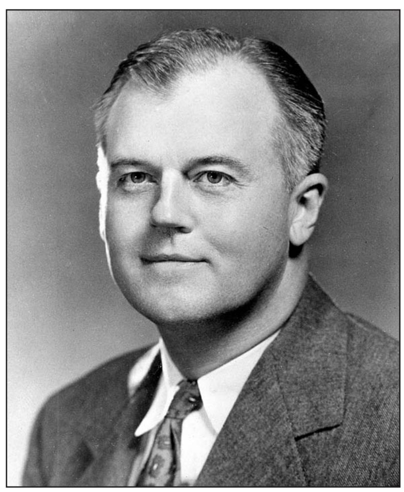
history | f.a. (tony) furfari

# A History of the Van de Graaff Generator

This month I write about an "atom smasher," the Van de Graaff generator. The Van de Graaff generator is defined in my dictionary as "an electrostatic generator in which electric charge is …transferred to a large hollow spherical electrode by a rapidly moving belt, producing potentials over a million volts, and used with an acceleration tube as an electron or ion accelerator" [1]. It was invented by Robert Jemeson Van de Graaff in 1930 while a post-doctoral physicist at the Palmer Physics Laboratory at Princeton University.

Robert Jemeson Van der Graaff was born on 20 December 1901 in Tuscaloosa, Alabama. His mother was Minnie Cherokee Hargrove and his father was Adrian Sebastian Van de Graaff. Robert attended the Tuscaloosa public schools and then attended the University of Alabama where he received a B.S. degree in 1922 and an M.S. degree in 1923. Both degrees were in mechanical engineering. After graduation, he worked for the Alabama Power Company for a year as a research assistant. He studied at the Sorbonne in Paris in 1924–1925 and, while there, attended lectures by Marie Curie on radiation. In 1925, he went to Oxford University in England as a Rhodes Scholar. At Oxford, he received a B.S. in physics in 1926 and a Ph.D. in physics in 1928 [2].

While at Oxford, Van de Graaff became aware of the deep interest of nuclear experimenters in the possibility that particles could someday be accelerated to speeds sufficient to disintegrate nuclei. By disintegrating atomic nuclei, much could be learned about the nature of individual atoms. Van de Graaff focused on this facet of technology after attending a lecture by Sir Ernest Rutherford (1871–1937), at the Royal Society. During the lecture, Rutherford, discoverer of the atom, stressed that there was a tremendous need for accelerating particles of controlled energy in the study of nuclear physics and implored the audience to do research in that field. Van de Graaff, being a young scholar, took Rutherford's admonishment very seriously, and was motivated to try to develop a working system to achieve particle acceleration.



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**Robert Jemison Van de Graaff.**

## Van de Graaff Produces His First Machines

For a discussion of how the Van Graaff generator came about and how it works, I sought the help of Dr. Chatham Cooke at Massachusetts Institute of Technology (MIT), and I share his descriptions with our readers. Dr. Cooke is senior lecturer and principal researcher at MIT's Department of Computer Science and Electrical Engineering.

In 1929, Van de Graaff, upon his return from Oxford to the United States, joined the Palmer Laboratory at Princeton University as a National Research Fellow. During the 1930s, the movement of electromagnetic charges was recognized as a possible process for creating very high voltage. Systems that move charged particles were envisioned by nuclear physicists as possibly being liquid, and not necessarily solid, such as a belt. Corona spray had been recognized as a charge that could be applied to a belt; but the question was how to collect the charge from a moving belt. Van de Graaff, being a physicist, recognized that if you ran a belt between pulleys, one pulley at ground and one at isolated environment, supported by insulators, voltage could be generated, but the difficulty was to move charges off of the belt that is carrying the charge. For instance, if charging with positive charges, when trying to bring more charges up, the sphere is trying to push them away. What Van de Graaff discovered was the concept of using a re-entrance structure, where the belt enters inside the sphere. That is the very key component, because once inside the sphere, the charges are naturally drawn to the sphere, trying to get to the outside surface of the sphere. There's a force to move charges from anywhere inside the sphere to the external surface of the sphere. By bringing the pulley inside the sphere, which is the charge-collector, it was very efficient and effective to remove the charges off the belt.

Van de Graaff constructed a first working model of an electrostatic accelerator; it developed 89,000 V. Improvements to his original design followed, and in November 1933, at a meeting of the American Institute of Physics he demonstrated his machine that produced 1 million volts and was only a few feet tall.

## Robert Van de Graaff Returns to MIT

Karl Compton, then president of MIT, became aware of Van de Graaff's accomplishments at Princeton and invited him to return to MIT as a research associate. It was there that Van de Graaff built his first large machine in an aircraft hanger. The machine used two polished aluminum spheres, each 15 ft in diameter, mounted on 25-ft high insulating columns that were 6 ft in diameter. The columns were mounted on railroad trucks that put the columns 43 ft above ground level. Each sphere had its own generator, one arranged to charge positive and the other negative, so that the voltage between the two spheres was twice that of the generator alone. The machine was displayed on 28 November 1933 and produced 7 million volts. The accomplishment was reported in a story in *The New York Times* for 29 November 1933 titled: "Man Hurls Bolt of 7,000,000 Volts.' In 1937, the machine was placed in a pressurized enclosure at MIT. There were two terminals in two machines: one designed to run positive and one designed to run negative, and the acceleration tube was set up to run between the two. The intent was to have each machine run at a couple of million volts and, therefore, get multimillion volt energy that could facilitate radiation of materials.

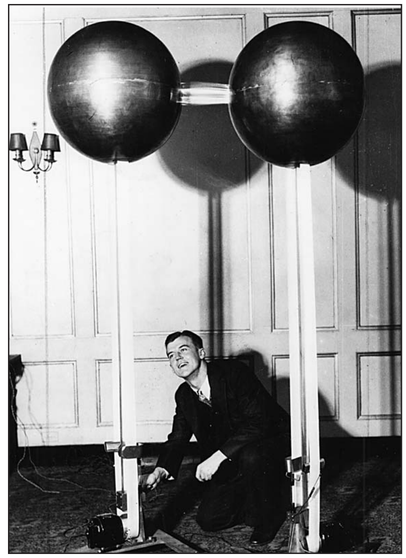
In 1935, Van de Graaff received U.S. Patent No. 1,991,236 for his invention. In 1936, Van de Graaff married Catherine Boyden. They had two sons, John and William. Robert J. Van de Graaff died on the morning of 16 January 1967 in Boston at the age of 65. At the time of his death, there were over 500 Van de Graaff particle accelerators in use in more than 30 countries.

## Compressed Gases Instead of Air Is Best

Much was learned about how to make machines at that time, but it was recognized that air was not going to be a successful medium. There was tremendous effort to develop gases that would be better insulators. Carbon-tetra-chloride was one of the early good ones, but it was unhealthy for humans, Unfortunately, besides being unhealthy, it also has a low vapor pressure, so its molecule cannot be in a gaseous state at high pressures, so it was difficult to get sufficient density of gas to make it electrically effective.

However, other gases and gas mixtures were explored, and high-pressure gases were used immediately, nitrogen, air, and carbon dioxide being the dominant ones. There continued during the early 1930s a major search to develop a better gas. Ultimately it was recognized that sulfur hexaflouride was a prime target for insulation, and researchers set about rather quickly trying to find a way to generate a high-voltage gas. After realizing it was a good electrical gas, the first application, was in Van de Graaff's machines.

It has been told that Van de Graaff spent about US$400 (which was a lot of money at that time) to get a few grams of SF6. The chemistry department at MIT specifically isolated it for Robert Van de Graaff, in order for him to make tests for its use as an insulting media for his generator. He discovered it was a great gas for insulating purposes. It was also not toxic, and it could be pressurized to a couple hundred psi, making it dense a terrific insulator. Also, in studying those properties, Van de Graaff recognized that, besides being a good insulator, when arcs did occur, they were quickly quenched. Going into compressed gas environment quickly became the recognized way to get much higher voltage machines. Several were built at MIT and other



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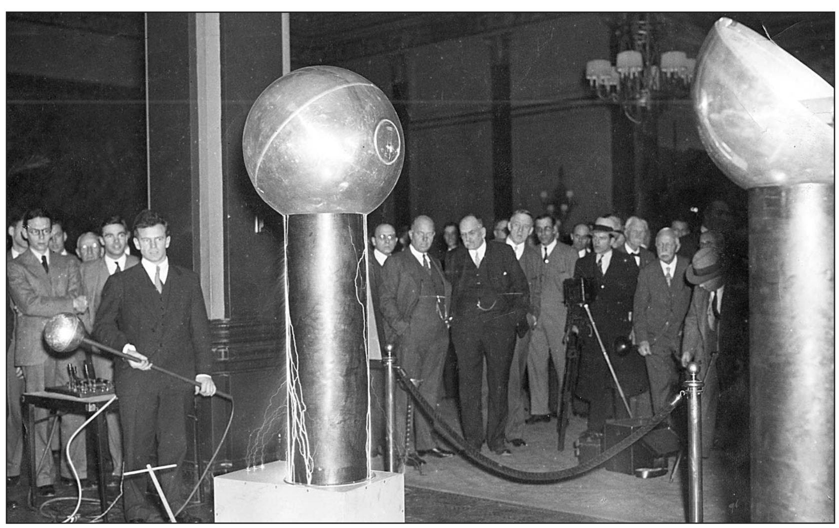
**This is an early Van de Graff generator being demonstrated by Robert J. Van de Graaff himself.**



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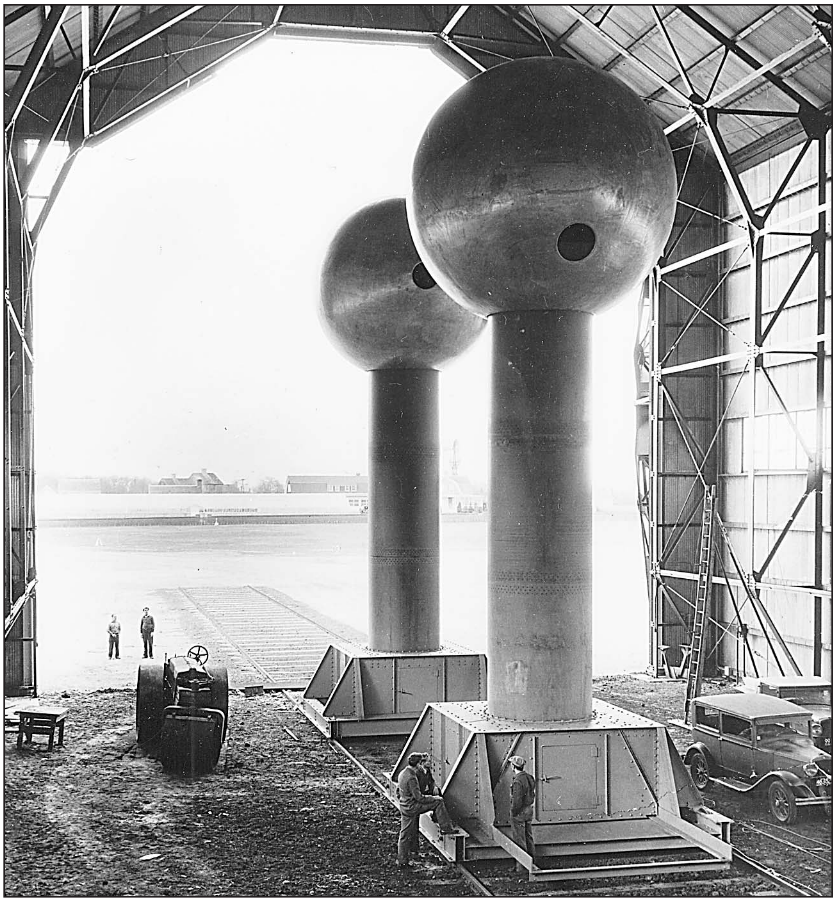
**The engineer's prototype of the generator being demonstrated by Dr. Van de Graaff at the Hotel Statler. It stood approximately 6 ft tall and was capable of producing about 1 million volts of static electricity.**



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**The Van de Graaff was constructed on railroad track bases so that it could be wheeled out of and within the hangar.**

institutions. Additionally, because of its thermodynamic and arc-quenching properties, SF6 was soon applied to high-voltage circuit breakers.

## Other Contributors to Technology

Van de Graaff worked with John G. Trump, a professor of electrical engineering at MIT, and with William W. Buechner, a professor of physics at MIT, developing a machine to use as a medical unit to produce X rays for treating cancerous tumors with precise penetrating radiation, first used clinically in 1937 at Harvard Medical School.

The Carnegie Institution in Washington, DC, sometime around 1935, developed a Van de Graaff accelerator for about 1 million volts. The machine was developed by Physicist Merle Tuve; it was air insulated and proved to be quite a successful machine. At the University of Wisconsin, physicist Raymond Herb (1908–1996) produced a compressed gas insulated machine of the Van de Graaff type; it was quite successful. Robert Van de Graaff and Ray Herb ended up transferring their technologies of electrostatic machines to applications in industry. The Van de Graaff technology was implemented by a company called High Voltage Engineering Corp. of Burlington Massachusetts. Ray Herb's technology was implemented by a company called National Electrostatics, just outside of Madison, Wisconsin. Both companies produced machines for many decades and were responsible for providing the technology that served nuclear physics for many years.

In 1948, an article summarizing some of this history was published by the American Physical Society, titled "Reports on Progress in Physics," authored by Robert J. Van de Graaff, John G Trump, and William Buekner, all of MIT. Trump was an electrical engineer and a close friend of Van de Graaff. Van de Graaff was a physicist, most interested in having the machine for physics research; Trump, on the other hand, was an electrical engineer, and saw a broader application for the machine. Trump turned to developing the machine for radiation therapy and became a leader of applying the machines to hospital environment, where cancer treatment with X rays had been performed for decades.

## Applications of the Van de Graaff Machine

The machines at MIT were used for physics research, a first target because of Van de Graaff's devotion to nuclear physics. After that, researchers recognized there were possible commercial values, causing changes associated with radiation, and using electrons to generate X rays by having them strike a heavy target. Some machines were applied to X-ray imaging, several machines were used by the government during WWII to X-ray interiors of navy ordinance. The high-energy X rays have tremendous power and can penetrate very deeply. Also, by creating a very intense, highly focused beam, X rays can be created that cannot be created from a radioactive source such as cobalt. Furthermore, because they can be pinpointed to create very high-resolution X rays, the source is a sharp point. X-ray tubes running up to about 250 kV were common, but getting higher energy tubes was not possible at the time. When the Van de Graaff machine came along, it provided reliable 2 million volts, or more, energy, and X rays became extraordinarily penetrative that could penetrate steel plate many inches thick.

Recently, there was a very large machine produced in Europe, designed for over 20 million volts, to meet the needs of researchers interested in using X rays to alter materials; radiation can be a very effective cross-linking agent to improve the properties of materials. An example of work MIT has done in cooperation with Massachusetts General Hospital involved the use of radiation to improve the material used in hip replacements. Before that development the material used for hip replacement would last 10–15 years, and then the patient would expect to undergo an operation for a new replacement. With the present use of radiated material technology, hip replacements appear to be permanent, not wearing out in one's lifetime. There are many other applications where radiation is a very effective application. Plastics of many kinds are cross linked to make them stronger, more durable, and operate at higher temperature, and organic materials can be made electrical conductors. Semiconductor devices can be irradiated to improve their operation [2].

In machines in which the high-voltage insulation is air, break down can be frequent, and the sparks are typically 10–20 ft long. In an exhibit at the Museum of Science, in Boston, the audience is protected by a series of wires that run vertically in space, about 6-in apart, and the screen acts effectively as a Faraday shield that isolates and protects the audience from the electric fields. The theater was created for it, and the grounding system for it is quite significant.

Going to compressed-gas environment quickly became the way to get much higher voltage; several high-voltage machines were built at MIT and other institutions. At the University of Wisconsin, Ray Herb produced a compressed-gas insulated machine of the Van de Graaff type that was quite successful. Both Van de Graaff and Ray Herb ended up transferring their technologies to industry for commercial use of electrostatic machines. The machines at MIT were used for physics research, their first target because it was Van Graaff's love and the motivation for developing the technology was originally for nuclear physics, and later recognized they could be used for radiation to improve the characteristics of materials.

## Miniature Van de Graff Generators

Some companies in the United States make miniature machines for education and entertainment purposes. Mr. James Davis, of the Wabash Instrument Company of Wabash, Indiana, told the writer that over 15,000 miniature Van de Graaff generators have been supplied by his company to schools in the United States. They are desk-size and used for teaching physics and chemistry. The small machines will produce up to 150,000 V. The maximum continuous current is only about 10 $\mu$A, so the units are quite safe; Sparks of 8-in long may go to 12–15 in [3].

## The Westinghouse Atom Smasher [4]

The Van de Graaff generator built by Westinghouse in 1937 at its research facility in Forest Hills, Pennsylvania, was constructed for the first nuclear physics program out in industry. It was intended for an unprecedented high voltage. The machine was designed by a group of Westinghouse engineers led by Dr. William H. Wells. Wells received the Ph.D. degree at Johns Hopkins University in 1934; he had been on the faculty of the University of Minnesota before joining Westinghouse Research on June 1936.

The design drew on the experience with pressurized machines by Barton, Mueller, and Van Atta at Princeton, and Herb, Parkinson, and Kerst at the University of Wisconsin. The pressure tank is 30-ft in diameter and 47-ft high, and the top of the machine is 65-ft above ground level. The air pressure of 125 lb/in$^2$ was used to increase the breakdown voltage for the internal sphere and column. Since the voltage was distributed along the column, lesser standoff distances were required at lower portions, which accounts for the pear-shaped design of the tank.

The 30 ft-long acceleration vacuum tube consisted of a stack of porcelain rings with 12-in inside diameter, interleaved with metal spacers that formed the accelerating electrodes. At the top of the accelerating tube, supported by four columns of porcelain insulators, is a spherical shell containing the ion source, a belt-driven generator for power, and sets of needles to charge the two main belts that traveled along the assembly. The inside of the tube was evacuated. At its lower end were magnetic analyzers to separate the accelerated particles into those of the proper charge and mass. The bombardment of targets took place on the ground floor, well below the ground level if extra shielding was desired.


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**An example of the mini Van de Graaff generator.**

By July of 1937, the tank had been erected, major internal structures lowered into place through the open top, and the tank closed. By this time, the company felt it was appropriate to let the world know what it was doing. Wells was cautious about the anticipated performance, as both MIT and the Carnegie Institution were having great difficulties obtaining high voltages with their newly constructed Van de Graaff generators. The machine was accordingly described to the press as a five million volt machine, and so it has become known. Although it did run above 4 million volts, it never actually achieved five. The striking appearance of the machine, the superlatives of voltages in the multimillions, atoms of incomprehensible smallness traveling at unimaginable speeds, and the glamour of penetrating into the scientific unknown, all made good copy, and newspapers and magazines published good accounts and pictures of the machine.

In 1984, the machine was nominated to be designated an IEEE Milestone in Electrical Engineering; it was so designated on 29 May 1985.

The Westinghouse Atom Smasher still exists, though its operation was discontinued around 1950 when it was replaced by a commercially built machine. All buildings of the original Westinghouse Research facility built in 1916 have been demolished; the Westinghouse atom smasher stands alone. Westinghouse built and moved to much larger and modern facilities in 1954. The present owner of the site is trying to dispose of the property, the ultimate fate is still to be determined.

## Early History of Electrostatic Machines [5]

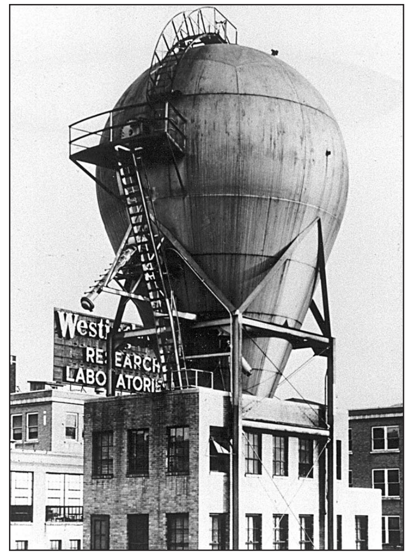
The Van de Graaff generator is the last in a long series of machines that date back to the earliest times in the history of electricity. Our word electricity comes from the Greek word for amber: "ilektron." In 600 B.C., Thales noted that when amber was rubbed, it would attract light objects, and in 1600 A.D., William Gilbert, in his epoch-making treatise on magnetism, was the first to use the term "electrical" in its modern sense.

The generation of electrical effects by friction was the basis for a number of electrical machines. Otto von Guericke (1602–1686), known for his famous experiment in which teams of horses could not separate the halves of an evacuated sphere, used a ball of sulfur turned by a crank and rubbed by the hand. Isaac Newton substituted a glass sphere for the sulfur ball. Further improved machines using glass disks and Leyden jars to store more substantial amounts of charge were important tools for describing the various properties of electricity.

Benjamin Franklin, one of the great pioneers of electrical science, used such a machine and provided an improvement that is one of the keys to the Van de Graaff generator. He showed that pointed needles, in close proximity to a charged body, would conduct copious amounts of electricity. He used this in the research that culminated in his famous 1751 demonstration that lightning was an electrical phenomenon, and that electricity derived from his kite string had all the properties of electricity generated in the laboratory by the friction machine.

Somewhat later, a quite new class of electrostatic generators came on the scene. These "influence machines" transferred charge from a source having low potential to one of higher potential. The principal is easily understood with the help of some elementary equations. A capacitor with capacitance $C$ and charge $Q$ will have a voltage $V = Q/C$. If the capacitor is made of two parallel plates, and those plates are separated, the capacitance $C$ will diminish, and since the charge $Q$ is constant, the voltage $V$ will increase. Now, the two plates of opposite charge attract one another, and in order to pull the plates apart, work must be done. The work done in pulling the plates apart appears as higher electrical energy. The charge carried by the separated plate is dumped conductively into another capacitor. The plate is then carried back to be close to the first plate, momentarily grounded, and the process repeated. In many of these machines the charge is fed back to the first plate, so the two opposite capacitor potentials climb up one after the other to quickly achieve values limited only by leakage or breakdown

Machines based on this principal first appeared in 1787, and over the years took a variety of forms, all involving some means of separating charged conductors, and discharging them conductively as appropriate. The most highly developed was the Wimshurst machine of 1878; it consisted of two closely spaced glass disks on a common axis, rotating in opposite directions, and carrying sets of metal foil carriers playing the role of capacitor plates. Conductors intermittently touching the foil carriers took the charges to the positive and negative terminals. That machine, having a substantial output at high voltage and being quite reliable, was widely used as a voltage source for X-ray machines. An elderly emeritus professor in the physics department at the University of Illinois was still using his Wimshurst X-ray machine in 1938—he saw no reason to update it as it worked fine. Interestingly, another feature used later in some Van de Graaff generators was introduced in 1900—the enclosure of the entire machine in a chamber that could be pressurized with air or carbon dioxide, enabling it to produce voltages as much as three times those obtained in open air.





**The Westinghouse Atom Smasher.**

The Van de Graaff generator is an influence machine. The capacitor plates are no longer easily visualized, as they are continuously distributed as the surface of the belt itself. Charges are carried mechanically by the belt and deposited on the high voltage terminal. The electrical energy thus derived comes from the mechanical energy put in to driving the belt.

The writer extends sincere appreciation to Drs. Chatham M. Cooke and John W. Coltman for their contributions and assistance in generating this history article.

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[1] *American Heritage Dictionary of the English Language.* American Heritage Publishing, 1970.

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