Ready References

Signal Conditioning and Data Acquisition Basics

Glass Blowing for the Laboratory

Notes on the Construction and Design of Instruments and Apparatus

Technique of High Vacuum

Relative Time Scale

Rocks and Layers

Fossils and Rocks

Cost: $100+ About These Ratings	Difficulty: ■■■■■	Danger 3: (Serious injury possible)	Utility:

How to Make an Electrostatic Machine to Accelerate Both Electrons and Protons

by C. L. Stong
January, 1959

THE PARTICLE ACCELERATOR HAS about the same relationship to nuclear physics that the telescope has to astronomy. The accelerator probes the microcosm; the telescope, the macrocosm. Like the telescope, the accelerator can open exciting vistas to the amateur. But unlike the telescope, the accelerator has failed to attract a large amateur following. The notion seems to have got around that a small particle accelerator is little more than a toy. But in 1932 the British physicists J. D. Cockcroft and E. T. S. Walton did important pioneer work in nuclear physics with a 150,000-volt accelerator of the electrostatic type which today can be built for less than $200. With it Cockcroft and Walton succeeded in transmuting lithium into unstable beryllium, which then broke down into helium with the release of energy on the order of 17 million electron volts-scarcely the performance of a toy. A beam of particles from a machine of this size is capable of cutting the time of chemical reactions, of inducing mutations in living organisms, of altering the physical properties of organic compounds and of producing scores of other interesting effects.

F. B. Lee, a chemical engineer and faculty member of the Erie County Technical Institute in Buffalo, N. Y., has designed an electrostatic accelerator suitable for amateur construction which is similar to the Cockcroft-Walton machine but has more than twice its power. "Unlike the accelerator preferred by the physicist," writes Lee, "this one is designed for the amateur chemist. The beam of electrons it produces is brought out of the accelerator to irradiate targets in the open air. The physicist usually requires a closely collimated beam in which all particles have about the same energy, whereas the chemist is satisfied with a more diffuse beam in which the energy of the particles varies considerably. Since the targets irradiated by the chemist are usually

rather thick, it is almost impossible to provide all sections of the irradiated material with electrons of uniform energy even if this were desirable. Fortunately it is usually satisfactory to have a large percentage of the electrons penetrate the target completely. The ions produced within the target by the beam are largely independent of the energy of the beam, but the permissible thickness of the target increases with the accelerating voltage. Electrons accelerated to an energy of 250,000 volts will penetrate metallic aluminum to a depth of about .25 millimeter; polyethylene, to a depth of some three millimeters; air, to a depth of some two meters. The depth of penetration is roughly inversely proportional to the density of the target material and to the square of its atomic weight.

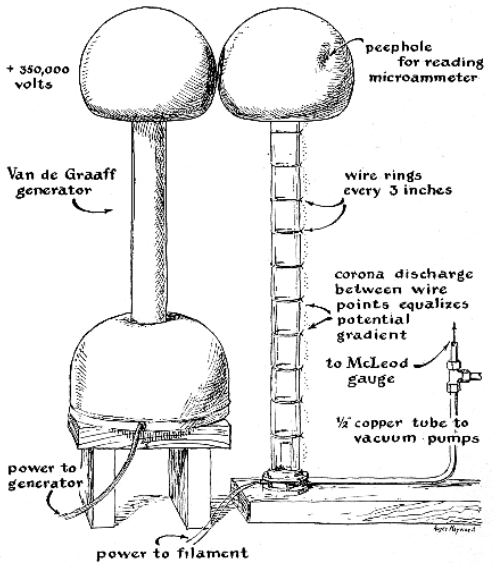


Figure 1: An electrostatic particle accelerator with a Van de Graaff generator as its power supply

"With the machine I shall describe amateurs can perform endless experiments based on the ionization of target materials by electrons. In the case of hydrocarbon targets numerous hydrogen atoms are dislodged from their sites in the molecule by the stream of fast-moving charged particles. Some of the atoms promptly combine into molecules of hydrogen (H_2) and escape as gas. Pairs of carbon atoms so stripped can then combine to cross-link the hydrocarbon molecules. Such cross-linking has a profound effect on the physical properties of the irradiated substance. For example, when molecules of the plastic polyethylene are cross-linked by irradiation, the plastic becomes much harder and melts at a higher temperature. The field is new and full of opportunities for the amateur who enjoys original work.

"The electrostatic accelerator may be thought of as a highly developed two-element electronic tube. It consists of an evacuated tube fitted with a source of electrons or protons at one end, an accelerating electrode at the other end, and a high-potential electric field between the two. If the accelerating electrode is made positive and the source is either a filament, a radioactive or photoelectric surface, or even a sharp point of metal, the resulting beam will be composed of electrons. If the accelerating electrode is made negative and a tiny amount of hydrogen is admitted to the tube, the gas will ionize and the beam will consist of hydrogen nuclei (protons).

"The major requirements for constructing a linear accelerator are a

source of high potential and a vacuum system capable of reducing atmospheric pressure (760 millimeters of mercury in a mercury manometer) down to .00001 mm. of mercury. The high potential may be generated by a Van de Graaff machine such as the one described in 'The Amateur Scientist' for May, 1957. A machine capable of delivering 20 millionths of an ampere (20 microamperes) at a potential of 500,000 volts can be built for less than $30.

"The tube for my accelerator was constructed from a junked piece of Pyrex pipe two inches in diameter and about three feet long. A 24-inch length would' have been preferable, but the dimensions are not critical. A hardwood plank eight inches wide, two inches thick and five feet long serves as a common base for the accelerator and vacuum pumps. The accelerator tube is mounted vertically near one end of the base, as shown in the accompanying drawing [*Figure 2*]. The cathode fitting, which closes the lower end of the tube, was machined from a piece of brass 2 1/2 inches in diameter and one inch thick. A hole is drilled in one wall to receive the half-inch copper pipe which connects the tube to the vacuum pumps. Another hole, in which an 1/8-inch pipe thread is cut, receives a standard quarter-inch compression fitting which serves as a gland for the filament assembly. The filament assembly is comprised of a quarter-inch rubber rod about half an inch long, through which two No. 18 enameled copper lead wires are run to support a half-inch length of No. 30 Nichrome wire. The lead wires were coated with vacuum grease before they were forced through the holes in the rod. The rod was then greased lightly and slid into the compression fitting, after which a collar of rubber tubing was slid over it. Finally the compression nut was run home to seal the assembly. Details of the gland are shown at upper left in the second illustration. The entire unit is vacuum-tight, easy to assemble and has given no trouble.

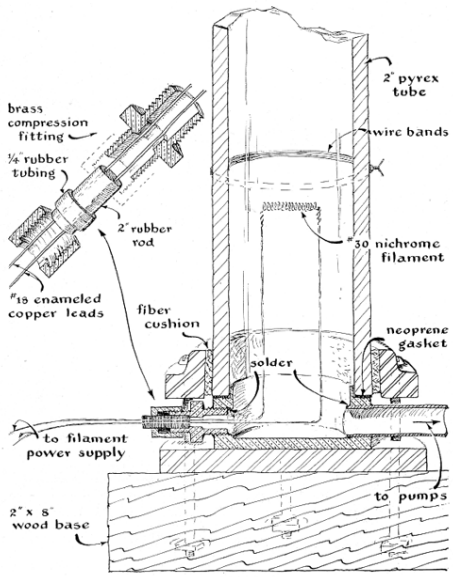


Figure 2: Details of the filament assembly for the accelerator

"With the Van de Graaff machine suggested, the tube develops a beam of only 10 to 20 microamperes, and the filament operates at a proportionately low temperature. The optimum filament temperature must be determined experimentally. The temperature is controlled by a rheostat in series with the power supply, which may be a simple doorbell transformer. When the temperature is too high, excessive emission lowers the resistance of the tube and consequently the voltage of the Van de Graaff machine. Lowered tube-voltage of course means lowered

beam-energy. In contrast, low filament-temperature results in scanty filament-emission, which lowers the beam current and increases the tube resistance. Thus at low filament-temperature the tube develops maximum voltage, and proportionately higher energy is imparted to individual particles in the beam. This compensates somewhat for the lower beam-current. For this reason downward departures from the optimum value of the filament temperature are preferable to upward departures.

"The electron beam is restricted to the axis of the tube by a symmetrical electrostatic field established by a series of rings spaced at three-inch intervals along the tube. The rings consist of four turns of 26-gauge bare copper wire. The ends of the wire are twisted tightly enough to hold the coil in place on the glass and are spread about half an inch apart. The points so formed act as corona electrodes and pick up charge from the surrounding air until electrical equilibrium is established between the air and the rings. In larger tubes, fixed resistors are substituted for the corona points. This, however, is not necessary in machines operating at 500,000 volts or less.

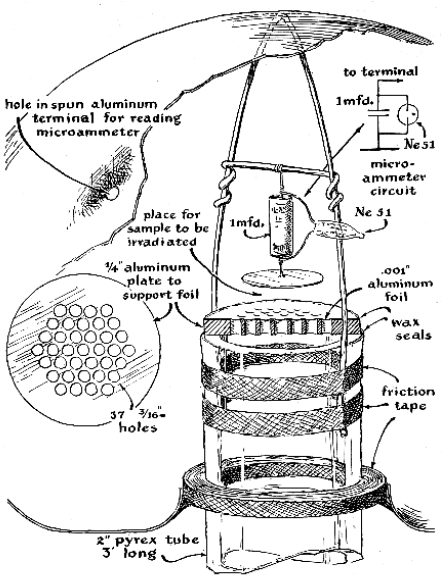


Figure 3: Details of the anode window and microammeter for the accelerator

"The upper end of the accelerator is closed by a window of aluminum foil through which the beam passes into the air. To prevent the foil from rupturing under atmospheric pressure, it is supported by an aluminum grid made of quarter-inch aluminum plate. The plate is drilled with 37 holes 3/16 of an inch in diameter and arranged in a hexagonal pattern [*see illustration in Figure 3*].

Approximately 50 per cent of the grid area is thus open. The grid is cemented to the upper end of the tube with vacuum wax. The foil window, which should not exceed .001 inch in thickness, is similarly cemented on top of the grid.

"High-vacuum equipment is sealed with special waxes which have a low vapor-pressure, *i.e.*, they evaporate so slowly that their vapors exert very little pressure. These include de Khotinsky wax, which has a vapor pressure of one micron of mercury; Dennison waxes, with a pressure of .01 micron; and Picein and Apiezon-W waxes, with a pressure of .00001 micron. The experimental physicist John Strong recommends a wax made by melting together equal parts of beeswax and rosin. The vapor pressure of this mixture approaches that of Picein and Apiezon-W. It is applied smoking hot with a medicine

dropper, and though it adheres well to cold surfaces, it is good practice to warm the glass or metal parts on which it is spread. I used Picein which chanced to be available. The parts were heated to the softening point of the wax, after which the joints were rubbed with the wax until a thin coating adhered. The pipe and grid were then pressed together until the wax set. Next the side face of the grid was coated, and the foil was pressed in place. The seal was completed by applying a thin bead of wax around the outside edges of both joints.

"A loop of 12-gauge brass wire was then attached to the top of the tube by friction tape as a frame to support the 12-inch spherical terminal. A simple microammeter, which consists of a high-resistance capacitor of one microfarad bridged by a 1/25-watt neon tube, is also supported by the frame. The input terminal of the microammeter is a 1/2 inch disk of 12-gauge sheet aluminum supported by one axial lead of the capacitor at a height of 3/4 inch above the aluminum window. The remaining lead of the capacitor is soldered to a cross wire attached to the brass loop.

"The electron beam enters the disk and eventually charges the capacitor to the firing potential of the neon tube, which then flashes and discharges the capacitor. A current flow of one microampere causes the tube to flash at 15-second intervals, the flashing rate being proportional to the intensity of the beam current. A dimple roughly two inches wide and half an inch deep is made in the spherical terminal opposite the neon tube, and a quarter-inch peephole is drilled at the bottom of the depression. The dimple prevents the concentration of a strong electrostatic field at the sharp edge of the hole and the loss of current through corona discharge. The neon tube can be observed safely at a distance of about two feet. The positive terminal of a 350,000-volt Van de Graaff generator is placed in contact with the accelerator terminal as the source of accelerating potential. Samples of material to be irradiated, such as hydrocarbon compounds or seeds, are placed on a carrier of thin polyethylene sheet between the aluminum-foil window and the disk electrode of the microammeter.

"The accelerator tube must be evacuated to pressure on the order of .01 micron of mercury to prevent excessive collisions between the accelerated particles and molecules of gas. Molecules ionized by such collisions are accelerated toward the filament as positive ions, collide with other molecules and create still more ions until the resulting avalanche of charged particles paralyzes the tube. At a pressure of .01 micron, gas molecules have a mean free path of 15 feet or more, and collisions

are accordingly infrequent.

"A vacuum of this quality requires elaborate pumping equipment and extreme care in eliminating leaks. The most inexpensive commercial equipment capable of attaining the desired pressure is priced at about $200; hence there is substantial inducement beyond the mere challenge of an interesting problem to use a home-built substitute-such as the compressor units from old refrigerators.

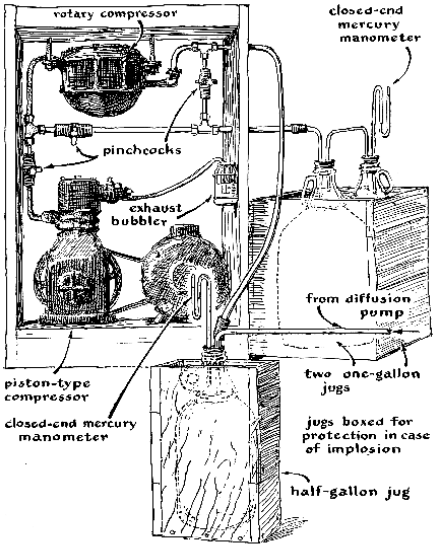


Figure 4: "Roughing" pump assembly for the vacuum system of the accelerator

"A rough vacuum of 20 millimeters or so is easily pumped either by a water aspirator or a refrigerator compressor (connected backward). Higher vacuums may be attained by connecting two refrigerator compressors of the rotary type in series to make a two-stage unit. Compressors of the piston type are not satisfactory unless they are modified, because the inlet valve which is actuated by gas pressure stops working when the system has been pumped down to a pressure of about 30 millimeters.

"It is possible to make a 50-per-cent improvement in the performance of piston compressors by bypassing the inlet valves. Rotary compressors, such as are used in the Frigidaire, have no valves and are easily adapted to multistage use. My system uses two second-hand units, one of the piston type and the other of the rotary, as "roughing" pumps. These were purchased from a local dealer in used iceboxes for $5 each, including the motors. The intake valve of the piston unit was bypassed by drilling a hole in the side of the cylinder just above the low point of the piston's travel. A short length of copper tubing was brazed to this port as the new intake. The piston covers the port as it ascends, thus eliminating the need of gas pressure to actuate the inlet valve. The intake of this unit is connected by a hose to the discharge port of the rotary compressor. A system of pipes and valves permits the discharge from the rotary compressor to be connected either to the intake of the piston unit or to a two-gallon reservoir. A similar system of pipe-and valve-connections permits the intake of the rotary compressor to be. connected either to the outlet of a diffusion pump or to the reservoir. Connected in tandem and exhausted into the air, the pumps will reduce the pressure to about one millimeter. But by exhausting into the two-gallon reservoir (previously pumped to a pressure of one mm.) it is possible to obtain a final vacuum of about .1 mm.

"Special oils of low vapor-pressure must be used for lubrication. The pumps are first

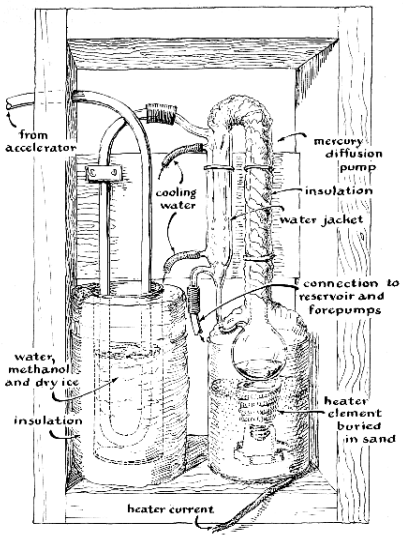


Figure 5: Mercury diffusion pump and cold trap for the vacuum system

drained of conventional oil, then filled with about half a pint of paraffin oil, operated for 10 minutes and drained. If the paraffin oil shows traces of the old oil, the pumps are again flushed with paraffin oil.

"They are now filled with vacuum oil. Some volatile fractions may still remain. These can be removed by several hours of operation. Unlike conventional vacuum pumps, refrigerator compressors have large areas of contact between the oil and gas on the discharge side of the pump and are accordingly susceptible to volatile fluids.

"My vacuum reservoir consists of a pair of one-gallon glass jugs connected with the pumps by half-inch copper pipe inserted through rubber stoppers coated with vacuum grease. The reservoir is first exhausted by the tandem pumps. The pinchcocks are operated to switch the reservoir to the output of the rotary compressor. If the system does not liberate too much gas, one pumping of the reservoir will last many hours.

"The final pressure at which the tube works is achieved by means of a diffusion pump. A half-gallon reservoir is connected between the inlet of the rotary pump and the exhaust of the diffusion pump. Pressure in both reservoirs is indicated by a manometer connected as shown [*see illustration in Figure 4*]. When the pressure of either reservoir rises above three millimeters, it is reconnected to the inlet of the rotary unit and pumped down to one mm.

"My attempt to make a mercury diffusion pump from spare pipe-fittings did not succeed. I must confess, however, that I did not try very hard. The project should not be difficult for those with access to machining facilities. Diffusion pumps of various designs and capacities are available on the market from $30 up. The small sizes require about three pounds of mercury, which costs about $12 more. A heating unit ranging from 100 to 300 watts must also be provided for vaporizing the mercury. My pump [*see illustration in Figure 5*] was made by a local glass-blower to operate against a back pressure of about four millimeters Judging by the literature, many commercial pumps require a back pressure of .3 mm. or less. In general, the rate at which diffusion pumps remove gas from the system varies inversely with the back pressure against which they operate. The ultimate pressure they produce depends on the vapor pressure of the pumping fluid, which includes various oils in addition to mercury. Vapor pressure, in the case of mercury pumps, establishes a lower limit of one micron (.001 millimeter) unless the system is

equipped with a trap to prevent the mercury vapor from entering the evacuated vessel. A cold trap made by refrigerating part of the plumbing between the diffusion pump and the accelerator tube enables the pump to achieve a pressure of .01 micron if the temperature of the trap is maintained at minus 40 degrees centigrade. My trap consists of a U-shaped section in the half-inch copper line. The section is inserted in a tin can insulated by a half-inch layer of cardboard covered by aluminum foil. The cooling mixture consists of equal parts of water and wood alcohol to which crushed dry ice is added as required. The trap is not chilled until the system has been pumped to one or two microns. This procedure prevents the formation of ice in the trap which will subsequently release water vapor as low pressures are attained, and thus increase the pump-down time substantially.

"The mercury is vaporized by a unit from a radiant heater to which an extra winding was added to reduce its rating to 150 watts. The heater is mounted in a tin can and buried in sand up to the top of the ceramic cone. Heat radiated from the center of the cone is sufficient to energize the pump. A 150-watt incandescent lamp would doubtless work as well. In selecting a site for the apparatus keep in mind that most diffusion pumps require a supply of cooling water.

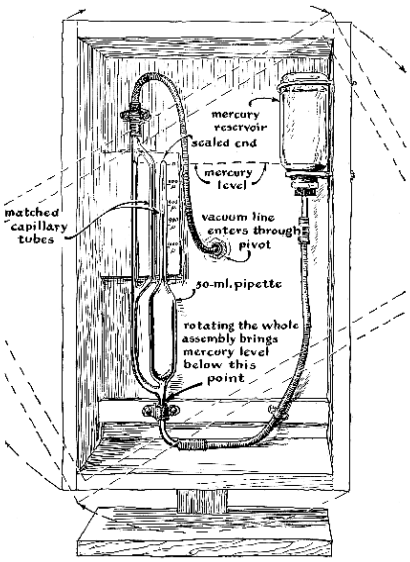


Figure 6: McLeod gauge for measuring low pressure in the vacuum system

"Once the vacuum system is complete, the easy part of the job is ended. One then locates and seals the leaks. This tedious procedure can consume days or weeks depending upon the experimenter's luck and the efficiency of his leak detection gear.

"At least three closed-end mercury manometers should be provided. These consist of quarter-inch glass tubes about 24 inches long. If soda-lime glass is used, one end can be sealed over a Bunsen burner. A short section six inches from the closed end is then heated to softness and bent 180 degrees so that it lies parallel to the long portion of the tube. The long portion is then heated at the point opposite the closed end and similarly bent 180 degrees. The result is a flat 'S' [*see illustration below*]. Enough mercury is introduced into the tubing to fill the closed leg of the 'S' and about 20 per cent of the center leg. This can be accomplished by placing the tube in a reclining position and rocking it as the mercury is introduced into the open end. The closed leg must be completely filled without a trace of bubbles. One manometer is inserted in each of the reservoirs and another is temporarily connected to the accelerator tube.

"The roughing pumps are now started. If the mercury has not separated from the closed end of the manometer at the end of 15 minutes, the tube may be tapped gently. If this does not cause separation, check the pumps for faulty operation. After the pressure has been reduced to about one millimeter, the individual elements of the system should be isolated by closing all pinchcocks. The pumps are then stopped. The manometers may be provided with cardboard scales calibrated in arbitrary units. Manometer readings are recorded at the end of the pump-down and compared with a second set of readings made after an interval of 12 to 24 hours. Each section of the system will doubtless show a rise in pressure. Vacuum grease is then applied to all joints where a leak is suspected and the procedure is repeated. Ultimately the system will appear to be tight. A run can then be attempted with the diffusion pump in operation. In my system a pressure of one micron is achieved at the end of about 30 minutes, and a usable vacuum in the accelerator tube is attained about eight hours later. The roughing pumps are used for about an hour or until the tube pressure drops to .5 millimeter, after which they are valved off and shut down. The half-gallon reservoir on the outlet of the diffusion pump has sufficient capacity to receive the exhaust for several days of continuous pumping.

"Most experimenters will want at least one high-vacuum gauge of the McLeod type to check leaks too slow to show on the manometers. The McLeod gauge operates on the principle of trapping gas in a chamber of substantial volume and then compressing it by a column of mercury into a closed capillary tube. The pressure of the compressed gas is then compared with that in the vacuum system by observing the difference in height to which a column of mercury rises in a matching capillary connected to the system. One of my gauges is shown in the accompanying illustration [*Figure 6*]. It was made of discarded laboratory pipettes that had broken tips but were otherwise usable. Readings made with it are accurate down to about 10 microns, but gas released from the rubber connections prevents measurements at lower pressures. A second gauge made by a professional glassblower detects .1-micron pressures. The instruments require about three pounds of mercury Dibutylphthalate ($1 per pound) has been substituted for mercury as an economy measure; I have also tried salad oil and olive oil. These are usable if they are boiled for a few minutes at one millimeter of pressure, but they absorb volatile materials easily and in time become erratic.

"Those who build this accelerator would be well advised to read the several reference texts listed in the bibliography before purchasing supplies.

"Several hazards should be noted. First, a large evacuated glass vessel

can, if it breaks, scatter glass at high velocity over a large area. It is essential that the glass reservoirs be enclosed in wooden or metal containers. Second, keep in mind that the accelerator is a close relative of the X-ray tube. The penetrating power of X-rays is determined in part by the atomic weight of the target bombarded by electrons. X-radiation emitted by light elements such as aluminum is readily absorbed by glass, thin metal or even air. But heavy metals, such as copper, generate penetrating and dangerous radiation. It is important, therefore, to expose only materials of low atomic weight to the beam. Third, the inexperienced worker should observe care in handling mercury, particularly when it is confined in glass tubes. If air is admitted abruptly to a manometer of the closed-end type, it is astonishing what damage the 'water hammer' (in this case mercury hammer) can do. Enclose the manometers in transparent plastic bags. Just having a few pounds of mercury around constitutes a substantial hazard because the vapor pressure of mercury is high enough to worry about even at temperatures as low as 80 degrees Fahrenheit. Fourth, although the voltage of the Van de Graaff generator is not necessarily hazardous in itself, an unexpected shock can throw one off balance and thus lead to an accident.

"I will be glad to provide assistance in locating supplies. Letters addressed to F. B. Lee, Erie County Technical Institute, Buffalo, N. Y., will be answered as promptly as possible."

Bibliography

MODERN PHYSICAL LABORATORY PRACTICE. John Strong, with H. Victor Neher, Albert E. Whitford, C. Hawley Cartwright and Roger Hayward. Blackie and Son, Ltd., 1938.

VACUUM EQUIPMENT AND TECHNIQUES. Edited by A. Guthrie and R. K. Wakerling. McGraw-Hill Book Company, 1949.

Suppliers and Organizations

The **Society for Amateur Scientists** (SAS) is a nonprofit research and educational organization dedicated to helping people enrich their lives by following their passion to take part in scientific adventures of all kinds.

The Society for Amateur Scientists
5600 Post Road, #114-341

East Greenwich, RI 02818
Phone: 1-877-527-0382 voice/fax

Internet: http://www.sas.org/

4,228.5.

James H. Bly of the Eligh Voltage Engineering Corporation in Burlington,'" Mass., recommends a change in the design of the particle accelerator described in this department last January. "In general, I think it is fair to say that we like the design approach to this machine very much," Bly writes. "However, we are somewhat concerned over those portions of the article that are concerned with the hazards involved. We agree wholeheartedly with what was said concerning the hazards of glass breakage and the use of mercury. We feel strongly, however, that there is inadequate discussion of the potential hazards due to X-rays and electrons. Even though the experimenter restricts himself to targets of low atomic number, there will inevitably be some generation of high-energy X-rays when using electrons of 200 to 300 kilovolt energy. If currents as high as 20 microamperes are achieved, we are sure that the resultant hazard is far from negligible. In addition, there will be substantial quantities of scattered electrons some of which will inevitably pass through the observation peephole. Although it is conceivable that it would be safe to look through this peephole from a distance of two feet, we are very doubtful that this is in fact the case. We believe the article would have been improved considerably if these hazards had been more thoroughly explored."

The apparatus described has been in operation for a year and has been tested exhaustively for radiation hazard. The article might well have pointed out, however, that one invites trouble by remaining near particle accelerators when they are in operation, or even by staying in the same room with them during prolonged periods of operation. F. B. Lee, who designed the apparatus, does not share Bly's concern about the hazard of scattered electrons from the peephole. As a precaution, however, the peephole may be covered on the inside by a small piece of window glass which will plug the hole completely for electrons. As an alternative the neon tube can be cemented in the peephole and connected with its circuit through a pair of contacts (an arrangement that would permit the high-voltage terminal to be removed when desired). The lamp could then be observed at a distance with the machine in operation.

George Gaylord Simpson, curator of fossil mammals and birds at the American Museum of Natural History, calls our attention to a hazard of a different sort. He writes: "In your February issue 'The Amateur Scientist' urges more amateurs to collect fossils and assures them that 'on public lands U. S. citizens can gather as many as they want.' That

Ready References

Essential Technologies for Making Accurate PC-Based Measurements

Technique of High Vacuum

Glass Blowing for the Laboratory

Notes on the Construction and Design of Instruments and Apparatus

Coating of Surfaces: Evaporation and Sputtering

Getting Information About Chemicals

A Great Source of Free Chemicals

Cost: $0-100 About These Ratings	Difficulty: ■■■□□	Danger 2: (Minor injury possible)	Utility: 😎

Experiments Which Show That the Earth Functions As an Electrostatic Machine

by C. L. Stong
May, 1957

■ ONE SUNNY MORNING last fall a jolt of electricity knocked Fred Ellis, an Ohio radio ham, from the roof of his barn. Fortunately Ellis landed on a stack of straw and lived to tell the tale. "I started to hook a ground wire to a 50-foot antenna tower on the roof," he writes, "when a fat spark jumped from the metal tower to my hand and knocked me off balance. Although the weather was hot and dry there had been no breeze of any consequence for several days. Hence the charge could not have been generated by wind friction. How do you account for it?" In Minneapolis a steeplejack was badly burned earlier in the year when a similar spark jumped from the base of a flagpole and touched off a nearby pile of gasoline-soaked rags. Again the accident occurred on a clear, still day. A television viewer on a Pennsylvania farm, plagued for months by a strange electrical disturbance which occasionally obscured his picture, finally cured the difficulty when he detected small sparks jumping from the sheet metal cupola on his house. The trouble was ended by grounding the cupola. In all three cases the explanation has to do with the sometimes-overlooked fact that the earth is, among other things, the negative electrode of a huge electrical generator of the Van de Graaff type. Many details of this natural generator await explanation; if you enjoy electrostatic experiments, here is a readymade project and a machine that goes with it.

Nature's generator works on the same basic principle as the man-made Van de Graaff machine-but differs remarkably in its geometry and details of construction. The conventional Van de Graaff employs a pair of spherical electrodes, held apart by a cylindrical

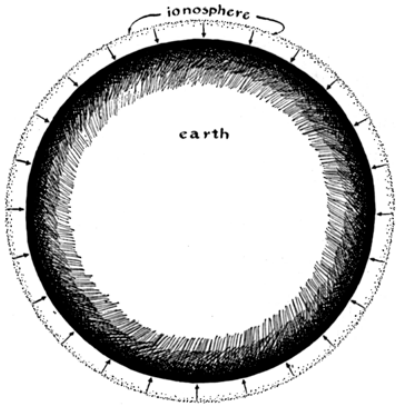


Figure 1: Principal components of nature's Van de Graaff generator

insulating column and charged by the action of a motor-driven belt. The arrangement resembles a big dumbbell. The belt "pumps" electrons out of one sphere and deposits them in the other. As the pumping action continues, an electric field builds up between the spheres. The voltage is limited only by the curvature of the collectors and the insulating properties of the column, belt and surrounding atmosphere. In nature's design, on the other hand, the parts of the generator take the form of concentric spheres. The earth, which is the negative electrode, is at the center. It is surrounded . by a hollow sphere of insulating material: the lower atmosphere. The insulator is in turn surrounded by the positive electrode: the ionosphere. A spherical pattern of thunderstorms within the insulator functions as the charging belt. The machine's effectiveness as a generator of high voltage leaves something to be desired because the atmosphere is a relatively poor insulator: its resistance amounts to only 200 ohms. Yet thunder- 6,;. storms do an astonishingly good job of keeping the electrodes charged.

Lightning, the counterpart of the . man-made machine's corona points, carries current amounting to thousands of amperes. On the average 100 strokes of lightning hit the earth every second. You can hear the resulting electromagnetic debris at any hour by hooking a long antenna to the input of an audio frequency amplifying system and turning up the volume [see "The Amateur Scientist; SCIENTIFIC AMERICAN, January, 1956]. It makes a sharp, buzzing s;. sound. The energy output of the 2,000 . to 6,000 thunderstorms in progress at any one time is sufficient to maintain an average potential of 360,000 volts between the earth and the ionosphere. This despite a leakage of current through the atmosphere of 1,800 amperes! The intensity of the field diminishes with height, but near the surface it amounts to about 100 volts per yard of altitude. Accordingly we walk around with our heads in air some 200 volts positive with respect to the ground at our feet [see "The Earth's Electricity," by James E. McDonald; SCIENTIFIC AMERICAN, April, 1953].

Given sufficient time, conductors insulated from the ground pick up the potential of the surrounding air. A negatively charged body attracts positive ions from the air until its negative charge is neutralized. Conversely, a positively charged body attracts negative

ions. The time required for a body to reach electrical equilibrium with the surrounding air depends largely on its size and the concentration of ions naturally present in air. The amount of electricity that a body can accumulate its capacity for holding charge is also proportional to its size. Ellis's antenna tower was so big, and had lost so much negative charge to the surrounding air, that he was knocked off balance by the swarm of returning electrons. Had he touched a small object, say a metal ventilator or several hundred feet of wire, the current would doubtless have been so small he would not have felt it.

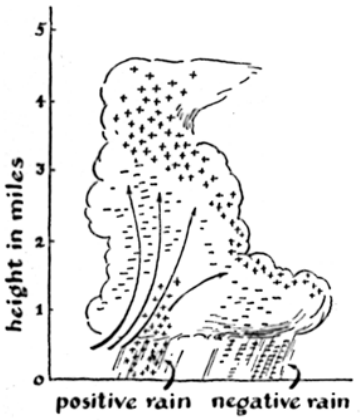


Figure 2: Distribution of charge in a thunderstorm

Several methods of measuring the intensity of the earth's field are based on the fact that conductors can reach electrical equilibrium with the surrounding air. These methods lend themselves to an interesting series of experiments. In principle the measurement is simple. You merely place a test structure (a few feet of wire will do) at a given height above the ground, insulate it from the earth, wait until it reaches electrical equilibrium with the air, and connect a voltmeter of appropriate sensitivity between the test structure and the earth. The meter reading is divided by the height in feet; the result is the field intensity in volts per foot. The field intensity varies considerably with location, topography, the hour of day and the state of the weather. Readings made at the top of mountains or steep hills average much higher than those made at sea or in prairie country. Conversely, observations made in valleys average somewhat lower. Usually the charge of the earth is negative, but under the trailing edge of a thunderstorm it is often positive. Here potential differences of 3,000 volts per foot have been recorded. The intensity of the earth's electrical field also varies during the day; this appears to be a consequence of the uneven distribution of the earth's land area. The number of thunderstorms reaches a peak when the continents of the Western Hemisphere are turned toward the sun; at that time Europe and Africa have just absorbed their daily quota of solar heat. This explanation, like many others concerning the generation and distribution of the earth's electric field, has not been tacked down as neatly as physical meteorologists would wish. Mori observations of the daily population of thunderstorms, together with corresponding information on the variation in field intensity, are needed.

Although the measurement of field intensity is simple in principle, it is made difficult in practice by the fact that considerable time may be required for a conductor to pick up charge

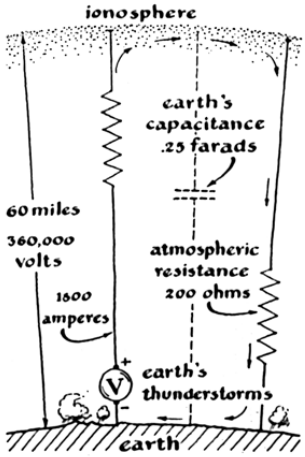


Figure 3: Diagram of the earth's electric circuit

from the surrounding air. Lord Kelvin devised ,' the first method of speeding up the process. He insulated a metal tank from the ground, filled it with water and arranged matters so that water would flow from a spray nozzle at the bottom, where the charge density is greatest per unit area. He called the arrangement a "water-dropper." The surface of each drop, immediately before it is detached from the stream, is an extension of the surface of the tank. Accordingly the potential difference between the drop and the air is equal to that between the tank and the air. When the drop is detached, it carries charge away. The process continues until equilibrium is established between the tank and the air. The test conductor need not consist solely of the tank. A relatively small water-dropper can be used for charging a test structure of any desired size. Garden sprays of the type which operate on compressed air supplied by a hand pump will charge a 30-yard length of wire in about 20 seconds. Fine spray is preferred to large drops because the higher ratio of droplet surface to volume not only conserves water but speeds the charging process.

The charging time can also be reduced by enriching the concentration of ions in the vicinity of the test structure. For example, a wire 10 to 15 feet long with a glass insulator at each end is suspended a yard or so above the ground between a pair of posts. A short length of the wire is then wrapped in string or paper that has been soaked in inflammable lead nitrate. When the string or paper is ignited, the flame produces ions in the vicinity of the wire; in a few seconds the potential of the wire will reach that of the ambient air. A torch waved in the vicinity of the wire will accomplish the same result but at some cost in terms of convenience. Where it is desirable to monitor the field continuously over long periods, radioactive materials may be called into service. A film of polonium electrolytically deposited on a wire will emit alpha particles which strongly ionize the surrounding air.

The practical measurement of field intensity is further complicated by the necessity of using measuring instruments of extreme sensitivity. Test conductors of reasonable size store little energy at low voltages at most a small fraction of a watt. If a substantial part of that little is consumed in driving the pointer of the measuring instrument, the accuracy of the reading will suffer. Lord Kelvin measured the potential of his water-dropper with a quadrant electrometer. This instrument consists of a metal vane suspended by a fine wire inside a metal structure which resembles a pillbox cut into four sectors. All the sectors are insulated

from the ground, and sectors diametrically opposed to each other are wired together. The two pairs of sectors are then charged in opposite polarity by a battery, and the vane is connected to the test structure under measurement.

A small mirror cemented to the wire from which the vane is suspended serves as a pointer; a spot of light reflected from the mirror moves as the mirror turns. The vane moves in response to the electrostatic attraction and repulsion between its charge and that of the sectors. In the finest quadrant electrometers the wire supporting the vane is replaced by a quartz fiber which has been made a conductor by depositing a film of gold on it. When the vane is charged, it draws almost no current; yet the device is extremely sensitive to changes in voltage. Amateurs who go in for instrument making will find the construction of such an electrometer a challenging and rewarding enterprise.

Most modern electrometers are built around vacuum tubes of the screen-grid type. The basic circuit is simple. Bias voltage is connected between the cathode and grid of the tube through a high resistance. A microammeter is inserted into the plate lead; an ordinary battery supplies both screen-grid and plate voltage. The test structure is connected to the grid and the cathode is grounded. The intensity of the earth's field determines the charge on the grid and hence the strength of the plate current. The device is calibrated by connecting a source of known voltage to the grid and noting the resulting; deflection of the microammeter.

A number of precautions must be observed or the grid will draw an intolerable amount of current. Some current, for example, is contributed by positive ions which are ejected by the cathode and strike the grid. Another source of current is gas atoms ionized by electrons accelerated between the grid and plate. In addition, some of these electrons strike the plate with enough energy to produce soft X-rays, which in turn dislodge electrons from the grid. Light falling on the grid also ejects electrons from it. Finally, grid current tends to leak along the surface of the bulb.

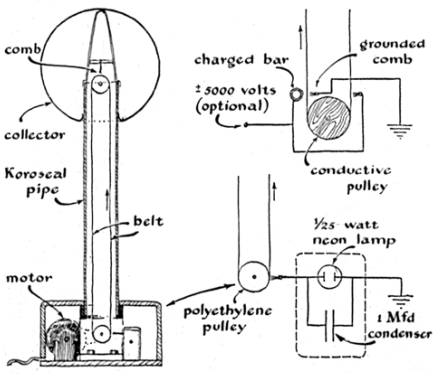


Figure 4: Van de Graaff generator with internal belt and external excitation

A number of techniques have been developed for reducing these currents. The production of positive ions can be reduced by operating the cathode at subnormal temperature. The grid can in effect be shielded by charging the screen grid to a higher positive potential (15 volts) than

the plate (8 volts). This has the effect of repelling positive ions ejected by the cathode. Reduced plate voltage prevents electrons from acquiring enough energy for ionizing the residual gas in the tube and lowers the production of X-rays. Photoelectrons are eliminated by enclosing the tube assembly in a light-tight box. Surface leakage is reduced by washing the glass envelope with alcohol and dipping the area surrounding the terminal of the control grid in ceresin wax. In applications demanding maximum sensitivity air is evacuated from the light-tight box.

By meeting these circuit requirements and using a tube of special design, such as the-General Electric FP-54, it is possible to detect currents of 60 electrons per second. Other special electrometer tubes include the Victoreen 5803 and Raytheon 5886. The RCA 954 and 959 and the Western Electric 259-B types may also be used in all but the most exacting electrometer applications. For maximum sensitivity the grid must be tied to the cathode through a resistance on the order of 100,000 megohms. Such resistors are manufactured by the S. S. White Company, Victoreen and the International Resistance Company.

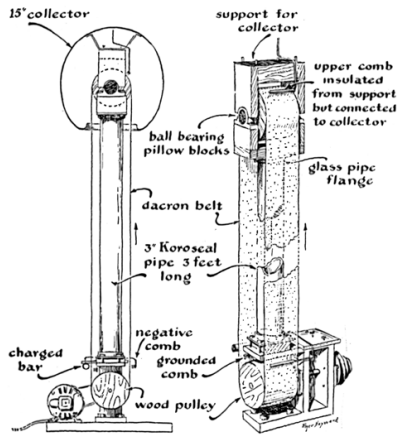


Figure 5: Van de Graaff generator with external belt and internal excitation

A third method of measuring the earth's field intensity eliminates the need for highly sensitive instruments by employing a device called a "field mill," which in effect transforms electrostatic charge into alternating current. Alternating current from the mill is amplified electronically and rectified. The output drives low-sensitivity direct-current ammeters, recorders and so on as desired. In effect, the field mill is comprised of a motor-driven variable capacitor which is connected in series with the capacitor represented by test structure, the earth's surface and the intervening air. As the capacity of the variable capacitor increases, current flows into it from the test structure. When the current of the variable capacitor decreases, current returns to the test structure. The frequency is made high in relation to the time required for the test structure to assume electrical equilibrium with the surrounding air. Hence the test structure remains substantially at the ambient potential, and energy lost through the weak oscillating current is not significant. Output from the mill is provided by voltage developed across a megohm resistor inserted between the variable capacitor and the test structure.

As usually constructed, the mill takes the form of a capacitor with three plates, two fixed and the third motor-driven. One plate is a shallow cylinder closed at the bottom and open at the top. The other two plates

form the lid of the cylinder. Each of these plates looks rather like a two-bladed paddle; it consists of opposing quadrants joined at the apex One of them is mounted flush with the open end of the cylinder, but is insulated from it. This plate covers two quadrants of the cylinder, leaving two quadrants open. The open quadrants are-closed by the other plate, which is mounted directly above them. This last plate is keyed to the end of a shaft which extends through the assembly to the motor, fastened to the bottom of the box. When the shaft rotates, the blades of the plate alternately cover and expose the fixed plates. The rotating assembly is mounted on insulators and grounded through the megohm resistor across which the output voltage is developed. The alternating-current output is rectified by a synchronous reversing switch, or commutator, keyed to the opposite end of the motor shaft. By rectifying the output synchronously, both field polarity and intensity can be observed. The mill is calibrated by comparison with a known voltage. It is both rugged and portable. Special designs have been developed for use in aircraft, and have contributed significantly in recent years to this phase of meteorological research.

Franklin B. Lee, a chemical engineer and faculty member of the lrie County Technical Institute in Buffalo, N. Y., has built a number of small Van de Graaff machines and passes along the results of his experiments to amateurs who prefer to work with generators less bulky than the earth. "Two important pieces of information for the designer of Van de Graaff machines," he writes, "are, first, approximately 50 square inches of belt per second passing over the pulleys will produce one microampere of current; second, the maximum potential developed by the machine will be equal to 70,000 times the smallest radius of curvature of the collector in inches. Thus a perfect sphere 12 inches in diameter will have a theoretical limiting potential of 420,000 volts. Holes made in the sphere to admit the belt assembly alter the pattern of the field and reduce the theoretical maximum. The most effective compromise with the ideal shape for a practical collector is a spheroid slightly flattened at the bottom, with minimum radius of curvature located at a reasonable distance from the insulator to discourage sparking along the insulator surface [see "The Amateur Scientist"; SCIENTIFIC AMERICAN, April, 1955].

"The designer's choice of maximum voltage determines the size of the collector. To realize a large fraction of the theoretical limiting potential, the collector must be at least two or three diameters removed from other metallic parts. The distance should be greater if sharp-edged metal parts are present, and may be somewhat less if all parts are covered by a rounded metal shield of large radius of curvature. The opening which admits the belt to the collector ought not to be much larger than half the diameter of the collector and should be smoothly curved inward, generous radius of curvature.

"Although a high polish adds to the attractiveness of the collector, it is not essential. Minor surface imperfections, if well rounded, limit the maximum voltage only slightly. Sharp edges or burrs must be ground down. Lint and dust particles will reduce the voltage to 40 per cent of the theoretical maximum if they protrude from the surface as much as 1 per cent of the radius. Unpolished commercial aluminum spinnings, free of lint and dust, will collect about 85 per cent of the theoretical maximum. A high polish will increase the voltage another 1 per cent. The concentration of charge around the hole through which the belt enters accounts for the remaining 14 per cent, a quantity which varies, of course, with the size of the hole and its distance from other conductors.

"The hemispheres from which my collectors have been assembled were procured from a local metal-spinner who, if not too busy, will turn them out for $4.50 each, a reasonable price considering the fact that he pays $2 for the 14-gauge blanks. I had to furnish the wooden die on which the parts were spun. They would otherwise have cost on the order of $25. Incidentally, I will be glad to supply any number of 12-inch hemispheres at cost plus postage plus 75 cents per pair for handling, boxing and so on.

"Selection of the desired current output determines the size of the belt and the speed at which it must run. Meeting this specification is not so simple as it might seem offhand, because the properties of the materials used for the belt and its driving assembly enforce speed limits on both the belt and the shaft bearings. For maximum current one should in theory use the highest possible belt speed. But there are disadvantages in running belts faster than about 100 feet per second. Higher speeds aggravate the tendency of belts to fray at the edges and to come apart at the splices. At high speeds, particularly in the case of small pulleys, extreme tension must be maintained; this leads to bearing problems. Lubrication difficulties limit the shaft speed of sleeve bearings to about 5,000 revolutions per minute. The noise level of ball bearings becomes annoying above this speed unless special steps are taken to minimize it. At belt speeds above 100 feet per second appreciable amounts of power are lost through air friction. Finally, part of the charge appears to be 'blown, off the belt at excessive speeds a phenomenon which I do not wish to be called on to explain.

"Belts may be made of almost any insulating material: paper, cloth, rubber, plastic and so on. Rubber, because of its poor resistance to ozone, has a h limited life, but with used inner tubes 't costing so little the inducement to improve on it is slight. Rayon, nylon, Dacron and cloth (made into belts with acetone cement) are almost as good. Incidentally, when these materials are substituted for rubber, the position of the corona-collecting combs must be shifted. Cloth belts are more durable than rubber, are quieter and require less driving power,

but tend to fray at the edges. This is easily remedied by a coat of lacquer. All things considered, I find that belts of neoprene joined with a diagonal splice are a good compromise.

"The upper pulley must be made of a material which is a good electrical c0nductor, such as wood or Bakelite Surprised? At such voltages these materials are very good conductors for the small currents involved. Scrap plywood may be glued together to make a highly satisfactory wooden pulley. The lower pulley should also be electrically conducting if. a separate 5,000 to 10,000-volt d.c. power supply is used for spraying charge onto the belt. If the machine is to be self-excited (that is, if the belt is to be energized by friction), the lower pulley should either be coated with or constructed of a material of extremely high resistivity. A 1/32-inch thickness of polyethylene makes a splendid covering for small wooden pulleys. The pulleys should be turned with a slight crown, the edge making a snug fit with the inside of the polyethylene tube. The tube may be made by cutting the ends off a round squeeze bottle. The tube is simply pushed over the wooden core. The choice of pulley and belt material for self-excited machines determines the polarity of the collector charge. A rubber belt running on a lower pulley of polyethylene or polystyrene will usually pump electrons from the collector and hence charge it positively.

"The belts may run on either the inside or the outside of the insulating support. Economy, simplicity and high currents favor running them on the outside. Appearance and neatness of construction require them to be on the inside. The former arrangement permits the use of a small, relatively inexpensive insulator with low current leakage and minimum deterioration due to corona discharge (the source of ozone). It also permits use of the widest belt possible for a given opening in the collector. Problems arising from unequal potentials throughout the insulator are similarly minimized. All hygroscopic or fibrous materials should be avoided in the selection of the insulating column because they invite leakage through the moisture which forms on the surface. The material must also be selected with an eye to its mechanical properties: strength, stiffness and toughness. FinalIy, it should be readily available at a reasonable price. Tubing of polyester glass-fiber laminate or polyvinyl chloride meets these requirements and is available in standard pipe sizes. In the three-inch (diameter) size, it costs $2.60 per foot. Polyvinyl chloride is the less hygroscopic of the two and may be flanged or formed to other contours by heating it to its softening point in hot paraffin.

"Combs or corona points for applying charge to the belt may be contrived in great variety. Often a common pin or a single phonograph needle can be as effective as the most elaborate comb. A tuft of wire, bound at one end and sheared like a broom at the other, makes h a

satisfactory comb, as does a small rectangle of wire screening. Care must be taken to avoid spraying areas of the belt with unwanted charge. This may happen if charges are permitted to mix on the front and back of the belt near the pulleys. The problem is met by mounting the combs on fixtures which provide easy adjustment over a wide range of positions, and by selecting comb sizes which restrict the areas that are sprayed with charge."

The simple Newtonian telescope that is shown at the right is submitted by W. Gorrell, Jr., of Buffalo, Wyo. A local school, having purchased a telescope kit and made a three-inch mirror, was stumped for an adequate mounting. On appeal, Gorrell solved the problem by a visit to a local automobile junkyard plus a few evenings of labor. The gadget he picked up in the junkyard should interest any amateur on the verge of assembling a small equatorial mounting.

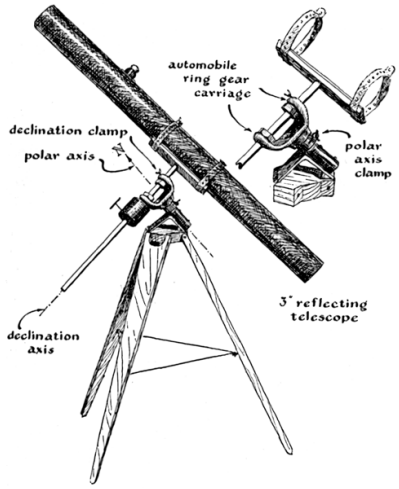


Figure 6: a simple equatorial mounting for a small telescope

The lucky find is a "ring-gear carriage," a component of the transmission h assembly in most pre-automatic-shift cars. "The holes through the yoke end," Gorrell writes, "are aligned precisely and make a snug fit with a .75-inch shaft. The bottom of the part is faced off. Both the outside and inside are turned. The shoulder and the top surface are nicely faced. I used only one of the inside bores (the smaller one), for which I turned a piece of pipe to fit. A brass collar on the pipe takes the downward thrust of the instrument.

"The ring-gear carriage turns in a short length of pipe, which is welded to an angle-iron base as shown. The 45-degree angle of the base is close enough to that of our latitude (44 degrees, 21 minutes) so that a slight tilt of the tripod compensates for the difference.

"Since the entire rig weighs only a few pounds and the center of the yoke is the center of balance between the 'scope and the counterweight, the instrument can be lifted off the tripod yoke, counterweight and all and reassembled without touching a single screw or clamp."

Bibliography

AMATEUR TELESCOPE MAKING: BOOK I. Edited by Albert G. Ingalls. Scientific American, Inc., 1951.

ELECTRONICS: EXPERIMENTAL TECHNIQUES. William C. Elmore and Matthew Sands. McGraw-Hill Book Company, 1949.

PHYSICAL METEOROLOGY John Clark Johnson. The Technology Press and John Wiley & Sons, Inc., 1954.

Suppliers and Organizations

Fry's Electronics retails over 30,000 electronic items within each store. Fry's has been keeping hi-tech professionals supplied with products representing the latest technology trends and advances in the personal computer marketplace for 15 years. Fry's has become the place where a technical customer can shop with confidence and comfort.

The **Society for Amateur Scientists** (SAS) is a nonprofit research and educational organization dedicated to helping people enrich their lives by following their passion to take part in scientific adventures of all kinds.

The Society for Amateur Scientists
5600 Post Road, #114-341
East Greenwich, RI 02818
Phone: 1-877-527-0382 voice/fax

Internet: http://www.sas.org/

Ready References

Control Instrument Applications

Signal Conditioning and Data Acquisition Basics

Hands-On Astrophysics (HOA)

First Aid for Electrical Accidents

Introduction to Fossils

A Glossary of Seismic Terms

Relative Time Scale

Cost: $0-100 About These Ratings	Difficulty: ■■■□□	Danger 4: (POSSIBLY LETHAL!!)	Utility:

About Historic and Modern Machines for the Generation of Static Electricity

by Albert G. Ingalls
April, 1955

■ NEAR THE CLOSE OF THE 17th century Otto von Guericke, the amateur physicist of Magdeburg, invented the world's first electrical machine-an electrostatic generator. He wrote down these instructions for building one:

"Secure one of the glass globes which are called phials, about the size of a youngster's head; fill it with sulfur, ground in a mortar and melted by the application of a flame. After it refreezes, break the phial, take out the sulfur globe and keep it in a dry place, not a moist one. Perforate it with a hole so that it can spin upon an iron axle. Thus the globe is prepared.

"To demonstrate the power developed by this globe, place it with its axis on two supports in the machine-a hand's breadth above the baseboard-and spread under it various sorts of fragments such as bits of leaves, gold dust, silver filings, snips of paper, hairs, shavings, etc. Apply a dry hand to the globe so that it is stroked or grazed two or three times or more. Now it attracts the fragments and, as it turns on its axis, carries them around with it.

"When a feather is in contact with the globe, and afterwards in the air, it puffs itself out and displays a sort of vivacity . . . and if someone places a lighted candle on the table and brings the feather to within a hand's breadth of the flame, the feather regularly darts back suddenly to the globe and, as it were, seeks sanctuary there."

After describing numerous other experiments, in some of which the globe produced light and sound, von Guericke concluded: "Now many other mysterious facts which are displayed by this globe I shall pass by without mention. Nature often presents in very commonplace things

marvelous wonders which are not discerned except by those who through insight and innate curiosity consult the oracle of experimentation."

Ten generations of experimenters have consulted the oracle since von Guericke's day. So fathomless are the mysteries of his sulfur ball that its "marvelous wonders" continue to charm and sometimes baffle experimenters, whether they twiddle the controls of a Van de Graaff accelerator or merely stroke the hairs on a cat's back. But electrostatics has remained chiefly a curiosity. Most people are acquainted with it only in the form of the crackling shock you get when you touch a metal doorknob after walking across a thick carpet in winter. Those who go in for amateur radio grumble that "static is something you cuss, not study!"

Static electricity has never become economically important, probably because nature has been more generous in supplying effective conducting substances and magnetic materials than she has in providing good insulators. Our electrical technology is based on electromagnetic devices; our electrical power is generated by magnets and moving conductors. Electrostatic machines have been harnessed for only a few specialties, such as generating high voltage for laboratory experiments and producing high-energy X-rays and sterilizing drugs in medicine.

Some engineers believe that electrostatics has big technological possibilities. One of them is John G. Trump, professor of electrical engineering at the Massachusetts Institute of Technology. He points out that the forces resulting from the presence of electric charge are the most direct and powerful in nature. He and his colleagues at M.I.T. are conducting certain investigations which may produce an electrostatic power generator that one day will compete with the electromagnetic generator.

Professor Trump illustrates how the power-generating capacity of electrostatic machines may be stepped up by asking you to consider two metallic plates, 100 square inches in area, facing each other and separated by an insulator.

If a voltage amounting to an electric field of 300 volts per centimeter is applied between them, the plates will be attracted to each other with a force of one 2,000th of a pound. Increase the field to 80,000 volts per centimeter and the attraction becomes half a pound. Now immerse the plates in a high vacuum-a good insulator, though one difficult to maintain-and increase the field to three million volts per centimeter. The force of attraction jumps to 5,700 pounds! "Force of this order," says Trump, "has more than passing interest for power engineers."

Trump and his associates are working on the problem of developing a

practicable system of vacuum insulation which would make possible a field intensity of millions of volts per centimeter in a large machine. If they succeed, an electrostatic power generator will become a reality. The working parts of such a machine would look like an oversized variable capacitor with intermeshing leaves. Only the rotor would move. The machine could be constructed of light metal. A generator of this type about the size of a hall bedroom and weighing only a few hundred pounds, could deliver 7,500 kilowatts of power. Its efficiency would be impressively higher than that of an electromagnetic generator.

The history of electrostatics began with the discovery of Thales of Miletus that rubbed amber attracted other objects. Through the centuries experimenters like von Guericke explored the "marvelous wonders" of static electricity with a succession of ingenious machines which amateurs may enjoy building.

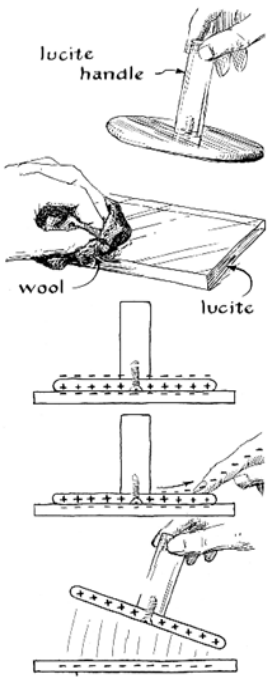


Figure 1: A modern version of Volta's electrophorus

One of the most important historically was Alessandro Volta's *elettroforo perpetuo*, now known as the electrophorus [*Figure 1*]. Volta wrote to Joseph Priestley of the Royal Society on June 10th, 1775: "I hereby draw your attention to a body that, after being electrified by a single brief rubbing, not only does not lose its electricity but retains obstinately the indications of its active force in spite of being touched repeatedly any number of times." The electrophorus consists of two working parts: (1) a rectangular block of insulating material such as lucite or, preferably, polyethylene, and (2) a metal disk fitted with an insulating handle. When the lucite is wiped with a woolen cloth, electrons are removed from the cloth and deposited on the lucite-in much the same way that a dirty rag smears a clean sheet of glass. Early experimenters (who used sealing wax, hard rubber or other resinous substances instead of plastic) said that the insulator thus stroked had been "electrified by friction." They failed to observe that the cloth took on an equal and opposite charge. When electrons rub off from the wool to the lucite (because, as it happens, some of the atoms in wool hold electrons less tightly than those in lucite do), the atoms that have lost electrons become positively charged ions. Accordingly the surface of the wool is peppered with tiny areas of positive charge while the lucite has similar areas of negative charge. The charges are static-bound at the places where they are deposited-because in an insulator electrons cannot move freely about in the substance.

Ever since Benjamin Franklin named the "positive" and "negative" ends

of the electric field, the field has been thought of as originating at the positive end. He might have prevented confusion if he had assigned the names the other . way around, because we now have to say that the current "flows" from positive to negative, although actually the electrons flow from negative to positive!

Be that as it may, the field between a pair of opposite charges is often pictured as a pattern of curving lines that radiate into space from a region deficient in electrons and converge on one where they are in excess. The field can be thought of as a bundle of stretched rubber strands, illustrating that there is a force of attraction between the charges of opposite sign.

Von Guericke demonstrated that an electrified insulator would communicate its charge to one that is electrically neutral. We now know that it accomplishes this by sharing its excess electrons with the uncharged body at points where the two touch. Von Guericke also showed that a body can become temporarily electrified merely by entering a field of charge, without touching the charged surface. He wrote: "If a linen thread supported from above is brought near the globe and you try to touch it with your finger or any other body, the thread moves away and it is difficult to bring the finger near the thread."

This was an important discovery. It demonstrated that charging by induction does not exhaust the charge on the body initially electrified, and also that charges of like sign repel each other. Charging by contact involves the sharing of electrons between two bodies, and each contact diminishes the number remaining on the charging objects. Charging by induction, in contrast, makes no demand on the free electrons but only on the field set up by them. The field causes the electrons of the uncharged substance to veer slightly from their normal orbits. This displacement sets up an "induced" charge in the previously uncharged substance. When the inductively charged body is removed from the exciting field, everything returns to normal and the induced charge disappears.

Induction can give a conductor a permanent charge, in the sense that the charge will remain on the conductor until it leaks off or is otherwise dissipated. All modern electrostatic generators are designed on the principle of inductive charging. And the charging process involves the transformation of mechanical energy into electrical energy. The principle is nicely demonstrated by the electrophorus.

When the metal disk is placed over the charged lucite, the lucite's negative field opposes that of the electrons

near the lower surface of the disk. These electrons move away to the upper surface of the disk. Consequently the lower surface becomes positively charged and the upper surface negatively charged. If, while the top of the metal is thus charged, you touch the top with your finger, the excess electrons will flow into your body-where, electrically, things are not so crowded. Now if you take your finger away and then lift the metal disk by the insulating handle, a net positive charge is trapped in the disk.

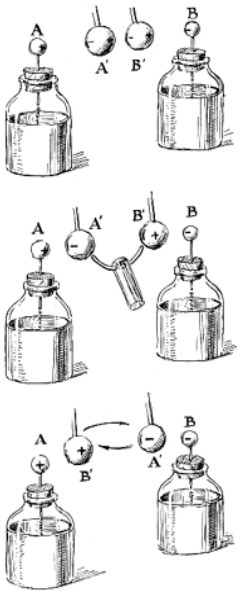


Figure 2: A primitive induction generator

This method of charging removes no electrons from the lucite, nor does it draw on the lucite's energy. Yet the metal disk is now energized with positive electricity (many protons have been denuded of their neutralizing electrons and hence their positive fields extend out into surrounding space). The disk will now attract other bodies just as the charged lucite does. Moreover, a spark will jump between the charged disk and your finger-which you can easily observe in a darkened room. The energy expended in the spark came from your muscles when you lifted the metal from the lucite. The spark was created by electrons colliding with molecules of air in their headlong rush from your body back into the disk.

A more effective arrangement for generating electrostatic energy by induction uses two Leyden jars [*Figure 2*]. One jar, A, has a tiny positive charge. When its positively charged terminal is brought close to a brass ball, A', electrons in the ball are attracted to the side of the ball nearest the terminal. Similarly the terminal on another jar, B, with a small negative charge, drives away electrons in the ball B', making the near surface positive. If the two balls are now connected by a metallic rod [*middle drawing*], electrons in B' (repelled by the field of B and attracted by that of A) will flow to A'. Removal of the rod traps the charges-just as the removal of your finger trapped those in the disk of the electrophorus. Now suppose we change the positions of the balls, moving A' toward B and B' toward A [*bottom drawing*]. To do this we must expend work, because A', for instance, is repelled by B and attracted by A. This work is transformed and stored as potential electrical energy as soon as we touch A' to B and B' to A. The excess electrons in A' flow into B, raising its negative charge to that of A', and A similarly acquires an increase of positive charge. The cycle can be repeated indefinitely. In theory the amount of energy stored in the jars (capacitors) can be increased without limit. In practice, the storage is limited by the fact that electrons leak away more and more rapidly as the charge increases.

Various induction machines have been designed for performing the sequence of operations automatically and with considerable speed. In these machines the "carriers" take the form of thin metallic sheets instead of balls, and the capacitors also are metal sheets, called field plates.

An early form of the machine, patented in 1860 by C. F. Varley of England, is easy to construct [*see Figure 3*]. It consists of a pair of field plates cemented to a square slab of lucite surmounted by a rotating disk of lucite to which six or more sectors of aluminum foil are cemented. Two brushes (of tinsel) momentarily connect opposite sectors, the carriers, with their respective field plates as each carrier enters the region of its plate. A similar pair of brushes again make contact with opposing pairs of carriers as they move from the region of the field plates. A pair of "corona" combs-quarter-inch metal rods fitted with steel phonograph needles spaced half an inch apart-graze the carriers at positions intermediate between the two sets of brushes. The machine's electrical output flows from the combs to a pair of spheres an inch or so in diameter which comprise a spark gap.

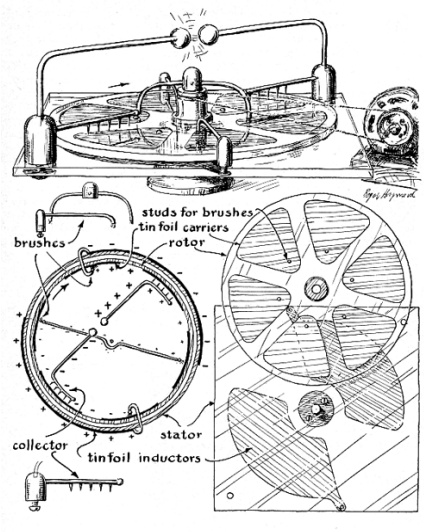


Figure 3: Varley's induction generator

The lower left diagram illustrates the action. Assume a charge on the field plates [*outer solid segments*]. Electrons flow into the carrier at the left, leaving the right-hand carrier with a positive charge. Work is now expended in moving the carriers "up the potential hill" to the opposite field plates. Here they make contact with the brushes and part of their newly acquired energy flows into the field plates; electrons enter the field plate [*top of drawing*] from the negatively charged carrier, while the opposite carrier withdraws electrons from the lower plate. The succeeding action of all carriers is similar. After a short period of operation the combs reach ionizing potential, and energy flows from the carriers to the gap, where vigorous sparking occurs.

The machine is not very efficient. This can be demonstrated by observing its operation in a dark room. The rotating carriers appear as a blurred disk of phosphorescence in colors ranging from greenish-blue through violet, while the field plates are outlined sharply in purple. Corona discharge at the combs is $2 brilliant. This display means that electrons are streaming from the thin, sharp edges of the foil and the points of the comb carrying negative charge and into those parts carrying a positive charge. Considered as an electrical "pump," the machine is leaky and

thus wastes energy.

The corona effect is explained by the geometry of the machine's conducting parts. Unless distorted by another charge, the electric field radiates into, space uniformly in all directions from a point charge. If the charge is enclosed by a conductor, the lines of force always emerge perpendicular to its surface. In the case of a spherical conductor (in effect, an enlarged point) the lines are, therefore, distributed uniformly over the surface. When the sphere is distorted to an egg shape, however, the lines bunch up at the little end and thin out at the big end-because they must emerge everywhere at a right angle to the surface. Crowding at the little end becomes more pronounced as the radius of the "point" is made smaller. This is another way of saying that the intensity of the field, or the potential gradient, increases inversely with respect to the radius of the conductor; in theory it would approach infinity at the point of a perfect needle. Even in practice, finely made points can concentrate fields of astonishing intensity. The exquisite needles used in field-emission microscopes [see "A New Microscope," by Erwin W. Müller, SCIENTIFIC AMERICAN, May, 1952] create field intensities of 750 million volts per inch in the immediate vicinity of the point-although the instrument operates from a power supply of only 5,000 volts! At this field intensity electrons are literally ripped from the metal point and ejected radially into space. Gas, if present in the tube, becomes heavily ionized. The collecting combs of the Varley machine similarly ionize adjacent air, negative charges being carried by dislodged electrons and positive charges by the ions.

In the early years of this century the Wimshurst generator, similar in basic principle to the Varley but carrying one or more pairs of disks that rotate in opposite directions, was a favored source of power for X-ray machines and other devices requiring relatively small amounts of current at high voltage. The largest machines carried as many as 12 pairs of disks seven feet in diameter and delivered potentials on the order of 200,000 volts.

The Wimshurst and other electrostatic generators of this era could not reach the million-volt range. By 1920 they had been largely replaced by electromagnetic induction coils and transformers as sources of high-voltage power.

The modern era of electrostatics began in 1929. In that year Robert J. Van de Graaff, a young Rhodes scholar from Oxford University who was working at Princeton as a National Research Fellow, invented the electrostatic belt generator

which is now known around the world by his name. He was interested in developing a steady constant-potential voltage with which to accelerate atomic particles to bombard nuclei in order to obtain evidence of their internal structure. Today the Van de Graaff accelerator can be found in nearly every large nuclear laboratory in the world; it is the work horse for precision research in this field. The accelerator has attained a particle energy of more than eight million volts, and this figure may soon be more than doubled. In smaller sizes the machine has found a wide variety of applications, particularly as the power source for the high-voltage X-ray treatment of disease.

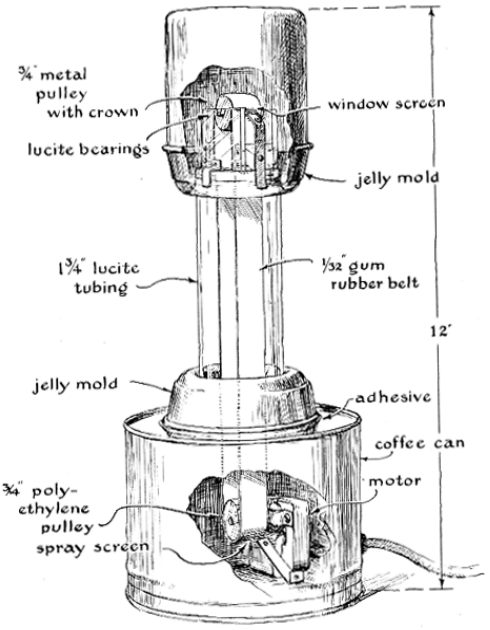


Figure 4: A low-power Van de Graaff machine

One of the nicest features of the Van de Graaff generator is its relative simplicity and low cost. Robert W. Cloud of the High Voltage Research Laboratory at M.I.T. has designed a small version as a special construction project for amateurs [*see drawing on next page*]. Its action is as simple as its design. A motor developing 3,000 revolutions per minute is housed in a coffee can. It drives a gum-rubber belt which passes over an insulated pulley inside the upper terminal. Spray screens, counterparts of the Varley machine's collecting combs, are situated close to the surface of the belt at each end of its run, and each connects with the respective terminal. As the machine goes into operation, frictional contact removes electrons from the belt at the driving end and deposits them on a plastic pulley. Positive charges resulting at the sites on the belt which have thus lost electrons are then carried by the belt to a metal pulley at the other end above. Electrons flow from the metal pulley onto the electron-deficient belt. As the machine continues to run, heavy charges build up on both pulleys. After a few seconds or minutes, depending on the humidity of the air, the field originating at the pulleys reaches ionizing intensity in the vicinity of the spray screens. Electrons are then withdrawn from the upper terminal and sprayed on the belt at the beginning of its downward run. Similarly electrons en route down the belt come within the region of ionization at the lower spray screen and flow by way of its supporting bracket into the lower terminal. Through this pumping action the belt continuously exhausts electrons from the upper terminal and discharges them into the earth through the lower one. This leaves the upper terminal with a net positive charge which, because of mutual repulsion of the positive "holes," distributes

itself uniformly over the terminal's outer surface. Accordingly the inner surface carries no charge. In theory, voltage across the upper and lower terminals increases without limit. As in the case of the Varley and Wimshurst machines, however, the charge is limited by the quality of the insulation. At about 100,000 volts charge leaks as corona from the upper terminal and as conduction current down the insulating column at a rate equal to the two microamperes which the belt is able to carry into the terminal. Although 100,000 volts is an impressive value, the machine creates no shock hazard because the capacity of the upper terminal to store charge is small.

If a well-rounded object is brought within an inch or so of the high-voltage terminal, a spark will jump. In this type of discharge the air is rapidly changed from a good insulator to a conductor and the spark completely discharges the terminal. Reduction of the terminal voltage permits the air to regain its insulating strength, and the terminal is recharged by the belt. If an object with sharp edges is brought near the terminal, it steadily drains charge by corona and decreases the potential. Such a device, with adjustable spacing, is often used in Van de Graaff generators to maintain a constant terminal potential.

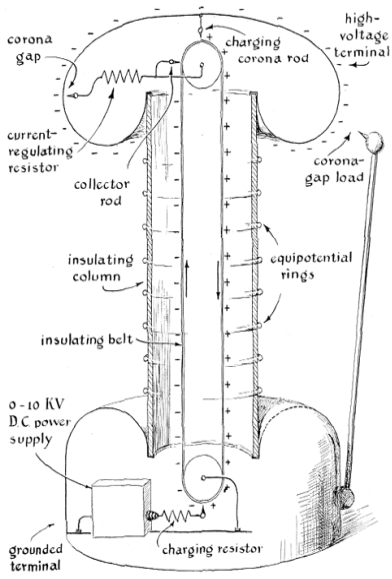


Figure 5: A high-powered Van de Graaff machine

Several manufacturers, including the South Research Laboratories, the Combosco Scientific Company and the American Electrostatic Company, now market small air-insulated machines, similar to the one described, for demonstration purposes at prices from $25 to $100.

A continuous source of high direct current voltage invites endless experiments. One of the most amusing is the "jumping ball" demonstration. A half dozen small balls made of pith or other light material are given a conducting surface of soot or graphite. They are placed in a cage, which may be made of a strip of transparent plastic rolled into a cylinder and capped with tops from peanut-butter jars. The caps are connected with the terminals of the Van de Graaff. As the machine goes into operation, the electrostatic field from the upper cap attracts the balls. They hop up to it, deliver their load of electrons, fall back and repeat the cycle as long as power is supplied.

Support a sewing needle by an insulator and connect it to the machine's upper terminal. Molecules of ionized air will rush from the point as though they were streaming from a jet under pressure. They easily blow out a match or candle. This electric wind can be made to drive a simple

motor. Cut a swastika, with sharply pointed tips, from aluminum foil and indent its center with the pointed end of a pencil. Pivot the indentation on the point of a pin which has been thrust up through a supporting base of cardboard. The swastika will then be free to rotate on the pin point. It will do so vigorously if the pin is connected with the high-voltage terminal of the Van de Graaff. Ionized air streaming from the four points sets up the reactive force of a jet engine.

The power capacity of the Van de Graaff is enough to charge a person to about 50,000 volts. This is 20,000 volts above the ionizing point of air at atmospheric pressure. It is also enough to make the experimenter's hair stand on end. To demonstrate this effect, stand in or on a large glass bowl or a wooden platform supported by four square milk bottles. Touch the high-voltage terminal. After a few seconds your hair will slowly rise. Incidentally, the body adds capacity to the terminal, and so a somewhat larger charge than normal accumulates. When you step down or touch a grounded object, you will experience a slightly painful shock-but it is not dangerous to a person in normal health.

Fluorescent lamps will light up brilliantly where they are touched to the high-voltage terminal. If the room is not too brightly lighted, filament-type lamps also will glow in various colors depending on the kind of gas they contain. You can even manufacture a miniature aurora borealis by boiling water in a thin flask until the air is displaced by steam and then stoppering it immediately. After the steam has condensed, the rarefied air inside will glow greenish and pink when the flask is brought in contact with the Van de Graaff.

Those who can blow glass and exhaust it-or who can induce a local manufacturer of advertising signs of the glowtube type to do so for them-may want to try their hand at assembling and operating a linear accelerator and related apparatus used for nuclear research. Such projects are on a par with amateur-built cyclotrons and, like marriage, are not to be entered upon lightly. They are, nevertheless, well within reach of amateur resources, particularly for groups.

To power such an apparatus you will require a larger version of the Van de Graaff [*Figure 5*]. It differs from the low-power design in a number of subtle, though important, particulars. The spray points for charging the upward run of the belt are supplied by a potential of 5,000 to 10,000 volts from a transformer-rectifier combination. The high-power machines employ metal pulleys at both ends of the belt, the upper one being insulated from the high-voltage terminal.

Charge is sprayed onto the belt as it passes through the corona between the lower points and the grounded driving pulley. A similar set of points, located just inside the upper terminal, removes charge from the upward

belt run and conducts it to the upper pulley. After a short period of operation the upper pulley acquires a high charge and current flows to the upper terminal through a current-regulating resistor. This circuit may also include a corona gap near the inner surface of the terminal. A second set of spray points (charging rod), connected directly to the high-voltage terminal, is situated at the top of the pulley. The difference in potential between the upper pulley (made "live" by the voltage drop across the current regulating resistor and corona gap) and the high-voltage terminal causes these points to spray a charge of opposite sign onto the downward run of the belt. The value of the current-regulating resistor is chosen so that both sides of the belt work equally. The value of the current-regulating resistor can be computed roughly by Ohm's law. Belts for high-power machines are usually made of rubberized fabric and run at speeds of 4,000 to 6,000 feet per minute.

The capacity of the upper terminal to store charge varies with its size. Its ability to hold charge varies with shape. The ideal terminal would be spherical. Unfortunately this ideal cannot be realized because provision must be made for the entry of the belt. The shape must be such that the intensity of the field at the high-voltage terminal is always less than the value at which spark or corona discharge occurs. Hence the aperture of the terminal must have re-entrant edges and the facing sides of the upper and lower terminals should be identical. Such terminals are commonly made of aluminum spinnings.

Large Van de Graaffs in the million-volt range, intended for scientific and industrial purposes, are now nearly all mounted within a steel tank containing Freon, carbon dioxide or a similar gas at many atmospheres of pressure. The high pressure serves to increase the voltage-insulating ability of the gas many-fold and thus increases both the voltage and current capacity of the machine. Such machines are marketed by the High Voltage Engineering Corporation

When Van de Graaff machines are designed for potentials above 200,000 volts, the distribution of charge along the insulating column (and even along the belt runs) becomes important. The columns of air-insulated machines using belts more than four inches wide should be fitted with equipotential rings spaced along the insulating column at intervals of about two inches.

Anyone undertaking the construction of a high-power Van de Graaff should remember that he is building no toy. These potentially lethal machines can reveal "marvelous wonders" beyond von Guericke's most inspired imagining, but, unlike his sulfur ball, they pack the wallop of lightning!

Bibliography

ELECTROSTATIC SOURCES OF ELECTRIC POWER. John G. Trump in Electrical Engineering, Vol. 66, No. 6, pages 525-534; June, 1947.

ELECTROSTATIC SOURCES OF IONIZING ENERGY. J. G. Trump in Transactions of the American Institute of Electrical Engineers, Vol. 70, Part 1, pages 1021-1027; 1951.

Suppliers and Organizations

Fry's Electronics retails over 30,000 electronic items within each store. Fry's has been keeping hi-tech professionals supplied with products representing the latest technology trends and advances in the personal computer marketplace for 15 years. Fry's has become the place where a technical customer can shop with confidence and comfort.

The **Society for Amateur Scientists** (SAS) is a nonprofit research and educational organization dedicated to helping people enrich their lives by following their passion to take part in scientific adventures of all kinds.

The Society for Amateur Scientists
5600 Post Road, #114-341
East Greenwich, RI 02818
Phone: 1-877-527-0382 voice/fax

Internet: http://www.sas.org/