# CODE

FOR

# PROTECTION AGAINST LIGHTNING

Miscellaneous Publication
of the
Bureau of Standards
No. 92

DEPARTMENT OF COMMERCE
BUREAU OF STANDARDS

MISCELLANEOUS PUBLICATION, BUREAU OF STANDARDS, No. 92

# CODE
FOR
# PROTECTION AGAINST LIGHTNING

April 8, 1929

Approved April 4, 1929, by the American Standards Association

PRICE 25 CENTS

UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON : 1929

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## PREFACE

The protection of persons and property against lightning is a subject of widespread interest and of considerable importance. Since the time of Benjamin Franklin the value of lightning rods in the protection of buildings has been recognized. Early in the art of utilization of electrical energy, the use of lightning arresters in connection with exposed overhead lines was introduced. In the fields of both buildings and electrical equipment there has been a great variety of practice, and many installations have been made which did not adequately fulfill the purpose for which they were intended.

In order to meet the definite need for standards of practice in connection with lightning protection, the American Engineering Standards Committee included in the first list of safety codes on its program a code of practice on this subject. The American Institute of Electrical Engineers and the National Bureau of Standards were designated as sponsors for this project, whose scope included the protection of buildings, oil tanks and other structures, trees, livestock, and persons; overhead electrical lines, and apparatus which is connected to them.

A sectional committee was organized by the sponsors in 1921 and has been working for a number of years upon the formulation of definite standards which should be a guide in securing protection from this hazard. The needs of both industry and the public have been kept in mind, and the standards now set up have been taken largely from American practice and experience, although foreign practice has also been given consideration.

The subject matter contemplated for this code comprises five parts, three of which are presented here. The other two parts, dealing with electrical apparatus and lines, are withheld for further consideration. In each part an introductory statement to the particular subject in hand is given, and the code is followed by an appendix in which is given a general discussion of lightning, its origin and characteristics, and the effects which it produces. An attempt is made in the appendix to indicate how much is definitely known about lightning and its properties and also theories of its origin and speculations regarding the magnitude of the electrical quantities involved in lightning phenomena. There is also appended a bibliography in which the more important contributions to the present state of the art are listed.

The part of the code dealing with specifications for lightning rods used to protect buildings goes into the questions of practical construction and sets forth in detail the requirements of good design for such installations. These are of general application, and particular types of buildings may need more specific consideration. For the protection of persons and of oil tanks the standards are not so detailed but are aimed rather to state the general principles which should be applied.

In spite of the value of lightning rods in the protection of buildings their use has at times and in places come into disrepute owing to a general lack of information as to the best methods of protection, and it is hoped that the publication of definite standards on this subject will enable the public to demand installations which will give them adequate protection.

Lightning is considered responsible for a majority of tank fires of the petroleum industries. A realization of the importance of this source of loss to the industry and to the resources of the Nation has awakened a general interest in proper standards of protection. In this field, as in the protection of ordinary buildings, many inadequate installations have been made in the past. By the application of the proper principles and standards of construction it is believed that this loss can be greatly reduced.

Further experience and the accumulating knowledge of the properties of lightning may lead later to changes in these specifications, and future revisions are contemplated from time to time as experience and progress in the art may warrant. Comments regarding these specifications and recommended changes are invited by the committee from all who may have experience in applying them.

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# CODE FOR PROTECTION AGAINST LIGHTNING

## Part I.—PROTECTION OF PERSONS[1]

### INTRODUCTION

The number of fatalities from lightning is shown by Census Bureau reports to be about 500 per year for the entire United States. From the ratio of deaths to injuries where both are known, the number injured is estimated at 1,300 per year. The same reports show that approximately nine-tenths of these casualties occur in rural districts, which, for census purposes, include all towns and villages having 2,500 inhabitants or less. This indicates that the lightning hazard is by far the greatest among persons engaged in outdoor pursuits, an indication which is substantiated by the general run of reports of such casualties.

The number of fatalities from lightning is insignificant in comparison with the number from all other accidental causes, which for the year 1925 was 90,341. The actual danger from lightning is, in general, very small, except under certain circumstances of exposure out of doors, which, as a rule, can be avoided. Within buildings of considerable size, and dwelling houses of modern construction, cases of injury from lightning are relatively rare. They are more frequent within

[1] This part of the code has been approved by the American Standards Association as an American standard.

small unprotected buildings of the older type. Isolated schoolhouses and churches where numbers may congregate during thunderstorms present a considerable lightning hazard if unprotected.

### 100. Purpose.

The purpose of the rules of this section is to furnish a guide for personal safety during thunderstorms.

### 101. Personal Conduct.

(*a*) Do not go out of doors or remain out during thunderstorms unless it is necessary. Stay inside of a building where it is dry, preferably away from fireplaces, stoves, and other metal objects.

(*b*) If there is any choice of shelter, choose in the following order:

1. Large metal or metal-frame buildings.
2. Dwellings or other buildings which are protected against lightning.
3. Large unprotected buildings.
4. Small unprotected buildings.

(*c*) If remaining out of doors is unavoidable, keep away from—

1. Small sheds and shelters if in an exposed location.
2. Isolated trees.
3. Wire fences.
4. Hilltops and wide open spaces.

(*d*) Seek shelter in dense woods, a grove of trees, a cave, a depression in the ground, a deep valley or canyon, or the foot of a steep or overhanging cliff.

## Part II.—PROTECTION OF BUILDINGS AND MISCELLANEOUS PROPERTY[1]

### INTRODUCTION

Data on property losses from lightning are incomplete, and it is not possible to make an accurate estimate of the total. Reports of the National Board of Fire Underwriters show losses paid averaging more than $13,000,000 annually, but this sum does not represent the total loss. Many mutual fire insurance companies and others pay lightning losses which are not reported as such for tabulation, and since farm property is more largely insured in mutual companies, it is probable that the total runs to more than that shown by the National Board. In some Middle Western States lightning leads the list of causes of fire loss (Iowa, Kansas, and Oklahoma in 1925).

The use of lightning rods to prevent fire losses from lightning has been quite extensive, and from such data as are available it seems evident that existing lightning-rod installations cause the present total of damage to be much less than it would be if they were removed. Moreover, extension of the use of properly installed equipment would decrease the damage that now occurs. It is not to be inferred, however, that it would be financially profitable to equip all buildings indiscriminately, because if this were

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done the annual cost in interest charges and maintenance would be many times the present annual loss by lightning. It is likely also that many existing installations represent wasted, or at least unwisely expended, money.

## RELATIVE LOSSES FROM LIGHTNING

The effectiveness of lightning rods in reducing losses from lightning is indicated by the reports of a number of fire marshals and insurance companies in the United States and Canada in which the losses on protected and unprotected buildings have been separated. The reports generally state that nearly all of the fire loss from lightning occurs in rural districts. The proportion of farm buildings equipped with lightning rods is not known except in Iowa, where a careful estimate indicates about 50 per cent. In the years 1919 to 1921, in this State, 28 rodded buildings were destroyed by lightning, the loss amounting to $87,979. In the same period 503 other buildings were destroyed, the loss amounting to $1,060,668. The value of rodded buildings lost was only 7.7 per cent of the total, although the number exposed was about 50 per cent. The condition prevailing in other mid-Western States is not much different. Over large parts of Minnesota, Kansas, Missouri, Illinois, Wisconsin, Ohio, Indiana, and Michigan installations are numerous, and it seems probable that about half of the farm buildings in this entire area, at least of the better class, are protected.

In making reports a building is considered protected regardless of the condition of the installation. There are many defective installations, and fire marshals are unanimous in their opinion that these contribute in large measure to the losses in "rodded" buildings. However, without reference to the condition of the protective equipment, and including a large area containing, at a reasonable estimate, as many protected as unprotected farm buildings, the ratio of destruction is 1 rodded building to 57 not rodded. The chance, therefore, of an unprotected farm building being destroyed appears to be fifty-seven times as great as that of a protected building. While this conclusion is not at all accurate, it seems to be as good an estimate of the effectiveness of lightning rods as can be made until more complete data are available.

Where fire marshals express an opinion on the subject (and many of them have done so in their reports), they urge the use of lightning rods, basing their opinions on the data they have gathered showing relative losses.

## FACTORS TO BE CONSIDERED

In determining how far to go in providing lightning protection for specific cases, it is necessary to take into account a number of factors. Attention will be called here to the existence of these, and their importance, without attempting any general decision as to when lightning protection should be provided. They are as follows:

(*a*) Frequency and severity of thunderstorms.
(*b*) Value and nature of building and contents.
(*c*) Local conditions.
(*d*) Relation to insurance premiums.
(*e*) Personal hazards.
(*f*) Indirect losses.

### Frequency and Severity of Thunderstorms.

The frequency of occurrence of thunderstorms varies throughout the United States from a minimum in regions where lightning is very infrequent to a maximum in regions where the average number of such storms is over 90 per year, as shown by the curves in Figure 3 of Appendix A. Moreover, the severity of lightning storms, as distinguished from the frequency of their occurrence, is much greater in some locations than in others. Hence, the necessity for protection varies over the country, although not necessarily in direct proportion to thunderstorm frequency. A few severe thunderstorms a season may make the need for protection greater than a relatively large number of storms of lighter intensity.

### Value and Nature of Building and Contents.

The value and nature of the building and contents obviously are vital factors in deciding whether the expense of protection is warranted. Buildings sometimes have a value for historical or sentimental associations which is uninsurable and may justify disproportionate expenses for protection. The nature of the structure will also have a large influence upon the extent of the protection to be considered. Thus an all-metal structure is practically immune to lightning damage because of its construction, and very simple measures usually suffice to make protection complete. Metal-frame buildings with terra cotta or tile facings are next in order as requiring somewhat more extensive measures, while as the amount of metal in the roof and sides of a building decreases the protective measures required approach more nearly a complete system. Buildings made entirely of nonconducting materials, such as wood, stone, brick, or tile, require complete systems with special attention to contents if they house large metal objects, such as machinery and the like.

Reinforced-concrete buildings, if the reinforcing is thoroughly bonded together, are of the nature of metal-frame buildings as regards protection against lightning, but if the reinforcing is discontinuous it should be treated the same as a building of nonconducting materials. Lightning strokes on reinforced-concrete buildings having loosely joined reinforcing material are likely to be very destructive by causing cracks at places where beams and floor slabs are connected to their supports.

The contents of the building must also be considered as to whether they are replaceable and as to whether they are explosive, combustible, or fireproof. Explosive dust may present a hazard in a building that is otherwise immune to lightning. Combustible contents like hay and raw cotton may make protective measures especially desirable.

### Local Conditions.

The exposure of a particular building will be an element in determining whether the expense of protection is warranted. In closely built-up towns and cities the hazard is not so great as in the open country. In the latter, farm barns in many cases are the most prominent target for lightning in a large area. In hilly or mountainous districts a building upon high ground is usually subject to greater hazard than one in a valley or otherwise sheltered area. Surrounding buildings may make special protection seem unwarranted, especially if they are much higher. A high water tower or steeple, for instance, considerably reduces the hazard to near-by dwelling houses.

### Relation to Insurance.

Regarded solely from the standpoint of fire insurance, it is obvious that it would not pay financially to protect all buildings indiscriminately, because it can readily be calculated that upkeep and interest on the investment would be many times the present fire loss from lightning, as stated heretofore. In this light the use of lightning rods should be considered particularly with the classes of property that are most susceptible to fire or serious damage and more particularly the portion of such property located in thunderstorm regions and remote from fire-fighting facilities.

### Personal Hazards.

Aside from economic considerations, there is also to be considered the hazard to human lives. As stated previously, casualties within buildings of modern construction are relatively rare, on account of the protective effects offered by the metal used in constructing them and by metal piping in exterior walls, but there are at the same time numbers of buildings in existence of the older type. A stroke of lightning upon an occupied building of this type is accompanied by serious danger to the occupants. Moreover, in buildings of any type short of those constructed of metal or with metal frames, a stroke of lightning may lead, if not to actual injury, to a considerable degree of discomfort. Hence, lightning protection may be deemed desirable where financial considerations do not enter.

### Indirect Losses.

Aside from fire losses, considerable losses arise in other ways, as by the killing of livestock and by damage to buildings where fire does not occur. There are also less tangible costs which sometimes accompany the destruction of buildings and their contents which are usually not covered by insurance. An interruption to business or to farming operations, especially at certain seasons of the year, may involve losses quite distinct from, and in addition to, the losses arising from the direct destruction of material property. There are also cases where whole communities depend for safety and comfort in certain respects on the integrity of a single structure, as, for instance, a brick chimney on a water-pumping plant. A stroke of lightning on the unprotected chimney of a plant of this sort might easily entail serious consequences from a lack of sanitary drinking water, irrigating water, or water for fire protection.

It is consequently not easy to state even in general terms when the installation of lightning protection should be undertaken. Each element affecting the situation has to be considered, and the decision in each case must be made by the person responsible, obtaining competent assistance where advice seems needed.

There is a tendency on the part of some to make protective installations more expensive than is necessary, especially in the use of some unusual type of conductor, ornaments, and other features. Economy lies in reducing the variety of equipment and in taking advantage of the constructional features of buildings as far as practicable. In the case of existing structures metal parts can sometimes be used to supplement an approved system of lightning conductors, or, under favorable conditions, to take the place of them, if a careful survey shows that their size and mechanical construction are adequate for the purpose. In the case of buildings which are roofed, or roofed and clad, with metal of substantial weight, or have metal frames, additional conductors can be dispensed with, due attention being given only to bonding and grounding such metal, and to caring for any upper portions which are susceptible to damage. Advantage may also be taken of architectural features to avoid the use of unsightly air terminals.

In the case of structures to be erected the matter of protection should be considered in making the plans, for the reason that many times the necessary measures can be effected in the architectural features without detracting from the appearance. This is particularly true of monument buildings, which are designed to stand for all time, and in which it is all too frequently found that the possible effects of lightning are neglected until construction is completed.

## FUNDAMENTAL PRINCIPLES OF PROTECTION

The fundamental theory of lightning protection for building is to provide means by which a discharge may enter or leave the earth without passing through a nonconducting part of the structure, as, for example, parts which are made of wood, brick, tile, or concrete. Damage is caused by the heat and mechanical forces generated in such nonconducting portions by the discharge, whereas in metal parts the heat and mechanical forces are of negligible effect if the metal has sufficient cross-sectional area. There is a strong tendency for lightning discharges on structures to travel on those metal parts which extend in the general direction of the discharge. Hence, if metal parts are provided, of proper proportions and distribution, damage can be largely prevented. However, because lightning has such a wide range of characteristics, it is difficult to provide any practical means which will afford protection under all conditions, although as indicated heretofore the degree of protection afforded by present practice is high if the installation is properly made.

The required condition that there be a metallic path for the part of the discharge which is intercepted is met most fully by a grounded metal or metal-covered structure which presents what might be thought of as an infinite number of parallel conductors from the uppermost part of the structure to earth. It is substantially met by a steel-framed structure, which, though faced with brick, terra cotta, or other building material, usually has, or at relatively small cost can be equipped with, a sufficient number of metal terminals or receiving points on the upper portions which connect with the frame to protect it thoroughly.

For a structure which is built wholly or partly of nonconducting materials, one of the best defenses against direct hits by lightning is to surround it with a ring of grounded metallic masts or poles of sufficient height. Or, if the structure is not large, a single mast erected near by may be sufficient. Experiments have indicated that, under certain assumed test conditions, such a vertical conductor will generally divert to itself all direct hits which might otherwise fall within a cone-shaped space, of which the apex is the top of the conductor and the base a circle of radius two to four times the height of the conductor. This agrees with theoretical deductions. Incidentally, any metallic structure, or adequately protected structure, will function in the same manner as a mast. Thus, a tall steel windmill or water tower or rodded steeple will tend to protect near-by structures of lesser height, although before relying upon such protection care should be taken that the structure lies well within the cone-shaped space mentioned above.

Generally, however, on account of architectural considerations, the mast type of protection is not feasible. More suitable protection is provided by the installation of lightning conductors. Here the required conditions of protection are closely approximated by placing air terminals or receiving points on the uppermost parts of the building, with interconnecting and grounding conductors attached to the building itself. By this means a relatively small amount of metal properly proportioned and distributed is made to afford a satisfactory degree of protection and at the same time, if necessary, to afford a minimum of interference with the contour of the structure. It should be stated, however, that this type of protection is to be considered only for structures in which very small induced sparks do not present an appreciable element of danger, as they do in oil tanks, cotton warehouses, and powder-storage houses. The latter classes of structures require much more elaborate precautions to insure their safety than do the general run of buildings.

When designing and installing a system of protection of the lightning-rod type the following principles should be followed:

(*a*) The structure should be examined and all points or parts most likely to be struck by lightning noted, with the view of erecting air terminals thereon for the reception of the discharge. The object is to intercept the discharge immediately above the parts liable to be struck rather than to attempt to divert it in a direction it is not likely to take. The receiving points should be placed high enough above the structure to obviate danger of fire from the arc; the more inflammable the roof material the higher the points should be placed.

(*b*) Conductors should be installed with the view of offering the least possible obstruction to the passage of a stroke between air terminals and ground. The most direct path is, in general, the best, and there should be no sharp bends or loops for the lightning to jump across. The obstruction is practically inversely as the number of widely separated paths, so from each air terminal there should be at least two paths to ground, and more if practicable. The number of paths is increased and the obstruction lessened by connecting the conductors to form a cage inclosing the building.

(*c*) When a stroke is about to take place to earth the surrounding surface of the ground for a radius of several miles carries an electric charge. As the discharge takes place this surface charge moves radially toward the ground end of the air path, forming an electric current in the ground. Near the point where the discharge enters the ground the current density becomes high, and if the flow takes place through the foundation wall of a building, damage may result. Ground connections should, therefore, be distributed more or less symmetrically about the circumference of a structure rather than grouped on one side. With ground connections properly distributed, the current will be collected at the outer extremities and a flow underneath the building minimized. In every case, for the foregoing reason, at least two ground connections should be made at opposite extremities of the structure.

(*d*) If a lightning-conductor system is placed on a building within or about which are metal objects of considerable size within a few feet of the conductor, there will be a strong tendency for sparks, or sideflashes, to jump from the conductor to the metal at its nearest point. To prevent damage an interconnecting conductor should be provided at all places where sideflashes are likely to occur.

(*e*) Within buildings where metallic objects may be liable to a dangerous rise of potential due to a lightning flash, the metal, if not interconnected with the lightning-rod system, should under some circumstances be independently grounded.

(*f*) Since a lightning-conductor system as a general rule is expected to remain in working condition for long periods with little attention, the mechanical construction should be strong and the materials used such as to offer high resistance to corrosion.

The features of construction described in the following specifications embody an attempt to apply the foregoing principles to the protection of buildings. These specifications are based upon what is believed to be the best current practice in protective work.

## SEC. 20. SCOPE, DEFINITIONS, ETC.

### 200. Scope and Purpose.

The rules of this part of the code apply to the protection against lightning of buildings and other property, with the exception of property devoted to the production, storage, and transportation of inflammable liquids and gases, and electrical lines and equipment.

The purpose is the prevention of fire loss and other damages from lightning by directing attention to the available means of protection which are believed to be effective.

### 201. Interpretation and Exceptions.

This code shall be liberally construed. In cases of practical difficulty or unnecessary hardships exceptions from its literal requirements may be made if equivalent protection is otherwise secured.

It is not intended that this code shall be interpreted as recommending the protection of every class of property to which it applies but shall constitute the standard where economic or other considerations make it appear that protection is necessary or desirable.

### 202. Mandatory and Advisory Requirements.

The word "shall" where used is to be understood as mandatory and the word "should" as advisory. "May" is used in the permissive sense.

### 203. Terms and Definitions.

*Air terminal.*—The combination of elevation rod, and brace, or footing placed on upper portions of structures, together with tip or point if used.

*Conductor.*—The portion of a protective system designed to carry the current of a lightning discharge from air terminal to ground.

*Branch conductor.*—A conductor which branches off at an angle from a continuous run of conductor.

*Cable.*—A number of wires twisted or braided to form a conductor.

*Copper-clad steel.*—Steel with a coating of copper welded to it as distinguished from copper-plated or copper-sheathed material.

*Down conductor.*—The vertical portion of a run of conductor which ends at the ground.

*Elevation rod.*—The vertical portion of conductor in an air terminal by means of which it is elevated above the object to be protected.

*Fastener.*—A device used to secure the conductor to the building.

*Ground connection.*—A buried body of metal with its surrounding soil and a connecting conductor which together serve to bring an object into electrical continuity with the earth.

*Metal-roofed building.*—A building with a roof made of or covered with metal.

*Metal-clad building.*—A building with sides made of or covered with metal.

*Point.*—The pointed piece of metal sometimes used at the upper end of the elevation rod to receive a lightning discharge.

*Roof conductor.*—The portion of the conductor above the eaves running along the ridge, parapet, or other portion of the roof.

## SEC. 21. LIGHTNING RODS FOR ORDINARY BUILDINGS

Rules 210 to 213, inclusive, hereunder apply more particularly to buildings of the ordinary types which have roofs of slate, tile, or other nonconducting material. Rule 214 sets forth modifications to the rules preceding it which may be made for the case of buildings which are roofed or roofed and clad with metal. Grounding and interconnection of metals are included in rules 215 to 217, while section 22 is to be referred to when buildings are equipped with spires, steeples, flagpoles, or towers.

### 210. Conductors.

(*a*) MATERIALS.—The materials of which protective systems are made shall be relatively resistant to corrosion or shall be acceptably protected against corrosion. No combination of materials shall be used that forms an electrolytic couple of such nature that in the presence of moisture corrosion is accelerated, but where moisture is permanently excluded from the junction of such metals, contact between them is not objectionable.

The following list of materials comprises those commonly used for protective systems, or parts of protective systems, and with their accompanying specifications constitute materials to be regarded as standard for the purposes of this section:

(1) *Copper.*—Where copper is used it shall be of the grade ordinarily required for commercial electrical work, generally designated as being of 98 per cent conductivity when annealed.

(2) *Alloys.*—Where alloys of metals are used they shall be substantially as resistant to corrosion as copper under similar conditions.

(3) *Copper-clad steel.*—Where copper-clad steel is used the copper covering shall be permanently and effectively welded to the steel core, and the proportion of copper shall be such that the conductance is not less than 30 per cent of the conductance of an equivalent cross section of solid copper.

(4) *Galvanized steel.*—Where steel is used it shall be thoroughly protected against corrosion by a zinc coating which will satisfactorily withstand the standard test of the American Society for Testing Materials for galvanized coatings.

The importance of resistance to corrosion of lightning-conductor materials should be emphasized at this point because corrosion, either soil or atmospheric, leads to deterioration and consequent impairment of the initial degree of reliability of a system and should be forestalled wherever possible. In this connection there are several combinations of metals, and alloys of metals, that do not lead to marked corrosion when placed in contact in the presence of moisture, whereas others do, and while it is not practicable to give here a list of such combinations, manufacturers and purchasers of lightning conductors are cautioned to use only those that have been shown by experience or adequate tests to be free from objectionable features. It may also be pointed out that atmospheric conditions in certain seacoast sections of the United States, notably the South Atlantic and Gulf coasts, are known to be destructive to galvanized steel, and in such regions galvanized steel should be used with caution, a preference being given to copper. Copper is also to be preferred where corrosive gases are encountered, but it needs to be reinforced with a lead covering under exceptional conditions, such as are found near the tops of smokestacks. (See rule 241(*e*).)

(*b*) Form and Size.—Conductors may be in the form of cable, tube, strip, or rod having round, square, star, or other solid cross section. The following subsections give minimum sizes and weights:

(1) *Copper cable.*—Copper-cable conductors shall weigh not less than 187.5 pounds per thousand feet (0.279 kg per m). The size of any wire of a cable shall be not less than No. 17 A. W. G. (0.045 inch=0.114 cm diameter).

(2) *Copper tube, copper solid section, and copper-clad steel.*—Tube or solid-section conductors of copper or copper-clad steel shall weigh not less than 187.5 pounds per thousand feet (0.279 kg per m). The thickness of any tube wall shall be not less than No. 20 A. W. G. (0.032 inch=0.081 cm). The thickness of any copper ribbon or strip shall be not less than No. 16 A. W. G. (0.051 inch=0.129 cm).

(3) *Galvanized steel.*—Galvanized-steel conductors shall have a net weight of steel of not less than 320 pounds per thousand feet (0.476 kg per m) and a zinc coating of not less than 2 ounces per square foot (0.061 g per cm$^2$) of galvanized surface. The thickness of any tube wall, web, or ribbon before galvanizing shall be not less than No. 17 United States Standard Sheet Gauge (0.056 inch=0.142

cm), and the diameter of any wire of a cable before galvanizing shall be not less than No. 14 Steel Wire Gauge (0.080 inch=0.203 cm).

(*c*) JOINTS.—(1) *General.*—Joints in conductors shall be as few in number as practicable, and where they are necessary they shall be mechanically strong and well made and provide ample electrical contact. The latter requirement is to be regarded as met by a contact area not less than double the conducting cross-sectional area of the conductor.

The following suggestions are offered in regard to the construction of joints in conductors:

Sections of cable conductor are preferably connected together by unraveling 6 inches or more of the ends and making a solderless wrapped joint. An alternative is found in couplings of malleable metal No. 14 A. W. G. in thickness (0.064 inch=0.162 cm), 3 inches (7.62 cm) in length, and of semitubular form with projections on the interior which, when the coupling is crimped, become embedded in the cable.

Sections of tube conductor may be connected together by dowel-type screw joints with the dowels secured to the tube by rivets or by screw sleeve couplings

Lengths of circular cross-section conductor may be connected together by the Western Union joint with or without solder, McIntyre sleeves, or by screw couplings. Lengths of rectangular cross-section conductors (ribbon) may be connected together by overlapping and riveting.

Lengths of star-section conductor may be connected together by means of screw joints formed from lugs of metal crimped over or formed on the end of the conductor.

Branch conductors are best connected to main conductors by joints similar to those used in main conductors, except that they may be in T or Y form.

Elevation rods are best attached to cables by means of crimped joints of malleable metal, similar to those described in the first paragraph of this note, except that they should be in T form and connect to the elevation rod by means of a dowel or screw coupling.

Elevation rods on forms of conductor other than cable may be attached in the same manner as branch rods, or by an equivalent means.

(2) *Mechanical strength.*—On structures exceeding 60 feet in height joints shall be so constructed that their mechanical strength in tension as shown by laboratory tests is not less than 50 per cent of that of the smallest of the several sections of conductor which are joined together.

(3) *Electrical resistance.*—Joints shall be so made that they have an electrical resistance not in excess of that of 2 feet of conductor.

(*d*) Fasteners.—Conductors shall be securely attached to the building or other object upon which they are placed. Fasteners, in general, shall be substantial in construction, not subject to breakage, and shall be, with the nails, screws, or other means by which they are fixed, of the same material as the conductor, or of such nature that there will be no serious tendency toward electrolytic corrosion in the presence of moisture because of contact between the different parts.

Fasteners shall be so spaced as to give adequate support to the conductor, generally not over 4 feet apart.

The firmness with which conductors are attached goes far toward determining their period of usefulness and security. Insecure fasteners not only lead to a reduction of the protective values of an installation but detract from its appearance and necessitate repeated repairs.

Conductors may be secured to wood surfaces by means of metal bands or straps, screw-shank fasteners, or an equivalent means. Strap or band fasteners should be made from sheet metal not less than No. 14 A. W. G. (0.064 inch=0.162 cm) in thickness, and not less than ⅜ inch (0.952 cm) wide, with screw or nail holes surrounded by an ample width of material. Screw-shank fasteners should be provided with a fork of substantial construction which can be closed by bending. The screw shank itself should be at least the equivalent in size of a No. 10 wood screw 1½ inches long (3.81 cm).

Conductors may be secured to brick and stone surfaces by means of screw-shank fasteners in the form of an expansion screw, by drive-shank fasteners having the shank ridged or barbed to grip the hole when driven, or by fan-shank fasteners to be laid in the walls as they are built.

Either the expansion screw or drive shank should be not less than ⅜ inch in diameter (0.952 cm) and 2 inches in length (5.08 cm). The fan shank should be approximately ½ inch (1.27 cm) wide at its narrowest place, $\frac{1}{10}$ inch thick (0.254 cm), and 3 inches long (7.62 cm).

Where screws are used they should be not smaller than No. 6, ¾ inch (1.9 cm) long. Nails should be not smaller in size than 4-penny standard. Copper-clad nails may be used with copper fasteners and galvanized nails with galvanized fasteners.

Fasteners may also be leaded into masonry or brickwork.

## 211. Points and Elevation Rods.

(*a*) Attachment of Points.—Separate points are not required but, if used, shall be of substantial construction and be securely attached to the elevation rods by screw or slip joints. The conducting cross-sectional area of the base shall be at least equivalent to the conducting cross-sectional area of the elevation rod.

(*b*) Elevation Rods.—(1) *Size.*—Elevation rods shall be at least the equivalent in weight and stiffness of a copper tube having an outside diameter of ⅝ inch (1.6 cm) and a wall thickness of No. 20 A. W. G. (0.032 inch=0.081 cm).

(2) *Form.*—Elevation rods may be of any form of solid or tubular cross section.

(3) *Height.*—The height of an elevation rod shall be such as to bring the tip not less than 10 inches (25.4 cm) above the object to be protected.

On flat surfaces a greater height than 10 inches is desirable, but the height need not exceed 5 feet. In most cases the proper height for an elevation rod between the limits just mentioned will depend upon the character of the object to be protected. On shingle roofs, for instance, or roofs of other inflammable materials, a greater height is needed for safety than is necessary on slate or tile roofs. The proper height may also be taken as depending somewhat on the contour of the object being protected; a spire, for instance, does not require so high an elevation rod as a silo having a peaked but much less sloping roof.

(*c*) Braces for Elevation Rods.—(1) *Use.*—Elevation rods shall be amply secured against overturning either by attachment to the object to be protected or by means of substantial tripod or other braces which shall be permanently and rigidly attached to the building.

(2) *Materials.*—The material from which braces are constructed shall be at least the equivalent in strength and stiffness of ¼-inch (0.625 cm) round iron, and with the nails or screws used in erecting must comply with the requirements of "210 (*a*) Materials" as to resistance to corrosion or protection against corrosion.

(3) *Form and construction.*—Braces shall be assembled by means of riveted joints or other joints of equivalent strength. Preference should be given to tripod or 4-legged braces, and when in place the feet should be spread until the distance between them approximates one-third the height of the brace.

(4) *Guides.*—Where elevation rods are more than 24 inches high, braces shall have guides for holding the elevation rod at two points located approximately as follows: The lower at a distance above the foot of the rod equal to one-third of its height, the upper at a distance above the lower equal to one-fourth the height of the rod.

Where elevation rods are 24 inches high or less, braces with a single guide may be used, holding the rod approximately midway of its height. Ten-inch (25.4 cm) elevation rods may be braced by means of substantial footings.

Where elevation rods are to be attached to house chimneys, they can be secured either by means of expansion-screw fasteners or a band surrounding the chimney. On horizontal masonry or brickwork, holes may be drilled and the rod set in cement. On woodwork, lag screws or strap fasteners may be used. Bracing in each case may be accomplished according to circumstances, but it is important that a good mechanical job be done to prevent overturning of the air terminal by the wind.

### 212. Prevention of Deterioration.

(*a*) General.—Precaution shall be taken in every instance to provide against any undue tendency toward deterioration due to local conditions.

(*b*) Corrosion.—Where any part of a protective system is exposed to the direct action of chimney gases or other corrosive gases, it shall be protected by a continuous covering of lead $\frac{1}{16}$ inch (0.158 cm) or more in thickness.

(*c*) Mechanical Injury.—Where any part of a protective system is exposed to mechanical injury, it shall be protected by covering it with molding or tubing preferably made of wood or nonmagnetic material. If metal tubing is used, the conductor shall be electrically connected to it at its upper end.

(*d*) Use of Ornaments.—The use of small ornaments, such as glass balls attached to elevation rods, is not objectionable, but elevation rods shall not be made to support vanes or ornaments having in any plane a wind-resistance area in excess of 20 square inches (129 $cm^2$).

Twenty square inches of area as a maximum for an ornament represents approximately the wind resistance area of a 5-inch (12.7 cm) glass ball. Where heavy or large ornaments are desired, they should be provided with a separate support.

**213. Location of Air Terminals.**

(*a*) General.—Air terminals shall be provided for all structural parts that are likely to receive, and be damaged by, a stroke of lightning.

(*b*) Projections.—In the case of projections, such as gables, chimneys, and ventilators, the air terminal shall be placed on, or attached to, the object to be protected where practicable, otherwise within 2 feet (61 cm) of it.

(*c*) Ridges, Parapets, and Edges of Flat Roofs.—Along ridges, parapets, and edges of flat roofs air terminals shall be spaced at intervals not exceeding 25 feet (7.62 m), and intermediate terminals need not be closer than 12.5 feet (3.81 m).

(*d*) Metal Projections and Parts of Buildings.—Metal projections and parts of buildings, such as ventilators, smoke-stacks, and other objects, that are likely to receive, but not be appreciably damaged by, a stroke of lightning, need not be provided with air terminals but shall be securely bonded to the lightning conductor with metal of the same weight per unit length as the main conductor.

Parts of structures most likely to be struck by lightning are those which project above surrounding parts, such as chimneys, ventilators, flagpoles, towers, water tanks, spires, steeples, deck railings, shaft houses, gables, skylights, dormers, ridges, and parapets.

The edge of the roof is the part most likely to be struck on flat-roofed buildings. On very large flat roofs it is desirable to erect air terminals at such points as are at a great distance from air terminals on parapets or projections. As a limiting value, 50 feet may be taken; that is, if on a large flat roof a portion is 50 feet or more from the nearest air terminal, it should have an air terminal erected upon it and be properly connected with the system.

(*e*) Coursing of Conductors.—Conductors shall, in general, be coursed over the roofs and down the corners and sides of buildings in such a way as to constitute, as nearly as local conditions will permit, an inclosing network.

(*f*) Roof Conductors.—Roof conductors shall be coursed along contours, such as ridges, parapets, and edges of flat roofs, and where necessary over flat surfaces, in such a way as to join each air terminal to all the rest.

Roof conductors surrounding decks, flat surfaces, and flat roofs shall be connected to form a closed loop.

(*g*) Down Conductors.—Down conductors shall preferably be coursed over the extreme outer portions of buildings, such as corners, due consideration being given to the best places for making ground connections and to the location of air terminals.

(*h*) Obstructions.—Conductors shall be curved around chimneys, ventilators, and similar obstructions in the shape requiring the shortest length of conductor.

(*i*) Bends.—No bend in a conductor which embraces a portion of a building, such as an eave, shall have a radius of less than 8 inches (20.3 cm). The angle of any turn shall not exceed 90°, and conductors shall everywhere preserve a downward or approximately horizontal course.

## 214. Metal-Roofed and Metal-Clad Buildings.

The materials and equipment required by this rule for the protection of metal-roofed or metal-roofed-and-clad buildings, shall comply with the requirements of rules 210 to 213, inclusive.

(*a*) Metal in Overlapping Sections.—Buildings which are roofed or roofed and clad with metal in the form of sections insulated from one another, or so applied that they are not in metallic contact, shall be treated in the same manner as are buildings composed of nonconducting materials.

(*b*) Metal Continuous.—When buildings are roofed or roofed and clad with all-metal sheets made electrically continuous by means of an interlocking or other contact, or by bonding, the following modifications may be made to the requirements of rules 211 to 217, inclusive:

Air terminals need be provided only on chimneys, ventilators, gables, and other projections, such as are likely to receive and be damaged by a stroke of lightning. Projections that are likely to receive, but not be damaged by, a stroke of lightning need not be provided with air terminals but shall be securely bonded to the roof.

Roof conductors may be dispensed with and elevation rods, if used, connected to the roof by soldered joints, or securely bolted joints, having an area of contact of not less than 3 square inches (19.3 $cm^2$). If the roof metal is in small sections, connection shall be made to at least four of the sections.

Down conductors shall be connected to the edges of roofs, or to the lower edges of metal siding, by soldered or bolted joints having an area of contact of at least 3 square inches (19.3 $cm^2$). If the metal is in small sections, connection shall be made to at least four of the sections.

### 215. Number of Down Conductors.

(*a*) Minimum.—There shall be not less than two down conductors on any type of building, and these shall be run so as to be as widely separated as practicable. The following rules shall apply as to additional down conductors.

In deciding upon the location and number of down conductors it should be kept in mind that it is very desirable to have at least two paths in parallel, and well separated, from the foot or near the foot of each air terminal to ground. This causes a stroke upon any air terminal to find a divided path, the impedance of which is less than that offered by a single path and offers an increased protective effect. The obstruction, or impedance, offered to the passage of the stroke is nearly in inverse proportion to the number of parallel paths if they are well separated.

(*b*) Rectangular Structures.—On rectangular structures having gable, hip, or gambrel roofs, and exceeding 110 feet (33.5 m) in length, there shall be at least one additional down conductor for each additional 50 feet (15.3 m) of length or fraction thereof.

On rectangular structures having French, flat, or saw-tooth roofs, and exceeding 300 feet (91.5 m) in perimeter, there shall be at least one additional down conductor for each additional 100 feet (30.5 m) of perimeter or fraction thereof.

(*c*) Irregular-Shaped Structures.—On an L or T shaped structure there shall be at least one additional down conductor, on an H-shaped structure at least two additional down conductors, and on a wing-built structure at least one additional down conductor for each wing.

On irregular-shaped structures the total number of down conductors shall in every case be sufficient to make the average distance between them along the perimeter not greater than 100 feet (30.5 m).

(*d*) Structures Exceeding 60 Feet in Height.—On structures exceeding 60 feet (18.3 m) in height there shall be at least one additional down conductor for each additional 60 feet (18.3 m) of height or fraction thereof, except that the application of this rule shall not cause down conductors to be placed about the perimeter of a structure at intervals of less than 50 feet (15.3 m).

(*e*) Metal-Roofed and Metal-Clad Buildings.—The number of down conductors and ground connections for metal-roofed and metal-clad buildings shall be determined in the same manner as for buildings composed of nonconducting materials; that is, according to the requirements of (*a*), (*b*), (*c*), and (*d*) above.

(*f*) Dead Ends.—Additional down conductors shall be installed where necessary to avoid " dead ends," or branch conductors ending at air terminals, which exceed 16 feet (4.88 m) in length, except that single down conductors descending flagpoles, spires, and similar structures which are adjuncts of buildings shall not be regarded as " dead ends," but shall be treated as air terminals.

Dead ends arise where an air terminal is placed on the peak of a dormer, or in some similar situation, and in the interest of economy is connected only to the nearest conductor, which usually is at the nearest ridge. A stroke on such an air terminal must traverse a single conductor until it reaches the ridge conductor where the path divides. The foregoing rule allows 16 feet (4.88 m) for the length of this single conductor. Where greater lengths are encountered the conductor must be extended from the air terminal to ground.

It is advisable to install additional down conductors at places along runs of roof conductors where the roof conductor descends into low places between parts of buildings, as it may in the case of an H-shaped structure where the end wings are higher than the connecting portion. This should be considered necessary, however, only where the descent amounts to a considerable number of feet, say 10 feet (3.05 m) or more.

## 216. Interconnection of Metallic Masses.

(*a*) Interconnection or Grounding.—Metallic masses about buildings which are a permanent portion of the structure, or are permanently installed within or about it, shall, with the exception of those of comparatively small size, be made a part of the lightning-conductor system by interconnection with it, or be independently grounded, or both, depending upon their location with respect to the lightning conductors and their surroundings, as more fully described in paragraphs (*b*) to (*h*), inclusive, of this rule.

The object of interconnecting the metal parts of a building with the conductor is to prevent the damage from sideflashes that has been found to occur, especially in the case of rather extensive metal objects that are near by. The main principle to be observed in the prevention of such damage is to pick out on a building the places where sideflashes are most likely to occur and provide metallic paths for them.

(*b*) Exterior Bodies of Metal.—Metal situated wholly on the exterior of buildings shall be electrically connected to the conductor at its upper (or nearest) end and, if of considerable length, shall be grounded or electrically connected to the conductor at its lower (or farthest) end.

Exterior bodies of metal include ornamental ridges, ventilators, roofs, valleys, gutters, down spouts, and structural iron. Connecting these into the lightning-conductor system not only serves to prevent sideflashes that cause damage, but makes the system a nearer approach to an inclosing network.

(*c*) Interior Bodies of Metal.—Metal situated wholly in the interior of buildings which at any point comes within 6 feet (1.83 m) of a lightning conductor, or metal connected thereto, shall be electrically interconnected with it and, if of considerable size or length, shall be grounded at its lower or farther extremity within the building.

Interior bodies of metal include radiators, piping systems, electric conduit, tanks, stationary machinery, stanchions, and various forms of structural metal. In general, experience has shown that sideflashes are not likely to occur to bodies of metal of ordinary size located more than 6 feet (1.83 m) from a conductor, whereas those that are nearer are likely to receive sideflashes which may damage a building or set fire to it. Very long or very large bodies of metal may, however, be a menace at more than 6 feet. The sideflashing to these near-by bodies is eliminated by interconnection, but the rise of potential due to dynamic discharge is not, so interior grounding becomes necessary. Unless there are water pipes or their equivalent that may be used for interior grounding purposes, there may be danger to persons and livestock about dwelling houses and barns. On this account, where water pipes are not available it is advisable to avoid as far as practicable the necessity for interconnection of interior bodies of metal by keeping conductors more than 6 feet (1.83 m) away from them—the farther the better.

(*d*) Metal Bodies Projecting Through Sides and Roofs.—Metal which projects through roofs or through sides of buildings above the second floor shall be bonded to the nearest conductor at the point where it emerges from the building and be grounded at its lower or extreme end within the building.

Metal which projects through the sides of buildings below the second floor shall be treated as though it were wholly within the building.

Metal projections through roofs and sides of buildings generally consist of soil pipes, metal flues, overflow pipes of hot-water heating systems and isolated gravity-type water systems, hayfork tracks, and ventilators. Metal hayfork tracks may be taken care of by connecting both ends to the conductor.

(*e*) Interconnection of Metals on or Within Metal-Roofed and Metal-Clad Buildings.—All parts of metal roofs, or roofs and sides, shall be securely bonded together.

All interior metal parts or contents of considerable size or extent that are a permanent portion of a structure or are permanently installed within it shall be independently grounded and, if within 6 feet (1.83 m) of sides or roof or a down conductor, shall be connected thereto.

The necessity for interconnecting and grounding the metal contents of metal-roofed and metal-clad buildings arises from the fact that in the event of a discharge the potential of the metal covering, even though grounded, changes sufficiently with respect to near-by objects to cause sideflashes, especially where the distance to be covered by the flash is short. Sideflashes from the metal coverings of buildings are likely to be especially destructive or dangerous because of the large electrostatic capacity involved. The chances for such sideflashes should be particularly considered in all buildings housing dusty operations, as flour mills. Care should be taken to ground ventilators projecting downward from roofs.

(*f*) Metallic Bodies to Be Independently Grounded.—Metallic bodies having any dimension exceeding 5 feet, and situated wholly within buildings, and which do not at any point come within 6 feet (1.83 m) of a lightning conductor, or metal connected thereto, shall be independently grounded.

It is generally safest to ground all metal within buildings that does not come close enough to a conductor to require interconnection with it, using an independent ground connection of any of the usual types, for the reason that it prevents sparks from accumulated static charges and from induction due to dynamic discharges.

(*g*) Substitution for Regular Conductors.—Extended metal parts of buildings shall not be substituted for regular conductors, except where they are permanently electrically continuous and have a conducting cross-sectional area at least double that of the lightning conductor that would otherwise be used.

In some cases of monumental structures and others where heavy and extensive metal parts are available, they may well be used in place of conductors to avoid expense and sacrifice of appearance, there being no difference whether they are on the interior or exterior of the structure where used for down conductors.

(*h*) Size of Interconnecting and Bonding Wires.—For bonding, interconnecting, and independent grounding of metallic masses the conductor used shall be at least the equivalent in strength and conducting cross-sectional area of a No. 6 A. W. G. copper wire, except where full-size lightning conductor is required by rule 213(*d*).

## 217. Ground Connections.

(*a*) Number.—A ground connection shall be provided for each down conductor, preference being given to water pipes and other large underground metallic structures.

(*b*) Distribution.—Ground connections (and down conductors) shall be placed at as uniform intervals about a building as practicable, and grouping of ground connections on one side of a building avoided.

(*c*) Moisture.—In making ground connections advantage should be taken of all permanently moist places where practicable, although such places should be avoided if wet with waste water which contains chemical substances especially corrosive to the metal with which the ground connection is made.

Chemical substances especially corrosive to lightning-conductor material are not ordinarily encountered in practice. They would usually be found about factories engaged in chemical processes. Barnyard seepage, which is the principal element encountered in the protection of farm property, appears to have no appreciable effect on copper and very little on thoroughly galvanized steel, so there need be no hesitation about making ground connections in soil beneath manure piles, although it would be advisable to use copper or copper-clad steel in such places.

(*d*) Permanency.—Ground connections shall in every case be thoroughly and permanently made, with due regard to the character of the surrounding soil.

(*e*) Water-Pipe Grounds.—Where a water pipe enters a building at least one down conductor shall be connected to it at a point immediately outside of the foundation wall by means of a substantial clamp to which the conductor can be attached by bolts or solder.

(*f*) Grounding Electrodes in Deep Soil.—Where the soil is moist clay, or other soil of similar character as to electrical resistivity, artificial grounding electrodes may be made by extending the rod itself into the ground a distance of not less than 10 feet (3.05 m). Where the soil is largely sand, gravel, or stones, more extensive artificial grounding electrodes shall be made by adding metal in the form of driven rods or pipes, or strips, plates, or lengths of conductor buried in trenches as in (*g*).

(*g*) Grounding Electrodes in Shallow Soil.—Where bedrock is near the surface, ground connections may be made by digging trenches radially from the building and burying in them the lower ends of the down conductors or their equivalent in the form of metal strips or wires. Where the soil is very dry or will not permit digging to a depth of more than 1 foot (0.305 m), in addition to the conductors laid radially, a similar conductor shall be buried which encircles the structure to be protected and connects all of the down conductors together.

(*h*) Trenches.—Trenches shall be long enough to accommodate 12 feet (3.66 m) of conductor when laid straight but need not be more than 3 feet (0.915 m) in depth.

Properly made ground connections are essential to the effective functioning of a lightning-conductor system, and every effort should be made to provide ample contact with the earth. This does not necessarily mean that the resistance of the ground connection must be low, but rather that the distribution of metal in the earth, or upon its surface in extreme cases, shall be such as to permit the dissipation of a stroke of lightning without damage.

Low resistance is, of course, desirable but not essential, as may be shown by the extreme case on the one hand of a building resting on moist clay soil, and on the other by a building resting on bare solid rock. In the first case, if the soil is of normal resistivity or from 200 to 5,000 ohm-centimeters, the resistance of a ground connection made by extending the conductor 10 feet (3.05 m) into the ground will be from 20 to 50 ohms, and two such ground connections on a small rectangular building have been found by experience to be sufficient. Under these favorable conditions providing adequate means for collecting and dissipating the energy of a flash without serious chance of damage is a simple and comparatively inexpensive matter.

In the second case it would be impossible to make a ground connection in the ordinary sense of the term, because most kinds of rock are insulating or at least of high resistivity, and in order to obtain the effect of grounding other and more elaborate means are necessary. The most effective means would be an extensive wire network laid on the surface of the rock surrounding the building, after the manner of counterpoise to a radio antenna, to which the down conductors could be connected. The resistance to earth at some distant point of such an arrangement would be high, but at the same time the potential distribution about the building would be substantially the same as though it were resting on conducting soil and the resulting protective effect also substantially the same.

In general, the extent of the grounding arrangements will depend upon the character of the soil, ranging from simple extension of the conductor into the ground where the soil is deep and of high conductivity, to an elaborate buried network where the soil is very dry or of very poor conductivity. In very dry ground, salt may be used to advantage to lower the resistance. Where a network is required it should be buried if there is soil enough to permit it, as this adds to its effectiveness. Its extent will be determined largely by the judgment of the person planning the installation with due regard to the minimum requirements of this rule, which is intended to cover the ordinary run of cases that are likely to be encountered in practice, keeping in mind that as a rule the more extensive the underground metal available the more effective the protection.

Some essential features of good practice in grounding for protection against lightning are as follows:

Where practicable each artificial ground connection should extend or have a branch which extends below the foundation walls of the building, as otherwise there is a chance of the wall being damaged.

The metal composing the ground connection should make contact with the soil from the surface downward, for if contact is made below the surface, as might be the case where a ground connection is made in a well, there may be flashing at the surface, with danger of burning off the conductor.

During a stroke of lightning on a system of conductors the grounding electrodes are to be thought of as the collecting points for a heavy flow of current radially toward the building in the surface of the earth and should, therefore, be distributed with the view of collecting this current in the most advantageous manner. This will generally be realized by placing them at the outer extremities, such as corners, and avoiding as far as possible the necessity for current flow under the building to reach a ground connection.

## 218. Radio Installations and Wires Entering Buildings.

(*a*) Separation from Lightning Conductors.—A separation of at least 6 feet (1.83 m) shall be maintained between telephone wires, electric-light wires, and radio leads and the nearest lightning conductor.

(*b*) Metal Radio Masts on Buildings.—Metal radio masts on buildings shall be bonded to the nearest lightning conductor.

(*c*) Wooden Radio Masts.—Wooden radio masts which extend more than 6 feet above the ridge or highest parts of the building on which they are placed shall be treated in the same manner as flagpoles.

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## SEC. 22. MISCELLANEOUS STRUCTURES

### 220. Spires, Steeples, and Flagpoles.

(*a*) General.—The materials, equipment, and ground connections required by the rules of this section for the protection of spires, steeples, and flagpoles shall comply with the requirements of section 21.

(*b*) Air Terminals.—A single air terminal may be used, which elevates the tip a distance of not less than 10 inches (25.4 cm) above the uppermost point of the structure.

(*c*) Down Conductors.—A single down conductor may be used, which, if the structure is isolated, shall be extended directly to a ground connection. If the structure is an adjunct of a building and near or touching the perimeter, the down conductor shall be extended directly to a ground connection but shall also be connected to the lightning-conductor system on the building. If it is set well within the perimeter, the descending conductor shall be connected to the nearest roof conductor.

(*d*) Interconnection of Metals.—Bells, clocks, structural iron, and other metallic masses shall be connected to the down conductor. If the length of a metallic body is comparable to the height of the structure, connection shall be made at the upper and lower extremities; otherwise connection may be made at the nearest point.

(*e*) Grounding of Metallic Spires and Flagpoles.—Spires and flagpoles composed entirely of or covered entirely with metal and resting on foundations of nonconducting material with the top so constructed as to receive a stroke of lightning without appreciable damage, need not be provided with air terminals or down conductors, but shall be grounded or connected to the nearest lightning conductor, or both, according as the structure is isolated, set within the perimeter of a building, or near it, respectively.

On spires and steeples exceeding 100 feet (30.5 m) in height it is advisable to use more massive conductors and fastenings than on ordinary types of buildings in order to resist the extraordinary conditions found on tall structures.

## 221. Water Towers, Silos, and Similar Structures.

(*a*) General.—The materials, equipment, and ground connections required by the rules of this section for the protection of water towers, silos, and similar structures, shall comply with the requirements of section 21.

On structures exceeding 100 feet (30.5 m) in height it is advisable to use more massive conductors and fastenings than on ordinary buildings in order to resist the extraordinary conditions found on tall structures, especially with regard to temperature effects and loading which may lead to alternate expansion and contraction.

(*b*) Air Terminals.—The number and location of air terminals shall, in general, comply with the requirements of rule 213, except that on silos and other towers having roofs ending in a peak a single air terminal may be regarded as sufficient.

(*c*) Conductors.—Where more than one air terminal is used they shall be connected together by a conductor which forms a closed loop about the structure near the top or passes over it, as the contour of the roof may require. From this, or from the single air terminal if but one is used, at least two down conductors shall be extended directly to ground connections on opposite sides, if the structure is isolated. If it is an adjunct of a building, near or touching the perimeter, one down conductor shall be extended directly to a ground connection while the other may be connected to the lightning-conductor system on the building. If it is set well within the perimeter, both down conductors may be connected to the lightning-conductor system on the building. If the height of the structure exceeds 100 feet (30.5 m), the down conductors should be cross connected midway between top and bottom.

(*d*) Interrconnection of Metals.—All metallic bodies of considerable size or extent, whether exterior or interior, shall be connected to the down conductors. If their length is comparable to the height of the structure, they shall be connected to the down conductors at both ends; otherwise connection may be made at the nearest point.

Metal objects about towers which are comparable in length with the height of the structure consist usually of stairways, elevator guides, and drainpipes carrying water from the roof.

(*e*) Grounding of Metal Towers and Tanks.—Towers and tanks composed entirely of, or covered entirely with, metal and resting on foundations of nonconducting material, with the uppermost portion so constructed as to receive a stroke of lightning without appreciable damage, need not be provided with air terminals or down conductors, but shall be grounded if isolated, connected to the nearest lightning conductor if set well within the perimeter of a building, or both grounded and connected to the lightning-conductor system if set near the perimeter.

## SEC. 23. BUILDINGS CONTAINING BALED INFLAMMABLE MATERIALS

It has been found that lightning flashes occurring in the immediate vicinity of cotton or other fibrous materials of an inflammable nature baled with metal ties may cause secondary discharges between the ties of sufficient intensity to cause ignition. To prevent fires of this type a greater degree of shielding is required than is afforded by the ordinary system of lightning rods. The required condition is inherent or readily realized in all-metal or metal-covered buildings, but in the case of other types made of nonconducting materials the nearest practicable approach to the necessary degree of shielding is found in a grounded network of sufficiently small mesh covering the roof. It has been found experimentally that the shielding effect of a network of given mesh increases with the height above the shielded object, also that the shielding effect decreases as the size of the mesh is increased. A mesh of 6 feet is a fair mean value if placed on or a few feet above the roof.

### 230. Methods and Materials.

The materials, equipment, and ground connections required by the rules of this section shall comply with the requirements of sections 21 and 22.

### 231. Metal-Roofed and Metal-Clad Buildings.

Metal-roofed and metal-clad buildings shall be treated in the same manner as required in section 21, rule 214.

### 232. Buildings of Nonconducting Materials.

The effect of an electrostatic shield may be obtained by constructing on or above the roof a network of wires or cables and grounding it about the perimeter at the same intervals as required for metal-roofed buildings.

## SEC. 24. SMOKESTACKS AND CHIMNEYS

### 240. Metal Smokestacks.

Metal smokestacks need no protection against lightning other than that afforded by their construction, except that they shall be properly grounded. If the construction of the foundation is not such as to provide ample electrical connection with the earth, ground connections shall be provided similar to those required below for stacks made of materials other than metal.

Metal guy wires and cables not in electrical contact with the earth at their lower ends shall be grounded.

Metal guy wires or cables attached to steel anchor rods set in earth or concrete may be considered as sufficiently well grounded. Only those attached to buildings or nonconducting supports need attention.

### 241. Brick, Hollow-Tile, and Concrete Stacks.

Where stacks of brick, hollow tile, concrete, or other material liable to damage by lightning are to be protected the following rules shall apply:

(*a*) Conductors.—Conductors shall be of copper of the grade required for commercial electrical work, generally designated as having 98 per cent conductivity when annealed.

The weight of the conductor shall be not less than 6 ounces per linear foot (375 pounds per thousand feet=0.558 kg per m).

The size of any wire in a cable shall be not less than No. 15 A. W. G. (0.057 inch=0.145 cm).

The thickness of any tube wall shall be not less than No. 15 A. W. G. (0.057 inch=0.145 cm).

The thickness of any web or ribbon shall be not less than No. 12 A. W. G. (0.080 inch=0.203 cm).

(*b*) Fasteners.—Fasteners shall be of copper or copper alloy substantially as resistant to corrosion as the conductor itself and must be strongly constructed. Each fastener must have a sufficiently tight grip to support its corresponding length of conductor.

Fasteners shall be spaced close enough to give ample support to the conductor, generally not over 4 feet (1.22 m) apart.

(*c*) Air Terminals.—Air terminals shall be strongly constructed of the same grade of material as the conductor and shall be uniformly distributed about the rim of the stack at intervals not exceeding 8 feet (2.44 m).

The height above the rim shall be not less than 30 inches (0.762 m).

They shall be secured to the rim of the stack by means of expansion bolts or fan-shank fasteners of substantial construction, or be set in a metal crown.

If there is no metal crown, the air terminals shall be electrically connected together by means of a metal ring or band which forms a closed loop about the stack 2 feet (0.61 m) below the rim.

(*d*) Down Conductors.—At least two down conductors shall be provided on opposite sides of the stack, leading from the ring or crown at the top to the ground.

On stacks exceeding 160 feet (48.8 m) in height the down conductors shall be cross connected approximately midway between top and bottom.

Where a metal ladder is continuous from the rim to the ground, and the vertical members have a combined cross section not less than twice that specified in 210(*b*)(3), such members may be utilized as down conductors.

(*e*) Lead Covering.—In order to prevent corrosion by gases, air terminals, conductors, and fasteners within 25 feet (7.62 m) of the top of the stack should have a continuous covering of lead at least $\frac{1}{16}$ inch (0.158 cm) thick.

(*f*) Joints.—Joints in conductors shall be as few as practicable and of such construction as to show by laboratory tests a strength in tension of at least 50 per cent of that of the conductor.

(*g*) Ground Connections.—Ground connections may be made in the manner prescribed for buildings. (See rule 217.)

If there is a water pipe near by, connection shall be made to it by means of a substantial clamp.

The ground connections shall be connected together by means of a conductor forming a closed loop about the foundation near or under the ground.

(*h*) Protection Against Mechanical Injury.—Down conductors near the ground shall be protected against mechanical injury by means of wood molding or other non-magnetic material.

If metal tubing is used for protective purposes, the down conductor shall be electrically connected to it at its upper end.

(*i*) Metal Linings.—Where stacks have a metal lining extending part way up, the lining shall be connected to the rod at its upper end and grounded at the bottom.

## SEC. 25. HANGARS, BALLOONS, AND AIRSHIPS

### 250. Prevention of Damage to Hangars.

Where buildings housing aircraft are to be protected against lightning the following rules shall apply:

Buildings for the housing of aircraft require special attention in regard to protection against lightning because of the hazardous nature of their contents, and in the case of buildings for housing rigid airships, because of their great height and area. Hangars constructed by the Navy Department range in size from 100 feet by 66 feet by 52 feet high (30.5 m by 20.1 m by 15.8 m) for the housing of kite balloons, to 804 feet by 350 feet by 200 feet high (245.2 m by 106.7 m by 61 m) for the housing of large dirigibles. They are of structural-steel framework, with corrugated-iron roofs and sides, or with composite or built-up roofing on wooden sheathing and corrugated-asbestos sides. Buildings for housing heavier-than-air craft are found constructed from combinations of materials ranging from wood frames covered with canvas to all-metal structures. The former, of course, are usually temporary field shelters. Permanent stations are usually all steel, steel over wood frames, or asbestos on either wood or steel. For the protection of all-steel structures it is considered sufficient to ground the framework (as indicated in paragraph (*h*) below), but for the protection of buildings of other forms of construction more extensive measures are necessary.

(*a*) Materials.—Materials used for the purposes of this section shall comply with the requirements of rule 210 (*a*), "Materials."

(*b*) Conductors.—Conductors may be in the form of cable, tube, strip, or rod, having round, square, star, or other solid cross section, and shall comply with the requirements of rule 210 (*b*).

It is recommended that where existing conditions are especially severe with respect to weather or other causes, as may be the case with very large buildings for the housing of aircraft, more massive conductors be used than required by rule 210 (*b*).

(*c*) Construction and Installation.—The construction and installation of conductors where used shall comply with the rules 210 (*c*) (*d*), 211, and 212.

(*d*) Structures with Steel Frames.—Where protection is provided for buildings with steel frames, all parts of which are securely bonded together, the air terminals may be connected to the steel frame at the nearest point and other conductors between air terminals and ground omitted. Where such connection is made, the connecting conductor shall comply with the requirements of rule 210 (*b*), as to weight, and shall be secured in electrical contact with the frame by means of bolts and nuts. The steel frame shall be grounded as provided in rule 250 (*h*).

(*e*) Construction of Air Terminals.—Air terminals shall be strongly constructed and shall be securely attached and braced against overturning.

The following construction is suggested for air terminals on the roofs of steel-frame buildings. The elevation rod may consist of a length of "extra strong" galvanized-steel pipe not less than 0.75 inch (1.90 cm) internal diameter, or an equivalent copper or copper-alloy tube, threaded at both ends, one to receive a threaded solid point 6 inches (15.24 cm) in length, and the other an attachment for securing the elevation rod to the roof.

This attachment should consist of a pair of wooden blocks bolted to the outer and inner surfaces of the wood sheating and cut to fit the roof, and afford horizontal parallel surfaces for mounting floor flanges. The roof and blocks should be drilled through at the hub of the flanges and the tube screwed through both flanges in a vertical position. The roofing should be laid on around the outer wooden block and copper flashing applied.

(*f*) Height of Air Terminal.—Where air terminals are placed on projections the height shall be such as to bring the tip not less than 10 inches (25.4 cm) above the object to be protected. Where air terminals are placed near projections there shall be at least 4 inches (10.2 cm) of additional height above the object to be protected for each foot of separation.

Where air terminals are spaced 25 feet (7.62 m) or less apart on roof ridges or flat surfaces, the height shall not be less than 4 feet 10 inches (1.47 m). For each additional foot (0.305 m) of separation above 25 feet (7.62 m) there shall be an increase in height of not less than 2 inches (5.08 cm).

Where air terminals are placed in rectangular arrangement as in (*g*) the height shall be determined by the longest side of the rectangle.

(*g*) Location of Air Terminals.—Air terminals shall be provided for all structural parts that are likely to receive, and be damaged by, a stroke of lightning.

In the case of projections, the air terminal shall be placed on the object to be protected where practicable, otherwise it shall be attached to the roof as near by as practicable.

Along ridges, parapets, and edges of both flat and pitched roofs, air terminals shall be erected at intervals not exceeding 25 feet (7.62 m).

Flat and sloping surfaces, except an indicated below, shall be divided into rectangles having sides not exceeding 50 feet (15.24 m) in length by drawing lines parallel to the edges of the roof, and air terminals erected at the intersection of these lines.

On gambrel roofs only the portion above the breaks need be considered, and is to be treated as a pitched roof.

On mansard roofs only the flat portion need be considered, and is to be treated as a flat roof.

(*h*) Ground Connections.—Ground connections for lightning conductors shall comply with rule 217.

Where the frame of the building is of steel it shall be permanently and effectively grounded, as follows:

If there is a water-pipe system entering the structure, the frame shall be bonded to it at the point of entrance with a conductor secured to the pipe by means of a substantial clamp with a lug, and to the frame with a bolt and nut. In addition, artificial grounds shall be provided for the steel pedestals, columns, or roof trusses, at not less than half of the footings, and distributed as uniformly about the perimeter as practicable.

If there is no water-pipe system available, an artificial ground shall be provided at each footing.

Where the soil is deep, artificial grounds may be made by extending the grounding conductor into the soil a distance of at least 10 feet (3.05 m), by driving a pipe or rod to a depth at least 8 feet (2.44 m), or by burying to a depth of at least 6 feet (1.83 m) a metal plate having an area of at least 4 square feet (0.372 $m^2$).

Where the soil is shallow, grounds may be made by digging trenches radially from the building and burying in them a length of grounding conductor, or its equivalent in the form of a metal strip. In addition, a trench should be dug surrounding the building and a conductor laid in it which connects all of the grounding conductors together.

Conductor for grounding purposes shall conform to rule 250 (*b*) above.

Where galvanized-steel pipes are used they shall be standard "extra strong" and have a nominal internal diameter of not less than 0.75 inch (1.90 cm).

Where copper strips or plates are used they shall have a thickness of not less than No. 14 A. W. G. (0.064 inch = 0.16 cm).

Grounding conductors shall be attached to buried electrodes by means of soldered, riveted, or bolted joints, and to the frame with bolts and nuts.

Trenches for grounding purposes must be long enough to accommodate 12 feet (3.66 m) of conductor when laid straight, but need not be more than 3 feet (0.915 m) in depth.

(*i*) INTERCONNECTION OF METALS.—Exterior metallic bodies, such as roof flashings and down spuots, shall be securely bonded to the lightning-conductor system. In the case of steel-frame buildings they shall be securely bonded to the frame, and all parts of the frame shall be securely bonded together.

Interior metallic bodies, such as piping systems and machinery, shall be independently grounded and if within 10 feet of a lightning conductor shall be securely bonded thereto. In the case of steel-frame buildings all interior metallic bodies within 10 feet of the walls shall be securely bonded to the frame.

Where water pipes are available they shall be used in preference to other means for grounding interior bodies of metal. Where artificial grounds are necessary they shall be constructed in compliance with rule 217.

For all bonding, interconnecting, and grounding purposes the conductor used shall be at least the equivalent in strength and conducting cross-sectional area of a No. 6 A. W. G. copper wire, except where full-size lightning conductor is otherwise required.

(*j*) SPARK PREVENTION.—Each structure, after its protective system is installed, shall be examined by competent authority with a view of determining whether all possible interior sources of sparks from a stroke of lightning on the building have been eliminated. If it appears that gaps between adjacent bodies of metal or between bodies of metal and ground are likely to give rise to sparks, suitable bonds or ground connections shall be installed in such a manner as permanently and effectively to prevent them.

### 251. Prevention of Damage to Aircraft.

To prevent damage from lightning and accumulation of static electricity, balloons and airships shall be treated as follows:

(*a*) Captive Balloons.—Captive balloons shall be grounded through the metal cable and winch by means of a pipe or rod driven 6 feet (1.83 m) in the ground, or its equivalent in metal buried in a trench.

(*b*) Free Balloons and Airships.—Free balloons and airships shall be provided with an effective grounding wire which is to be dropped just previous to landing, and a good ground contact made for carrying off such electrical charges as may have been accumulated by them while in the air.

(*c*) Interconnection of Metallic Parts.—All metal parts of lighter-than-air craft shall be interconnected so that any charge that may accumulate may be distributed rather than remain concentrated.

## SEC. 26. SHIPS

### 260. Vessels to be Protected.

Vessels shall be protected as indicated below, irrespective of the geographical area in which they operate.

### 261. Radio Antennas.

Radio antennas shall be provided with means for grounding during electrical storms.

### 262. Vessels with Steel Hulls and Steel Masts.

If there is metallic contact between steel hulls and steel masts no further protection against lightning is necessary.

### 263. Vessels of Other than Steel Construction.

The grounding of radio antennas constitutes sufficient protection for vessels of other than steel construction, except where wooden masts or spars are employed, in which case all metal fittings, such as trucks and bands, shall be effectively and permanently grounded by means of 1 by $\frac{1}{32}$ inch (2.5 by 0.08 cm) copper strips secured to spars by brass screws and led to the nearest grounded metal-hull structure. Similar grounding of metal fittings at the extremities of wooden masts and spars constitutes adequate protection where no radio antenna is installed.

### 264. Metal Standing Rigging and Jacob's Ladders.

Where metal standing rigging and Jacob's ladders are installed they shall be effectively grounded at the lower ends in all cases (that is, whether the vessel is equipped with a radio antenna or not) except where such rigging or Jacob's ladders are broken up into insulated sections not over 10 feet (3.05 m) in length for radio purposes by means of suitable insulators, in which case grounding at the lower ends is not necessary. Grounding shall be carried out by means of stranded wire shunts ¼ inch (0.635 cm) in diameter, around deadeyes, lanyards, shackles, rigging screws, thimbles, etc., these shunts to be stranded, laid around the bright rigging, then parceled and sewed.

### 265. Ground Connections.

In vessels having a steel hull, the hull itself constitutes an adequate ground. In vessels having wooden hulls, ground connection shall be made by means of a copperplate not less than 36 square feet (3.3 $m^2$) in area secured to the outside of the hull below the light water line.

## SEC. 27. TREES

The protection of trees against lightning has been done on an increasing scale during the last few years, especially trees of historical interest or of unusual value. The rules of this section for the installation of lightning conductors on trees are based on what appears to be the best information obtainable.

### 270. Methods and Materials.

Where it appears desirable to protect trees against lightning the following rules shall apply:

(*a*) Conductors.—Conductors may be copper, copper-clad steel, or galvanized iron, and shall conform to the requirements of rule 210.

(*b*) Coursing of Conductors.—In general, a single conductor shall be run from the highest part of the tree along the trunk to a ground connection. If the tree is forked, branch conductors shall be extended to the highest parts of the principal limbs. If the tree is very large, two down conductors may be run on opposite sides of the trunk and interconnected near the top.

The conductors should be extended as close as practicable to the highest part of the tree.

(*c*) Attachment of Conductors.—Conductors shall be securely attached to the tree in such a way as to allow for continued growth of the trunk, and for swaying in the wind, without danger of breakage.

A suitable method is to place loose girdles of wire incased in flexible tubing about the tree and attach the conductors to them. As the tree grows it is necessary to loosen the girdles from time to time to prevent checking of the flow of sap.

Another method is to use screw-shank fasteners of galvanized iron which hold the conductor at a distance of about 2 inches (5.08 cm) from the trunk. With growth the fasteners become embedded and are replaced with others.

To allow for swaying of the tree in the wind the conductor should be attached with an appreciable amount of slack between points of support.

(*d*) Ground Connections.—Grounds for conductors on trees shall be made as follows: From each conductor, descending the trunk of the tree, extend three or more radial conductors in trenches 12 inches (0.305 m) deep, spaced at equal intervals about the base where practicable, to a distance of 10 to 25 feet (3.05 to 7.62 m), depending upon the size of the tree. If the roots are very extensive, the radial conductors may well be extended more than 25 feet (7.62 m). It is desirable as a further protective measure to connect the outer ends of the radial conductors together with a conductor which encircles the tree at the same depth as the radial conductors. In very dry soil the network should be supplemented with driven pipes, rods, or buried plates at its outer extremities.

The object of the shallow network is to pick up the ground current accompanying a lightning flash near the surface and at a distance from the trunk rather than among the roots, which are as susceptible to damage as the top.

## SEC. 28. LIVESTOCK IN FIELDS

The information on this subject is limited, but the best obtainable has been made use of in formulating the following rules. On account of the nature of the exposure it is not possible, of course, to eliminate the hazard entirely, but it is believed that if these rules are applied it can be much reduced.

The loss of livestock by lightning is caused in large measure by herds drifting against ungrounded wire fences during thunderstorms

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and receiving a sufficient discharge to kill them, either from accumulated static electricity or from a stroke on the fence itself. The fences that give rise to the most trouble of this kind are those constructed with posts of poorly conducting material, such as wood or concrete. Fences built with metal posts set in earth are as safe from lightning as it is possible to make them, especially if the electrical continuity is broken as provided hereafter. Breaking the electrical continuity is very useful in that it prevents a lightning stroke from affecting the entire length of a fence, as it may if the stroke is direct and the fence continuous, even though grounded.

Isolated trees in pastures where stock congregate seeking shade are also a source of loss. In pastures where shade is available from wooded areas of considerable size, isolated trees should be removed but otherwise should be protected by suitable rodding as described in rule 282 below.

## 280. Grounding of Wire Fences.

Where it appears desirable or necessary to mitigate the danger from wire fences constructed with posts of non-conducting material, the following rules shall apply.

(*a*) Iron Posts.—Ground connections may be made by inserting at intervals galvanized-iron posts, such as are ordinarily used for farm fencing, and attaching in electrical contact all of the wires of the fence. If the ground is normally dry, the intervals between metal posts shall not exceed 150 feet (45.7 m). If the ground is normally damp, they may be placed 300 feet (91.5 m) apart.

(*b*) Iron Pipe.—A less expensive ground connection than (*a*) may be made by driving a length of ½ or ¾ inch (trade size) galvanized-iron pipe beside the fence and attaching the wires by ties of galvanized-iron wire. The spacing shall be the same as for the posts under (*a*) above.

(*c*) Depth of Grounds.—Pipes or posts shall be extended into the ground at least 3 feet (0.915 m.).

## 281. Breaking Continuity of Fence.

In addition to grounding the fence, its electrical continuity shall be broken by inserting insulating material in breaks in the wires at intervals of about 1,000 feet (305 m.). These insertions may be in the form of fence panels of wood or lengths of insulating material to the ends of which the wires can be attached. Such lengths of insulating material may consist of strips of wood 2 by 2 by 24 inches (5.08 by 5.08 by 60.9 cm), or their equivalent as far as insulating properties and mechanical strength are concerned.

## 282. Trees.

Where a tree is isolated and the vicinity is much frequented by livestock the danger from lightning can be reduced by installing a single conductor extending from the top of the tree to a distance of at least 6 feet (1.83 m) into the ground.

## Part III.—PROTECTION OF STRUCTURES CONTAINING INFLAMMABLE LIQUIDS AND GASES [1]

### INTRODUCTION

In a Report on Records of Oil-Tank Fires in the United States, 1915–1925, published by the American Petroleum Institute, it is stated that lightning caused 55 per cent of the fires recorded.

#### Reduction of Damage.

Certain types of structures used for the storage of inflammable liquids and gases are essentially self-protecting. Protection, of a greater or less degree, may be secured in the case of others through the installation of various types of protective equipment, such as screens, rods, protective towers, and by other means.

#### Fundamental Principles of Protection.

Protection of structures and their contents from lightning involve the following principles:

(*a*) The storage of inflammable liquids and gases in all-metal structures essentially gas-tight.

(*b*) The use in all necessary breathing vents of efficient flame arresters.

(*c*) The maintenance of containers in good condition, so far as potential hazards are concerned.

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[1] This part of the code has been approved by the American Standards Association as a tentative American standard.

(*d*) The avoidance, so far as possible, of the accumulation of explosive mixtures in and about such structures.

(*e*) The avoidance of spark gaps in metallic conductors or between metallic conductors at points where there may be an accumulation of explosive mixtures or an escape of inflammable vapors or gases to the air.

(*f*) In connection with structures not inherently self-protecting, the establishment of cones of protection through the use of grounded screens, rods, or towers, or the equivalent.

(*g*) The location of structures containing inflammable liquids and gases not inherently self-protecting, in positions of lesser exposure with regard to lightning. Thus elevated positions should be avoided.

## SEC. 30. SCOPE, EXCEPTIONS, ETC.

### 300. Scope and Purpose.

This code applies to the protection of structures containing inflammable liquids and gases and their contents from lightning or electrical discharges, regardless of their origin. It applies particularly to above-ground structures containing gasoline, kerosene, refined oils, fuel oils, and crude oils; also to such materials as turpentine and inflammable gases. It is primarily intended to give as much fundamental information as possible as to the kind of structures most suitable for the protection of their contents from lightning or electrical discharges and to indicate ways and means of protecting such structures as are not inherently self-protected.

This code is concerned only with the prevention of fires from electrical discharges and in no way whatever with ways and means of extinguishing fires when once started.

### 301. Interpretation and Exceptions.

This code shall be liberally construed. Exceptions from its literal requirements may be made if equivalent protection is otherwise secured.

It is not intended that this code shall be interpreted as recommending the protection of the class of property to which it applies but shall constitute the standard where economic or other considerations make it appear that protection is necessary or desirable.

### 302. Mandatory and Advisory Requirements.

The word "shall" where used is to be understood as mandatory and the word "should" as advisory. "May" is used in the permissive sense.

### 303. Terms and Definitions.

The following terms and definitions apply specifically to the structures, material, etc., involved in Part III of this code:

(1) *Breathers or vents.*—These are the openings provided to allow for the passage of air in or out of otherwise wholly or partially gas-tight tanks, when emptying or filling, or due to changes in temperature. Vents are usually provided with some form of flame arrester.

(2) *Flame arrester.*—A device used to prevent passage of flame where explosive mixtures or combustible vapors and gases are present on both sides of the device.

(3) *Cage.*—A system of noncorrodible wires or cables, forming an inclosing cage, especially over the roof of the tank, and forming an essentially continuous mesh or network over the tank and the protecting roof, this cage including the necessary conductors, which are connected to the tank and to an adequate ground.

(4) *Cone of protection.*—The space inclosed by a cone formed with its apex at the highest point of a lightning rod or protecting tower, the diameter of the base of the cone having a definite relation to the height of the rod or tower which has been determined experimentally. This relation depends on the height of the rod and the height of the cloud above the earth. The higher the cloud, the larger the radius of the base of the protecting cone. The ratio of radius of base to height varies approximately from two to four.

(5) *Flashpoint.*—Flashpoint is that temperature to which oil or inflammable liquids must be heated to give off vapor in sufficient amount to form a mixture with air which can be ignited by a flame under specified conditions.

(6) *Gas tight.*—So constructed that gas or air can not either enter or leave the structure except through vents or piping provided for the purpose. This is supposed to be accomplished by steel tanks riveted and calked, or completely welded.

(7) *Spark gap.*—As used in this code the term "spark gap" means any short air space between two conductors not electrically connected to each other.

In an oil tank such a gap might occur between a section of metallic sheathing and the tank proper or between two sections of such sheathing or as a gap formed by an ill-fitting hatch cover in a steel roof or in many other ways.

(8) *Inflammable vapors.*—The vapors given off from inflammable liquids which will burn when mixed with air.

(9) *Explosive mixtures.*—When inflammable vapors are mixed with air in certain proportions the mixture becomes explosive when ignited by any means. The range for ordinary petroleum products is from 1½ to 6 per cent of vapor by volume, the remainder being air.

## SEC. 31. PROTECTIVE MEASURES AND PRECAUTIONS

### 310. Classification of Structures.

Class A.—Steel tanks, including roof, essentially gas-tight, except for necessary vents for breathing, these vents being properly flameproofed (steel tanks riveted and calked or welded).

Steel tanks with floating roofs providing for the least possible exposure of the contained liquids.

Class B.—Steel tanks with steel tops, hatch covers, etc., but with no special precautions for making them gas-tight.

Steel tanks with roofs of nonmetallic material, so constructed that they are gas-tight with the necessary flameproof vents for breathing.

Steel tanks with roofs of nonmetallic material, such as wood, sheathed with thin layers of metal but not gas-tight.

Class C.—Earthen containers, lined or unlined, with or without roofs.

The sizes of the structures listed above vary from the small tanks, such as are used for the storage of gasoline for filling stations, to enormous earthen reservoirs, capable of storing several million barrels of crude oil. The usual steel tanks vary in size from those containing a few hundred barrels of oil to tanks containing 150,000 barrels of oil. The greater number of tanks in use requiring protection range in size from 50 to 150 feet (15 to 45 m) in diameter and from 30 to 45 feet (9 to 14 m) high.

Except where these tanks have been recently constructed or rebuilt they are generally steel tanks with nonmetallic roofs. The condition of the tanks will vary from the newest type of gas-tight steel tank of the best possible workmanship to tanks which have been in the field for many years and whose condition reflects the care or lack of care which has been taken in keeping them in good condition. In many of the older tanks with nonmetallic tops no special precautions have been taken to connect metallic parts together and to avoid spark gaps.

There are many of the older tanks in use with nonmetallic roofs either sheathed with thin metal, such as tinplate, or unsheathed where no attempt has been made to make them gas-tight.

In the case of the earthen reservoirs, lined with reinforced concrete, in most cases no attempt has been made to metallically bond and ground the reinforcing metal within the cement mixture or to ground all parts of the reinforcing metal.

### 311. Structures Which Are Inherently Self-Protecting.

The extent to which structures containing inflammable liquids or gases will be self-protecting is approximately in the order given in rule 310, which lists the various classes of structures which are used for this purpose.

All-steel gas-tight tanks with vents adequately flame-proofed are considered to be completely protected. This requires that such tanks be either riveted and calked or all joints welded. It also requires that all pipes, cables, etc., entering the tank be metallically connected to the tank at the point of entrance and that the metal cover be of sufficient weight to avoid being fused in the case of a direct stroke of lightning. Tank covers as used in commercial practice have been found adequately heavy.

Tanks with floating roofs which prevent the accumulation of vapors and explosive mixtures and with provision for minimum exposure of the contents are considered in the same class with the gas-tight tanks above.

No special precautions need be taken in regard to the grounding of tanks in the above class.

### 312. Structures Which Are Not Self-Protecting.

Structures in classes B and C are not self-protecting, and the recommended measures in the following paragraphs refer to precautions with regard to the tank structures themselves, with the idea of making them as nearly self-protecting as possible. Additional protective measures are listed in the following rule. Steel tanks having steel tops and hatch covers, not necessarily gas tight, which contain volatile oils, should have all openings and joints made as close-fitting as possible to reduce to a minimum the escape of accumulated gases and vapors. Breathing vents should receive the same consideration as in the gas-tight tanks.

Where it can be done, replacement of the gases and vapors above the liquid level with noninflammable gases will do much to prevent the starting of fires from any cause.

On steel tanks with roofs of nonmetallic materials, sometimes sheathed with very thin metal to avoid the entrance of water, all metal parts on the roof and all pipes and cables entering the gas space should be thoroughly bonded together and connected to the tank and to an adequate ground.

Steel tanks embedded in soil, or with underground piping connections, are usually sufficiently well grounded inherently.

Roofs of nonmetallic material should have adequate slope to prevent the formation of pools of water, particularly in the neighborhood of openings, as induced discharges may occur from pool to pool of water or from pool to grounded metal.

Spark gaps between isolated masses or sheets of metal or between such sheets and grounded metal, or in partially closed circuits of metal whether grounded or not, particularly in the gas space above the stored liquids, should be avoided.

Tanks with nonmetallic roofs but made gas tight, except for breathing vents, should have the same precautions taken for grounding any necessary metal, such as cables, clamps, entering pipes, or wires, for the avoidance of spark gaps, as above.

In reinforced-concrete reservoirs, all reinforcing metal, particularly that which might be exposed at points at which there would be vapor or explosive mixtures, should be connected together, and all spark gaps between such metal not completely buried in the concrete structure should be avoided. It is desirable that all reinforcing material be completely buried in the concrete. Where roofs are used, all necessary metal should be thoroughly bonded together and connected to adequate grounds at frequent intervals, and spark gaps avoided.

### 313. Additional Protective Measures.

So-called Faraday cages, wire screens, etc., afford additional protection largely in proportion as they approach complete metallic shielding. All electrostatic or Faraday cages should be free from spark gaps and should be adequately grounded in enough points to prevent heavy electric currents.

Lightning rods, properly spaced, offer a large, if not a complete degree of protection against direct strokes of lightning. They do not, however, offer protection from sparks caused by electrostatic induction or electromagnetic induction.

A lightning rod will generally afford protection from a direct stroke within a circle (cone of protection) whose radius is two to four times the height of the rod above the roof of the tank. This ratio will vary somewhat with the height of the rod above the roof of the tank and with the height of the cloud.

Rods should be spaced at least one-half of the rod length away from the tank, and a sufficient number should be used so that the entire tank is covered by their cones of protection. Rods should be thoroughly grounded and also connected to the tank.

Grounding wires shall be no smaller than No. 6 A. W. G. and be of noncorrodible, high-conductivity material, preferably copper.

Ground plates should be of noncorrodible material buried to a sufficient depth to insure contact with moist earth at all times.

All connectors intended to carry discharges should be free from loops and sharp bends and form as direct lines to grounded metal as possible.

### 314. Flame Arresters.

Flame arresters of any type should be such as have been proved by adequate investigation and test to be effective for the conditions under which they are installed and used.

For pipe larger than 4 inches (10 cm) in diameter the effectiveness of flame arresters employing screens on the Davy principle is questionable, and for larger pipes other means should be employed, such as arresters in the form of tubes, plates, and their equivalent so constructed as to present sufficient areas of metal surface to extinguish flames when interposed in the tank space to be protected.

Flame arresters should be substantially incased and capable of withstanding the effects of cleaning and of flame and pressures without material distortion or injury.

Where screens are used they should be in duplicate and should be made of noncorrodible wire with a mesh of about 40 per inch (16 per cm). They should be protected so far as possible from mechanical injury.

## Appendix A.—LIGHTNING; ITS ORIGIN, CHARACTERISTICS, AND EFFECTS

The term "lightning" is applied to certain types of heavy electrical discharges in the atmosphere. Within a comparatively recent period its meaning was extended to include a variety of overvoltage phenomena arising in the operation of electric circuits, but owing to the resulting confusion this use of the term is no longer considered desirable. The following discussion will be confined to atmospheric electric discharges, chief attention being given to the kind known as "streak" lightning or, to use a less scientific term, "chain" lightning, as it is this that causes damage and injury.

The necessity for protection against lightning was recognized during the earlier periods of recorded history. The devices and methods then used, however, were characteristic of the times. They consisted chiefly in exorcisms by the priesthood, the wearing of holy charms, the ringing of church bells that had been especially dedicated to the purpose, and the torture and burning of persons suspected of witchcraft. The latter were believed to be able to summon storms at will by reason of their being in league with demons and evil spirits.[1] The origin of such beliefs was in the abyss of superstition and fear which formerly engulfed almost

[1] J. C. Shedd, Proc. Colo. Sci. Soc., 8, p. 387; 1907.

the entire human race and from which a considerable portion has not yet emerged.

Deliverance in this particular from the thralldom of imaginary demons, witches, and angry gods came during the period 1749–1752 with the invention by Benjamin Franklin of the lightning conductor, and his proof by means of his kite experiments of the identity of lightning with the electric spark. This work of Franklin marks one of the definite points of departure from a line of reasoning which ascribed all natural phenomena to capricious supernatural intervention and gave an impetus to logical inquiry into the laws of nature. Such inquiry, however, has progressed but slowly with respect to lightning flashes, only a few roughly quantitative measurements having been made, and these in very recent times. Nevertheless, the results now available enable us to estimate the magnitude of the quantities involved, and much has been gained from laboratory and field work in protection of property. It is the purpose here to summarize the existing information and attempt to distinguish between what is known and what is purely speculative.

### Sources of Lightning.

The chief source of lightning is the familiar summer thunderstorm, which derives its name from the sounds resulting from its electrical discharges. Lightning has also been observed in the dust, steam, and gas clouds arising from volcanoes in eruption, in the dust clouds of deserts, and in clear skies, probably from charged bodies of air which drifted near each other or near the earth. In addition, there are silent luminous discharges within cloud layers and haze which have been observed at all times of the year, especially in regions where thunderstorms are scarce.

## TYPES OF LIGHTNING

The most familiar type is streak lightning. Variations of this, but not distinct types in themselves, are ribbon, rocket, and bead lightning, and also forked and zigzag lightning. Other types more rarely observed than streak lightning are ball or globular lightning and sheet lightning.

### Streak Lightning.

Streak lightning exhibits a white or pink path of comparatively small diameter, from an inch to a foot apparently, and of a length which may be from a fraction of a mile to several miles, depending upon the conditions of the discharge. The path in many cases is sinuous and forked with extensive ramifications, while in others it appears as a single streak, the ramified forks being absent or invisible. The streak lightning of a thunderstorm may occur within a cloud, between separate clouds, between clouds and earth, or between a cloud and surrounding air. It is invariably accompanied by thunder of greater or less intensity. In the majority of cases its duration is very short, although there is a wide variation in the duration and intensity of streak-lightning flashes, which is discussed in greater detail later.

### Ribbon Lightning.

Occasionally a flash of streak lightning appears as a number of more or less distinct parallel streaks, to which the name "ribbon lightning" has been given by reason of its appearance. What seems to be a satisfactory explanation is given by photographs of lightning flashes. It has been shown that most streak discharges consist of several successive discharges, which have appreciable time intervals between them. It has also been shown that in the intervals between discharges the path may be shifted by the wind through considerable distances. Thus, several successive discharges displaced in space may, on account of persistence of vision, appear as parallel streaks.

### Rocket Lightning.

The term "rocket lightning" has been applied to streak discharges occasionally seen, the growth of which is so slow as to appear like a rocket. It may occur between clouds and earth, within clouds, or between clouds and surrounding air. In one case at least it has been observed between clouds and upper atmosphere.[2] It has been explained as the discharge, under certain conditions, of a positively charged cloud.[3]

### Bead Lightning.

In this the path of the discharge appears as a string of luminous globes or beads, separated by darker intervals. It is rarely observed, especially in pronounced form. Several explanations of this phenomenon have been offered. One is that it is due to variations of the path of the discharge with respect to the line of sight. Another that striæ of haze obscure portions of the path. A third is that it is a combination of streak and globe lightning.[4]

### Forked Lightning.

This refers to the branching of the streak discharge at its lower end in some cases, which results in its striking two or more objects at the same time. Thus two trees, or a tree and a house, some distance apart, may be damaged by the same stroke.

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[2] Nature, **68**, p. 599; 1903.

[3] G. C. Simpson, Proc. Royal Soc., **111**, p. 56; 1926.

[4] Sci. Amer., **106**, p. 587; 1912. Humphreys, Physics of the Air, p. 351.

## Zigzag Lightning.

This refers to streak discharges which assume an extremely sinuous path. In some cases, because of the relation of the line of sight to the path, it appears to describe a loop. Such discharges present altogether different appearances from different points of observation.

## Globular Lightning.

The term "globular lightning" is applied to the second distinct type which consists of the luminous globes, or globular-shaped masses, sometimes seen during thunderstorms to move along the ground, about objects resting on the ground, or through the air, in a manner quite inexplicable to the observer. These globes seem in some cases to explode with a loud noise and cause serious damage. They are held by some to be an optical illusion arising from persistence of vision which causes one to see a ball of fire in any position toward which the eye is directed after a particularly brilliant flash of streak lightning. This explanation can hardly be accepted, however, in view of a number of observations where persistence of vision did not seem to be a factor. It is now conceded that globular lightning, or something resembling it, actually exists on rare occasions. Dr. Walther Brand, of Marburg, Germany, has assembled 600 accounts of ball lightning, of which 215 are sufficiently detailed and accurate to be worthy of study. From these he has summarized the characteristics of this singular phenomenon but does not attempt to explain it. It is thought to be a more than ordinarily brilliant brush discharge moving along a path of low dielectric strength in the storm's electric field, probably immediately preceding

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or following streak lightning, which would account for the apparent explosions. It is now known that the electric fields of thunderstorms are of sufficient strength to cause such discharges, especially beneath the center of greatest electrical activity [5]

Sheet Lightning.

The proper application of this term is to the silent discharges occasionally observed in clouds and haze, which constitute a third distinct type of lightning. These discharges appear to be somewhat similar to the brush discharge of the laboratory but are of white color usually, and on a vast scale. In some cases great areas of the sky glow momentarily, and sometimes intermittently, with sufficient brightness to arrest the attention. The proper application of the term is significant, because the discharge appears to occur as a sheet, although actually it is most likely a volume effect. It is distinguished from the aurora by the fact that it takes place in the cloud layers, whereas the aurora is observed only in the rarefied upper atmosphere where clouds do not form. The phenomenon may be observed at times in winter on cloudy nights. It also occurs at other times of year, especially in regions where streak lightning is rare, and occasionally in the wake of cyclonic thunderstorms.

The term "sheet lightning," or, more popularly, "heat lightning," is erroneously applied to the illumination arising from streak lightning, the source of which is invisible on account of cloud banks, or being below the horizon, and so distant that the thunder either can not be heard or comes too late to be associated in the mind of the observer with the

[5] H. Norinder, Electric Thunderstorm Researches: Elect. World, **83**, p. 223; 1924.

illumination. Sheet lightning is readily distinguished from the illumination of streak lightning by its persistence and its relatively slow variation of intensity.

Nothing beyond speculation is offered to account for glow discharges in clouds, but possible causes are these: (1) The agglomeration of charged vapor particles to form water drops by which means the potential of the drops is raised to a point where a coronal discharge occurs to the surrounding air. (2) The changing of charged vapor particles to snow crystals or ice particles which increases potential due to agglomeration and at the same time produces shapes which facilitate discharge. (3) The drifting of charged masses of vapor or ice particles from regions where the potential is high to regions where the potential is lower. The charge in the case of glow discharges is most likely negative, because, as indicated by Simpson (*l. c.*), discharges from negatively charged clouds are likely to be of this character.

### St. Elmo's Fire.

This consists of silent discharges at the surface of the earth which appear as blue flamelike brushes at the tips of various pointed objects. It occurs most frequently in dry regions on the approach of storms, and also on mountain tops, especially if it is cold and dry. It is not confined to these places, however, as it occurs at sea on the masts and rigging of ships. It is not to be regarded as a type of lightning, although it may attend lightning storms.

### Characteristics and Effects.

From the point of view of protective measures streak lightning is the only kind that needs consideration, since the others are rare in occurrence or harmless. Streak lightning, however, causes considerable damage and loss of life, especially in those regions where thunderstorms are frequent and severe. Its potentialities for damage are dependent upon the electrical characteristics which it has in common with electrical discharges produced in the laboratory—viz, current, voltage, and time—and their combination in power to cause explosion and energy to cause heat. Of these factors the maximum current and its duration determine its fusing or igniting effects, while the steepness of the wave front determines the extent of its secondary or induced effects. The voltage gradient very largely determines the extent of its effects on electric-power transmission and communication circuits. Of less importance from the point of view of protection, but nevertheless of considerable interest, are the following: The magnitude of the total voltage involved, whether the discharge is oscillatory or damped to such an extent as to make it a single impulse, and the cause of the noise and light. These characteristics are discussed here under the following headings: Source of static charge, voltage, energy, maximum current, wave front and duration, induced effects, thunder, illumination, character of damage, effects on persons, and thunderstorm data.

## SOURCE OF STATIC CHARGE

The work of G. C. Simpson [6] at the Meteorological Office of the Government of India, Simla, gave results which form a basis for an explanation in part at least of the mechanism by which the separation of electric charges in thunderstorms is produced. Two lines of research were adopted: (1) A

[6] Trans. Royal Soc., **209**, p. 279; 1909.

systematic record was obtained by means of self-registering instruments of the electricity brought down by the rain throughout one rainy season; (2) laboratory experiments were made with the object of determining the source of the electricity of thunderstorms.

The chief results of the first part of the work may be briefly summarized as follows: The aggregate amount of rain which fell during the periods of rainfall investigated was 30.04 inches (76.3 cm). The total quantity of positive electricity which fell on each square centimeter of surface was 22.3 electrostatic units, and of negative electricity 7.6 units; thus 75 per cent of the electricity brought down by the rain was positive. During 71 per cent of the time that charged rain fell the charge was positive. Considering that falling rain carrying a positive charge is equivalent to a positive current and rain carrying a negative charge to a negative current, then positive currents greater than $300 \times 10^{-15}$ ampere per square centimeter were measured in six storms and negative currents of greater than $300 \times 10^{-15}$ ampere per square centimeter in two storms.

In seven storms it was found that the rain carried positive charges greater than six electrostatic units per cubic centimeter of water, and in two storms negative charges greater than this amount were recorded. The heavier the rainfall the more the positively charged rain preponderated over the negatively charged rain, and all rainfall having a greater rate than a millimeter in two minutes was positively charged. Light rain was more highly charged than heavy rain. The proportion of negative electricity brought down by the rain was slightly greater in the second than in the first half of the storm. The potential gradient was more often negative[7] than positive during rain. No relationship between the sign of the potential gradient and the sign of the electricity of the rain could be detected.

The laboratory experiments showed that when a large drop of water is broken up into small drops in air the water becomes positively and the air negatively charged. In the first series of experiments drops of water having a volume of 0.24 cc fell on a vertical jet of air which broke them up into smaller drops. Under these circumstances the water of each drop, after having been broken up on the jet, carried a charge of $5.2 \times 10^{-3}$ electrostatic unit of positive electricity. Further, the presence of an original charge on the drops did not alter the effect. Drops originally charged positively had their charges increased, and drops charged negatively had their charges decreased.

In the second series of experiments water was introduced through two small tubes into a vertical current of air which carried the water upward. Part of that which escaped from the air current was caught in an insulated vessel and was found to be positively charged, the charge being $15 \times 10^{-3}$ electrostatic units per cubic centimeter of water.

In the third series of experiments drops of water were broken up in a manner similar to that employed in the first series, but within a compartment from which the air could be drawn through an Ebert apparatus. It was shown that the breaking up of the drops caused an ionization of the

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[7] Negative potential gradient in the atmosphere exists when the potential of a point decreases with increasing vertical distance from the earth, as would be the case with a negatively charged cloud and a positive charge on the earth beneath. Positive potential gradient is found under the opposite condition of a positive cloud and a corresponding negative charge on the earth.

air. The breaking of each drop released $3.3\times10^{-3}$ electrostatic unit of free negative ions and $1.1\times10^{-3}$ electrostatic unit of free positive ions. The excess of negative ions, or $2.2\times10^{-3}$ electrostatic unit, corresponds to the positive charge retained by the water. The discrepancy between $2.2\times10^{-3}$ and $5.2\times10^{-3}$ as given previously is accounted for by the author by the fact that parts of the ions were discharged to the walls of the Ebert apparatus.

In 1904 Professor Lenard[8] proved that drops of water which have a diameter greater than 5.5 mm are unstable when falling through air and rapidly break up into smaller drops. He also proved that the final velocity of any drop which has a diameter less than 5.5 mm does not exceed 8 m per second when falling through still air of normal density. Thus, no water can fall through an ascending current of air of normal density which has a velocity of 8 m per second or more, for all drops less than 5.5 mm in diameter are carried upward, and all drops of larger diameter are quickly broken up into smaller drops. These facts, together with the results of the observations and experiments described above, have led to the formation of the following theory for the origin of the electrical separation of thunderstorms.

It is probable that in all thunderstorms there are upward currents of velocities greater than 8 m per second. Such currents support large amounts of water which can not fall through the ascending air. Hence, as the top of the vertical air current is approached where its upward velocity greatly decreases due to the lateral outflow, there will be an accumulation of water in the form of drops which are continually going through the process of growing from small drops into

[8] Meteor. Zeit., **21**, p. 249; 1904.

drops large enough to be broken. Each time a drop breaks a separation of electricity takes place, the water receiving a positive charge and the air a corresponding negative charge. The moving air carries away the negative ions but leaves the positively charged water behind.

A given mass of water may be broken up many times before it finally falls to the ground and, consequently, may obtain a high positive charge. When it finally reaches the ground it is recognized as positively charged rain. The ions which travel with the moving air are rapidly absorbed by the cloud particles in the upper part of the cloud, and in time this would become highly charged with negative electricity. Now, within a highly electrified cloud there may be combination of the water drops and from it considerable rain may fall at certain stages of the storm. This rain will be negatively charged, and under suitable conditions both the charges on the rain and the rate of rainfall could be large.

A rough quantitative analysis shows that the order of magnitude of the electric charges produced by the breaking of a drop of water is sufficient to account for the electrical effects observed in the most violent thunderstorms. All of the results of the observations of the electricity of rain described above are capable of explanation by the theory, which also agrees well with the actual meteorological phenomena and is quite generally accepted. It is thought by some that, while precipitation is the primary cause of the separation of electricity, the action, instead of being due to separation into parts of water drops, is similar to that of the influence machine.[9]

[9] Elster and Geitel, Wied. Ann., **25**, p. 116; 1885. Physikal Zeit., **14**, p. 1287; 1913. Geitel, Physikal. Zeit., **17**, p. 455; 1916.

Electrification of clouds, however, has been observed where vertical convection and rapid condensation did not occur. According to Simpson [10] these phenomena can be accounted for by an extension of his theory. It has been shown that electrification can be produced by the separation of almost any substance. Thus, in duststorms and snowstorms separation takes place by collision and abrasion between particles in much the same way as in the breaking of water drops, which leads to electrification, with the attendant phenomena. It is rare that electrification of this type produces lightning, because separation of charges does not occur, although it may occur in the case of a snowstorm accompanied by soft hail, because the hailstones acquire a high charge in their downward course by collision with snowflakes and take their charges with them to the ground.

## VOLTAGE

The voltage of lightning discharges—that is, the difference in potential between the points marking the extreme ends of the path of the discharge immediately preceding its occurrence—has long been a matter of conjecture. The nearest approximation so far made to the voltage of a lightning flash places it at about 100,000 volts per foot. This value was obtained by comparing the induced voltage on a model transmission line, where the total voltage was known to be 2,000,000, with induced voltages from lightning measured on an actual transmission line.[11] Other experiments indicate that at the most intense part of the electric field of a thunder-

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[10] Nature (London), **112**, pp. 727–728; 1923.

[11] F. W. Peek, jr., High-Voltage Phenomena: J. Franklin Inst., **197**, p. **1**; **1924**.

storm the electric intensity approaches the limiting value at which coronal discharges begin.[12] Hence, it appears that for a discharge a mile in length the potential difference at the beginning of the discharge is of the order of $5 \times 10^8$ volts.

A comprehensive series of measurements of the changes in potential gradient near the surface of the earth has been made by C. T. R. Wilson.[13] During the years 1914, 1915, and 1917 records were obtained during 864 discharges. The discharge was between negative cloud and positive earth in 528 of these, or at least of a kind to cause a change in potential gradient at the instrument of the same nature. This predominance of discharges with the cloud negative appears not to be in accord with the observations of Simpson, who found the cloud usually positive, but the latter drew his conclusions from photographs of flashes to earth, while in Wilson's case flashes from cloud to cloud were included.

From the magnitude of the change in potential gradient, and the distance between instrument and path of discharge, it was estimated that the average value for the quantity of electricity involved was 20 coulombs. (A change of about 15,000 volts per meter was observed at a distance of 5 km.) If this amount of charge is distributed through a spherical mass of cloud with a radius of 250 meters it would produce an electric field of nearly 30,000 volts per cm at its surface and would have a potential of about $10^9$ volts. This electric field is the limiting value at which air breaks down when the field is uniform, and it will break down at lower values where

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[12] H. Norinder, Electric Thunderstorm Field Researches: Elect. World, **83**, p. 223; 1924.

[13] Proc. Royal Soc. of London, **92**, p. 555; 1916. Phil. Trans. of Royal Soc., **221**, p. 73; 1920.

the field is nonuniform, as near surfaces having curves of short radius.

If a voltage of this value produces a discharge over a path 2 km long, the average gradient is much less than the above critical value. It does not seem necessary for the gradient to equal the critical value over the entire path for a discharge to start. Starting at the point of intense field local breakdown causes a readjustment of the field, which leads to progressive breakdown along the entire path.

In Norinder's observations gradients as large as 100,000 volts per meter were recorded at points closer to the discharge.

## ENERGY

The total energy dissipated by a flash of lightning may be roughly estimated in various ways. An estimate by Peek from his measurements of lightning voltages places the energy at $1.3 \times 10^7$ watt-seconds.

Another estimate has been made by Wilson in connection with the work mentioned in the preceding section, where the quantity of electricity discharged by a lightning flash was found to be 20 coulombs and the voltages $10^9$, which gives for the energy $10^{10}$ watt-seconds, or nearly one thousand times as much as that estimated by Peek.

The discrepancy between these two estimates may in part be attributed to the fact that most lightning flashes consist of several separate discharges along the same path, usually 1 to 10, and in one instance at least as many as 40. The estimate based on the voltage would take account only of a single discharge, and thus the $10^7$ watt-seconds found in this manner should, perhaps, be multiplied by the number of separate discharges that constitute the entire flash or else a larger cloud area considered.[14]

On the other hand, the estimate based on the quantity of electricity takes account of the total change of electrical condition, but, as pointed out heretofore, $10^9$ volts may be too high, in which case the energy would be less. It seems not unreasonable to take $10^8$ to $10^9$ watt-seconds as the order of magnitude of the energy of a lightning flash.

It is interesting to note that where lightning flashes occur at intervals of one second or less, as they may in severe cyclonic thunderstorms which cover a large area, an energy dissipation of $10^9$ watt-seconds for each flash means that the power being dissipated is around 1,000,000 kilowatts. This is an impressive value, and the question may be raised as to the source of the energy. The most probable source is the vertical convection, the gravitational process so pronounced during the thunderstorm, which results in excessive condensation accompanied by electrical separation. An idea of the power involved can be gained from a consideration of the rainfall.

In a heavy storm a rainfall at a rate of 10 cm per hour is not unusual, and at this rate the power derived from the falling water, taking the height of fall as 1 km, would be $3\times10^{15}$ ergs per second per $km^2$, or 1,000,000 kw for about 3 $km^2$. Thus, a rainfall of the foregoing amount over an area of 3 $km^2$ would involve sufficient power to produce a flash per second. The total power available for the production of lightning flashes may obviously greatly exceed the estimate based on the rainfall.

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[14] Trans. Roy. Soc., **221**, p. 73; 1920–21.

## MAXIMUM CURRENT

What appears to be the first work on current intensities of lightning flashes was done by F. Pockels,[15] who made use in his measurements of some of the peculiar magnetic properties of basalt, and at the same time assumed that lightning discharges are unidirectional. In the course of some laboratory experiments Pockels found that for unidirectional magnetic fields the residual magnetism of prisms of nepheline basalt depended neither on the duration nor the time variation of the field, but only on its maximum value. Basalt consists of crystals of magnetite distributed through a badly conducting mineral medium, and it is upon this formation that its peculiar magnetic property depends, there being no eddy currents set up in it by a varying magnetic field which would retard the magnetization of the specimen. A magnetic field lasting only about one-millionth of a second showed the same residual and probably also the same temporary magnetization as was induced by a field kept up indefinitely at the same strength. This being the case, the residual magnetization of the basalt might be taken as a measure of the maximum magnetic field to which it had been subjected and, consequently, to the maximum value of the magnetizing current.

In order to test the method, Pockels discharged condensers of known capacities which had been charged to known differences of potential through magnetizing circuits of known resistance and self-induction, the constants of the circuit having been chosen to give a highly damped discharge. He then calculated the maximum value of the current by means

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[15] Ann. Phys. Chem., **63**, p. 195, 1897; Ann. Phys. Chem., **65**, pt. 2, p. 458, 1898; Phys. Zeit., **2**, p. 306, 1900.

of the constants of the circuit and compared them with the values determined from the residual magnetization. The resistance of the spark gap was neglected in making these calculations, but the results agreed very well in the two cases.

The results of these experiments were made use of by Pockels in making an approximate determination of the current intensity of lightning flashes, assuming, as previously stated, that the discharge in a flash of lightning is unidirectional. The first measurements were made on specimens cut from outcroppings of basalt rock which showed irregular and local magnetization which could only be due to lightning flashes. Knowing the strength of the field necessary to produce the residual magnetism shown by the specimens, only the distance to the path of the flash was necessary to make a rough determination of the current. This distance was in some cases assumed to be the distance to the surface of the rock; in others a damaged tree was assumed to give the necessary evidence. One estimate made by assuming the distance to the flash to be the distance to the surface of the rock led to a minimum of 2,900 amperes as the current intensity; three others, on specimens obtained from the vicinity of damaged trees, gave 6,400, 6,600, and 10,000 amperes, respectively. These values are probably too small, because of the period of time which elapsed between the time of the flash and the time of making the measurements and also because of the disturbance of the basalt in cutting it out.

Other observations were made on basalt prisms exposed in the vicinity of a branch of the lightning conductor on the observation tower on Mount Cimone, in the Appenines. One of the prisms which had been placed at a distance of

6.4 cm from the conductor and had been subjected once to the magnetizing effects of a lightning stroke gave $i=10,200$ amperes. A second prism, which had been subjected to the magnetizing effects of four strokes, gave $i=5,530$. A third prism was only slightly magnetic. There were two ground connections to the lightning conductor, so it is quite probable that the current divided symmetrically. The total currents in the two cases were, therefore, 20,000 and 11,000 amperes, respectively. These values are doubtless also too small, because the prisms were not examined until several months after having been exposed and were subjected to some vibration in the meantime.

Another method of arriving at an estimate of the current intensity of a lightning flash is to calculate it from the total quantity of electricity discharged as found by Wilson and make assumptions as to the duration and number of discharges per flash. The quantity may be taken as 20 coulombs, the number of discharges per flash about five, and the duration of each discharge about 0.000028 second. The latter value is based on experimental evidence that many lightning flashes are less than 0.000028 second in duration. The quantity for each discharge would then be 4 coulombs, and the current 4/0.000028, or 142,000 amperes. This is seven times as great as by the previous method.

A third estimate has been made from the fusing effect of a lightning flash on metal.[16] In this case the metal was in the form of a copper tube with a brazed seam which constituted part of a lightning-rod terminal. The terminal was struck and heated to a sufficient temperature to volatilize some of the solder used in brazing and make the copper plas-

[16] Crushing of a Copper Tube by Lightning. W. J. Humphreys, Monthly Weather Review, 43, p. 396; 1915.

tic enough to collapse throughout its length of 5 feet under the pinch effect of the current. The temperature rise is estimated to be about 1,025° C. The average resistance of the tube for the estimated temperature range was found to be 17 microhms per cm. and the weight 2.9 g per cm. To bring 2.9 g of copper to 1,025° C. requires about 327 g-calories. The duration of the flash was assumed to be 0.01 second, much greater than in the previous paragraph, but this seems to be justified by the fact that the fusing effects were uncommonly severe. Moreover, the entire flash, perhaps consisting of as many as 40 separate discharges, is considered,[17] which would introduce a considerable factor to increase the time as compared with a single discharge.

From the preceding values for temperature, resistivity, and time it is found that

$$I=\sqrt{H/0.2389\,R\,t}=\sqrt{327/0.2389\times 17\times 10^{-6}\times 0.01}=$$

90,000 amperes, approximately. The pinch effect of such a current on the tube is calculated to be 400 lbs./in.$^2$ (28 kg/cm$^2$). If the discharge were unidirectional, the quantity of electricity would be $90{,}000\times 0.01=900$ coulombs, which is eighteen times the greatest observed by Wilson.

The foregoing values for the maximum current of lightning flashes differ widely, as might be expected where deductions are made from such meager data; but they are the best available at this time and, if they show anything, indicate that the maximum current ranges from thousands of amperes to tens of thousands. That such a wide variation exists is suggested by visual observation. In dry air, or in advance of a thunderstorm, lightning usually presents a

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[17] Alex. Larson, Photographing Lightning with a Moving Camera: Ann. Rept. of Smithsonian Inst., 1905.

thin blue appearance, while where the rainfall is heavy it presents a fat, white or pink appearance, which is most likely due to difference in current intensity and diameter of path, the rainfall seeming greatly to facilitate discharge.

Corroborative evidence of the magnitude of the currents of lightning flashes is found in recent laboratory experiments with artificial-lightning discharges which produce effects similar to those in nature. Here currents of 10,000 amperes at 2,000,000 volts have been attained.[18]

### WAVE FRONT AND DURATION

The well-known flickering of lightning flashes, which is visible to the unaided eye, indicates that a flash of lightning does not always consist of a single discharge of electricity, but, on the contrary, consists in many cases of a number of successive discharges which follow each other with very short-time intervals between them. By standing where the light from a flash does not blind the eyes, an observer can detect the successive discharges for each complete flash of lightning, the number of which varies, for different flashes, from 2 or 3 to 10 or more. By means of swinging or rotating cameras photographs have been made which show separately the constituent parts of a flash in so far as they can be shown by taking impressions on a photographic plate moving at rather a slow speed. From these photographs have been calculated the total duration of the flash for a number of cases and also the intervals of time between the successive discharges. Moreover, by visual means using

[18] F. W. Peek, jr., High-Voltage Phenomena: J. Franklin Inst., 197, p. 1, 1924.

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rotating disks, and other apparatus, the duration of the constituent parts of the flash have been estimated.

The first photographic evidence of the multiple character of lightning flashes was obtained by Kayser [19] and Rümcker, each using a stationary camera, the path of the flash being shifted by the wind. The durations of the flashes were estimated from these photographs, but, owing to the fact that the velocity of the wind was not known accurately in either case, the results are not to be relied upon. These photographs are of importance, however, from the fact that they show the distance through which the path of a lightning flash may be shifted by the wind while the successive discharges are taking place.

A few years after Kayser's and Rümcker's photographs of lightning were taken L. Weber [20] showed that it was possible to make a time analysis of any lightning flash by moving the camera while the exposure was being made, thus spreading the image of the flash over the plate and separating it into its constituent parts. The best work on photographic time analysis of lightning flashes has probably been done by B. Walter.[21] Walter succeeded in analyzing the sparks from an induction coil by means of a moving film and at once saw that the method would be applicable to the analysis of lightning flashes. For this purpose he mounted his camera on a fixed axis around which it was made to rotate by clockwork at a uniform rate. With this apparatus Walter took a number of photographs of lightning flashes and determined the total duration of the flashes and also the intervals of time between the successive discharges.

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[19] Berichte der Königl. Akad. Berlin, p. 611 : 1884.
[20] Berichte der Königl. Akad., Berlin, p. 781; 1889.
[21] Annalen der Physik, **10**, p. 393; 1903.

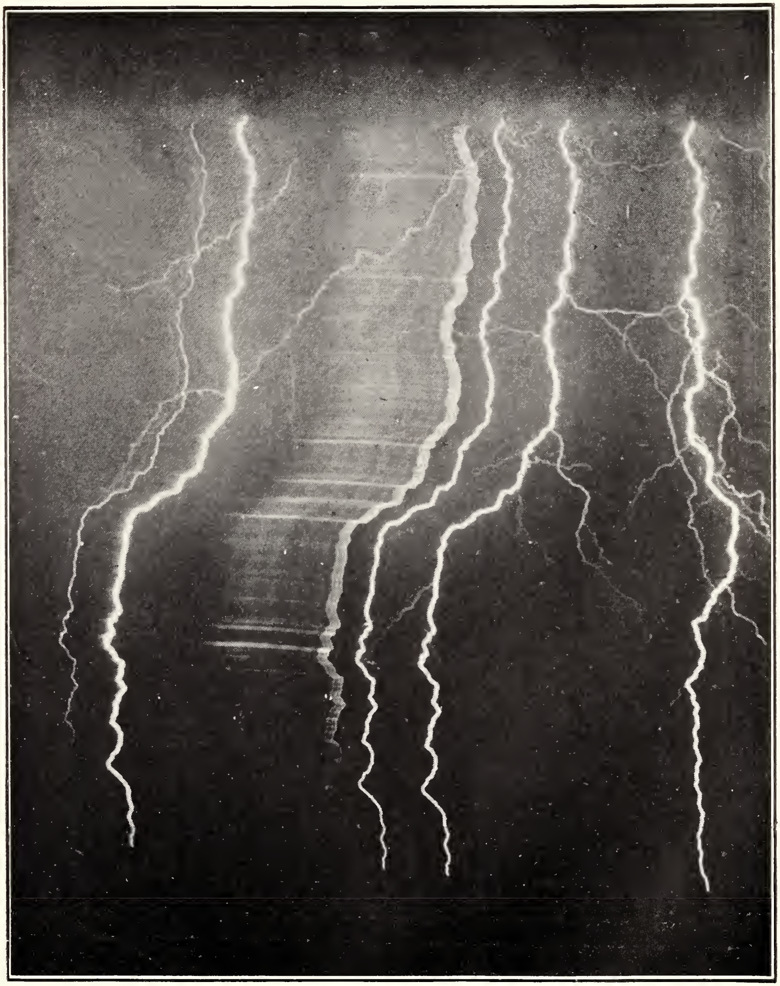

FIG. 1.—*Photograph of a lightning flash taken with a moving camera by Doctor Walter*

Fig. 2.—*Same lightning flash as in Figure 1, taken with a stationary camera*

In the case of a flash consisting of five successive discharges the total time was found to be 0.2447 second, while the successive discharges were at intervals of 0.0360, 0.0364, 0.0283, and 0.1440 second, respectively. These are fairly representative of the total duration and time intervals of the flashes of which photographs were taken. The durations and intervals are variable, however, and range for different flashes from near zero to 0.6 second or more for the duration, depending apparently on the number of successive discharges in a flash, and from near zero to 0.2 or 0.3 second for the intervals. A photograph taken by Larsen [22] with a rotating camera shows 40 distinct discharges in a single flash, the duration being 0.624 second and the average interval 0.0156 second. The intervals between the successive discharges varied from 0.0026 to 0.0520 second. This flash is exceptional because of the large number of successive discharges which occurred.

Figure 1 is a reproduction of a photograph from the collection of B. Walter, which shows in a marked way the general character of a lightning flash. Beginning at the right, the first complete discharge is shown in a nearly vertical position. The succeeding discharges branched off from the original path part way down, as may be seen by tracing the similar kinks in the different images for a short distance from the top. The remaining discharges all followed the same path, but changed markedly in character, the fourth from the right being apparently a unidirectional discharge along a thoroughly ionized path lasting a considerable time. When the cloud is exhausted by this continuous discharge a short cessation occurs, after which there is a final discharge

[22] **Photographing Lightning with a Moving Camera**: Ann. Report of Smithsonian Inst., p. 119; 1905.

usually much weaker than the first discharges. These phenomena are more or less clearly shown by the reproduction given in Figure 1. Many variations from this procedure may occur, but, in general, a flash of lightning is made up of the constituent discharges just described.

The characteristics of the constituent discharges of a flash of lightning are of great interest in connection with the design of lightning protection. The duration of these constituent discharges has been studied by K. E. F. Schmidt[23] using a rotating disk having marked upon it a white cross which was observed by the light of lightning flashes. This work confirmed that of Walter, showing that the constituents of a lightning flash vary greatly with different flashes of lightning. The most important conclusion, however, was that for the most part the duration of the constituent discharges of a flash is 0.00003 second or less. A number were observed in which the duration was greater, but these were few. This establishes, in some degree at least, the upper limit of the duration of a lightning discharge; that is, the path must be formed and the current grow to a maximum and die out in less than 0.00003 second. This suggests also something as to the steepness of the current wave front. If the maximum current reaches 100,000 amperes, as seems possible from previous discussion, the average rate of increase is $7 \times 10^9$ amperes per second, assuming that the current reaches its maximum in one-half the duration. It is obvious that any circuit connected inductively to the path is in a way to have a considerable e. m. f. set up in it, even though the mutual inductance is very small.

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[23] Elektrotech. Zeit., 26, p. 903; 1905.

The duration of lightning flashes has been studied by others [24] and somewhat similar results obtained, although in many cases longer durations were observed.

In connection with the wave front of the constituent discharges it is interesting to note that these are now considered to be unidirectional rather than alternating. From considerations of the discharge path they may be of an oscillatory character but highly overdamped, so the discharge represents the beginning of an oscillation which dies out before the first quarter wave is completed, the current dropping to zero without reversing.[25] On account of the steep wave front, however, oscillations with reversal of current may be set up in near-by metallic circuits.

In a paper by G. C. Simpson [26] a theory of the formation and extension of lightning flashes is advanced which is based upon the relative mobilities of positive ions and negative electrons. The theory is tested by laboratory experiments on a small scale and examination of a large number of photographs of lightning. The chief conclusions advanced are as follows:

1. The conducting channel of a lightning flash originates in the region of maximum electric field and develops only in the direction of the seat of negative electricity.

2. A negatively charged cloud can only be discharged by a discharge which originates in a positively charged cloud or in the induced positive charge on the earth's surface.

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[24] De Blois, Proc. A. I. E. E., **33**, p. 563; 1914.
[25] Steinmetz, Trans. A. I. E. E., **43**, p. 126; 1924.
[26] Proc. Roy. Soc., **111**, p. 56; 1926.

3. A positively charged cloud may be discharged by discharges starting in the cloud and terminating either in the surrounding atmosphere or on the earth's surface.

4. If a lightning flash is branched, the branches are always directed toward the seat of negative electricity.

5. The application of these conclusions to 442 photographs of lightning discharges reveals the fact that the preponderance of the lower clouds from which lightning discharges proceed are positively charged.

In a paper by N. Ernest Dorsey [27] a second theory is given for the formation and progress of a lightning flash which differs materially from Simpson's. It is based upon some peculiar lightning strokes, the effects of which indicate that the direction of a stroke is not dependent upon the direction of a preexistent field due to a charged cloud but is only initiated by such a field and progresses in a manner analogous to that of a beam of cathode rays. The path of the stroke is described as being formed by an elongated dart of flying negative electrons which originates in a region of intense electrostatic stress and acquires sufficient velocity to maintain itself in weaker fields, and as an extreme case to penetrate an adverse field, until it strikes some solid object, such as a tree, with a resulting explosion as the dart is suddenly impeded. Trailing electrons combine with positive residues to form the flash, and while the path remains highly ionized the cloud may be partly discharged with a heavy flow of current.

An experiment by C. V. Boys in photographing a flash of lightning with a special camera having a pair of separated lenses revolving in a circle before a stationary plate has led

[27] J. Frank. Inst., 201, p. 485; 1926.

him, after stereoscopic examination of the images, to the conclusion that a lightning flash originates at both positive and negative ends nearly, if not quite, simultaneously.

It should be noted that Simpson's theory of formation of a lightning flash requires that it originate at the seat of positive electricity. Dorsey's requires that it originate at the seat of negative electricity, while the photograph of Boys's indicates that it originates at both ends and meets midway. This diversity indicates the speculative character of much of the discussion of lightning beyond the results of actual measurements.

## INDUCED EFFECTS

The induced effects of lightning discharges are of serious consequences in some cases and may be due to either electromagnetic induction, electrostatic induction, or both, depending upon conditions. At a distance from the flash they consist of minor electrical discharges from insulated metallic bodies to earth or to near-by objects. They may be severe enough to cause fires, damage, or injury to persons. They are observed principally upon the approach of thunderstorms when everything is dry. Rainfall usually prevents them by reducing or destroying the insulation. Such discharges, in the form of sparks ranging in length from a small fraction of an inch to more than an inch, have been noted at distances of several miles from the apparent center of activity of the storm.

The magnitude of the potentials which may be attained by insulated bodies may be inferred from the values of change in potential gradient due to lightning flashes found by Wilson. In several cases changes amounting to 15,000 volts per meter (4,600 volts per foot) were observed as a consequence of flashes as much as 3 miles away. A wire clothesline supported in such a field on dry wooden posts 2 m (6.56 feet) high would have accumulated on it a charge such that immediately following the flash its potential to ground would be around 30,000 volts. A person touching it at that instant would act as a discharge path and, if the capacity were considerable, would be severely shocked. Shocks from this cause have been received not only from insulated wire clotheslines, but also from wire fences, down spouts, and other objects. A metallic object which is grounded would, of course, show no effect other than a current discharge through the ground connection.

In the immediate vicinity of a flash the induced effects become more severe and appear as sideflashes and oscillatory disturbances in metallic circuits, the effects of which may be comparable in many cases with the effects of the main stroke. Sideflashes or branch discharges from the main path have been observed to jump gaps of several feet, especially where there are metallic objects near by. Oscillatory disturbances may be set up in electric circuits of sufficient magnitude to break down even high-voltage insulation.

Lightning may cause voltages in conductors by induction or by a direct stroke. Although most disturbances on transmission lines due to lightning are caused by induction, the highest voltages are caused by direct hits. This follows, since inductive effects may be experienced at a considerable distance from the discharging cloud, while for a direct hit it is necessary for the cloud to be nearly overhead. Induction may be electrostatic or electromagnetic. In comparison with the electrostatic effect, electromagnetic induction by lightning is generally negligible.

A charged cloud causes an electrostatic field between it and earth. Part of the field will terminate on any transmission line within the field of influence of the cloud. The line is then said to have a "bound charge." This bound charge will have a sign opposite to that of the cloud, the charge of the same sign being driven off to earth by leakage over the insulation of the line or through the station equipment or to a distant portion of the line beyond the cloud's field. If the voltage between cloud and earth or cloud and cloud becomes high enough, a lightning flash will occur. Although this flash may be a mile away from the line, the charge on the line is released and the insulated line rises from earth potential to some higher value with polarity opposite to that of the cloud. The effect is that of a voltage suddenly applied between line and ground. The field that extended between line and cloud is succeeded by one between line and ground. The voltage wave travels over the line at the velocity of light. If the line insulators are strong enough or have a high enough impulse ratio, it may travel to the powerhouse to break down apparatus or to be harmlessly discharged to ground over the arrester if it has low resistance and low impulse ratio.

The voltage that the line assumes at the instant of a very sudden discharge is that of the equipotential surface at the height at which the line is located.

The induced lightning voltage on a transmission line thus varies with the height of the line. It is approximately equal to the height of the line times the voltage gradient, where the discharge is very rapid, as is usual in the case of lightning.

Thus $V=ga\ h=Gh$, where

$V$=induced volts,

$g$=actual gradient in volts per foot where line is located,

$a$=a factor less than unity,

$G=ga$ = apparent gradient.

$h$=height of the line in feet.

The exact value of $a$ depends upon the rate at which the clouds discharge. This is because in slowly discharging clouds the charge is dispersed over the line for a considerable distance before the cloud becomes completely discharged. The highest values are attained in the case of a direct stroke. Values of $G$ as high as 50 kv/ft. have been measured on transmission lines in practice. The actual gradient $g$ may be as high as 100 kv/ft., so that for rapid discharges and direct hits the induced voltage (in kilovolts) approaches the height of the line in feet multiplied by 100.[28]

As the disturbance gets well under way and half of the energy of the surge becomes electromagnetic, the voltage is reduced to half. Corona and $I^2R$ (resistance) losses draw upon the total energy as the surge travels on and the voltage is further reduced.

The induced voltage appears on the line as a direct voltage very rapidly applied or as a highly damped oscillation. There is thus usually simply a rapid rise (a steep front) to maximum voltage, then a more or less gradual tapering off or decrease in voltage (a long tail) to zero.

Due to probable variations in $a$, both the steepness and the magnitude of the surges occurring during any given storm will vary over a wide range, but the highest voltages

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[28] F. W. Peek, jr., The Effect of Transient Voltages on Transmission Lines: J. A. I. E. E., 43, p. 697; 1924.

(where $a$ approaches unity) are of necessity associated with the steepest fronts. Where protection is to be obtained, it must be secured from these steepest fronts. If protection from the steep-fronted surges is secured, there will be no cause for worry over the less steep ones. On overhead transmission lines the induced voltages may reach high values, 1,000 to 1,500 kv being frequently recorded. On extremely high-voltage lines these induced voltages may not be so troublesome, since the line insulation may be strong enough to prevent spark over by most of these voltages, but on lower voltage lines they may be very troublesome. Not only will a lightning spark over be most likely to damage the insulators, but it will also generally be followed by a power arc over which may complete the destruction. At any rate the power arc requires the tripping out of the circuit to extinguish the arc, causing an interruption in the continuity of service, the maintenance of which is constantly becoming of increased importance.

When a grounded conductor or ground wire is placed near the conductors of a transmission line it has a marked effect on the voltages due to lightning that appear on the line. The ground wire reduces the voltage in two ways: First, it reduces the number of lines of force terminating on the line conductors. This reduces the magnitude of the bound charge on the conductors and the total energy later to be released in the surge. In the second place, it increases the capacitance of the line conductor to earth, so that with a given quantity in the surge the voltage to which the line conductor is charged is less, from the equation $Q = CV$. As $C$ is increased $V$ is decreased for a given quantity $Q$.

It has been found experimentally [29] that one ground wire will reduce the induced voltage to approximately 50 per cent

[29] F. W. Peek, jr., J. Frank. Inst., 199, p. 141; 1925.

of its original value, two ground wires to approximately 33 per cent, and three ground wires to approximately 25 per cent, etc. There is also a protection against direct hits to the line conductor, since the ground wire is generally arranged above the line conductors to take the direct hits. The experimental values given above are in general agreement with the mathematical results and apply to wires provided with good grounds made with short grounding conductors at frequent intervals. Poor grounds, or grounds infrequently made, considerably reduce the theoretical or maximum efficiency to be obtained. Troubles with the ground wire in the past have often been due to poor mechanical design. The ground wire should have a life fully as long as the line conductors. They should be strung as near as possible to the line conductors and yet far enough away to prevent flash overs at times of high wind, heavy sleet loadings, etc.

The question whether protection from induced lightning voltages is or is not to be provided is an economic one. The protection to be secured by one, two, or three ground wires is to be balanced against the cost.

The induced effects of lightning are responsible for a large majority of fires occurring in oil tanks, reservoirs, and oil farms as a result of sparks produced in or about the tanks where escaping gases can be ignited. Warehouses containing baled hay and cotton have also been fired by induced-voltage sparks between the baling wires, which ignite the combustible material.

## THUNDER

It is now thought that the sound of thunder is caused largely, if not entirely, by a sudden increase of pressure due to heating, dissociation, and ionization along the path of a lightning stroke. As stated heretofore, the energy of a stroke may amount to $10^8$ or $10^9$ watt-seconds, of which the greater portion is expended in heating the air. If the path is assumed to be a foot in diameter and a mile long, $10^8$ watt-seconds would heat it to about 650° C., with an increase of pressure of about 2 atmospheres. The dissociation would add to this by increasing the number of gas molecules. This increase of pressure, which may in reality be much greater than 2 atmospheres, takes place very abruptly and is sufficient to account for the ear-splitting crash which accompanies a near-by flash of lightning.

The intensity of different claps of thunder is as variable as the current of lightning flashes, near-by strokes of lightning having been observed with no thunder audible to the observer. One such occasion is recorded in connection with the Washington Monument when, on April 5, 1885, during the passage of a heavy thundercloud, at least five immense sparks or bolts were seen within a period of 20 minutes to flash between the terminal and cloud, without audible sound.[30] On other occasions disruptive discharges were observed, accompanied by thunder.

One of the chief characteristics of thunder, especially at a distance, is the prolonged rumbling produced, sometimes interspersed with tremendous bumping sounds that apparently carry a great deal of energy, enough to rattle windows and cause buildings to tremble. The rumbling arises chiefly from the fact that the source of the sound is long and irregular and different parts of it are at different distances from

[30] Report of engineer officer in charge of public buildings and grounds, Washington, D. C.; 1885.

the observer, and from echoes and reflections. The crashing noise heard near at hand is smoothed out until at a distance of a few miles a rolling sound is produced. The bumping sounds just mentioned may arise from some particularly favorable condition of reflection or from direct transmission of sound from some portion of the path. A succession of bumps may arise from several successive discharges.

The distance to which thunder can be heard ordinarily does not exceed 15 miles (24 km), and usually it is less. As compared with gunfire this distance is surprisingly short, but gunfire is heard at great distances only under favorable conditions for the transmission of sound, while thunder occurs only when conditions are bad and is consequently muffled, although the total atmospheric disturbance is undoubtedly greater.

## ILLUMINATION

The illumination from a lightning flash has heretofore been attributed by many to the heating of the air by the passage of the current, but this does not seem to be an adequate explanation for the reason that air heated to any practical temperature has not been shown to be more than faintly luminous. It has been found that gases, in general, which are highly transparent to visible rays of light at ordinary temperatures, as are the constituents of air, do not emit them in quantity when heated. Luminosity from gases of this sort is obtained only by ionizing them under a strong electric field, thereby producing electronic vibrations of the frequency of visible rays. Since air conducts electricity only by ionization, the air along the path of a lightning flash must be highly ionized, and from this it seems likely that the electric field rather than the temperature is the exciting cause of the illumination. The abrupt disappearance of the light at the conclusion of the flash also indicates the same thing. If the temperature were high enough, of course, a sufficient degree of ionization might be produced independently of the electric field to give rise to the illumination, but temperatures of this magnitude, of the order of $10^5$ degrees C., do not seem likely from consideration of the probable energy and dimensions of lightning flashes. As indicated in the preceding section, the temperature is not likely to exceed those producible by laboratory means.

## CHARACTER OF DAMAGE

When lightning strikes to earth the object which receives it usually suffers more or less damage, depending upon its relative conducting power. Metal, for instance, receives a lightning discharge with little damage to itself. In most cases even slender conductors, such as telegraph, telephone, and electric-light wires, will carry a discharge without fusing except where the discharge enters the metal. There 1 or 2 cc of metal may be fused to a globular mass. Occasionally fusion is more extensive, in rare instances having affected several hundred grams of metal, but such cases are exceptional. In other exceptional cases there may be electromagnetic damage to metal conductors, they being torn from their fastenings or bent out of shape as a result of the passage of the current.

When insulating or semi-insulating material receives a discharge, however, the damage is usually severe and takes on an explosive character. Trees, for instance, whether dry or green, are in frequent cases blown to splinters and in any event are split or stripped of more or less bark. The damage may also extend underground to the roots. Wood, in general, is subject to the same kind of splintering, and brick and stone work are sometimes demolished locally and pieces thrown to distances of 100 feet or more.

The extent of damage of this kind seems to depend in some degree upon whether the material is externally wet or not when struck. Prior to rainfall the damage is the most extensive; afterwards it becomes less, the discharge apparently keeping more to the outer surface. Trees struck when thoroughly wet in many cases show only a small piece of bark stripped off here and there, the remainder of the path along the trunk being barely traceable by slight superficial damage, while trees struck when dry externally are almost invariably stripped or splintered from top to bottom.

The cause of damage of this sort is generally attributed to the formation of steam at high temperatures within pores of the material, all porous materials exposed to air being known to contain more or less moisture. It is conceivable, however, that there may be more to it than formation of steam, although this would be a contributory cause. It is possible that under the high current intensity and potential gradient of a lightning discharge some of the material itself is decomposed or distilled with the formation of gaseous products, such as hydrogen, oxygen, hydrocarbons, ions, and electrons. When hydrogen, for instance, changes from the ionic, or combined state as in water, to gaseous state at atmospheric pressure the volume occupied at ordinary temperatures increases about one thousand three hundred times and becomes much greater than this at the temperatures probably developed by lightning discharges. Hence, a capillary tube in wood filled with moisture at atmospheric pressure would be subjected to an internal pressure much greater than 1,300 atmospheres if all the hydrogen contained in the moisture were suddenly released in gaseous form by lightning. This would be equivalent to an explosion of dynamite and ample to account for the explosive effects of lightning, especially where coupled with the formation of steam, oxygen, and other products arising from the decomposition of the material. There is also to be considered the electrostatic repulsion between the electrons traversing the pores, which may be very great. It has been suggested by Dorsey that this repulsion between the fibers of even a small piece of wood may be many tons.

The greatest damage to property from lightning, of course, comes from fires started by it. In some classes of property the losses are serious, especially in oil tanks, farm barns, and structures generally which house inflammable materials. Lightning fires are started chiefly by the discharge, a branch of it, or an induced spark, penetrating something easily ignited, such as explosive gases, dust, lint, hay, straw, or paper. It is seldom that fires are started in dry wood that is solid. Forest fires from lightning start usually in dry decayed wood or beds of leaves or needles.

## EFFECTS ON PERSONS

When persons are subjected to direct lightning strokes the result is nearly always fatal, although instances have been recorded of extraordinary escapes from what seemed to be direct strokes. It is possible, however, that what appeared to be direct strokes actually were not. When lightning strikes, the light is so intense and the brush effects so widespread that it is difficult for an observer to be certain of what happened until the spot is examined afterwards, and even then the traces may be confusing. Moreover, the shock from a direct stroke is so great that it does not seem within reason that a person could survive it. Where the subject does survive it is highly probable that the greater portion of the stroke was expended upon some other object. The major part of lightning casualties arise from secondary phenomena, such as sideflashes and induced discharges.

The injuries inflicted by lightning consist of electric shocks of greater or less severity which may be combined with burns, and in some cases tearing of the flesh, apparently by an explosive action of the discharge. Burns by lightning frequently assume fantastic forms, and cases are reported where images of various kinds were imprinted upon the body. That such burns happen to be the image of anything is doubtless a matter of chance. Their origin is probably in surface discharges over the skin or in the layer of clothing damp with perspiration next to it. This layer, especially in thunderstorm weather, offers considerable inducement to a discharge to follow it, and the resulting heat, or burning by ultraviolet rays, might cause almost any kind of an image to be imprinted. First-aid treatment for injuries by lightning is the same as that for other electric shocks and burns. First-aid treatment, especially artificial respiration if administered in time, would doubtless prevent many deaths from lightning which otherwise result from the fact that nine-tenths of such accidents occur in isolated places where few or none are acquainted with the proper procedure.

## THUNDERSTORM DATA

Such data on this subject for the United States as are available have been accumulated by the United States Weather Bureau, through its various observation stations, and have been summarized in Weather Bureau publications. Records for a period of 20 years are contained in an article by William H. Alexander.[31] Maps are shown with isoceraunics, or lines of equal thunderstorm frequency, drawn upon them for the different months of the year. Quoting the original article:

During the winter months—December, January, and February—the center of thunderstorm activity for the United States is in the vicinity of Vicksburg, Miss. In February, however, the general thunderstorm area tends to drift southeastward, with a marked secondary over Pensacola, Fla. In March the center of activity is still over the lower Mississippi Valley, with the general storm area spreading rapidly northeast over the Tennessee and Ohio Valleys. In April the center appears to be in the vicinity of Shreveport, La., with the general area spreading northeast over a large part of the Eastern States, but also north and west.

The interesting thing about the May chart is the definite appearance of the primary center over Tampa, Fla., and a strong secondary over the lower plains States. Great thunderstorm activity now prevails over the entire eastern half of the country, except in the Canadian border States, including the whole of New England. There is also an increased activity in western Montana.

During June the thunderstorm area continues to spread northward and covers the entire country east of the Rocky Mountains except possibly the extreme Northeast. The center of greatest activity is in the vicinity of Tampa. There are also definite indications of the development of a secondary center over the southern Rocky Mountain States. One of the most surprising things revealed by the July chart is the increased activity over the Rocky Mountain States, with a secondary over Santa Fe, N. Mex., almost as strong as the primary over Tampa. Marked activity also continues in southwestern Montana and in the vicinity of Yellowstone Park. The distribution in August is very much the same as in July, but with a notable decrease in intensity along the Canadian border and a marked weakening of the center over Santa Fe. The two centers, Tampa and Santa

[31] Monthly Weather Review, 52, p. 327; 1924.

Fe, persist, though weakening, through September. In October the southeastern (Tampa) center seems to have dropped a little south and is now over Key West, while the Santa Fe center has disappeared or shifted to eastern Texas and the southern plains States, and the general storm area is rapidly diminishing. In November, as during the winter months, the active area is over the lower Mississippi Valley, and the general area is limited largely to the Mississippi and Ohio Valleys.

Chart 13 (fig. 3 herewith), which shows the average annual number of days with thunderstorms during the 20-year period at a large number of stations in the United States and Canada, has a number of interesting features and is worthy of considerable study. Note that no part of the country is entirely free from thunderstorms and that they are comparatively rare along the Pacific coast; that there are two centers of maximum activity, one over Tampa, with an annual average of 94 days with thunderstorms in the 20 years, and the other over Santa Fe, with an average of 73 during the same period. The average at Tampa and Santa Fe is nearly the same for the two 10-year periods.

This chart, however, gives no indication of the intensity of individual thunderstorms as regards electrical display, nor does it show where the greatest number of intense storms occur. In general, however, the lightest thunderstorms occur in regions where they result from local convection. The most intense and longest continued thunderstorms occur in the southeast quadrant of cyclonic storms which are most frequent in the upper Mississippi Valley States and those between the Ohio River and the Canadian border. Thus it may be said that the most destructive thunderstorms occur in the central portion of the United States, with an arm of slightly diminishing intensity toward Florida, and with rapidly diminishing intensity toward the west, north, and northeast. Intense thunderstorms may occur occasionally, however, in almost any part of the United States, except perhaps on the Pacific coast and in the extreme northeastern portion.

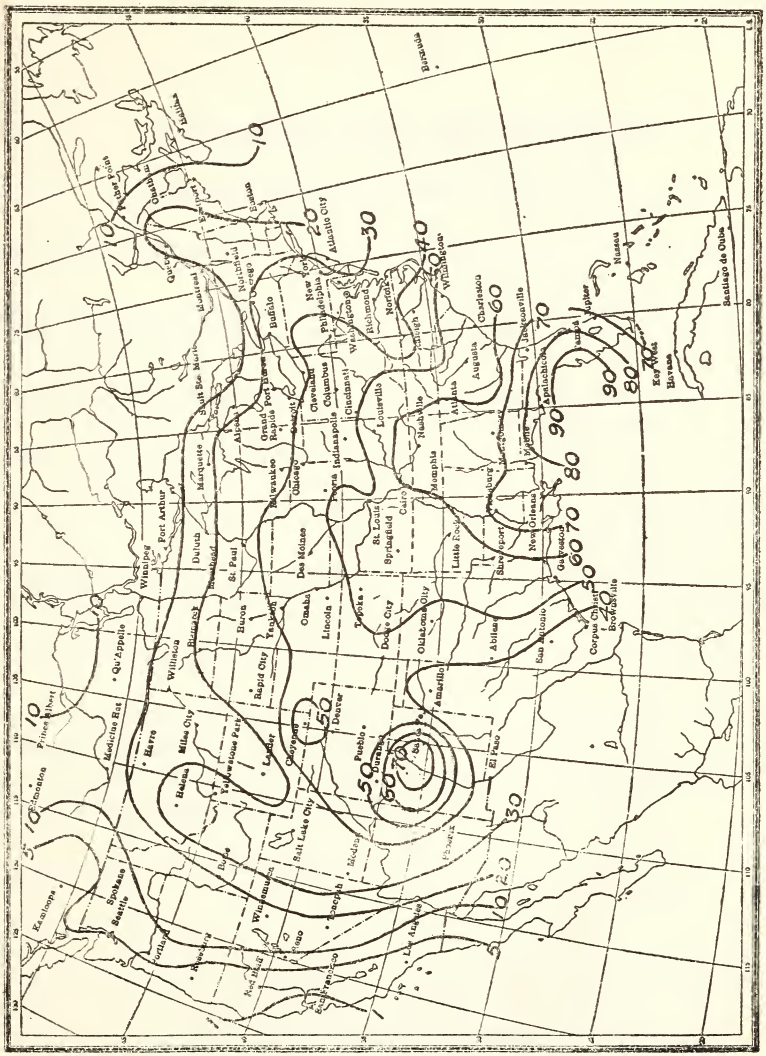


FIG. 3.—*Average number of days per year on which thunderstorms occur*

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