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STATIC ELECTRICITY IN NATURE AND INDUSTRY

Part 1.—General observations and experiments
Part 2.—Industrial hazards and safeguards

BY
PAUL G. GUEST

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CONTENTS

ILLUSTRATIONS

STATIC ELECTRICITY IN NATURE AND INDUSTRY [1]

By Paul G. Guest [2]

INTRODUCTION

Notwithstanding the great progress in physical and chemical science during recent years, man has acquired no knowledge of what electricity really is. Investigators agree, however, that it has a dual nature, being composed of positive and negative parts, and that its varied phenomena depend upon the relation and interaction of these two entities. Thus, the dynamic or current electricity familiar to all is believed to be due to differential movement of positive and negative electricity along or through a conductor, whereas static electricity is the phenomenon associated with opposite charges separated and virtually at rest with respect to each other.

In this bulletin "static electricity" is used in its commonly accepted meaning to include the various manifestations that result from the coming together or neutralization of positive and negative charges which have been separated by friction between unlike substances or otherwise.

Although static electricity is one of the most common phenomena in nature it can not always be detected except with delicate instruments and frequently escapes notice. But at times conditions for its manifestation are particularly favorable, and it is recognized by the appearance of a spark or the mutual attraction of oppositely charged bodies or perhaps by the physiological effect known as shock. One of the most familiar manifestations of static electricity is the rasping, crackling noise often heard during radio reception. This noise usually is due to electromagnetic waves from a distant spark or, more directly, to actual discharge through the receiving set of electricity picked up from the ever-charged atmosphere.

Probably everyone has observed other manifestations of static electricity, such as the crackling or sparking that accompanies the stroking of a cat's fur and the combing of one's hair in cold, dry weather or the sticking together of sheets of paper suddenly torn from a pad or rubbed. In whittling or planing wood the shavings often cling to the blade or hand. Mason (1)[3] states:

> It sometimes occurs that on brushing the clothes it seems impossible to remove the dust and the more vigorously the brush is wielded the more tenaciously the dust seems to stick. This is due to the electrification of the cloth and the consequent attraction of the dust particles.

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[1] Work on manuscript completed December, 1931.
[2] Assistant electrical engineer, U. S. Bureau of Mines.
[3] Numbers in parentheses refer to bibliography at end of this bulletin.

When weather conditions are favorable charges are sometimes picked up by a person walking across a deep-pile rug, and a spark intense enough to ignite gas can be drawn from the finger.

Lightning is no doubt the most spectacular and in itself the most dangerous discharge of static electricity; but the unsuspected, seemingly insignificant sparks from built-up charges through unintelligent handling of inflammable and explosive materials are perhaps a greater industrial hazard. Explosions initiated by such sparks have been particularly common and severe in the grain and oil industries, but the danger exists wherever combustible dusts or vapors are handled.

In recent years much study has been given dust explosions, particularly in coal mining and in threshing, handling, and milling grain; and numerous articles have been written. The United States Bureau of Mines (2) has made an exhaustive research with large-scale coal-dust explosions in its Experimental Mine at Bruceton, Pa.; and much has been learned on the ease of ignition, speed of flame propagation, pressures developed, and means of preventing such explosions. Rock dusting has been developed to a high degree of perfection as a preventive measure. Other countries, especially Great Britain and France, have devoted much study to these problems.

The principal work in this country on the study of dust explosions in grain-handling and milling plants has been that of the chemical engineering division of the Bureau of Chemistry and Soils, United States Department of Agriculture, under David J. Price (3, 4). Because of its experience in this field the Bureau of Chemistry and Soils has assisted in investigations of dust explosions in many other industries, especially those preparing or manufacturing starch, sugar, sulphur, cork, and wood (5, 6).

In this country alone the damage from dust explosions has totaled many million dollars, and hundreds of lives have been lost. The growth of this hazard has been notable.

Although small dust explosions had undoubtedly occurred before, the first large-scale dust explosion seems to have occurred in a coal mine at Haswell, England, in 1844 (7). Faraday, in 1845, recognized the importance of dust as a contributing cause of this disaster. To-day such explosions are common, and dust is known to be one of the greatest industrial hazards.

In many bituminous-coal mines dust is a far greater potential danger than methane (fire damp), although an explosion of this gas usually precedes the more extensive coal-dust explosion.

Price states (8) that in 1929 more than 28,000 manufacturing plants in the United States, employing some 1,325,000 workers and with a total output valued at more than 10 billion dollars annually, were liable to dust explosions. Although dust explosions in these growing industries have occurred with increasing frequency during the past 20 years, marked progress has also been made in combating the evil.

Sugar and starch are conspicuous among dusts for their ease of ignition and violence of explosion, and many disastrous explosions have occurred in their manufacture. Whether the substances themselves or the methods employed in their manufacture are at fault, these dusts seem unusually susceptible to ignition by static electricity.

Beyersdorfer (9) reports that five sugar-dust explosion disasters occurred in Germany during the 10 years preceding 1922. As a result of these and other disasters he thoroughly investigated the nature and cause of sugar-dust explosions. Some results of this research are discussed later, but the following statement from his conclusions is of interest here:

> The technical possibility of thermal as well as electrical causes of dust explosions has been determined, and it has been found that the electrical cause is the more frequent.

Recent collation of statistics indicates that static sparks (10) initiate a large percentage of starch-dust explosions.

The widespread occurrence of static electricity in nature and in industry is brought to mind forcibly in the statements of two recent investigators. Amaduzzi (11) states:

> Electricity pervades everything: the most elementary molecular and atomic edifices, all material bodies, the earth, the sky, the universe.

According to Clark (12), fires caused by static electricity—

> are found to occur in the presence of cotton fiber or cotton dust; in machinery which handles or treats cereals, starch, and the like; in machines grinding sulphur and organic materials; and in locations where benzine, gasoline, or other inflammable liquids are being evaporated or discharged through pipes and orifices. The occupancies affected by the hazard include rubber mills, cloth-coating plants, japanneries, dry-cleaning establishments and other places where inflammable volatiles are used, cotton gins, card and picker rooms of cotton mills, threshing machines, grain elevators, grain-cleaning machines, and in sulphur and dye grinding operations.

The growing importance of this subject has prompted an investigation of static electricity as a possible cause of some mysterious gas and dust explosions in coal mines. Thus Rees (13) believes that in many such disasters "since other possible causes can be eliminated in turn, it is possible that obscure electrical effects * * * form the true solution," and Hargreaves (14) has expressed the opinion that "static electricity has played a very important part in coal-mine explosions." Before a program of experimentation was adopted to determine, if possible, some questions raised in this connection, a large amount of literature bearing more or less directly on the subject was studied. The author believes that much of this material has general interest and sets forth in the following pages the most important facts disclosed.

Although the scope of this report is rather broad, it deals primarily with static electricity as a hazard. Casual and experimental observations recorded herein are thus given for a background and for the purpose of suggesting *hazards not yet recognized*. Emphasis has therefore been placed upon the *fact* of electrification and the possibility of spark discharge rather than upon the purpose of the various experiments reported or interpretation of their results.

In considering the statements made in this paper, particularly in connection with reported accidents and their causes, the reader should remember that some of the information is third or fourth hand or perhaps only a rumor. The fact should not be overlooked that in disasters mental stress and imagination may lead witnesses to exaggerate the importance of observations.

To preserve the original opinions set forth and to guard as much as possible against the introduction of his own convictions, the author has made extensive use of quotations in this review although, of course, selection and arrangement of such quotations imply a certain prejudice.

The bibliography of the literature studied contains only a small part of the literature available on static electricity and kindred subjects, but it is believed fairly representative and adequate.

ACKNOWLEDGMENTS

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Part 1.—GENERAL OBSERVATIONS AND EXPERIMENTS

EARLY HISTORY

600 B. C. TO 1600 A. D.—ELECTRIFICATION FIRST OBSERVED

No article on static electricity seems quite orthodox which does not state that Thales of Miletus made the first observation of electrical effects other than those due to atmospheric electricity. About 600 B. C. this philosopher noted that amber rubbed with silk could attract light bits of straw, lint, and other materials. Although virtually all substances are now known to acquire this property to some extent, the ancients knew but two—elektron (amber) and lyncurium (supposedly tourmaline or topaz). Electrical attraction was long confused with magnetism, which had been observed in loadstone as early as 2637 B. C. and employed in navigation for centuries (15). The attraction produced by friction, however, was erratic and short-lived and had no practical application; it seems to have aroused no particular interest until about 1600 A. D. However, two other effects of static electricity had received some superstitious attention. St. Elmo's fire—a pale, phantomlike glow sometimes observed at the top of ship masts—was considered a good or a bad omen by navigators, depending upon the type of its appearance. Sparks generated in combing or rubbing the hair were usually attributed to supernatural power.

GILBERT—ELECTRICS AND NONELECTRICS

In this day of scientific achievement one can hardly realize that the first glimmers of light on the nature and universality of electricity were seen but a little more than 300 years ago, for it was then that William Gilbert, called the "father of electric and magnetic science" (16), published De Magnete, the first report on this subject. One of Gilbert's most important discoveries was that many substances besides amber could, by rubbing, be endued with the power of attraction. He states (15):

> An ordinary piece of amber * * * attracts by friction, without which latter, few bodies give out their natural electric emanation or effluvium. * * * By friction a body is made moderately hot and also smooth; these conditions must in most cases concur.

Gilbert believed that bodies which give off odors upon being rubbed were the most easily electrified "because their effluvia are stronger and more lasting." Substances that could be electrically charged he called electrics, and those that could not be charged, nonelectrics. Careful observation convinced him that "all bodies are attracted by electrics save those which are afire or flaming, or extremely rarefied" and that heat from the sun heightened by means of a burning glass "dissipates and spoils all the electric effluvia. * * * Moist air blown from the mouth, moisture from steam, or a current of humid air from the atmosphere" were also recognized as inhibiting or dissipating conditions. Many of Gilbert's observations were made possible by his invention of the versorium, a simple form of electroscope consisting of a delicately pivoted needle capable of moving by attraction toward any weakly charged body.

CABÆUS—ATTRACTION AND REPULSION

In 1629 Cabæus discovered that bodies after being attracted to a charged electric were often repelled immediately, but more than a hundred years passed before this action was explained satisfactorily.

VON GUERICKE—FRICTIONAL ELECTRIC MACHINE

After Gilbert's investigations interest in the new science grew rapidly. Great impetus was given its study in 1660, when Von Guericke invented the first electric machine—a large sphere of sulphur mounted on a spindle so that it could be rotated with a crank while friction was applied with the palm of the hand or a piece of fabric. More efficient frictional machines were soon developed, and static electricity for experiment and entertainment was readily obtained.

GRAY—CONDUCTORS, ELECTRICAL TRANSMISSION

In 1729 Stephen Gray made the important discovery that some bodies are conductors and others nonconductors of electricity. Shortly afterward he and a friend transmitted a charge of electricity 650 feet along a wire supported on insulators (nonconductors) of silk thread. Gray also discovered that static charges normally reside only upon the outside surface of hollow conductors.

DUFAY—TWO KINDS OF ELECTRICITY

Charles Dufay repeated Gray's experiments in 1733. His interest was directed particularly to insulation; he soon discovered that the real difference between electrics and nonelectrics is in conducting ability and that under suitable conditions all substances can be electrified. Thus he wrote (17): "Electricity is a quality universally expanded in all the matter we know, and which influences the mechanism of the universe far more than we think." Perhaps his greatest discovery, however, was that there are two kinds of electricity. That found upon glass and crystal he termed "vitreous" and that upon amber and copal, "resinous." Dufay also established the fundamental law that like charges repel and unlike charges attract.

VON KLEIST—INVENTION OF CONDENSER

One of the most important advances in the field of electrostatics was Von Kleist's invention of the Leyden jar, in 1745 (16). This device, which can store a strong electric charge in a small space, was the forerunner of the modern condenser which has such wide application in electrical engineering. It is simply a bottle or flask of good-grade hard glass coated within and without about two-thirds of the way to the neck with tin foil. Two opposite electric charges may thus be brought close together and bound in small compass by mutual attraction without the possibility of neutralization, that is, actually coming together. A condenser embodies the same principle; but the separating material or dielectric, as it is called, is usually in sheet form and is placed alternately between several conducting plates.

CANTON—ELECTROSTATIC INDUCTION

In 1754 John Canton discovered electrostatic induction and additional facts regarding the two kinds of charge. He (17) noticed—

that an insulated body under the influence of a neighboring charge acquired two charges, the one nearest the influencing charge being of the opposite kind and the one farthest away being of the same kind, as the inducing charge, and that they disappeared on the removal of the latter. If, however, the insulated body were touched prior to the removal of the inducing charge, it was left with a charge of the opposite kind.

Long before electrons were discovered electricity was believed to be corpuscular, and its movements to the outside of conductors and its distribution over large surfaces were thought due to mutual repulsion of similarly charged particles. In the induced charges just mentioned, removal of the remotest charge by touching was effected by providing a much larger area (a person's body), upon which it could expand and become rarefied. It was early discovered that the most effective way of removing a charge was by grounding or earthing it. Müller (18) says:

Electricity always distributes itself according to the amount of surfaces on passing from one insulated conductor to another; in order, therefore, to deprive an insulated conductor of all its electricity, we must bring it into contact with another, having an infinitely larger area, as for instance with the ground, for it is thus brought in contact with the whole earth's surface in which its electricity is wholly lost from being regularly distributed over so vast an extent.

By 1754 it was generally believed that all bodies contain equal quantities of two electric "fluids." In the natural state of a body these fluids were supposed to neutralize each other, but by friction they could be separated entirely or in part, resulting in an unbalanced condition or charge. Fonvielle (19) says:

This neutral electricity is especially remarkable for the surprising facility with which it is decomposed into two elements, the sole ambition of which seems to be that of combining together again and which agitate the material world in endeavoring to attach themselves one to the other. It seems as if nature had given to the electric matter a species of soul, similar to those Plato speaks of, which are composed of half of a being and only find repose when they have met with the other half of which they are deprived.

This idea of the neutralization of opposite charges led to their designation as positive (+) and negative (—), which, though purely arbitrary, is an improvement over Dufay's nomenclature.

FRANKLIN—SINGLE-FLUID THEORY

Benjamin Franklin (17), who definitely established the identity of static sparks and lightning, believed that there was only one electric fluid in matter—an excess giving a positive charge and a deficiency a negative. Strangely enough, the essential parts of both Franklin's theory and the 2-fluid theory find a place in the present-day conception of electricity.

Not so closely related to present considerations, but equally important, are the discoveries and work of Coulomb, Cavendish, Laplace, Biot, Poisson, and others, who developed the theoretical and mathematical foundation of this branch of electrical science.

VOLTAIC ELECTRICITY—ELECTROPHORUS

With the discoveries of Galvani and Volta near the close of the eighteenth century that an electric current may be set up by mere contact of dissimilar metals attention was largely diverted from frictional electricity to the newer and more promising form, and the "conception arose that common electricity was electricity in tension and that voltaic electricity was electricity in motion" (17).

Volta is said (20) to have recognized the probable identity of voltaic and frictional electricity as propounded years later (1882)

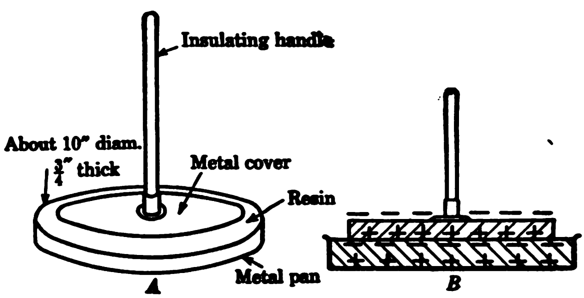

FIGURE 1.—Electrophorus (Volta)

by Helmholtz (21). Volta made other important and perhaps more obvious contributions to electrostatics, no doubt the greatest being his invention of the electrophorus. This simple device, which so well illustrates a number of the principles of static electricity and forms the basis for later important inventions, including all of the highly efficient static machines of the "influence" type, merits a brief description (see also fig. 1, *A*) (22).

If the plate of resin or, as in later forms, ebonite is rubbed briskly with cat fur or flannel it becomes strongly charged with (−) electricity. As no readily prepared surface is an exact plane, the cover when placed upon the nonconducting resin acquires only a negligible amount of the resin's charge but has opposite charges induced upon it according to the principle discovered by Canton (see fig. 1, *B*). If the cover is now removed by means of its insulated handle, first being touched momentarily with the finger to liberate the repelled (−) electricity, it is found to have a strong (+) charge which may be withdrawn as a bright spark. The cover may be replaced, touched, removed, and discharged repeatedly with no diminution of effect except that due to the slow leakage of charge from the resin plate to the air. It is important to note, however, that although a large amount of electrical energy may be accumulated thus, it is acquired only as a transformation of the mechanical energy expended first in separating the initial charges on the fur and plate and then in separating the plate and cover, gravitational and atmospheric resistance being neglected.

Lichtenberg (23) is said to have built an electrophorus 6 feet in diameter, from which sparks 16 inches long could be obtained.

MAGNETO ELECTRICITY

Magneto electricity—that produced by the movement of conductors through a magnetic field—which now is almost the exclusive source of electric light and power, need not be discussed here, nor the related work of Oersted, Ampere, Maxwell, Faraday, and many other brilliant investigators of the nineteenth century. The work of some of them, however, is mentioned in other parts of this report.

DYNAMIC ELECTRICITY

Electricity moving along a conductor as current and as a result of an electric pressure or difference of potential is known as dynamic or kinetic electricity. Much of the useful work performed by an electric current is due to the fact that it produces a magnetic field. An electric charge moved from place to place even by ordinary mechanical means is accompanied by magnetic effects which may be very pronounced when the movement and charge are great enough, as they sometimes are during electrical and magnetic storms. During the discharge or neutralization of static electricity a current may flow momentarily, when the phenomena are, strictly speaking, those of dynamic electricity (24).

DEFINITION OF STATIC ELECTRICITY

According to Atkinson (25):

> The terms used to distinguish different classes of electric phenomena, as *frictional*, *static*, *galvanic*, *chemical*, *magneto*, *thermo*, take their origin from the different methods by which electricity is generated and the various conditions under which its phenomena have been observed and should not be understood as referring to any difference in the nature of the electricity produced. The term "frictional" has been used to designate that class of phenomena now under consideration, since friction is one of the principal agencies by which the electricity is generated. But it seems more appropriate to use a term embracing not merely one agency by which the electricity is generated but also the various phenomena produced and distinguishing these phenomena from those pertaining to electricity generated by other methods. And since these phenomena refer chiefly to electricity when stationary, the term "static" from the Latin "sto," to stand, has been adopted to distinguish electricity observed under these conditions from electricity observed chiefly in a state of motion.

MODERN INVESTIGATIONS

ELECTRICAL NATURE OF MATTER

The present era of advancement in physical science may truly be said to have begun with discovery of the electron. So important has this discovery become that all matter must in the last analysis be regarded as electrical. Undoubtedly, therefore, all electrical phenomena are fundamentally electronic.

The idea that electricity is corpuscular vaguely permeated the writings of many early investigators (16). Among the most suggestive evidences of such a structure was Faraday's discovery that "the movement of a certain quantity of electricity through an electrolyte is always accompanied by the transfer of a certain definite quantity of matter from one electrode to another." In 1881 Helmholtz wrote, "If we accept the hypothesis that elementary substances are composed of atoms, we can not well avoid concluding that electricity also is divided into elementary portions which behave like atoms of electricity."

Toward the end of the third quarter of the nineteenth century it therefore became clear that electricity, whatever be its nature, was associated with atoms of matter in the form of exact multiples of an indivisible minimum charge which may be considered to be "nature's unit of electricity." This hypothetical ultimate particle of electricity was christened "electron" by Prof. Johnstone Stoney in 1881.

Among early discoveries that led to the present knowledge of these particles was that, although gases at ordinary pressures offered high resistance to the passage of electricity through them, the resistance was greatly lowered if the pressure was reduced enough. The passage of electricity through tubes filled with certain gases gave beautiful effects of light and exhibited other phenomena which aroused considerable interest. "Many eminent physicists had an instinctive feeling that the study of the passage of electricity through gases would shed much light on the intrinsic nature of electricity." The studies of Varley, Hittorf, Crookes, and others demonstrated that the discharge consisted of actual particles which seemed to proceed from the (−) terminal or cathode. In a remarkable series of experiments beginning in 1897 Thompson showed that these (−) particles or corpuscles, as he called them, had a mass of only about 1/2000 [4] that of an atom of hydrogen, although they carried a charge of the same magnitude as had previously been determined for hydrogen in electrolytic solutions.

Contemporary discoveries in radioactivity and the vast amount of study and research devoted to these subjects since the dawn of the present century have revealed many of the secrets long sought in regard to the nature of electricity and the constitution of matter. It is now generally believed that every neutral atom in the universe is a balanced system of unit electrical charges; that is, it is a nucleus having a preponderance of positive charges or protons surrounded by a requisite number of unit (—) charges or electrons, the kind of substance or matter being chiefly determined by the charge of the nucleus (26).

In every solid body there is a continual atomic dissociation, the result of which is that mixed up with the atoms of chemical matter composing them we have a greater or less percentage of free electrons. The operation called an electric current consists in a diffusion or movement of these electrons through matter.

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[4] Recent determinations assign to the electron a mass of between 8.944 and 9.035×10^{-28} grams, or about 1/1844 that of a hydrogen atom. Its charge is given as 4.77×10^{-10} absolute electrostatic units (E. S. U.) (27).

But while—

the electrons can move freely through so-called conductors, their motion is much hindered or restricted in nonconductors. Electric charge consists, therefore, in an excess or deficit of negative electrons in a body (16).

By various means other than spontaneous disintegration an atom may be stripped of one and sometimes more outer electrons, leaving it with an excess of (+) charges. Such an atom is called a (+) ion. A liberated or free electron, on the other hand, may be acquired by a neutral atom, which then becomes a (−) ion. The same is true of molecules or groups of atoms. A molecule with more than a normal amount of electrons is a (−) ion and one with less a (+) ion.

A body or group of many molecules is said to be ionized when a number of its molecules have by some method become ions. A solution containing free ions is called an electrolyte. Electrolytes are formed spontaneously when salts, acids, or alkalies are dissolved in water. Of importance in connection with static electricity is the fact that upon the surface of many solids exposed to a normal atmosphere is a thin film of moisture which may have become a highly ionized solution by its dissolving action upon the solid (28, 29). Moreover, according to Thomson (30):

There are numerous reasons for believing that the arrangement of the molecules at the bounding surfaces of bodies is different in many cases from the interior arrangement. The remarkable phenomena of surface tension are to be explained on this basis.

Studies of the special orientation of surface molecules—

tend to show that the surface conditions bulk large in many of the phenomena of nature. Contact electricity is undoubtedly intimately associated with some of these phenomena (30).

Many theories have been advanced to explain these surface conditions and their part in the production or manifestation of static charges. Thus, to explain the electric potential at certain interfaces, Quincke, Helmholtz, Lenard, Gouy, Nernst, Langmuir, and others (31) have developed the idea of a double layer of molecular dimensions in which (+) and (−) ions are normally arranged in a somewhat definite order; for example, according to one conception the outermost surface of pure water in contact with air is composed of OH^- ions, while just beneath it is an H^+ layer.

Freundlich (32) says:

It is obviously necessary to analyze every frictional electrical process, particularly with the object of deciding which electrical double layer is actually torn apart, how thick the adsorbed layer of water is under the experimental conditions, how strong the mechanical tangential force is, and what are the rubbing surfaces * * *. Upon close contact of the rubbing particles [he is here speaking of the electrification of dust] the adsorption layers are partly combined; during the rubbing they are again torn apart. Where this process of shearing will tear the double layer can not be predicted and can only be determined by particular examination of the experimental conditions. Anyhow, it is not difficult to recognize that according to the circumstances the particles may remain behind positively or negatively charged.

It may be postulated, therefore, that any process by which portions of a double layer can be separated will result in external manifestation of an electrical charge.

During recent years many experiments of early investigators have been repeated and extended in an effort to clarify some discrepancies and to learn more of the true nature and cause of electrification. In addition, the annoyance and danger of static electricity in the rapidly growing industries and its interference with communication have demanded an investigation of many of the related problems.

Among other things, these studies have shown that, except in a restricted sense, the terms "frictional" and "tribo" electricity are misnomers (30), for several means other than friction are capable of producing static electric charge. In presenting the following groups of experiments and observations the author has attempted to arrange the subjects according to the state of matter involved and the treatment supposed to be responsible for the charge. Such arrangement is necessarily arbitrary in places; for example, a dust cloud is composed of both solids and gas and might be supposed to receive its electrification either through friction or impact of particles.

ELECTRIFICATION OF SOLIDS

BY FRICTION

During the early study of static electricity investigators devoted much time to arrangement of materials in lists or electrostatic series, as they are called. In the following list, found in Ganot's Physics (22), the substances are arranged in such order that each becomes positively electrified when rubbed with any of the bodies following, but negatively when rubbed with any that precede it—

1. Catskin.	5. Glass.	9. Wood.	13. Resin.
2. Flannel.	6. Cotton.	10. Metals.	14. Sulphur.
3. Ivory.	7. Silk.	11. India rubber.	15. Gutta-percha.
4. Rock crystal.	8. The hand.	12. Sealing wax.	16. Guncotton.

High charges are obtained most easily if the two substances selected are far apart in the series. Considering that the very foundation of matter is electrical it is not surprising that the arrangement of materials in an electrostatic series often corresponds closely with arrangements based upon other physical or chemical properties (29).

Although such electrics behave, in general, according to rule, some of them have been found either to remain neutral after rubbing or show reversed sign under certain conditions. At times a given body may become charged negatively but upon greatly prolonged rubbing appear positive. Shaw, Richards, Vieweg, and others have carefully studied these irregularities. A few interesting facts gathered from their experiments follow.

According to Shaw and Jex (33), solid surfaces may be modified in two ways: (1) Addition of material, such as adsorbed films of gas or water vapor; and (2) physical changes, as by strains or reorientation of surface particles. The test pieces for most of their experiments considered here were small glass rods very carefully prepared, cleansed, and rubbed with well-cleansed masses of fibers and fabrics. It was found extremely difficult to cleanse the latter perfectly, and the slightest trace of organic oil or wax therein caused erratic results. All test pieces were handled with clean tongs. Two uncharged glass rods when rubbed together developed no appreciable charge, but when one was slightly heated it acquired a (−) charge due perhaps to expulsion of water vapor.

Although the glass rods ultimately received a (+) charge when rubbed with ordinary or impure textiles, when materials were absolutely free from contamination the glass could receive only a (−) charge, regardless of the extent of rubbing. An interesting relation was shown between this behavior and the character of the glass surface. Continued rubbing with ordinary textiles changed the coefficient of friction for glass, and a critical value ($\mu=0.18$) was found below which the glass received a (+) charge and above which a (−) charge; if, then, the glass surface was near this critical state, it could receive either a (+) or a (−) charge, depending on whether the pressure of rubbing was light or heavy. Because of their effect on the coefficient of friction yarns and mixed fabric charged glass (+) or (−), according to whether rubbing was along or across the surface fibers.

If the rods which had been rubbed were left exposed to the air, they slowly regained their original coefficient of friction—$\mu=0.5$ or 0.6.

Similarly, Owen (34) has found that less work is required to develop a given charge upon a previously rubbed surface than a fresh one.

Reviewing the work of several earlier investigators, Vieweg (29) points out that many substances, such as fur, paper, wood, and cloth, often found in triboelectric series, can not be described accurately and should not be expected always to give reproducible results. He therefore arranged a new series, comprising chiefly such materials as pure chemical compounds, elements, and crystals. He discusses difficulties encountered in building up an electrostatic series, considering particularly substances with reversed polarity, and shows that different crystal faces of the same substance give different potentials, which in some instances may be enough to make the position of the substance in the series uncertain. In rubbing two substances together he found that the most consistent results were obtained when pressure was applied, because of "the adsorbed films [35, 36] which exist on some surfaces, the properties of which, rather than those of the surfaces themselves, are tested by gentle rubbing." Vieweg also made careful determinations of the effect of humidity upon the charge acquired by friction and found that moisture on a substance always adds to it a (+) charge. He states:

> The naturally negative substance might be negative, neutral, or positive; the other surface was always positive. In the extreme case, where the substances had come to equilibrium with an atmosphere saturated with water vapor, the general result was to charge any two substances positively.

The corresponding negative charges were shown to have been acquired by the air. Under certain conditions this effect was so great, indeed, that the positions of two substances in the series were reversed. Experiments with weak solutions of acids and alkalies applied to the surfaces gave interesting results. Critical concentrations of these electrolytes were found below and above which opposite charges were manifested. He states further:

> It is evident that since certain films on the surface of a solid tend to add a negative charge while others tend to add a positive one, the possible variations

of effects are many. For example, the normally positive surface might have on it a film which would acquire a negative charge, while the other substance was covered with a film tending to become positive. The results obtained in this case would vary with the extent to which the two solids were rubbed together. No doubt much of the confusion in the past has been due to effects of this nature. * * * The necessity of working in the absence of moisture, if reproducible results are desired, is apparent.

Richards, however, contends (37) that—

if electrification by friction were an exceedingly small and fugitive effect, the lack of agreement among the data obtained by different experimenters might reasonably be attributed to undetermined contaminations of the surfaces of contact; but the triboelectric charges are, on the contrary, so large that the inability of one observer to reproduce the results of another or, indeed, his own, must clearly be referred to other causes. Of the alternative explanations which may be suggested, the most probable and, if found true, the most important, is that the frictional charge results from the superposition, in proportions varying with the manner in which contact is made, of two or more different effects.

Many investigators have concluded that electrification of dielectric substances by friction is similar to voltaic electrification in dissimilar metals and that friction or pressure simply serves to establish good contact. The existence of this voltaic effect seems to have been clearly demonstrated by Richards, and his experiments show that—

previous discrepancies may be ascribed partly to the impossibility of defining the area over which contact actually occurs in the usual experiment of rubbing a hard solid with a soft buffer, partly to an electric effect of compressing an amorphous material, and partly to the fact that in certain cases the relative velocity of two bodies at the moment of contact determines whether or not an effect due to the inertia of the mobile electrons [38] will be sufficiently large to mask the voltaic electrification.

In connection with the influence of surface contamination, Jones (39) claims that bodies rubbed together in various gases and even under oil still exhibit a charge of the same sign as when rubbed in air.

BY IMPACT

Several investigators believe that electrification by friction is so likely to be influenced by unknown factors that another method should be employed if reliable information is to be obtained. One method which has been considered favorably is that of impact. When two bodies collide, electricity separates and the bodies become charged. By dropping small spheres of dielectric or insulating materials upon a metal plane Richards (40) obtained charges ranging from 0.16 to 9.83 E. S. U. with potentials of 2.41 to 183.8 volts. It was found that the magnitude of the charge depended more upon the velocity than upon the mass of the impinging sphere but that the electrical energy showed no direct dependence upon the mechanical energy lost in impact. By this method readings could be duplicated, and there was no evidence of the erratic variations which had so often characterized electrification by friction. However, in four tests, at least, the sign of the charge was opposite to that produced by rubbing the same substances together, an effect which seemed to be attributable to a change in the relative importance of two distinct charging mechanisms, one the contact (or voltaic) electrification and the other a separation due to the inertia of " free " electrons.

Tagger (41) mounted spheres of glass, ebonite, hard rubber, and other substances upon the end of a swinging arm so that they could be made to fall upon a polished steel anvil at known velocities. Comparison of the charges developed with the amounts of mechanical energy involved indicated that the energy available as charge was only a small part, probably less than 1 per cent, of the total transfer of energy.

BY PRESSURE

It is well known that quartz and other crystals show electrical polarity when pressure is exerted upon them. Electricity produced thus is called piezo-electricity. This property of quartz crystals especially is utilized in certain types of high-pressure manometers. The fact that such crystals also show the converse effect—that is, change their dimensions slightly when placed in an electric field—has been utilized in radiobroadcasting in a device which keeps the carrier wave at absolutely uniform frequency.

By wringing together (pressing tightly with a slight rotary motion) optically flat surfaces of glass and steel, Richards (37) found that the charge formed was independent of the amount of friction once intimate contact was established, and that it was proportional to the area of contact. He discovered that ionization of the residual air molecules between the plates by means of a strong beam of X rays in no way diminished the charge, and that it persisted even after the plates were in contact for many hours, thus apparently proving the presence of a true voltaic field.

By pressing two kinds of sheet rubber having dielectric constants of 2.94 and 3.96 against seven hard materials having dielectric constants of 2.8 to 7.8, Richards obtained charges which were independent of the nature of the material against which the compressible dielectric was pressed, proving, it was believed, that the effect here was not that commonly known as voltaic and that amorphous as well as crystalline substances can be electrified by pressure.

When two bodies are in close contact, electrification upon the adjacent surfaces is of low voltage and can be observed only indirectly. With metals or other good conductors an appreciable current may be made to flow in evidence of it; but with nonconductors elaborate technique is required, and few determinations have been made.

Richards's ascertainment of voltaic charge on such bodies, however, has been mentioned. More recently Perucca (21), using an induction method, has made measurements of the potential difference between glass and oil, which he believes "are a strong argument in support of the contact theory of triboelectricity."

BY CLEAVAGE

Splitting or fracture along cleavage planes of crystalline or laminated bodies is often accompanied by a manifestation of static electricity. Before such a separation, however, the laminæ have been in intimate contact, and the electrical elements have adjusted themselves along the interfaces in some sort of polarized equilibrium. Cleavage is therefore not the initial cause of the separation of charges, but the means whereby they are further separated and given potential energy. Therefore, cleavage, or, in its less restricted meaning, separation, should perhaps be considered not so much a distinct method of electrification as a factor in most, if not all, methods.

Thus, in speaking of frictional electricity Naylor and Ramsey (42) state: "Friction has been merely the means of securing intimate contact, which has been immediately followed by separation, causing such an increase in potential as made the charge readily evident." It is easily seen that the same process is involved in electrification by impact. The role of separation is made clear when the following fundamental electrical relationships are considered.

$$E=\frac{Q}{C}, \tag{1}$$

where E=potential difference in volts, Q=quantity of charge in coulombs, and C=capacity of system in farads.

$$C=K\frac{A}{X}, \tag{2}$$

where X=thickness in centimeters of the separating medium or dielectric, A= cross-sectional area in square centimeters of the space between the charged surfaces, and K=a constant whose value is determined by the nature of the dielectric. Therefore

$$E=X\frac{Q}{AK}. \tag{3}$$

Since K, A, and Q may be regarded as unchanged, the voltage is directly proportional to the separation.

In connection with static machines of a certain type Thomson (30) points out that the potential difference caused by contact of the plate and rubber may be of the nature of only a few volts or less; but as the plate moves away, the great change in the capacity of the system causes a corresponding change in voltage. After a certain point is reached, at which presumably the maximum contact is made, further increase in pressure of the rubbing pad, though sufficient to heat the glass plate, will not increase the electrical output of the machine.

If cork and glass are pressed together and separated, they will be found to be charged. Glass dipped in clean, dry mercury and withdrawn takes on a noticeable charge. Coehn and Lotz (43) have shown that a wax-coated metal ball immersed in distilled water acquires a strong (−) charge. Boning (44) states:

> When pieces of wax, icicles, sugar, or other substances are broken or when folded film or paper is torn apart, the separate pieces show electrical charges of different sign. A number of the processes show in the dark an appearance of light at the places where they separate, as for instance sugar, films, etc. Which one of the pieces will be (+) and which (−) can not be determined in a particular case; the average of many experiments show as many pieces to be (−) as (+).

If large crystals of sugar or pieces of hard candy are forcibly rubbed together in the dark or thrown upon a stone or pavement, brilliant flashes of light may be seen. Crystals of uranium nitrate shaken together show strong triboluminescence (45). A bright bluish glow may be seen at the boundary of cleavage in a roll of electricians' friction tape when a portion is rapidly unrolled; an almost identical example of static electricity, but on a large scale, is that developed upon the driving belts of machinery. Under suitable conditions, not fully understood, such belts often become very highly electrified, throwing out brush discharges to any object within a few feet and emitting a peculiar singing noise. Such charges may be due in part to friction produced by the belt slipping on the pulley and by its passage through the air; most, however, appear to be produced by the pressure and subsequent separation of the belt and pulley, and the highest charges occur near this line of separation (5). Voltages up to 80,000 have been measured on belts in various industries (44); Thomson (30) states that he has seen sparks several feet long jump from belts 4 or 5 feet wide. Generation of conspicuous amounts of electricity by this means, however, is relatively rare; many belts may be inspected before one is found which noticeably exhibits the phenomenon. Naylor and Ramsey (42) relate that in a certain plant three compressors of the same type, belt driven by individual 100-horsepower motors, were placed side by side. There seemed to be no difference in the operation of these compressors, yet only one belt showed electrification and that very strongly.

Nukiyama and Nakata (46) in quantitative experiments with laminated fabric, such as that used in the construction of balloons and airships, have found charges up to 26 E. S. U. per cm^2 on pieces of the cloth which have been stripped or pulled apart. Aluminum foil stripped from blocks of carnauba wax or shellac gave values of about 12 E. S. U. per cm^2.

BY INDUCTION

When any object is placed near a charged body or in an electric field, it becomes charged. If this object is a conductor, the two charges developed in it will reunite when the field is removed unless one of them is previously carried away by grounding or some other means. If a nonconductor or dielectric, the two charges will remain on the surface until brought together and neutralized through some conducting path. Usually leakage through the body itself will soon bring about this loss of charge. An apparent exception, however, was recently discovered. Certain wax mixtures, if melted and allowed to solidify in an intense electric field, are found to be highly charged and polarized, and these charges will persist for years even though the piece of wax is handled frequently. Such "permanently" charged bodies are called "electrets" (47, 48).

Inasmuch as any live conductor or power line is surrounded by an electric field, static charges can be induced in objects merely by holding them near such a wire. Ordinarily glass, sealing wax, ebonite, etc. (because of surface films which conduct the repelled charges to the hand), become electrified if held for a few seconds near a wire carrying direct current in a 200-volt circuit (33). High-voltage lines of course induce proportionately larger charges.

ELECTRIFICATION OF DUST

NATURAL

Whenever a cloud of dust is raised electric charges are developed, the amounts depending on a number of factors, such as the quantity of dust involved, the rapidity with which it is dispersed in the air, the nature of the dust, and the atmospheric conditions.

Above active volcanoes.—Nature provides large-scale examples of dust electrification. A spectacular effect sometimes attributed to charged dust (49) and sometimes to steam has frequently been observed in the pineal clouds formed above active volcanoes. These dark clouds of finely divided particles of ejected matter are often brightened by vivid flashes of lightning discharging through the cloud to the rim of the crater. At such times a sudden agglomeration and precipitation of dust may follow, the particles no longer repelling each other by their similar charge (7, 44).

In an interesting account (15) of the formation many years ago of a volcanic island near the Azores, Captain Tillard says:

> Suddenly a column of the blackest cinders, ashes, and stones would shoot up in the form of a spirè, rapidly breaking into various branches resembling a group of pines, these again forming themselves into festoons of white feathery smoke. During these bursts the most vivid flashes of lightning continually issued from the densest portion of the volcano. * * * In less than an hour a peak was visible and in three hours a crater was formed 20 feet high and from 400 to 500 feet in diameter.

Dust storms.—Because of their extent and violence, dust storms in the Sahara Desert are often accompanied by strong electric charges. Rudge (50), making investigations in South Africa where the climate on account of its dryness is eminently suitable for observations on atmospheric electricity, states that during a dust storm the potential gradient of the atmosphere, which normally seldom exceeds 200 volts per meter, may be reversed in polarity and rise to as much as 500 volts per meter (−). Contrary to expectations, both the dust particles and the earth's surface at the place were charged (−). Even the dust gently raised by a caravan of camels could change the sign of the air's charge. On the other hand, in England it was found (51) that the dust, which is usually calcareous, imparted an additional (+) charge to the atmosphere.

Because of its length an airship passing through a dust cloud may receive enough opposite charges to cause sparks. It has been suggested (44) that such sparks may have brought about the *Dixmude* disaster.

Kercher (7) observed a most unusual exhibition of dust electrification. He states that wind preceding an approaching storm one evening raised a cloud of street dust high into the air and that electricity thus formed discharged through the cloud with a flash of light.

In a sand storm near Las Cruces, N. Mex. (52), the charges picked up on a small radio antenna gave a rapid succession of sparks about 4 cm long. When the storm was at its height sparks up to 7 cm long jumped between the aerial and ground leads. At Lahore, India, high-voltage electrical discharges have frequently been observed (53) from radio antennæ during sand storms. Benade states:

> On a perfectly still day when the air is heavily laden with dust the aerial potential may fluctuate for hours between 5,000 and 10,000 volts, though * * * the current amounts to only about 1 microampere.

Occasionally such dust clouds have caused serious overvoltage on high-tension transmission lines.

During west Texas sand storms (54) the atmosphere is in a very unusual electrical condition. Severe shocks are sometimes received from radio antennæ, fence wires, and automobiles. Automobile ignition systems refuse to function in very severe storms.

A practical demonstration of dust electrification may be performed with a comparatively simple apparatus designed by Rudge (55) (see fig. 2, *A*). Sparks 4 or 5 cm long may be drawn from charge-collecting cylinder *b* after the machine has been operating a few moments with a fairly strong current of air. Rudge states elsewhere (56):

It does not matter much—save in respect to the sign of the charge—what the nature of the dust is, for sand, coal dust, flour, or iron filings all give rise to strong charges.

Dust-mixing chamber *a*, cylinder *b*, and the tubes are made of brass or other metal. Insulating support *c* and other shaded parts are of ebonite. The cylinder in the original design was about 5 cm in diameter and 25 cm long, but exact dimensions of the parts are said to be relatively unimportant.

Drifting snow.—If the definition of dust as "fine, dry particles of matter" is accepted, it may not be out of place to consider blizzards in this connection. In a snowstorm supported wires may be so charged as to give sparks; in one case (44) a telegraph line 5 km long discharged continuously through a gap of 3 cm.

Snow blown against a lump of snow or ice becomes charged (44); this charge is (+) on the smaller particles and (−) on the larger. Icicles suspended in the open air and exposed to wind-blown snow are said to show a (−) charge, but when suspended high above the ground so as to be struck by the finer snow they receive a (+) charge. Sand blown against sandstone also receives a charge.

EXPERIMENTAL

Lichtenberg.—Probably the first definite experiments with electrified dusts were Lichtenberg's, about 1776 (16). He discovered that dust shaken through a cloth bag becomes charged with (+) or (−) electricity, depending upon the kind of dust. By sifting a mixture of red lead and sulphur dusts upon an ebonite plate having an invisible design traced upon it with charged conductors of opposite sign, the particles will arrange themselves in falling so that the sulphur will mark out the (+) lines and the red lead the (−). This action has been very successfully utilized in studies of field distributions, leakage paths, polarity of other dusts, etc.

Davy.—In 1806 Davy (57) showed that dry, solid acids in contact with metal plates charged the latter (+), but that powders of dry, alkaline substances charged them (−).

Knoblauch.—Little more seems to have been learned about dust electrification until Knoblauch (28) reported his investigations in 1901. He made some 2,500 tests with many kinds of dust dropped from plates of platinum, sulphur, glass, and paraffin. Figure 2, *B*, is a diagram of the apparatus. In testing the nonmetallic plates they were fastened to a metal base and attached to the handle instead of the platinum plate shown in the figure.

In making a test the powder was placed upon the hinged plate and the ground connection closed. The connection was then opened and the plate tilted by the insulated handle until the dust slid off upon the grounded copper plate, the charge on the electrometer being noted meanwhile.

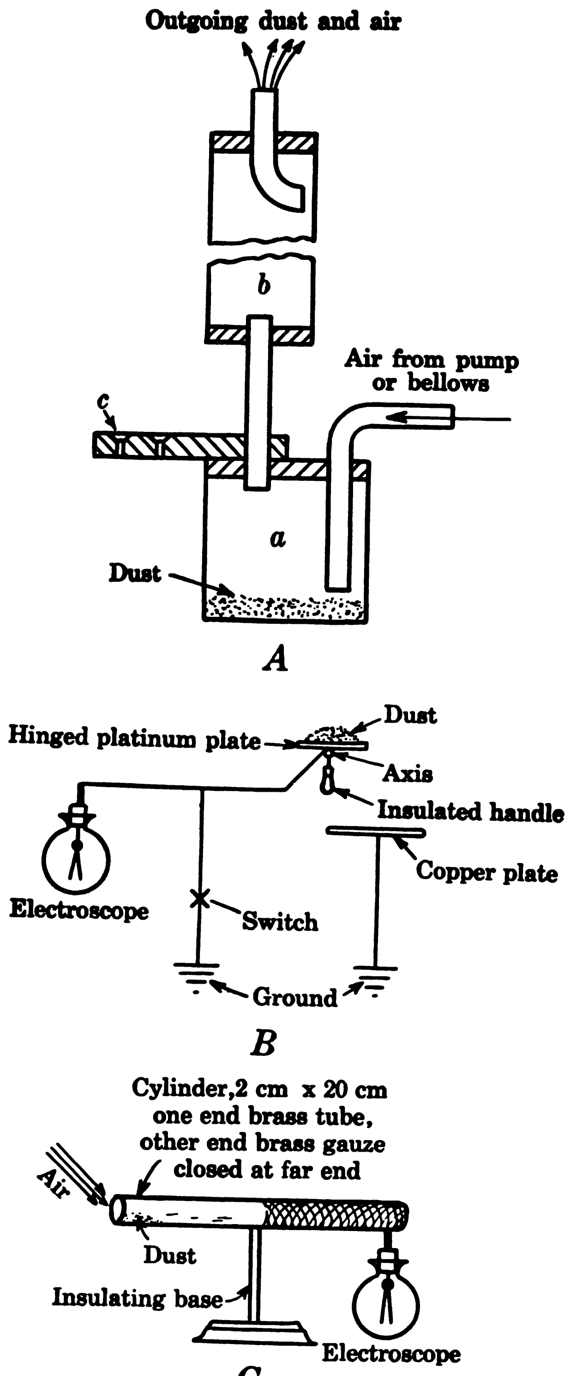

FIGURE 2.—*A*, Dust electrical machine (Rudge); *B*, apparatus for testing electrification of various dusts (Knoblauch); *C*, apparatus for testing electrification of dust clouds (Rudge)

Great care was exercised in handling the substances to prevent formation of undesirable charges before dust and plate were separated. Preceding each experiment the plates and special spoons (of the same material as the plate tested) were carefully cleaned and discharged by flame or otherwise.

The general results obtained follow. The platinum and paraffin plates were nearly always charged (+) with acid substances and (−) with alkaline. Sulphur was usually charged (−) but with a few acids (+). Glass was usually (+) but with a few alkalies (−).

These charges were believed to have been developed in an exceedingly thin film of water, perhaps only a few molecules thick, which is normally upon the surface of all bodies. As already mentioned, such a film of water may contain dissolved ions from the surface beneath. With glass the solution would be alkaline; with sulphur, acid; with platinum and paraffin, neutral or nonionized, etc. Most organic substances were believed to contain, if not acid or alkaline principles, esters which decompose in the presence of water to form alcohols and acids.

Assuming that such ionized liquid layers exist, two bodies in contact are actually separated by a double-film layer in which an exchange of ions occurs according to their concentration and mobility. Electrification by contact between two liquids was demonstrated by Davy in 1801 (58).

Knoblauch believed that insulators as well as metals can produce such ions but in much smaller amounts, the mechanism of the separation of charge thus being the same in each case. In this way a common cause was proposed for frictional and voltaic electrification.

Rudge.—Rudge's experiments, which seem to have been suggested by his extensive observations of natural dust electrification, have clarified the subject and form a groundwork for later investigators. The apparatus used in many of his experiments (51) was essentially that shown in Figure 2, *C*. A puff of air from a bellows was directed obliquely upon the pile of dust, which was scattered and driven through the gauze to which it imparted a charge. As a result of dozens of tests with a great many substances, the following rules were established:

1. Nonmetallic elements give positively charged clouds when the finely divided material is blown into a cloud by a current of air.
2. Metallic elements give negatively charged clouds when the finely divided material is blown into a cloud by a current of air.
3. Solid acids and acid-forming oxides give positively charged clouds and basic oxides negatively charged ones.
4. The charge upon the dust is opposite to that associated with the ion of the same substance when in solution.
5. In the case of salts, the charge apparently depends on the relative strengths of the acidic and basic ions.
6. Similarly constituted bodies give similar charges.

Tests with cylinders of finer-mesh gauze or chiffon indicated that the charges observed were actually carried by the dust particles and not by the air, which was believed to carry a charge of the opposite sign. From additional observations, however, Rudge concluded:

> That in all cases the charge upon the air is really due to very fine particles which do not readily settle or which move with such velocity that they escape capture by the charged electrodes used in certain experiments.

Observations which led to this conclusion follow:

1. A dust-and-air mixture blown through a gauze and thence upon a radioactive collector imparted to one obstruction a (—) charge and to the other a (+).
2. Other gases than air generally caused no difference in results.
3. Air blown over various dusts cemented to electrodes showed no charge unless particles of the dust were detached; air passing gently through a tube containing dust carried no charge unless some of the dust also passed through the cotton-wool plugs.
4. Oppositely charged electrodes placed in a dust-laden atmosphere each attracted a certain amount of dust. In most cases there was a marked difference in the amount of dust collected on the electrodes and the greater this difference the greater the charge carried away by the air. The charge carried away by the air was always opposite to that upon the electrode which carried the greater quantity of dust.

The first three observations show that the charges are not due to mere increase of surface contact or to friction between the air and the dust. Tests made by blowing dust through tubes of various materials which could be inserted in the apparatus shown in Figure 3 indicated that the nature of the substance from which, or upon which, the dust was blown did not affect the charge. Mercuric sulphide (HgS) developed the highest charge of any of the dusts tested; 0.00047 gram blown into the air caused a rise in potential of 6 to 8 volts, the density of the cloud being only 5×10^{-9} gram per cm^3. A few grams of corn flour blown into a room caused a rise in potential of 200 volts, which persisted for some time. Commenting upon these observations, Rudge says (49):

> It is thus easy to understand how the very high potential gradient—over 10,000 volts per meter—may arise during a dust storm.

It has already been pointed out that like substances rubbed together can become charged. Rudge states:

> It appears that practically every material is found to become charged when rubbed on another piece of the same material, the two pieces becoming oppositely charged.

But Hesehus states that two pieces of the same material receive the same kind of charge, whereas the fine dust which is abraded in the process has a charge of the opposite sign. Rudge, however, concludes, "The total electrification of dust and air is zero" (49).

Whitman.—The whole question of the residence of the charges apparently has been fairly well settled by Whitman's experiments (59) at the Uniated States Bureau of Standards in 1926. In these experiments—

> dust clouds were formed by blowing various pure chemical substances through tubes, and the net electric charge imparted was determined as a function of the composition of the dust, tube material, area of contact between dust and tube during the blowing process, velocity with which the dust moved through the tube, and length of path of dust through the tube.

By means of a "particle polarity recorder" the individual particles in a dust cloud were photographed as they fell between electrically charged plates. Whitman states:

> Such photographs show the presence of positive, negative, and neutral particles in all dust clouds even of very pure substances. The ratio of positive to negative electrification in a cloud is found to change as the larger particles * * * settle out, but evidence is obtained which contradicts the hypothesis that the large particles carry an opposite charge from the small particles in a given cloud.

Stager.—Stager's experiments (60) just before those of Whitman, however, indicate that distribution of the charges at least in some degree accords with differences in particle size. A fine screen moistened with glycerin and water was charged with one polarity by dust caught upon it, whereas the very fine dust which passed through had a charge of the opposite kind. Stager suggests that dust striking a screen and bouncing off thereby acquires a charge which may have led to large errors in the experiments of some former investigators. He refers to this source of error as the "screen effect."

Boning.—To develop if possible a new and more comprehensive theory of dust electrification, Boning (44) experimented with many kinds of dusts. Although the theory that electrification was brought about by friction or contact between dissimilar substances was generally accepted, Boning pointed out that charges could also be produced by the operation of like substances upon each other. Therefore, to isolate the essential mechanism, most of his experiments were performed with substances of like kind. These experiments were mostly confirmatory and in general upheld his belief that the charge was developed as a result of differences in size and mass of the dust particles. His idea was essentially that all particles carry with them rather loosely bound, very much smaller negatively charged particles, probably "free" electrons. He assumed that in collision the main masses behave like elastic spheres, the separation of electricity or "charging" of the particles being accomplished as follows:

Consider two colliding particles of the same substance:

(*a*) Mass (1) collides with equal mass (2). Result: An equal exchange of (—) charge.

(*b*) Mass (1) collides with smaller mass (2). Result: Mass (2) accelerates so fast that it loses its attached charge, which is gained by mass (1).

(*c*) Mass (1) collides with a larger mass (2). Result: Mass (1) rebounds and loses its charge, which is acquired by mass (2).

(*d*) General case of mixed masses of same or different material. Result: Charge determined by the net gain or loss.

Dust of various materials in suspension in air was blown through a grounded metal tube containing irregular pieces of material having the same composition as the dust and thence into a collector connected to an electroscope. In all tests the collector received a (+) charge; the (—) charge was left behind where collision with the larger masses occurred. (See fig. 3, *A*.) Readings of the electroscope corresponding to potentials of 3,000 to 9,000 volts were obtained thus.

In another series of experiments various dusts were sifted from a cloth bag and allowed to fall upon the collector of an electroscope (fig. 3, *B*, *a*). If the dust was a good dielectric (for example, sulphur), some of the (—) charges imparted to it by the sifting process were removed by grounding the electroscope; but those on top of the layer remained, and when the ground was removed an induced (+) charge was left on the plate (fig. 3, *B*, *b*). Then if the dust was gently blown away (fig. 3, *B*, *c*) this previously bound (+) charge became manifest. A similar effect was obtained, however, when the collector (fig. 3, *B*, *d*) was covered with a plate of sulphur, and the original charge (imparted by sifting) was removed by thermionic means before the dust was blown from the plate. Each of several other dusts tested was likewise negatively charged when blown from a surface of identical composition. Boning explains this last result by his "tearing-effect" hypothesis, according to which the duct acquires free electrons at the instant of separation from the plate.

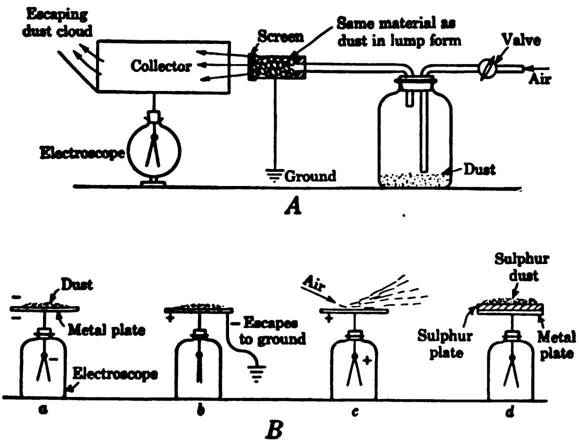

FIGURE 3.—*A*, Apparatus for determining electrification of dust clouds (Boning); *B*, method for determining nature of dust electrification (Boning)

Israel.—Israel (61) made similar experiments shortly afterwards. Charges were determined for 11 kinds of dusts blown from as many kinds of plates. In 71 combinations of the materials the dust carried a (−) charge. In a very few tests a (+) charge was noted, but this

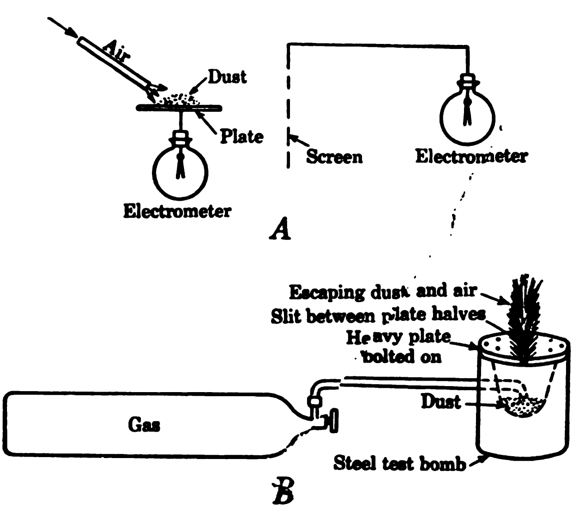

FIGURE 4.—*A*, Apparatus for determining electrification of dust clouds (Israel); *B*, method of demonstrating charge and luminescence of sugar-dust clouds (Beyersdorfer)

was not interpreted to imply that the usual charge mechanism was not present, but rather that some unknown factors had entered which overbalanced it. Israel's test set-up was essentially that in Figure 4, *A*.

While agreeing in part with Boning on the source of charge, Israel thinks that the carriers lost by collision, friction, or other means may not be electrons but simply vestiges of double ion layers. In connection with these hypotheses attention should be called again to the experiments of Tolman and Stewart (38), which showed that abrupt stopping of a rapidly rotating coil of wire results in a flow of current due to inertia of the free electrons in the wire.

Beyersdorfer.—In 1922 Beyersdorfer (7) thoroughly investigated sugar-dust electrification. Although many facts of scientific interest were brought out, the work was undertaken primarily to determine whether the formation of static charges might be seriously considered a cause of numerous explosions in the sugar industry. These had long been attributed to thermal causes, but no one had seriously considered discharges of static electricity.

Simple experiments showed that sugar dust blown through glass tubes charged them (+); copper tubes were charged (−). By using a method similar to that of Dolezalek and Holde—that is, blowing the dust through a long, narrow tube—potentials up to 20,000 volts could be obtained. When the charge was accumulated in a condenser heavy sparks 1 cm long were produced. Ten milligrams of sugar dust blown with a bulb through the air for 10 cm into a small metal cylinder charged it to a potential of 200 volts (9). Beyersdorfer recognized that clouds of very fine dust which he calls "aerosols" are similar in many respects to liquid colloidal solutions and states that suspensions of sugar dust exhibit Brownian movement and the Tyndall effect. If the charge on the particles in such a cloud exceeds a critical value, it may leak off in a visible glow. Luminescence, presumably from such a cause, was produced by blowing sugar dust under high pressure through a narrow slit between two steel plates in an apparatus similar to that shown in Figure 4, *B*. When air was used the light, which could be seen only in a darkened room, was pale blue. A piece of copper wire held just above the slit was electrically charged, and sparks ½ cm long jumped between it and the plates. When other gases were used the color of the glow was the same as that given by the gas alone in a discharge tube. Spectroscopic comparison was made of the light given by different gases and sugar dust. The information thus obtained showed that the luminosity was not a chemical or intercrystalline phenomenon. Beyersdorfer pointed out that O_3 and N_2O_5 are formed in a silent or brush electrical discharge; and in his opinion these gases might be formed in highly charged dust clouds, making them more susceptible to explosion.

Blactin and Robinson.—Explosions are perhaps more prevalent in coal mining than in any other industry. Most of them are attributed to dust. It is therefore desirable to ascertain whether in mining or the subsequent handling of coal the dust clouds formed can become sufficiently charged with static electricity to bring about, under other suitable conditions, autoignition or the ignition of gas. Although coal dust has not yet been ignited by this means experimentally, Blactin and Robinson (62) have exploded methane mixtures by the spark from a charge built up in the passage of a coal dust-air mixture blown at high velocity through a long large-diameter iron pipe.

Figure 5 shows the apparatus, which with the exception of the meter and the test bulb was mounted outdoors. These investigators state:

In carrying out an experiment the speed of the air and the rate of feeding the dust were adjusted to the desired figures * * * and, when convenient, the shutter closing the apex of the hopper was withdrawn. The voltmeter responded rapidly to the electrification and normally reached a steady deflection within 5 to 10 seconds of opening the shutter.

In one experiment with an air speed of 450 linear feet per minute the effect of three different rates of feed of dust was tested. The initial rate of feed developed 4,000 volts. On doubling the rate of feed 5,800 volts and on quadrupling the rate 7,000 volts were developed. When the velocity of the stream was increased to 2,600 feet per minute, potentials as high as 20,000 volts were obtained. To ignite a mixture of 8.5 per cent methane in air they found—

that the gap had to be adjusted to break down at 4,300 volts, the capacity in circuit being the natural capacity of the steel tube, leads, voltmeter, and

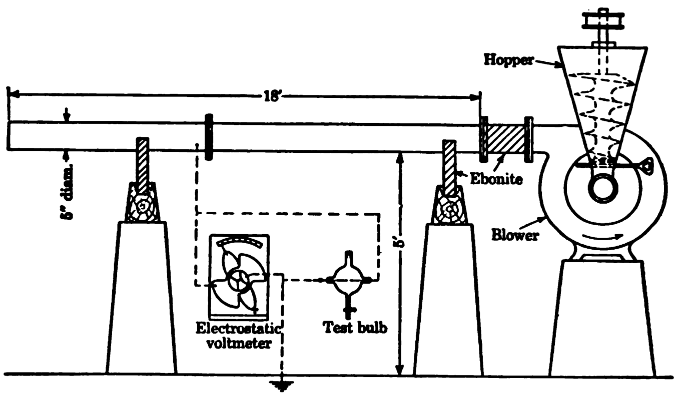

FIGURE 5.—Apparatus for determining coal-dust electrification (Blactin)

explosion vessel only, which approximated to 0.0002 microfarad. Sparks crossing such a gap invariably ignited the test mixture, while those crossing a slightly shorter gap, which broke down at 4,100 volts, failed to do so.

The ignition tests were made with air moving at a linear velocity per minute of 2,700 feet (368 cubic feet). With this velocity the amount of dust required to produce an incendiary spark with three kinds of coal was only 0.0041, 0.0015, and 0.0011 ounce per cubic foot, respectively. With the latter quantity the investigators state that the cloud issuing from the tube was so faintly colored "as to be invisible unless silhouetted against a white background." Further:

The smallness of the critical concentration with all three dusts indicates clearly that, given favorable atmospheric and electrical conditions, an air current containing only a minute burden of dust, but moving at a rapid speed [yet well within the limits of mining practice] can readily produce sufficient electrical energy on a well-insulated duct to give rise to sparks capable of igniting fire damp.

The experiments showed that on many days no charge could be developed, whereas on others conditions were so critical that the temporary passage of a cloud before the sun prevented their formation.

The apparatus became completely "dead" if the relative humidity of the atmosphere rose above about 65 per cent. * * * There did not appear to be any gradual transition from one state to the other. If the apparatus functioned at all, it functioned well, and intense electrification resulted.

Grounding the pipe through "leaks" of extremely high resistance showed assuredly that—

accidental contact of a mine-ventilation duct with earth at a number of places along its length, or a single deliberate "earth" connection will provide leakage that will effectively prevent the accumulation of an electrostatic charge on the duct, even though the conditions for electrification (e. g., high air velocity, high concentration of dust in suspension, and low relative humidity of the atmosphere) may be otherwise favorable.

The fact must not be overlooked, however, that in many places "where auxiliary ventilating systems are installed, more particularly in hot and deep mines, it is a matter of some difficulty to obtain a good 'earth'."

In an earlier series of experiments (63) with other and much smaller apparatus, Blactin had compared the electrification produced with different kinds of coal, potato and rice starches, and Lycopodium spores. In the tests with the last substance he took advantage of the fact that—

approximately half the mass of each spore can be removed by extraction with suitable solvents, the residue consisting of a shell which seems to have undergone no change in size nor shape during the extracting process.

By comparing the charge developed upon treated and untreated Lycopodium he could ascertain, with the same substance, the relative importance of size and mass in the process of electrification. Equal numbers of particles were found to acquire the same amount of charge in each case. These experiments form the basis of the hypothesis that the chief factor determining the chargeability of a dust is the fineness of the particles, which seems to have been largely confirmed by the results obtained with starch grains of widely different sizes and with numerous coal dusts. In fact, some more or less successful attempts have been made to utilize the electrification of coal dust as a measure of its fineness.[5]

Differences in the electrification of coals from various sources were attributed partly to an unknown fineness factor and to surface changes due to exposure to the air. The dust used in most of the later experiments is described as that of which 85 per cent passed through a 200-mesh screen (I. M. M. series).

Walther and Franke.—An interesting series of experiments with coal dust has recently been performed in Germany by Walther and Franke (64). The investigators state that although considerable study has been given the general problem of dust electrification, coal dust has not received the specific attention it deserves in view of the many disasters attributed to it. Their own experiments, however, though not immediately concerned with ignition, have supplied much of the need in this respect and while made only with brown coal (a type similar in some respects to our lignite) the results should be generally applicable.

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[5] Mason, T. N., and Wheeler, R. V., The Inflammation of Coal Dusts. The Effect of the Chemical Composition of the Dust: Great Britain Safety in Mines Research Board Paper 33, 1927, 20 pp.

Their work may be briefly described as follows: Measured amounts of dust were admitted at a known rate to a horizontal glass tube through which a current of air or other gas was passing. After being caught by this stream the dust traveled about 1 meter through the glass tube and thence through a short length of copper tube connected to the electrometer. A piece of copper wire was wrapped around the glass tube for much of its length and in most tests was grounded. The following tables list a few of the more interesting relationships observed.

Effect of area of contact

Diameter of glass tube, mm	Voltage	Size of particles, mesh [1]	Voltage
6	1,950	80	2,630
2	3,100	115	2,920

The screen sizes given are for Tyler standard sieves, which it is believed correspond closely with the figures given in the original paper.

Effect of temperature and humidity

Temperature	Relative humidity, per cent	Voltage
100° C.	90	5,000
100° C.	0	7,930+
Room.	90	2,000
Do.	0	4,460

Effect of bitumen content of brown coal

Coal	Bitumen content, per cent	Voltage
Werminghoff	8.0	2,020
Böhlen	8.6	2,500
Fürstenberg	23.7	8,500

Effect of moisture (room temperature)

Initially dry coal		Initially dry air	
Air; relative humidity, per cent	Voltage	Coal dust; moisture, per cent by weight	Voltage
90	2,000	8.7	880
50	2,300	0	3,200
0	4,460		

90 per cent humidity in air, 8.7 per cent weight H_2O in coal } 430 volts.
Dry air, Dry coal } 4,030 volts.

Effect of different atmospheres

Gas	Relative humidity, per cent	Voltage
Air	0	4,460
	90	2,000
N_2	0	3,150
	90	900
CO_2	0	2,740
	90	450

The data show that the voltage increases with increase in amount of dust; pressure of the air stream; dust concentration; total dust surface, which is proportional to the fineness of the dust; temperature; and bitumen content. It decreases with increase in diameter of pipe; moisture in the air or in the coal; and replacement of air with inert gas.

The dust in all tests was (−); the tube (+).

ELECTRIFICATION OF LIQUIDS

Although all substances can be made to develop electric charge, in general such charge is most conspicuous upon bodies which are poor conductors, usually because of the difficulty or impossibility of completely separating the conducting bodies before the charges neutralize or because of the subsequent rapid leakage to surrounding objects or ground. What has thus been shown in its relation to solids is, in many instances, equally applicable to liquids. Consequently liquids of high resistivity, such as oils and many organic solvents, are very susceptible to electrification (42, 65).

WATER

It is popularly believed that water is a good conductor of electricity, but in fact *pure* water is one of the poorest liquid conductors. Thunderstorms supply convincing evidence of the electrification of water.

WATERFALL ELECTRICITY

Natural.—It has long been known that the air surrounding waterfalls is charged with (−) electricity. In 1890 Elster and Geitel observed that this charge could be detected 500 meters above the falls. Soon Lenard (66) became much interested in the electricity of waterfalls and thoroughly studied the whole subject, making observations and measurements at 10 or more large falls and many smaller ones in various parts of the Alps. These observations confirmed those of previous investigators and furnished a background for a long series of laboratory experiments. All can not be described in detail here but certain results should be given. In actual waterfall measurements, not far from the breaking up of the water, the charge shown by the air was always (−); but within the spray, particularly close to the wet rock, a (+) charge could be detected.

Experiments.—The first laboratory experiments were made at Heidelberg with a bathroom shower. After the water had run a

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few minutes the air in the room showed a strong (−) charge. Similar tests in another city showed no charge, owing to impurities in the water, as shown later. It was soon discovered that enough electrification could be obtained from one fine stream of water to make practical measurement possible; most of the experiments were therefore made with such streams. In fact, it was later found that increasing the number of streams did not increase the electrical effect proportionately. As observed with the multiple stream of the shower, the charge was greater when the drops fell upon a wet, solid surface (a water film) or into a shallow pool than when they fell into a large volume of water; thus the charge on the air diminished as the level of water in the receiving vessel was raised. Part of the decrease was no doubt due to shortening of the falling stream, as it was found that within certain limits the charge increased with elevation of the source; in one experiment it was ten times as great with a stream that fell 70 cm as with one that fell only 30 cm. Another condition was perhaps more important. It was found that in deep water the entrained air of the stream was carried far below the surface and that the charge of the surrounding atmosphere decreased as more time was required for the charged bubbles to escape. The prominent part of escaping air in the production of waterfall electricity was shown in many ways. For example, after distilled water stood in a vessel a couple of days it became somewhat contaminated from the air and perhaps from the vessel; bubbles rising to its surface would linger perceptibly before breaking. Under these circumstances the charge developed was less than when the water was fresh. The following table shows the rate of building up of charge on the instruments when several combinations were tried:

	Volts per minute
Contaminated water falling upon contaminated water; many floating air bubbles	0.146
Pure water upon contaminated water; many floating air bubbles	.244
Contaminated water falling upon pure water; very few floating air bubbles	.333
Pure water falling upon pure water; very few floating bubbles	.654
Pure water upon moistened zinc plate	1.472
Pure water upon moistened zinc plate with ventilation by gentle fanning	1.875

The increased electrification produced by added ventilation at the foot of the falling stream was even more noticeable in other experiments. The fact that an increased length of stream, although the final velocity of the drops might be the same, gave greater electrification was shown to be largely due to a greater entrainment of air.

With contaminated water the slower escape of air may not alone have accounted for the smaller charge. The early experiments with bath showers had shown a great difference between pure water and that which contained traces of dissolved salts. The following tabulations show the effect of impurities in two tests; in the first distilled water gave more than 40 times the charge of city water.

	Volts
Distilled water	—140
Tap water	—3.4
Salt water (22.9 per cent NaCl)	+1.5

NaCl, per cent by weight	Charge in per cent of that for pure water	NaCl, per cent by weight	Charge in per cent of that for pure water
0	100.0	2.5	[a]69.5
.005	6.7	5.0	[a]99.1
.025	[a]17.4	10.0	[a]83.5
.05	[a]22.9	22.9	[a]14.0
.5	[a]28.2	Tap water	14.9

Comparison of test results with room air and with carefully purified air showed little or no difference, but the charge was smaller in atmospheres of hydrogen or illuminating gas. When the air in the test chamber was laden with tobacco smoke the charge was stronger than normal, and its period of decay was greatly increased. Probably the last effect may explain the first, for with the smoke the charge in the air was still appreciable after two hours, whereas normally it decreased to a greater extent in 15 minutes. But mere persistence of suspended particles seems inadequate to explain the retention of charge, as it was found that although the charge given clean air disappeared almost entirely in 45 minutes the presence of aqueous fog could be detected after 13 hours, and if a trace of NaCl was present in the water it could be seen spectroscopically to persist even to 27 hours.

Twenty-five other liquids, including mixtures of alcohol and water in different proportions, were tested. Turpentine and mercury gave the air a charge, respectively, two and fourteen times that obtained with distilled water. With these two exceptions pure water gave the highest charges.

Of special interest in the present study is the fact that in one test with a stream of water 0.8 mm in diameter and 1.2 meters long Lenard obtained a charge having a potential of 4,000 volts. In this experiment both water reservoir and receiving vessel were carefully insulated. The fine stream of water separated into drops about one-third of the way down and fell upon a metal plate suspended in the receiving vessel.

Although some charge may be imparted to the water stream by friction with the nozzle or an intercepting surface, it probably constitutes only a small part of the total waterfall electricity, for the final effect was scarcely altered by the use of jets of glass or metal or receiving plates of various substances, including ice, which is said to be the only material that is (+) with respect to water. If, however, a waxed plate was used, which could not be wetted easily, electrification of the surrounding air diminished considerably.

By far the largest part of waterfall electricity—usually taken to mean the (−) charge of the air, although many observations indicate that an equal (+) charge is also separated—is caused in some manner by the impact of water upon a water surface. Breaking up the water stream alone is not sufficient; no noticeable charge is acquired by the air where a stream of itself breaks into drops, as shown by one of Lenard's experiments in which a fine horizontal stream of water was projected out of the laboratory through an open window. A wire cage so placed that the stream could pass through without hitting it on either side did not become charged, even though drops formed after the water had passed only halfway through the cage. When the

[a] Charge opposite in sign to that for pure water.

solid stream was split with a sharp, thin knife only a small (+) charge was detected although a great deal of water spray was produced. A large (−) charge, however, was immediately observed when the stream was allowed to strike a small board held near the exit of the cage. A draft of air then blown across the stream removed enough of the negatively charged air to enable the cage to accumulate the (+) charge of the water spray.

Furthermore, the process does not require drops falling upon a water surface to be broken. That drops may so fall with but slight deformation was earlier shown in photographs by Worthington (67).

These experiments and many others point to the theory already mentioned that upon a pure water surface is normally a double layer of ions arranged with the (−) on the outside and the (+) underneath. In other liquids and electrolytes the arrangement may differ. When the velocity and density of air passing along such a surface are great enough— as at the moment of impact of two water surfaces—the outer layer of (−) ions on the water is snatched away by the air, which then shows a (−) charge, while most of the (+) ions are retained by the water. Lenard states:

> If this takes place rapidly enough it [the air] may have gone a considerable distance before the electrical charge would have time to combine completely with the opposite charge of the water; the two parts of the electrical double layer are thus separated mechanically.

Assuming that the maximum charge of a drop is given up when it sinks below a water surface to one-half its diameter, Lenard calculates a charge of 2.1×10^{-12} coulombs per square centimeter of area. He points out that if such a charge were to be placed upon one plate of a condenser of this area, the other plate separated by 0.000001 mm and carrying an equal charge of the opposite sign, the voltage would be only 2.4×10^{-6}. Thus it may be seen how small a potential difference is required between the charged layers on a normal water surface to account for the phenomena observed in the experiments.

INFLAMMABLE LIQUIDS

Much of the information found on electrification of benzine, gasoline, oil, benzol, ether, and carbon disulphide has been reserved for discussion under industrial hazards. A few less specific experiments and observations will be mentioned here.

Richter.—In connection with an investigation of the cause of fires in a chemical industry, Richter in 1907 noted that both ether and carbon disulphide may be strongly electrified by flowing through copper tubing (68), whether the liquid discharged directly from the tube or passed through a spout of insulating material.

Dolezalek.— A few years later Dolezalek (69) studied this kind of electrification in benzol and ether. The apparatus used (fig. 6, *A*) essentially duplicated on a small scale (1/5 size) that used in an aniline factory, where trouble from static electricity had been experienced.

Various metal pipes, 1 to 2 cm in diameter and several meters long—copper, brass, iron, lead, and aluminum, such as are used in practice—were tested in position *a*. Pressures of 0.1 to 3 atmospheres could be applied to the liquid. With benzol flowing through the pipe at 4 meters per second, voltages up to 4,000 were obtained, roughly proportional to the rate of flow and greatest with iron. The different metals showed different characteristics, some giving the benzol a (+) and some a (−) charge. Pure benzol usually gave higher voltages than the commercial grade. With brass pipe pure benzol was (−) and commercial benzol (+). By mixing only a small amount of the commercial benzol with the pure, a product was obtained which did not charge electrically. Dolezalek stated that the nature of the inside surface of the pipes had much to do with the character of the charge, as the test results usually were more consistent after the metal had lain exposed to the air some time. Charges were built up with dry ether about

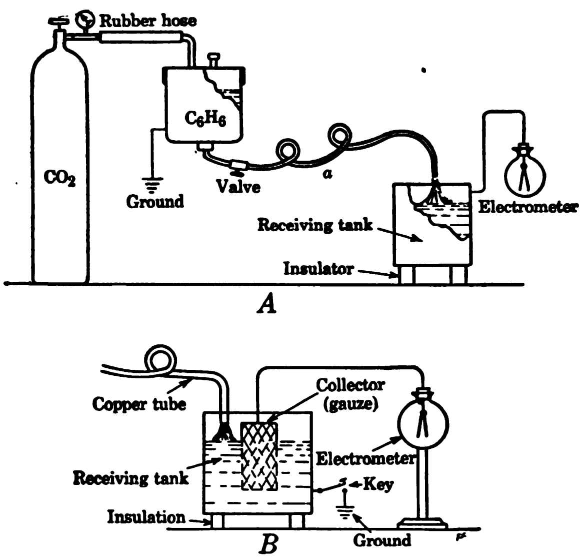

FIGURE 6.—*A*, Method of testing electrification of inflammable liquids (Dolezalek); *B*, method of showing complete removal of electrification of liquid by grounding (Holde)

as readily as with benzol; 4,000 volts were obtained in one test. Ether containing traces of water showed lower charges.

A difference of opinion arose in Germany following the experiments and safety recommendations of Richter and Dolezalek as to whether grounding benzine containers was a safety measure or a hazard. Richter's recommendations, which had been generally adopted by the chemical industry, included (1) grounding of all metal pipe and containers carrying inflammable liquid and (2) using glass in place of metal where grounding was impracticable.

But E. de Haën (70) stated that sparks had been seen to jump from a glass tube, due probably to a film of moisture on its surface, which acted like one coating of a Leyden jar. He believed that glass was also charged more easily than metal and therefore should never be substituted for the latter.

Dolezalek held that grounding was not a sure safeguard if very dry benzine had become charged; and that in such circumstances the container, whether grounded or not, constituted one plate of a condenser and the bulk of benzine acted as the dielectric. He contended further that the danger might thus even be increased by grounding; he had measured the electrical conductivity of several solvents and was convinced that a charge could leak away only very slowly.

In answer to these charges Richter pointed out (71) that although benzine is a very poor conductor it, like any liquid, can not be strictly classed as an insulator and grounding is therefore effective, yet the very resistance which makes such a liquid susceptible to high electrification prevents it from giving up its charge rapidly enough for more than an insignificant spark to be drawn from its surface. For a dangerous spark the benzine must be in contact with a large surface that conducts well, such as that offered by a metal container. Grounding certainly would remove such a charge.

Holde.—To clear up the question Holde (72, 73) later repeated some of Dolezalek's experiments and made additional measurements of conductivity of various solvents and mixtures thereof. The apparatus was essentially the same as that used in the original tests, except that it was smaller and only copper tubing was used. High charges were easily obtained; but if the receiving vessel was connected to ground only momentarily the entire charge of even the least conducting benzine immediately disappeared.

Measurements were then made of the charge upon an insulated collector suspended in the benzine (fig. 6, *B*). As the liquid flowed into the container the charge built up as before; but when the container was grounded, the charge left completely, as in the first case. Holde thought that in its turbulent inflow the benzine deposited its charge upon the walls of the containing vessel and that the charge found upon the gauze was one of induction. He believed these tests show that grounding a tank protects adequately against static charges.

Dolezalek's observations that the charge of benzol was influenced by the nature of the interior surface of the pipe and that a mixture of pure and commercial benzol could be made which would develop no charge correspond interestingly with some recent findings (74). According to an account of these in the Electrical World (75):

> If the gasoline or other hydrocarbon is in a highly insulating condition, the frictional effect is very small. As the conductivity increases (from a very low value), the frictional charge increases up to a certain conductivity, but beyond that it decreases rapidly, there being a critical conductivity for which the static generated is a maximum. The actual value of this maximum is also related to the velocity and the sectional area of the passage. The effect is increased by passing the liquid through the filings of certain metals, and it is reduced virtually to zero by the filings of certain other metals. In extreme cases potential differences as high as 30,000 volts were measured.

Rodde (76) states that in certain experiments a best velocity of flow was found for the production of static electricity. If the velocity was too great, no charges were developed.

ELECTRIFICATION OF GASES, VAPORS, AND SPRAYS

The bodies considered here bear the same relation to liquids that dust clouds do to solids; probably much the same mechanism is responsible for building up charges in both cases, and other conditions are similar. Thus, if clouds of extremely fine dust are aerosols, as Beyersdorfer regards them, so no doubt are vapor clouds (77). If, as with the former, agglomeration and precipitation take place upon neutralization of charges the same may be expected here.

Referring to the sudden heavy fall of rain that is often observed just after a lightning discharge, Atkinson (25) says:

> The small drops which were before kept apart by mutual repulsion from being highly charged and at the same potential now coalesce and form the large drops, which being too heavy to be sustained in the atmosphere, fall.

In considering dust clouds it was shown that the air alone could not be charged perceptibly and that both (+) and (−) charges are carried by suspended particles. So it is with liquid aerosols such as steam and fine sprays.

STEAM

Hydroelectric machine.—That escaping steam can become heavily charged with static electricity was discovered accidentally by a colliery engineman. Shortly afterwards, about 1840, Lord Armstrong (16) built his hydroelectric machine, a large insulated boiler whose steam outlet was a series of wood-lined nozzles. At first it was believed that electrification was caused by expansion of the steam and then, because it was found that dry steam developed no charge, that it was due to condensation. Faraday's explanation, which was generally accepted, was that the friction of liquid particles on the wooden lining of the nozzles was the cause (22). K. Richter (78) describes an experience which was quite similar to that of the engineman. Standing near a leaking safety valve and allowing the escaping steam to strike his body, he alone or with others joining hands received a strong shock and saw a spark when the knuckle of a finger was brought near the metal of the boiler. When standing so that the steam did not strike or drift over against the body no such phenomenon was observed. He says:

> It is very probable that all steam escaping with friction against metal surfaces has this property to some small degree.

Volcanoes.—The high state of electrification of material ejected from active volcanoes has already been mentioned. Because water and steam are often present in large amounts in such eruptions, the subject is of interest here. According to Judd (79):

> Every volcano in violent eruption is a very efficient hydroelectric machine and the uprushing column is in a condition of intense electrical excitation. This result is probably aided by the friction of the solid particles as they are propelled upward and fall back into the crater. The restoration of the condition of electrical stability between this column and the surrounding atmosphere is attended with the production of frequent lightning flashes and thunderclaps, the sound of the latter being usually, however, drowned in the still louder roar of the uprushing steam column.

In connection with an eruption of Vesuvius, Judd says:

> Around this column of vapor the most vivid lightning constantly plays and adds not a little to the grand and awful character of the spectacle of volcanic eruption, especially when it is viewed by night.

Some unusual manifestations.—The following citations have a distinctly practical bearing in the consideration of industrial hazards and show how potent and insidious steam may be as a source of static electricity.

An empty gasoline truck which * * * was allowed to stand during lunch hour was found heavily charged by the workmen on their return. No other truck in the vicinity was charged, and this truck did not become charged in any other location. A run on the asphalt paving failed to reproduce the charge. A little investigation revealed a small leak at a fitting on a near-by steam pipe, the wind being in such a direction as to carry the vapor across the body of the truck. It should be noted that the white cloud of steam had died out almost entirely before reaching the truck. Several rearrangments of truck and trailer and other trucks verified the conclusion that the steam leak was the direct cause of the charge. In experimenting to reproduce these conditions it was found that steam at 75 pounds per square inch gage pressure escaping through a 1/16-inch round hole charged a truck sufficiently to give a 3/4-inch spark in five seconds (80).

A steam automobile exhausting against a barbed-wire fence charged the wire to such a voltage that sparks were drawn from it. At the same time the automobile also was charged and gave shocks to those touching it (42).

An electrical engineer constructed a static-sensitive device to indicate the approach of storms. It worked well—too well in fact—for it sometimes rang the alarm even in very fair weather. One clear starlit night it operated at frequent intervals. An investigation showed that the device had been actuated by the steam and smoke exhausted by a shifting locomotive on a near-by railroad track (42).

Rudge's experiments.—In addition to his extensive investigation of dust electrification, Rudge made some interesting experiments with steam (81). Most of the laboratory tests were performed with steam produced in an insulated copper boiler 20 cm in diameter, with a gage and an exhaust pipe into which nozzles of various sizes could be inserted.

On one occasion steam allowed to escape for about five minutes through an orifice 1 mm in diameter charged the atmosphere in a 13 by 16 by 10 foot room to such an extent that—

the charge could be detected in the room for more than one hour afterwards. * * * If an electroscope having a collector attached is carried in a closed railway carriage, no charge is indicated. If the window is opened, a charge can be detected upon that side of the train from which the steam is being carried.

On passing through a tunnel with a window open a strong charge is shown which will persist for many minutes if the window is promptly closed before leaving the tunnel.

Laboratory tests with small exploring needles and rings showed that the steam issuing from the nozzle of the small boiler contained charges of both signs; the boiler carried a strong (−) charge. (See fig. 7.)

The results of these and other experiments, some with steam from a high-pressure power boiler, may be summarized as follows:

The charge given to the air by the steam from pure water is always (+).

Volatile bodies mixed with water may give a (−) charge to the air. Undoubtedly some electrification originates with friction of the escaping jet at the orifice if the steam is not perfectly dry, but this will account for only a part of the charge.

The charge acquired by the air appears to be due to something which occurs in the cloud of condensed vapor.

Pothmann's experiments.—In 1918 Pothmann (82) made experiments to determine the electrification produced by the escape of steam and of hydrogen from orifices. Steam escaping under pressure was found heavily charged; the maximum value was obtained in the center of the stream some distance from the orifice and where condensation was beginning. An electroscope showed deflections, however, even when held some distance from the side of the steam cloud. With an apparatus in which steam and compressed air could be mixed Pothmann found that air alone gave no charge, but small amounts of added steam gave almost the same charge as the same pressure of steam alone. Working with mixtures in which well-

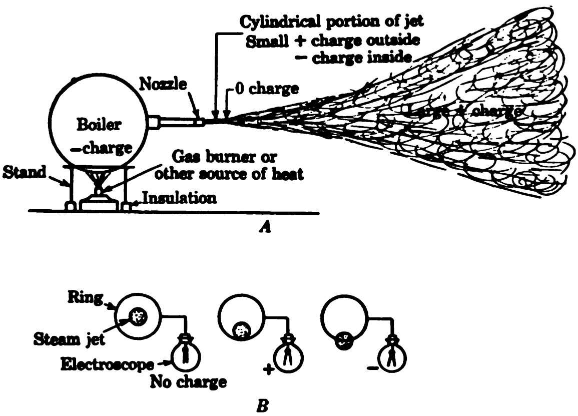

FIGURE 7.—Apparatus for testing electrification of steam (Rudge)

defined liquid particles were present Pothmann observed a glow of light after dark. To investigate the subject thoroughly the apparatus shown in Figure 8, *A*, was set up. Because of its large gas capacity a high-pressure flow could be maintained long enough to

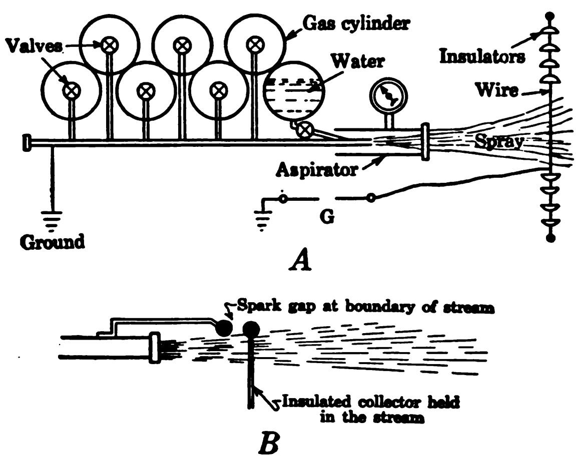

FIGURE 8.—*A*, Apparatus for determining electrification of gas and water sprays (Pothmann); *B*, means of producing autoignition of hydrogen gas containing traces of water (Pothmann)

make the necessary observations, and both hydrogen and air could be tested. Even at pressures of but 2 atmospheres a glow was seen. At higher pressures more light was produced, and sparks occurred in gap *G*.

At 40 to 80 atmospheres the glow was very pronounced and was bluish white. At 80 atmospheres it extended 40 to 50 cm but did not ignite hydrogen gas and air mixtures. When the flow of either gas or water was decreased greatly, the glow disappeared. Under some conditions sparks up to 7 cm in length were obtained at *G*. By arranging electrodes as shown in Figure 8, *B*, autoignition of hydrogen was obtained.

CARBON DIOXIDE SNOW

Strong charges of static electricity are carried in sprays of many kinds. Whether the suspended particles are liquid or solid apparently makes little difference. Carbon dioxide snow ("dry ice") may be made on a small scale by inverting a cylinder of soda-fountain gas and allowing liquid CO_2 to rush out into a bag or box closed in about the valve. As the liquid escapes through the small hole in the cylinder it evaporates so rapidly under the reduced pressure that the temperature of the liquid is carried below its freezing point. During the process static electricity is produced, and sparks one-half inch long may be drawn from the metal cylinder (83). The spray charge is carried by solid particles but probably originated while the CO_2 was still in the liquid phase.

FOG

Geitel (84) and others (85) have shown that even quietly formed mists such as fog carry electric charge. In fact, the very persistence of fog has been attributed to the repelling force of similar charges upon the individual particles. Geitel performed an interesting experiment in which an artificial cloud of ammonium chloride was formed above a charged plate. The plate was then grounded momentarily and the exterior of the cloud and the air about it discharged by the approach of a flame or a radium compound. When the cloud was blown away, an electroscope connected with the plate deflected, showing that a bound charge had been held on the plate by the internal charge of the cloud.

AIR AND PURE GASES

Many authorities believe that pure gas or air forced through pipes and orifices is not electrified and that for charges to be developed liquid or solid particles must be present. Several attempts, however, have been made to detect charges on air alone. Tagger (86), having observed in previous experiments electrification by impact of solids, concluded that gas molecules in their constant agitation ought to become charged by impact when they bombard a solid surface. Experimental difficulties, however, such as removing the adsorbed gas layer so that the molecules in question could actually reach the surface, could not be entirely overcome, and no very significant results seem to have been obtained.

That electrification of dust clouds increases as the particles decrease in size is a well-established fact. It might seem logical, therefore, to suppose that gas molecules, being so much smaller than any dust or liquid particle, should show a marked effect. McDiarmid (87) recently claims to have obtained very small charges upon pure air. Great care was exercised in cleaning and drying the air, which was then forced by a novel method calculated to preserve the purity through various tubes of glass, quartz, ebonite, copper, brass, lead, and aluminum. The air collected showed a charge opposite that of the tube; it varied with the material of the tube, the velocity of the air current, and the diameter and length of the tube, increasing with each of these three magnitudes, almost directly with the last. McDiarmid states that the first rush of air through a tube gave the highest charge, that subsequent passages might even result in a charge of the opposite sign, and that heat treatment usually restored the original condition of the tube. These results should be compared with the observations of Shaw and Jex on the influence and vagaries of surface contamination. The question thus naturally arises as to whether the air, although initially clean, may not have become contaminated somewhat in its passage through the tubes.

BALLO ELECTRICITY

Electricity manifested in the breaking up of liquid surfaces is called ballo electricity. If air or other gas is bubbled through a liquid, it becomes charged by removing ions from the surface of contact (88). With pure water the charge carried by the air is (−), but with strong electrolytes and some other liquids it may be (+) owing to a different arrangement of the ions at the interface. Vieweg (29) attributes the (−) charge of air passing through water to its preferential adsorption of the OH^- ion. He finds that a reversal in sign of charge usually occurs in electrolytes when the concentration reaches about 0.1 N and gives the following figures from some experiments of Mozer to show the distribution of (+) and (−) carriers in air which had bubbled through solutions of KNO_3.

Concentration	Positive carriers	Negative carriers
0.001 N	5	50
.01	13	22
.1	15	11

Lenard, it will be recalled, made similar observations with salt-water streams, although the concentration for reversal of sign was much less.

Mere evaporation of water is probably ineffective in charging air; neither is electrification produced by bubbles due to boiling, as, for example, in liquid air. The charge given water or electrolytes by spraying is said to be opposite that derived by the waterfall method. So "it appears that we must regard the mechanism of rupture of the liquid as of the same importance as the nature of the material used" (88).

MERCURY VAPOR

Although the experiment was performed in high vacuum (10^{-6} mm Hg), it is none the less interesting, especially in connection with Tagger's experiment, to note that Perucca (89) measured potentials up to 560 volts when mercury vapor impinged against an insulated metal target.

TERRESTRIAL AND ATMOSPHERIC ELECTRICITY

EARLY IDEAS

Although there is no definite knowledge whether the ancients had any conception of the nature of lightning, it is said (15) that as early as the time of Moses means were known for controlling it to some extent and that Solomon's Temple was built with sharp gold points on its roof, connected to earth by metal. However, if such knowledge existed before Franklin's time, it must have been forgotten for many centuries. Amaduzzi (11) mentions two attempts to explain lightning, or its manifestations, as recently as 1740 to 1747. According to one theory it was due to sulphurous emanations from the earth which ascended and formed clouds; these collided with like clouds of similar or other volatile or bituminous substances and, as a result of high wind velocity and the sun's heat, ignited. The rapid combustion or explosion that followed accounted for the flash and thunder. This explanation was not altogether satisfactory. Maffei in 1747 voiced the opinion that the "bolt" originated at the point where it seemed to strike, as the damage was done too soon after the flash for the lightning to have had time to fall from the heavens, and because, if it did fall from such a height, it should be visible for a much greater distance than was apparent. The electrical nature of lightning was well demonstrated by Franklin in 1751 and shortly afterwards by Dalibard, De Romas, and Richman, and a new field of study—that of atmospheric electricity—was opened.

HARNESSING LIGHTNING

Many attempts have been made since Franklin's time to harness the electricity of the clouds and put it to useful work. The great difficulty has been that of reducing the excessively high voltage and increasing the available current. Lately, however, advances in the study of cathode rays and the promise they offer in solving problems of atomic disintegration and transmutation have made the necessity of obtaining extremely high potentials paramount. In recent experiments (90) of the Physical Institute of the University of Berlin static charges from the clouds capable of giving an almost steady discharge 15 feet long are said to have been successfully collected and handled. The charges were collected by wire mesh several hundred square yards in area, suspended upon insulated cable supports hung between two mountain peaks in Switzerland. It was believed at the time that slight changes in the arrangement and elevation of the collector would make it possible to obtain charges of as high potential as 30,000,000 volts.

LIGHTNING PROTECTION

In many ways lightning discharges behave like their prototypes in the laboratory. The effects and nature of lightning in many of its phases can therefore be studied by discharges from high-voltage condensers. The havoc wreaked by lightning on transmission lines and power equipment, both by direct hits and by induced surges, has made this study important to most of the large electrical manufacturing companies. Much pioneering work of this character has been done by the General Electric Co. and described in numerous articles by F. W. Peek, jr. (91, 92). Of particular interest is the description of a lightning generator (93) capable of giving, without rectification, direct-current surge discharges of as high as 2,000 kilovolts. This generator has made possible a study of the effect of artificial lightning upon model villages, arsenals, oil reservoirs, miniature transmission lines, etc., and has aided the development of suitable and efficient lightning protection.

Every system of lightning prevention is based upon the well-known electrostatic principle that the highest potential gradients between two charged bodies exist where points or sharp edges occur on the surface and that the greatest leakage of charge will be from such points. If the charges in a thunderstorm are not being built up too rapidly, the earth charge may leak off of a lightning rod quietly and thus forestall a stroke. The greater the number of points, of course, the greater the leakage and the better the protection (94). If, however, the charges build up faster than they can escape and lightning strikes, it will usually hit the rod, as this offers a path of low resistance. Lightning arresters on telephone and power lines permit the charge to escape to earth without allowing more than a negligible part of the normal current of the circuit to follow. Several successful lightning arresters of this type have been devised.

ST. ELMO'S FIRE

St. Elmo's fire is a good illustration of leakage of earth charge from points. Such leakage in the form of a brush discharge or small streamers occurs in the atmosphere whenever the potential gradient at any place reaches a value of about 30,000 volts per centimeter (95). Professor Hoag states that just before an electrical storm the sharp points of the rocks on a certain mountain peak in Colorado fairly spit fire from static electricity and that while he was in the vicinity sparks one-half inch long jumped from his body.

NATURE OF LIGHTNING

Ever since lightning was shown to be a manifestation of static electricity attempts have been made to explain it on the basis of laboratory experience; but because of the mystery surrounding the nature of electricity and the vagaries of lightning itself, no entirely satisfactory explanation of the various phenomena has been found. Of these vagaries Dorsey says (96):

> In addition to ball lightning, which appears to be in a class by itself, there are a number of other well-attested effects produced by lightning which do not accord satisfactorily with the opinions commonly accepted. * * * the following may be taken as typical: (1) Lightning may strike down into a cavity which is surrounded by high conductors which are well earthed; (2) it may knock a section out of a wall without disturbing the portions above or below the hole; (3) it may pierce a hole through a pane of glass and do so even when the pane is small and forms a window in what is essentially a closed metallic surface; (4) in dry sand it may form long fulgurites.

Furthermore, lightning discharges may pass from a cloud "to the surrounding atmosphere without reaching the ground" (97).

BALL LIGHTNING

This mysterious and very rare phenomenon is a product of electrical storms and at times is as dangerous as ordinary lightning. It moves about slowly, however, much like a toy balloon blown in a breeze. Descriptions by the relatively few persons who have seen it sound more like tales of Munchausen than statements of fact. The following abbreviated report by M. Babinet, whom the French Academy of Sciences appointed in 1852 to investigate the story of a tailor in whose home the phenomenon appeared, exemplifies the attributes of this oddity (98).

During an electrical storm, shortly after hearing thunder, the tailor saw a paper screen in front of his fireplace fall as if blown by the wind. A yellowish ball about the size of a child's head and looking somewhat like a yellow cat curled up asleep appeared. It approached the man's feet and then rose to a point near his head, but although luminous it did not seem to be hot. The ball passed slowly and quietly across the room in mid-air and went out by another opening in the chimney. As it reached the top it exploded and threw down a large number of chimney stones.

Several other stories almost as unbelievable might be cited, but the following experience of L. V. Clark, assistant physical chemist, Pittsburgh Experiment Station, Bureau of Mines, will suffice. Clark says that during a thunderstorm near Harlansburgh, Pa., in 1913 he took shelter not far from a large pine tree. The storm had about cleared when he saw floating slowly down from the sky a large luminous yellow or orange ball perhaps 18 inches in diameter. It hit the top of the tree and exploded, splintered the tree all the way down, and tore a hole in the ground.

Numerous articles on ball lightning have been written by Mathias (99, 100), who has made a thorough study of the subject and collected much information regarding the size, color, behavior, and composition of this substance, which he terms "fulminating matter." The appearance and destructiveness of ordinary lightning he believes are largely due to the explosion of fulminating matter (probably unstable compounds of nitrogen and oxygen) formed in the initial discharge. Under peculiar atmospheric or discharge conditions, however, the gases do not always explode immediately (101) and may by some unknown combination of opposite electric charges or by a vortical movement collect in a ball which decomposes slowly or may, if its equilibrium is suddenly disturbed, explode. Mathias gives figures to show that the energy of explosion of 1 gram of fulminating matter is about four times that of 1 gram of nitroglycerin (102). In his conception that all lightning involves the formation, contraction, and explosion of fulminating matter, Mathias believes (103) he has reconciled the essential mechanical elements of two early theories for thunder—(1) the centripetal theory of Arago that lightning creates an empty space into which the surrounding air rushes noisily and (2) the centrifugal theory of Schopenhauer that lightning causes the explosion of oxygen and hydrogen previously separated electrically from water vapor.

The theories for lightning as the term is generally understood may best be considered under two groups—those that apply to the generation of the charge and those concerned with the nature and mechanism of the discharge.

GENERATION OF CHARGES

Simpson.—Simpson's theory (104) of the origin of electricity in a thunderstorm, which is most generally accepted and has been substantiated by many statistical facts, is very briefly as follows: Wind entering the storm area takes an upward course as it enters the cloud. "The vertical component increases as the air passes into the storm and reaches a maximum in the lower half of the cloud" (105). At a certain point in this upward current the falling raindrops are broken up into smaller ones. In the process they are robbed of negative electricity, which is carried on the wind to the top of the cloud. The small positively charged drops are also carried upward, but they soon recombine and fall to be broken once more; additional charge is thus developed. Under favorable

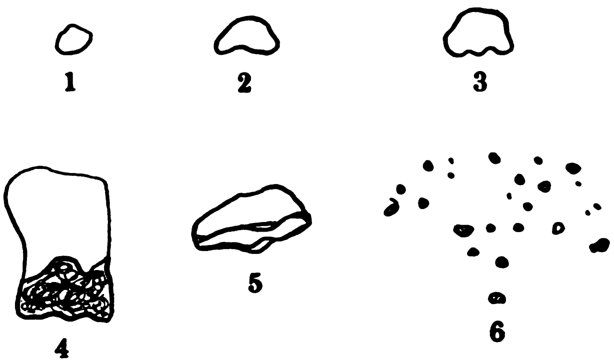

FIGURE 9.—Progressive stages of water-drop disruption (Hochschwender)

circumstances this condition continues until enough charge for a lightning flash is acquired.

Hochschwender.—Lenard (106) has shown from Hochschwender's experiments that such electrification is produced most easily with water drops 4 to 6 mm in diameter falling against an upward air stream of about 8 meters per second velocity. Single drops falling upon such a column of air provided by a blower were observed. At a certain point in their fall they seemed literally to explode. Such a falling drop was found to take the form of an inverted cup, which enlarged until its upper wall was extremely thin and was finally ruptured by the air current. The invisible fine negatively charged particles of the disrupted membrane were carried along with the air, while the remaining ring of water broke into numerous small drops. When the experiment was performed in darkness, the action was accompanied by the momentary appearance of light. Figure 9, reproduced from the original, shows the progressive stages of a drop of water undergoing disruption. The illustration is natural size.

Smaller drops were more stable and required a very turbulent air stream to break them up. The following figures for the smallest and largest drops tested indicate that an appreciable variation in velocity is required for this type of drop splitting:

Size of falling drop, mm	Velocity of air to float the drop, meters per second	Increase in velocity to rupture drop, meters per second
2.5	6.4	14
6	8.0	2

Drops larger than 6 mm in diameter either do not form or are so unstable that they break up more simply. With drops 4.78 mm in diameter Hochschwender found the charge developed was approximately 1.4×10^{-11} coulombs per cubic centimeter of water.

Other theories.—Other theories not generally deemed so important (97, 84, 41) have ascribed the charges to the normal potential gradient and ionization of the atmosphere; photo-electric effect of sunlight upon water particles, particularly the higher frost particles; difference in the velocity of different-size drops; waterfall effect due to the collision of drops; and capture by the water particles of more (—) than (+) ions from the atmosphere because of the greater mobility of the (—) ion.

In 1898 Thomson (107) suggested that if the (—) ions in the air were to differ from the (+) in their power to condense water vapor upon themselves (it is now well known that they are much more efficient in this respect)—

> we might get a cloud formed around one set of ions, and not around the other. The ions in the cloud would fall under gravity and thus we might have a separation of (+) and (—) ions and the production of an electric field, the work required for the production of the field being done by gravity.

Apparently, all clouds and rain carry some charge. The electrification of fog and mist has been mentioned. Geitel (84) states that balloon soundings have shown the lower boundary of high atmospheric clouds to be predominantly (—) and the upper boundary (+). This accords well with his idea that fogs or clouds become charged by impeding the normal movement of ions in the atmosphere.

DISCHARGE OF LIGHTNING

Whatever the method or methods involved in charging of thunderclouds, an enormous amount of electricity is stored thereby. The average lightning discharge is said to have a voltage of 100 to 200 million and to carry about 20 coulombs of electricity. Simpson (108) has recently estimated that—

> the electrical energy released in a thunderstorm lasting for two hours with one flash every second would supply the whole of the British Isles with electrical energy for 10 days, and this would be a very moderate storm.

Various other estimates have been given. Basing his figures on the fusing and discoloration of kite wires, McAdie (109) has estimated that the energy of an average lightning discharge is probably about 28 kilowatt-hours.

Rise of potential.—The rise in electric potential due to the separation of two unlike charges has been mentioned. The effect can be shown with a good variable condenser. According to Simon (95):

> The condenser must be well insulated and the plates sufficiently far apart so that a spark does not go over as the voltage rises; a standard 1,000-mmf.

condenser placed over P_2O_5 [an effective drying agent] does very well. The potential of two 45-volt B batteries is easily transformed to 1,500 volts.

The same process is responsible for the tremendous potentials of lightning. Suppose clouds to be highly charged as postulated by Simpson, the (−) charge being carried high into the clouds while the (+) charge remains in the lower part. As the separation of charges thus increases, the capacity decreases and the voltage rises. Many changes in potential may afterwards occur as the clouds are driven about by shifting winds. If oppositely charged clouds come close together or if they pass each other after the manner of the plates in the variable condenser experiment, the potential gradient may become steep enough for a discharge to occur between the nearer cloud parts; if they are separated greatly along a common axis, a discharge to earth may occur. Cloud conductivity and precipitation of rain also have much to do with the increase of potential and stress.

Probable nature of discharge.—It is sometimes thought that a lightning discharge is simply a gigantic spark passing through a medium which had no part in the process, much as a bullet is shot through the air. Such, however, is not the case. Dorsey (96) states:

Sir J. J. Thomson and J. S. Townsend each called attention to the fact that a spark does not pass unless at some point the field is of such an intensity that it will confer upon a free electron, in the interval between two collisions with the molecules of the gas, such a velocity that it is able to dislodge an electron from the molecule with which it collides. But if a spark can not occur at the point *A* unless free electrons have this critical velocity at that point, then the same must be true at every other point of its path. That is, the spark marks the trail of electrons flying with such velocity that they ionize the gas. The flying electrons ionize the gas; the laggard electrons combine with the resultant positive residues and so give rise to the brilliant flash; the ions make a conduction current of the usual type possible if the field is maintained, but this current is distinctly subsequent to the spark.

By a peculiar dartlike formation of groups of the ionizing electrons Dorsey accounts for the erratic paths taken by lightning and some of its otherwise inexplicable pranks. Fortescue (110) considers that lightning discharges like those between sphere gaps occur in three stages: (1) The initial stage of ionization by collision; (2) the secondary stage, characterized by thermionic emission; and (3) the breakdown stage, in which highly conducting streamers are formed. He states that these brilliant streamers, which have a velocity about one-tenth that of light, are probably caused by dissociation of the gas molecules by ultra-violet light in stage (2). About two-thirds of the way across the gap these streamers, which first appear at the pole where the gradient is steepest, meet somewhat similar ones from the opposite pole. The meeting of two such streamers provides a low-resistance path, and the arc forms. If the potential builds up rapidly again in the cloud, another or several discharges may travel over the same path. Torok (111) has taken photographs that show interrupted streamers of this type.

In the formation of initial streamers, Simpson (108) states:

It is only necessary for the strong field of 30,000 volts per centimeter to occur in a small region of the electrical field * * * for if the discharge starts anywhere because of the high local field, the discharge itself, by making the air a conductor, concentrates the field in its neighborhood and the rent is continued far into regions where the original field was relatively weak.

ATMOSPHERIC LAYERS

Before the subject of atmospheric electricity in clear weather is considered a few facts regarding the atmosphere itself will be given. This "ocean of air" extends several hundred miles outward and exerts a pressure of about 14.7 pounds per square inch at the surface of the earth. In addition to oxygen and nitrogen, it contains appreciable amounts of water vapor, carbon dioxide, hydrogen, argon, neon, ozone, and traces of many other substances.

Convection currents and steep pressure and temperature gradients, with their accompanying storms, characterize the lower atmosphere to a distance averaging 6 to 10 miles above the earth. Beyond this region the vertical rate of change in temperature is small, and convection currents are greatly diminished or disappear.

The atmosphere is thus divided into two distinct layers; that nearest the earth is called the troposphere and that above, the stratosphere. Within the troposphere, at least, water in each of its states and dust of many kinds are important constituents of the atmosphere. Both dust and water greatly influence the electrical manifestations in this region in clear as well as stormy weather.

In considering atmospheric electricity it is generally recognized that the stratosphere contains several somewhat distinct layers which have special characteristics largely determined by the prevailing mode of ionization and degree of radiation absorption.

Although the density of the atmosphere decreases to very low values in the upper stratosphere, nothing very definite appears to be known concerning its temperature.

Balloon soundings, however, show that the mean temperature of the air falls to about 50° C. below zero 6 to 7 miles above the earth, beyond which it remains virtually constant to a height of perhaps 18 miles (112, 113). Indirect evidence indicates that above this height the temperature rises again until it is about the same as, or even higher than, at ground level. This phenomenal rise, which may reach a maximum 40 to 50 miles from the earth, is attributed to the absorption of long-wave radiation by water vapor and by ozone which has previously been produced by ultra-violet light or other means (113).

Although such turbulent conditions as prevail near the earth are absent in the stratosphere, the movements of auroral bands, meteor trails, and luminous night clouds indicate that at certain levels winds blow at velocities greater than 300 to 400 miles an hour. Variations in solar radiation are believed to produce elevations and depressions of considerable magnitude in the upper boundaries of the atmosphere.

NORMAL POTENTIAL GRADIENT AND IONIZATION

Lemonnier is said (11) to have been the first to show that even in calm weather the atmosphere is charged with electricity, but not until the discovery of ions in the atmosphere years later was this phase of meteorology studied seriously. To-day, however, the literature contains many references to the subject, and many of the problems seem to have been solved. Some facts established concerning atmospheric electricity in a calm and serene sky follow:

1. Between the surface of the earth and a region high in the atmosphere is an electric field whose normal direction over at least the greater part of the globe, land and sea alike, is toward the earth; that is the earth is (—).

2. This field has a potential gradient of 100 to 150 volts per meter near the surface of the earth, but this diminishes to a comparatively insignificant value at a height of about 6 miles (114).

3. This gradient varies somewhat in different localities, not only day by day but by seasons. During thunderstorms and dust storms it may change markedly in local characteristics and even reverse its direction.

4. Throughout the atmosphere (+) and (—) ions are scattered, though not uniformly.

5. The existence of an electric field and the presence of ions in the air result in a movement or flow of the ions, the (—) upward and the (+) downward. This flow is equivalent to about 1 ampere in 100,000 square miles.

6. The earth's charge, and consequently its field, is maintained by some unknown means; otherwise the ionic current would reduce it approximately 90 per cent in 10 minutes (114).

7. The ions in the atmosphere give it electrical conductivity. "Above the lowest kilometers—that is, above the influence of ionizing radiations having their origin in the ground—the conductivity increases with the height and the potential gradient diminishes accordingly" (97). This increase in conductivity is due partly to the presence of a large number of ions and partly to their greater mobility in the thinner air. Information from various sources shows that the conductivity of the upper air is very great. At an elevation of 60 miles it about equals that of dry earth, or 10,000,000,000 times that of dry air at sea level.

8. This height corresponds approximately with the lowest level for auroræ, which are produced by electrical discharges through highly ionized air and other gases at low pressures. Argon and neon contribute much beauty to these discharges.

9. The densest part of this cloud of ions appears to be about 100 miles above the earth and is termed the Kennelly-Heaviside layer in honor of its discoverers. The reflection of radio waves, making possible communication around the globe, is attributed to this layer, which is a far better electrical conductor than the surface of the earth.

10. Various movements in the highly ionized upper air brought about by conditions on the earth or on the sun are believed responsible for magnetic storms and unusual auroral displays.

Possible causes.—Many attempts have been made to account for the above conditions. The fundamental problems involved are, of course, the cause of ionization and the maintenance of the electric field. Many considerations and facts indicate that ionization in the Kennelly-Heaviside layer is caused chiefly by ultra-violet light from the sun (115). This, however, can not account for the presence of any appreciable number of ions in the troposphere. Some additional source is required. It is known that the soil contains small quantities of radioactive materials and that traces of emanation are present in the air; freshly fallen snow has been found to be radioactive (116). According to Wilson (97), "A considerable part of the ionization of the air near the ground is due to the radioactive emanations of radium and thorium which have diffused out of the ground." To account for the earth's persistent negative charge, Ebert proposed the theory that ions formed by these means or brought to the earth by rain were absorbed by the pores of the soil, but that at times of low barometric pressure only the (+) ions were released. Although this theory is in itself plausible, it could apply only over the land areas. Moreover, 90 per cent of the rain that falls upon the earth carries a (+) charge. Swann therefore holds that it is "improbable that the Ebert theory can figure as the main cause responsible for the earth's charge."

Lenard (66) has shown that the splashing and breaking of ocean waves release many (+) ions to the air, thus contributing to the earth's (−) charge.

Other investigators have suggested that ionization at the earth's surface may be brought about by corpuscular radiation from the sun, but experimental evidence that such radiation reaches the earth has not been adduced. Moreover, a peculiar averting circumstance arises. Swann (117) states that a corpuscle injected into the atmosphere in the vicinity of the equator, in order to reach the surface of the earth without being turned back by the earth's magnetic field, would have to have a velocity too great to permit it to ionize the air through which it passes. Such radiation might indeed reach the earth at the magnetic poles, particularly during sun-spot maxima, and even cause a locally reversed earth current, but this has not been proved.

Electrical discharges during thunderstorms may be one answer to the puzzle of a maintained (−) earth charge. According to Wilson (97):

> A thundercloud is situated between two parallel or concentric conductors—the earth and the ionized upper atmosphere—which together form a condenser of high capacity.

A cloud is normally an object of high resistance, as it diminishes the conductivity of the air within it by destroying the mobility of the ions which become attached to the cloud particles. Considering these facts and that the normal potential difference of about 1,000,000 volts between the earth and the conducting layer is small compared with the potentials of thunderclouds, it will be seen that whether (97)—

> the return current (continuous or discontinuous), by which the charges recombine after being separated within the cloud, passes mainly by the direct route from pole to pole of the cloud or via the upper atmosphere and the earth will depend on the relative resistances of these two circuits.

Discharges from the upper part of a cloud upward into a clear sky have not infrequently been observed. Some forms of sheet lightning are believed to be discharges to the upper atmosphere.

> There can be little doubt that the electromotive force of a thundercloud must maintain a considerable current—probably of the order of some amperes—between the ground and the upper atmosphere. The average number of thunderclouds in action at a given time is probably of the order of 1,000 at least; and the effect of the much larger number of shower clouds which do not produce lightning can not be neglected. It is at least possible that the upward currents due to clouds of positive polarity may more than counterbalance the downward currents due to clouds of negative polarity, and that the excess may be sufficient to maintain the positive potential of the upper atmosphere and compensate for the downward current of fine weather. (See also 118.)

This assumption seems to disagree with the main requirements of the Simpson theory, but Wilson states that one of the chief proofs of that theory—the charge carried by falling raindrops—is not a safe criterion, as in any case it is "probably a small fraction of the total current and may be no reliable measure of its magnitude and not even indicate its sign correctly. * * * The excess of positively charged rain may indeed be partly a consequence of negative potential gradients being more frequent than positive in heavy showers."

Simpson (119), however, states that out of 245 specimens of forked lightning photographed, 242 branched definitely away from the cloud. Now, from experimental evidence in the study of spark discharges, this action would be expected if the lower part of the cloud carried a (+) charge in accord with his theory of electrification. But opinions differ as to the interpretation of 173 well-defined photographs which showed no branching. Pointing out that "the branches on a branch discharge are always much less intense than the main discharge," which may have been photographed through cloud or rain, Simpson has "little doubt that a large proportion of them were branched away from the cloud although the branches could not be seen on the photographs." On the other hand, Lewis and Foust (120) believe that such discharges, after passing through a converging field, branch upward within the cloud and should therefore be reclassified and placed with the very few forked discharges that did not branch downward. They state that out of 100 Lichtenberg-figure records[7] of lightning discharges to transmission-line towers "not a single case of positive stroke to tower structures has been obtained," whence they conclude that "the great percentage of lightning strokes which terminate on transmission lines are initiated by breakdown streamers which progress from the line (positive) to the cloud (negative)."

Although much has thus been discovered about atmospheric electricity, the subject is deeply involved and offers a field for considerable investigation. During the past few years, however, interest in these matters has been increasing rapidly, and scores of articles on lightning and its immediate problems have been published in scientific and engineering journals. These investigations promise an early answer to the question of "whether there is an excess of the upward currents and whether this is sufficient to compensate for the air-earth currents of fine weather" (97).

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[7] So called because they resemble certain Lichtenberg dust configurations. The records are made by the discharge passing across a piece of photographic film clamped between two terminals. Their appearance differs greatly with the direction of the discharge.

Part 2.—INDUSTRIAL HAZARDS AND SAFEGUARDS

AVIATION

Static electricity may be generated in many ways in airships (121)—by tearing of fabric or its friction against metal, fabric, or other parts; by throwing of dry-sand ballast overboard; by normal release of hydrogen gas; by flow of fuel through pipes; by friction of propellers and ship through the air; and by exhaust gases from the motors (76).

TEARING OF FABRIC

In connection with tests to determine the electrification produced by tearing apart laminated fabric, Nukiyama and Nakata (46) said:

> At first we were interested in the practical problem whether there is any danger of kindling the hydrogen in a balloon or an airship by sparks caused by the electric charge which may appear when the ripping panel is torn off. We know many examples in which the cause of explosion could probably be ascribed to some defects in this ripping panel.

ENGINE EXHAUST

Wigand and Schlomka (122) tried to measure atmospheric potential differences in situ and determine at the same time the electric self-charging of their airplane. It was soon discovered that the engine exhaust produced static charges of such value as to make the other proposed measurements impossible; the gases themselves were (−) and the engine (+).

FILLING BAGS WITH HYDROGEN

During the war fires and explosions of hydrogen gas for filling dirigibles were so frequent that the German Government conducted special research thereon. Nusselt (123), to whom one phase of the problem was assigned, soon found that the hydrogen often carried particles of iron oxide, which seemed a necessary factor for ignition. Pure hydrogen could never be made to ignite. Conducting experiments with such gas under pressure near evening, he discovered that a pale blue glow, apparently due to electrical discharge, was produced as the gas left the orifice before it ignited. The effect was studied by placing various wire and screen conductors in the outcoming stream of gas. Nusselt found that a sharp-pointed copper wire placed directly in the path of the gas and grounded reduced the glow to but a small point; when the wire was moved slightly to the side the glow reappeared, and ignition followed. The apparatus used in these experiments is pictured in Figure 10.

Further experiments showed that iron oxide formed rapidly in pipes carrying hydrogen at high pressure if small amounts of water were present. One hydrogen cylinder of a few liters capacity yielded some 300 grams of iron rust. Trouble from fire was finally largely overcome by drying the gas before it was stored. The results should be compared with those of Pothmann given on page 36.

POTENTIAL GRADIENT OF ATMOSPHERE

In very large airships the normal vertical potential gradient of the atmosphere may, unless precautions are taken, cause dangerous sparks. In storms, including wind and dust storms, the dangers are greatly increased. A supposed case of this kind was mentioned in connection with dust storms. Haner (80) states:

When the *Shenandoah* broke loose from its moorings, sparks from 12 to 18 inches long could be obtained from the airship. The reason the ship got back safely was probably due to the fact that it was filled with helium * * * instead of hydrogen.

According to Simpson (108), very large charges are—

induced on an airship when it is in the strong electrical field of a thunderstorm. The positive charge is concentrated on one part and the corresponding negative charge on another part. If now the field is suddenly destroyed,

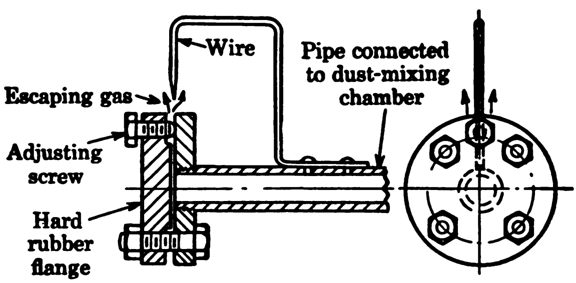

FIGURE 10.—Apparatus for studyig luminescence and autoignition of hydrogen containing traces of dust (Nusselt)

as for example by a distant lightning flash, the force holding these induced charges apart ceases to exist and the charges rush together in the form of violent and large electrical currents. These currents set up induced currents in the various elements of the framework, and sparks may jump from one piece of metal to another in the interior of the ship. This is a serious danger, which can only be overcome by the most careful design of every piece of metal in the ship.

LIGHTNING

Both lighter and heavier than air machines have been struck by direct lightning or static discharge. During a race at Brussels in 1923 three balloons were lost in a storm. Scherz, the sole survivor, says that in passing through a storm area he heard a sound like a shot; his companion fell dead with blood streaming from a wound, and immediately the balloon was afire. Herrera (124), who reports this incident, believes it was caused by a heavy electrostatic discharge and gives recommendations on manning a ship at such times and methods of dissipating the charges.

Lightning, however, sometimes strikes an airship without destroying it. The Friedrichshafen Museum has lightning-scarred parts of airships that have withstood thunderstorms successfully (121).

The greatest safeguard against the lightning and static hazard in aircraft and the one generally recommended is electrical interconnection of all metallic parts. Where possible, conducting coverings should be provided for the rest of the structure; these also should be connected in the general network. Properly bonded all-metal machines are, of course, safest from this standpoint.

A very large outdoor testing laboratory has recently been erected at Barberton, Ohio, for study of the effects of artificial lightning upon aircraft (125). The transformers used, said to be among the largest ever built, give a combined voltage of more than 3,000,000. By this means much should be learned, not only on proper construction of aircraft but also on the effect of intense electric fields on the operation of the engines and the well-being of the pilot and passengers.

BUILDING, CONSTRUCTION, AND MAINTENANCE

SPRAY PAINTING

In applying paint by spraying dangerous charges of static electricity have been produced. This method, although unsuited to every requirement, has been used very extensively during the past few years, particularly in applying lacquers and other coverings not loaded with heavy pigment. As many such substances contain highly volatile and inflammable solvents, care should be exercised in applying them in confined places where an explosive mixture may be built up. In connection with painting tanks for storing and dispensing petroleum products "it has been found that 10,000 volts will quickly build up on insulated tanks being painted with a spray gun" (126).

GUNITING

Concrete can be applied in much the same way that paint is sprayed. A mixture of cement, sand, and water (gunite) is fed under control into a nozzle, from which it is forced by compressed air against the object to be covered. Owing to the comparatively small amount of water used gunite can be heavily applied to vertical and overhead surfaces and is being employed extensively in mines for constructing barriers, supports for shale and bad rock, fireproofing, and many other purposes (127). Use in gaseous atmospheres, however, either in a mine or elsewhere, may be dangerous. Unless properly grounded the nozzle and perhaps other parts of the machine may become charged. Pickard (128) states:

> The sand should not be used too dry, as dry sand sets up static electricity in the material hose which produces shocks that make holding the nozzle very difficult.

Sparks up to 1 inch long have been drawn from an ungrounded nozzle. In the dark a blue glow may sometimes be noted in the issuing material.

About the only precaution necessary in these cases is grounding of the machines, particularly the nozzles. The latter is usually effected by using hose reinforced with spiral wire. The object being covered should also be grounded if possible.

CHEMICAL INDUSTRY AND MANUFACTURING

The chemical industry is particularly subject to the static-electricity hazard not only because many substances handled are both inflammable and capable of readily becoming highly charged but because the great variety of products and operations makes it difficult in some instances to determine the presence of charges or to remove them.

DUSTS

Probably dry dusts and powders have caused the greatest trouble. Some of the first explosions reported occurred during the manufacture of aluminum dust.

ALUMINUM

In 1905 M. Richter (129) investigated the cause of numerous dust explosions in the German aluminum-bronze industry. Thermal effects seemed inadequate to account for the facts, and Richter turned his attention to possible electrical causes. Statistics showed that most explosions occur in elevating and polishing. He therefore made experiments with a test machine built somewhat like an actual polishing machine. At first no appreciable static charges could be detected, but after the metal drum had been coated with shellac at the part of its surface where the rotating brush made contact (the shellac was considered to correspond somewhat to the wax or grease used in actual operations) charges capable of giving sparks intense enough to ignite benzine were obtained. No actual explosions of aluminum dust were brought about.

Richter suggested various means of overcoming the electrification and sparks. Two of these, which were strongly recommended, were to (1) ground all the metal parts of the machine and (2) impregnate the brush bristles and wooden parts with a 3 per cent solution of H_2SO_4. This treatment gave the brush permanent hygroscopicity without in any way injuring the bristles or affecting the aluminum-bronze powder. Aluminum dust might be supposed to be such a good conductor that the building up of charges would be impossible, but Richter showed (130) that each particle is covered with an oxide film that can withstand 0.5 volt. Any process to remove static by dampening the aluminum dust with steam or otherwise should be avoided because of the exothermic reaction:

$$2Al+6H_2O \rightarrow Al_2(OH)_6+3H_2.$$

Although the amount of hydrogen liberated ordinarily should not form an explosive mixture with air, it might add to the explosibility of the dust cloud.

NITROCELLULOSE AND SMOKELESS POWDER

The manufacture of smokeless powder includes several operations wherein high electric charges are often developed. After the cotton has been nitrated and washed it is placed in large drums and dried by upward circulation of air. It then becomes very fluffy and at times so highly charged that a glow produced by myriads of tiny tenuous sparks can be seen distinctly, and the cotton will cling to the hand in large masses. The drums are well grounded, however, and as there are no other metal parts to store up the electricity the sparks do not attain enough intensity to become definitely hazardous.

In the final preparation of smokeless powder the last traces of solvents are removed by a process in which air is blown upward through pans having screen bottoms. Here again static electricity is very much in evidence, but tests (131) have shown that although charges of several thousand volts are developed upon certain grades of powder, there is not enough energy in the sparks to cause ignition. Charges are also developed in subsequent handling and packing of the product, particularly as it leaves the bins en route to the metal containers. Thus, although explosions of these products rarely occur as a result of static, the hazard is ever present, and only the strictest surveillance in grounding and keeping away conducting bodies which might act as condensers prevents disaster.

SULPHUR

As sulphur is an excellent dielectric and has a low ignition temperature it ought to be easily inflamed by static electricity. Price and Brown (5) have described several explosions of sulphur dust; two at least were undoubtedly caused by static.

Other authenticated instances have come to the author's attention. One in particular might be mentioned. A certain company experienced much trouble from explosions while large cars of crude lump sulphur were being dumped into the hold of a ship. In a communication an official writes:

> The explosion seems to come from any part or parts of the loading equipment from the head of the chute to the bottom of the ship and we think is caused by the static discharge * * *. The idea of having grounding chains, etc., drag through the sulphur has been tried, but it is impossible to have all particles touched and they soon become covered with a layer of sulphur, which is a good insulator.

OTHER POWDERS

An investigation into the cause of several serious explosions during the manufacture of an insecticide powder has been described (132). The powder, known as dry lime-sulphur, has approximately the following composition: Calcium polysulphide, 75 per cent; calcium thiosulphate, 5 per cent; free sulphur, 8 per cent; inert matter, 12 per cent. At least one explosion was traced to sparks of static electricity. Trouble from static was generally found to occur in the dust collectors. Some of these bags, of the type used in starch mills, are manufactured with a chain running from end to end inside and connected through rings to ground, to drain off static charges. At this plant, however, the chains were inefficient and even dangerous, inasmuch as dust forced between the links formed gaps across which the charges sparked when they had built up sufficiently. Potentials of 2,000 to 10,000 volts were often observed during normal operation, and at times values as high as 25,000 volts were recorded.

Undoubtedly many other dry explosive dusts handled in the chemical industry are subject to high static charge, awaiting only perhaps some minor change in manufacturing procedure to disclose a distinct hazard of this character. Pure soap dust has been found to be very explosive in proper suspension in air. In discussing the results of some tests of soap dust Smith and Hartgen (133) state:

> With care, most ordinary sources of ignition may be eliminated. However, there is an insidious source of ignition which frequently arises due to the very presence of the dust cloud itself. Whenever the particles of most fine, dry dusts are rubbed against each other or against dry surfaces or blown by air currents, static electricity is generated. Conducting surfaces in contact with such dusts are often charged to potentials of several thousand volts. Under such conditions electric sparks may pass from one conducting surface to another or to grounded parts of the equipment. These sparks of static electricity are frequently sufficient to explode dust clouds through which they pass.

Several years ago the author was working in a small building where, in connection with another investigation, a mixture of aluminum dust, sodium chlorate, and lampblack was being prepared, as on many previous occasions, in a hand-operated mixer. Immediately upon resuming operations in the afternoon a severe explosion in the mixer killed the operator, seriously injured the other occupants of the building, and demolished the latter. A searching investigation of this explosion was made, but it was impossible to determine the cause definitely. Static electricity was strongly suspected; tests showed that charges of a few hundred volts were probably present, but other tests indicated that sparks of higher voltage and undoubtedly more current could not ignite the dust in bulk or in suspension. Differences in the size and weight of the particles composing the powder, however, may have provided, during the short cessation of operations, just the right proportion of dusts in suspension to be particularly sensitive to small static sparks; or a high potential may have been built up by gravitational separation of oppositely charged particles.

In a certain research hydrogen was being admitted to a chromium-lined test bomb or explosion vessel containing air. According to Fenning and Cotton (134), "The inrush of hydrogen was accompanied by a noise from the open outlet valve, which suggested that an explosion had occurred." This valve was found to be warm and the interior of the vessel was coated with water, showing that combustion had occurred. Further investigation revealed that the inrushing hydrogen had carried with it a small quantity of iron oxide and other foreign material. This dust was thought to have produced static electricity which caused the explosion, but subsequent efforts to bring about an explosion by the deliberate injection of iron rust and other dusts failed.

LIQUIDS

The experiments of Richter, Dolezalek, and Holde, made chiefly because of trouble from static electricity in the chemical and allied industries, have shown to what extent certain liquids can be charged when forced through pipes and orifices.

Rodde (76) states that while a batch of tar was being distilled an asbestos packing or gasket on a flange gave way and a long stream of the light distillate spurted out. About 6 feet from the opening the liquid ignited as a result of high electrostatic charges. After the gooseneck connection on a saturation chamber in an ammonia plant had broken, sparks caused by the flow of the ammonia could be heard distinctly.

Fires from static sparks are most likely to occur with liquids of low electrical conductivity and of course with those having low ignition temperature. Consequently many fires and explosions attributed to this cause have occurred in the manufacture and use of benzene (benzol), ethyl ether, and carbon disulphide. The latter substance is very easily ignited by static sparks; it has an ignition temperature of only 120° C. (135).

ORDINARY HANDLING

Backhaus (136) has summarized the most common ways by which electricity may be generated in such substances as follows:

1. By liquid solvent flowing through pipes or tubing.
2. By liquid solvent passing from vessel or tubing into air or other gaseous medium.
3. By solvent vapor issuing from an opening into a gaseous medium.
4. By gas passing through a liquid solvent.

Backhaus discusses each of these means briefly. Concerning the first two, he states: "Many solvents are fairly good conductors. Such solvents, when flowing through pipe lines, are safe statically * * *. Real danger starts where the pipe line ends." He believes that in this condition (liquid leaving pipe and falling through the air) high electric potentials may develop in any liquid, even water. In filling tanks with inflammable liquids this condition can be avoided by discharging the liquids into the bottom rather than the top of the tank. In connection with the passing of gases through liquids, he says, "The use of air for agitation is a common practice in the chemical industry. It is doubtful if this practice is a safe one in the case of solvents having low conductivity."

A few additional observations on electrification of liquids might be cited. Hencke observed sparks resulting from friction of benzol vapor escaping from a leaking valve (137). A chemical concern states that a worker received shocks and at night saw sparks when he touched a metal funnel through which ether was flowing. In one instance sparks were seen to jump from a glass tube carrying benzine. It was thought that a film of moisture on the glass made it conductive.

In one laboratory (134) an explosion occurred while a sample of $2H_2+O_2$ was being transferred by mercury displacement into a measuring burette. Static electricity was considered a possible cause and it was suggested "that the ignition may have been due to the projection of the fine stream of mercury into the dry glass explosion vessel."

Dolezalek (69) has pointed out that whenever electrification occurs in liquid flowing through an insulated metal pipe the charge on the liquid is carried off, but the charge of opposite sign on the pipe builds up until of sufficient potential to escape as a spark to some near-by conductor. He warns industries particularly against the charges often produced as the last portion of liquid forced through a pipe by gas or air leaves as a spray.

CLEANING AND DYEING

Various liquids, usually inflammable, have been employed in commercial dry cleaning. Before modern methods of handling the solvents were developed fires caused by static electricity were not uncommon, generally occurring when woolen or silk goods were lifted out of a tank of benzine. Mere separation of solid and liquid set up differences in electrical potential sufficient for sparks to jump from the garments to the edge of the tank (12).

RICHTER'S INVESTIGATIONS

In 1893 Richter (138) investigated this hazard. Among other interesting observations he found that the charges were much higher when the benzine (defined as the fraction of petroleum distilling at 70° to 90° C.) was cold than when slightly warm, the relation of charge to temperature being as follows:

Temperature, °C.	Intensity of charge	Sign of charge
−15	Very good	Wool (+)
0	Good	Benzine (−)
+15	Average	
+22	None	

These figures agree with statistics, which show that most fires in washing plants have occurred in winter. Tests with cotton goods showed that they, too, could be highly electrified, but it was necessary first to dry them carefully in an oven. Richter found that a small percentage of magnesium oleate added to the benzine prevented the accumulation of static charges but did not impair its washing qualities. The cause of this change in chargeability has been attributed to increased conductivity of the benzine; an addition of 0.05 per cent of the oleate raised the value in one instance from 2×10^{-12} to 1×10^{-10} mhos.

Experiments with ether and carbon disulphide (68) showed that both solvents are very susceptible to charging, the latter so much so that voltages of 10,000 to 13,000 were indicated for one passage of wool through the liquid. Indeed it is stated that benzine is one of the hardest of a number of inflammable liquids to electrify (71).

COMMONPLACE DANGERS

Even the use of gasoline in the home for sponging and cleaning gloves is said to have caused static sparks and fire (80). Huestis (139) describes a fire caused by washing silk curtains at home in gasoline and gives practical rules for dry cleaning.

Akin to these considerations is the famous hairdresser's accident in which a woman was fatally burned when a hair wash containing gasoline was ignited by a static spark while being applied (140).

COTTON

GINNING

During the summer and fall of 1917 an unusually large number of fires occurred in ginning cotton in Texas and Oklahoma (141, 142). Persistent rumors of alien-enemy activity, perhaps, led to a thorough study of the causes by the United States Department of Agriculture. The presence of matches in the raw cotton was suspected, but tests showed that even large quantities of matches could not account for the fires. As the weather was extremely dry and similar to that observed in the study of fires in another industry, the Government specialists tended to believe that static electricity was the chief cause. According to Price and Brown (5), information gathered from various sources showed—

that the fires occurred almost entirely during this dry weather and that very few started after the rains began. During this time static electricity was present in such large quantities in some gins that it was not possible to operate them and steps had to be taken to remove or dissipate the charge. It was not only noticeable on the machinery, but it was present in such large quantities that it was almost impossible to handle or approach any part of the machinery. It would also cause the cotton to stick in the lint flue and in other parts of the gins, gradually clogging them until they would not operate, holding the cotton as a magnet holds pieces of steel. At such times it was often necessary to close down the gin and to clean out the cotton before operation could be continued. In many cases sparks 4 to 6 inches in length could be drawn from various parts of the machinery. During this entire period fires were occurring so frequently that it was not unusual to have six or more fires in a gin during a single day.

Through humidifying the air in the rooms, however, by such simple means as the injection of steam or by hanging wet burlap and blankets around and sprinkling the floors, the trouble was largely overcome and "it is interesting to note that practically no more fires occurred in the gins which employed any of these measures to remove static electricity."

On the other hand too much moisture tends to make the cotton cling to the huller ribs and otherwise interferes with ginning; this method is therefore not very practicable. A system of interconnecting and grounding all stationary and moving parts of the machinery was devised and has proved satisfactory (143).

As experiments also showed that cotton can be easily ignited even with small sparks, the investigators believe that there can be "no chance to doubt that static electricity will ignite cotton and that it is one of the most common causes of fires in cotton gins" (5).

In India weather conditions so favor the development of static charges that the machinery used in nearly every operation must be grounded (144).

GRINDING OIL CAKE

Large hydraulic presses remove cottonseed oil from the waste product of the gins. The residue of seed left after the oil has been extracted is known as oil cake. This material is broken and ground for feed and fertilizer in massive hammer mills. Here again fires and explosions have occurred which could be explained only on the basis of static discharges (5).

GRAIN AND GRAIN PRODUCTS

THRESHING

From 1914 to 1917 some 600 fires and explosions occurred in the Pacific Northwest during normal threshing operations. Price and

Goodenow (145) state that the wheat crops contained a large amount of smut and that the—

fires in many cases were due to the formation of an explosive mixture of smut dust [fungus spores] and air and the ignition of this mixture by the discharge of static electricity.

The Department of Agriculture studied these conditions to determine the quantity of electricity generated and its relation to the kind of grain, season of the year, humidity, and temperature. Price and Brown (5) state:

It was very evident in the beginning of the investigation that a large quantity of static electricity was generated in a variety of ways during the operation of the separator. It may be generated by the friction produced by the rubbing of metallic parts or by the slipping of belts on pulleys, or it may result from the rubbing of grain, straw, and dust against the metallic surfaces of the machine.

The maximum voltage measured was 40,000, occurring between a driving belt and the ground. The experiments of Price and Goodenow (145) "proved conclusively that static electricity is present on all types of machines during the operation process, under favorable atmospheric conditions." According to Price and Brown (5), danger from fire was practically eliminated by "connecting wires from all affected parts to one conductor and grounding that conductor."

STORING

Probably no industry, except possibly coal mining, has sustained greater losses from dust explosions than that engaged in handling and preparing grain. A large proportion of these explosions have occurred in grain elevators or storage buildings. As in most accidental explosions, the causes are often obscure. A few cases have been definitely attributed to static electricity.

Tests in several parts of the country showed that dangerous static charges are often carried by both conveyor and power belts. A maximum of 75,000 volts was recorded on a 22-inch main-drive leather belt running from an electric motor to a main shafting. In spite of the slow speed and negligible friction (5)—

45,000 volts were recorded on one rubber conveyor belt carrying grain from the elevator head to storage bins. * * * Small charges were found on the suction pipes of pneumatic unloading systems. However, it was stated by men working at these that on certain days, when wheat was being unloaded, and especially smutted wheat, very heavy charges were present.

Under these conditions the friction of the grain as it passes over the metal is the probable source of the charge. Chandler (146) states: "In grain elevators the danger from static electricity can be successfully coped with by grounding all elevator and conveyor head spouts."

GRINDING AND BOLTING

Many explosions in flour mills and cereal plants have been due to foreign material getting between the grinding rolls or plates or to the use of open lights. Undoubtedly static electricity also causes explosions and fires in grinding machines. Price and Brown (5) cite the following example: In an attrition mill used for grinding oat hulls into feed seven explosions occurred within a week. The miller, suspecting static electricity, procured an electroscope and made some tests. The frame of the machine was found to be strongly charged. A small glass window was inserted to obtain a view within the mill. When operations were resumed blue sparks, at first intermittent but later continuous, could be seen. When the sparks seemed to be streaming around the outer edges of the grinding plates, the most violent explosion of any occurred in the mill and elevator leg. At once, steps were taken to ground all attrition mills in the plant. The trouble ceased, and no explosions have occurred since.

Hargreaves (14) writes:

> The possibility of static electricity as a source of cereal-dust ignition was very clearly established by an explosion in the dextrine department of a starch factory in one of the Eastern States in September, 1914. The origin of the explosion was traced to the production of static electricity by friction of particles of dextrine on 80-mesh brass gauze surrounding a revolving reel.

Numerous explosions have been due to static electricity generated in centrifugal reels when the brushes rub against the silk dressing (10).

A preliminary report by Price and Brown (147) is believed to have been the first published account of grain-dust explosions in the United States. This gives an interesting but brief history of the chief explosions up to that time and the results of laboratory tests of dust of many kinds. Static electricity is here accorded a place among the possible causes of grain-dust explosions, and the following statement may indeed have some related significance in the light of certain observations in the sugar industry mentioned later (pp. 73–74):

> The fact that explosions have been known to occur at times when the feed of grinding machines was cut off seems to indicate that an unknown factor may be the responsible agent.

MINING AND HANDLING COAL

COMMON CAUSES OF MINE EXPLOSIONS

Many explosions of gas and dust in coal mines can be attributed to carelessness of the miners or operators or the failure of some piece of equipment. However, there have been numerous mine explosions which could not be definitely or satisfactorily explained by any generally accepted agency.

ABRASIVE SPARKS

One cause, often suggested though frequently doubted or ridiculed, is that the gas might be ignited by sparks from a miner's pick or from falling roof. According to Coal Age (148):

> As early as 1896 when an explosion occurred in the Maindy pits, Flamorgan County, South Wales, the disaster was attributed to sparks struck by rock falling from the roof in an abandoned area of the mine.

Explosions in the Bellevue mine, Alberta, are thought to have been due to the same cause. In this connection Brownrigg, a fire boss at Bellevue (149), states that where a piece of roof falls on the wrought-iron sheets in the chutes a continuous streak of vivid sparks can be seen, and also that when a chute is abandoned the sheet iron is left in place. Miners drawing pillars had observed that when a cave-in occurred the glow of sparks from the falling rock lit up the place and made the timbers visible, the lamps having previously been extinguished by the rush of air from the fall. Rice (150) has recently published an account of these explosions and a later one at Bellevue.

Recent elaborate tests in England have shown conclusively that mechanical or abrasive heating and sparks produced by heavy impact of rock upon rock and metal upon rock can, under favorable conditions, ignite methane-air mixtures (151).

ADIABATIC COMPRESSION OF GAS MIXTURES

It is perhaps not impossible that falls of roof may initiate explosions by other means. A hypothesis suggested after the first Bellevue explosions, and actually accepted by the jury as the cause of the disaster, was that adiabatic compression of a gas mixture by a very extensive roof fall might so raise its temperature as to cause ignition. Much opposition to this idea and to the verdict of the jury has been expressed. But, whatever the action by which the gas was actually ignited, the underlying cause seems to have been roof fall. In the discussion of a paper by Sterline and Cadman (152) Doctor Atkinson stated that "taking all cases that were known there appeared to be no possible doubt that an explosion might be started by a fall of roof." While not necessarily accepting the "air-percussion theory" of ignition by roof falls, Halbaum said that he "was quite prepared to believe that the energy liberated might take on other forms which he himself had never witnessed."

SPARKS FROM STATIC ELECTRICITY

FALLING ROOF

One such form may be electrical, as suggested by accounts of the appearance of flashes of light and sparks not alone at the point where rock falls upon the floor of a passageway but also along the line of roof cleavage. Rees (13) holds that such phenomena may be explained by piezo-electricity. He says:

> If a mass of crystals is under heavy load as in the case of certain types of roof in mining practice the surfaces of the crystals become electrified. When the pressure finds a vent at a break in the roof a very rapid change in character of electrification takes place and the electric charges are dispersed. If the rock breaks with pointed edges, then point discharges of electricity take place * * *. The principles of piezo-electricity or electrical charges due to pressure are thus sufficient to account for the manifestations that present themselves at the sudden fracture of quartzite roofs under heavy loading * * *. With a siliceous roof there is a possibility of gas being forced out suddenly by a fall and of the gas being ignited by electric sparks.

The electrification developed when laminated bodies are torn apart along their cleavage planes has been mentioned. The paper-faced cloth used in binding books, celluloid film stripped from the drums during manufacture, and many other substances show such electrification to a marked degree. Obreimoff (153) recently described electrical effects produced when mica is split in air at atmospheric and reduced pressures. Sparks and glow discharges of various intensities were in evidence, even with the small samples used.

It has been suggested that the separation of shale and rock strata during roof falls of large area might, under suitable conditions of moisture content and manner of falling, occasion electric discharges along the line of cleavage, particularly at the point of final separation.

The great differences often found in the composition of adjoining strata point to such a hypothesis, and the peculiarily favorable conditions for ignition of gas provided by the initial sagging and bending of the lower rock and accumulation of methane in the crevice make it worthy of consideration. Thus, in discussing ignition by abrasive sparks Professor Briggs has said of such crevices (150):

> It is possible in the circumstances for a large volume of gas to exist between two belts of rock and at the same time for the air circulating through the workings to be reasonably pure.

Static electricity may have played an unsuspected part in certain luminous phenomena observed by J. W. Powell (154), a superintendent at the Bellevue mines, who writes:

> I am of the opinion that there is much danger of an accumulation of gas being ignited in any mine where the roof is of such a nature as to emit sparks when subjected to the grinding action that occurs immediately before a fall. On certain occasions I have heard the roof rock crack with a sound like the report of a large gun. Bright flashes also are emitted when such rocks strike each other when pieces of the roof fall.

Mayer (155) and Sauer (156) have reported numerous similar phenomena in German mines, the effects being likened to lightning, explosions of gas (although no gas was present either before or after the fall), brush discharges, glowing, and the burning of chaff, which made distinguishable the pillars, crossbeams, and falling rock.

An idea of the immensity of roof falls in some mines may be had from the fact that at Bellevue one fall 4 feet thick extended over an area of about 500 by 80 feet (152). Large falls, especially in level beds, often initiate destructive air blasts; some of these have been so strong that they blew down props and doors and even killed men working near by. In British India the coal seams are very thick, ranging from 20 to 150 feet. According to Penman (157):

> The roof is as a rule strong, and in consequence large areas are often mined out before the main roof gives way. Sometimes the goaf may be standing like a colossal hall, perhaps 400 feet square, and not a sign of a break be apparent. A collapse of such a size in a 20-foot seam would displace a volume of air of over 3,000,000 cubic feet.

From previous statements regarding the electrification of high-velocity dust clouds it would seem likely that an air blast of such magnitude as this might carry with it a quantity of highly charged dust, especially if it were to pass through a relatively small opening, such as a hole in a stopping.

ROCK BURSTS

In connection with the possibility of development and discharge of static electricity by sudden rock cleavage other types of large-scale breakage should be mentioned. In deep mines the weight of overburden may become so great that even large pillars are crushed. Violent ruptures thus produced are known as rock bursts or in coal mines as bumps. Occasionally the burst may follow a break of roof or a cave at some higher level. Herd (158) observes:

This blow due to the weight of overhead strata at considerable depth exercises great force; and although it may lower the roof only a fraction of an inch, the impact is such as to burst the solid coal into the roadways, break the floor, split pillars and occasionally, owing to the jar, bring down roof stone.

Crane (159) says:

In certain localities signs of disturbance may be observed for hours, days, and occasionally weeks before rock bursts occur. They consist of sounds such as cracking, popping, grinding, and rending, accompanied by spitting and flaking of small fragments from the walls. * * * Occasionally flashes of light that can be observed in the dark accompany the flaking. In other localities no sound of breaking off of fragments from the rock face can be observed, but failure takes place suddenly, masses slumping off, or fragments being hurled with varying degrees of violence.

Sometimes large rock bursts are accompanied by great turbulence of the air (160). Crane (159) describes an actual air blast in a copper mine as follows:

The air being expelled violently from the workings through the shafts caused much damage underground and forced out of the mine great volumes of air charged with dust, dirt, and small fragments of rock, sticks, and other débris which rose 150 feet or more in dense columns * * *. The air was so filled with dirt and small particles of ore that they obstructed the view and cut the face and hands like a sand storm. Furthermore, everything in the mine was covered with a thick layer of dust, so thick, in fact, that it was difficult to distinguish the bodies of men killed in the blast from rock and timber.

OUTBURSTS

An outburst is a phenomenon that resembles a rock burst or bump in some particulars. The movement of rock and coal in this case, however, is due largely, if not entirely, to the presence of imprisoned gas, usually methane, but sometimes CO_2. In one recent outburst of CO_2 more than 150 men in the mine were asphyxiated (161). Herd (158) says:

Outbursts, as applied in coal mining, mean instantaneous outbursts of gas which throw out coal with much dust violently from the face as from a blast, in some cases a huge blast, throwing out thousands of tons of coal.

OTHER CAUSES OF ROCK FAILURE

Various attempts have been made to correlate mine explosions with meteorological and seismological changes. Although it is doubtful if any very general relationship has been proved, earthquakes or smaller earth movements probably cause strains and fractures in coal and rock strata sufficient to facilitate the escape of methane or to bring about falls of roof. At any rate, Denison (162) has shown that between 1899 and 1910, 22 per cent of the 114 explosions listed for North America occurred upon the day of a quake, 18 per cent on the day after, and 8 per cent upon the day before; that is, 48 per cent occurred within 24 hours of a quake. Mintrop (163), however, found no such analogy of events in his statistical investigations, although he believes that if a source of ignition were always present some such relationship between seismic disturbances and fire-damp explosions might be shown.

As indicated by the seismograph, the rock mantle of the earth is about 30 miles deep. Doctor Hecker, of Berlin, has found that this portion of the earth's crust rises and falls several inches every day as a result of solar and lunar attraction (162).

ELECTRIFIED COAL-DUST CLOUDS

The experiments of Walther and Franke and of Blactin and Robinson have shown that coal dust carried along by a current of air may develop a high electrostatic charge. Under suitable conditions, as noted, a charge sufficient to give an igniting spark for methane may be obtained (62, 164). Whether such conditions might occur in a coal mine is still a question. Several investigators, however, have believed it possible. During his studies of dust electrification Rudge (56) on one occasion measured a potential of nearly 300 volts in a moderate cloud of coal dust raised by a trip of cars in a mine. Experiments in the laboratory with the same dust blown through a metal tube gave sparks up to 1 cm long. He says:

> If, then, such a combination should occur as that of a sudden cloud of coal, or perhaps other dust, an insulated conductor, an earth-connected conductor near it, and an explosive mixture of gases, it is not inconceivable that an explosion might follow. I make the suggestion quite tentatively.

This opinion is supported in almost the same words by Ashworth (165) and Hargreaves (14), referring, however, to roof falls as a suitable cause of the requisite high-velocity dust stream.

LIGHTNING

A static-electrical hazard perhaps more tangible and certainly better authenticated is lightning. Several premature explosions during blasting operations in mines have been definitely attributed to it. An account is given of three such explosions in the Rochebelle and Fontanes mines of France. The part of the mine in which the shots were fired was more than 600 feet below the surface and about a mile from the shaft. Just how lightning reached this remote place is not definitely known, but it is believed that part of its path was along an air pipe line which paralleled the firing cable for several hundred yards. Ferey (166) believes that a discharge 7 or 8 inches long may have jumped between the cable and the pipe and states that on several occasions he has observed such sparks in mines during electrical storms.

Two explosions of gas, attributed to lightning (167), or to current induced by it in a section of track, occurred in an unwired mine at Salina, Pa. No one was in the mine on either occasion. The second explosion did considerable damage inside and demolished the surface fan house.

According to the Mt. Carmel Item (168), lightning entered a mine near Ashland, Pa., through a 12-inch pump column used for pumping water to the surface, causing no damage until it had followed the pipe line into the mine 600 feet. At that point it shattered the pipe connection on the pump.

In the summer of 1929 a shot was fired in the Wachusett-Coldbrook tunnel, Massachusetts, by lightning, which struck the firing line and followed it down the 411-foot shaft toward the face of the tunnel a mile distant; the discharge jumped both safety switches in its path.

Rice and Ilsley (169) have published the following details of an unusual explosion of fire damp in a coal mine at Sitalpur, India:

The explosion occurred during a thunderstorm, and the evidence showed that a flash of lightning had, to all appearances, passed down the shaft, causing disruptive discharges at certain points between the guides and the winding rope, rending the latter at two places situated respectively 228 feet and 278 feet from the surface. The distance between the winding rope and the side of the shaft was 5 feet 4 inches, indicating a spark gap of this width and an intensity of discharge which could not fail to ignite the explosive mixture of gas and air known to be present in the shaft.

The Lightning Research Committee in 1905 recommended as follows (170):

Undoubted evidence exists of the explosion of fire damp in collieries through sparks from atmospheric electricity being led into the mine by the wire ropes of the shaft and the iron rails of the galleries. Hence, the headgear of all shafts should be protected by proper lightning conductors.

Undoubtedly lightning may enter a mine by power wires, rails, hoisting cables, boreholes, or ventilator shafts. It is perhaps even possible that current enough to fire a blasting cap or cause a spark may find its way in through conducting earth strata or an underground stream. Evidence that lightning can travel some distance into solid earth is afforded by fulgurites (171, 172). These lightning tracks through rock or sand often are long slender tubes with walls fused like glass by the current of the discharge. Many of these tubular fulgurites, especially in rock, are only a few feet long, but in dry earth or sand may extend many yards beneath the surface of the ground. "After following one for a length of 10 feet along its course, there appeared no indication of a change in size, and further excavation was impracticable" (170). Their course in rock generally lies along well-defined streaks or filaments of ore or iron oxide. How far the current may penetrate into the ground after its main force has been expended and before neutralization of charges is complete depends, of course, upon orientation of the strata and their conductivity.

An incident in support of the idea that lightning may find its way to great depths in the solid earth is recounted by Fonvielle (19). In the summer of 1855 a number of men working in the mines of Himmelsfurth and dispersed along a lode of ore some thousand feet underground—

received very violent shocks * * * some of them felt a blow upon the back whilst their neighbors were struck about the arms and legs. It appeared as if they were roughly shaken by an invisible, mysterious hand, which at one instant came out of the ground and at another from the sides or roof of the gallery.

STRAY CURRENT

LEAKAGE FROM POWER LINES

Stray current from power lines and electric rails frequently is a source of danger in electric blasting. Sometimes there may be enough voltage between a rail and a pipe line underground or between two rock strata to give a dangerous spark. Often the origin of such leakage is near by, and the trouble can be corrected by bonding or better selection and distribution of grounds (80, 173). The cause is not always located so easily, however, as it may be at some point on the surface miles distant. Under these last conditions the effects from stray currents, though usually less important, may be very widespread (174).

CHEMICAL, THERMAL, AND SOLAR SOURCES

Earth currents are also produced by chemical and thermal processes and by solar radiation. Although usually of no importance as a hazard in mining perhaps they are not entirely exempt. Matthews (175) has shown that a fairly strong current may be set up between anthracite and iron rails, pipes, or chutes when partly immersed in mine water. Earth currents of solar origin (176) are believed to be caused by induction from rapidly moving static charges or clouds of ions produced by ultra-violet or corpuscular radiation in the outer atmosphere and, as is well known, are often strong enough to affect telegraphic communication seriously (25). Such currents collected by an extended system of rails or other good conductors might constitute a hazard in blasting during very severe auroral and magnetic storms.

McAdie and Henry (177) give an interesting account of a storm in November, 1882; at the time of the disturbance a large sunspot covered about 1/400 of the sun's visible surface. Earth currents were so strong that " not a wire of the Western Union Telegraph Co. could be used for three hours." Elsewhere a message was sent 700 miles on the earth current, all batteries having been disconnected. Even small incandescent lamps were lighted by this natural electricity. At night there were most unusual and brilliant auroral displays.

RELEASED STATIC CHARGES

Electrostatic charges of considerable magnitude are sometimes induced upon the earth's surface by thunderclouds. As such charges are " bound " by the clouds above them neutralization can not occur, even though areas of opposite sign are near together. If, however, lightning occurs between the clouds (95)—

> the primary charges in the cloud are suddenly neutralized and the induced charges on the earth previously "bound" are now left "free." Stress will then immediately appear between these two charges and they will rush to recombine. If the surface earth of the earth, together with all objects on it, were a good conductor, this recombination could be effected almost instantaneously without any appreciable secondary effect; however, since this is not always the case, pools of this charge may be left isolated and for the moment at high potential relative to the earth, so that secondary sparks may occur.

Recombination of such charges through the ground would be expected to take place along the better conducting strata, even though the path thereby lay far below the surface.

STATIC FROM STEAM, COMPRESSED AIR, AND BELTS

In addition to the foregoing processes which may occasion electrostatic effects in mines are those sometimes accompanying the use of steam, compressed air, and belts. The latter are still used in some mines for driving pumps and compressors, while long, wide belt conveyors for transporting coal are increasing in favor. With either type of belt static electricity is liable to be produced as in other industrial plants unless adequate grounding is provided. Experiments have shown that enough electricity can be produced by the friction of a small pulley and belt to ignite natural gas readily (5, 14). As early as 1830 compressed air was proposed for operating machinery, especially in gassy mines. It is recorded (178) that a compressed-air-driven longwall coal cutter was in use in a Lancanshire colliery in 1866, but it was not until 1882 that electricity was first used for lighting and pumping in a mine. Compressed air and steam are still used underground for driving machinery, but the latter source of energy is now seldom used, except for operating pumps near the entrance. In the United States the use of compressed air for mining coal is generally restricted to operation of portable picks and drills. Usually the air for these is supplied by portable electric compressors. Occasionally, to promote safety in gassy mines more extensive use is made of pneumatic machinery, and the compressed air is piped considerable distances. Influenced perhaps by habit as well as by a feeling of greater safety and the fact that pneumatic machinery often costs less to install and maintain, many countries have been slow to adopt electrical equipment. Advances made, however, in the design of flameproof motor and accessory compartments and the growing favor toward Government-approved "permissible equipment" are rapidly bringing about the introduction of electricity in mines where conditions permit the installation and protection of cables.

Thus Engineering (178) states that in 1928, 3,586 electrically operated coal cutters and 1,341 utilizing compressed air were in use in British mines.

Possible danger from electric sparks by using steam and compressed air in atmospheres containing methane has been pointed out recently in the following brief editorial in Coal Age (179):

> Static electrical charges of rather high potential are sometimes generated by leaks in steam and air lines. These charges are equalized by sparks jumping from the charged cloud of steam or atmosphere near the leak. Such discharges, or so-called sparks, may be several inches in length and even though of static origin might ignite a mixture of gas and air. We are not too sure yet that no static discharges or mechanical sparks will ignite methane, and it is well still to act cautiously lest, in a gassy mine where compressed air or steam is used to the exclusion of all electricity, fire or explosions may be caused by steam or air leaks. There is only one reasonably safe procedure. Do not allow an accumulation of gas in any mine at any time.

Audibert and Delmas (180) mention several accidents in which fire damp is believed to have been fired by sparks produced by the electrification of escaping compressed air. They apparently were unable to reproduce the phenomenon of ignition experimentally, but sparks were observed whenever dust and air were blown through the apparatus.

STATIC CHARGES IN POWDERED COAL USED FOR FUEL

Although coal-dust suspensions in air have not yet been ignited experimentally by static sparks, there is not enough evidence to warrant an assertion that such ignition is impossible. Whether or not this danger exists is an important question in view of the widespread and increasing use of powdered fuels. Tracy (181) calls attention to an explosion of dry lime-sulphur reported by Edwards (132):

Although the * * * illustration pertains to a material other than pulverized coal, it nevertheless serves as a warning to plants that have pulverized-coal installations with collectors of this type to see that proper ground connections are made. A spark caused by a high static charge might, if the proper conditions existed, ignite a cloud of coal dust and cause serious damage. Similarly, all parts of machinery that in any way are liable to build up a static charge, such as pulverizing mills and belt-connected conveyors, should be thoroughly grounded.

PAPER AND PRINTING

STATIC ELECTRICITY AN ANNOYANCE

Many materials in sheet form are easily electrified by friction, particularly paper, which when dry is a good insulator. While writing, one may observe, especially in winter, that the paper adheres to the desk or to the hand due to friction with the fingers. A few passes of the hand across the paper will electrify it so strongly that it will cling to a vertical surface for many minutes. Tiny sparks, visible in the dark, several inches in length may be drawn from the sheet when freely suspended in air. If one terminal of a small neon tube is moved about over the surface of the paper, it will flash brightly though intermittently for five minutes or more before the charge becomes too feeble to affect it. Such charges have proved very troublesome in handling paper in duplicating machines and other office equipment.

Static electricity is often generated in large quantities in paper mills, paper and fabric coating plants, newspaper and other large printing establishments. Hornaday (182) states:

In the dry and more altitudinous part of west Texas and all through the Southwest there are times when static electricity is so bad that it is almost impossible to operate printing presses. In summer this troublesome period lasts for several weeks at a stretch.

DANGER OF STATIC ELECTRICITY

Not only is static a source of annoyance in such industries because its attracting and repelling effects make paper hard to handle, but it may constitute a real hazard if the same effects cause the machines to clog or if shocks received by the workmen cause them to jump or move involuntarily. In preparing coated or waxed papers and artificial leather static sparks may ignite the solvents employed.

REMEDIES

Various means have been devised for removing the charges as developed. These include: The static neutralizer, a metal comb with sharp points placed close to the sheet material and charged with a high alternating potential; ultra-violet light and other ionizing radiation; several forms of humidifiers; and, of course, grounding wherever possible (183). In the manufacture of certain coated papers and fabrics humidification has been carried to the point of passing the sheet through a steam bath which dampens it perceptibly. Sometimes conducting or hygroscopic substances are added to the material as it is being manufactured or a fine wire is pressed or woven into it. Static charges have been removed from paper passing through the rolls in a mill or in printing presses by applying flame to the paper, perhaps by a series of jets across its width. When the paper is moving rapidly it is not injured by the flame, and the ionization prevents accumulation of static (184). A simple method of keeping the potential of charge at low value and the one most often used on large rotary presses is that in which a grounded wire is stretched across and close to the paper at several places in its travel. In reciprocating or job presses a specific remedy often employed is to dampen the tympan with a mixture of glycerin and acetic acid.

PETROLEUM

EASE OF GENERATING STATIC ELECTRICITY

The fact that many liquids, including distilled water, may be highly electrified by simple and often unsuspected means has already been considered. In general, liquids of poor electrical conductivity were found to charge most easily. Gasoline and oils of various grades are therefore readily charged and if sparks occur may even be ignited as a result of normal handling. The greatest trouble from this cause results when petroleum distillates are transferred from one container or tank to another. Whether this transfer is by pipe line, hose, pump, or simply pouring, it is almost always associated with danger.

CHARGES ON TANK TRUCKS

According to Bean (185):

> Several gasoline-truck fires which have proved more or less serious have been directly caused by static electricity being generated and held in storage in the truck body and frame by the tires until such time as a ground has been established. * * * Static electricity is generated in a truck by friction and may be caused by the slush of the liquid in the tank, by contact with the pavement when moving rapidly, and by the sliding motion of the tanks on the cradle or the cradle moving on the frame. * * * Dependent upon the charge of static electricity in the truck, the static spark may jump all the way from one-eighth of an inch to an inch.

In addition to these means, static charges and sparks might conceivably result from the friction of the driver's clothing against the truck seat or by his shoes upon an asphalt pavement (83). Actual fires from a similar cause have been reported. While a naval officer was walking to his garage charges developed by friction between his fur coat and rubber boots produced a spark which ignited the gasoline in the tank of his car (42).

FIRES CAUSED BY DRAWING GASOLINE AND FILLING TANKS

W. L. Wedger (186), of the Massachusetts Department of Public Safety, gives an interesting account of several fires caused by static electricity. A chauffeur hung a 5-gallon pail on the spout of a pump and began drawing gasoline. After he had pumped 2 gallons a spark jumped around the wooden handle on the bail and ignited the vapor. Not understanding the cause of the trouble at first, the chauffeur put out the fire and resumed pumping. The gasoline was again ignited.

On another occasion the gasoline tank of an automobile was being filled through a lined fabric hose with a metal nozzle, which was not making actual contact with the tank but was close enough for a spark to pass.

A chauffeur poured gasoline from a 5-gallon can through chamois stretched over the top of a funnel into a tank under the seat of a car. To make the funnel stand vertically in the tank it was provided with a wooden collar. Before all the gasoline had been poured a static charge had been built up intense enough to spark across the wooden collar and ignite the gasoline. Wedger, using the same funnel and chamois, made experiments demonstrating the production of electrostatic sparks to several men at the garage.

Several thousand gallons of gasoline were lost in tank fires in Albany before it was found that the fires were caused by electric sparks jumping from the pipe of an overhead storage tank; it was the practice to run the cars under the tank to a position where the pipe entered but did not touch the filling hole.

A similar fire also occurred in a submarine chaser at the Charlestown Navy Yard during the early days of the World War.

Pending repair of a leaking distillate connection in a certain manufactory (187) a bucket was hung up to catch the drip. The bucket was not grounded, however, and when the attendant went over to remove and empty it—

> a spark jumped either from his hand to the bail or vice versa, and the distillate in the bucket was ignited. It seems rather obvious that the consistent dripping of the liquid caused a charge to accumulate on the bucket, there being a small amount of electricity carried by each drop.

LUBRICATING OIL HIGHLY CHARGED

In filling some tanks with filtered cylinder stock (viscosity, 110–140) the oil was permitted to fall in a stream through the air about 20 feet. On dry days a charge of enormous voltage accumulated on the surface of the oil and discharged from time to time to the tank or to a vertical pipe in the center. Haner (80) says he has seen "discharges as long as 4 feet in a jagged line across these tanks accompanied by sharp reports." Because the grade of oil being handled was heavy, there was no great danger from fire. However, means of eliminating the charge were sought. First a long brass chain was suspended from the center of the strainer to lie within the stream, but this did not prove effective, probably because of the film of oil between the links. Two types of baffles were then used to deflect the oil stream over against the sides of the tank; but the oil fell away from the baffles and tank walls, and large charges were still produced. The remedy finally found was to convey the oil through a funnel and long spout to the bottom of the tank (42). It is important to note that before this was done, although the discharge pipe, strainer, and tank were grounded, discharges up to several hundred thousand volts were possible.

Naylor and Ramsey (42) say that at least two fires are known to have occurred from pumping hot oils through grounded pipes into grounded tanks.

PRECAUTIONS

Although, as in the examples just given, supplementary measures may be necessary to prevent splash and spray (136), grounding is the simplest and most effective of any general method of safeguarding against the static hazard in handling inflammable liquids. Dolezalek and Holde have shown that grounding will remove the charge almost instantly from a body of liquid in a tank unless some other ungrounded conductor is present to take up and hold the charge.

Watterson (126) believes that—

> an all-steel vapor-tight tank which has been electrically grounded by resting directly on moist earth and all-metal connections interconnected or bonded is an extremely low fire hazard.

At least in warm weather explosions from any cause may not be expected to occur within such closed tanks for, as he states:

> It is generally agreed in the oil industry that the air-and-gasoline mixture in the upper part of a tank is too rich to be ignited by an electric spark.

Drag chains for grounding tank trucks have sometimes been looked upon with disfavor because of their inefficiency and the false sense of security they may give, but it is generally agreed that bonding by chain or preferably by cable to loading and unloading points is very important. Apparently, however, drag chains can at least do no harm and in many instances are an added safeguard.

In cleaning oil or gas tanks with steam the tank and steam line should be electrically bonded together and grounded (12).

LIGHTNING

DIRECT HITS

Many fires in large storage tanks have been caused by lightning, but it is now possible in most cases to provide adequate protection against direct hits. By means of artificial lightning of two or three million volts it has been shown (91) that a lightning rod over 1.1 per cent of the cloud height will protect an area having a radius four times the height of the rod regardless of the position of the cloud. Three or four rods of moderate height placed properly may therefore be relied upon to protect a fairly large tank from a direct hit by lightning.

CAGE SYSTEM OF LIGHTING PROTECTION

Much better protection than that afforded by lightning rods, however, is claimed for the recently developed Cage system of neutralization. Instead of pointed rods, steel towers are erected at suitable intervals around the area to be protected, and upon these are strung three or more wires having sharp points or barbs every few inches along their length. The wires are grounded thoroughly at several places and effectively collect and dissipate the induced earth charges before they attain anything near the potential required for lightning. It is said that one company has installed the Cage system to protect a 12,500,000-barrel oil reservoir (94).

INDUCED AND BOUND CHARGES

Fires, however, may be caused by sparks induced by lightning even when the tank is not struck directly. According to Peek (188):

> Partially insulated or grounded metal or other conducting parts assume a potential above ground when a cloud discharges. * * * Sparks may thus pass between isolated metal parts or between metal parts in poor contact, due to cloud discharges at considerable distance. * * * Insulated metal parts assume the potential of the space in which they are located. Sparks may occur between two conductors at different heights above ground in the field of a charged cloud. It is not necessary for a cloud to discharge to produce these sparks. * * * In a metal tank it is important that all parts be in electrical contact. A slightly insulated pipe or other conductor projecting in from the outside, even if grounded, could cause a spark.

Two fires caused by induced charges might be mentioned at this point, although the application is pertinent to nearly all activities where inflammables are used. According to Haner (80), a tank car was being loaded when a thunderstorm came up. The galvanized-iron building where the work was being done was not grounded and so acted as an accumulator of atmospheric charges. When these—

> became great enough they discharged at the point of least resistance, which in this case was between the filling line and the tank car, in a location where there was of necessity an explosive mixture present.

McAdie (177) cites the other example. The town hall at Brussels—

> was so well protected that scientific men pronounced it the best-protected building in the world against lightning, yet it was damaged by fire caused by a small induced spark near escaping gas. * * * The building probably did not receive even a side flash.

Wilcox (94) states that sparks caused by neighboring lightning discharges—

> may vary in length from the infinitesimal to several feet, depending altogether on the circumstances in each individual case, the intensity of the charge, the capacity of the body, and its distance from the center of primary discharge. In any event the secondary spark, whether small or great, is a source of grave danger, being probably responsible for many more fires than are primary discharges. Should this spark, no matter how small, occur in the presence of any inflammable or explosive gases, disaster follows immediately.

Oil is frequently stored in very large quantities. According to Peek (188):

> This storage is often so great, in fact, that, economically, metal tanks are said not to be feasible. The tanks or reservoirs which are usually made of reinforced concrete are frequently 500 feet in diameter, but sometimes in oval form as large as 600 by 1,200 feet and 30 feet deep. Occasionally some of the smaller tanks are of metal. The capacity ranges from 700,000 to 3,000,000 barrels. A group of tanks makes up a farm.

With such reservoirs the necessary conducting parts for induced discharges might be found in pipes, metal used for reinforcing, water, or merely damp concrete.

An interesting experience related by Dr. F. W. Lee, senior physicist, United States Bureau of Mines, illustrates a point, which has been made, that a heavy discharge from lightning may occur between two well-grounded conductors. During a severe thunderstorm there was a sudden crash in the basement of his home; it sounded as though lightning had struck there. The charred remains of a piece of rubber hose revealed that an electric discharge 4 or 5 feet long had indeed passed between a water pipe and drain. Both pipes apparently were perfectly grounded—the water pipe was underground and connected with a spring 300 feet away; the drain pipe was covered with soil for 40 feet.

SUGAR

Sugar dust in cloud form is one of the most easily ignited and violently explosive common substances. After studying the explosibility of more than 60 different dusts Wheeler (5) concludes that—

sugar, dextrine, starch, and cocoa are the most dangerous, sugar exceptionally so. Sugar ignites when projected as a cloud against a surface heated to below red heat, and when ignition has taken place the flame travels throughout the dust cloud with great rapidity.

BEYERSDORFER'S INVESTIGATIONS

Beyersdorfer and Braun (189) have shown for comparison the ignition temperatures and explosive limits for 200-mesh sugar and sulphur dusts. The figures are as follows:

Substance	Temperature, ° C.[8]	Explosive limits, grams per cubic meter
Sulphur	200–215	132–1,400
Sugar	410	160–600

Elsewhere (7) much wider limits—17.5 to 13,500 grams per cubic meter—have been given for extremely fine sugar dust (10^{-5} to 10^{-6} cm diameter of particle). Although explosions may result from the latter concentration Beyersdorfer calls attention to the fact that enough oxygen is present in a cubic meter of air to burn only ¼ kg of sugar; he believes that additional oxygen is carried by the dust particles, having previously been adsorbed by them. This theory accounts in part for the great difference in explosive limits of the two grades of dust and places extremely fine sugar dust almost within the category of self-contained explosives. If, in addition, N_2O_5 and O_3 are formed in a highly electrified sugar aerosol, the latter may indeed become very sensitive to ignition and be fired as Beyersdorfer suggests by spark discharges within the cloud (9). He says:

Dust explosions initiated by electrical causes may be considered as dust storms or clouds, where the cloud forming the lightning discharge is consumed by it. Such meteorological conceptions of dust explosions as a whole become more probable when after the example of A. Schmauss[9] we take into consideration for this problem the fundamentals of colloidal chemistry.

The following description of a dust storm in the Southwest in 1895 by Neal shows that discharges may occur through the body of a dust cloud without the aid of metal collectors (190):

The dust passed along in a column fully 1,000 feet high; the wind rose to a speed of 35, then 45 miles per hour, with gusts reaching 55 miles; the temperature fell rapidly and we saw for the first time (about 9 p. m.) flashes of light that apparently started from no particular place but pervaded the dust everywhere. As long as the wind blew, till 2 a. m., January 21, this free lightning was everywhere, but there was no noise whatever. It was a silent electrical storm.

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[8] Temperature of aluminum block upon which dust was blown.
[9] Schmauss, A., Meteorologische Ztschr., 1920, Heft 1/2.

Thus, no small significance is attached to the fact that Beyersdorfer actually brought about an explosion of sugar dust in oxygen and a definite burning of sugar dust in air by passing the dust clouds through the electric field of a Siemens ozonizer (191).

ELECTRICAL IGNITION VERSUS OTHER CAUSES OF EXPLOSION

Block (192), however, has objected to the electrical theory of sugar-dust explosions. He holds that sugar which has adsorbed oxygen may ignite spontaneously when heated in the presence of a catalyst of iron oxide. Other causes assigned are heated bearings, heat produced by crushing and pulverizing, and particularly abrasive sparks due to the presence of foreign material in the sugar. Strangely, however, a large percentage of sugar-dust explosions and, indeed, explosions of other dusts have occurred immediately after work has begun or after a short intermission; it is a curious fact and one that would seem to require a different explanation from that usually given—heated bearings or sparks from machinery. Both Beyersdorfer (7), who says that 16 out of 17 major sugar-dust explosions so occurred, and Boning (44), who places the figure at 7 out of 8, lay special emphasis on this peculiarity in their consideration of electrical causes. The latter investigator gives three conditions which he believes favor electrically incited dust explosions: (1) Time for the electrified dust to settle upon an insulated conductor; (2) sudden removal of the dust; (3) the proximity or approach to the conductor of another conductor to which a spark may jump. Grounding of both stationary and moving parts of all machinery and the employment of inert atmospheres wherever possible in pulverizers and conveyors are usually prescribed as remedies.

OTHER INDUSTRIES AND OCCUPATIONS

Undoubtedly many industries and pursuits not named here have been troubled with static electricity. Consider for example the following explosions which are believed to have been caused by sparks from rubbing the fur of animals:

According to Gill (193), "It is the custom of dog (and cat) catchers to asphyxiate their catch in a 'tank' or 'dispatch' with ordinary illuminating gas." Several explosions occurred while thus disposing of small animals in Providence, R. I. The New York Society for the Prevention of Cruelty to Animals experienced so much trouble from such explosions that they finally had to adopt other methods. Their last explosion was very severe; it not only wrecked the large steel dispatch, but tore a hole in the ceiling of the room and seriously injured some of the attendants.

Recently a similar accident occurred in Spokane, Wash. The following is quoted from an item appearing in the Pittsburgh Post Gazette (194): "Morse was pulling the cat into the lethal gas chamber at the humane society barns at the time of the accident. Static electricity from the doomed animal ignited the gas. The cat escaped."

DISCUSSION AND RECOMMENDATIONS

A rather large amount of material dealing particularly with methods of safeguarding against static electricity in industry has been reserved for separate treatment here. As many of the safety measures recommended are the same for several industries the author believes that the facts can be presented more concisely and much more effectively in this way.

Before discussing these, however, a few additional statements will be given to summarize the subject of static electricity in nature.

PREVALENCE OF ELECTRICITY IN NATURE

In one way or another electrical relationships probably are involved in all chemical reactions, whether atomic, molecular, or colloidal. Loeb (195) says:

> There are two tendencies in atomic behavior: The one is a striving for a dynamical stability depending on the arrangement of the electrons about the nuclei in certain apparently preferential and stable configurations; the other is a striving after electrical stability, that is, electrical neutrality. These two tendencies govern the whole general behavior of the atoms and molecules, including their chemical properties.

On a larger scale, there is the probability that the sun and planets are mutually electrified (25), the sun having a positive and the planets a negative charge. In this connection Lodge (196) holds that the earth's electrification is "largely or mainly due to particles coming from the sun." Sanford (197) states that the experimental evidence seems to be "in favor of the earth's being a negatively electrified planet. * * * But the characteristic or natural charges of the elements must still be dependent upon their own structure, while all are modified alike by the earth's induction." Lodge (196) recognizes the important function of terrestrial electricity in many phenomena, but calls attention particularly to its part in the growth of plants. From his own observations and some experimental work of Lemström he shows that the earth is constantly losing electricity to the atmosphere by way of every blade of grass, pointed leaf, and twig and "that the needlelike shape of the leaves in fir trees and the beard on the ears of most cereals have the discharge of electricity as their function." Experiments have repeatedly shown the stimulating effect of electricity on plant growth. According to Lodge, "Berthelot considers that the clue to the advantage of the electric discharge is to be found in an entrance of atmospheric nitrogen into the plant metabolism, but suggests that this is due not only to the formation of oxide of nitrogen, but also to the combination of gaseous nitrogen with carbohydrates within the plant."

Of interest in this conection are the experiments of Schonland (198) in which the (+) electricity escaping from a thorn tree during thunderstorms was measured. Such measurements indicate that enough (+) electricity is lost from point discharges during stormy weather to account largely for the maintenance of the earth's normal (−) charge.

Watson (199), writing in 1746, states:

> Electricity seems to furnish an inexhaustible fund for inquiry, and sure phenomena so various and so wonderful can arise only from causes very general and extensive, and such as must have been designed by the Almighty Author of Nature for the production of very great effects and such as are of great moment to the system of the universe.

ELECTRICAL CHARGE A DEFINITE AND WIDESPREAD HAZARD

Enough evidence has been produced to show that electricity is ever present in nature, that the initial or latent electrical charges may be separated easily and so manifest themselves on almost all substances and in nearly every conceivable condition, and that without proper control such separated electricity may be a definite hazard in many industries. The truth, however, should not be overlooked that in assembling so many facts and theories there is the danger of exaggerating the hazard, and that static electricity can never be in reality quite as conspicuous among other phenomena as it appears to be in this report.

CONDITIONS FAVORING BUILDING UP AND DANGEROUS DISCHARGE OF STATIC ELECTRICITY

The fact that high charges of static electricity are found most often upon substances that are good insulators is due to two causes: (1) Complete separation, after intimate contact has been made, can be effected before neutralization can occur; and (2) the subsequent rate of loss is small. Gilbert early discovered that insulators lose their charge rapidly if placed in a current of damp air. Coloumb found that "dissipation of electricity along insulators was chiefly owing to adhering moisture but in some measure also to a slight conducting power." He believed that some loss of charge took place through the atmosphere and that the loss was "nearly proportional to the cube of the quantity of moisture in the air." But—

> modern researches have shown that the loss of charge is in fact dependent upon the ionization of the air, and that, provided the atmospheric moisture is prevented from condensing on the insulating supports, water vapor in the air does not *per se* bestow on it conductance for electricity.

Curtis (200) has shown that "the surface resistivity of most materials changes through wide limits when the humidity of the surrounding air is varied. It is often a million times as great at low humidity as at high humidity." Under such conditions insulators become relatively good conductors, and the usual difficulties of charging conductors arise.

It is therefore not surprising that static electricity is developed most easily under conditions that favor low humidity of the air, that is, low temperature or, as in hot climates where static charges are nevertheless very troublesome, lack of available moisture. Of course, in view of the many examples of water and steam electrification the statement that static electricity can be developed *only* where the air is dry is untrue. In fact, according to certain theories of electrification, a trace of moisture is essential to the process; it is likely in any event that by slightly increasing the surface conductivity of a highly insulating body and allowing its charge to migrate somewhat the presence of a minute amount of moisture facilitates a strong spark discharge (83) and so increases the possible hazard.

RELATION BETWEEN SPARK INTENSITY AND HAZARD OF STATIC ELECTRICITY

Generally, however, sparks of sufficient intensity to ignite inflammable substances can not be drawn from so-called nonconductors. Richter (71) has stated that a quantity of benzine does not take upon itself a "volume charge" and that dangerous sparks can be drawn only from the containing vessel. Usually discharges from power belts are of the brush type and relatively harmless, but if allowed to accumulate upon the machinery or upon insulated neighboring conductors, bright incendiary sparks may be drawn (137). Sometimes, however, if a continuous stream of tenuous sparks is permitted to play upon a substance such as cotton until it becomes hot and chars slightly, ignition may be obtained. But "unquestionably," according to Brown (142), "cotton is ignited by the sparks of static electricity which jump between the metallic parts of the machinery."

The electricity separated upon a glass rod or tube by rubbing it with fur is so thinly distributed and so incapable of moving over the surface that, although audible sparks an inch or more in length (thus indicating a potential of many thousand volts) can be drawn from it, they are invisible and quite harmless. However, upon condensing a charge of this character by drawing the glass through a tassel of conducting threads attached to a metal pipe carefully insulated by a suspension of dry silk threads, Watson (199) succeeded in obtaining sparks intense enough to ignite alcohol and other inflammable liquids.

No doubt the intensity of spark discharge necessary to ignite different inflammable substances varies over a wide range, depending not only upon the nature of the substance but upon its distribution in the air and the shape and duration of the spark (201). Wheeler (202) has shown that for gaseous mixtures to explode a certain minimum sphere of the mixture must be raised to the ignition point. In a study of preflame combustion Coward and Meiter (203) passed thousands of low-intensity sparks between electrodes in a small vessel containing an explosive mixture of methane and air, each spark causing the combustion of not more than 0.5 mm^3 of the mixture. Morgan (204) determined a minimum spark energy of about 0.002 joule for igniting 8.8 per cent mixtures of methane and air, although he found that differences in spark length, shape of the gas region adjacent to the spark, and the effective cooling area of the electrodes introduced appreciable variations in any series of tests. Blactin and Robinson (62) obtained this same energy value in their experiments with electrically charged coal-dust clouds.

It is generally believed that the sole function of an electrical spark in the ignition of a gas is to furnish an intense source of thermal energy. A number of investigators, however, hold that the reaction is at least aided materially by purely electrical means (205). Recently after extended experiments on the ignition of electrolytic gas ($2H_2+O_2$) Finch and Cowen (206) concluded that—

> ignition is conditioned by the attainment, in some portion of the gas traversed by the discharge, of a certain definite concentration of suitable ions or electrically charged particles, in the building of which water vapor materially assists, and that flame propagation is also essentially an electrical phenomenon.

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It would seem that electrical effects of this character might, in certain cases such as that pictured by Beyersdorfer (191) in a self-consumed sugar "Staubgewitter," far outweigh in importance the thermal effect of an electrical discharge.

It is fairly well known that a strong electrostatic field can modify the propagation of flame. Guenault and Wheeler (207) and Lewis (208) have recently shown that flames distorted by such a field move in the direction of (+) ion flow or toward the cathode. In a study of the ignition temperatures of natural gas-air mixtures surrounding heated metal bars the author (209) showed that ignition may be caused by considerably lower bar temperatures when the region of reaction is traversed by an intense electrostatic field, the bar itself being the anode. This would be expected if the reacting gases are thus drawn from the relatively cooler bar into the fresh mixture.

The function of ionization in various combustion phenomena is a subject arousing considerable interest at the present time, but the extent to which the presence of ions prepares the way for ignition of inflammable gases and dusts by electrical discharge is still a question. However, some unpublished work by Lewis and Kreutz at the Pittsburgh Experiment Station, Bureau of Mines, may be interpreted to indicate that the injection of ions into an explosive mixture of methane and air lowers its ignition temperature.

RELATION BETWEEN ATMOSPHERIC CONDITIONS AND PREVALENCE OF EXPLOSIONS

Because bodies often acquire a high state of charge in a dry atmosphere, some related significance may be attached to the following statements on the occurrence of static and of explosions in several industries.

Richter (129) says that the majority of the aluminum-dust and benzine explosions he investigated occurred in winter and spring, when the humidity and ionization of the atmosphere were low. Of the benzine explosions 39 were attributed to static electricity. (See fig. 11.)

According to Clark (12) one authority states: "An examination of fire records shows that about three-quarters of the rubber-factory fires in processes in which benzine is used occurred in the winter time." He blames static electricity for most of these fires. Johnson (210) says that "according to statistics about 15 per cent of all gasoline fires are caused by static electricity" and suggests that a like number attributed to unknown causes might well be placed in the same category.

In regard to the accumulation of charges on gasoline trucks Bean (185) says:

> Static electricity is seldom if ever generated in damp weather. Very dry cold days or an extremely dry hot day are the times best suited for the development of this condition. Trucks operating in a high altitude are more susceptible than those in a low country.

Jurgensen (211) found that belt electrification was greatest in the winter and during very dry weather.

Lambie (212) asserts that "during the winter and spring months, the dangers of a gas or coal-dust explosion are greatly increased."

Scholz (213) has made an extended study of the effect of humidity on mine explosions; he says:

The striking features developed by these investigations are:

1. Explosions occur more frequently in the colder months of the year; the colder the winter the more frequent the explosions. If a certain district has extremely cold weather and other sections of the country are comparatively warm, the latter sections are freer from explosions.

2. Mining fields located in higher altitudes are more productive of explosions than those at lower elevations.

3. The hygrometric condition of the atmosphere has the greatest effect upon the cause of explosions. Every practical mining man knows that the majority of explosions take place between November 1 and March 15. * * * Every mine examiner instinctively feels danger when he enters the mine on a cold, crisp morning.

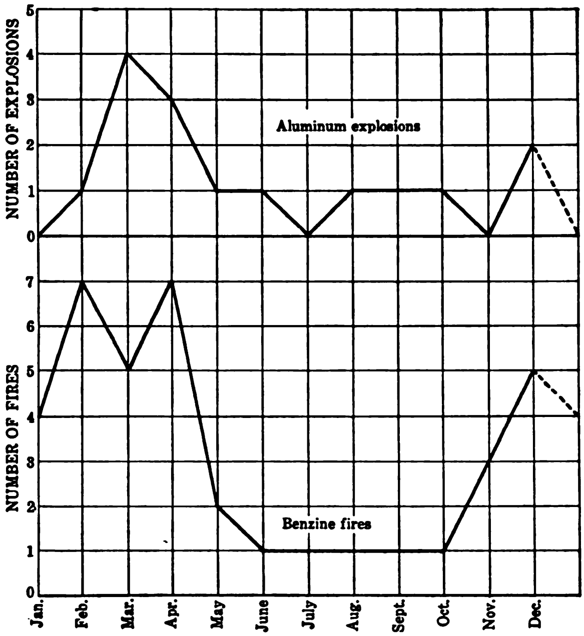

FIGURE 11.—Comparison of aluminum-dust explosions and benzine fires, showing these to be most prevalent in winter and spring (Richter)

Many Bureau of Mines tests, however, have shown that unless moisture actually condenses out in a mine and is deposited the state of the humidity has no noticeable influence either on the ignition of coal-dust clouds by recognized means or on the propagation of explosions.

SAFETY MEASURES

Fortunately, dangerous static charges can not only be removed safely but often can be prevented from forming by simple and inexpensive measures. Wherever such charges are known to exist or where, based upon the accumulation of related evidence, there is a reasonable likelihood that static electricity may be generated in the presence of inflammable or combustible matter adequate remedial or preventive safety measures should be provided.

On the other hand, Watterson (126) has wisely pointed out that protection against static hazards may be set up when dangers are purely theoretical. Referring more particularly to the oil industry, he says:

> An elaborate system of bonding and grounding to guard against static would be very costly and a burden on the industry and also might result in a feeling of security which would allow for dangerous hazards to exist unnoticed.

However, a study of conditions and a few tests with an electroscope or other static indicator (132) should obviate such extremes and still make possible almost perfect protection in any industry. Certainly, in view of past disasters some expenditure to prevent static electric sparks is justified.

CLEANLINESS

The trend toward cleanliness and efficiency in modern industrial plants is encouraging. This change from former conditions not only has inestimable value with respect to production and general health and safety but has been the means of almost eliminating the fire hazard in many erstwhile dangerous occupations. In many places recognition of dust as an explosion hazard has been responsible for this change.

What is true of dust explosions in general is true to a greater extent in operations where dust may be subject to static electrical ignition. Many writers on the hazard of static sparks in industrial plants have urged general tidiness, regular removal of dust, substitution of clean painted walls and ceilings for constructions that favor the collection of dust, and installation of efficient ventilating systems.

Wherever possible or economical combustible dust should be removed by vacuum through grounded metal conductors. Air washing is sometimes advisable. When dust can not be removed by pneumatic conveyors it should be brushed gently into a suitable collector without unnecessary scattering. Dusting by compressed-air blast should be avoided. The need for such precautions, though quite apparent, is emphasized by the following considerations.

Beyersdorfer (7) has shown that disastrous dust explosions are usually series of explosions of increasing magnitude, each explosion raising dust for the next; therefore the amount of dust in the air before an explosion is often not as great a hazard as that lying around. In fact, one of the greatest difficulties presented in the experimental study of dust explosions is to keep dust, once raised, in suspension while ignition is being attempted (214). This is particularly true of coal dust and other heavy types. On the other hand, powdered cork, an extremely light powder, is easily suspended in the air and in such a state is highly explosive. Reid (215) says:

> Great care must be taken to protect all lights about cork mills or mixing machinery, and even with the greatest precautions small explosions are sometimes caused by sparks from the machinery. Speaking after considerable experience with both materials, I would rather handle dynamite in bulk than ground cork in a loose state.

According to Wheeler (216), the amount of dust raised by a progressive explosion may often be just what is required to allow propagation of flame to continue; owing to the upper limit of inflammability, if too much were raised the speed of the flame and the subsequent raising of dust would be reduced. Clearly, then, as long as enough dust is available to satisfy the lower explosive limit an explosion may be propagated.

Munroe (140) has said that the "quantity of flour in an ordinary sack of flour when mixed with 4,000 cubic feet of air will generate force enough to throw 2,500 tons mass to a height of 100 feet." This amount of flour spread evenly over the floor of a room 20 feet square would form a layer less than $\frac{1}{16}$ inch thick.

GROUNDING

The most effective and generally applicable method of removing dangerous static charges is grounding. Chamberlain (10) says, "Every possible source of static sparks should be thoroughly grounded *in a permanent manner*." According to Price (214), "The main difficulty with any grounding system is that the wires may be broken, which in some cases makes a greater hazard than if the machine were not grounded." Roethe (143) says:

> The installation of a good grounding system requires clean tight contacts and connections. The best of systems, no matter how carefully installed, will be practically useless if not properly maintained. Too often contacts and connections become and remain loose, and wires break and are not replaced.

In general, ground wires should be of copper and fairly heavy gage so as not to be broken easily. Where possible they should be protected from injury by placing them behind rugged parts of the machinery or by passing them through conduit. Particular care should be exercised in supporting wires designed to remove static electricity from moving material or belts so that they can not sag and become entangled and broken.

Grounding systems should be not only substantial but good electrically, that is, have low resistance. An earth connection of small area in dry or sandy soil may be so poor that static charges build up faster than they can leak away. The best earth is usually a water pipe leading to an underground main. If the joints and fittings are corroded or "doped" the water itself serves as the conductor. In many instances a large metal plate buried in perpetually damp soil is preferred; the connecting wire must be so firmly attached that it can not corrode loose. Gas pipes, steam pipes, sprinkler systems for fire extinction, and structural steel seldom make good grounds, and electrical conduit is not always dependable (183). If the machinery or equipment affected by static electricity is some distance from actual earth, a heavy copper wire should be run direct to a ground connection in the basement of the building. As paint and other insulating substances may interfere with good connection, ground wires should be attached to machinery by brazing or soldering if possible.

Chain should never be used for grounding when a solid or stranded cable can be employed. In comparative tests of 21 ground chains of various types Johnson (217) showed that the resistance between links is often so high that voltages of several thousand must be applied to start any appreciable flow of current. One copper-plated chain 5 feet long, composed of links about ½ inch across, was declared to be in good condition and yet a power voltage of 4,540 was required to break down its resistance. While the test was being made the chain was under a load of 30 pounds and was continually twisted back and forth through an angle of about 60°.

Requiring a light, flexible conductor in some recent electrostatic experiments the author employed about 3 feet of the fine, gold-plated chain commonly used for stringing beads. It seemed to function well at first, but Wheatstone bridge measurements later showed that it had a resistance consistently above 10,000,000 ohms when slack. A strain of 4 pounds applied to the chain reduced the resistance to about 13 ohms.

There is no sharp distinction between conductors and nonconductors or insulators. Atkinson (25) perhaps has defined them as accurately as anyone:

> A conductor is any substance of such low resistance that it can be used practically for the transfer of electricity; and a nonconductor is any substance of such high resistance that it can be used practically to prevent such transfer.

Grounding the framework of machinery is frequently not sufficient protection against static; where there is shafting it also should be grounded by a brush or tightly rubbing contact of woven copper or spring bronze (145, 183). However, oil in the bearings of machinery may not offer as much resistance to the flow of electricity as has usually been supposed. Perry (183) calls attention to the fact that in the design of electric generators insulation for the bearing pedestals is sometimes incorporated to prevent circulation of large induced currents of low voltage between the shaft and the frame. Watson (218) states that vaseline and heavy oils may actually lower the resistance between sliding electrical contacts. Recent studies (75) of the conductivity of hydrocarbons in films 0.01 mm or less thick reveal that at stresses of about—

> 100 kv. per centimeter the liquids become conducting, approaching the behavior of metals in this regard. This conductivity is not a breakdown, as there is no evidence of spark and the liquid is restored to its original condition on removal of the stress.

In addition to any special property, suspended metal and dirt in the oil of bearings might be expected to give it some appreciable conductivity.

Poorly conducting bodies and insulators may be grounded effectively if covered tightly with a metallic coating or a network of wires. But ordinary aluminum paint can not be relied on to conduct away a charge unless an abnormally large amount of the powdered metal is present.

Attention is again called to the fact that with flowing liquids or moving belts it may be necessary to provide grounds at several places to prevent building up successive charges. To provide a continuous ground, it is therefore advisable where possible to convey liquids to the bottom rather than the top of receiving tanks (136).

Beyersdorfer (7) states that sugar is twice as good an insulator as glass and recommends that in grounding sugar machinery care be taken to insure against possible introduction of an insulating layer in the circuit. This advice is, of course, equally applicable in grounding machinery for many other substances, such as sulphur, resins, and mastics.

In this connection, something further might be said on protection from lightning. The statement has been made that if a lightning rod is higher than a certain small percentage of the height of the charged cloud a definite area of protection or immunity from lightning could be expected.

In view, however, of other recent experimental data and early writings on the subject the question might be raised as to the exact area protected by such a rod and whether an occasion might ever arise when no protection would be afforded. McAdie and Henry (177) believe that "very little faith is to be placed in the so-called area of protection" and state that "buildings are struck sometimes within this very area" (that is, the area whose radius is equal to the height of the rod only). Lodge (170) states that—

> there is no space near a rod which can be definitely styled an area of protection, for it is possible to receive violent sparks and shocks from the conductor itself, not to speak of the innumerable secondary discharges that are liable to occur in the wake of the main flash.

He also postulates in connection with his impulse theory of lightning that under certain conditions "any number of points, or a rain shower or any other form of gentle leak" may be inoperative.

> Then can a violent discharge occur even to the sharpest point and a hot column of air such as rises up a chimney is even preferred to a conductor. These are the flashes against which points and rain are no protection and these are probably those which do the most damage to protected buildings.

Experimental evidence, however, has shown that properly erected lightning rods are an effective measure against lightning of the usual type and that considerable confidence may be placed in the reliability of carefully determined areas of protection. Of interest in this connection are the data of Lewis and Foust (120), whose experiments were made with a rod having a height about 2.3 per cent that of a spherical artificial cloud and standing upon a plane conductor. These figures attach considerable importance to the effect of polarity upon the protected area.

	Cloud, positive; rod, negative	Cloud, negative; rod, positive
Number of discharges	100	100
Number striking rod	40	100
Protected area; radius=rod height times	2–3	10–15

HUMIDIFICATION AND OTHER MEANS OF REMOVING OR PREVENTING STATIC

In many instances grounding can not be successfully employed to eliminate static electricity. Of the various alternative devices humidification is most common and perhaps, next to grounding, most effective. The inhibiting action of traces of water in building up static charges on nonconductors has been discussed. Advantage is often taken of this action as a safety measure by adding moisture directly to the material troubled with electrification or to the surrounding air, from which it is condensed upon or absorbed by the material. As only a minute quantity of water is required, it is usually added most conveniently by the indirect method whereby, too, it is less liable to damage the material.

The amount of moisture required and the method of introducing it in the air differ somewhat with each application. In plants with ventilating systems the problem is comparatively simple; in others the water is introduced most easily by exposing large areas to evaporation or by means of an escaping steam jet. The humidity, however, should be under control both as to the amount of moisture in the air and the presence of this conditioned air where needed (12, 219). Besides decreasing or preventing the formation of static electricity, high humidity in the air often performs the important service of causing suspended dust particles to agglomerate and precipitate (10).

Although humidification has these advantages, there are processes in which much humidity is not only undesirable but dangerous. Hoxie (220) states:

> When the relative humidity in the picker room is below 25 per cent, the cotton may become so dry that it is readily ignited by a small spark and when it is above 80 per cent cotton becomes so limp that it winds up and packs on moving parts of pickers, thereby causing fires.

Obviously, humidification can not be employed to advantage to remove static in handling hygroscopic powders or substances that suffer chemical change in the presence of moisture.

In textile mills static electricity appears in many operations, and unless the humidity is carefully controlled produces very inferior goods and may even result in the breaking down of delicate and expensive machinery. As each operation requires individual consideration to determine the most suitable percentage of moisture, not only for the elimination of static but for the best handling of the various materials, control of humidity is a major problem in the manufacture of textiles (221).

As the surface conductivity of most insulating substances is increased with increase of moisture in the air, so the conductivity of the air itself is increased with increase of ions. Where grounding and humidification are impracticable static electricity can often be removed by leakage through the air. The normal atmosphere near the surface of the earth usually contains a thousand or more ions of various kinds per cubic centimeter, but the ratio of large to small ions varies greatly with differing weather conditions. A foggy, dusty, or smoky atmosphere favors the formation of large, sluggish ions; a bright, clear day presages a greater number of small ions. Because of their much greater mobility the small ions may be regarded as the only important carriers of charge. Yaglou, Benjamin, and Choate (222) have recently studied the variation in number of these small ions in normal air indoors and outdoors. They find that the maximum variation in the particular group of ions studied (those with mobilities[10] of 0.2 cm or more per second) is from about 50 on gray winter days to about 700 on clear days in summer. No doubt, such a change in ionization may well account for part of the difference in the chargeability of substances in summer and winter. Certain other observations of these investigators are of interest in this connection.

[10] Mobility in a field of unit intensity, 1 volt per centimeter.

They find, for instance, that the ionic content of unoccupied heated rooms is about the same as that outdoors, but in occupied rooms it falls abruptly to a very low value. Both positive and negative ions begin to increase as soon as the occupants depart. With artificial ionization, however, "it is fairly practicable to control the ionic content in occupied rooms at any desirable level up to a maximum of 10,000 ions per cubic centimeter, without producing a perceptible quantity of ozone."

Both ultra-violet light and X rays have been proposed for ionizing the air where inflammable gas, dust, or spray is present (136, 223). While no doubt effective in certain operations, the method introduces hazards of its own. With either type of radiation great care must be taken to protect the workmen from burns (183). Moreover, ultra-violet light brings about chemical changes in many substances and therefore can not be used indiscriminately (224). Such radiation directly or by the previous production of ozone from the oxygen in the air may conceivably bring about such rapid reactions in some materials as to cause fires or explosions.

One pretty sure way of preventing explosions of most dusts and liquids is to place them in an atmosphere devoid or nearly devoid of oxygen. In many operations this is feasible and may be accomplished satisfactorily either through the use of inert gases, such as nitrogen, CO_2, or flue gas (214), or by means of a vacuum (183, 192). A few general facts concerning the explosion limits of several common dusts should be mentioned. According to Trostel and Frevert (225) the minimum amount of cornstarch, sulphur, or aluminum dust (200-mesh screen) that will explode in air is 7 mg per liter. For Pittsburgh coal dust 17.2 mg per liter are required and for corn, wheat, and sugar dusts, about 10.3. These values are for ignition by an incandescent platinum wire; in general, more dust is required when ignition is by arc or induction-coil spark. Price (214) states that grain dusts will not explode if less than 12 per cent of oxygen is present. The safe maximum for starch is 12 per cent;[11] sulphur, 8.6 per cent; hard rubber, 13 per cent; and coal dust, 17.5 per cent. Normal air contains about 21 per cent oxygen.

With respect to either the dust or oxygen content of the air, coal dust is the most difficult to explode of any of the substances mentioned (226). In a study of coal-dust ignition and coal-dust electrification the observations of Bouton and Hayner (227) are of interest. They state that the inflammability of Pittsburgh or Pocahontas coal dust when suspended as a dust cloud—

> does not increase indefinitely with fineness but seems to reach a maximum and then fall off, or at least remain constant, as the fineness is still further increased. * * * The range of 10 to 25 microns in diameter includes particles of maximum inflammability.

They give three possible explanations of the relative noninflammability of the finest dust:

> (*a*) There may be chemical as well as size segregation as a result of elutriation; (*b*) the smallest particles may undergo relatively greater oxidation during elutriation; (*c*) the finest dusts may form agglomerates which resist dispersion in forming the dust cloud.

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[11] This figure (12 per cent) has been determined in some recent unpublished work by Price.

Blactin (63) found that fresh coal dust was much more susceptible to electrification than dust which had been exposed to the air. He also experienced trouble from agglomeration of fine coal dust and in some of his earlier experiments had to mix a certain proportion of emery flour with the coal.

SPECIAL NOTES ON COAL MINING

In 1891 Stratton (228) suggested that moisture be added to mine air to keep down dust. On first consideration this recommendation may seem to solve the problem of coal-dust explosions; but it has been shown that 100-mesh coal dust can carry as much as 30 per cent of water and still propagate flame (229). Furthermore, unless humidification is conducted on a large scale and constantly, it accomplishes little. Callen (230) says:

> The only way in which sprinkling or any local application of water can be but temporarily effective is to have the air current saturated with moisture so that it can not evaporate any water from the mine.

Keeping the air in this condition by any method would be difficult, for Callen has calculated that the loss of water by evaporation into the outgoing air of an average mine may easily amount to as much as 19,000 gallons per day during the winter and that "the greater part of this water is abstracted from the dust and fine coal in the mine rather than from standing bodies of water."

Rock dusting (231) is the most practicable and perhaps economical remedy for dust explosions in coal mines. In applying rock dust the ease with which fine dust may build up static charges should be kept in mind. In some mines rock dusting is done with a gunite machine. Greater need of interconnecting and grounding the machine for this use than for guniting seems obvious. Rudge (56) has observed that flue dust and rock dust charge oppositely to coal dust. Commenting on this, an editor of Engineering (232) says: "The observation would supply an additional argument in favor of stone dusting in coal mines." The manufacture of powdered products is sometimes facilitated by adding to the mix a dust that takes an opposite charge (183).

Electric lines for shot firing, which enter the mine from outside, should be so arranged with flexible connections near the foot of the shaft or slope that they may be opened, leaving a gap of 5 or 6 feet to prevent lightning from reaching the shot. As a further precaution it is well also to ground the incoming lines when the circuit is opened. Other refinements for protecting these circuits from lightning have been recommended (169).

According to Coal Age (148), the only adequate remedy for the mysterious coal-mine explosions which are variously attributed to abrasive sparks, adiabatic compression of gas mixtures, static electricity, or other obscure causes is—

> the thorough ventilation of the working places to keep them free from accumulations of gas and the adoption of a method of working that will reduce to a minimum the liability of heavy falls of roof.

Lambie (212) says:

> A well-ventilated mine is one that has an adequate volume of air constantly maintained in every portion of it whether working or idle.

BELTS

The use of grounded wires and combs for removing static electricity from belt drives has been mentioned. This method has some disadvantages. The device may be in the way or may get caught on the belt; moreover, all of the charge is not removed, and a strong brush discharge may be objectionable or even dangerous. Other methods, such as humidification, may be equally unsatisfactory. Recently, after much experimentation engineers of the United States Department of Agriculture have perfected belt-dressing compounds for both rubber and leather belts which are highly efficient in preventing the formation of static electricity and which have virtually none of the disadvantages of such substances as fish oil and glycerin formerly used. In one test—

> a rubber conveyor belt 850 feet long and 42 inches wide was coated on both sides with the dressing. * * * When the belt was run again there was no indication of any static charges on the belt. Before the dressing had been applied potentials greater than 10,000 volts were measured on the belt.

In most cases one application suffices for several months. Details for compounding these dressings are given in a pamphlet by Edwards and Reed (184).

In general, fabric belts are less subject to electrification than leather and rubber belts (233). The charge usually increases with the speed of the belt but not appreciably with the load. Resins, heavy fats, or gums on driving belts generally aid in the production of static electricity (78, 137).

SAFETY MEASURES IN CASE OF FIRE OR EXPLOSION

If precautionary measures have been neglected and a fire or explosion has occurred, the careful observance of prescribed recommendations may yet preclude a widespread disaster. These measures can not be discussed in detail here. A few recommendations, however, have come to the author's attention in the course of this work and should be included.

Price (8) warns firemen particularly against raising clouds of dust. He shows that dust explosions often occur when a heavy stream of water is played upon a pile of dust or when floors give way and bins fall during the fighting of fires. During hasty efforts to remove the contents of bins a cloud of dust may be raised which will ignite from a near-by flame or smoldering spark. He recommends that plants should be systematically inspected by firemen so that the latter may become acquainted with any dust-explosion hazards. Dust in bins should be wet down when necessary with a fine spray rather than an ordinary hose stream. The direct application of water, however, should be avoided; whenever possible the oxygen in rooms and bins should be replaced by steam or inert gas.

Clark (12) says:

> Despite all efforts made to combat static dangers, fires may still occur. Sole reliance should therefore not be placed in grounding, high relative humidity, and other preventive measures; suitable fire protection should also receive due consideration.

He strongly urges installation of extinguishers of the sprinkler and foam types for general protection and quick-acting drains for tanks of inflammable liquids.

SAFETY MEASURES IN GENERAL

For additional information regarding safety measures the reader is referred to the various specific codes developed by the American Standards Association, a list of which may be found in any public library. A few selected publications dealing with safety recommendations are given in the bibliography (references 235–240). Finally, as enjoined by Vanzandt (234), it is the duty of all who handle explosive or inflammable materials "to be acquainted with the risks which may arise and to take all means of protection both in their own interests and in the interest of the public."

SUMMARY

1. One fundamental property of the constituents of all matter is electrical charge.

2. Static electricity, which results from separation of the inherent (+) and (−) charges of matter, is easily produced by several common mechanical operations in nature and industry.

3. Sparks caused by neutralization of accumulated opposite charges of static electricity (which at the instant are then no longer static) constitute a real hazard wherever inflammable substances are present.

4. Sparks of this character and indeed the building up of charges may often be prevented by simple precautionary measures.

5. Many industries fully recognize the hazard of static electricity and regularly employ effective means to control it; others have not yet appreciated its prevalence and danger, and explosions and fires result.

6. There have been numerous rumors and some more substantial evidence that static electricity has been responsible for certain coal-mine explosions, and therefore constitutes a hazard in underground gassy atmospheres.

7. Studies have been made of the electrification of coal-dust clouds, and sparks capable of igniting fire damp have been obtained under conditions that might exist in mines. Virtually no investigations have been made, however, of the electrification produced in mines through the extensive use of compressed-air machinery, steam, belts, conveyors, etc., and especially through fracture of rock, particularly in falls of roof. There appears to be a need for such investigative work.

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