CODE FOR PROTECTION AGAINST LIGHTNING

Handbook 46

U. S. Department of Commerce
National Bureau of Standards

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U. S. Department of Commerce — Charles Sawyer, Secretary
National Bureau of Standards — A. V. Astin, Director

CODE FOR PROTECTION AGAINST LIGHTNING

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The present draft is sponsored jointly by the National Fire Protection Association, American Institute of Electrical Engineers, and the National Bureau of Standards and following its approval by the Sectional Committee has been approved by each of these organizations as sponsor and by the American Standards Association.

The current revision recognizes aluminum as a suitable material for lightning protective systems. The extensive use of sheet aluminum for the exterior finish of buildings and the growing use of stranded aluminum cable for the transmission of electric power make the use of this material desirable for this purpose, both from the standpoint of availability and because when used with aluminum roofing and siding, it eliminates the junction of dissimilar metals in locations not normally accessible. Aluminum grounds are not permitted.

New rules on grain elevators and on vents and stacks emitting explosive dusts, vapors or gases are included. These rules are intended to eliminate or reduce the possibility of ignition of such dusts, gases or vapors by lightning.

As a result of experience obtained in the field, additional bonding requirements have been added for steel tanks containing flammable liquids and gases.

Each Part of the code contains an introductory statement and in this, as in the other editions published by the National Bureau of Standards, there is given, as Appendix A, a general discussion of the origin and characteristics of lightning. For the earlier editions this Appendix was first prepared by M. G. Lloyd, then chairman of the Sectional Committee. For the present revision, it has been in part rewritten and brought up to date by F. B. Silsbee, one of the members representing the National Bureau of Standards.

This Appendix is not officially a part of the Code as approved by the Sectional Committee, the sponsors and the American Standards Association, but is included to supply background material which may prove of interest and value in connection with lightning protection.

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. The requirements are of general application, and particular types of buildings may need more specific consideration. The needs of both industry and the public have been kept in mind and the standards here set up have been taken largely from American practice and experience, although foreign practice has also been given consideration.

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. 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.

Further experience and the accumulating knowledge of the properties of lightning may lead later to changes in the requirements, and future revisions in the code 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.

The assistance and cooperation of Robert S. Moulton, Technical Secretary of the National Fire Protection Association, in handling the work of this committee is gratefully acknowledged.

A. V. Astin, *Director.*

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CODE FOR PROTECTION AGAINST LIGHTNING

PART I.—PROTECTION OF PERSONS

INTRODUCTION

The number of fatalities from lightning is shown by Census Bureau reports to be about 400 per year for the entire United States. From the ratio of deaths to injuries where both are known, the number injured is estimated at 1,000 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. The lightning hazard is greatest among persons whose occupations keep them outdoors, a conclusion which is supported 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 exceeds 100,000 annually. The actual danger from lightning is, in general, very small, except under certain circumstances of exposure out of doors. Within buildings of considerable size, and dwelling houses of modern construction, cases of injury from lightning are relatively rare. They are more frequent within 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 part 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 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 a cave, a depression in the ground, a deep valley or canyon, the foot of a steep or overhanging cliff, dense woods, or a grove of trees.

PART II.—PROTECTION OF BUILDINGS AND MISCELLANEOUS PROPERTY

INTRODUCTION

Data on property losses from lightning are incomplete. Estimates of the National Fire Protection Association for the five year period ending in 1950 show an average of 27,500 fires annually in the United States with a loss of $24,000,000.

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 have reduced the present total of damage to much less than it would be without them. Moreover, extension of the use of properly installed equipment would decrease the damage still further. It is not to be inferred, however, that it would be financially profitable to equip all buildings indiscriminately, because if this were done the annual cost in interest charges and maintenance would be many times the present annual loss by lightning.

RELATIVE LOSSES FROM LIGHTNING

The effectiveness of lightning protection systems 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 for the period 1919–21 indicates about 50 percent. In these years, 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 percent of the total, although the number exposed was about 50 percent. The condition prevailing in other midwestern 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 equipped with rods is listed as "rodded" 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 estimating as many protected as unprotected farm buildings, the State of Iowa in the 5-year period 1926–1930 had 29 buildings "not rodded" destroyed for every rodded building destroyed by lightning. In a larger area during a previous period, this ratio was 57. It is quite evident that the chance of an unprotected farm building being destroyed is many times as great as that of a rodded building.

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 protection systems, 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*) Personal hazards.
(*d*) Local conditions.
(*e*) Indirect losses.
(*f*) Relation to insurance premiums.

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 need 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 can be made 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 the installation of complete lightning protection 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. Lighting 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 noncombustible. 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.

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 and wiring 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.

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.

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.

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.

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

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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 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 monumental 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 and adequately grounded, 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 sole purpose of lightning rods or grounded metal roofs is to protect a building in case a stroke occurs, there being no evidence or good reason for believing that any form of protection can prevent a stroke.

The required condition that there be a metallic path for the part of the discharge which is intercepted is met 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 grounded 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.

Experiments have indicated that, under certain assumed test conditions, such a vertical conductor will generally divert to itself 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 approximately two times the height of the conductor. Incidentally, any metallic structure, or adequately protected structure, will function in the same manner as a mast. Thus a tall steel windmill, steel water tower, or rodded steeple may afford some protection to low adjacent structures, but unless low impedance grounds are provided, reliance cannot be placed upon such protection even though the structure lies within the cone-shaped space above mentioned.

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.

(*b*) Conductors should be installed with the view of offering the least possible impedance to the passage of a stroke between air terminals and ground. The most direct path is the best, and there should be no sharp bends or loops for the lightning to jump across. The impedance 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 impedance 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, 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 and in some cases both interconnected and 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 apply the foregoing principles to the protection of buildings. These specifications are based upon what is believed to be the best current practice in the installation of lightning protection systems.

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 flammable liquids and gases, explosives manufacturing buildings and magazines 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 structure which supports it.

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 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 PROTECTION 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*).)

(5) *Aluminum.*—Where aluminum is used, care should be taken not to use it in contact with the ground or elsewhere where it will rapidly deteriorate, and precautions should be observed at connections with dissimilar metals. Cable conductors shall be of electrical conductor grade aluminum.

(*b*) Form and Size.—The following subsections give minimum sizes and weights for main and branch conductors. Conductors used for bonding and interconnecting metallic bodies to the main cable, and which will not normally be required to carry the main lightning current, may be reduced in size.

Conductors for interconnection to domestic water systems, steam or hot-water heating systems or other metallic masses having low resistance to ground shall be full size, since in the event of a direct stroke, the major portion of the discharge current may flow to ground over such a system.

(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 Gage (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 Gage (0.080 inch= 0.203 cm).

(4) *Aluminum.*—Aluminum cable conductors shall weigh not less than 95 pounds per thousand feet and the size of any wire of the cable shall be not less than No. 14 A. W. G. (0.064 inch=0.163 cm). Aluminum conductors for bonding and interconnecting metallic bodies to the main cable shall be at least the equivalent in strength and cross-sectional area of a No. 4 A. W. G. (0.204 inch=0.518 cm) aluminum wire. Aluminum strip conductors for interconnecting metallic bodies to the main conductor cable, if void of perforations, shall be not less than No. 14 A. W. G. (0.064 inch=0.163 cm) in thickness and at least ½ inch (1.27 cm) wide. If perforated, the strip shall be as much wider as the diameter of the perforations. Aluminum strip

for connecting exposed water pipes shall be not less than No. 12 A. W. G. (0.080 inch=0.203 cm) in thickness and at least 1½ inch (3.81 cm) wide.

Aluminum connectors shall be not less than No. 12 A. W. G. (0.080 inch=0.203 cm) in thickness and of the same design and dimensions required for stamped copper connectors.

Aluminum tubular points shall be not less than ⅝ inch (1.59 cm) O. D., No. 16 A. W. G. (0.050 inch=0.127 cm) wall thickness and of the same lengths as required for copper points. Solid aluminum points shall be not less than ½ inch (1.27 cm) in diameter and of the same lengths as required for copper points.

Aluminum air terminal supports (for points and elevation rods), when stamped, shall be not less than No. 14 A. W. G. (0.064 inch=0.163 cm) in thickness and of the same design and dimensions required for copper supports.

Cast aluminum parts (fasteners, clamps, connectors, fixtures, etc.), shall be of the same designs and dimensions required for copper alloy fittings and equivalent in strength and conductivity.

Copper, copper-covered and copper alloy fixtures and fittings shall not be used for the installation of aluminum lightning protection systems. Aluminum, galvanized iron or aluminum alloy fixtures and fittings are the only types permitted, except for ground connections as provided in the next paragraph.

The use of aluminum materials for direct grounding of aluminum lightning protection systems is not acceptable and they should never be buried in earth. Galvanized iron ground rods, leads and clamps are satisfactory for grounding aluminum systems. Copper or copper-covered ground rods and leads may be employed, provided the clamps for connecting the aluminum down conductors to the copper or copper-covered grounding equipment are types specially designed for making the connection between the two dissimilar metals. The connection of the aluminum down conductors to the grounding equipment shall be made at a point not less than one foot (30.5 cm) above ground line. Protecting the connection from mechanical injury and displacement by the use of suitable guards is required.

(*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:

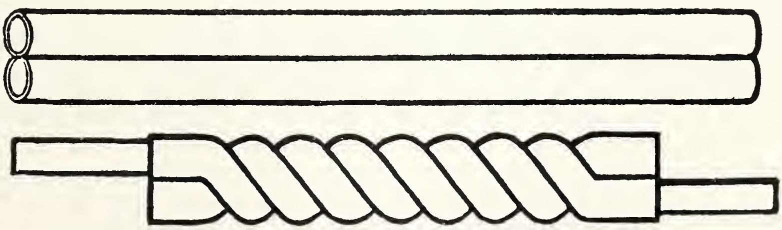
Sections of cable conductor are preferably connected together by unraveling 6 inches (15.2 cm) or more of the ends and making a solderless wrapped joint. An alternative is found in couplings of malleable metal No. 14 A. W. G. in thickness (0.064 inch=0.162 cm), 3 inches (7.62 cm) in length, and of semitubular 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, McIntire sleeves, or by screw couplings. Lengths of rectangular cross-section conductor (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.



McIntire sleeve joint—Above: Sleeve. Below: Completed joint.

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 (18.3 m) in height, joints shall be so constructed that their mechanical strength in tension as shown by laboratory tests is not less than 50 percent 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 (60.9 cm) 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 (1.22 m) 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, if of copper from sheet metal not less than No. 20 A. W. G. (0.032 inch=0.081 cm) in thickness, and not less than ⅜ inch (0.953 cm) wide; or if of aluminum, from sheet not less than No. 16 A.W.G. (0.050 inch, 0.127 cm) in thickness and not less than ½ inch (1.27 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 (0.953 cm) in diameter and 2 inches (5.08 cm) in length, or of a type that will withstand a pull of at least 100 pounds (45.5 kg). The fan shank should be approximately ½ inch (1.27 cm) wide at its narrowest place, 0.1 inch (0.254 cm) thick, and 3 inches (7.62 cm) long.

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).

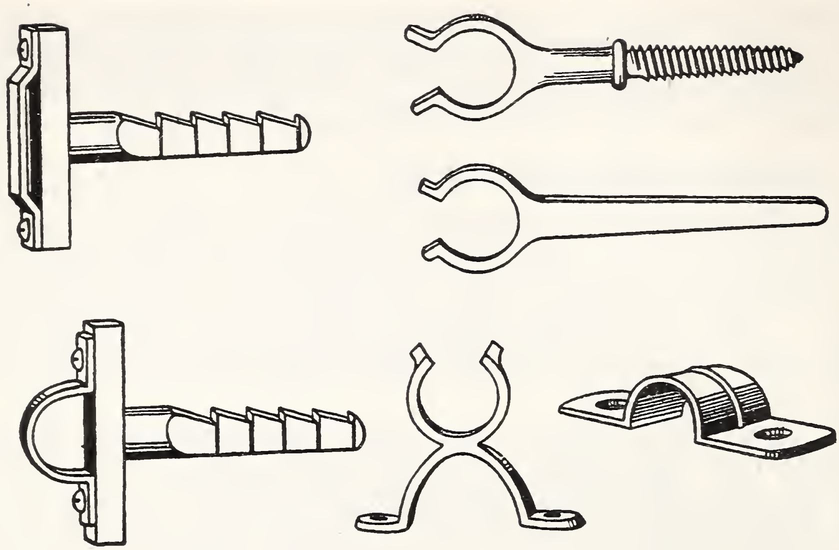
(2) *Form.*—Elevation rods may be of any form of solid or tubular cross section.

(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.

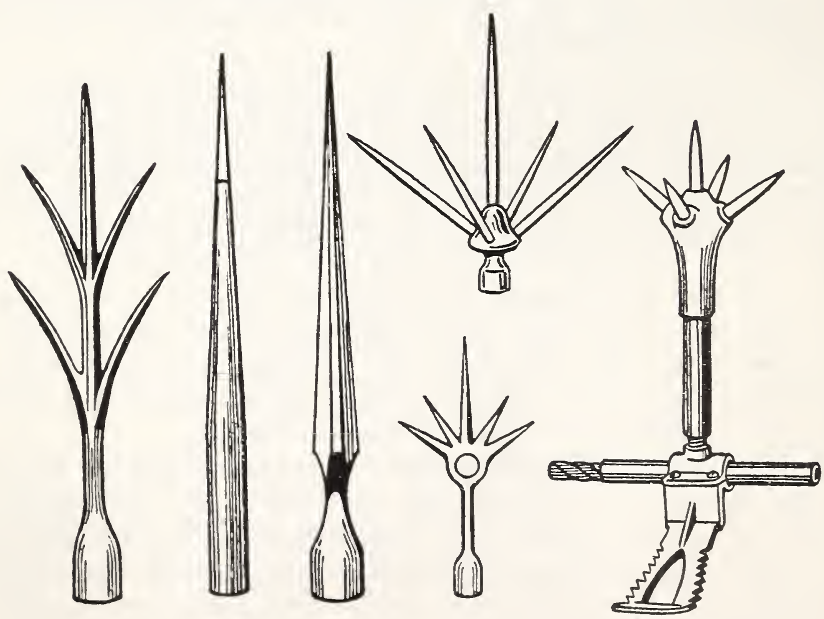
On flat surfaces a greater height than 10 inches is desirable, but the height need not exceed 5 feet. In most cases the proper height for an elevation rod between the limits just mentioned will depend upon the character of the object to be protected. The proper height may also be taken as depending somewhat 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 shall comply with the requirements of "210 (*a*) Materials" as to resistance to corrosion or protection against corrosion.



FASTENERS AND SUPPORTS



LEAD-COVERED
AERIAL TERMINAL

AIR TERMINALS

(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 (61 cm) 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 (61 cm) 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 1/16 inch (0.158 cm) or more in thickness.

Aluminum parts, including fasteners and anchors, shall be protected from direct contact with concrete or mortar wherever such concrete or mortar is wet or damp, or may become intermittently wet or damp.

(*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. Air Terminals and Conductors.

(*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).

(*d*) Metal Projections and Parts of Buildings.—Metal projections and parts of buildings, such as ventilators, smokestacks, 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 large flat and gently sloping roofs it is desirable to erect air terminals at points of intersection of lines dividing the surface into rectangles not exceeding 50 feet (15.3 m) in length.

In parts of some buildings, relatively thin layers of brick, stone, tile, or similar masonry material have been laid on top of structural steel. Lightning then has to break through the brick, stone, etc., to reach the steel, and this may result in fragments of brick, stone, etc., being thrown down into the street. Such construction should be avoided, but where already existing, the situation may be improved by covering the masonry with metallic sheathing, which is in turn connected to the lightning protective 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.—Horizontal conductors shall be coursed around chimneys, ventilators, and similar obstructions in a horizontal plane and without abrupt turns.

(*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 Not Continuous.—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 electrical 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, acceptable to the code enforcing authority 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.

The roof metal should have adequate thickness (see rule 311) to prevent a hole being burned in the metal in case of a direct stroke to the roof, which could cause a fire if flammable material were stored below.

(*c*) Metal Roof Not Electrically Continuous With Metal Siding.—The siding shall be connected to the roof at each corner, and down conductors shall be connected to the lower part of metal siding, in the manner specified in (*b*) above, with a connection between roof and siding directly above the down conductor in every case, and the down conductor grounded as specified in rule 217.

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 affords increased protection. 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 sawtooth 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 endwings are higher than the connecting portion.

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, 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 (1.5 m), 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. (0.162 inch = 0.411 cm) 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 metal 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.

(*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 metallic water pipe enters a building at least one down conductor shall be connected to it preferably 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*). Where a grounding electrode consists of a driven rod or pipe, the length of the electrode shall be permanently marked upon it at the top.

(*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. 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 and at least 2 feet away from 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 only below the surface, 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 points through which the heavy current flows between the air terminals and the surface of the earth about the building and should, therefore, be distributed with the view of carrying this flow of current in the most advantageous manner. This will be generally realized by placing them at the outer extremities, such as the corners, and avoiding as far as possible the necessity for current flow under the building.

218. Radio Installations and Wires Entering Buildings.

(*a*) Wires Entering Buildings.—Wires entering buildings shall conform to requirements of the latest edition of the National Electrical Code which are applicable.[1]

[1] Copies of the current National Electrical Code may be obtained from the National Board of Fire Underwriters, 85 John Street, New York 7, N. Y.

(*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.

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 permeter 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*) Interconnection 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 Water 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, shall be grounded by means of two earth terminals on opposite sides of the structure.

222. Grain Elevators.

(*a*) General.—The rules contained in Section 21, except as modified by rule 222 (b) and 222 (c), shall apply to grain elevators, and to other structures in which combustible dusts may be produced in quantities sufficient to form explosive or ignitable mixtures with air or in which such dusts may accumulate on ledges or other surfaces in quantities sufficient to sustain smouldering fire.

(*b*) Conductors.—Roof conductors and down conductors shall be of copper or aluminum cable conforming to Rule 210.

Due to the physical deformation of such structures through cycles of loading and unloading, it is necessary that conductors have sufficient flexibility to guard against breakage.

(*c*) Interconnection of Metallic Masses—Interconnection of metallic masses shall conform to rule 216, except that all interior metallic masses having any dimension greater than 5 feet, and all metallic masses except those of comparatively small size, which are within 6 feet of grounded metallic masses including lightning conductors and metal connected thereto, shall be interconnected with each other and with the lightning conductors. Interconnected networks of interior metallic masses shall have at least one interior ground connection in addition to the lightning conductor grounds.

SEC. 23. BUILDINGS CONTAINING BALED FLAMMABLE MATERIALS

It has been found that lightning flashes occurring in the immediate vicinity of cotton or other fibrous materials of a flammable 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 (1.83 m) 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 for stacks made of materials other than metal as provided in rule 241 (*g*).

Metal guy wires and cables shall be grounded at their lower ends.

Metal guy wires or cables attached to steel anchor rods set in earth may be considered as sufficiently well grounded. Only those set in concrete or 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 percent conductivity when annealed.

The weight of the conductor shall be not less than 6 ounces per linear foot (375 lb per 1,000 ft=0.558 kg per m).

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

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

The thickness of any web or ribbon shall be not less than No. 12 AWG (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 shall be strongly constructed. Each fastener shall have a sufficiently tight grip to support its corresponding length of conductor.

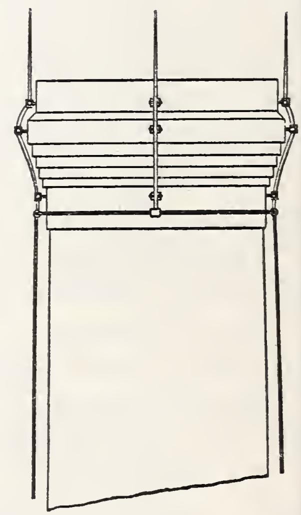
Fasteners shall be spaced close enough to give ample support to the conductor, generally not over 4 feet (1.22 m) apart.

(*c*) Air Terminals.—Air terminals shall be strongly constructed of the same grade of material as the conductor, or may be made of stainless steel, monel metal, or other equally corrosion-resistant metal, 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 top of the stack by means of expansion bolts or fan shank fasteners of substantial construction. The air terminals shall be electrically connected together by means of a metal ring or band which forms a closed loop about 2 feet (0.61 m) below the top of the chimney. If there is a metal crown, the air terminals should be connected thereto.

(*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.



Typical arrangement at top of stack

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, copper air terminals, conductors, and fasteners within 25 feet (7.62 m) of the top of the stack shall have a continuous covering of lead at least 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 percent 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.

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

242. Reinforced-Concrete Stacks.

(*a*) Reinforcing Metal.—Stacks consisting partly or entirely of reinforced concrete shall comply with the requirements of rule 241, and in addition the reinforcing metal shall be electrically connected together and shall be electrically connected to the down conductors at the top and bottom of the concrete.

In existing stacks whose reinforcement may not be electrically continuous, it is recommended that additional connections be made at points where the reinforcing rods are accessible.

(*b*) Joints.—Joints between iron or steel and copper, within 25 feet (7.6 m) of the chimney top, shall be protected against corrosion by being coated with lead or imbedded in the concrete.

243. Vents Emitting Explosive Dusts, Vapors or Gases.

Air terminals on capped or hooded vents emitting explosive dusts, vapors or gases should extend not less than five (5) feet (1.5 m) above the opening.

When explosive dusts, gases or vapors are emitted under forced draft from open stacks, the air terminals should extend not less than fifteen (15) feet (4.6 m) above the vent opening.

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. Permanent structures 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 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 aluminum, 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. By "equivalent" is meant of equivalent strength and conductivity.

This attachment should consist of a pair of wooden blocks bolted to the outer and inner surfaces of the wood sheathing 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 or aluminum flashing applied.

(*f*) Height of Air Terminals.—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 as 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

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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, welded, 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 spouts, 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 (3.05 m) of a lightning conductor shall be securely bonded thereto. In the case of steel-frame buildings all interior metallic bodies within 10 feet (3.05 m) 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. (0.162 inch = 0.411 cm) copper wire, except where full-size lightning conductor is otherwise required. See rule 216 and notes.

(*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 Airships.

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 $\frac{1}{4}$ 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 the same metal as the conductors, 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 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 or 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 FLAMMABLE[2] LIQUIDS AND GASES

INTRODUCTION

Reduction of Damage.

Certain types of structures used for the storage of flammable liquids and gases are essentially self-protecting against damage due to lightning strokes. 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 rods, masts, overhead ground wires, and by other means.

In part II of this code are given recommendations for the protection of buildings and miscellaneous property against lightning damage. Because of the nature of contents of the structures considered in part III, extra precautions must be taken. In these structures a small spark that would ordinarily cause little if any damage might cause the complete destruction of the structure due to explosion of its contents.

Fundamental Principles of Protection.

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

(*a*) The storage of flammable liquids and gases in all-metal structures, essentially gastight.

(*b*) The closure or protection of vapor or gas openings against entrance of flame.

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

(*d*) The avoidance, so far as possible, of the accumulation of flammable air-vapor mixtures about such structures.

(*e*) The avoidance of spark gaps between metallic conductors at points where there may be an escape or accumulation of flammable vapors or gases.

(*f*) The location of structures not inherently self-protecting in positions of lesser exposure with regard to lightning. Elevated positions should be avoided.

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[2] In accordance with the modern trend in usage, the term "inflammable" used in previous editions has been replaced by "flammable" without change of meaning.

(*g*) In connection with structures not inherently self-protecting, the establishment of zones of protection through use of grounded rods, masts, or the equivalent.

SEC. 30. SCOPE, EXCEPTIONS, ETC.

300. Scope and Purpose.

This code applies to the protection of structures containing flammable liquids and gases from lightning or electric discharges. It applies particularly to structures containing alcohol, benzol, petroleum, petroleum products, turpentine, and other liquids which produce flammable air-vapor mixtures at atmospheric temperatures.

This code is primarily intended to give fundamental information as to the kind of structures most suitable for the protection of their contents from lightning or electric discharges and to indicate ways of protecting such structures as are not inherently self-protecting.

This code is concerned only with the prevention of fires or explosions from electric discharges and is not concerned with 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 be interpreted as recommending the protection of the class of property to which it applies, but it 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. The word "may" is used in the permissive sense.

303. Terms and Definitions.

The following terms and definitions apply specifically to the structures, materials, and contents involved in part III of this code:

Vapor openings.—These are openings through a tank shell or roof above the surface of the stored liquid. Such openings may be provided for tank breathing, tank gaging, fire fighting, or other operating purposes.

Flame protection of vapor openings.—Self-closing gage hatches, vapor seals, pressure-vacuum breather valves, flame arresters, or other reasonably effective means to minimize the possibility of flame entering the vapor space of a tank. Where such a device is used, the tank is said to be "flameproofed."

Cage.—A system of wires or cables forming an essentially continuous mesh or network over a structure and roof, including the necessary conductors that are connected to the structure and to an adequate ground.

Cone of protection.—The cone of protection provided by a grounded lightning rod or mast is that space adjacent to the rod or mast that is substantially immune to direct strokes of lightning. When overhead ground wires are used, the space protected is called a zone of protection or protected zone.

Flash point.—Flash point is the minimum temperature at which a liquid will give off vapor in sufficient amount to form a flammable air-vapor mixture that can be ignited under specified conditions.

Gastight.—Structures so constructed that gas or air can neither enter nor leave the structure except through vents or piping provided for the purpose.

Spark gap.—As used in this code, the term "spark gap" means any short air space between two conductors electrically insulated from or remotely electrically connected to each other.

Flammable vapors.—The vapors given off from a flammable liquid at and above its flash point.

Flammable air-vapor mixtures.—When flammable vapors are mixed with air in certain proportions, the mixture will burn rapidly when ignited. The combustion range for ordinary petroleum products, such as gasoline, is from 1½ to 6 percent of vapor by volume, the remainder being air.

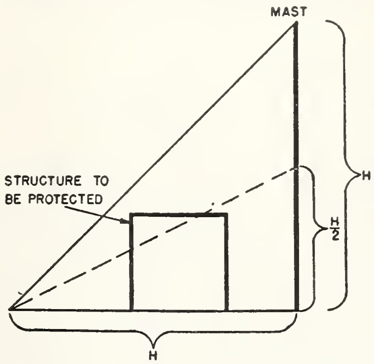
SEC. 31. PROTECTIVE MEASURES

310. Conductors, Air Terminals, and Ground Connectors.

Conductors for protective systems shall be selected as to material, form, and size in accordance with part II of this code. Details as to air terminals, down conductors, interconnection of metallic masses, and ground connections are also given in part II. Connections to ground and interconnections between metallic bodies should be as short and direct as possible.

311. Sheet Steel.

Experience in the petroleum industry demonstrates that the use of $3/16$-inch steel roof sheets on tanks has been adequate. Sheet metal substantially less than $3/16$-inch in thickness may be punctured by severe strokes and should be protected by suitable air terminals.



Cone of protection.

312. Rods, Masts, and Overhead Ground Wires.

The zone of protection of a grounded rod or mast of conducting material is conventionally taken as the space enclosed by a cone, which has its apex at the highest point of the rod or mast and a radius at the base which bears a relation to the height. This relation depends upon the height of the cloud above the earth relative to the height of the rod or mast.

A radius of base equal to the height of the rod or mast in important cases, or up to twice the height in less important cases, has been found to be satisfactory. No part of the structure to be protected should extend outside of the cone of protection.

If more than one rod or mast is used, the shielded region between them is somewhat greater than the total of the shielded regions of all of the rods or masts considered individually.

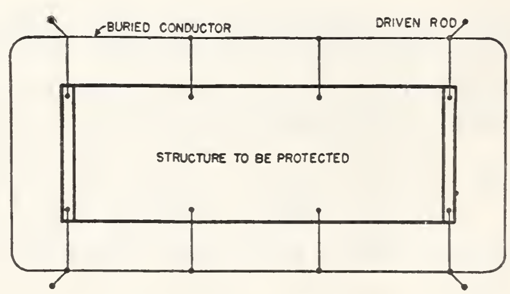
Masts separate from the structure to be protected must be far enough away from the protected object so that the stroke will not side flash. Calculations indicate that between one-fourth and one-half the height of the protected object should usually be sufficient. The masts should be thoroughly grounded and connected to the structure to be protected, if the latter is of metal. A sufficient number of masts should be used, so that the entire structure is covered by their cones of protection.

In case of overhead ground wires, the zone of protection is conventionally taken as a triangular prism or a wedge, with the ratio of one-half base to height ranging between one and two.

313. Ground Resistance.

The resistance of ground rods driven in the earth and separated by distances of 10 feet or more will be reduced in approximate proportion to the number of rods in parallel.

The resistance of a conductor buried in the ground decreases almost directly in proportion to the increase in length of the buried conductor. Such conductors are usually buried from 1 to 3 feet beneath the ground surface and running parallel with the ground surface.



Method of grounding by means of buried conductor and ground rods.

314. Electrostatic Shielding.

The electrostatically induced voltage on isolated objects in the field of a storm cloud may cause sparks to ground when a lightning discharge occurs to some adjacent object. Isolated objects within a structure that is adequately shielded will themselves be electrostatically shielded. If the structure is not shielded or is only partially shielded, then the isolated objects should be grounded to prevent electrostatic sparks. For further discussion of the grounding of isolated internal objects see Rule 216.

315. Flame Protection of Vapor Openings.

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

For pipe sizes larger than 4 inches, the effectiveness of flame protection employing screens on the Davy principle is questionable. Pressure relief valves that remain closed at pressure differentials of less than 1-inch head of water, and arresters in the forms of tubes, plates, and their equivalent, have been found to be reasonably effective flame protection devices.

Flame protectors should be substantially encased and capable of withstanding the effect of cleaning and of flame and pressures without material distortion or injury.

Where screens are used, they should be made of corrosion-resistant wire with a mesh of about 40 per inch. They should be protected so far as possible from mechanical injury.

SEC. 32. PROTECTION OF SPECIFIC CLASSES OF STRUCTURES

320. Steel Tanks.

Steel tanks, with steel roofs, are considered to be self-protecting against lightning discharges if they conform to the following specifications:

(*a*) All joints between steel plates riveted and calked, or welded.

(*b*) All pipes entering the tank electrically connected to the tank at the point of entrance.

(*c*) All vapor or gas openings closed or flameproofed.

(*d*) The metal tank and roof to have adequate thickness, so that holes will not be burned through by lightning strokes ($\frac{3}{16}$-inch roof sheets on tanks have proved adequate).

(*e*) The steel roof to be in intimate electrical contact with the tank or else well bonded to the tank.

(*f*) Any internal metallic structural members shall be bonded to the tank wall or metal roof (see Rule 216).

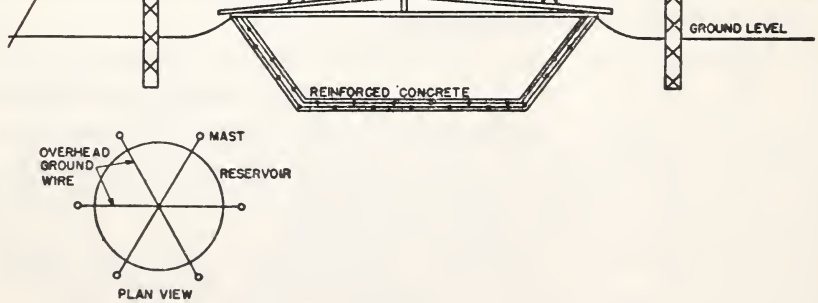
Steel tanks with floating metal roofs, the roof being thoroughly electrically bonded to the tank and the tank otherwise conforming to the above specifications, are considered to be self-protecting.

Steel tanks with wooden or other nonmetallic roofs are not considered to be self-protecting, even if the roof is essentially gastight and sheathed with thin metal, and with all gas openings closed or flameproofed. Such tanks should be provided with air terminals of sufficient height and number to receive all strokes and keep them away from the roof. The air terminals should be thoroughly bonded to each other, to the metallic sheathing, if any, and to the tank. Isolated metal parts should be avoided or else bonded to the tank. In lieu of air terminals, conducting masts may may be used, suitably spaced around the tank, or overhead ground wires, or a combination of masts and overhead ground wires.

Tanks should be well grounded to conduct away the current of direct strokes and avoid building up potential that may cause sparks to ground. Steel tanks that are in intimate contact with the ground are sufficiently well grounded inherently.

321. Earthen Containers.

Earthen containers, lined or unlined, with or without roofs, may be protected by air terminals, separate masts, overhead ground wires, or a combination of these.



Oil reservoir protected by masts and ground wires.

APPENDIX A—LIGHTNING, ITS ORIGIN, CHARACTERISTICS AND EFFECTS

Sources of Lightning

Since the time of Benjamin Franklin (1750) lightning has been recognized as being a gigantic spark occurring between an accumulation of electric charge in a cloud and the earth or another charged cloud. The most common source of such charged cloud centers is the thunderstorm, of which there are two main classes: (a) local convectional thunderstorms and (b) frontal storms. The former are the result of local heating of the air adjacent to the ground in summer, whereas the latter are the result of the overrunning of warm moist air by a mass of colder air, giving rise to turbulence as a result of relative motion of the air masses. In either case there results an unstable condition that causes the warm moist air to rise at an accelerating rate and by the condensation of its moisture to form a tall cumulo-nimbus cloud. In such a thunderstorm cell, there is at first a violent updraft, followed later by strong down drafts. The little understood processes that lead to the separation of large amounts of positive and negative electricity are doubtless related to these vigorous air movements. The usual thunderstorm involves several such circulation "cells," and in the case of a frontal storm, these may extend in a row for many miles. Usually negative electric charges accumulate in the lower portions of the cloud, whereas positive charges are carried to the upper portions, with the result that enormous differences of electric potential are developed between the top and bottom of the cloud and between the latter and the earth.

Lightning has also been observed in the dust, steam, and gas clouds arising from volcanoes in eruption, in dense smoke clouds over large fires, in the dust clouds of deserts, and in clear skies, probably from charged bodies of air that drifted near each other or near the earth. In addition, there are apparently silent luminous discharges within cloud layers and haze that have been observed at all times of the year, especially in regions where thunderstorms are scarce.

Details of the Lightning Flash

During the last two decades experiments by Schonland, McEachron, and others, using the Boys camera, in which photographs are taken by a pair of rapidly moving lenses, have yielded a great deal of detailed information on the development of the lightning flash itself. It appears that first a "pilot leader stroke" propagates downward at about 100 miles a second from the cloud to the earth. The current in this first pilot streamer is only a few amperes, but it is followed by successive "stepped leaders" which follow the same path with very much greater velocity, each step advancing the tip by a distance of the order of 150 feet. These increase the luminosity and doubtless the electrical conductivity of the stroke channel. These leaders often show numerous branchings and forkings. As soon as one of these leader strokes reaches the earth, the current at the ground end of the path and its luminosity increase enormously, and the main stroke propagates upward through the channel already blazed by the leaders. This upward propagation of illumination and of current proceeds at about 20,000 miles a second and develops currents that may become as high as 200,000 amperes in extreme cases. This current increases for an interval of 1- to 10-millionths of a second to a high peak value, after which it drops rather more gradually to a lower value, often a few hundred amperes. In many cases, after the lapse of a few hundredths of a second, a second stroke occurs along the same path as the previous main stroke. Such later strokes consist of a fairly rapid "dart leader" followed by a return stroke which is similar to the original and which usually reaches a crest current of the same general order of magnitude. It is presumed that these later strokes are the result of a tapping of additional charged regions within the cloud. Occasionally the later strokes correspond to currents of opposite polarity from that in the first stroke because of a contribution from a region in the cloud charged with opposite polarity. As many as 40 component strokes have been observed in a single lightning flash, but most flashes have three or four strokes.

Types of Discharge

In common parlance a number of different adjectives are used to describe different appearances of lightning. "Streak Lightning" is the usual type which exhibits a vividly luminous sinuous path which is often forked. "Heat Lightning" is a name often applied to flashes where, because of distance, or of the low value of crest current developed, the noise of the electrical discharge is not heard. "Ribbon Lightning" is a name that is sometimes used to describe an appearance when the stroke seems to have a considerable width. This is probably caused by a shifting of the discharge path by the wind between the occurrences of multiple strokes within a single flash. "Sheet Lightning" is a term sometimes applied to cases in which the lightning stroke itself is not seen, but large areas of cloud are seen illuminated by a flash which is itself hidden by thicker intervening clouds.

The existence of "globular, or ball, lightning" has been a subject of controversy for many years. An exhaustive study of nearly 300 reported cases of this phenomenon was made by Dr. W. J. Humphreys.[3] He found that in a large majority of cases the observed phenomenon could be attributed to the effect of the persistence of vision. In these cases the persisting image (called "after image") on the observer's retina of a portion of a bright flash of streak lightning looked like a luminous object or "ball," which, subsequent to the flash, as a result of the motion of the observer's eyeballs, appeared to move about as he instinctively tried to direct his vision more closely toward the flash. Other cases of this phenomenon could be attributed to prolonged luminosity at the place where the streak lightning hit the ground, to momentary inductive discharges between metal objects in a building, and even to an owl that had been nesting in a hollow tree lined with phosphorescent "fox fire."

Another type of discharge often associated with thunderstorms, and perhaps the basis of some reported cases of "ball lightning", is the corona discharge, St. Elmo's fire, or corposant. This is a silent or faintly hissing discharge

[3] W. J. Humphreys, Ball lightning, Proc. Am. Phil. Soc. **76,** 613 (1936).

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accompanied by a pale bluish or purplish light that appears concentrated at the tips of pointed conductors in strong electric fields. This has been observed on the masts and rigging of ships, on propellers and other projecting portions of aircraft, and on tree tops or projecting metal points on mountain tops. The electric field that produces it is usually that developed by an incipient thunderstorm, although there are many cases on record in which, in the presence of a cloud, a sustained corona discharge was observed but did not develop to the stage where a lightning stroke occurred.

In numerous cases brilliant flashes of streak lightning have been seen nearby without the observers hearing any accompanying thunder. Presumably in these cases the current increased much more slowly than usual and did not reach the high crest values usually associated with thunder.

Measurements on Lightning

A number of devices have been invented for the quantitative study of natural lightning. The Boys camera mentioned above, used in conjunction with another camera, the film of which is moving at a moderate speed, enables the observer to analyze the multiple strokes of a single flash and to time the development of the leader and main stroke in great detail. The cathode-ray oscillograph combined with the Norinder relay permits the quantitative measurement either (a) of the current in the stroke itself, if a stroke occurs directly to an antenna to which the oscillograph is connected, as in the work of McEachron at the Empire State Building, (b) of the signal in a radio antenna that receives the electromagnetic radiation from a distant stroke, or (c) of the voltage produced on a transmission line by a direct or induced stroke at some point along the line usually remote from that at which the oscillograph is connected. The fulchronograph consists of a number of bars of magnetic alloy mounted around the periphery of a rapidly rotating disk, and located in the magnetic field of a coil. The passage of the lightning current from an antenna through this coil on its way to ground, permanently changes the magnetic condition of the links and from these changes the magnitude of the current at various instants during the discharge can be deduced.

The same principle is utilized in a simpler form in the magnetic links which are mounted on transmission line towers or poles in a definite geometrical relation to the probable path of any lightning current which might strike the line near such a tower. Periodic measurements on the magnetization of such links give a quantitative basis for estimating both the frequency of occurrence and the approximate crest magnitude of the lightning currents in the towers or grounding conductors. Such magnetic links are also used in connection with pick-up coils or noninductive shunts to give an indication of the rate of rise of current and of the total integrated value of a current surge. The klydonograph is a device in which the partial electric discharges over the surface of a photographic plate from a pointed electrode, coupled to a transmission line, produce Lichtenberg figures on the photographic plate. From the appearance and size of these figures the polarity and approximate values of the magnitude and duration of the voltage at the pointed electrode can be estimated.

By the use of these instruments a large amount of quantitative information concerning natural lightning and the electrical effects produced by it on transmission lines has been accumulated. An excellent summary is given by Wagner and McCann.[4] Some of these results may be summarized as follows:

Median number of strokes per flash	3.
Average time interval between component strokes of multiple flashes	.02 second.
Median crest current	25,000 amperes.
Maximum crest current	200,000 amperes.
Median total charge in stroke	30 coulombs.
Maximum total charge in stroke	164 coulombs.
Median time to first crest of current peak	1 microsecond.
Median rate of rise of current	10^{10} amperes per second.
Median time for current to drop to half its crest value	50 microseconds.

Estimates of the total voltage and total energy of a lightning flash are rather academic because they involve many rather uncertain factors, particularly the height of the effective charge center above the ground. Laboratory ex-

[4] C. F. Wagner and G. D. McCann, Lightning phenomena, Elec. Eng. **60** (Aug., Sept., Oct., 1941).

periments have shown that when the voltage gradient exceeds about 10,000 volts per centimeter, drops of water will be pulled out into elongated ellipsoids by the electric forces and that corona discharge will develop at the tips of the ellipsoids, with a resulting ionization of the air in the neighborhood. It is probable that the final initiation of the leader stroke is the result of such a local development of electric gradient at some point within the cloud. An estimate of this gradient, with reasonable assumptions for its decrease with distance, leads to voltages in the order of tens or hundreds of millions of volts or an energy per flash of 10^8 to 10^9 joules. There is ample mechanical energy in the air movements accompanying a thunderstorm to provide the energy needed for discharges of this magnitude.

Separation of Charges

A number of mechanisms have been proposed to explain the meteorological processes within the thunder cloud which cause the rapid separation of electric charges. In 1904 Lenard showed that large drops of water falling through a rising column of air break up, the smaller outer portions being carried upward with a negative charge, and the center portion continuing downward with a positive charge. Simpson has applied this idea to explain thunderstorm electricity in a series of researches that have established that this process can occur and may constitute a large factor in the development of thunderstorms. However, in its simpler form, Simpson's theory would predict the accumulation of negative charges aloft and positive charges at the bottom of the cloud. This is opposite to the arrangement usually observed. C. T. R. Wilson proposed an explanation based upon an amplification of the normal fair-weather electric field of the earth, which produces a steady flow of negative ions upward. According to Wilson, a falling rain drop captures more of these negative ions than it does of the positive ions, which are also going downward, and as a result brings negative charges to the bottom of the cloud. Still other theories have been proposed, the more promising of which involve the processes of freezing or melting of snow or hail particles. It is observed that the zone in which the active separation of charges occurs is that which includes or is somewhat lower in temperature than the freezing isotherm. Recent work by Workman and by Gunn have shown that the freezing of dilute solutions may give rise to very marked differences of potential between the ice and the liquid. None of these theories explains the electrical discharges observed in dust clouds, and there is much need for further study in this field.

Path of Stroke

The circumstances that determine the path and point of impact of a lightning discharge with the ground are but little understood at present. The development of the pilot streamer, whether it is the usual negative streamer or the less common positive streamer, has been studied in the laboratory by Loeb and others using electrified points, and is a very complex phenomenon. Such a streamer can develop and "bore a path through the air" at voltage gradients much less than that required to produce a spark between parallel plates, because the electric field tends to be concentrated at the tip of the advancing streamer, giving a very intense local gradient. The streamer follows, in general, the direction of the original electric gradient, but its direction of development at any particular moment depends upon the fortuitous presence near the tip of the streamer of previous ionizatoin resulting from cosmic radiation or other effects. The discharge therefore follows a sinuous path. Many instances have been observed in which lightning having descended for a considerable distance below the bottom of a cloud has then continued in an almost horizontal direction for several thousand feet before again turning downward. As the tip of the pilot streamer approaches the earth, its presence causes the local electric gradient at the surface of the earth to become very large and streamers of opposite polarity tend to develop from projecting points, tree tops, church steeples, lightning-rod air terminals, etc. in the vicinity. Such streamers, usually positive, grow upward in the last moments of the process until one of them meets a fork of the pilot leader and initiates the main return stroke, thereby fixing the location of any later component strokes of the flash.

Because of the extremely high voltage that initiates and propagates the lightning discharge, it is entirely impracticable to insulate an object as a means of protecting it from lightning. The commonly used term "lightning arrester" is a most unfortunately chosen word, since such protective devices do not "arrest" the lightning in the usual sense of the word, but merely offer it an alternative and more attractive, but harmless, path. The same principle is, of course, the basis for Franklin's lightning rod, and the sharp tips used on lightning-rod air terminals definitely contribute to the easy development of the upward streamers, which attract the pilot leader. Presumably the resistance of the main lightning stroke, and particularly that of the invisible branches within the cloud mass by which various regions in the cloud are tapped, is so large that the magnitude and duration of the lightning current are not appreciably affected by any impedance it may experience in the objects that it may encounter near the ground. The damage that results is, therefore, dependent upon this predetermined current and the electrical resistance and other characteristics of the objects struck.

Induced Effects

The induced effects of lightning discharges are of serious consequence in some cases and may be due to either electromagnetic induction, electrostatic induction, or both, depending upon conditions. Even at great distances, say 50 miles, lightning discharges cause appreciable radio interference (sferics). At lesser distances induction effects may cause minor electrical discharges from insulated metallic bodies to earth or to nearby 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 about 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 the disturbances caused on transmission lines by induction are more numerous, the highest voltages are caused by direct strokes, and it is these that do the most damage. On high-voltage lines the insulation may be great enough to prevent outages by induction and most of the outages may be caused by direct strokes. On low-voltage lines outages may be caused by both induction and direct strokes, with most of the outages caused by induction. Induction may be electrostatic or electromagnetic. In comparison with the electrostatic effect, electromagnetic induction by lightning is generally negligible.

Owing to the rapid attenuation of a surge as it is propagated along the conductor, spark-over will ordinarily occur near the point of origin if at all. However, spark-over may occur at dead ends or other voltage reflection points even when they are at a considerable distance from the point of origin.

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 depends upon 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 $V = gah = Gh$, 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 (164 kv/m) have been measured on transmission lines in practice and 85 kv/ft (279 kv/m) on a special antenna. One case of 90 kv/ft (295 kv/m) has been recorded. The actual gradient g may be as high as 100 kv/ft (328 kv/m), so that for rapid discharges and direct hits the induced voltage (in kilovolts) approaches the height of the line in feet multiplied by 100.

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.

If expulsion tube lightning arresters are connected to the line, they serve to lead the surge directly to ground.

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 (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 sparkover by most of these voltages, but on lower-voltage lines they may be very troublesome. Not only will a lightning sparkover 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.

Higher voltages than the above have been recorded for direct hits, in one case 4,500 kv being reached. It is usually direct strokes that do damage.

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 conductors. 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.

It has been found experimentally that one ground wire will reduce the induced voltage to approximately 50 percent of its original value, two ground wires to approximately 33 percent, and three ground wires to approximately 25 percent, 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. Troubles with the ground wire in the past have often been due to poor mechanical design. The ground wires should have a life fully as long as the line conductors. If economically feasible, they should be strung far enough from the line conductors so that in case of a direct stroke to the ground wire in midspan, flash over will not occur to the line conductors.

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 nearby flash of lightning.

The intensity of different claps of thunder is as variable as the current of lightning flashes, nearby 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. 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 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.

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. A No. 13 A. W. G. copper wire should carry the most intense discharge observed by McEachton to the Empire State Building (1941), for which the integrated value of the square of the current was 200,000 ampere^2-seconds. At the point where the discharge enters or leaves the metal, there will be produced a local development of heat equal to the product of the total charge in coulombs by the electrode drop in potential, which may be 6 to 8 volts. This can melt about ½ mm^3 of metal per coulomb in the stroke. Most of the charge is carried by the relatively low current that flows for the fairly long intervals between component strokes, and such discharges are most likely to do damage by melting and by igniting solid materials. In contrast, the transient high current peaks tend to tear or bend metal parts by the momentary electromagnetic forces that are developed in proportion to the square of the instantaneous 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 is 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. When the moisture in the pores of the wood is changed to superheated steam, its volume increases over 1000-fold and generates tremendous local pressure with explosive results.

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 flammable 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. The high percentage of fatalities from lightning shocks is in part due to the fact that nine-tenths of such accidents occur in isolated places where few or none are acquainted with the proper first-aid 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 and maps are shown with isoceraunics, or lines of equal thunderstorm frequency, drawn upon them for the different months of the year. Quoting an article by W. H. Alexander:[5]

> 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.

[5] Monthly Weather Review **52**, 337 (1924).

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 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.

The accumulated results of thunderstorm records from a large number of stations for 40 years are summarized in figure 3, which shows the contours of equal thunderstorm frequency. The number opposite each line is the average number of days a year on which thunder is heard. Note that no part of the country is entirely free from thunderstorms, although they are relatively infrequent along the Pacific coast. There are two centers of maximum activity, one over Tampa and a lesser one over Santa Fe.

This chart, however, gives no indication of the intensity of individual thunderstorms as regards electric 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

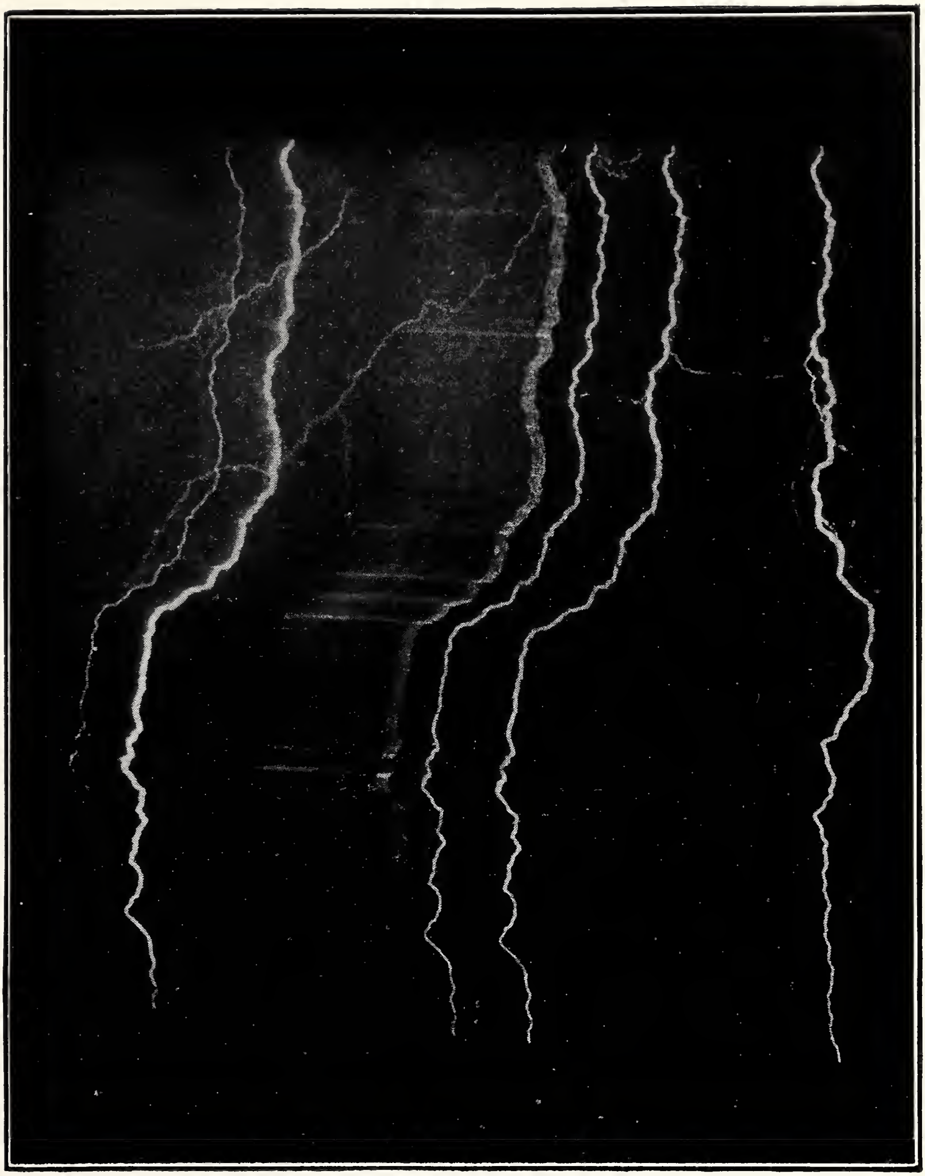

FIGURE 1.—*Photograph of a lightning flash taken with a moving camera by Doctor Walter*

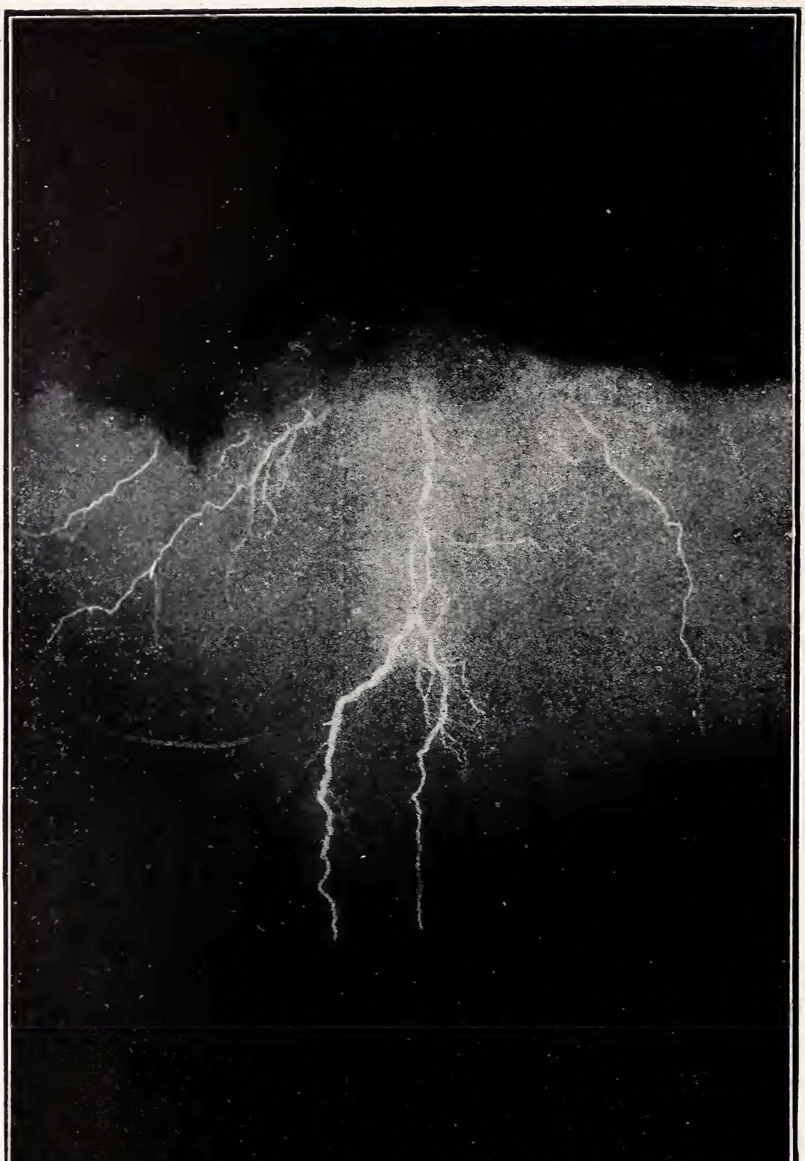

FIGURE 2.—*Same lightning flash as in Figure 1, taken with a stationary camera*

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.

The heights of the cloud bases above earth during thunderstorms depend to a considerable extent upon the topography, and range from less than 1,000 feet (305 m) to more than 9,000 feet (2,740 m). The more usual heights are between 3,000 feet (914 m) and 5,000 feet (1,520 m). In some localities where extensive lightning studies have been made, the average cloud height has been found to be 1,500 feet (457 m), and in still other localities heights of 500 feet (152 m) have been observed.

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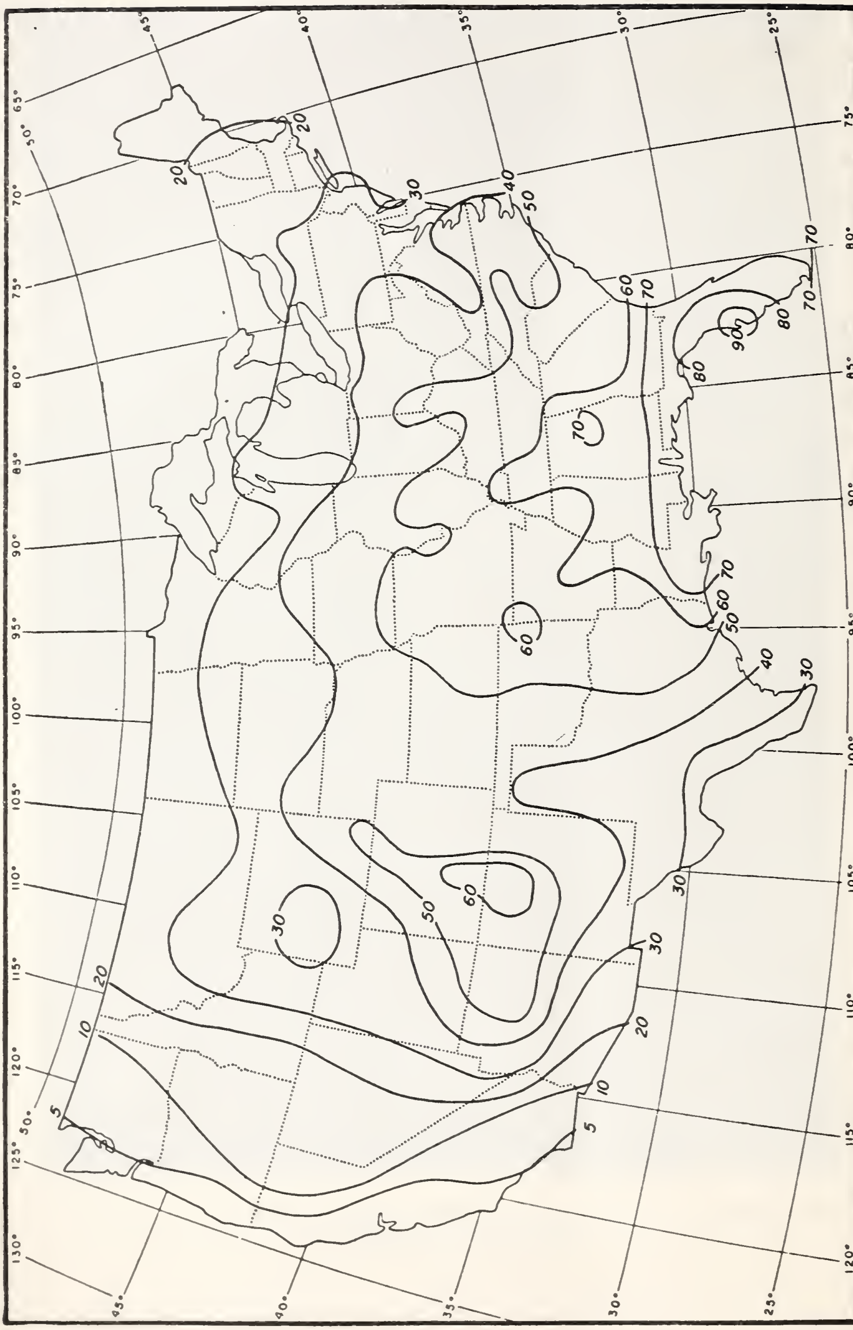

FIGURE 3. *Average number of days with thunderstorms.*
Annual 1904 through 1943. Based on 217 first-order stations.

APPENDIX B.—BIBLIOGRAPHY

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