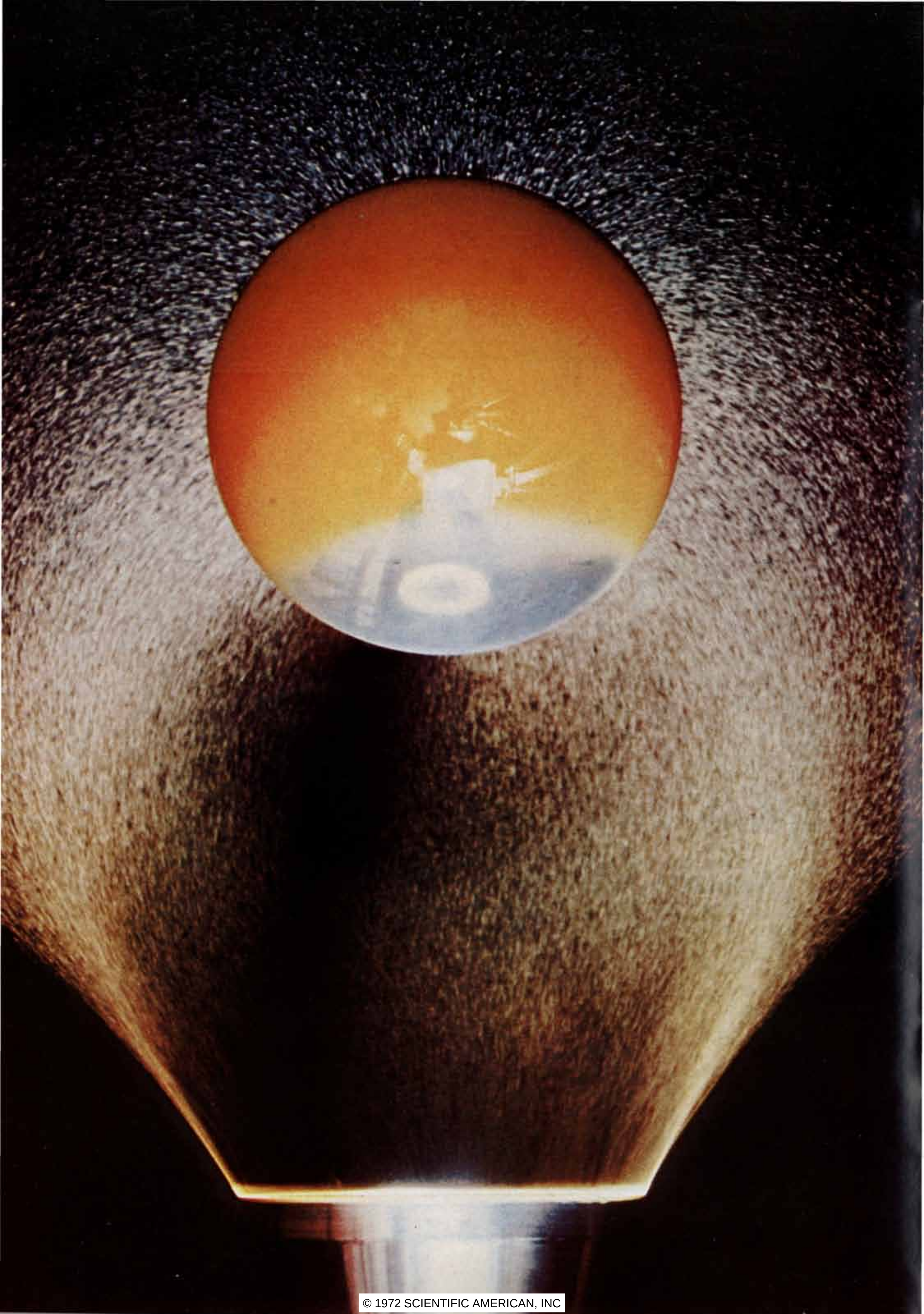


ELECTROSTATICS

The field around a charged body is used to manipulate particles of matter. Among the modern applications of electrostatics are fly-ash precipitators, paint sprayers and Xerox copying machines

by A. D. Moore

Anyone who has ever walked across a rug in a dry room and received a shock from a metal doorknob has had a firsthand experience of an electrostatic effect. On a grander scale, thunder and lightning are examples of electrostatic effects that are familiar to all. Yet it is a curious fact that many manifestations of natural electrostatic processes remain almost completely unknown.

For instance, although most children know from playing with toy compasses that they live within the earth's magnetic field, very few adults realize that we spend much of our lives in a natural electric field as well. The atmosphere of the earth is somehow supplied with a positive charge that sets up a downward electric field amounting to between 100 and 500 volts per meter on a clear day. In an open area at the higher value there would be 1,000 volts between the ground and a point two meters up. If a two-meter man were standing there, would he have 1,000 volts acting on him from head to foot? If so, he would soon be dead. Actually there is no voltage on him. He is a grounded conductor, his skin is an equipotential surface that warps the electric field of the atmosphere and he is totally unaware of the field that surrounds him.

Of course if our two-meter man is a golfer finishing a game under a low thundercloud, the situation can change drastically. The base of such a cloud is usually negatively charged, and the electric field, now reversed, can rise to 10,000 volts per meter. This is still too low to warn the man by making his hair stand up. When he raises his steel-shafted club for the next stroke, however, a different kind of stroke unleashes an electric current measured in the tens of thousands of amperes.

The branch of human curiosity that deals with such matters is called electrostatics. In recent years this enterprise has rapidly expanded, and the scope of modern electrostatics goes far beyond the limited domain of nonmoving electric charges implied by the literal definition. Man has learned to apply his newfound understanding of electrostatic effects in diverse ways. The four main areas of application are electrostatic precipitation of particulate industrial wastes, such as fly ash, dust and fumes; electrostatic separation of mixed granular solids, principally minerals; electrostatic coating, both wet and dry, and electrostatic imaging, the best-known example of which is the xerographic process. Before taking up these and other achievements of modern electrostatic technology, I shall explain some of the general attributes and effects of electric charges and electric fields, and in particular introduce the central concept of corona discharge.

Charges and Discharges

Consider a capacitor consisting of two parallel plates, between which is inserted a long electrically conducting rod [*see upper illustration on page 49*]. The device sets up a uniform electric field except near the center, where the lines of force of the field are gathered inward and end on the rod. Any small element of electric flux ending on the rod exerts an outward pull at right angles to the rod's surface. The pulls on opposite sides of the rod are equal, giving a net force of zero. Positive or negative charges can be induced on the rod because electrons are free to move both within the rod and along its surface.

If the conducting rod is now removed and a dielectric, or insulating, rod is substituted for it, this freedom no longer prevails. Now the field is gathered in toward the rod and passes right through it. Even so, the forces are much the same as before, and again there is no net force acting on the rod.

Next consider a pair of concentric electrodes forming what might be regarded as a kind of coaxial capacitor [*see illustration at lower left on page 49*]. When a voltage is applied to this device, it sets up a radial electric field. When a long conducting rod is inserted in such a nonuniform field, the rod again warps the field, and as a result forces

ELECTROSTATIC PAINT SPRAYER shown in operation on the opposite page was photographed in the test laboratory of the Ransburg Electro-Coating Corporation. The atomizer (*bottom*) consists of a bell-shaped member charged to 90,000 volts and spinning at a rate of 900 revolutions per minute; paint is fed into the four-inch-diameter bell at its center, flows out centrifugally to the edge as a film and is there subjected to the high electric field. The paint film at the edge is electrically shaped into a series of spaced liquid streamers (*see illustration on page 53*). Highly charged paint droplets are repelled from the tips of the streamers and follow the lines of force of the electric field to the grounded target (*top*), in this case a steel sphere. Paint that would otherwise miss the target and be wasted is thus made to curl around and coat the sides and rear of the object. The paint droplets were illuminated for this photograph by means of two high-speed stroboscopic lamps, one mounted next to the camera and the other mounted behind the steel sphere. The bright spot near the bottom of the sphere is the reflection of the mouth of the atomizer. Other images appearing on the target are the reflections of various pieces of photographic equipment.

act on opposite sides of the rod. A new effect comes in here. If two small elements of electric flux ending on the rod have the same flux but different areas, the smaller element will exert the greater pull. Thus the forces exerted by, say, larger outer flux elements ending on positive charges will not be equal to the forces exerted by smaller inner elements ending on negative charges. As a consequence there will be a net radial force acting inward on the conducting rod. Much the same effect holds for a dielectric rod. In other words, both types of object would tend to move inward toward the more intense field.

It might appear that the device just described amounts to an electrostatic precipitator: particles moving through the electric field could simply be forced to move to the inner electrode, where they could be collected. Actually the forces involved in such a simple arrangement are far too weak to be useful for industrial precipitation. The achievement of Frederick G. Cottrell in inventing the first effective electrostatic precipitator in 1905 was finding a way to exert forces large enough to make particles in such a nonuniform field configuration move outward, to be collected on the outer electrode. To do this Cottrell had to exploit the then little-known phenomenon of corona discharge.

Suppose the central electrode is now a thin wire in a duct 20 centimeters in diameter [*see illustration at lower right on opposite page*]. If one applies a negative potential of 100,000 volts to such a wire, the voltage acts over the radial distance of 10 centimeters, yielding an average field strength of 10,000 volts per centimeter. Since the threshold at which air breaks down is about 30,000 volts per centimeter, it might seem that no electrical breakdown of the air would occur. The calculated value of 10,000 volts per centimeter, however, is only an average value, and such averages can be misleading. In this particular nonuniform configuration the field strength is much less than 30,000 volts per centimeter out near the duct wall, whereas it is much more than 30,000 volts per centimeter in the intense-field region near the wire.

The result is a corona discharge, a zone of ionization that manifests its presence in air by a greenish glow around the wire. The placid, inactive field of the earlier examples is replaced by an intensely active field. Billions of molecular ions are produced within the zone of the discharge and move outward. The visible glow comes from photons emitted by excited atoms. The wire is now called the active electrode, whereas the duct becomes the passive electrode.

The physical intricacies of the corona cannot be covered fully here. Suffice it to say that when the active electrode is negative, electrons come whizzing off its surface. Most of the electrons promptly attach themselves to oxygen molecules in the air, making the molecules negative ions. At this point the Coulomb effect takes over: the effect by which the force exerted by the field on a small charged object is proportional to its charge times the strength of the field. As a result the ions move outward toward the walls of the duct, constituting a veritable ionic current.

The operation of an actual industrial precipitator can now be easily understood. The duct carries the flue gas, or other gas, loaded with waste particles. The ions charge the particles. If the velocity of the gas is of the order of 10 feet per second or less, the particles will move across the gas stream by the billions and will collect on the walls of the duct. If the waste particles are solid (as they are in the case of fly ash), the duct is rapped periodically to shake the residue down into a hopper. If the particles are liquid (as they are in most fumes), the residue runs down the duct walls. Industrial precipitators are designed for a negative corona, because higher voltages can then be used without too much sparking. Electrostatic home air cleaners, on the other hand, operate on a positive corona.

The contribution of Cottrell's invention to antipollution efforts would be hard to overstate. Long before most towns and cities stopped dumping raw sewage into streams Cottrell precipitators made life livable near cement mills and ore-processing plants. The first electrostatic precipitator to remove fly ash from coal-burning power plants was installed by the Detroit Edison Company in 1923. It is estimated that at present the fly ash trapped in this country alone —at better than 99 percent efficiency— amounts to some 20 million tons per year.

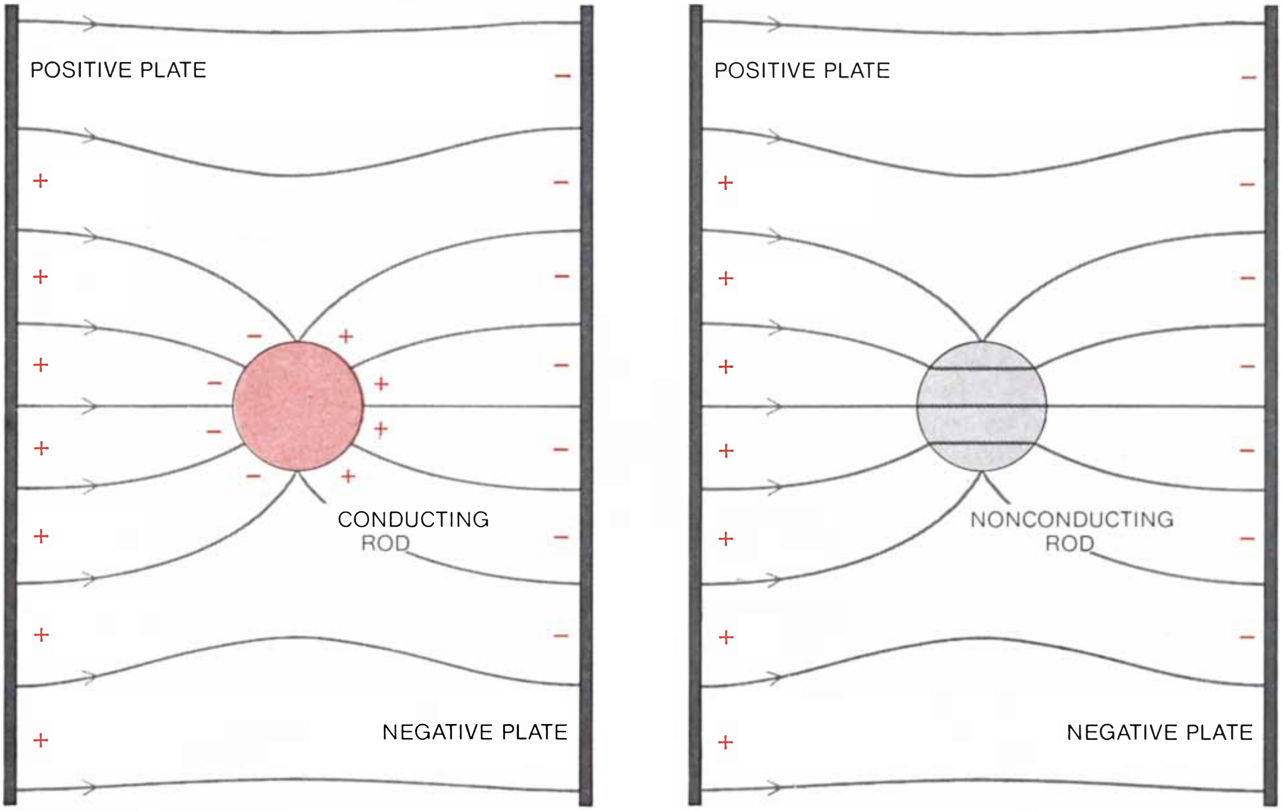
Further Uses of Corona

The principle of corona discharge is the key to many other important applications of electrostatics. For example, in the separation of granular mixtures by one electrostatic approach the two kinds of particle to be separated differ from each other in their conductivity, one kind being a conductor and the other an insulator. In a typical separator [*see top illustration on page 56*] the mixture comes down from a hopper to form a thin layer on top of a rotating steel drum. The drum, which is grounded, passes under a wire that is generating a corona discharge. As a result ions flood to the drum. The charges of those ions that hit conducting particles are passed directly to the drum and accordingly the particles fall right off the drum. The charges of ions that hit insulating particles, in contrast, coat the outer surfaces of the particles and "pin" them to the drum, from which they later fall or are scraped. In addition to this common type of electrostatic separator, which is used mainly in the mineral industry, a number of quite different designs exist.

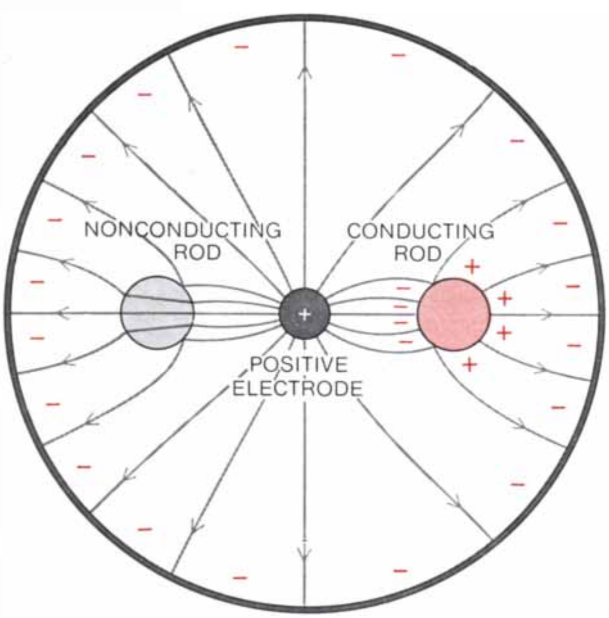
The world's largest electrostatic-separation plant for the beneficiation of iron ores, installed in 1965 at the Wabush Mines in Canada, handles six million tons per year. It has been estimated that some 35 other mineral mixtures are currently being separated electrostatically. Moreover, the electrostatic approach has been adopted for a number of other separation tasks, including the removal of rodent excreta from rice, the extraction of garlic seeds from wheat and the separation of nut meats from shells.

The electrostatic stratagem for pinning insulating particles to a drum in the preceding example can also serve to pin an insulating web to a roller. (In several industries a continuous moving sheet of paper or film is termed a web.) Normally tension is applied to such a web by pairs of rollers at each end. If one side of the web is coated with some sticky substance such as ink or adhesive, however, the two-roller system clearly will not work. Instead the web can be pinned to a single roller electrostatically. A corona bar is installed to supply ions to charge the outer surface of the web. A noteworthy application of this technique is the manufacture of thin films such as Mylar, which in the final operation are stretched to give them high strength. Various other kinds of web are also handled by electrostatic pinning.

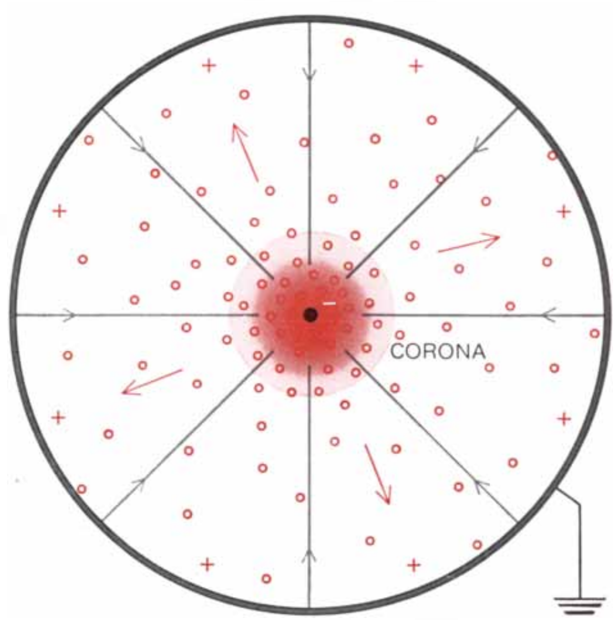
A little-known but important industrial process in which electrostatics, and specifically corona discharge, plays a central role is electrocoating, a process that is currently being harnessed on a large scale to apply various coatings, including wet paint, grit particles, dry powders and even short fibers. In a typical arrangement a spray gun with a corona point emits a fine mist of paint particles; the particles gather the field lines to themselves and attract the ions from the corona, thereby acquiring a charge. The force tending to pull the particles back to the more intense field



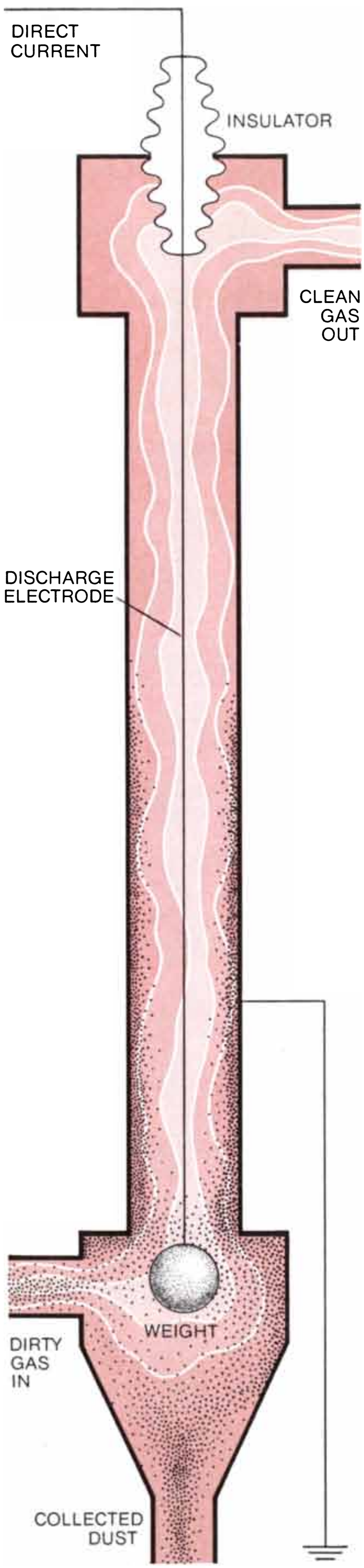
PARALLEL-PLATE CAPACITOR normally sets up a parallel electric field, which becomes warped near the center when a long rod of either a conducting material (*left*) or a nonconducting material (*right*) is inserted between the plates. In the case of the conducting rod the lines of force of the field (*gray arrows*) are gathered inward and end on the rod; positive and negative charges (*colored signs*) can be induced on the rod because electrons are free to move both within the rod and along its surface. In the case of the nonconducting rod the field is gathered inward and passes right through the rod; no charges are induced on the rod. In both cases the outward pulls exerted by the electric flux on opposite sides of the rod are equal, yielding a net force of zero on the rod.



RADIAL ELECTRIC FIELD is set up when a voltage is applied to two concentric electrodes. When a conducting rod and a nonconducting rod are inserted in such a device, they warp the field as shown. If two small elements of electric flux ending on either rod have the same flux but different areas, the smaller element will exert the larger pull; hence there will be a net radial force on each rod tending to move it inward toward the more intense field.



CORONA DISCHARGE (*colored area*) develops when the inner electrode of the preceding example becomes a thin wire and enough voltage is applied to ionize the air molecules in its vicinity. With the inner, or active, electrode negative electrons from the surface of the wire attach to oxygen molecules in the air, making the molecules negative ions (*open circles*). The ions are pushed outward by the Coulomb force to the outer, or passive, electrode.



is still there, but it is overcome by the far larger Coulomb force driving the particles out more or less along the lines of force of the field toward the grounded target. Paint that would otherwise miss a target and be wasted can thus be made to curl around and coat the sides and rear of the object [*see illustrations on page 52*].

For many purposes a spinning disk or bell serves as the sprayer; the paint is fed in at the center, streams out centrifugally to the edge and is thrown off. On leaving the sprayer the paint forms streamers with a remarkably uniform spacing [*see illustration on page 53*]. The streamers break up into droplets that become charged and hence seek the target. In an automatic operation designed for long runs the targets can be carried past the spray gun by means of a conveyor system; for large objects several spray guns can be used in tandem, and they can be mounted to move up and down.

It has been estimated that the savings in paint alone attributable to the electrocoating approach amounts to some $50 million per year. In addition there is a growing interest in electrocoating as a technique for spraying insecticides on plants in such a way that the undersides of the leaves are also coated. Environmental pollution is thereby reduced, and smaller amounts of insecticide are made to do a better job.

A variation of the electrocoating approach called flocking can be used to give a surface such as a wall a velvet finish. If the wall is nonconducting, it is first covered with aluminum paint, to which an adhesive is applied. The operator holds a hopper filled with short fibers. As the fibers are shaken out of the hopper they are charged by ions from a set of corona points mounted on the hopper. At this stage three important effects take over. First, the fibers are impelled along the field lines by the Coulomb force. Second, the mutual repulsion of like charges keeps them apart. Third, they align themselves with the field, arriving end on to stick to the adhesive. In this way more than 200,000 fibers per square inch can be applied. The process can also be used to put pile on carpeting, to make artificial suede and to cover the interior of instrument cases. By printing the adhesive in patterns on cloth one can create decorative designs.

ELECTROSTATIC PRECIPITATOR is based on the principle of corona discharge. In this simplified diagram a single grounded duct (the passive electrode) carries the flue gas, loaded with solid waste particles. Ions produced around the weighted central wire (the active electrode) charge the waste particles, which move across the gas stream and collect on the walls of the duct. The duct is rapped periodically to shake the residue into a hopper. An actual industrial precipitator consists of a large assembly of units.

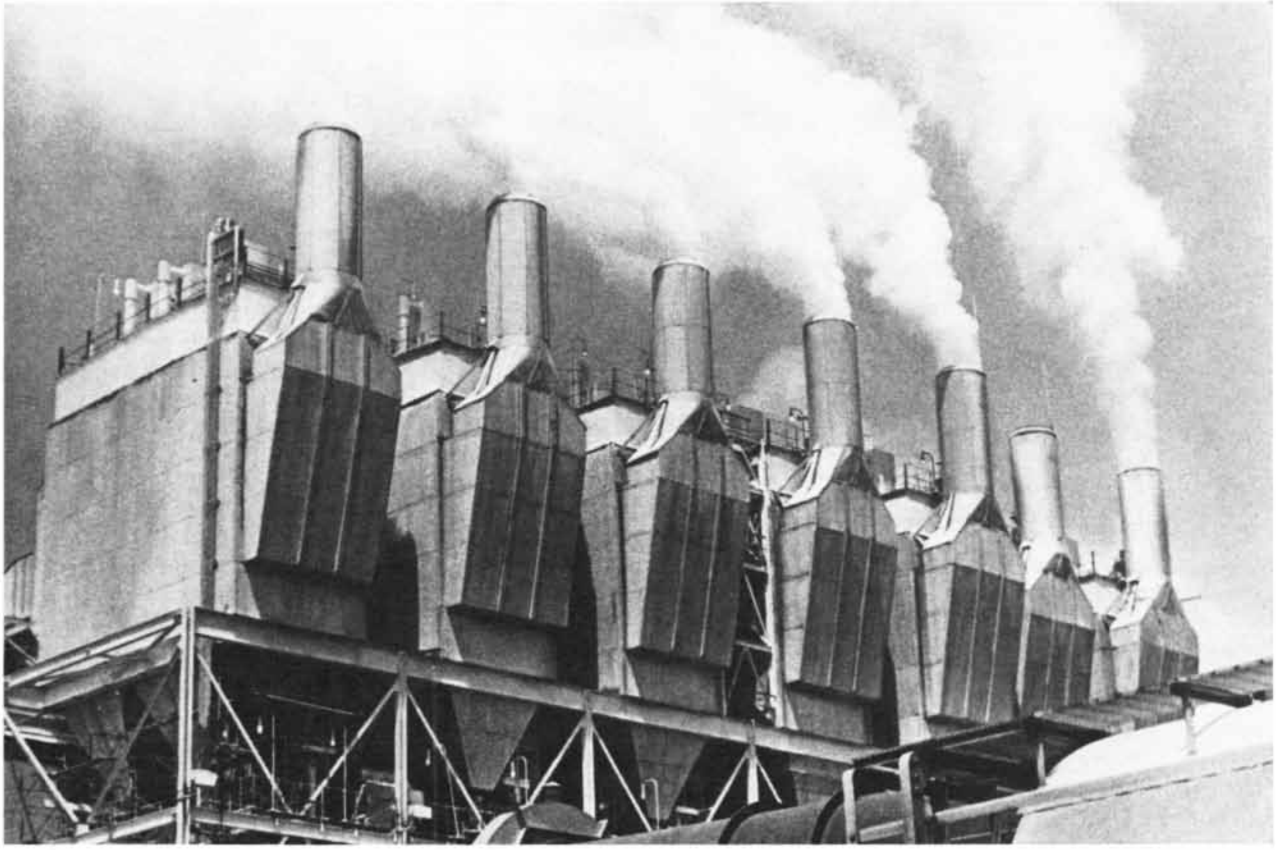
Somewhat the same process is used to make coated abrasives, a business amounting to some $200 million per year. Superior sandpapers and coated cloth abrasives are turned out electrostatically on huge machines. For a "filled" abrasive the operation continues until all the spaces are filled. For "open" coatings the rate of feed is lowered, and the electrostatic-spacing effect makes for a uniform rather than a patchy coating.

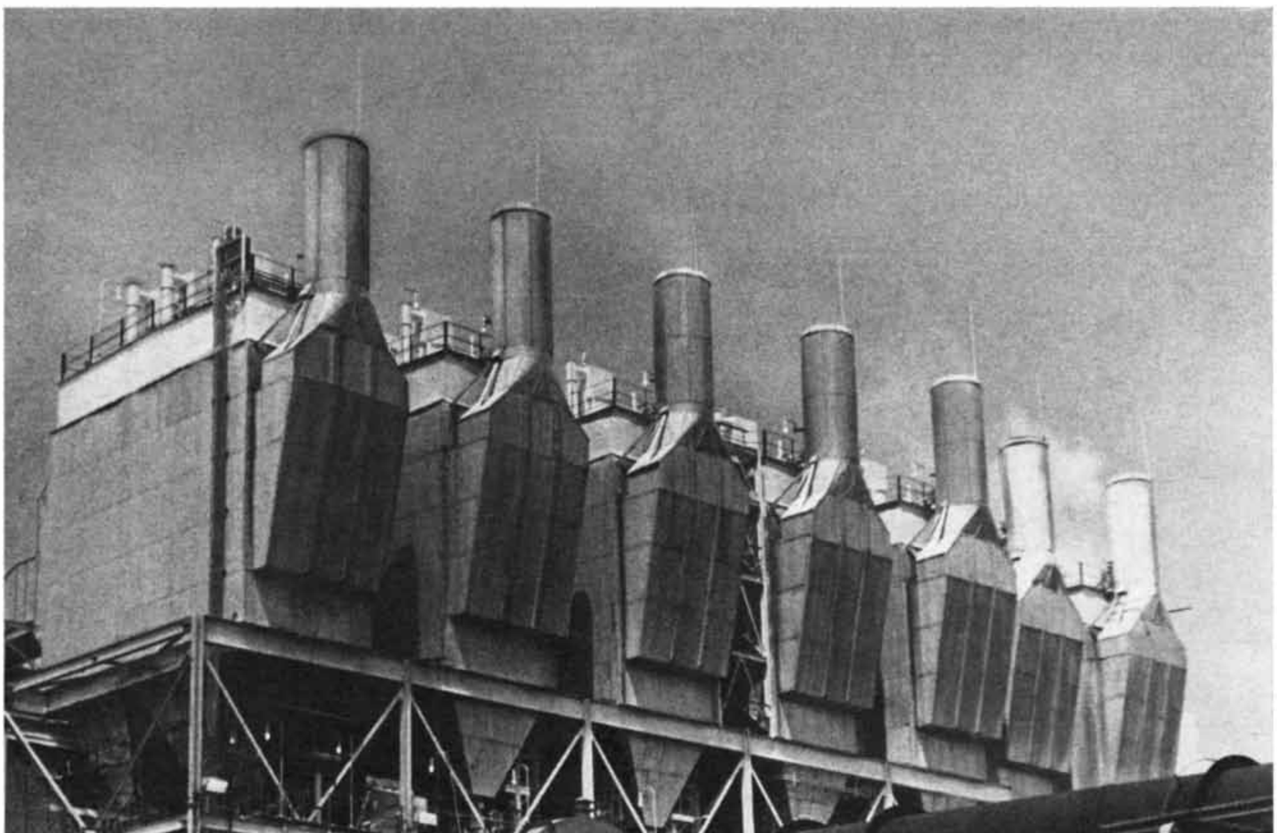
Xerography

Perhaps the best-known application of modern electrostatics is the dry-copy imaging process known as xerography. This is not to say that many people know how a Xerox machine works, even though they are expert at operating it. The xerographic process, invented by Chester Carlson in the mid-1930's, depends on the photoelectric property of certain materials such as zinc oxide or selenium. In a typical Xerox dry-copying machine [*see illustration on page 55*] a rotating selenium-coated drum is charged in the dark by a corona bar. Next an optical system focuses an image of the page to be copied onto the drum. The light removes all the charge except where the images of the black areas appear. These images are then made to attract a black dust called the toner. Farther along the paper, which is precharged, is fed in, makes contact with the drum and attracts the toner from the drum to itself. The paper then moves through a rapid-heating stage that fuses the toner to itself to make a permanent copy. Meanwhile the drum passes a brush that removes the remaining dust and is exposed to light once again to remove the remaining charge. The drum is then recharged by the corona bar and is ready to make the next copy.

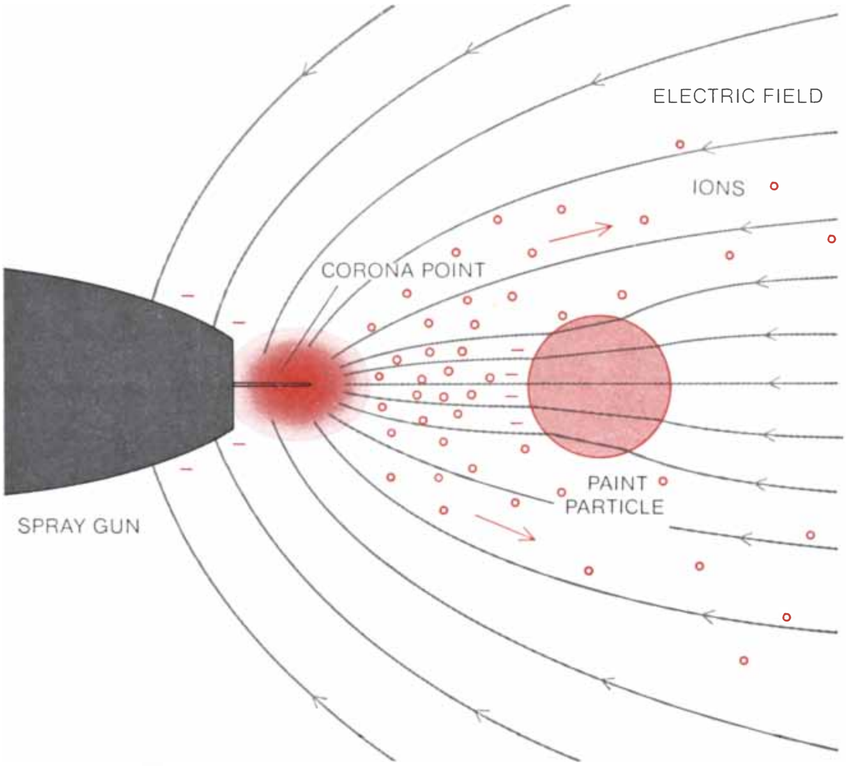
In early models of Xerox copiers a problem was encountered in trying to apply the toner evenly. This was solved by mixing the toner with a "carrier" consisting of tiny glass spheres. The spheres and the dust stick together, being oppositely charged by contact electrification. When the drum comes to the toner-application stage, the toner is attracted and the carrier is repelled.

If all of this sounds simple, take a look inside a large Xerox machine and see the

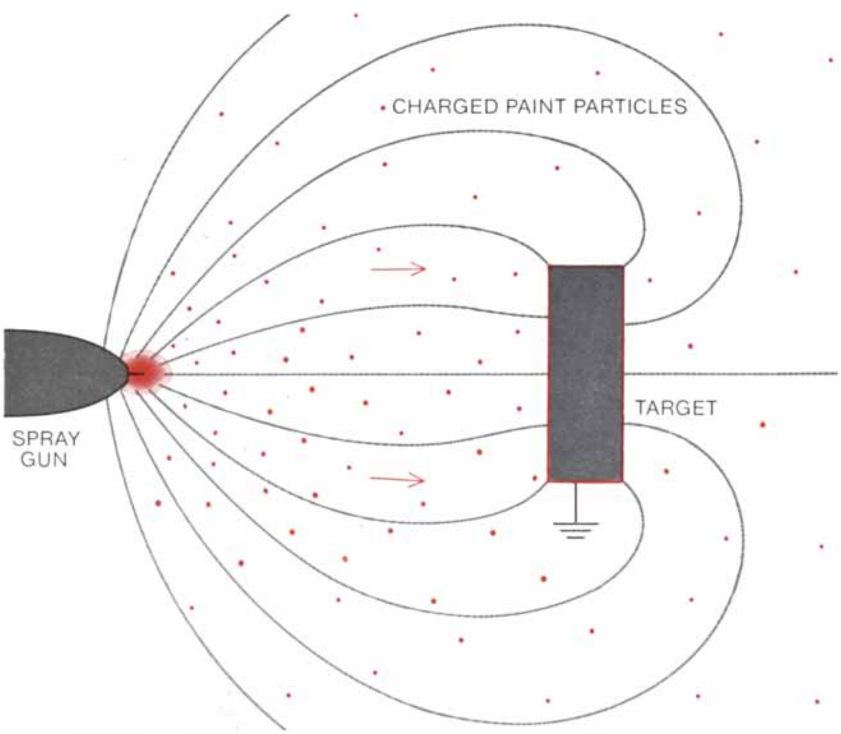




EFFECTIVENESS OF ELECTROSTATIC PRECIPITATOR in preventing air pollution is dramatically demonstrated by this pair of photographs, which show a battery of electrostatic precipitators that were momentarily turned off (*top*) and then on again (*bottom*) during the normal operation of large alumina-processing plant. The system was designed and built by Research-Cottrell, Inc.



PAINT PARTICLE leaving an electrostatic spray gun is shown greatly enlarged in this schematic diagram. The negative corona point on the spray gun emits electrons (*not shown*), which attach themselves to the air molecules in the vicinity of the corona, producing a flood of negative ions (*open colored circles*) that stream outward more or less along the lines of force of the electric field. The paint particle gathers the lines of force to itself, thereby attracting the ions and hence acquiring a negative charge of its own.



CHARGED PAINT PARTICLES (*solid colored dots*) are shown more to scale in this diagram. The paint particles, impelled toward the grounded target by the Coulomb force, tend to follow the electric-field lines, curling around to coat the sides and back of the target.

complex arrangement of automatic-control devices required to achieve the final copy. Various aspects of the xerographic process are even now being intensively developed. For example, it seems only a matter of time before we have full-color electrostatic reproduction of high quality. The social and economic impact of the success of the electrostatic dry-copying process can be roughly gauged from the fact that the worldwide business of the Xerox Corporation reached a new high last year of almost $2 billion.

In all four of the major applications involving corona discharge taken up so far, no mention has been made of space charges. As a matter of fact space charges, in the form of ions and other charged particles, can radically alter the electric field. As a result any attempt to make an accurate mathematical analysis of an electrostatic process is forbiddingly complicated. Fortunately persistent inventors, experimenters and other assorted tinkerers have rushed in where theoreticians have feared to tread, and as a result many marvelously workable devices have been achieved.

Some Noncoronal Applications

Up to this point I have described only those electrostatic techniques employed for moving particles in gases. Particles can also be moved electrostatically in liquids without a corona. To cite the simplest example first, in electrophoresis charged particles are moved through a liquid to an electrode of opposite charge.

Dielectrophoresis is a more complex process whereby uncharged particles in a liquid are moved to the more intense part of a nonuniform electric field [*see bottom illustration on page 56*]. The field shifts the electron cloud surrounding a neutral molecule slightly to one side, in effect shifting the positive nuclei the other way. Such a shift of charge takes place in any field, even a uniform one. In a nonuniform field, however, the force on the inner charged side is slightly stronger than the force on the outer charged side. As a result there is a very weak net force in the direction of the more intense field.

The phenomenon of dielectrophoresis has long been known, but it has been rather neglected because the effect was so small. Nonetheless, according to Herbert A. Pohl of Oklahoma State University, one of the pioneers in opening up this area to further investigation, "nonuniform electrical fields produce unique and frequently mystifying effects on matter—even neutral matter. With nonuniform fields one can pump liquids or powders, clean up suspensions, classify organisms and even separate live from dead cells. And this just starts the list. Its applications in biophysics and cell physiology to studies of normal and abnormal cells are at an early but exciting stage. In colloid science the new technique is helping to resolve surface properties. At the molecular level, nonuniform effects are seeing renewed use in determinations of molecular polarizabilities, in maser operations and in laser control."

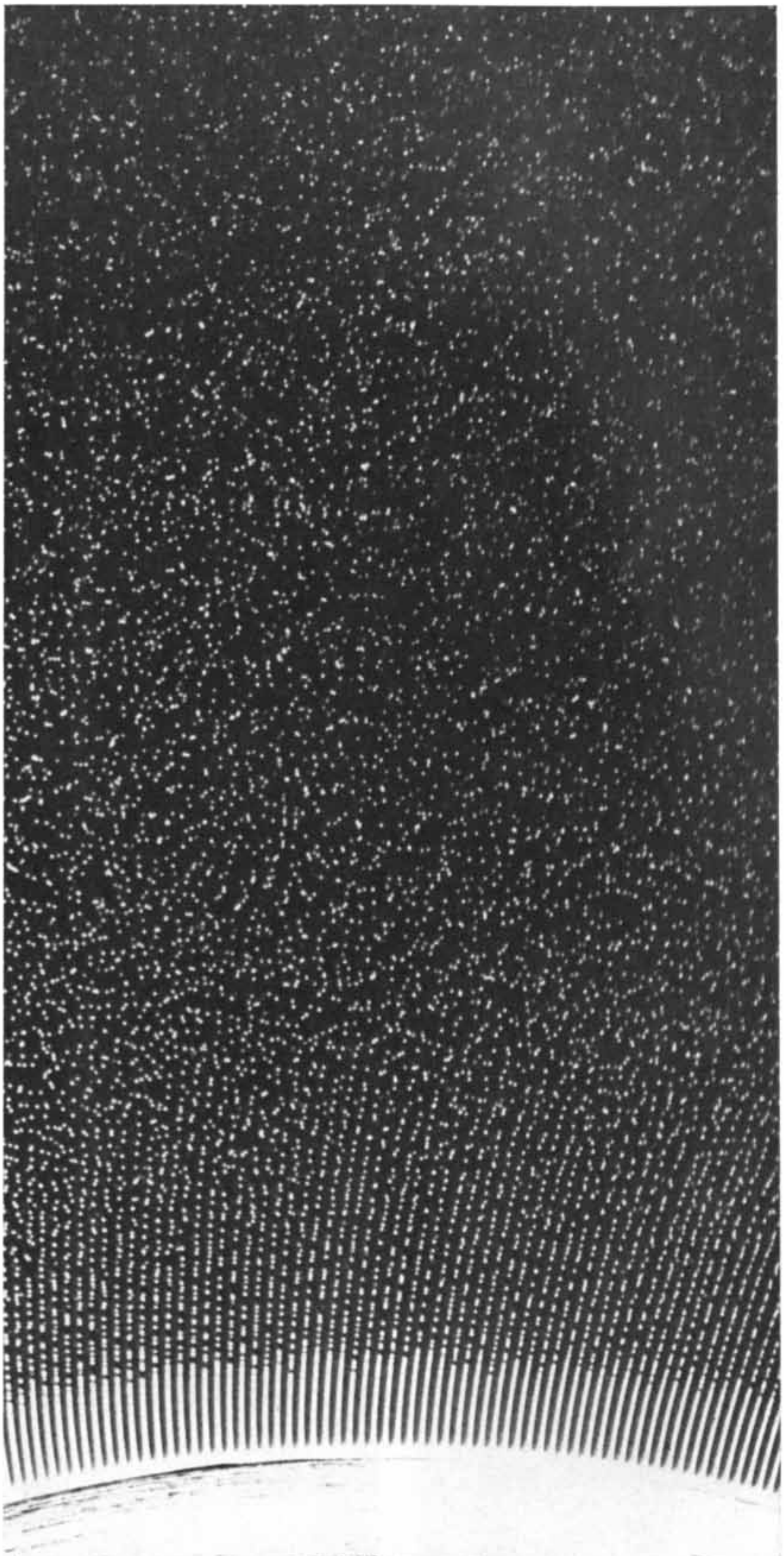
In passing it should be mentioned that whereas the electrostatic manipulation of charged particles in air requires a constant, or at least a unidirectional, field, dielectrophoresis can operate with either a direct-current or an alternating-current field. With alternating current the molecular polarization simply reverses with the field, up to high frequencies.

Contact Electrification

If this article had traced a historical development, it would have started with frictional electricity. Such electricity was supposedly known to the ancient Greeks, particularly Thales of Miletus, who observed about 600 B.C. that when amber was rubbed, it would attract small bits of matter. The term "frictional electricity" gave way to "triboelectricity," although since "tribo" means "to rub," the newer term does little to change the concept. Then it was discovered that charge transfer can be achieved without rubbing--that mere contact between unlike surfaces would do the job. The prevailing view today is that rubbing merely enhances the effect by bringing more tiny areas together.

When two metals are placed in contact, electrons pass from one to the other because of the difference in the metals' quantum-mechanical work functions. This process continues until an equilibrium is reached. With the metals still in contact there can be a potential difference between them of anywhere from a tiny fraction of a volt to several volts. When the metals are separated, they have opposite but equal charges. If one member of the pair is an insulator, with its comparatively fixed electrons, the situation is much less clear, and it is even less so when both members are insulators. In both cases continuing investigation is gradually yielding clarification.

Contact electrification is a subject of considerable importance, since it accounts for many of the nuisances and hazards of electrostatics. Industry is



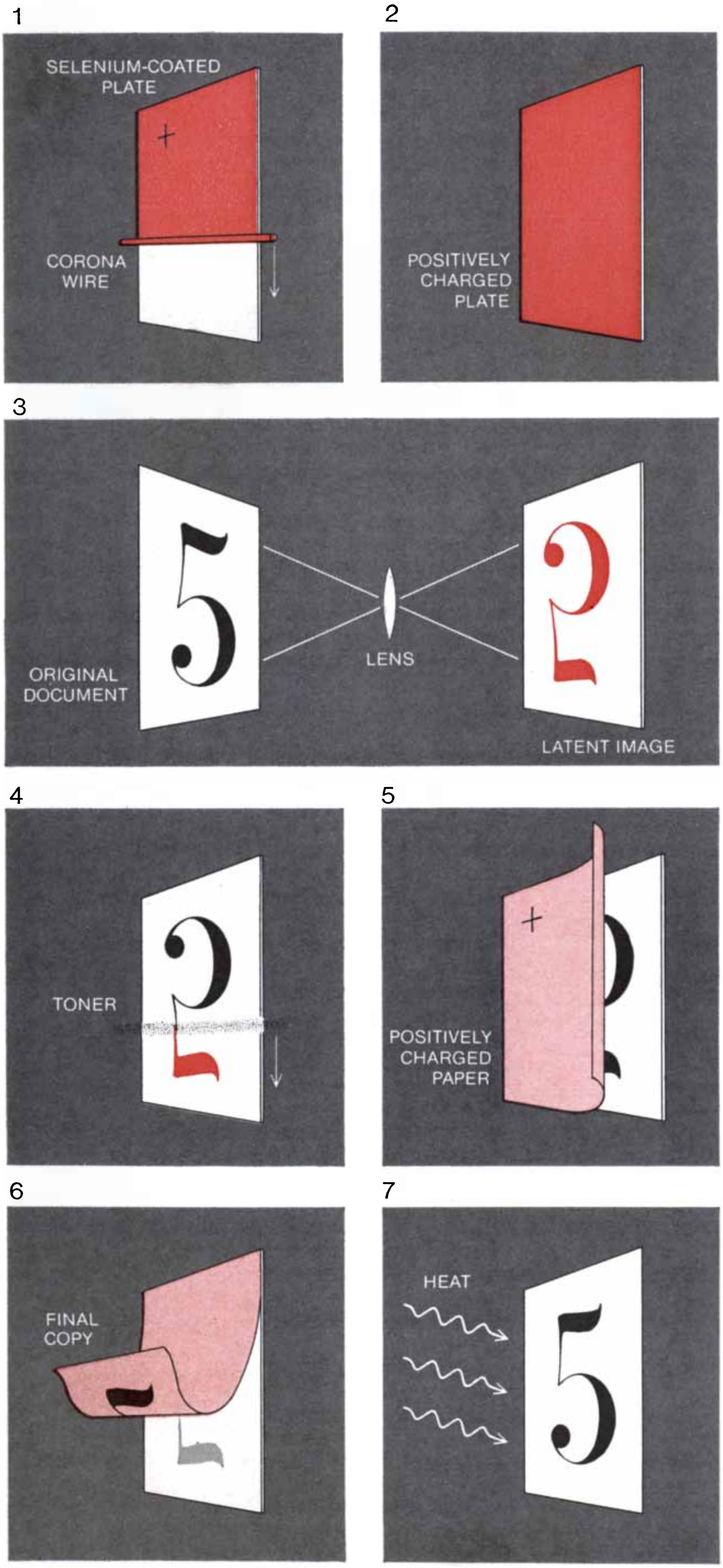
PAINT STREAMERS leaving the edge of a bell-type electrostatic atomizer exhibit a remarkably uniform spacing. Each streamer becomes the source of a string of droplets, which are highly charged and hence seek the target. The spark flash used for this shot lasted only a third of a microsecond. Photograph was supplied by the Ransburg Electro-Coating Corp.

forever building electrostatic generators without intending to do so. It is impossible, for example, to move sugar, flour or any similar dry powder through ducts without charging the powder. Belts running over pulleys develop high voltages, giving rise to sparks. Yarns, plastic films, paper and kindred materials moving at high speeds inevitably lead to triboelectric troubles. If a resulting spark has enough energy, inflammables are ignited and explosions are set off.

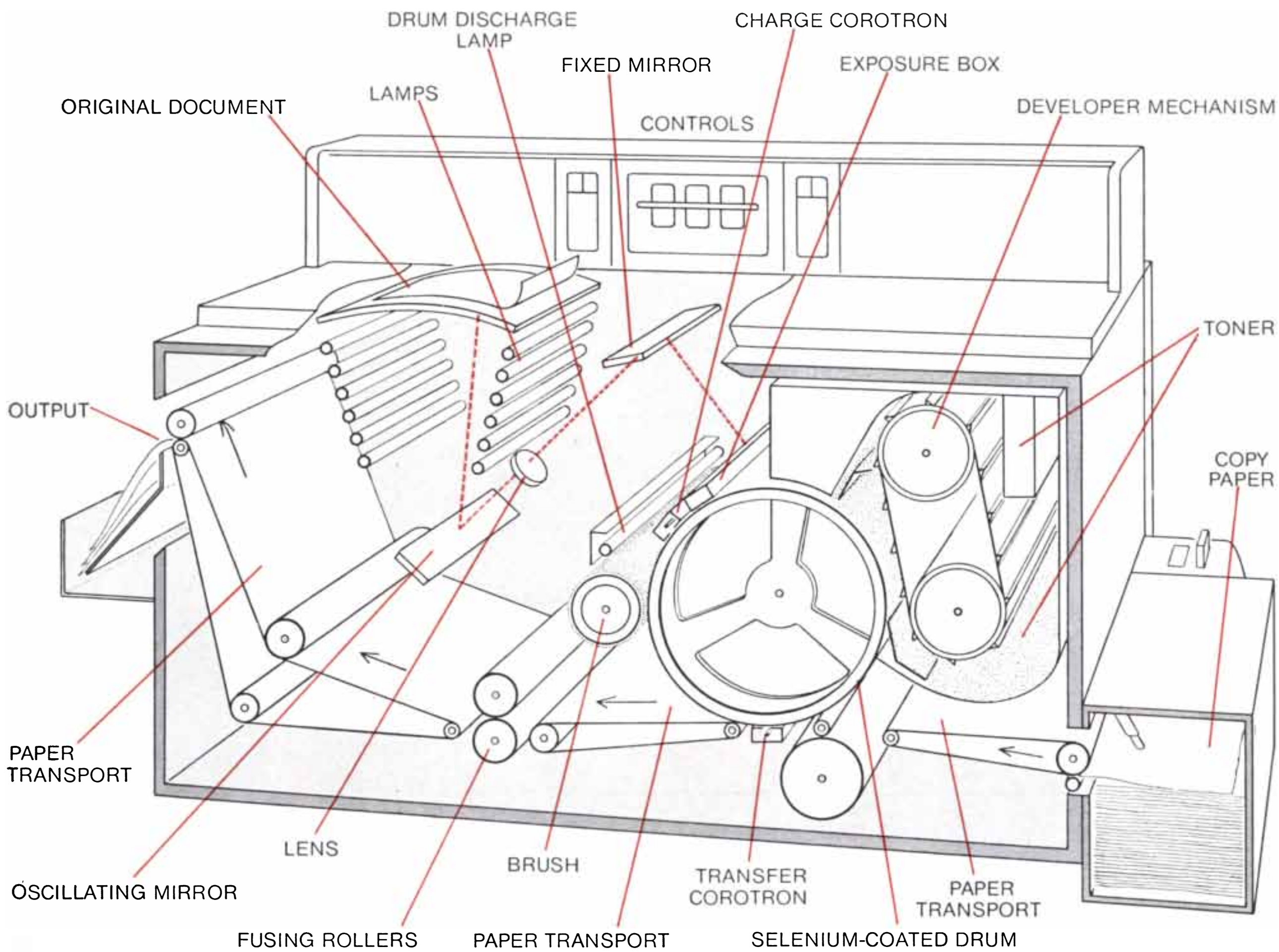
The infrequent disasters, however, are far outnumbered by the nuisance effects. Charge may accumulate to the point where an industrial process will have to shut down temporarily. Sometimes simply raising the humidity increases conductivities enough to "bleed" the excess charge away. Another means of getting rid of the charge is to place grounded "tinsel" in contact with the charged objects. Finally, the local air can be made more conductive by ionizing it with a corona discharge or a radioactive isotope.

Airplanes and helicopters can also become highly charged, either from flying through dust, sleet or snow or from encountering strong electric fields in clouds. Their communications equipment can be knocked out or their control system can be damaged by subsequent discharges. Moreover, they become a prime target for a lightning stroke. The protection of aircraft and their electrical equipment from the hazards of contact electrification is an exceedingly complex problem, of great interest in both industrial and government circles. Electrostatics is also strongly suspected in several recent disastrous explosions aboard oil tankers, and an intensive research effort is under way in this area as well.

Indoor and outdoor dusts are almost invariably charged. Dust blown in contact with almost anything will acquire a charge. Further, an uncharged particle in the air will pick up ions. Cosmic rays



XEROGRAPHIC PROCESS is illustrated in this sequence of highly simplified diagrams. First a selenium-coated plate is charged in the dark by a corona wire (*1, 2*). Next an optical system focuses an image of the page to be copied onto the plate (*3*); the light removes all the charge except where the images of the black areas appear. These latent images are made to attract a black dust called the toner (*4*). Precharged paper is then brought in contact with the plate (*5*) and attracts the toner from the plate to itself (*6*). The paper is finally exposed to a rapid-heating stage that fuses the toner to itself to make a permanent copy (*7*).



TYPICAL XEROX DRY-COPYING MACHINE (designated Model 2400) employs a rotating selenium-coated drum instead of the flat plate shown in the preceding illustration. After transferring the toner to the paper the drum passes a brush that removes the remaining toner and is exposed to light once again to remove the remaining charge. The drum is then recharged by a corona bar (called the charge Corotron) and is ready to make the next copy. This diagram shows only a few of the major components of the Model 2400 machine; actually a much more complex arrangement of automatic-control devices is required to achieve the final copy.

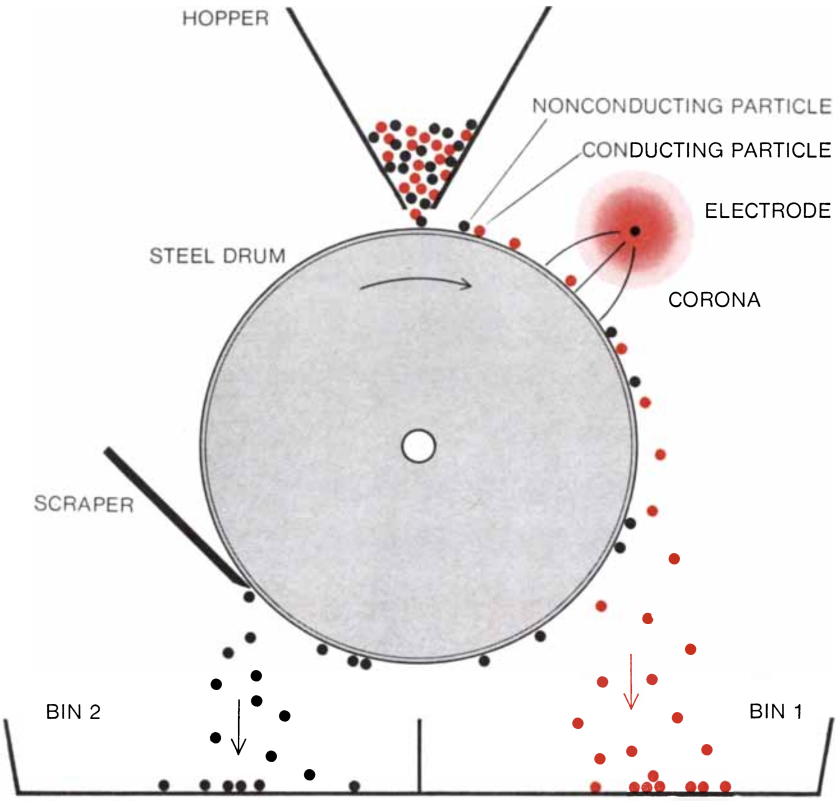
and terrestrial radioactivity constantly break up air molecules, forming an average of between 10 and 20 new pairs of ions per cubic centimeter per second. The ion pairs constantly recombine, but nonetheless clear air may contain anywhere from 100 to 500 pairs per cubic centimeter. Thus an uncharged particle in air is very likely to pick up an excess charge of one sign or the other. The same probability applies to water droplets in a cloud.

Charge transfer is not confined to contacts between solids. Many insulating liquids flowing through pipes or hoses can also become charged, leading to fires and explosions. Charges can even be separated when a liquid separates from itself! A fascinating and important instance of this phenomenon has been studied by Duncan C. Blanchard of the State University of New York at Albany. He observed that when sea waves break, large numbers of bubbles are buried. The rising bubbles, on reaching the surface, burst. At a certain stage a jet from the center of the bursting bubble goes up at a high velocity, and from the tip of the jet four or five droplets continue upward [*see illustration on page 58*]. It turns out that most of these droplets are positively charged. The droplets evaporate, leaving behind positively charged salt nuclei, which are carried farther upward by the wind and eventually become the nuclei for the formation of rain droplets. All of this amounts to a partial answer to a question raised at the beginning of this article: How does the earth's atmosphere maintain its positive charge?

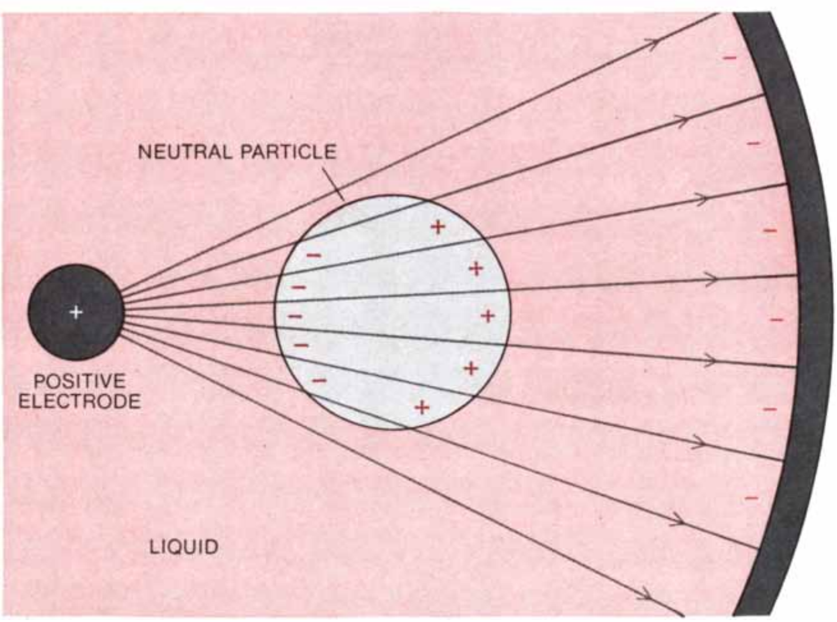
Meteorological Effects

The huge space charges represented by thunderclouds are partly drained by lightning within the clouds. As for lightning that strikes the ground, there has been a certain amount of confusion about it over the years. Even though a cloud's electric potential may be as high as 150 million volts, the field just under the cloud is usually less than 10,000 volts per meter, or 100 volts per centimeter. Since the breakdown strength of air is 30,000 volts per centimeter, how could a lightning stroke ever happen? Studies of this problem finally led to the discovery that a "leader" stroke develops inside the cloud in a stepwise fashion and comes to the ground first. Its ionized path is then followed by the main upstroke or by repeated strokes.

The negative base of such a thundercloud induces positive charges in objects on the ground. A field of 100 volts per centimeter is enough to give rise to tiny point discharges on the tips of leaves and grass. The positive ions produced in such discharges can be carried by updrafts to add positive charge to some other part of the cloud, thereby helping to main-



ELECTROSTATIC MINERAL SEPARATOR also employs a corona discharge. The mineral mixture, consisting of conducting particles (*color*) and nonconducting particles (*black*), comes down from a hopper to form a thin layer on top of a rotating, grounded steel drum. The drum passes under a corona-discharge wire that sends a flood of ions to the drum. The charges of ions that hit conducting particles are passed directly to the drum and hence these particles fall right off the drum into Bin 1. The charges of ions that hit nonconducting particles "pin" these particles to the drum, from which they later are scraped into Bin 2.



DIELECTROPHORESIS is a noncoronal application of electrostatics whereby uncharged particles in a liquid are moved in a nonuniform electric field. The field shifts the negative electron cloud surrounding the neutral molecules slightly to one side, in effect shifting the positive nuclei the other way. Since the force on the inner side is now stronger than it is on the outer side, there is a weak net force in the direction of the more intense field.

tain the net positive charge of the atmosphere.

Recently Roger V. Cheng of the State University of New York at Albany studied a mechanism whereby charges can be separated inside a cloud. When a supercooled water droplet freezes, its outside freezes first; this freezing is followed by the development of spicules, which emit large numbers of far smaller droplets. These "daughter" droplets are positively charged, whereas the "mother" droplet remains negative. If such a process really does operate on a large enough scale, along with gravity separation, very large charge separations would result.

An electric field in a cloud can have precisely opposite effects on a water drop, depending on its size. Large enough drops in a strong enough field can be pulled apart, giving birth to oppositely charged twins, whereas small enough drops lined up with the field can be drawn together to form a larger drop [*see illustration on opposite page*]. The latter process, called electrostatic coalescence, is precisely the same as the "desalting" process used to remove water and salts from crude oil before it goes to the refinery.

While on the subject of meteorological effects involving electrostatics, the last and perhaps the strangest effect of this type I should like to mention is earthquake lightning. It has long been observed, particularly in Japan, that earthquakes are sometimes accompanied by flashes of light, in the atmosphere, even when the sky is clear. During a Japanese earthquake in 1930, for example, more than 1,500 such flashes were recorded. The area in which the event took place is characterized by quartz-rich lavas. It has been suggested that given the right kind of crystalline order and the right kind of seismic waves, rock formations of this type may be capable of generating millions of volts of electrostatic energy by the piezoelectric effect. In view of this strong possibility it seems reasonable to propose that if there are quartz-rich layers anywhere in the vicinity of the San Andreas fault, stations for continuous monitoring of the electric field of the atmosphere could be set up; if field disturbances are found to coincide with ground tremors, an earthquake early-warning system might come of it.

The Diversity of Electrostatics

The world's electrical energy is supplied by electromagnetic generators made of iron and copper, and much of it goes to motors of the same type. Both the generators and the motors have their electrostatic counterparts. The best-known electrostatic generator is the giant belt-driven Van de Graaff machine, used for high-voltage testing and the acceleration of subatomic particles. A tabletop version of the Van de Graaff generator and the classic rotary Wimshurst generator are widely seen in classroom demonstrations. A newcomer to the tabletop family is my own Dirod electrostatic generator, a rugged and reliable new design of the old induction generator.

Electrostatic motors, on the other hand, are little known. Yet the world's first electric motor, invented by Benjamin Franklin, was an electrostatic device! Much imagination was displayed in the early days of electrical research in turning out a surprising variety of electrostatic motors. This neglected art has been revived in recent years, chiefly by Oleg Jefimenko of West Virginia University, who has been busy making models of both old and new designs. One of his new electrostatic machines, a corona motor about five inches long, has developed a tenth of a horsepower. Recently Jefimenko accomplished the remarkable feat of putting up a wire by balloon and running a motor on energy from the atmosphere's electric field. Because of their very light weight and high speed, such motors may find special applications, perhaps in space research.

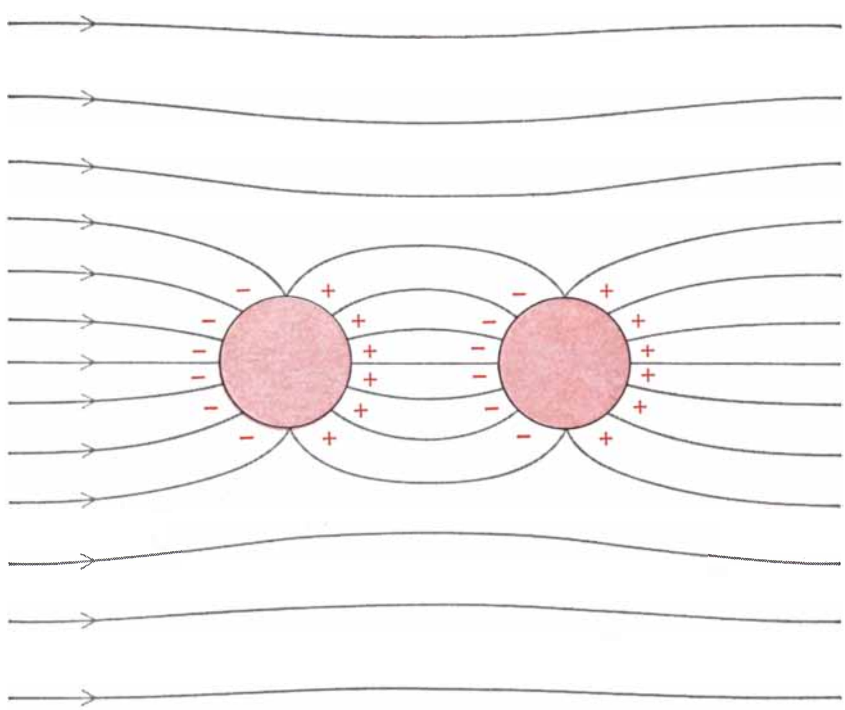
The diversity of modern electrostatics is by no means exhausted by the foregoing examples. None of them, for example, hints at nonimpact printing, an application that, like the horseless carriage, is named for what it is not. This article was born in the noisy impact printing of a typewriter; computer print-out machines also employ noisy and still comparatively slow impact-printing methods. A recent form of nonimpact printing produces a jet of ink with a tiny tube; the tube is vibrated at rates as high as 100,000 times per second to break the jet up into uniform, evenly spaced droplets. The droplets are then charged by induction. As they pass through two pairs of charged plates they are successively deflected back and forth and up and down in order to write characters silently at a high speed. A somewhat different electrostatic process, developed recently by Electroprint, Inc., can write 20,000 lines per minute on wide computer paper. Undoubtedly far higher nonimpact-printing speeds are possible. As computer speeds rise they strain the limits of impact printing, and electrostatic nonimpact printing stands ready to take over.

Other industrial applications that illustrate the versatility of electrostatics include corona devices that hold large sheets of paper to flat surfaces; electrostatic "chucks" that hold nonmagnetic objects in place for machining; electrostatic fluidized beds that spread powder evenly on a surface, preparatory to the fusing of the powder by heat to form a coating; electrostatic spinning machines that make cotton yarn, and electrostatic transducers, such as microphones, that are based on the electret, the electrostatic equivalent of the permanent magnet.

It is worth mentioning a number of other fascinating effects under the heading of electrokinetics. For example, one effect of moving gases and liquids electrostatically is to increase convective heat transfer. When a corona point drives ions away from itself, the ions drag the rest of the air along with them. One would expect such an electric wind from a corona point to enhance heat transfer. Actually the enhancement turns out to be much greater than the enhancement such a wind could accomplish alone. It may be that ions arriving at a heated surface break up the stagnant film of air that characteristically forms around such surfaces. Inter-Probe, Inc., has applied this cooling effect associated with corona probes to plasma-arc welding with several beneficial results: better control of the weld, the reduction of gaseous inclusions and greater strength due to the finer grain structures. This success may perhaps be explained in part in terms of corona chemistry, another old art much neglected until recently, in which a corona discharge creates numerous free radicals that go to work as chemical catalysts [see "Corona Chemistry," by John A. Coffman and William R. Browne; SCIENTIFIC AMERICAN, June, 1965].

A curious new device in this general category, developed by Senichi Masuda of the University of Tokyo, is called the electric curtain. In one form there is a series of rings set one below the other in order of decreasing size to form a funnel-like skeleton. Three-phase 60-cycle voltage is applied to create an electric field that sweeps downward, without a corona. If a cloud of charged particles is poured into the top of the funnel, the particles do not scatter. Instead they flow down through the rings and come out the bottom in a thin stream. The device as it stands constitutes a promising new particle-transport system.

The virtuosity of modern electrostatics research is further illustrated by an application totally different from any cited

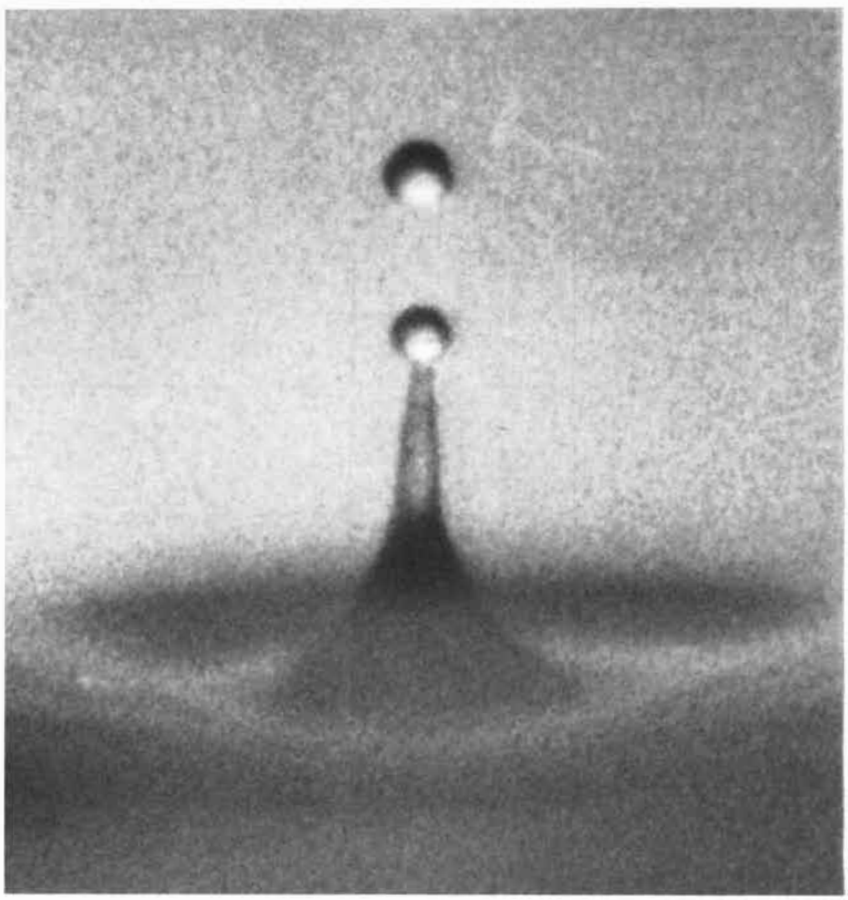


ELECTROSTATIC COALESCENCE of rain droplets under the influence of an electric field inside a cloud, illustrated schematically here, is precisely the same process as the "desalting" process used to remove water and salts from crude oil before it goes to the refinery.

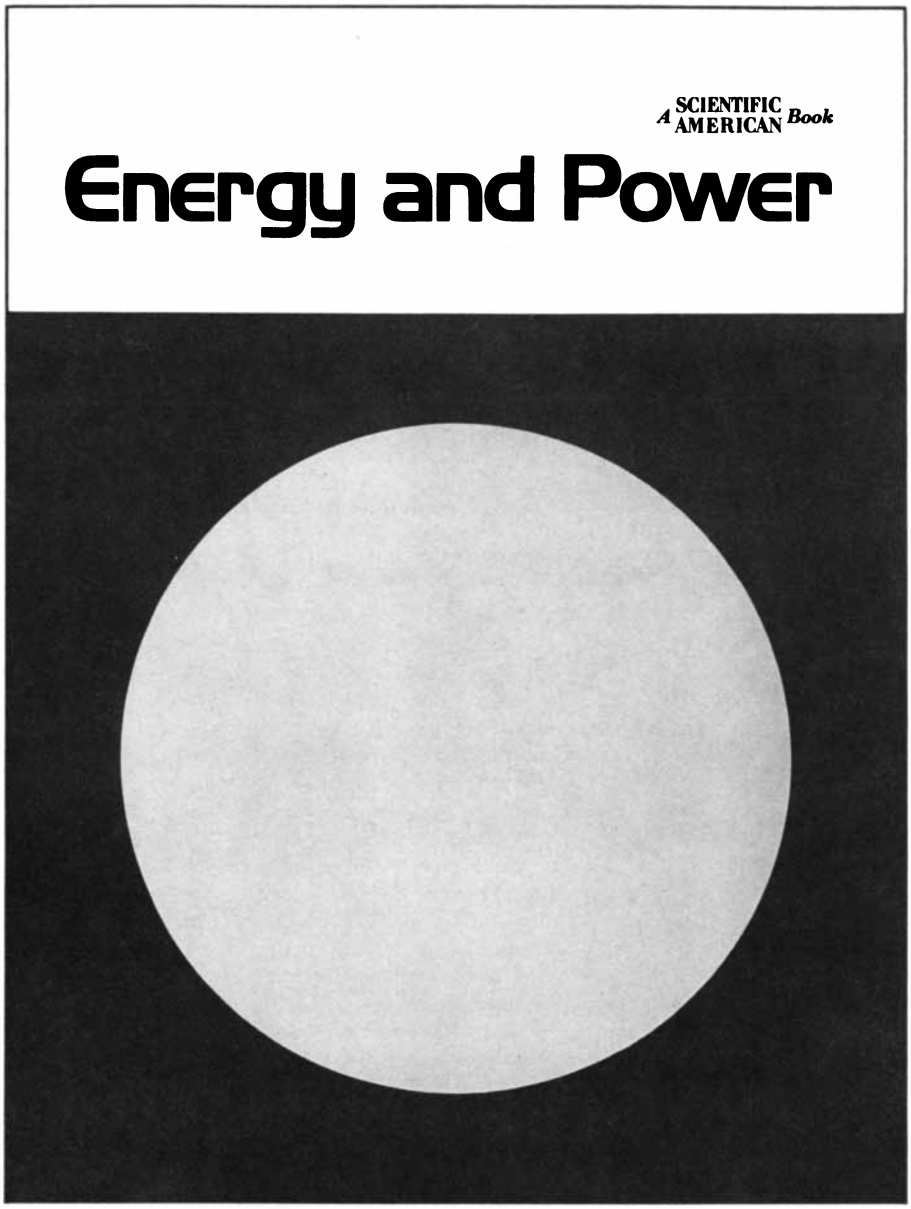
so far. Electrostatically operated signs, developed by the Display Technology Corporation, are just now entering the market. In these devices small blackened vanes are placed edge to edge to make a square array of any size. When all the vanes are flipped to be seen edge on, a white background shows through; when they are flipped back to be seen face on, they appear black. One can electrostatically flip selected vanes to make a mosaic, creating letters, cartoons or other designs. Commands can be given locally by various means or from a distance by teletype. The many advantages of this electrostatic innovation suggest that a real revolution in signs lies ahead.

Last but hardly least, man's internal electrostatic processes rival in ingenuity any that man has been able to devise. Every cell of the body is surrounded by a membrane capable of maintaining a potential difference of about 70 millivolts between the contents of the cell and the intercellular environment. For all cells but nerve cells this potential difference remains constant. In the case of nerve cells, when a neuron is fired by an incoming stimulus, an electrostatic discharge races along the long tubular membrane of the cell at speeds as high as 100 meters per second to deliver the message to, say, a muscle fiber. Then the membrane restores itself in due course to carry succeeding impulses many times per second.

The diverse effects and applications of electrostatics cited in this article, together with many others I have not mentioned, indicate that the field of electrostatics research is in a stage of rapid development. With so many electrostatic effects available, there is obviously much more to come in the way of ingenious applications. I have no doubt that such contributions will continue to flow, as in the past, not only from highly trained workers but also from persistent amateur experimenters, among whom I have always counted myself.



CHARGE-SEPARATION MECHANISM thought to be responsible in part for maintaining the positive charge of the earth's atmosphere is represented by this high-speed photograph of a bubble bursting after rising to the surface of a body of water. A jet from the center of such a bursting bubble goes up at a high velocity, and from the tip of the jet several positively charged water droplets continue upward. When this happens at sea, the droplets, on evaporating, leave behind positively charged salt nuclei, which can be carried farther upward by the wind and eventually become the nuclei for the formation of rain droplets.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