U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

# STATIC ELECTRICITY

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U. S. DEPARTMENT OF COMMERCE
JESSE H. JONES, Secretary

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LYMAN J. BRIGGS, Director

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## PREFACE

The purpose of this Circular is to give a general outline of the various ways in which manifestations of static electricity introduce appreciable hazards into many industries, and to present, in convenient form, a quantitative basis on which engineers can develop such safety measures as may be required. The references in the bibliography have been selected largely because they contain pertinent detail for which space is lacking in the present paper.

Lyman J. Briggs, *Director.*

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By Francis B. Silsbee

ABSTRACT

The nature and origin of the charges of static electricity arising in industrial processes are discussed and various methods of mitigation of the hazards which they introduce are suggested. By defining suitable units for the quantities involved and stating quantitative relationships between them, a basis is given for an engineering treatment of the phenomena.

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# I. INTRODUCTION

## 1. PURPOSE

Static electricity is a source of fire hazard or of mechanical trouble in many industrial processes. It is the purpose of this Circular to assist the public in reducing these hazards by giving a general qualitative discussion of the nature and origin of static electric charges and of the general methods of mitigation, together with a discussion of certain processes in which charges are found to occur, and of applicable remedies. This is followed by a brief quantitative summary of the theoretical relations and the experimental procedures useful in solving practical problems. The first part is intended for the lay reader, whereas the quantitative part is necessarily more technical.

In the preparation of this Circular no attempt has been made to cover exhaustively the practices in any of the branches of industry mentioned. Statements regarding such practices are based on random correspondence and conversations with visitors to this Bureau. The Circular is limited to those phases of industry in which there is some general public interest, and many specialized problems in the elimination of static, such as in the preparation of photographic film or in petroleum refining, are not discussed.

## 2. DEFINITION OF "STATIC"

In the strict sense of the words, "static electricity" means electricity that is standing still.[1] The term is primarily used to distinguish effects such as the attractive and repulsive forces which are observed between electrically charged bodies from the very different class of effects—such as the production of heat, chemical action, and magnetic forces—which are the result of "dynamic electricity" (that is, electricity in motion). In some circumstances the truly static effects, such as the mutual repulsion of charged textile fibers or the attraction between sheets of paper in printing plants, may be of industrial importance. However, the fact that an electric charge is produced on some machine by an industrial process usually means that as the process continues, more and more charge will accumulate until finally the mutual repulsion of these charges will exceed the insulating ability of the surrounding air and the electricity will escape as a spark.

Everyone is familiar with the accumulation, noticeable in dry weather, of electric charge, as he walks on a rug in the house, office, or hotel corridor, and with the consequent shock and spark when his hand approaches a grounded metal object. In most cases the spark is harmless, and the shock is annoying only because it is unexpected. If one can develop the habit of expecting a shock whenever he touches a bridge lamp or steel desk, the nervous jolt is materially reduced. On the other hand, in industrial plants such sparks may be produced in a space which contains flammable gas or dust, and they then constitute a very serious fire and explosion hazard. Of course, the electricity which flows in the spark is at that instant very far from "static," but because of the origin of the charge and perhaps because the spark is usually different in appearance from the "arc" which commonly results from a failure of the insulation on conductors

[1] From the Latin *stare:* to stand.

carrying dynamic electricity, such sparks are often called "static sparks" and considered as manifestations of "static electricity."

A further extension of the meaning of the term "static" has been made in the radio field. The escape of electricity from a conductor charged to a high potential may occur, not as a single vigorous spark, but intermittently as a brush discharge (also called corona, or St. Elmo's fire). Such a discharge consists of a succession of tiny partial sparks which do not extend very far from the charged body but each of which dissipates a small portion of the charge into the surrounding air. Each of these partial discharges sends out a radio wave which is picked up by neighboring radio receiving sets, and the succession of such discharges results in the "frying" noise familiar to all listeners. Of course, the noise is the same whether the brush discharge is the result of an accumulation of truly static charges or is the result of the dynamic charge supplied by a high-voltage circuit. The radio operator has therefore extended the meaning of "static" to include such diverse things as the sudden electric surges induced by distant lightning flashes and the sparking of truly dynamic electricity at a defective insulator or even at the commutator of a d-c motor. This Circular does not deal with radio static.

## II. FUNDAMENTAL CONCEPTS

In order to make the discussion which follows more definite, it may be desirable to give first some of the elementary ideas which underlie the present conception of electric phenomena.

### 1. ELECTRIC CHARGE

Electricity may be thought of as an exceedingly penetrating and fluid substance. Curiously enough, it comes only in parcels of one or the other of two standard sizes. The kind of electricity which is called "negative" comes in exceedingly small and light parcels called "electrons." The kind of electricity called "positive" comes in parcels which are much heavier (by a factor of about 2,000) and which are called "protons." All matter is believed to consist of atoms, each of which is an aggregation of electrons and protons together with particles of a third type which are electrically neutral and which are called "neutrons." When in any given lump of material there are just as many electrons as protons, the piece as a whole is "neutral" electrically and exhibits no external electrical effects. This is the normal state of all matter and the one to which any collection of electrons and protons tends to come if free from constraint.

If there is an excess of electrons present in any body, the body is said to have a "negative" charge. If there is a deficiency of electrons, the body has a positive charge. The charge depends only on the amount of excess electricity of either sign which is present in the body. It is found that although charges of opposite signs attract and try to come together and neutralize one another, charges of the same sign (both + or both −) repel one another. These forces of attraction and repulsion act directly upon the elctrons and protons, and if the electrons are free to move, as is the case in certain classes of materials called conductors, only the electrons will move as a result. If the charges are confined to a particular object, such as a bit of paper, however, they will tend to drag the object with them and thus produce a mechanical force. The mechanical forces of attraction and repulsion are called electrostatic forces and are usually very feeble. It is only when they act on very light objects, like paper or textile fibres, that they are of practical importance. They are, however, often useful in instruments used to indicate the presence of electric charges. The electromagnetic forces used in the electric transmission of power are of entirely different origin, and are usually much more powerful.

Neither electrons nor protons are destroyed in any process of electrification but are merely separated. It is therefore a fundamental fact that for every positive charge there must be a corresponding and numerically equal negative charge, developed somewhere by the same action.

## 2. POTENTIAL (VOLTAGE)

If two bodies are charged differently, one being positive and the other negative, the attraction of the opposite charges will produce a force and the system can do mechanical work by overcoming an opposing force if one body is allowed to approach the other. This electrostatic force increases with an increase in either charge and with a decrease in the distance between them. Also, if a small quantity of the positive electricity is allowed to move across to the negative body, it also can be made to do work by its motion. The amount of work, per unit charge, serves as a convenient measure of the electric forces which are present and is called the potential difference, or voltage, between the two bodies.

In the analogy, which is often useful, between electricity and water, electric charge corresponds to the quantity of water while potential difference corresponds to the pressure difference which forces the water to flow.

In a system which consists of several bodies, there will in general be different voltages between each pair. A worth-while simplification is obtained by choosing one body as a basis of reference and describing the state of affairs by stating the voltage between each other body and the reference body. The voltage, $V_{AR}$, between a body, $A$, and the reference body, $R$, is often called the "potential" of $A$ with respect to $R$, because it is a measure of the capability (or potentiality) of a unit charge initially on $A$ doing work by moving to $R$ under the electric forces of the system. For most engineering purposes the earth is chosen as the reference body and potentials are measured with respect to the earth. In some mathematical studies, however, it is more convenient to set up an imaginary body at a very great distance away from the system considered and to measure potentials with respect to such an "infinitely distant" base.

A concept related to potential is that of "Potential gradient." If two large metal plates are placed parallel to each other and charged to a difference of potential $V$, each will become covered with a fairly uniform surface charge, positive on one plate and negative on the other. If we consider a small positively charged particle in the space between the plates, it can be seen that as it moves away from the positive plate any decrease in the repulsion by the positive charge resulting from its increased distance will be largely offset by an increase in the attraction from the negative plate which is being approached. Moreover, much of both charges is off at the side and their distance from the particle changes only slightly. Hence the particle will experience a constant force all the way across from one plate to the other. In such a case the work done, and hence the change in potential, in each unit length of the path is the same as in each other. The potential therefore changes uniformly. The rate of change of potential with distance is called the potential gradient, and in the case here considered the potential gradient is constant and equal to the quotient of the voltage divided by the distance.

In contrast with this, consider the case of a positively charged needle placed opposite a flat metal plate. Now the positive charge is largely concentrated near the tip of the needle while the negative charge is spread over the plate, being only slightly concentrated in the region opposite the needle. As a positively charged particle moves away from the tip of the needle, the force of repulsion drops off rapidly because of the increasing distance from the whole of the positive charge. Much of the negative charge is spread toward the edges of the plate so that there is little offsetting increase in the attraction. Hence the total force drops off rapidly with distance from the point. The potential gradient in this second case is strong (or steep) near the point and weak near the plate. Any region in which a potential gradient exists is often called an "electric field." In this case the electric field is said to be "concentrated at the point."

### 3. DISTINCTION BETWEEN CHARGE AND POTENTIAL

It is important to avoid confusing the two distinct quantities "charge," which measures the excess or deficiency of electrons, and "potential," which measures the possibility of work being done if a charge is available to do it. To illustrate the distinction, consider that the operation of a steel-bodied bus with insulating tires has caused a positive electric charge to accumulate on the body of the vehicle. The mutual repulsion of the like charges insures that all of the accumulated positive charge will spread to the outer surface of the metal body. Also, a considerable negative charge will be attracted to the surface of the ground immediately beneath the vehicle. One can therefore correctly say that the bus is "charged" and is "at a high positive potential." There is indeed the potentiality of a spark from the filling cap of the gas tank to the hand of the garage attendant. However, there is no charge on the passengers within the bus, although if a unit charge were, in imagination, taken from a passenger and moved to the ground it would do work. Therefore, it is correct to say that the passengers are "at a high potential" but that they are "uncharged." Conversely, a blade of grass growing beneath the vehicle has attracted to its tip an appreciable negative charge and experiences a mechanical force of attraction. Yet the grass is already connected to earth and no work can be done by allowing this charge to go to ground. (In fact, it doesn't go even though the grass is an excellent conductor.) Hence it is correct to say that the blade of grass is "highly charged" but nevertheless it is "at zero potential."

Another term commonly used in describing electrostatic phenomena is "bound charge." In the foregoing example the negative charge on the grass, which does not "wish" to flow away is said to be "bound" by the presence of the positive charge on the vehicle above it. If the bus moves away or if the positive charge on the bus is removed by connecting the body of the bus to the ground, the hitherto "bound" charge on the grass will be "released" and will cease to remain concentrated in the area under the vehicle.

Closely related to the concept of "bound" charge is that of "induced" charge. To illustrate this, suppose a tank truck drives up to a filling station with an accumulation of negative charge on its chassis and the operator neglects to ground it. A person standing near who does *not* touch the truck but who happens to be touching a grounded object will have a positive charge attracted onto him from the ground, though he remains at ground potential. Then, assuming that he is wearing insulating rubber shoes, if the person ceases to touch the grounded object and walks away from the truck, his potential will rise; and if he later brings his hand close to the filling pipe of an underground tank, a spark may pass from his hand to the pipe with disastrous results. The charge which arrived on the person's body is an example of what are called "induced" charges, and resulted from a process in which the object which obtained the induced charge, in this case the person, was at no time in contact with the initially charged body, in this case the tank truck. Because of this fact it follows that the process will be just as effective if the initially charged body is an insulator. Sparks to an insulating object are usually very feeble, but by this inductive action, charged insulating objects may cause sparks to pass between other bodies which are conducting, and such sparks may be very intense.

Another hazard from induced charges is present in the old-style oil-storage tanks which have wooden roof structures covered with sheet-metal plates. The wooden supports are moderately good insulators; but if a negatively charged thunder cloud floats overhead, a considerable positive charge will gradually leak over the supports and accumulate on the metal plates. When the cloud is discharged by a lightning stroke, perhaps at a considerable distance, the induced positive charge is no longer bound and, in returning to ground, may produce dangerous sparks between adjacent sections of the roofing or between the roof and the tank wall unless all these metal parts are well bonded. In such cases the suddenness of the release of the charge makes the momentary current correspondingly large, and well-distributed bonds of very low impedance are required if dangerous potential differences are to be avoided. An alternative remedy is to interpose a suitably grounded shield between the object to be protected and the external inducing charge. The presence of even a few ground wires will greatly diminish the amount of charge induced on objects below them, and the shielding wire can be located away from possible flammable material.

## 4. CAPACITANCE

If a large charge is accumulated on a small body, the tendency to repel charges of the same sign may become very considerable, whereas if the same amount of charge is spread over a larger body the repulsive force will be less. This suggests that any piece of material has a certain electrical "capacity," which is the ratio of its charge to its potential and thus is a measure of the charge it will hold with a given repulsive effect. In general, large bodies have large capacity, but this electrostatic capacity (more properly called "capacitance") is not directly proportional to the actual volume of the body. It depends also on the presence of neighboring bodies.

In studying static phenomena, it is sometimes useful to have on hand bodies which can serve as reservoirs to hold a considerable charge. The primary function of such an apparatus is to have capacitance, and they are therefore called "capacitors." They were formerly called "electric condensers," because in the early days it was thought that the electric charge "condensed" in them, much as steam might condense, and could thus be stored at low voltage, so that a large mass could be stored at a low pressure. Capacitors are usually made by coating both sides of one or more large thin sheets of insulating material with metal foil, and rolling or folding the sheets into a package of convenient size.

### 5. IONIZATION

A concept which enters in analyzing the mechanism of electric discharges is "ionization." If, for example, a beam of X-rays is sent through a gas, some few gas molecules are affected by the radiation to such an extent that an electron is jarred loose from each of them. Such a loose electron may move freely among the other gas molecules; it may become attached to a previously neutral molecule; or it may find a molecule which already lacks an electron and recombine with it to form a neutral molecule. The free electrons and also the molecules which have lost, or gained, one or more electrons are, of course, charged particles and like any other charged particles will move in an electric field. They are called "ions" (Greek for "wanderers").

Other agencies—radium, ultraviolet light, and many chemical reactions—may also produce ionization, and since a flame is the seat of very intense cnemical action, flames also contain ions. Because the ions carry charges, their motion constitutes an electric current, and for a given potential gradient, the current will be greater, the greater the density of ions.

Because of its extremely small mass, an electron accelerates rapidly in an electric field. If its velocity becomes sufficiently high, it acquires the power of ionizing a gas molecule with which it may happen to collide. Therefore, if the potential gradient in a region is sufficiently great, any electron initially present will produce other ions by collision and the ion density will thus be built up cumulatively and with ever-increasing rapidity. The streamer of highly ionized gas thus formed constitutes the spark, and provides a conducting path between the charged bodies which allows the charges to flow until their potentials are equal. In those special cases, however, in which the region of high gradient is limited in volume, as it is in the neighborhood of a sharp needle point, the ionization process will also be limited to this region. The ions of the same sign as the point, which are produced near it, will be repelled all the way to the other electrode but during the later part of their travel will move too slowly to produce other pairs of ions or to cause a visible glow. Such a limited discharge is called a brush, or corona, or, if it occurs in nature, St. Elmo's fire.

### 6. RESISTANCE

If a charge of electrons is placed upon one end of a piece of material, their mutual repulsion will tend to make them spread over the entire

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body. Different materials, however, possess different powers of resistance to the motion of the electrons. All metals offer relatively little resistance to the passage of electricity and, so far as the static effects in which we are at present interested are concerned, may be thought of as being perfect conductors of electricity. Other materials—such as glass, hard rubber, dry wood, and silk—offer a very great resistance to the flow of electricity. Such substances are called insulators. There is no sharp line of demarcation between conductors and insulators. All substances will permit at least some slight flow of electricity, and the rate at which it flows, that is, the amount of charge which passes a given cross section of the material in a unit of time, say 1 second, is proportional to the voltage which has caused the charge to flow, and inversely proportional to the resistance of the body to the flow of electricity. This relation is known as Ohm's law.

The property of a material by reason of which it offers resistance to the flow of electricity is called its "resistivity." The resistivity of different materials varies over an enormous range which is probably greater than the range of any other physical property of matter. Thus, a solution of salt or acid, such as the electrolyte in a storage battery, has 1,000,000 times the resistivity of a piece of copper of the same dimensions. Average city water ("tap water") without the addition of salt or acid to make it conducting has a resistivity something like 5,000 times that of the storage-battery acid. Such organic liquids as gasoline or benzol have so much greater resistivity, however, that even tap water is by comparison an excellent conductor. Thus, the resistivity of clean benzol is roughly 1,000,000,000 times that of tap water. Some solid substances also have very high resistivities, glass having 10,000,000 times that of tap water while hard rubber and sulfur have even greater resistivity. From the point of view of static phenomena, a material may be considered a conductor even if its resistivity is as high as 10,000 times that of tap water, but it is a good insulator if its resistivity is as high as the values which we have given for glass or clean benzol. (See table 1, p. 33.)

When a voltage is applied to an insulating material, a small current, that is, a flow of charge, takes place which depends upon the resistance of the substance. If, however, the voltage is made very great, a physical change takes place in the material. It is said to "break down" and it no longer offers its original resistance to the flow. If the material is transparent, as in a gas or liquid, a visible spark is seen to take place when the insulator breaks down and a charge passes through it. A voltage of about 28,000 volts is required to produce a spark 1 inch long between needle points. (See table 4, p. 34.) It is, of course, the fact that static electricity often discharges itself through such sparks which makes it the source of a serious fire hazard in many diverse industries.

A clear distinction should be made between the resistance of a body, which is the ratio of the voltage applied to it and the current which flows, and its breakdown voltage, which is the value of the voltage at which the material breaks down and changes its properties. Air has an almost infinite resistivity and may be considered as a perfect insulator. It does, however, break down with a sparking voltage which is low compared to the sparking voltage in such substances as gasoline or Bakelite. The contrast between electrical resistance and breakdown voltage is analogous to that between the mechanical properties of stiffness and strength. Thus if a thread is tied to a heavy rubber band and both are pulled, the rubber will stretch much more and allow more extension for a given force than the thread, but at a certain force the thread will break while a much greater ultimate force would be required to break the rubber. Here the thread is analogous to an air gap with high electrical resistance but low breakdown strength, while the rubber is analogous to marble with only moderate resistance but high breakdown strength.

## III. PRODUCTION OF CHARGES

### 1. PROCESS

Let us now consider the ways in which charges may be produced. In electric power plants, charges are being continuously produced and circulated by means of dynamos or batteries which may be thought of as forms of pump for maintaining a steady circulation of electric charge. Other and very simple processes also may produce electric charges. In practically any case in which two bodies are suddenly separated or in which a piece of material is broken, it is found that one body is charged with electricity of one sign and the other with that of the opposite sign. This is because the electrons and protons are so intermingled that an excess adheres to one side or the other of the plane of separation. A typical example of such effects is the charge produced on belting as the belt leaves the pulley with which it has been in very intimate contact. A somewhat similar action occurs when a wheeled vehicle rolls over a road surface. The surface of the tire is repeatedly pressed firmly against the road and then separated from it rather rapidly. The blowing of dust particles or water droplets through pipes is also sometimes an effective source of static electricity. Similar effects occur in jets of water or other fluids where the breaking up of the drops causes a separation of charge. It is supposed that the electricity in thunder storms is produced by a quite similar process, as the raindrops fall downward through a swiftly moving up-current of air which tears some of the water from the outer surface of the drop.

Static electricity is often spoken of as "frictional" electricity (also called "triboelectricity"). This is because convenient methods of producing such charges are by the rubbing of one body upon another, such as a glass rod with a silk handkerchief, or a stick of hard rubber with a piece of fur. It seems highly probable, however, that in all such cases the friction between the two bodies is merely incidental and the charge results from the fact that in the process of rubbing the materials are first brought into intimate contact and are then separated.

The evidence all seems to point to the fact that both bodies involved must be solid or liquid. The passage of a pure gas over a solid or liquid surface has not been found to produce any electrification unless dust particles or droplets are present.

It is probable that the division of electrons between the two bodies while they are in contact is governed by complex surface forces similar in nature to those which produce the contact differences of potential which are observed between different metals. These potential differences usually amount to only a few tenths or hundredths of a volt, but they act across such very short distances, namely, those between adjacent molecules, that the resulting electric fields are relatively intense and can considerably alter the sharing of electrons between the two bodies. As the bodies move apart, a surplus of electrons is trapped on one or the other of the bodies and the potential difference between the bodies increases in proportion as the capacitance between them decreases. The mechanical separation of the surfaces against the electric force of attraction provides whatever energy is required.

Many experimenters have prepared lists (see table 2, p. 34) of substances arranged in such an order that when any two are rubbed together, the one higher in the list becomes positive with respect to the other material. Such a list is called a "tribo-electric series." However the surface forces which determine these electric effects are very greatly affected by contamination with traces of foreign substance, by the presence of films of adsorbed, gas, and by other conditions, so that the magnitude and even the sign of the effect may vary with slight changes in these conditions. Even when an attempt is made to make the two bodies which are put in contact exactly alike, some separation of electricity is usually found. Therefore it is only rarely feasible to obtain a satisfactory reduction in trouble from static electricity by matching the types of material which are involved.

All attempts to get a quantitative verification of the theory outlined above as to the origin of "frictional" electricity have been rather unsatisfactory, partly because of the disturbing effects of surface contamination and partly because of the difficulty of determining just how closely, and over what effective area, the two bodies are actually "in contact." Presumably there should be for any pair of substances an upper limit of charge per unit area which could be developed on separation. When the effect has built up to this extent, the resulting electric field should prevent any further separation of charge on repeated cycles. In view of the fact that molecular distances are of the order of only a hundred-millionth of a centimeter, a contact potential difference of only 0.01 volt might well be multiplied up to 1,000,000 volts by a separation of a centimeter or so if other complicating circumstances did not enter. However, the limits obtained are much less than this and in most experiments seem to be the result of a balance between the production of charge and its loss by imperfect insulation rather than the result of a true saturation effect.

### 2. LIMITING CHARGE DENSITY

A quite different consideration, which also points to another and much smaller upper limit to the charge per unit area which may be expected to develop when two bodies separate, can be based on the breakdown voltage of air. Experiments [21, 22, 23] [2] have shown that as the spacing between parallel plates in air at atmospheric pressure is increased from an initial very low value, the voltage required to produce a spark is at first large; that it decreases to a minimum value of about 350 volts at a spacing of only 0.01 millimeters; and that it then increases until finally for large spacings it corresponds to about 30,000 volts per centimeter. For simplicity, let us fix our attention on two plane surfaces of large area initially close together and charged with uniform surface density by charges of equal magnitude but opposite signs. The electric capacitance between the surfaces will be roughly inversely proportional to the separation, and the voltage

[2] Figures in brackets indicate the literature references at the end of this paper.

between the surfaces will therefore increase directly in proportion to the separation, thus maintaining a nearly constant potential gradient. If the initial-charge density is low, this gradient will be small and no sparking will occur. However, if the initial density of charge is high, the rate of increase of voltage with distance and the potential gradient will be proportionately high; and if this rate (that is, the voltage gradient) materially exceeds 30,000 volts per centimeter, a condition will be reached at some rather small separation where the developed voltage exceeds the breakdown voltage of the air space. The result will be a spark discharge between the plates. If the plates are of insulating material, each spark will discharge only the portion of the plates where it occurs, but by this process the average charge per unit area and hence the average voltage between the plates will be reduced. If this reduction is sufficient, it may prevent the occurrence of sparks at neighboring portions of the surface. The final result will be that the surfaces when finally separated will be charged to an extent which approximates but should not exceed the charge which, between parallel planes, produces a voltage gradient of 30,000 volts per centimeter. This charge density is $2.65 \times 10^{-9}$ coulomb per square centimeter (8 esu per square centimeter).[3]

The conditions in the neighborhood of the line where a belt leaves its pulley are to some extent analogous to those just considered. In such cases, for instance, when adhesive tape is unwound from its roll, a row of tiny sparks is often visible in the dark and seems to fill the chink where the spearation is occurring, with a faint bluish glow. In certain experiments in which the layers of a two-ply rubber-coated balloon fabric were peeled apart, similar flashes were observed and the charge per unit area was found to average $2 \times 10^{-10}$ coulomb per square centimeter. In the operation of static generators of the Van de Graaff type, charge densities of one-fourth the theoretical limit have been obtained on the charging belts; and in the experiments of French [27], similar charge densities were reached.

A single sheet of insulating material might have a charge density of twice this value ($5.3 \times 10^{-0}$ coulomb per square centimeter, or 16 esu per square centimeter), because the electric field would extend on both sides. With different geometrical arrangements the maximum attainable charge density might be slightly different, but these figures can be taken as a good approximation to the greatest charge densities likely to be met with in practice, in the open air, and hence constitute a basis for the estimation of permissible leakage resistances.

## IV. METHODS OF MITIGATION

### 1. GROUNDING

The fundamental method universally employed for eliminating or mitigating the hazard from static electricity is to provide means whereby the electric charges are led away harmlessly as fast as they are produced. When all the objects concerned are conducting, this can be readily accomplished by connecting all of them to a common grounded conductor. This prevents the production of sparks between conducting parts, and such sparks are usually far more intense and likely to start a fire than are the much feebler sparks which occur

[3] For meaning of units, see section VI.

between insulating surfaces. This procedure has the added advantage that it provides safety against electric shock to the operator of an electrically driven machine which might result if an accidental leakage connection or "ground" should occur between the live part of any electric circuit and the frame of the machine. When a ground connection is present, any failure of the circuit insulation permits a large flow of current which immediately blows a fuse or trips a circuit breaker, thereby calling attention to the defect. In the absence of the ground connection, the machine might become charged to the full potential of the electric circuit and constitute a serious hazard. Such grounding of machinery is required under many conditions by the National Electrical Safety Code [4] and other official regulations.

To be effective in discharging static electricity as fast as it accumulates, only a very feebly conducting path to ground would be required. However, to perform satisfactorily the function of grounding the machine against leakage from the electric circuit, a path is required which is of low resistance and capable of carrying enough current to blow the circuit fuse; furthermore, under some circumstances such ground connections may be called upon to carry without damage currents due to lightning strokes. Hence it is common practice to use conductors at least as large as No. 10 AWG, and often No. 6 wire is used. Such large wires have the further advantage of being stronger and less likely to be broken.

A point to be kept in mind when laying out a plan for bonding machinery is that the energy in a spark increases not only with its voltage but also with the electric capacitance which is connected to the points between which the spark occurs. Hence if several pieces of metal are bonded together, and then a short gap should develop (perhaps by the breaking of a grounding wire) between them and ground, the spark at this gap would be more intense than that which would occur if only one of the pieces of metal had been involved. Thus an imperfect grounding system may do more harm than good.

The use of chains as ground connections to stationary objects is usually deprecated because possible oxidation of the links may develop layers of fairly high resistance and thus defeat the purpose of protection from accidental short circuits.

By far the most feasible way for grounding moving objects—for example, trucks, persons, etc.—is by making the floor a sufficiently good conductor of electricity. Metal floors are ideal electrically but tend to wear smooth and slippery. Metal grilles embedded in tile floors have been used in some cases, but unless the grille is of rather fine mesh an object like the leg of a chair or table may fail to touch the metal. Some types of flooring cements contain magnesium oxychloride or salts of copper and are fairly good conductors unless very dry. However, different samples of such materials differ widely in their resistivity, and it is therefore desirable in important installations to check the resistance experimentally after the floor is laid and has had time to dry out thoroughly. The conductive rubber recently put on the market can be used as a floor covering and has a satisfactorily low resistance, particularly if a metal screen is embedded in it.

Of course the bodies of the personnel constitute electrically conducting objects which may become charged, and in many cases it is desirable to insure that each person is effectively grounded. Older methods are the use of metal rivets (preferably of a soft metal, such as copper, to avoid percussion sparks) through the soles of the shoes or small chains around the ankle and connected to a metal heel plate. Recently shoes with soles of conductive rubber have been developed.

The literature contains occasional references to particular individuals who are abnormally liable to become electrified. It seems probable that the sole difference between these "human dynamos" and their fellows lies in their lesser tendency to perspire, so that their clothing, and particularly their shoes, is drier and hence a better insulator.

Oil is a good insulator, and the oil film between a shaft and its bearings may under some conditions have an appreciable resistance. Values of 8 megohms have been observed. Hence it is desirable that shafting and other rotating metal parts be grounded by metal (or graphite) brushes rubbing on the side or end of the shaft.

## 2. HUMIDIFYING

When one or both of the bodies involved is not electrically conducting, the problem of conducting away electric charge becomes much more difficult. One procedure which is widely used is to maintain a high relative humidity in the ambient atmosphere. It happens that the great majority of insulating materials possess the property of adsorbing on their surface a very thin layer of moisture. This layer usually contains enough dissolved material to make it slightly conducting electrically. Hence if two metal electrodes are attached to the surface of such an insulator, the electrical resistance between them is found to become less and less as the atmospheric humidity increases. The resistance measured between such a pair of electrodes is sometimes called the "surface resistance," and for a relative humidity of 80 percent this surface resistance of a substance may be less by a factor of 1,000,000 than it is at a relative humidity of 30 percent. A few substances, such as paraffin and other waxes, do not develop a surface conductance in the presence of water vapor, but they are exceptions to the general rule.

The definite relation between atmospheric humidity and the prevention of manifestations of static electricity has led some to the erroneous belief that the presence of water vapor makes the *air* conducting. Actually the almost infinitesimal conductivity of air is slightly *decreased* by the presence of water vapor, and its beneficial effects are mainly the result of films adsorbed on the surface of the solid insulating materials. There is also some indication that adsorbed moisture films on the contacting surfaces also reduce the tendency for the separation of electric charges, quite apart from the leakage effect.

Certain observations and experiments have led to the suggestion that the carbon dioxide normally present in the atmosphere, by dissolving in the adsorbed film of moisture, contributes materially to its conductivity. Calculations based on data for water solutions in bulk, however, indicate that this effect of carbon dioxide should be very slight, and that the process of washing the air in air-conditioning equipment should not materially change its carbon-dioxide content unless the wash water is alkaline.

No sharp line can be drawn between humidities which are dangerous and those which are safe. In winter with an outside temperature of 32° F saturated air would contain only 26 grains of moisture per pound. When such air is brought indoors and heated to 70° F, the relative humidity becomes only about 25 percent and there is a high probability of obtaining static effects. If the humidity can be raised to 75 percent, such effects are practically certain to disappear.

High humidity may be produced by blowing steam into the workroom from jets preferably located near the source of static. As a temporary expedient, wet cloths may be hung up and the floor sprinkled frequently. To maintain a high humidity requires a surprisingly large rate of evaporation. In the case cited, the moisture content must be raised to 81 grains per pound of air. For a room 20 by 40 by 10 feet and with only two air changes per hour, this would require the evaporation of about 1 gallon of water per hour. Many types of air-conditioning equipment are now available for automatically controlling humidity.

Although widely used to mitigate static, humidification is not a panacea for several reasons. Certain industrial operations, for example, those involving hygroscopic powders, and various processes in textile mills, must be performed in a dry atmosphere. Moreover it takes an appreciable time for the conducting moisture film to build up on a freshly exposed insulating surface, so that a humid atmosphere is of little help in giving conductivity to paper or other sheet material if it unwinds rapidly from a dry roll. Still another objection is the fact that condensation of water will occur on the windows of a humid room in cold weather. This tendency can be much reduced by using double windows [2]. For an inside humidity of 60 percent, condensation may be expected on a single window at 50° F outside temperature, but on a double window only at 20° F. For a humidity of 75 percent, these values become 59° and 40° F, respectively.

### 3. NEUTRALIZATION

A third procedure is to provide in the neighborhood of the charged object a supply of ions of opposite sign. These will then be attracted by the charged object and on reaching it will neutralize the original charge. This procedure is exemplified in its simplest form in the combs placed near the surface of a belt where it leaves a pulley. Here the charge on the belt itself produces the electric field which, being largely concentrated near the tips of the teeth, produces some ionization. This ionization in turn supplies the ions which neutralize the original charge. Other examples of neutralization are the use of a row of small gas jets close to the paper in a printing press, and the "electric neutralizers," in which a row of teeth are charged from a transformer to such a high alternating potential that ionization occurs. The charged object, near these teeth, then attracts the ions of sign opposite to its own charge until the charge is neutralized. The ions of opposite sign are repelled and blow harmlessly away. (See section V–8 below.)

## V. PARTICULAR PROCESSES

This section gives a brief mention of the particular hazards met with in certain industries and the methods of mitigation which are applicable. A more complete discussion of many of these methods, with sketches in much greater detail showing how they may be carried out, will be found in publications of the National Fire Protection Association [2] and of the National Safety Council [3].

## 1. BELTING

Belting, whether used for tbe transmission of power or for conveying materials, is a frequent source of static trouble. The shaft bearings of all pulleys, including idlers should, of course, be bonded to ground, but this precaution alone is often inadequate. A common device is that just mentioned of a grounded metal comb so placed that its teeth project toward and are almost in contact with the belt over its full width. If the comb is applied to the inside of the belt, the ions discharged from the comb will directly neutralize the charge on the surface of the belt. If the comb is on the outside of the belt, the charges from the comb will accumulate on the outside, where they in effect "bind," and are "bound" by, the corresponding charges of opposite sign on the inside of the belt. This combination of charges will produce very little electric effect at points external to the belt. If the material of the belt possesses even a very slight conductivity, the opposite charges will gradually flow through its thickness and truly neutralize. It is usually much more convenient mechanically to mount the comb on the outside of the belt. Its position should be displaced by a small amount, about half the width of the belt, from the line of separation of belt and pulley, in the direction in which the belt moves. The use of a comb in actual contact with the belt, or of an idler pulley, is seldom satisfactory, both because of the whipping of the belt and the increased wear and because it introduces just one more place where there is a contact and separation of materials and hence a source of static charge. A "tinsel bar" such as is used to remove static from wide sheet materials (see p. 21) can also be used effectively with belts. While such a bar or a comb is usually effective in eliminating the danger of having long sparks pass from the belt to persons or other objects near it, the brush discharges and possible short sparks from the teeth offer some hazard as a source of ignition of flammable gas mixtures.

Another common practice is the use of special belt dressings [7] which make the inner surface of the belt conducting enough to lead the charges back to the pulley as fast as they are produced. Many of these dressings contain hygroscopic material, like glycerine, which readily take up water from the air and thus develop a high surface conductivity. Such dressings should be renewed at regular intervals.

There has recently been put on the market [a] [4] a type of conveyor belt which has a layer of electrically conducting rubber. Such a material should prove an excellent remedy for static troubles.

## 2. RUBBER-TIRED VEHICLES

The rolling of a wheel on the surface of the ground involves very much the same relative motion as that between a pulley and belt. It is therefore not suprising that the metal bodies of rubber-tired trucks, busses, and other automobiles frequently become charged with static electricity. This effect has been studied rather extensively by Beach,

[4] Letters in brackets refer to the list of "Sources of Equipment' at the end of this paper.

Cadwell, and others [8, 9], who find that the primary effect is the accumulation of negative charge around the circumference of the tire treads. These charges may leak across the tires and charge the entire body, or in extremely dry weather may be confined to the treads but by inductive action raise the potential of the body.

At toll gates, devices such as water jets or spring wires are sometimes installed to bring the car body to ground potential before the collector touches it. Drag chains and strips of conductive rubber are often used on tank trucks and on busses, respectively, to discharge them. These devices are effective only if the ground is sufficiently conducting, and it seems probable that dry, or oil-soaked concrete or sandy ground may have such high resistivity as to make a drag chain ineffective. The drag chain should always be supplemented by a more positive metallic connection between truck body and underground tank before any flammable liquid is transferred.

### 3. HANDLING PETROLEUM PRODUCTS

The American Petroleum Institute (50 West 50th St., New York City) has a very active committee studying problems arising from static electricity and is supporting research at California Institute of Technology.

In addition to the effect from the rolling of the tires of gasoline-laden trucks, which has been already discussed, static charges may be developed in many other ways in the petroleum industry. If gasoline is filtered through a porous material like chamois skin, a very marked separation of charge occurs. Formerly many fires were caused by this source of static, but it is now widely recognized and guarded against.

The turbulent flow through metal pipes of liquid hydrocarbons, particularly if they contain traces of other materials, such as tetraethyl lead, moisture, etc., will produce a separation of charges, a negative charge being acquired by the oil while the positive charge is left on the pipe. If the pipe is long enough, an equilibrium is reached in which the liquid carries a certain amount of charge per unit volume regardless of the rate of flow. This volume charge is of the order of $3 \times 10^{-5}$ coulomb per cubic meter (corresponding to a current of two billionths of an ampere per gallon per minute) [10]. Splashing of the liquid and the bubbling of air through it, particularly when in contact with water solutions, are even more effective processes for separating electric charges. The volume resistivity of many grades of petroleum products is so great that many minutes may be required for a given charge to leak away by conduction. These products also have a high electric breakdown strength (three or four times that of air), so that sparks seldom pass inside the liquid. (Such a spark would not start a fire even if it did occur, because of the absence of oxygen.) However, because of their mutual repulsion, some electric charges will accumulate on the free surface of the liquid and may produce potential gradients sufficient to produce sparks in the air over the surface. In many cases the mixture of vapor and air may be too rich to be explosive, but such sparks constitute a potential hazard.

Fortunately the more moderate splashing caused by the motion of tank trucks, cars, and ships is less effective than the splashing when tanks are being filled from above or are agitated by air jets, and the former process is seldom the cause of fire.

The charges in the liquid will in all these cases attract an equal and opposite charge to the inner surface of the metal container, and the combination will give no external evidence of the electrification. Hence, the splashing does not contribute anything to the charge often observed on the body of a tank truck when it arrives at its destination, and conversely temporarily grounding the tank and removing its free charge will not reduce the internal charges. If the charged liquid is drained out, the (negative) charge will go with it, leaving the (positive) charge on the tank now free and dangerous. It is evident from this consideration that it is essential to keep the tank grounded at all times during the flow of liquid. The use of metal-lined hose with the fittings at both ends bonded to the lining is now almost universal practice and secures the desired result, provided the operator is careful to keep the nozzle at all times in contact with the filling pipe. Similar precautions are required at all points where flammable liquids are transshipped, as from tank cars to storage tanks, storage tanks to tank trucks, etc. It is standard practice to bond together and to ground all tanks, pipes, and other metal parts, including the rails on which the tank cars rest. Such bonds may also have to carry stray leakage currents from power or traction circuits, and perhaps lightning currents, so it is important that the grounding conductors be of good size (No. 6 AWG).

It is also desirable whenever possible to have the orifice through which a flammable liquid enters a tank submerged below the surface of the liquid. The splashing is thereby much reduced and hence the breaking of drops and the separation of charges also.

A still further source of hazard arises in the "steaming" of empty tanks. (see "Spraying" below, p. 20.)

### 4. DRY CLEANING

The dry-cleaning industry formerly offered a very serious hazard, because it involved the use of large quantities of volatile flammable solvents in conjunction with a variety of types of materials which in the cleaning process were tumbled about in close contact and then separated. Many devices have been used to minimize the hazard. One is the use of a ring connected to ground by a chain and worn on a finger of the workman, who was supposed to discharge each garment by bringing his hands or the ring into contact with it while it was submerged. Another precaution is to always rip off fur trimming from silk dresses, to clean these materials separately, and then sew the trimming on again. Another [2] is the use of magnesium oleate or other soaps which are moderately soluble in most cleaning fluids and render them somewhat conducting electrically. The fire hazard has been considerably reduced by using as the cleaning fluid a petroleum distillate of very "narrow cut." This contains almost none of the highly volatile constituents which are the most likely to produce explosive mixtures, and also is free from the constituents of high boiling point, which are hard to drive off and which, if left in the garment, produce their characteristic and unpleasant odor. This liquid is usually known as Stoddard solvent [16].

In the more modern designs of dry-cleaning machinery the problem has been attacked from a different point of view and with good success. The washers, solvent storage tanks, and piping are made to form a closed system from which the air is pumped out before the solvent is admitted and from which the solvent vapor is pumped out, while the washer is heated by steam, before air is admitted. Under this control, an explosive mixture cannot be produced and there is no need to worry about the presence of sparks.

### 5. ANESTHETICS

A field in which considerable attention has recently been given to the static hazard is the administration of anesthetics in the operating rooms of hospitals. For an excellent discussion of this, see Horton [12, 13]. Most of the gases used to produce anesthesia form explosive mixtures with oxygen, and it is therefore important to eliminate all possible sources of ignition from operating rooms. It has been standard practice to imbed a grounded metal grille in the terrazzo floors, but there is still the possibility that rubber tires on the anesthesia machine and operating table and rubber-soled shoes on the personnel might permit the accumulation of charges. A number of forms of electrically conductive rubber goods have recently been developed [a, b, c, d]. The use of such material for tires, shoe soles, and for flooring should go far to reduce the hazard.

Another suggestion is the use of an "intercoupler" which connects the patient, anesthetist, surgeon, operating table, and anesthesia machine to each other and to ground through rather high resistances (1 megohm). Such a connection is ample to carry off static charges, but will limit the current and hence the shock experienced if a person accidentally touches the live (ungrounded) side of the electric supply circuit. Such connectors are, however, rather a nuisance mechanically. Ordinarily rubber-soled shoes are good insulators and should never be worn in an operating room. A simple device to check that the shoes of the personnel have sufficiently low resistance consists of two separate conducting plates, insulated from the floor, on which the individual can stand with one foot on each. An ohmmeter is connected to indicate the resistance from one plate to the other, and this value is of course four times the resistance between the body and the floor.

The other aspect of this problem is also being attacked. The United States Bureau of Mines [15] has developed anesthetic gas mixtures in which part of the air is replaced by helium to a sufficient extent to render it nonexplosive. Also, it is probable that a procedure can be developed by which the anesthetic gas is purged from the patient's lungs and replaced by air to a sufficient extent that the resulting mixture is nonexplosive, before the mask is removed and thus before any mixture is allowed to escape into the room. Of course many other possible sources of ignition—such as d-c motor commutators, electric switches, cauteries, "radio knives," thermostat contacts on sterilizers, etc.—must be guarded against in an operating room, and it would seem desirable to make every effort to confine the gas mixture as well as to minimize the likelihood of a spark. The NFPA [12] has issued a "tentative recommended safe practice for the use of combustible anesthetics in hospital operating rooms" which set up a carefully considered and very conservative standard.

### 6. AERONAUTICS

The flammable nature of the hydrogen gas often used in balloons makes it imperative that all sources of ignition be kept away from such lighter-than-air craft. Fires have occurred when balloons were being filled with hydrogen from storage cylinders. Nusselt attributes the static in such cases to bits of rust from the cylinders being swept against the piping by the gas stream. The pulling open of the "rip panel" or any accidental tearing of a multi-ply fabric may involve a separation of materials and the production of static. There are records of a number of fires originating when the rip panel was opened, and later designs provide a metallic frame to cure this trouble. A row of tiny sparks along the full width of such separating fabrics has been seen in the dark. In experimental trials, however, those sparks were found too weak to ignite a hydrogen-air mixture. The rubbing of fabric against the rigging or the ballonet is also a potential source of charge, and much effort has been spent in attempts to make balloon fabrics conducting.

An anchored barrage balloon of course forms an ideal lightning rod and is very liable to be struck. Even without a direct hit, the electric field under a thundercloud is so intense that charges from the ground are attracted to the top of a captive balloon and would flow off from any projections on its upper surface as a corona discharge, or St. Elmo's fire. Experiments have shown that sufficiently intense corona discharge can ignite hydrogen-air mixtures. It is probable that such a discharge caused the destruction of the dirigible airship *Hindenburg* in 1937.

In comparison with hydrogen-filled balloons, airplanes are relatively immune from static hazards. Certain static phenomena do occur, however, which are of some interest. A plane flying through rain, cloud, or snow commonly acquires a very considerable electric charge. Presumably this is a result of the repeated contacts and separations, although it is possible that the drops or snowflakes may be already charged and merely share their charge with the plane. At times such an accumulation of charge is noted when there is no precipitation. It is probable that when this occurs the plane is passing through a mass of air which at some earlier time had been part of a thunderstorm. The upper part of a thundercloud contains many positively charged fine drops or ice crystals. These may evaporate so that the charge is left associated with individual gaseous ions which will remain in suspension for a long time.

The accumulated charge changes the potential of the airplane relative to its surroundings until the mutual repulsion of the charge is sufficient to produce corona discharge from the extremities of the aircraft. Such corona usually appears at the wing tips, the tips of the propeller blades, the rudder and tail surfaces, etc., and is plainly visible at night. The detailed molecular mechanism by which corona is produced gives inherently a succession of intermittent bursts of current, and these abrupt changes cause radio disturbances which interfere seriously with radio communication. Devices are now being developed which it is hoped will produce a more gradual discharging of the plane and thus eliminate this "precipitation static." Another effect of these accumulations of charge is to make the plane more effective in triggering off lightning flashes between clouds.

Many cases are on record in which airplanes have been struck by lightning. The damage is usually limited to the fusing of small holes in the aluminum sheet, but occasionally the radio apparatus is burned out. The metal fuselage of a modern plane provides such a perfect electrostatic shield that the passengers are often unaware that the plane has been struck.

Another manifestation of the accumulation of charge is the sparks which have been observed to pass between a plane and ground on landing. Sparks 4 feet long have been reported as occurring between the pontoons of a descending seaplane and the water.

In the design of the dump valves intended for the quick discharge of gasoline from airplanes in an emergency, great care is taken to make certain that none of the liquid can come in contact with the fuselage, lest the static charges thus developed might ignite the fuel.

### 7. SPRAYING

Nearly 100 years ago an English experimenter named Armstrong [28] built what he called a "hydroelectric machine," which consisted of a steam boiler, the steam from which passed out through an insulated nozzle. When the steam was dry, no effect was noted; but when drops of water blew out with a jet of steam, the nozzle charged up rapidly and could be used as a source of electricity for other types of experiment. He obtained currents of over 100 microamperes in this way. Substantially the same situation exists in numerous industrial processes, such as spray painting, steaming out tanks which have contained flammable liquids, etc. The first important step in avoiding sparks in such operations is to ground the nozzle either by using metallic hose or by running a wire to the nozzle. Any metal objects which the jet may strike, including of course the object being painted, if it is metal, should also be grounded.

### 8. SHEET MATERIALS, PAPER, AND PRINTING

In printing and other industries in which large amounts of paper are handled, static electricity introduces a serious problem. The difficulties arise primarily from the mechanical attractive or repulsive forces which are caused by the electric charges and which interfere with the proper movement, registration, and stacking of the paper. However, certain of the inks used in high-speed printing contain so much volatile material that there is a distinct fire hazard also.

The charges may originate as the paper unwinds from the feed roll, as it passes through the driving rolls, or as it separates from the type.

An attempt is usually made to keep the humidity high, but the rate of penetration of water vapor into a tight roll of paper is so slow that this procedure is not very effective. A very old device for removing static is the use of a row of small gas flames extending across the width of the press at the delivery end. The paper passes close over these flames so rapidly that it is not ignited. The chemical rearrangement of the atoms which is occurring in the flame involves the temporary release of some electrons and gives the flame a conductivity which is sufficient to discharge the paper. Of course this form of neutralizer should not be used with flammable inks, and an interlock should be provided to shut off the gas if the paper should stop.

A somewhat analogous and much safer device which is widely used is known as an "electric neutralizer." This consists of a row of sharp metal points insulated from the frame and connected to the secondary winding of a small transformer, the primary winding of which is energized from a 60-cycle, 115-volt circuit. The points are thereby raised to a high potential (10,000 to 15,000 volts) which is made alternately positive and negative. The potential is so high that a slight brush discharge (corona) is produced from the point during the crest of each half-cycle. The charged ions that are opposite in sign to the static charge on the paper are attracted to it and neutralize the charge. The ions of the same sign are repelled and have no effect. The alternations follow one another so rapidly that substantially all of the paper is neutralized. In order to minimize the danger of sparks from the points to ground, each point is coupled separately through a capacitance of very small value to a heavily insulated "inductor bar," which in turn is connected to the transformer. With this arrangement the energy in any spark from a point cannot exceed the very small value which would suffice to charge the coupling capacitor to the transformer voltage. The electric power required to operate such a device is very small. It is widely used in textile plants, as well as in paper mills and printing shops.

In handling paper and other sheet materials, the presence of a "tinsel bar" close to, but not touching the material just beyond the point of separation from the rolls is often beneficial [2]. Such a device is made by wrapping a helix of tinsel around a wooden dowel and grounding the tinsel. The numerous grounded metal points, in the presence of a charge on the sheet, will give off a brush discharge, the ions from which will tend to be attracted to and neutralize the charge on the sheet.

### 9. BLOWER SYSTEMS

A number of fires and explosions have been attributed to static electricity in apparatus such as cotton gins [19], threshing machines [20], etc., in which finely divided material is blown along a duct by a current of air [18]. The particles repeatedly touch and separate from the walls of the duct and may generate a very considerable charge. Many of these dusts are highly combustible and when suspended in air form a truly explosive mixture.

The principal precaution which can be taken in such apparatus is to carefully bond together all metal parts of the system, including vehicles, storage tanks, etc.

## VI. UNITS OF MEASUREMENT AND QUANTITATIVE RELATIONS

The foregoing discussion has given only general and qualitative descriptions of the phenomena and of the underlying concepts in terms of which these phenomena are best described. For a true engineering attack on the problems involved, a more definite and quantitative approach is required, even though the measurements involved may at best be of very low precision.

The first requirement for such a quantitative study is a set of units for the various quantities considered. Several different systems of electrical units have been devised during the development of the science. One of these is known as the cgs (centimeter-gram-second) electrostatic system and is from a mathematical viewpoint perhaps the most convenient for treating electrostatic phenomena. In the technical literature where this system is often used, the units are identified sometimes by the prefix "stat-", and more often by the initials "esu" (electrostatic unit) printed after the numeric.

However, the far more extensive development of dynamic electricity led to the invention of other systems of units, and the one now almost universal in electrical engineering is the so-called practical or mks (meter-kilogram-second) system. As it, also, is entirely adequate for the treatment of electrostatic phenomena, it, or units simply related to it, will be used in the following discussion. Table 3 (see p. 34) indicates the relative values of the units of these two systems and also of other convenient units for a number of electrical quantities.

## 1. CHARGE

For the unit of electric charge, it might seem natural to take the charge on a single electron, because this seems to be a very definite constant of nature. However, it would be inconveniently small and difficult to use and was not known when the systems of electric units were first invented. The mks unit of electric charge is the *coulomb*, which is $6\times10^{18}$ times [5] as large as the charge on an electron. This is as much too large from an electrostatic point of view as the electron is too small, and it is often more convenient to use the *microcoulomb*, which is one-millionth of a coulomb. Even this is a pretty large charge. If such a charge could be concentrated on a sphere 4 inches in diameter, the surrounding air would be stressed to the verge of breakdown.

## 2. POTENTIAL DIFFERENCE (VOLTAGE)

The mks unit of potential difference is the *volt*. It is of the order of magnitude of the electromotive force produced by electric batteries. The common dry cell gives 1.5 volts. One cgs electrostatic unit of voltage (i. e., 1 statvolt) equals 300 volts. To produce a spark between needle points one-half inch apart requires 14,000 volts.

The volt and the coulomb are so related that the energy developed by the passage of a coulomb of charge between two points which are maintained at a difference in potential of 1 volt is 1 *joule*. The joule is the unit of energy in the mks system and is therefore equal to twice the mechanical kinetic energy possessed by a mass of 1 kilogram which has a velocity of 1 meter per second. One horsepower is 746 joules per second. One watt is 1 joule per second.

## 3. CAPACITANCE

The charge which must be initially placed on a body in order that it should acquire a given potential is proportional to the "capacitance" (formerly called electrostatic capacity) of the body. In order that the system of units be self-consistent, the unit of capacitance

[5] The number, here expressed as $6\times10^{18}$, means the number obtained by writing the digit 6 followed by 18 zeros before the decimal point. This exponential notation is very convenient when writing very large or very small numbers. Thus two and one-half million (2,500,000) is written $2.5\times10^{6}$. For numbers less than one a minus sign is written before the exponent. Thus two and one-half ten thousandths (0.00025) is written $2.5\times10^{-4}$. The exponent applied to the 10 is the number of places by which the decimal point has been shifted in passing from the number in the usual form, to the number written as the first factor in the exponental form. The minus sign indicates that the decimal point has been moved to the right.

must be that of a body which rises in potential by 1 volt when it is given a charge of 1 coulomb. The name for this mks unit of capacitance is the *farad.* This is an exceedingly large quantity. For much electrical work a unit one millionth of this, namely the *microfarad,* is used. For electrostatic phenomena even this is too big, and a unit smaller than the microfarad by another factor of one million is used. This unit is called the *micromicrofarad* (sometimes also called the picofarad) and is equal to $10^{-12}$ farad or $10^{-6}$ microfarad. The standard abbreviation for microfarad is "$\mu$f" and for micromicrofarad is "$\mu\mu$f." One micromicrofarad equals 0.9 cgs electrostatic unit of capacitance (or statfarad). The cgs electrostatic unit of capacitance is also occasionally called the "centimeter."

For a few simple shapes it is possible to calculate the capacitance of a body from its dimensions and the properties of the medium by which it is surrounded. Thus for a spherical conductor isolated in space at a great distance from other bodies, the capacitance, $C$, is given by the formula

$$C = 1.1R \text{ micromicrofarads,} \tag{1}$$

where $R$ is the radius of the sphere in centimeters. This seems like a very useless statement, of academic interest only, but actually the capacitance is affected only slightly by shape, so that one may use this relation to estimate roughly the capacitance of many objects of various shapes. Thus to guess the capacitance of a 6-foot man standing on a platform of dry wood, take as $R$ one-half his greatest dimension, namely 100 centimeters, and estimate his capacitance at 110 $\mu\mu$f. Moreover, neighboring bodies will affect the capacitance by not over 11 percent if their distance from the center of the sphere is not less than 10 times the radius, and by not over 25 percent if their distance is 5 times the radius. An accuracy of 25 percent is ample in many studies of static effects.

A second calculable shape, which is often useful, is a flat conducting sheet parallel and close to a similar conducting sheet. Here "close" means that the separation is small compared to the dimensions of the sheets, so that edge effects can be neglected. The capacitance, $C$, is given by the formula

$$C = 0.088KA/t \text{ micromicrofarads.} \tag{2}$$

In this formula $A$ is the area of either sheet in square centimeters and $t$ is the separation in centimeters. $K$ is a factor known as the "dielectric constant," which depends on the nature of the insulating material which separates the plates. If this is a gas (or a vacuum), $K=1$; but for most solid and liquid materials $K$ is greater than 1 and ranges from 2 to 10.

If a man is standing on a metal floor, the soles of his feet will have a capacitance to the floor which can be estimated by this formula. If the area of each foot is 250 square centimeters, the thickness of the shoe sole is 0.8 centimeter, and the dielectric constant, $K$, of the sole is 5, the capacitance, for both feet, will be $C=273$ $\mu\mu$f.

The capacitance between a wire of radius $r$ which lies along the axis of a metal tube of radius $R$ and of length $l$ centimeters is given by

$$C = 0.24Kl/\log_{10}(R/r) \text{ micromicrofarads,} \tag{3}$$

where, as before, $K$ is the dielectric constant of the material between the electrodes.

### 4. CURRENT

When electric charges are moving steadily past a given reference point, this phenomenon constitutes an electric current. The mks unit of current is the *ampere* and corresponds to the passage of 1 coulomb of charge per second. The ampere is of a very convenient size for dynamic effects but is rather large for electrostatic ones. Thus if a belt 10 centimeters wide is charged to the high charge density of $2\times10^{-9}$ coulomb per square centimeter and is running at the rate of 10 meters per second, the current will be only $2\times10^{-9}\times10\times1{,}000=2\times10^{-5}$ ampere (or 20 microamperes). In this example the current is associated with an actual motion of matter as well as of electricity and may be called a "convection" current. More often the matter is stationary and the electrons move through it as a "conduction" current.

### 5. RESISTANCE

The resistance of a conducting path to the passage of electric current is defined as the ratio of the difference of potential between the ends of the path to the conduction current which it produces. Hence in the mks system the unit of resistance (called the *ohm*) is that of a path such that a potential difference of 1 volt causes a current of 1 ampere. This unit is rather small for expressing the resistance of a path through an insulator, and a unit one million times as large, called a *megohm*, is often used.

It is sometimes convenient to describe a circuit by stating its ability to let electricity pass through it rather than by stating its resistance. The former property is called "conductance" and is the reciprocal of the resistance. The unit of conductance is the *mho*. A path which has a resistance of 1 ohm has a conductance of 1 mho. A path which has a resistance of 1 megohm ($10^6$ ohms) has a conductance of 1 micromho ($10^{-6}$ mho).

A machine often offers a number of interconnected paths by which static charges may leak away. The rules for combining such conducting paths are: (1) for paths connected end to end (i. e., in "series") the resistance of the combination is the sum of the resistances of the individual paths (i. e., $R_s=R_1+R_2+R_3 \ldots$); (2) for paths connected side by side (i. e., in "parallel" or in "multiple") the conductance of the combination is the sum of the conductances (i. e., of the reciprocals of the resistances) of the individual paths (i. e., $\frac{1}{R_p}=\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3} \ldots$).

When conduction occurs throughout the volume of a homogeneous poorly insulating material, the resistance, $R$, of the path is given by the formula

$$R=\rho l/A. \tag{4}$$

In this formula $l$ is the length of the path in meters, $A$ is its cross section in square meters, and $\rho$ is a coeffcient which measures the inherent ability of the material to resist the passage of electricity and which is called the "volume resistivity" of the substance. It will be seen that if a sample of material in the form of a cube 1 meter on each edge is considered, both $l$ and $A$ become unity and the resistance is in this case numerically equal to the volume resistivity. The volume resistivity of a material can therefore be defined as being the resistance between opposite faces of a unit cube of the material. The unit of volume resistivity in the mks system is therefore the *ohm-meter*. The practical use of the mks system has not yet been extended to the tabulation of values of the resistivity of materials and a unit smaller by a factor of 100, namely the *ohm-centimeter* (i. e., the resistance between opposite faces of a cube 1 centimeter on each edge), is universally used. Table 1 gives values of the volume resistivity in ohm-centimeters for a number of substances. For insulating materials volume resistivities are sometimes expressed in *megohm-centimeters*.

Similarly the electric conductivity of a material is the reciprocal of its volume resistivity and is commonly expressed in "mhos per centimeter."

When, by reason of the presence of a humid atmosphere, the conduction which occurs over the surface of an insulating material greatly exceeds that throughout its volume, this latter conduction can be neglected. In such circumstances the resistance, $R$, of the path over the surface is given by the formula

$$R=\sigma l/W. \quad (5)$$

Here again $l$ is the length of the path, while $W$ is the width of the path measured along the surface at right angles to the flow lines of current. The coefficient $\sigma$ is called the "surface resistivity" of the material and of course depends greatly on the humidity of the surrounding atmosphere. If a sample is so arranged that the conduction occurs only in a square film between two electrodes which lie on opposite sides of it, $l/W=1$ and the resistance is in this case numerically equal to the surface resistivity. It will be seen that the size of the square happens to cancel out, and the surface resistivity of a material can therefore be defined as being the resistance between opposite faces of a square. The unit of surface resistivity is therefore also the ohm (or, if preferred, the megohm).

## 6. USEFUL RELATIONS

We are now in position to express quantitatively in terms of these units a number of useful relations:

(1) The force of repulsion between two charges of $Q_1$ and $Q_2$ microcoulombs concentrated at points (or on small spheres) $l$ centimeters apart in air is

$$F=90.Q_1Q_2/l^2 \text{ newtons.} \quad (6)$$

(1 newton $=10^5$ dynes $=10^2$ grams $=0.225$ lb $=3.6$ oz.) Of course if the charges are of opposite sign, the force will be an attraction of the same magnitude.

(2) If two parallel flat plates of area $A$ square centimeters spaced $b$ centimeters apart are charged to a potential difference of $V$ volts, the force of attraction is

$$F=4.4\times10^{-12}V^2A/b^2 \text{ newtons.} \quad (7)$$

(3) If a dust particle charged with $Q$ microcoulombs is in a region where the potential gradient is $g$ kilovolts per centimeter, the force on the particle is

$$F=0.10\ Qg \text{ newtons.} \tag{8}$$

(4) If a capacitor, or other body, having a capacitance of $C$ micro-microfarads is charged to a potential of $V$ volts, the charge, $Q$, is

$$Q=10^{-6}\ CV \text{ microcoulombs.} \tag{9}$$

(5) The energy, $W$, in *joules* stored in such a charged capacitor is

$$W=5\times10^{-13}\ CV^2=5\times10^{-7}\ QV=0.5\ Q^2/C \text{ joules.} \tag{10}$$

(6) An isolated sphere of radius $R$ centimeters charged to a potential of $V$ kilovolts (referred to an infinitely distant base) has a charge

$$Q=1.1\times10^{-3}\ VR \text{ microcoulombs} \tag{11}$$

and a potential gradient at its surface

$$g=900\ Q/R^2=V/R \text{ kilovolts per centimeter.} \tag{12}$$

(7) If any conducting surface is charged with a charge density of $q$ microcoulombs per square centimeter, there is at points very close to the surface a potential gradient perpendicular to the surface and of intensity

$$g=1.13\times10^{+4}\ q \text{ kilovolts per centimeter.} \tag{13}$$

## VII. INSTRUMENTS AND METHODS OF MEASUREMENT

### 1. MEASUREMENT OF VOLTAGE

The most essential tool in any study of electrostatic phenomena is a means for measuring, or at least of detecting, the presence of differences of electric potential. The classic form of detector is the gold-leaf electroscope. The essential element of this instrument in its usual form consists of a thin strip of gold leaf about 3 millimeters wide and 6 to 8 centimeters long, which is hung over a short horizontal wire so that the two halves of the strip hang side by side. If the strip is charged electrically, the two halves repel one another and move apart to form an inverted V. A simple way to mount such an element and protect it from air currents is to thrust the supporting wire up through the insulating stopper of a wide-mouth glass bottle. The stopper may be of paraffined cork or of cast sulfur. The outer end of the wire may be fitted with a knob or small metal plate.

If the knob of such an electroscope is brought near a body which is at a high positive potential, negative charge will be attracted to the knob and the corresponding positive charge will be repelled to the leaves, which will diverge. If the knob touches the charged body the divergence will be still greater, and in extreme cases the force of repulsion may be so great as to tear the gold leaf.

To determine the sign of potential being measured, a convenient procedure is to use a stick of sealing wax which has been rubbed vigorously on a woolen cloth or piece of fur. The wax is then certain to be itself charged negatively. In the case chosen above, with the electroscope knob near but not touching a body at positive potential, the approach of the negative wax near the knob will oppose the original effect and cause the leaves to fall toward each other. On the other hand, if the stick of wax is brought near the leaves themselves, which already have a positive charge, they will be attracted toward the wax and will diverge still further. In a polarity test of this kind, an indication of further divergence is slways desirable, because a decrease in the separation might be brought about either by leakage or by the approach of an uncharged body. Of course if the charge on the body under examination had been the opposite of that assumed above, the changes in position of the leaves would also have been opposite.

If a scale is arranged so that the position of the leaves can be measured, the electroscope becomes an electrometer and can be calibrated with sources of known potential and then used to measure unknown potentials quantitatively. A scale can sometimes be obtained by projecting a shadow of the gold leaf on a screen or by observing it through a telescope which has a scale in its eyepiece.

Another simple and inexpensive detector of high potential is the neon-tube tester. This device is designed primarily for checking the presence of potential at the terminals of spark plugs. It consists of a glass tube containing rarified neon gas. Metal electrodes are sealed in at each end. When the difference of potential between these electrodes exceeds a few hundred volts, the gas becomes conducting and glows with a characteristic red light. The glow only lasts while a current exists in the gas. Therefore if an insulated person, holding one terminal, touches the other to the charged body, there will be a momentary flash while electricity flows through the tube to charge the experimenter's body up to the potential of the object under examination. The glow then ceases, although both ends of the tube are still at a high potential. The external spark which passes from the charged body to the terminal of the neon detector is usually intense enough to ignite an explosive mixture, and hence a neon detector should *not* be used when there is any possibility of explosive gas being present at the time the test is made.

Of course the way in which static potential differences are most frequently detected is by the spark which they produce. If no flammable gas mixture is present, the spark itself can be used as a quantitative basis for measuring voltage by letting it occur across a gap of measured length between electrodes of known size and shape. The recognized relation between voltage and gap length is given in tables in standard No. 4 of the American Institute of Electrical Engineers (revised January 1940) [23]. Similar tables for other sizes of electrodes will be found in the International Critical Tables [24]. Gaps between needle points are often used because for a given voltage the gap length is greater and more easily measured. Also, the electrodes are more readily available. On the other hand, the sparking voltage of such gaps depends somewhat on the atmospheric humidity, and is more erratic. Table 4 (see p. 34) gives the sparking voltage for a few types of electrodes and spacings, the values being obtained from the above-mentioned tables.

Between large spheres or parallel flat plates, sparks occur at a potential gradient of about 30,000 volts per centimeter; but to produce breakdown in short gaps, the potential gradient must be markedly higher than this value. Because of the variation in sparking gradient with gap, the sparking voltage is only roughly proportional to the gap. For very short gaps the sparking voltage passes through a minimum and actually increases as the gap is further reduced. This minimum voltage below which a true jump spark will not pass in air is about 350 volts. Of course if a gap is opened in a circuit in which a current already exists, the current tends to persist as an arc even at low circuit voltages.

If the electrodes are sharply curved (e. g., needle points), the potential gradient is no longer the same in all parts of the gap, and in the regions close to the points the potential gradient for a given voltage and separation may be far greater than that which would exist between parallel plates at the same voltage and separation. Hence, for a given separation, a discharge will occur at a much lower voltage. The quotient of the sparking voltage divided by the separation may then be much less than 30,000 volts per centimeter. However, if the true potential gradient in the most stressed part of such a gap is computed from its dimensions and from this lowered value of sparking voltage, the maximum gradient turns out to be materially greater than 30,000 volts per centimeter.

In gases other than air or at other pressures and temperatures, the sparking voltage would of course be different. If droplets of water are present, as in clouds, there is evidence [31] that breakdown occurs at lower gradients, perhaps down to 10,000 volts per centimeter.

The obvious way to measure the difference of potential developed by static charges is to use a suitable direct-reading voltmeter. The usual types of instrument are not suitable for this because their operation requires an appreciable and sustained drain of current from the source being measured. Voltmeters of the electrostatic type, however, are well suited to the conditions and are marketed by a number of makers [e, f, g, h]. This type of instrument is in effect a modification of the gold-leaf electroscope and is used in much the same way. The electrostatic forces are inherently proportional to the square of the measured voltage, with the result that the instrument scale is unavoidably cramped at the lower end in spite of the ingenuity which has been applied to improving the uniformity of the rest of the scale. The capacitance of the instrument is usually greater than that of an electroscope and may affect the potential which is to be measured. Care must be taken in using these instruments, because as a rule they are less rugged, more sensitive to error from tilting, and less effectively damped than voltmeters of the usual type. In measuring static (or other d-c potential differences), it is seldom feasible to extend the range of the instrument with a series capacitor, because the division of the total potential between the instrument proper and the capacitor in series with it changes from an initial state in which the voltages are inversely proportional to the two capacitances to a final state in which the voltages are directly proportional to whatever resistances may be present in leakage paths around the capacitances. Only if both these leakage resistances are exceedingly high will there be time to get a reading before they have introduced an error. Of course both the instrument and its capacitor must be discharged just prior to each measurement to remove any charge acquired during previous use.

### 2. MEASUREMENT OF CAPACITANCE

The measurement of capacitance is often of value in analyzing static problems, because the magnitude of a charge is most readily determined by multiplying the voltage by the capacitance (see formula 9). The energy can also be computed (see formula 10) from the voltage and the capacitance. It many cases a very rough estimate of capacitance, based on formulas such as formulas 1 and 2, is sufficient and very useful.

Indicating instruments [m] are available for capacitances above 100 $\mu\mu$f. Commercial bridges [k] are available with ranges down to 5$\mu\mu$f. If a radio-frequency oscillator is available, a capacitance can be measured readily by loosely coupling to the oscillator a circuit containing inductance and a calibrated tuning capacitor and tuning this circuit to resonance with the oscillator. The unknown capacitance is then connected in parallel with the tuning capacitor, and the latter is then reduced in value until resonance is restored. The reduction in the tuning capacitance is then equal to the unknown capacitance.

### 3. MEASUREMENT OF RESISTANCE

A great variety of devices is available for measuring resistances of low and medium values. These range from the simple buzzer circuit or test lamp of the wireman to the very precise bridges of the laboratory. For checking the continuity of grounding circuits, a buzzer or one of the simpler direct-reading ohmmeters is very useful. Another widely used instrument is the Megger [i]. This comprises in a single case a hand-driven magneto generator and a two-coil ohmmeter. It is exceedingly useful for testing the insulation of electric circuits and reads directly the value of resistance. In its usual forms it can measure resistances ranging from a few thousand ohms up to several thousand megohms. Even this latter value is not sufficient to be of much use in studying static conditions, for even the highest resistance measurable with a megger may be almost a short circuit from the static point of view. Electronic devices known as megohmmeters and megohm bridges are available [k] which permit resistances as great as $5\times10^{10}$ ohms and of $10^{12}$ ohms, respectively, to be measured.

An exceedingly useful and simple method for measuring a high resistance by the use of an electrostatic voltmeter is based on the rate at which charge initially in a capacitance, $C$, will leak away through a resistance, $R$, which shunts the capacitor. If at some initial time, $t_1$, the voltage across the capacitor is $V_1$, then the voltage, $V_2$, at some later time, $t_2$, is given by the formula

$$V_2=V_1e^{-(t_2-t_1)/RC}. \tag{14}$$

Hence if the voltages $V_1$ and $V_2$ are read on the voltmeter at times separated by an interval (conveniently measured by a stop watch) of $t_2-t_1$ seconds, then the resistance of the leakage path is given by

$$R=\frac{0.43(t_2-t_1)}{C(\log_{10}V_1-\log_{10}V_2)}. \tag{15}$$

If $t_2-t_1$ is measured in seconds and $C$ in *farads*, then $R$ will be in ohms. In the special case where $V_2=V_1/2$, this formula becomes

$$R=1.44(t_2-t_1)/C. \tag{16}$$

This method is quite flexible and can be used over a wide range of $R$, for if the value of $R$ is low and the time interval $t_2-t_1$ is uncomfortably short, one can connect an additional capacitor in parallel with the electrostatic voltmeter.

The upper limit of measurement is fixed by the length of time during which the circuit can be kept free from changes in conditions. Thus if $C=100$ $\mu\mu$f and the voltage drops by 10 percent in 2 hours, then $(\log_{10}V_1-\log_{10}V_2)=0.046$, $(t_2-t_1)=7{,}200$, and $R=0.43\times7{,}200/0.046\times10^{-10}=6.8\times10^{14}$ ohms.

This procedure may of course be worked backward and used to measure an unknown capacitance, $C$, if the resistance, $R$, and the rate of loss of voltage are known.

## 4. MEASUREMENT OF CHARGE

Strangely enough, it is seldom necessary to measure directly the magnitude of an electric charge. It is usually easier to compute it by multiplying the measured potential in volts by the capacitance in farads (estimated or measured), to get the charge in coulombs. The charge on a small and movable object can be measured by the following procedure. An electrostatic voltmeter, or calibrated electrometer, of small capacitance is connected to a well-insulated metal can. The charged object, hanging from a silk thread or other insulating support, is lowered into the can. If the voltmeter then shows a potential of $V$ volts and if the combination of instrument and can has a total capacitance of $C$ farads, then the charge on the test object is $Q=VC$ coulombs. It does not matter whether or not the test object makes contact with the interior of the can, but the can should be so deep or the opening so small that the object is substantially surrounded by the can. This method is obviously applicable to insulating as well as to conducting objects.

It is sometimes desired to measure the average density of charge in a cloud of steam or of dust. This can be done by connecting to the electrometer a long thin wire leading to an insulated metal sphere. Surrounding the sphere and concentric with it should be placed a (roughly) spherical screen of wire netting which is grounded. The wire connecting the inner sphere to the electrometer should pass through an opening in this outer screen. When the cloud of charged particles blows in through the screen and fills the space around the inner sphere, the potential of the inner sphere, and of the electrometer, will rise to a value of $V$ volts, which can be read on the instrument. The charge density, $q$, in the cloud in microcoulombs per cubic centimeter is then given by

$$q=5.3\times10^{-7}V\left(\frac{C_1+C_2}{C_1}\right)\left(\frac{b}{b^3+2a^3-3a^2b}\right)\text{microcoulombs per cubic centimeter.} \tag{17}$$

In this formula, $a$ is the radius of the inner sphere and $b$ is the radius of the outer screen, both in centimeters. $C_2$ is the capacitance of the electrometer alone, and $C_1$ is the capacitance of the capacitor formed by the two concentric spheres. $C_1$ may be measured, or it may be computed by the formula

$$C_1 = 1.1\frac{ab}{b-a} \text{ micromicrofarads.} \quad (18)$$

Of course, $C_1$ and $C_2$ must be expressed in the *same* units when used in formula 17.

The charge on a capacitor or other metallic body can be measured by discharging the body through a galvanometer and noting the maximum (ballistic) throw of the instrument. Very sensitive ballistic galvanometers can detect changes of $3\times10^{-10}$ coulomb, but portable instruments require about $10^{-8}$ coulomb to give an indication.

## VIII. IGNITING POWER OF SPARKS

A very considerable amount of effort has been spent in attempts to determine the energy required to ignite explosive gas mixtures. Most of this pertains to the arc produced by interrupting a current-carrying circuit, but some experimenters [17] used jump sparks. The energy required for ignition appears to depend on a great many variables, including the composition and pressure of the gas mixture, the shape and spacing of the electrodes, etc. In general it has been found that the energy required is less as the sparking voltage is greater. Thus for a certain mixture of gasoline vapor and air, a 4,800-volt spark discharging a capacitance of 350 $\mu\mu$f and hence delivering 0.004 joule was just able to produce ignition, but a 5,250-volt spark produced ignition when the capacitance had been decreased to 72 $\mu\mu$f and the energy was therefore only 0.001 joule. Ignition has been produced in hydrogen by as little as $2\times10^{-5}$ joule at 1,300 volts.

Very feeble sparks sometimes occur which discharge electricity from a small area of the surface of an insulator. Thus if an area of 1 square millimeter is charged to the limiting density of $2.6\times10^{-9}$ coulomb per square centimeter, it will yield only $2.6\times10^{-11}$ coulomb and at 1,300 volts corresponds to an energy of only $1.7\times10^{-8}$ joule, which is far below that required for ignition. Tests have shown that such tiny sparks produced at the line of separation of the plies of balloon fabric were incapable of igniting an explosive hydrogen-air mixture. On the other hand if a charged insulating body is near a grounded metal point, the potential gradient at the point may cause a streamer which discharges an appreciable area of the insulator and has enough intensity to produce ignition.

## IX. PRINCIPLES FOR COMPUTING SAFE LIMITS

A question which frequently confronts the engineer is "How low must the resistivity of a material be in order that it may be considered 'conducting' as regards static?" The fundamental principle on which a logical answer to such a question can be based is that the aggregate conductance must be so great that even at a voltage so low that no spark can jump, the charges will be conducted away as fast as they are produced.

In the simple case of an insulated machine driven by a belt of width $W$ centimeters, running at a linear velocity of $V$ centimeters per second, the belt may be assumed charged to the maximum charge density of $2.6\times10^{-9}$ coulomb per square centimeter and the rate of production is equivalent to $2.6\times10^{-9}$ $WV$ coulombs per second. If the leakage to ground is to carry this current with a potential difference which is less than the minimum sparking potential of 350 volts, the resistance must be less than $R=350/(2.6\times10^{-9}WV)=(1.3\times10^{11})/WV$ ohms. If the width, $W$, happens to be 10 centimeters and the velocity, $V$, 1,000 centimeters per second, the resistance should be less than $1.3\times10^7$ ohms (13 megohms).

If the charge under consideration happens to be developed on one side of a sheet of insulating material, the other side of which is effectively grounded, it follows from formulas 2 and 9 that if the material has a thickness $e$ and a dielectric constant $K$, a charge of $Q$ coulombs on an area $A$ square centimeters will produce a potential difference of $V=(1.1\times10^{13}Ql)/KA$ volts and, if the material has a volume resistivity $\rho$ ohm-centimeters, the resistance will be $R=\rho l/A$ ohms. The initial leakage current will be $V/R=(1.1\times10^{13}Q)/\rho K$ amperes, and both tne charge and the potential will have dropped to 1 percent of their initial values in a time $t=4.0\times10^{-13}\rho K$ second. If it can be assumed that the movement which removes one of the contacting bodies and thereby releases tne previously bound charge on the surface of the sheet requires 0.001 second for completion, then a material such that the product $\rho K$ is less than $2.5\times10^9$ may be considered conducting. Hence if $K=2.5$, $\rho$ may be as much as $10^9$ ohm-centimeters (1,000 megohm-centimeters). It is interesting to note that in this treatment the dimensions of the sheet cancel out; and it may be concluded that if a material having uniform volume resistivity is conducting in one application, it will be so in others except as shorter time intervals may enter.

A somewhat different case arises when a charged body rests on a floor or other surface which has a high volume resistivity but which has a relatively lower surface resistivity, so that the significant part of the leakage takes place across the surface. Such circumstances are likely to arise wnen an attempt is made to remedy static troubles by raising the atmospheric humidity. A rough estimate of permissible resistances may be obtained by considering a hemispherical metal block of radius $a$ centimeters resting, flat side down, at the center of a circular platform of radius $b$ centimeters. If the periphery of the platform is grounded and if the upper surface of the platform has a surface resistivity of $\sigma$ ohms, the resistance offered to tne radial flow of charge from the block to the periphery is given by the formula

$$R=0.37\ \sigma \log_{10}(b/a) \text{ ohms.} \tag{19}$$

An approximate value for the capacitance of the block is $1.1a$ $\mu\mu$f, or $1.1\times10^{-12}a$ *farad*. Hence, by formula 15, the time required for 99 percent of an initial charge to leak away is given by

$$t=1.9\times10^{-12}\sigma\ a \log_{10}(b/a) \text{ seconds.} \tag{20}$$

As a typical example, assume a machine of diameter 2 meters ($a=100$ centimeters) in a room 10 meters across ($b=500$ centimeters). Then

$t=1.3\times10^{-10}\sigma$. A value of $\sigma=8\times10^6$ ohms (8 megohms would therefore, in this case, suffice to drain away all but 1 percent of the charge in 0.001 second. Of course few rooms are circular and few machines are hemispherical, but the errors in estimation introduced by taking $b$ as the distance to the nearest water pipe or other good ground and taking $a$ as half the length of the machine are not significant compared to the great variations in $\sigma$ with humidity and perhaps other conditions.

The principles illustrated by the foregoing examples will lead to a useful estimate of the resistance corresponding to a given decay time (0.001 second).

In applying this estimate to obtain specification limits, an appropriate factor of safety should of course be included. The value of this factor should depend on the possibility of occurrence of changes in resistance and of the combination of resistances in series, on the seriousness of the consequences of a spark, and on the ease of obtaining low values of resistance. The factor of safety may therefore range from 1 in unimportant cases to 500 or more, as in the NFPA standards for hospital operating rooms.

---

TABLE 1.—*Resistivity (in ohm-cm) of various materials*

| Material | Resistivity |
|---|---|
| | *Ohm-centimeters* |
| Silver | [a] $1.5\times10^{-6}$ |
| Copper | $1.7\times10^{-6}$ |
| Mercury (liquid) | $96.\times10^{-6}$ |
| "Semiconductors" | $10^{-4}$ to 10 |
| Sulfuric acid solution | 1 |
| Conductive rubber | $2\times10^{2}$ to $2\times10^{3}$ |
| Graphite | $1.4\times10^{3}$ |
| Soil | $6\times10^{2}$ to $5\times10^{5}$ |
| Tap water | $3\times10^{3}$ to $8\times10^{3}$ |
| Flame | $4\times10^{5}$ |
| Distilled water (in equilibrium with $CO_2$) | $10^{6}$ |
| Pure water | $2.5\times10^{7}$ |
| Fiber | $10^{9}$ |
| Bakelite | $10^{11}$ |
| Glass | $10^{13}$ to $10^{16}$ |
| Air, normal | $10^{16}$ |
| Amber | $10^{16}$ |
| Liquid hydrocarbons | $10^{10}$ to $10^{18}$ |
| Sulfur | $10^{17}$ |
| Fused silica | $10^{18}$ |
| Paraffin | $10^{18}$ |

[a] For the meaning of this exponential notation, see footnote 5 on p. 22.

TABLE 2.—*Triboelectric series*

[Each substance becomes positively charged if rubbed against any substance listed below it in this table.]

+

Asbestos
Glass
Mica
Wool
Cats fur
Lead
Silk
Aluminum
Paper
Cotton
Woods, iron
Sealing wax
Ebonite
Ni, Cu, Ag, brass
Sulfur
Pt, Hg
India rubber

—

TABLE 3.—*Units used in electrostatic measurements*

| Quantity | Symbol | mks unit | cgs electrostatic unit | Other convenient unit |
|---|---|---|---|---|
| Charge (quantity of electricity). | *Q* | Coulomb | Statcoulomb, $=\frac{1}{3}\times10^{-9}$ coulombs. | Microcoulomb, $=10^{-6}$ coulombs. |
| Potential difference (voltage). | *V* | Volt | Statvolt, =300 volts | Kilovolt, =1,000 volts. |
| Potential gradient | *g* | Volt per meter | Statvolt per centimeter, $=3\times10^{4}$ volts per meter. | Kilovolt per centimeter, $=10^{5}$ volts per meter. |
| Capacitance | *C* | Farad | Statfarad, $=1.1\times10^{-12}$ farads | Micromicrofarad, $=10^{-12}$ farads. |
| Current | *I* | Ampere | Statampere, $=\frac{1}{3}\times10^{-9}$ amperes. | Microampere, $=10^{-6}$ amperes. |
| Resistance | *R* | Ohm | Statohm, $=9\times10^{11}$ ohms | Megohm, $=10^{6}$ ohms. |
| Resistivity (volume) | $\rho$ | Ohm-meter | Statohm-centimeter, $=9\times10^{9}$ ohm-meters. | Ohm-centimeter $=10^{-2}$ ohm-meters. |
| Resistivity (surface) | $\sigma$ | Ohm | Statohm, $=9\times10^{11}$ ohms | Megohm, $=10^{6}$ ohms. |
| Conductance | | Mho | Statmho, $=1.1\times10^{-12}$ mho | Micromho, $=10^{6}$ mho. |
| Force | *F* | Newton | Dyne, $=10^{-5}$ newtons | Pound, =4.45 newtons. |

TABLE 4.—*Sparking voltages* (*crest value*)

| Gap | Needle points | ½-in. square rods cut square | Sphere diameter, cm | | |
|---|---|---|---|---|---|
| | | | 0.25 | 1.0 | 6.25 |
| *cm* | *Volts* | *Volts* | *Volts* | *Volts* | *Volts* |
| 0.01 | ---------- | ---------- | 1,080 | 860 | ---------- |
| .05 | ---------- | ---------- | 2,920 | 2,780 | ---------- |
| .1 | ---------- | ---------- | 4,730 | 4,670 | ---------- |
| .2 | ---------- | ---------- | 8,340 | 8,080 | ---------- |
| .5 | 8,000 | ---------- | 15,800 | 17,400 | 17,000 |
| 1.0 | 12,500 | ---------- | 20,500 | 29,800 | 31,300 |
| 1.5 | 17,800 | ---------- | 22,900 | 39,900 | 44,500 |
| 2.0 | 23,000 | 26,000 | ---------- | ---------- | 57,000 |
| 4.0 | 41,000 | 47,000 | ---------- | ---------- | 93,600 |
| 6.0 | 55,000 | 62,000 | ---------- | ---------- | ---------- |

## X. SOURCES OF EQUIPMENT

*Conductive Rubber:*

[a] U. S. Rubber Co., 1 Market St., Passaic, N. J.
[b] Buffalo Weaving & Belting Co., Buffalo, N. Y.
[c] Boston Woven Hose & Rubber Co., with John Schneider & Sons Inc., 46 Melrose St., Brooklyn, N. Y.
[d] L. H. Gilmer Co., Tacony, Philadelphia, Pa.

*Electrostatic Voltmeters:*

[e] Central Scientific Co., 1700 Irving Bldg., Chicago, Ill.
[f] Ferranti Electric Co., Inc., 30 Rockfeller Plaza, New York, N. Y.
[g] General Electric Co., Schenectady, N. Y.
[h] Sensitive Research Instrument Corp., 4545 Bronx Bldg., New York, N. Y.

*Other Measuring Apparatus:*

[i] J. G. Biddle Co., 1211 Arch St., Philadelphia, Pa. (Meggers).
[j] The Cambridge and Paul Instrument Co. of America Inc., 3512 Grand Central Terminal, New York, N. Y. (Electrometers, galvanometers).
[k] General Radio Corp., Cambridge, Mass. (Capacitance test bridge 740B, Megohmmeter 487A, megohm bridge 544–B, capacitors).
[l] Leeds & Northrup Co., 4901 Stenton Ave., Philadelphia, Pa. (Galvanometers, capacitors).
[m] Weston Elec. Instrument Corp., Newark, N. J. (Capacitance meters, ohmmeters).

*Neutralizers:*

[n] Kidder Press Corp., Dover, N. H.
[o] Simco Mfg. Co., 430 Race St., Philadelphia, Pa.
[p] Static Eliminator Co., 239 Center St., New York.
[q] Static Eliminator Bar Co., 9514 Avenue K, Brooklyn, N. Y.
[r] Baker Specialty Co., 1317 East 22d St., Brooklyn, N. Y.

## XI. REFERENCES AND NOTES

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