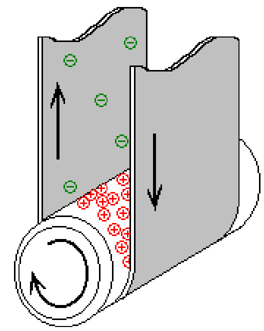
UAID: 010582409

The Van de Graaff generator is a machine that relies on electrostatics or charge separation in order to create large amounts of voltage. It was invented by Robert J. Van de Graaff in 1929 in order to be used in the study of particle acceleration and aspects of nuclear physics. The Van de Graaff generator would inspire designs for similar machines that are still used in research today. (Brenni, 1999) However, while there are many variations of the Van de Graff generator, the most basic design includes a motor, two pulleys, two combs, a conveyor belt, and a large metal conducting sphere.



Internal visual of generator components and charge distribution inside the generator. (Berg, 1990)

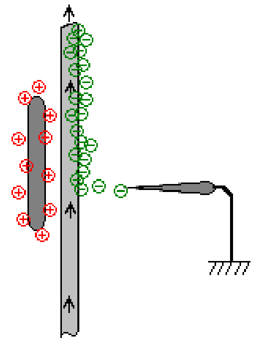
The lower pulley or roller is made of a dielectric, usually plastic, and is sometimes covered with some type of cloth on the surface. (Berg, 1990) The lower pulley is turned by an electric motor. As the lower pulley turns, the rubber conveyor belt is moved causing friction between the pulley and the belt. Because the belt and pulley are made from two different materials, "frictional charging" takes place. (Beaty, 2005) Frictional charging happens when the two different materials touch causing bonds to form and unequal sharing of charges of the surface atoms. When the belt and pulley are separated, those charges are separated as well which will eventually cause a strong build-up of positive charge on the lower pulley. This will also cause a build-up of negative charge on the conveyor belt, but the charge will be more spread out across the entire conveyor belt as opposed to the concentration on one pulley. (Beaty, 2005)



Shows concentration of positive charges on the lower pulley while there is an even, but more spread out distribution of negative charges on the conveyor belt. (Beaty, 2005)

Next, a metal comb is positioned near the lower pulley where the tips are as close to the conveyor belt as possible without the belt and tips touching. The other end of the comb is grounded. Due to the close proximity to the positively charged pulley, the negative electrons in the comb are attracted towards the pulley. Because charges gather at sharp points or edges, the concentration of electrons at the tips of the comb creates an intense negative charge that is strong enough to affect the air around them. (Cunningham, 1994) In fact, the charge becomes so strong that the air molecules that come close to the comb are separated into electrons and positive nuclei. These freed electrons are repelled away from the comb causing them to break up other air molecules as well. Soon, a body of free electrons and positive nuclei form around the tips of the comb. This mass is called “corona discharge” or “plasma” (the fourth state of matter). (Beaty, 2005) This body of plasma acts as a conductor. The free electrons in the plasma begin to attach to other neutral air molecules, creating many negatively charged molecules. At the same time, all of the free positively charged nuclei are attracted to the comb and take electrons from it when they run into it. Basically, the comb begins to give off a steady flow of electrons, which is made possible by the fact that the comb is grounded so it is able to draw on an almost unlimited amount of electrons from the earth in order to meet the continual demand for electrons as the generator runs.

As all of these negatively charged particles are formed, they are attracted to the positive charge of the pulley. However, the rubber conveyor belt, a conductor, is in the way, so instead of charges cancelling on the pulley, one side of the conveyor belt is negatively charged by induction, since "the positive roller induces a charge on the tip of the [comb]." (Beaty, 2005) This steady transference of electrons is made possible by the mass of plasma because it acts as a bridge for the electrons from the comb tips to the conveyor belt. This steady transference of charge is also referred to as "charging by corona wind." (Beaty, 2005) It should be noted that there must be plenty of air molecules available for this plasma effect to take place. If a Van de Graaff generator is in a vacuum, it will not work. (Beaty, 2005)



Shows the flow of electrons from the comb to the conveyor belt at the lower pulley. (Beaty, 2005)

Next, the conveyor belt carries the negative charge up the shaft of the Van de Graaff generator to the upper pulley. This second pulley is the opposite of the first pulley. It is usually made from a neutral metal, and it will obtain the opposite charge, in this case negative, as the generator runs. As the conveyor belt passes over the second pulley, the electrons on the belt are repelled by the negative charge on the upper pulley. Again there is an interaction between the pulley and the comb except this time the negative charge of the pulley causes the tips of the comb to become intensely positively charged. This causes another mass of air particles to separate into plasma, only this time the electrons are attracted to the comb and the positive nuclei are attracted to any remaining negative charge on the conveyor belt. (Beaty, 2005) Since the other end of the comb is attached to the inside of the Van de Graaff sphere, the electrons that are repelled by the upper pulley and attracted by the upper comb travel through the comb, through a wire that connects the comb to the inside of the dome, and eventually the electrons spread out across the surface of the sphere. (Berg, 1990)

In this example, it was assumed that the lower pulley of the generator obtains a positive charge and the belt obtains a negative charge. However, the opposite can also be true. Using a conveyor belt made of plastic and a lower pulley made of rubber would make the lower pulley have a negative charge and the belt have a positive charge. The polarity would also be reversed if a metal pulley was put as the bottom roller and a rubber pulley was put as the top roller. In both of these examples, the direction of current would also be reversed. (Beaty, 2005)

Since Van de Graaff generators do not work well in humidity, there are some changes that can be made to the design to help the generator have a stronger discharge in a humid environment. Some generators are made where both of the rollers develop strong charges. This means that one charge would go up the conveyor belt and the other charge would come down the other side of the conveyor belt so that both sides of the belt are continually charged. Another design replaces the lower pulley with a metal pulley that is connected to a high voltage power supply. This creates a better charge on the conveyor belt when it is too humid for “frictional charging” between the pulley and the conveyor belt to take place effectively. (Beaty, 2005)

So, now that the internal workings of the Van de Graaff generator are explained, now it is time to discuss what the Van de Graaff generator actually does. The charge on the outside surface of the sphere continues to increase as the motor runs until suddenly there is a spark that looks like lightning, and a portion of that charge is discharged into the air. This process of charging and discharging will continue to happen as long as the motor is running. The generator will also spark if someone or something conductive gets close enough for there to be a transference of charge. (Cunningham, 1994)

The reason for this sparking is that dry air is a dielectric, and therefore can only stay insulating as long as the electric field $|\vec{E}| < 3 \times 10^6 N/C$. Once the electric field of the Van de Graaff generator reaches that point, sparking occurs, and current flows into the surrounding air in order to reduce the electric field back into the range that the dielectric can handle. However, not all Van de Graaff generators discharge at the same time, threshold, or with the same amount of voltage. Larger generators discharge much greater amounts of voltage than smaller generators. (Berg, 1990) The extremely large ones can discharge voltages of at least 7,000,000 V, which is way more than the sparking threshold of dry air. (Brenni, 1999)

The reason for the range in voltages discharged is as follows. Electric field is given by the following equation for any radius *r* greater than the radius of the sphere of the generator.

$$E = \frac{Q}{4\pi\varepsilon_o r^2}$$

Capacitance, *C*, of an isolated sphere with radius *a* is

$$C = 4\pi\varepsilon_o a$$

Charge is given by the equation

$$Q = CV$$

where *C* is the capacitance and *V* is the voltage with which the Van de Graaff generator discharges.

Substituting into the original equation, it is found that the electric field for a sphere of radius a is

$$E = \frac{CV}{4\pi\varepsilon_o r^2} = \frac{V}{a}$$

Therefore,

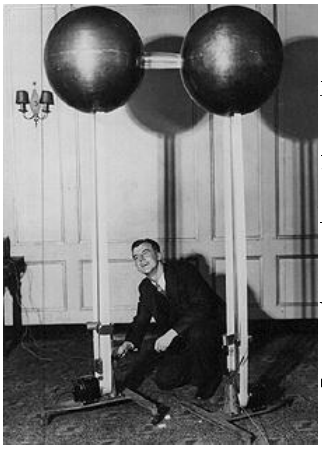
$$V = Ea$$

So the maximum potential, V_a, for a dome with a radius a surrounded by dry air is

$$V_a = 3{,}000{,}000a\ Volts$$

where a is measured in meters. Therefore, the maximum amount of voltage with which a Van de Graaff generator can spark is directly related to the size of the sphere of the generator. (Berg, 1990) However, this does not mean that the generator will always spark at this voltage. Other factors play a role such as the humidity of the environment and the smoothness of the sphere. If it is humid, the threshold is much lower, and the sphere discharges more frequently with much smaller voltage. It sounds more like a constant crackle, and it is difficult to see any sparks. If the sphere has any dings, dents, or chips, charge will accumulate faster at those sharp points and will cause the generator to spark more frequently. (Cunningham, 1994)

The motivation for the Van de Graaff generator originated with British physicist Ernest Rutherford's experiment in 1917 in which he successfully transformed nitrogen atoms into hydrogen and oxygen atoms by bombarding the nitrogen with alpha particles. While scientists were excited to learn that it was possible to transform elements, they soon realized that achieving this level of atomic bombardment required large amounts of energy. This was especially true if they wanted to penetrate the potential barrier, the Coulomb wall, of the nuclei of heavier elements. Scientists believed the solution was that since electric field equals charge times voltage, they could break through the Coulomb wall if they found a way to produce enough voltage. This started a race between scientists to find a way to produce a high amount of voltage. (Brenni, 1999)



Robert Van de Graaff with his first working generator in 1929. (Museum of Science in Boston, 1995)

While several designs were proposed with some success, including Tesla coils, resonance transformers, and moderate electric fields, Robert Van de Graaff's generator was one of the better ideas. Van de Graff finished his first version of the generator in 1929 while working at Princeton University. In 1931, he joined the MIT research department and began construction on a large double generator which he finished in 1933. While his first generator produced about 80,000V, Van de Graaff's 1933 generator produced about 7 million volts. The columns of the generators were 23ft high and the supporting aluminum spheres were 6ft in diameter. Each column had two conveyor belts, and each dome had a small laboratory inside for the scientists to collect data. (Brenni, 1999)

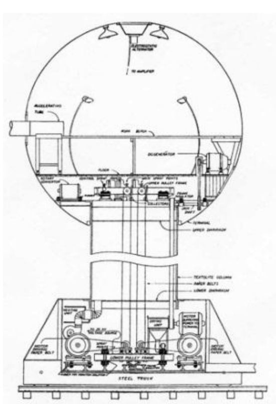
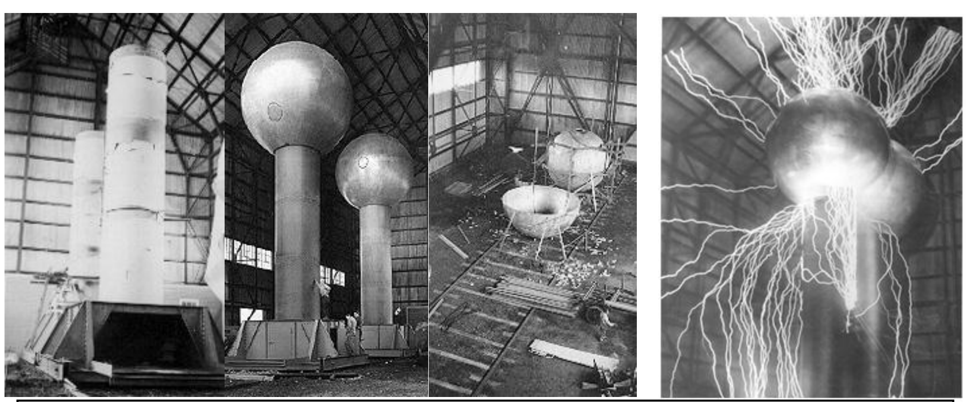


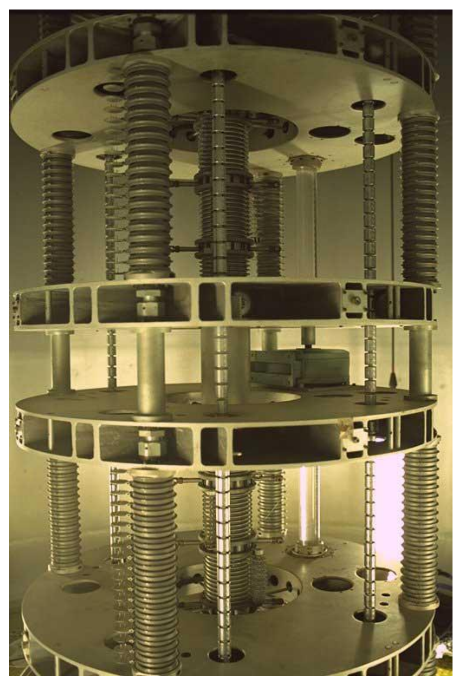
Diagram of the inside of the generators including a laboratory inside the dome. (Brenni. 1999)



Photos of the double Van de Graaff generator that Robert Van de Graaff completed in 1933 at MIT. Today the generator is displayed at the Museum of Science in Boston. (Museum of Science in Boston, 1995) (MIT Institute Archives & Special Collections, 2003)

Although this model created vast amounts of voltage, the reality was that it was too big to work efficiently as a particle accelerator since it was difficult to discharge the generators after use. The generator was eventually moved to MIT (it was originally built in an abandoned airplane hanger). The generator was modified and used for atom smashing and high-energy X-rays research. The design of the generator spread rapidly in the 1930's, and scientists began making their own adjustments to the original design by finding which materials worked better or which mechanical adjustments made it run smoother or last longer. (Brenni, 1999)

Two inspired designs that are still in use today are the Pelletron accelerator and the Tandem-generator. The Pelletron accelerator is similar to the Van de Graaff generator except that the conveyor belt is replaced by one or more chains made of metal pellets that are connected by insulating nylon links. This design is much more spark-proof, so it has a longer life-span and the potential voltage goes up to 25-30 MVolts. The Tandem-generator lies horizontal and has multiple rows of conveyor belt that wind back and forth to create a larger voltage. The machine is highly-efficient, and its voltage can also reach up to 30 MVolts. (Brenni, 1999)



Pelletron accelerator. (Brenni, 1999)

While there are designs based off of the Van de Graaff generator that are still used in research today, the main use of the original design of the Van de Graaff generator today is physics demonstrations in the classrooms. (Cunningham, 1994) These demonstrations include the presence of static electricity, electric wind, lightning, lighting a light bulb, and electric fields. For static electricity, just going near the charged sphere will cause the hair on the arms to rise. Another way to show static electricity is to have a person stand on a thick insulator, such as a plastic stool, and place their hand on the sphere of the generator (while the generator is OFF). Then, while keeping their hand on the sphere, the generator is turned on, and, as the hairs become negatively charged and repel each other, the hair will rise. (Clarion University, 2012)

Electric wind is created when a thin, light, metallic rod is attached perpendicularly to the dome. Since charge concentrates at sharp points, the tip of the needle will be so strongly charged that it will ionize the air around it. Negative ions will go to the dome to neutralize their charges, but the positive ions will move away from the dome. This flow of positive ions creates a “wind.” If someone held a child’s pinwheel in the path of the ions, it would actually start to spin. The stream of ions can also be seen with a candle flame. As the flame enters the stream, it will start to flicker or even be blown out. (Clarion University, 2012)

Lightning can be replicated using a Van de Graaff generator. When the generator is on, bring a metal conductor (usually called a discharge wand) near the sphere. When the wand is close enough and there is enough charge on the surface of the generator, there will be a big spark that jumps from the generator to the top of the wand causing a loud zapping sound. (Clarion University, 2012) This discharge happens for the same reason that a person gets shocked on a doorknob. There is an imbalance of charge between the generator and the conductor that is within zapping range of the generator. (Cunningham, 1994)

When a person holds the middle of a long fluorescent light bulb, and brings one end close to the Van de Graaff generator, the end that is pointing towards the generator will light up. (Clarion University, 2012) However, the light bulb will not glow in the section of the light bulb on the other side of the hand pointing away from the generator. The light bulb lights up because it becomes charged by inductance. However, since the human body acts as a sort of ground to the light bulb, the bulb cannot light up after the hand. (Cunningham, 1994)

Finally, Van de Graaff generators create electric fields. Earlier in the paper, it was explained that depending on the inside materials of the generator, a Van de Graaff generator can be made to create a positive or negative electric field. To see that there is an electric field, get two Van de Graff generators of opposite charge and bring them near each other. Then light a candle and place it in between the two generators. The flame will quickly blowout. The flame will blow out away from the positive and towards the negative dome since fire is plasma which contains a lot of ionized positive particles. Therefore, the fire is repelled by the positive dome, and since there is such a strong force from a type of electric wind, the flame is blown out. (Gore, 1995)

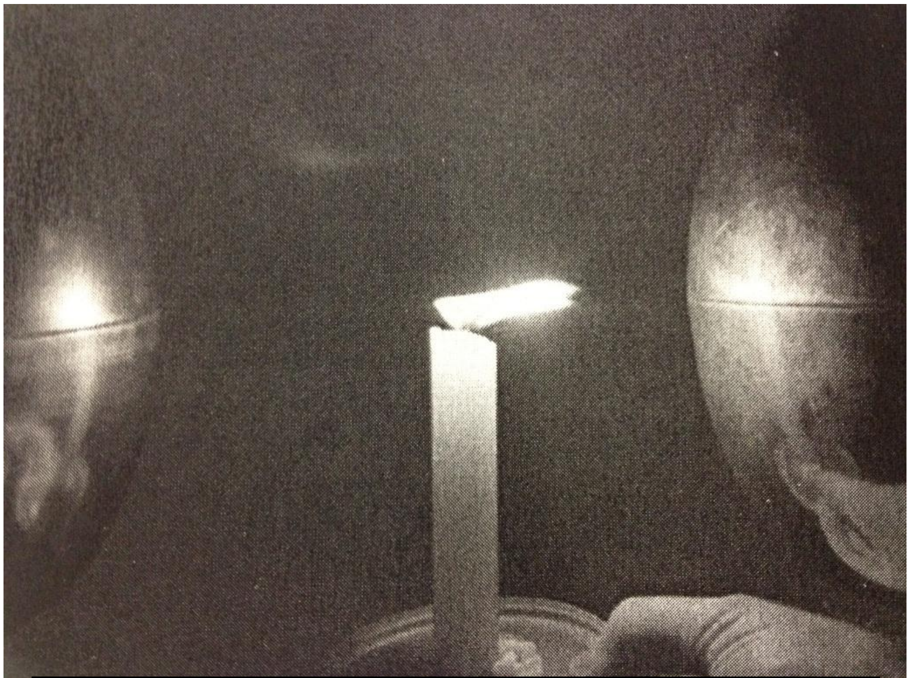


Photo of the flame being blown by the electric wind between the positive and negative generators. The flame lasted about ¼ second before it was extinguished. (Gore, 1995)

The Van de Graaff generator has had a dramatic impact on physics since its creation. For its time period, the Van de Graaff generator was revolutionary in the amount of voltage that it could produce. Its design would help with many scientific experiments from the mid-1930's-1950's in topics ranging from particle acceleration to X-ray research. Many schools still use miniature versions of the generator in order to demonstrate electromagnetism in physics classes. Even though by today's standards the original large designs of the generator are considered obsolete, the concepts and principles of the design led to new machines that are still used in research today. (Brenni, 1999) These elements make the Van de Graaff generator an important invention in the history of physics.

Works Cited

Beaty, Bill. "Van de Graaff Machine: Belts and Rollers," last modified May 2005, http://amasci.com/emotor/belt.html.

Berg, Richard E. "Van de Graaff Generators: Theory, Maintenance, and Belt Fabrication." *The Physics Teacher*, (May 1990): 281-285.

Brenni, Paolo. "The Van de Graaff Generator: An Electrostatic Machine for the 20th Century," Scientific Instrument Society, last modified 1999, http://lyonel.baum.pagesperso-orange.fr/sis.html.

"Charging and Discharging Two Van de Graaff Generators," MIT, accessed April 21, 2012, http://ocw.mit.edu/ans7870/8/8.02T/f04/visualizations/electrostatics/30-vdgdischarge/30-vdgdischarge320.html.

Cunningham, James, and Norman Herr. *Hands-on Physics Activities with Real-Life Applications*. San Francisco: John Wiley & Sons, Inc, 1994.

Gore, Gordan. "The Flame and the Van de Graaff." *The Physics Teacher* Vol. 33, (1995): 44.

"History of the Van de Graaff Generator," Museum of Science in Boston, last modified 1995, http://www.mos.org/sln/toe/history.html.

"Instructions and Applications for Van de Graaff Generator," Clarion University, accessed April 18, 2012, http://www.clarion.edu/217391.pdf.

"The Van de Graaff Generator, 1933," MIT Institute Archives & Special Collections, last modified May 2003, http://libraries.mit.edu/archives/exhibits/van-de-graaff/.

"Van de Graaff, Robert Jemison [1901-1967]," The New Netherland Institute, last modified April 2012, http://www.nnp.org/nni/Publications/Dutch-American/vandegraaf.html.