# Van de Graaff Generator

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H1

4/19/10

# Introduction

A Van de Graaff generator is an electrostatic device capable of producing very high voltages while maintaing a smaller, constant current. The first Van de Graaff generator was built in 1929 by Robert J. Van de Graaff, American physicist and inventor. This first model produced voltages of around 80,000V. Only two years later, Van de Graaff and his research partner Nicholas Burke constructed a larger generator capable of much higher voltages (about 7 million volts). This groundbreaking feat earned Van de Graaff a research fellowship at MIT, the position of director of the High Voltage Radiographic Project during World War II, and the T. Bonner Prize from the American Physical Society in 1965 ("History of the Van de Graff Generator").

Aside from its use in educating physics students about the properties of electrostatics, the Van de Graaff generator has been most frequently implemented as a power supply for particle accelerators. Van de Graaff-powered x-ray machines have been used for imaging and medical treatment (Beaty). Van de Graaff generators can also power the process of food sterilization with gamma radiation. Before the invention of more powerful, modern particle accelerators like the Linear Accelerator Ring and Cyclotron, the Van de Graaff generator played a central role in nuclear physics by powering proton collision for radioactivity research. The generator was also at the forefront of particle physics research before being rendered obsolete by the Pelletron VG generator, an improvement upon the original design that utilized a chain of conductors and dielectrics ("Van de Graaff Generator"). In order to understand how this device has influenced the scientific community and the world as a whole, it is important to grasp the fundamental concepts of its structure and operation.

# Schematics and Operation

Van de Graaff generators derive their charge from one of two supplies, either from an adjacent DC source or from the potential difference generated from differing roller materials. The latter is known as the triboelectric effect. The triboelectric effect refers to different materials' tendencies to acquire either positive or negative charge from other kinds of material. That is, when two different materials come into contact and then separate, the physical properties of the two materials dictate that one will come away with a positive charge while the other will receive a negative charge ("Triboelectric Effect")

Calculation of the exact value of transferred charge is complicated by factors such as humidity and amount of contact. Therefore, broad generalizations of the triboelectric behavior are predicted using the triboelectric series, eerily similar to the chemical activity series, in which different materials are listed vertically, from more positive charge acquired (at the top) to more negative charge acquired (Fig I). The magnitude of transferred charge is partly dependent upon the distance between the two materials in the triboelectric series.

Fig I


http://www.ecd.com/blog/index.php/2009/04/10/triboelectric-series-and-its-effect/

The simplest Van de Graaff generator design utilizes differences in roller material in order to produce a net movement of charge via triboelectrification (Zavisa).

The triboelectric model consists of a dielectric (rubber) belt looped around a vertically oriented two-pulley system. In this design, the bottom roller is covered in silicon tape (very low in the triboelectric series), and the top roller is made of nylon (higher in the series). A grounded, conducting comb with sharp metal teeth is positioned near to the bottom roller. An identical conducting comb is placed near the top roller, and is attached to a hollow conducting sphere which encases both the top roller and top conducting comb. An electric motor (or hand crank) is attached to the bottom roller so as to propel the dielectric belt around the system of pulleys (Fig II) ("Van de Graaff Generator").

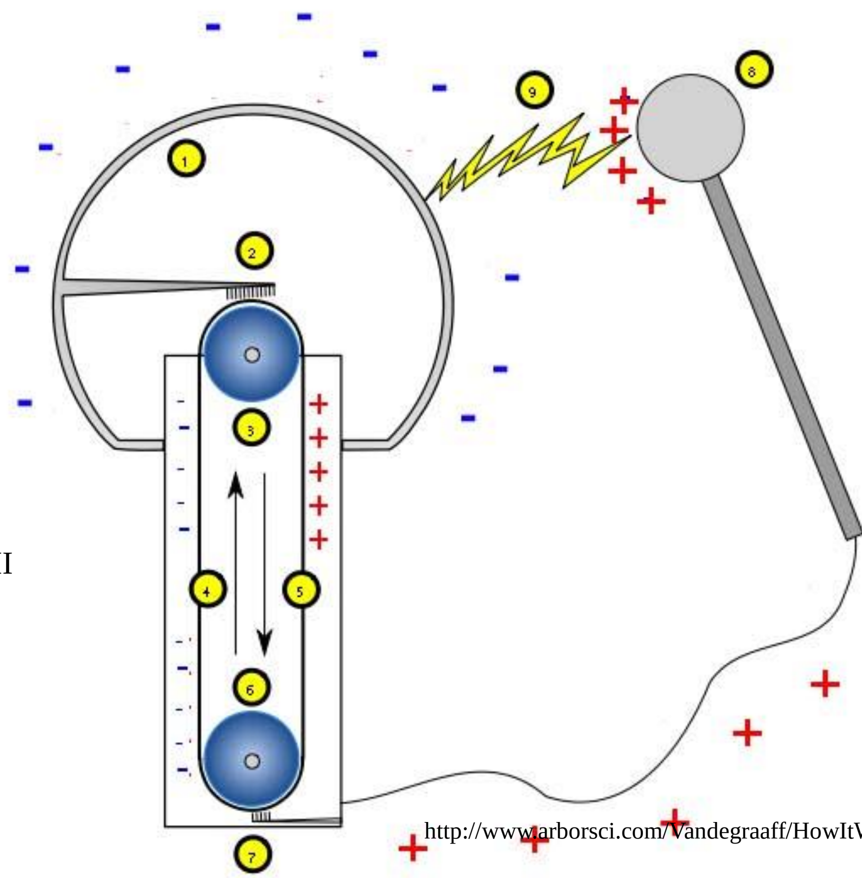

Fig II

http://www.arborsci.com/Vandegraaff/HowItWorks.htm

As the rubber belt comes into contact with, then separates from the lower silicon roller, the roller acquires a negative charge and the belt receives a positive charge . Since the belt has a larger area than the lower roller, and the belt's movement causes the charge to be distributed throughout the area of the belt, it follows that the charge density of the roller is much higher than that of the belt. This means the electric field of the roller is more significant than that of the belt. The resulting negative electrical field causes a few changes to the system. First, it induces a positive charge on the tips of the comb. The negatively charged roller removes the electrons from the comb by repelling them through the ground. Second, the field ionizes nearby air particles by stripping them of their electrons. These free electrons move away from the negatively charged roller and toward the positively charged tips of the lower comb, leaving the positively charged air particles to move toward the lower roller. However, the belt is situated between these ionized air particles and the roller, so the positively charged particles stick to the dielectric belt, and are carried upward (Zavisa).

Since the upper roller is made of nylon, and nylon is higher in the triboelectric series than rubber, the upper roller has been accumulating positive charge. This positive electric field induces a negative charge on the tips of the upper comb by attracting its electrons and ionizes the surrounding air as before. In this case, the stripped electrons are attracted to the positively charged belt and the positively charged air particles are attracted to the tips of the comb. The positive charges that are repelled through upper comb accumulate on the surface of the much larger metal sphere. The sphere can be seen as a ground relative to the smaller comb as it removes any excess charge on the comb. The belt then returns to the bottom roller for the process to be repeated (Zavisa).

The second design is essentially the same as the first, except the relative positions of the roller materials in the triboelectric series is not as important. Instead, a high potential is placed on the bottom roller by an adjacent DC source. Since the (electrical) potential in this design is derived from a regulated power source, it has the (not electrical) potential of producing higher voltages. For the same reasons, humidity, impurities, and other issues in the immediate environment are not as detrimental to the workings of the DC-powered Van de Graaff generator as they are to that of its triboelectric counterpart. In the case of either design, it makes little difference whether the charge on the sphere is negative or positive, only that a net charge is present.

Assuming the generator's conducting sphere is large enough and the distance between the top and bottom rollers/combs is great enough, the generator will continue to charge the sphere until the process exceeds the limits imposed by humidity, air impurities, and the dielectric breakdown of air. Humidity limits the effectiveness of the Van de Graaff generator when water droplets accumulate on the inner and outer surface of the apparatus. The conductive properties of water cause the overall charge to dissipate as it distributes across the surface area of the water droplets (Kurtus). Significant concentrations of dust or other impurities hamper the process by altering the charges on the surfaces of the generator. As the dust particles come in and out of contact with the parts of the generator, they can triboelectrically rob the system of charge (Kurtus). Finally, the dielectric breakdown of air can hinder the performance of the Van de Graaff generator by completely discharging the sphere or any other surface. When points of great enough potential difference come close enough together, air loses its insulating properties and temporarily becomes a conductor. As a spark or corona occurs, charge is transferred, and voltage is lost (Martins and Pinto).

## Improvements

Since the construction of the first Van de Graaff generator in 1929, a number of significant improvements have been made upon the original design. As the generator began to gain more attention as a particle accelerator, Van de Graaff and those who followed after him sought ways to generate higher voltage, which led to the capability to study a greater range of particles. First, they simply increased the dimensions. In 1933, Van de Graaff oversaw the construction of a 40 ft tall model on Round Hill at MIT (“History of the Van de Graaff Generator”) . A new breakthrough was reached when two large generators were operated in tandem. A particle could be shot from one  sphere to the other. The spheres themselves were so large that each housed a laboratory, one to operate the machinery for firing the particle and the other to house the equipment for collecting the resulting data. The entire apparatus was housed inside an empty hangar (Fig III), and the two generators were situated on railway track so that the distance between the spheres could be altered during experimentation ("History of the Van de Graaff Generator").


Fig III

http://www.aip.org/history/newsletter/fall2004/mit-photo.htm

Another significant improvement was the change in gas insulation. The use of sulfur hexaflouride inside the spheres allowed for higher voltage, as the dielectric breakdown for sulfur hexafluoride is considerably greater than that of air. With the implementation of these advances, the tandem Van de Graaff generators could produce voltages up to 14 million volts ("Van de Graaff Generator").

# Common Construction Problems

## Charge Leakage

When building a classroom-size Van de Graaff generator (or one of professional grade for that matter), one commonly encounters a number of obstacles which can detract from voltage production and the overall performance of the generator. A commonly faced issue during construction of home-made Van de Graaff generators is charge leakage along the seam of the conducting sphere, which is often made from two salad bowls resting rim to rim. As the leakage saps charge from the apparatus, the rate at which the generator produces voltage is greatly decreased, or the production is halted altogether. To prevent this, the two hemispheres can be sealed using an epoxy and the seam covered with electrical tape. The integrity of the sphere can be tested by running the generator with the lights off. Any leakage around the seams of the hemispheres can be seen as small sparks or corona discharge are emitted from the area. Leakage can also occur on parts of the generator that form sharp edges (Zavisa).

## Comb Calibration

Another issue is the distance between the combs and the belt/roller system. The charged roller is approximately cylindrically symmetric, so the electric field felt by the comb decreases as distance between the roller and comb increases. Therefore, if the comb is positioned too far away from the roller, the charge induced on the comb is not strong enough to produce the desired potential difference. On the other hand, if the comb is placed too closely to the roller, it may contact the the band and scratch its surface. This scratching can produce debris which, like dust particles, can prevent adequate surface charge from accumulating on the band (Beaty). The optimum distance between comb and roller is dependent upon the other dimensions of the apparatus, as well as the strength of the triboelectric effect (or DC source) applied to the bottom roller. In the case of the student or hobbyist, this calibration is achieved through the process of trial and error, less so for the nuclear physicist.

## Dielectric Breakdown

Sparking or corona discharge between parts of the generator can also occur, as the dielectric strength of the interstitial airspace is exceeded. Since the unit of dielectric strength is voltage per unit distance, and high voltage is the goal of the device, it follows that the sparking obstacle can be overcome by increasing the distance between parts of the device. That means greater distance between oppositely charged regions, as well as between charged regions and grounded ones. A good rule of thumb is to increase separation of parts proportional to the increase in size of the parts themselves (Martins and Pinto).

## Humidity and Dust

As mentioned before, humidity and dust diminish the voltage of the generator by coating its parts and providing a path of lower resistance for the conduction of charge. Although the understanding of the mechanisms by which humidity and dust affect the generator requires knowledge of triboelectric properties of the dust particles and conductive properties of the water molecule, the prevention of said mechanisms requires only the knowledge of cleanliness and dryness. With respect to a tabletop Van de Graaff generator, these problems can be most easily solved by cleaning the belt with alcohol and drying the device with a hair dryer (Zavisa).

As the design and construction of most homemade Van de Graaff generators are usually far from ideal, some degree of leakage and corona discharge is to be expected. However, since the net voltage is equivalent to the voltage produced by the generator minus the leakage through imperfect design and environmental conditions, the overall voltage can also be increased by simply increasing the gross output of the generator. This can be achieved by increasing the power of the DC source (up to the point in which dielectric breakdown occurs), altering the materials of the rollers and belt, and by increasing the output of the electric motor in order to increase the speed of the belt, in turn increases speed of charge delivery to the sphere.

## Common Demonstrations

### Hair-Raising

The most well-known demonstration of the electrostatic properties of the Van de Graaff generator is the charging of a physics student in order to stand his or her hair on end. This demonstration is most effective on long, blonde, untreated hair. This is because blonde hair is physically lighter than hair that is darker in color, hair that is treated with product (spray, gel, color) is usually heavier and stiffer than untreated hair, and long hair simply makes the effects of the demonstration more visible.

The student stands on an insulating platform next to the Van de Graaff generator. She places her hand on the conducting sphere, and the generator is switched on. As the generator charges the surface of the sphere, the charge is transferred to the student's body through her hand. Depending on the configuration of the Van de Graaff generator, the student assumes either a net positive or negative charge. When the charge moves to the student's individual hair follicles, like charge repel, causing the hairs to deflect from one another and stand on end (providing the generator produces sufficient voltage and the student's hair is light enough). The generator is then switched off, and the student touches car keys or some other angular conductor in order to dissipate her net charge. The sphere of the Van de Graaff generator is then touched with a grounding wand, which consists of a small conducting sphere attached to a grounded wire that is coated with an insulating handle. The system now has little or no net charge.

## Tissue Paper Deflection

A similar demonstration involves taping small ribbons of tissue paper to the sphere of the generator. When the generator is switched on, the pieces of paper deflect and stand on end just as the student's hair did. The physical principle are essentially the same as the first experiment, but the tissue paper demonstration offers an adequate visual representation of the concepts of voltage and electric field without any danger of shocking students (Martins and Pinto).

## Pie Pans

A third experiment in electrostatics involves placing a stack of lightweight, aluminum pie pans upside down on the conducting sphere of the Van de Graaff generator. When the generator is switched on, the sphere accumulates a net charge (for the sake of explanation, a negative charge). Since the pie pans are aluminum, they conduct the negative charge to the surface farthest from the source of the charge (the top pan). Through the operation of the generator the sphere quickly restores any charge lost to the pie pan. Since the pie pans are lightweight, and since like charges repel, the force between the negatively charged sphere and the negatively charge pie pan overcomes the force of gravity acting on the top pie pan, lifting it off the stack and into the air. When the pie pan is far enough away from the sphere that the electric field is negligible with respect to the force of gravity, the pan falls to the ground. The process continues as each pie pan is lifted off the generator one by one. This demonstration is best performed in a room with relatively still air (so that no draft affects the trajectory of the flying pan) and on a stable Van de Graaff generator (so that the vibration of the operating generator does not knock the stack of pie pans off the sphere before the electrostatic forces do) (Martins and Pinto).

The tabletop Van de Graaff generator can be used to demonstrate many different physical principles through countless set-ups and demonstrations. The three demonstrations above are some of the most common because of their simplicity, cheapness of materials, and relative safety.

## Conclusion

Through the simplicity of it design and the elegance of the physical theory behind its operation, the Van de Graaff generator has proven invaluable throughout its history in the research and experimentation with particle acceleration and nuclear physics. Whether concerning the vast amounts of experimental data it produced during its heyday, or its vital role as a developmental stepping stone toward the advent of more advanced particle accelerators, the Van de Graaff generator has undoubtedly shaped the path of modern physics. Even in its “obsolescence”, the humbler tabletop model remains one of the most effective educational tools in classrooms and teaching labs alike.

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