

Lightning Protection Systems: Advantages and Disadvantages

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Abstract—The successful 200-year-old method of using a (Franklin) rod to collect, control, and convey to earth the awesome and destructive power of lightning has produced other controversial, potential alternate methods. The mechanics and interaction of lightning-producing thunderclouds and earth are discussed. Compared to the Franklin Air Terminal (rod) and Faraday Cage method, the debatable advantages and disadvantages of the early streamer emission-enhanced ionizing air terminal and multipoint discharge systems are examined, along with conceptual future methods of lightning protection.

I. INTRODUCTION

THE forces associated with lightning are enormous and unpredictable. Controlling and directing the energy of lightning to protect humans, buildings, and equipment is a concern of the electrical engineer. This paper will present an overview of lightning protection from the methods currently available in the marketplace to ideas conceived for the future. The methods range from the 200-year-old Franklin Rod to laboratory concepts, from mature methods to immature procedures, from the codified to the controversial.

To properly select a system to protect buildings and structure from lightning damage, one needs to know the types of interaction that occur between clouds and earth. The types of lightning discharges and the methods of initiation of a lightning discharge are a concern.

The problem with lightning is the multitude of differences recorded regarding the parameters. There is a profuse amount of information, data, and theories concerning lightning that needs to be codified. At the present, statistically significant comparisons of climatological and geographical data need to be made. This is understandable when one considers the different characteristics of a thunderstorm, such as intensity, duration, speed, height, terrain, polarity, geographical location, etc. With information on lightning being collected all over the earth's surface, it is no wonder different values are cited for the various parameters. For instance, the numerical data for charge in an intracloud discharge have seven entries, ranging from a low of 10 C (Coulomb) to a high of 90 C, with the average

being 33 ± 27 C [1]. Thus, for any value given for a parameter, a different value can usually be found.

A. History

From the oldest civilizations to today, man has been fascinated with the fireworks in the sky. Like yesterday, myths, fiction, and imagination pervade the subject. Ben Franklin's possible fear of ridicule prompted him to perform his kite flying experiment, to prove lightning was the same as electricity stored in a Leyden jar, with only his 21-year-old son in attendance. The first mention of lightning rods was a note published in *Gentleman's Magazine*, May 1750 and in the London edition of this book on electricity, published in 1751, where Franklin recommended the use of lightning rods to "...Secure Houses, etc. from Lightning."

In 1876, James Clerk Maxwell suggested that Franklin's lightning rods attracted more lightning strikes than the surrounding area. He suggested that a gunpowder building be completely enclosed with metal, forming a Faraday's Cage. If lightning struck the metal enclosed building, there would be no current flowing within the building. The current would be constrained to the exterior of the building. It would not be necessary to even earth the metal building.

Since 1904, the National Fire Prevention Association's (NFPA) Standard No. 78 (renumbered to Standard No. 780) for "Specifications for Protection of Buildings Against Lightning" has existed. In 1945, a reorganization occurred, and the American Institute of Electrical Engineers (now the IEEE) joined the combined sponsorship of the Standard. In 1947, the NFPA assumed control of Standard No. 78, and has periodically revised it.

NFPA 78 covers lightning protection requirements for ordinary structures; miscellaneous structures and special occupancies; heavy-duty stacks; and structures containing flammable vapors, gases etc. The purpose is the safeguarding of persons and property from exposure to lightning [2].

NFPA has subdivided Standard 78 into two standards and has renumbered it. NFPA 780, entitled, "The Lightning Protection Code," and NFPA 781, "Lightning Protection Systems Using Early Streamer Emission Air Terminal," are the new numbers and titles. NFPA 781 is under development and consideration.

The ionizing method of lightning protection came from the inspiration of J. B. Szillard, who presented his idea in

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a paper read to the Academy of Sciences in Paris on March 9, 1914. Gustav P. Carpart, who was also a colleague of Madame Curie, patented the first ionizing lightning method in 1931 [3]. Alphonse Capart, son of Gustav, improved the device in 1953, leading to commercial development. (See Section V for a detailed discussion.)

In 1774, Dr. Franklin reported his intent to "draw the electrical fire silently out of a cloud before it became high enough to strike, and thereby secure us from that most sudden and terrible mischief." Thus, Franklin proposed two methods for lightning protection: the rod to control the strike, and the dissipation method. He evidently discarded the dissipation method in favor of the rod.

The multipoint discharge method of lightning protection was patented in 1930. (See Section VI for greater detail.)

In 1955, the Lightning Protection Institute (LPI) [4] was formed. In 1978, it was chartered as a not-for-profit corporation. LPI generates standards on installation, LPI 175, which is similar to NFPA 78; and materials, LPI 176; and the inspection guide, LPI 177.

Roy B. Carpenter, Jr. entered the lightning protection field using the multipoint discharge system in 1971. Concern over the validity of the claims being made by R. B. Carpenter, Jr. and his companies prompted J. Hughes to organize a "Review of Lightning Protection Technology for Tall Structures," which was held at the Lyndon B. Johnson Space Flight Center in Clear Lake City (Houston), TX on November 6, 1976. The final report was issued January 31, 1977.

The last significant event was the Federal Aviation Administration (FAA) report on the "1989 Lightning Protection Multipoint Discharge Systems Tests Orlando, Sarasota & Tampa, Florida.

The "zone of protection" concept, before the late 1970's, consisted of the traditional straight line "cone of protection" from the tip of the lightning rod to the ground. The steeper the angle, the greater the degree of reliability of protection that could be achieved. The rolling ball concept was introduced in the late 1970's. (See Section IV for a detailed discussion.)

II. NATURAL OCCURRING LIGHTNING

A. The Thundercloud Formation

The definition for thundercloud or thunderstorm is the requirement that thunder must be heard. The only natural occurring disturbance that results in the sound of thunder is lightning. Thunderstorms are composed of strong wind and rain, with possible hail and snow, and are usually convective cumulonimbus clouds. About 1000 thunderstorms are active at any one time over the surface of the earth.

The solar heating produces vertical air movement that meets the cooler upper air, depositing water vapor. Since mountaintops are higher and become warmed first, before the valleys, they often contribute to the unstable air condition. The rotation of the earth results in the birth of new storms moving west as the day progresses. As the sun moves west, the earth is heated. The rising air currents

carrying water vapor contribute to the formation of the thundercloud late in the afternoon. Storms develop along active cold fronts. The greatest activity for storms is in the temperate zones, and the frequency tapers off as the poles are approached.

Thunderstorms range in size from 3 km to more than 80 km long. To be capable of generating lightning, the cloud needs to be 3 or 4 km deep. The taller the cloud, the more frequent the lightning. The duration of the life of a storm is about 2 h. There are many factors that contribute to the life of a storm, such as location, solar heating, water vapor, etc.

The surface of the earth is charged negatively on the order of 5×10^5 C, resulting in an electric field intensity of approximately $0.13 \text{ kV} \cdot \text{m}^{-1}$. The opposite positive distributed space charge is contained in the lower atmosphere. Charge is carried to earth by rain droplets. The storm cloud becomes a dipole, with the top of the cloud positively charged and the bottom of the cloud negatively charged. When the surface field strength exceeds $1.5\text{--}2 \text{ kV} \cdot \text{m}^{-1}$, objects with small radii or with sharp points begin point discharge of ions.

B. Point Discharge

The process of point discharge can begin on naturally occurring drops of water within a cloud or on trees, or on a sharp pointed metal protrusion. When the field strength is sufficient, electrons are accelerated and collide with gas molecules, ionizing them. This small amount of ionized air is at the tip of the sharp point or water droplet. The ionizing potential is less than the kinetic energy, and additional electrons are released.

The excessive electrons build up into an electron avalanche and form a corona discharge. To start this process, an initial electron is required. Cosmic-ray activity or radioactive decay can furnish the initial electron. This action of radioactive decay, ionization, is the basis of the early streamer emission-enhanced ionizing air terminal method of lightning protection.

The ionized air produces an electric current flow that weakens the electric field. This action occurs when the field strength is as low as $2 \text{ kV} \cdot \text{m}^{-2}$. Current densities of $10 \text{ nA} \cdot \text{m}^{-2}$ (nanoamperes) have been observed when the electric field strength is $10^4 \text{ V} \cdot \text{m}^{-1}$ [1]. In 1925, Wilson demonstrated "that these point discharge currents act to limit the strength of the electric field near the earth and that in the presence of these currents the strength of the field beneath a widespread storm should increase with altitude..." [5]. Point discharge current is the foundation for the multipoint discharge system.

C. Types of Lightning Discharges

There are four (4) classifications of lightning discharges. They are

- 1) intracloud discharges (IC),
- 2) cloud-to-cloud,
- 3) cloud-to-air, and
- 4) cloud-to-ground (CG).

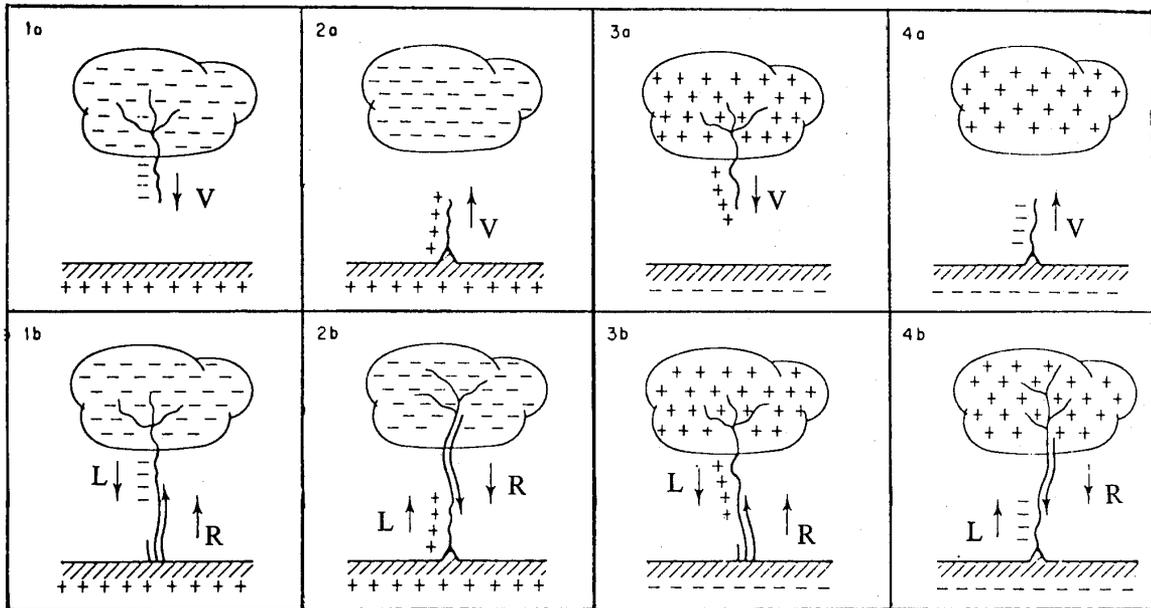


Fig. 1. Eight types of lightning strokes, based on direction of leader and return strokes. L: Leader, R: Return Stroke, V: Direction of Propagation, +: Positive Charge, -: Negative Charge.

Over 50% of the lightning flashes occur within the cloud. A few flashes start within the cloud, and ended either in an adjacent cloud or in the air. Other than induced fields and the change in earth charge location, which can generate adverse voltages in electrical circuits, the atmospheric strike is of less concern than the cloud-to-ground strike. Electronic systems can be protected from lightning discharges [19], [20].

1) *Cloud-to-Ground (CG)*: The cloud-to-ground strikes are classified into types of lightning flashes. Uman [6] has four categories, while Golde [1] has eight types. Golde takes into account the return stroke. See Fig. 1.

The majority, 90% of the cloud-to-ground flashes, or 45% of all the flashes, are Category 1, Table I. The discharge starts as a negative leader from the cloud. The cloud is positively charged at the top. 10% of the cloud-to-ground discharges are initiated from the top of the cloud with a positive leader moving down toward the earth. This is Category 3, Table I, and constitutes 5% of all lightning flashes.

The extremely rare flashes are the upward moving ground to cloud leaders, Categories 2 and 4 from Table I. They occur from high mountaintops and tall man-made structures. Uman reports that at the Kennedy Space Center, individual storms produced between 1 and 4000 lightning strokes. "Roughly 30 to 40% of these flashes, depending on the storm, were CG and well over half were IC." The average flashes, mean duration, and density for the Kennedy Space Center will be of little value, unless your facility is located at the Space Center.

D. The Mechanics of the Lightning Strike

According to Tables I and II, there are several types of lightning strokes that are of concern. The majority of the

strokes are negative leaders from the cloud to the ground. The other category of concern is Category 3, Table I, the positive leader, cloud-to-ground strike. The ground-to-cloud strokes are less common, but a concern, depending on the location of the facility. The intracloud and the cloud-to-air strikes can produce electromagnetic coupling with electric systems. This subject and the method of protection has been covered in [19] and [20].

1) *Negative Leader, Cloud-to-Ground*: The negative downward leader begins as a series of distinct steps. Ionization at the bottom of the cloud occurs as described above for the point discharge. There is no agreement about the exact process within the cloud, but it seems as if what occurs on the ground also should occur in the cloud. As the wind blows away the leading ionized air, the leader has to "regroup" and build up the ionization breakdown of the air again, producing another discrete step.

Some typical values for the leader are [6] as follows.

- 1) The time for the leader to move to the next step is 1 μs in duration.
- 2) The length of the leader is tens of meters.
- 3) The pause time between steps is 20-50 μs .
- 4) A fully developed leader can effectively lower 10 C or more of negative charge.
- 5) Charge is lowered in tens of milliseconds.
- 6) Downward speed of propagation is about $2 \times 10^5 \text{ ms}^{-1}$.
- 7) The average leader current is between 100 and 1000 A.
- 8) The leader steps have peak pulse currents of at last 1 kA.
- 9) The starting and stopping of the leader produce downward branches.

TABLE I
TYPES OF LIGHTNING CLASSIFICATIONS
BETWEEN CLOUD AND GROUND [6]

Category	Originate From	Leader Charge
1	Cloud	Negative
2	Earth	Positive
3	Cloud	Positive
4	Earth	Negative

TABLE II
TYPES OF LIGHTNING CLASSIFICATIONS [1]

Type	Originate From	Leader Charge	Return Stroke
1a	Cloud	Negative	None, Air discharge, open country, no buildings.
b			Yes, Ground Strike.
2a	Earth	Positive	Charge flow to Earth, Tower is Negative.
b			Multiple flash, example Empire State Building.
3a	Cloud	Positive	Intra-cloud displacement current.
b			Positive up return stroke, rare.
4a	Earth	Negative	Tip cathode, positive cloud and positive continuous current, rare.
b			Imitated as 4a, after 4-25 ms sever positive down discharge, mountain areas.

10) The potential difference between the leader and the earth is in excess of 10^7 V.

As the electric field increases, additional ionization in the form of point discharges occurs on the ground. With the potential difference between the leader and the earth in excess of 10^7 V, breakdown occurs and ground discharges begin to move up toward the downward moving leader. The two leaders meet some tens of meters above the ground.

Uman [7] describes the transfer of charge. "The leader is effectively connected to ground potential. The leader channel is then discharged by an ionizing wave of ground potential that propagates up the previously ionized leader channel. This process is the first return stroke. The electric field across the potential discontinuity between the return stroke, which is at ground potential, and the channel above, which is near cloud potential, is what produces the additional ionization."

Some typical values for the return stroke are [7] as follows.

1) Upward speed of the return stroke is typically one-third to one-half the speed of light near the ground and decreases as it approaches the cloud.

2) The total time between ground and cloud is on the order of 100 μ s.

3) Peak current of the first return stroke is 30 kA.

4) Time from zero to peak is a few microseconds.

5) Currents at the ground decrease to one-half in 50 μ s.

6) Hundreds of amperes may flow from a few seconds to hundreds of milliseconds.

7) Leader channel is heated to 30 000 K.

8) All the charge contained in the leader, step branches, and in the cloud charge cell are deposited on the ground. Additional average lightning stroke parameters are the following.

9) The total charge transferred is from 2 to 200 C.

10) Currents range from 20 to 400 kA.

11) The leader travels from 1 to 210 ms^{-1} .

12) The time between return strokes 3 to 100 ms.

13) The number of return strikes ranges from 1 to 30, with the average being 4.

14) The rise time ranges from a few nanoseconds to 30 μ s and to 50% of peak rise time in 10-250 ns.

If additional charge is available in the cloud, another leader can use the ionized path and additional return strokes can develop.

2) *Positive Leader, Cloud-to-Ground:* Positive cloud-to-ground strokes originate in the upper part of the thundercloud where the positive charge resides. The difference between the negative stroke and the positive one is the leader and is continuous without steps. There is only one return stroke. The positive stroke discharges the largest amount of current, in the 200-300 kA range. Although they are rare in summer storms, constituting only 1-15% of the flashes [7], the last stroke may be a positive one. Positive strokes occur in winter storms, in the higher latitudes, and in mountainous regions. After the return stroke transfers the initial large current, a continuous current continues to flow.

Information supplied by WSI Real-Time Lightning Information showed that the number of positive strokes may be larger than indicated above. In one 6 h period in northeast Texas, the graphical display indicated that approximately 35% of the strikes were positive. During another 21 min period of the 78 strokes recorded on March 11, 1993 at 5:00 PM, 32% were positive strokes. It is evident that additional studies are needed.

3) *Leaders, Ground-to-Cloud:* Tall man-made structures and mountain peaks can generate either positive or negative leaders from the ground to the clouds, Categories 2 and 4, Table I. The negative leaders, either from cloud-to-ground or from earth-to-cloud, are stepped, whereas the positive leaders are continuous. The positive leaders from ground-to-cloud discharge between 100 and 1000 A of current.

Not only must the engineer, in selecting lightning protection, be concerned with the Isokeraunic Map, with the expected number of thunderstorms per day, but the latitude and height of the structure must be considered also.

III. CONNECTION TO EARTH

The most important consideration is the connection to earth. The most effective and least costly is the use of the

Ufer grounding or rebar ground, as described in Fagan and Lee's paper [8]. The National Electrical Code, Section 250-81(c) permits the use of either the reinforcing bars or a 20 ft (6.1) length of copper conductor to be contained within the foundation. Golde [1] indicates that $300 \text{ kg} \cdot \text{m}^{-3}$ ($18.7 \text{ lb} \cdot \text{ft}^{-3}$) of cement should be contained in the foundation and it should be 10 cm (3.9 in) thick. The German regulations prescribe the use of a steel plate in the bottom of the foundation. Likewise, the Finnish Electrical Safety Code also requires the use of conductive material in the foundation.

The earth electrode can act as a surge impedance when a large value of current is injected into the ground system. The surge can be propagated like a wave, with the normal rules of reflection applying. The soil can act like a dielectric, and due to the high-voltage gradients at the electrode surface, the soil can actually break down. This breakdown of the soil can increase the resistivity of the soil during the surge.

A. Risk Assessment

One can determine the risk of loss, or the susceptibility due to lightning, from an equation found in [2] and [9]. The risk index considers the

- 1) type of structure
- 2) type of construction
- 3) relative location
- 4) topography
- 5) occupant and contents
- 6) lightning frequency isocerauic level.

Lightning protection can be divided into two methods: 1) capture, divert, and control of the lightning strike, or 2) artificially initiated lightning. The methods that capture, divert, and control lightning strikes are

- Franklin Air Terminal (Rod)
- Faraday Cage
- Early Streamer Emission-Enhanced Ionizing Air Terminal
- Multipoint Discharge Systems.

Some will question including the multipoint discharge systems in the same classification as the Franklin Rod. From the extensive testing that has been performed, there seems to be little doubt that the multipoint discharge systems function the same as the Franklin Rod.

IV. FRANKLIN ROD AND FARADAY CAGE

Although the Franklin Rod and the Faraday Cage are two different methods, they are installed together most of the time, and thus will be discussed together.

A. The Franklin Rod

Franklin chose the sharp-pointed rod over the blunt rod to intercept the lightning stroke and transfer the electric charge to earth. Disagreement originated in England with King George III who installed blunt rods in the belief that sharpened rods would attract lightning.

Llewellyn [10] described extensive research on the dif-

ferences between the blunt and the pointed structures. The equipotential lines are approximately parallel and very close to a sharp, 3.3 cm radius structure. The equipotential lines for a blunt structure of 3.3 m radius assume a 45° angle from the edge to the distance equal to the height of the structure where the lines become parallel to the earth.

Llewellyn plotted the effect of the wind on ion emission. He concluded that a sharp point goes into the corona in low fields of $100 \text{ V} \cdot \text{m}^{-1}$ and just immediately around the tip, whereas the blunt point goes into the corona only in high fields of $10\,000 \text{ V} \cdot \text{m}^{-1}$, but out to a distance twice that of the sharp point [10].

In 1901, the British Lightning Committee was formed. It addressed the area of protection that a vertical lightning rod would afford, and concluded that the area would be the angle from the tip of the rod to a distance on the ground equal to the height of the rod, a 45° angle. This area under the straight line from the rod tip to the ground was called the "zone or cone of protection." Experience over the years indicated that the straight line for the "cone of protection" could not always be depended upon. It was found that lightning was striking the side and not the top of tall structures.

Negative lightning leaders advance in discrete steps of 45.7 m (150 ft) as they advance from cloud to earth. When the leader is within 45.7 m (150 ft) of the earth, the leader will be attracted to a object. This explained why tall structures are struck below the top. This led to a new concept in the late 1970's, the rolling ball concept.

One needs to visualize a sphere of 45.7 m (150 ft) radius and roll this ball over the surface of the earth. Where the ball's surface rests on two protruding projections, everything under the surface of the ball would be protected. In the case of a tower over 45.7 m (150 ft) high, the ball would rest against the tower at an elevation of 45.7 m (150 ft), and would rest on the surface of the earth 45.7 m (150 ft) away from the base of the tower. Everything under the ball would be in the "zone of protection." (See Fig. 2.)

Details of installation are covered in [2] and [9].

B. The Faraday Cage

A Faraday Cage consists of metallic material completely surrounding an object, which results in an electrostatic shield around the object. The *IEEE Standard Dictionary of Electrical and Electronic Terms* does not contain a definition for a Faraday Cage or electrostatic shielding. When used in the context of lightning protection, conductors are spaced in a criss-crossed fashion across the structure's roof and down the sides.

The closer the spacing of the conductors, the more effective is the Faraday Cage in attenuating any radio frequencies (RF) or electrostatic interference. As the conductor spacing increases, the efficiency decreases. With the larger spacing and the decreased protection, Franklin Rods are installed. The combination of the cross conduc-

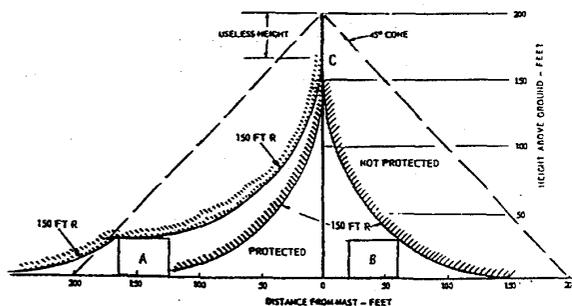


Fig. 2. Zone of protection. Rolling ball concept.

tors connecting the Franklin Rods results in the Franklin Rod and Faraday Cage concept of lightning protection.

The cost of an effectively constructed Faraday Cage for lightning protection by itself is more costly than the combination. The Faraday Cage will not protect the interior of the structure from the surge due to a close lightning stroke and the electromagnetic pulse that ensues.

Modern steel frame buildings with a reinforcing bar in the concrete and connected to the steel type of construction approach the Faraday Cage concept. The width of the "mesh" of this type of construction was examined by Schwab [11], and he concluded that the risk of a lightning stroke penetrating the "mesh" was extremely small.

V. EARLY STREAMER EMISSION-ENHANCED IONIZING AIR TERMINAL

The early streamer emission-enhanced ionizing air terminal consists of a Franklin rod with a radioactive radium and or thorium source for the generation of ions connected to a special down conductor attached to an earthing system.

A. The Air Terminal

There are several shapes available for the air terminal. One has the point of the air terminal protruding through a spherical or ellipsoidal shaped "ball," approximately 300 mm (11.8 in) in diameter, containing radioactive material. Another design has a plate mounted under the "ball," which contains the radioactive material.

In 1914, the Hungarian physicist Szillard raised the question, "Would the Franklin Rod be enhanced by the addition of radioactive material that could supply ions to increase the attraction of a lightning stroke?" Such radioactive rods have since been installed all over the world.

Several radioactive materials have been used. Tests by Müller-Hillebrand in 1962 comparing two sets of terminals under natural thunderstorm activity concluded that there was no advantage to the use of a radioactive radium 226 device. In clear conditions, the radioactive rods produced an emission current of 10^{-8} A with no measurable current in the standard rods. Under thunderstorm conditions, when the field strength reached $1000 \text{ V} \cdot \text{m}^{-1}$, both sets of rods reached the same current flow.

Several other experimenters have conducted tests on radioactive rods. The strength of radioactive material has

been limited to approximately 1 mCi (milliCurie), which is safe to humans. Gillespie in 1965 suggested that if radioactive material would contribute to the attraction of lightning, then would not the use of typical radiotherapeutic devices, using stronger material such as 3 kCi of cobalt 60, stronger by a factor greater than 10^6 , draw lightning to the roofs of hospitals? There is no indication that hospitals are struck more than any other structure [1].

It has been shown that, with an increase in height, the availability of ions decreases. Cassie concluded that if a source of 3 kCi were used and if a negative stroke of 200 kA occurred, the distance would be decreased by about 6 cm [12]. Up to 1977, the conclusions were that the addition of radioactive material was no more effective than using a standard Franklin Rod. Solidifying this conclusion was the event in Rome where the papal crest was struck by lightning although it was "protected" by two 22 m (72 ft) high radioactive conductors [1]. However, the distance between the nearest radioactive conductor and the crest was 150 m (492 ft). A 22 m high mast has a zone of protection, using the rolling ball theory, of only 33.5 m (110 ft).

Tests performed at the John Lapp High Voltage Laboratory in Leroy, NY, under what could be referred to as "natural conditions," were reported in a paper presented at the IEEE Power Engineering Society's 1988 Summer Meeting [13]. Additional test data are contained in a paper presented at the Industrial and Commercial Power Systems Department Technical Conference in May 1993 [14].

A test facility was set up outside. Mounted overhead at an elevation of 6.81 m (22.34 ft) was a bare wire mesh 7.7 m (25.26 ft) square. The distance between the tip of the air terminals and the overhead mesh varied between 3.47 m (11.4 ft) and 3.64 m (11.9 ft).

The conclusion reached using radium $72 \mu\text{Ci}$ and/or thorium $0.72 \mu\text{Ci}$ enhanced air terminals under high relative humidity and electrical (dc) bias was that the ionized terminal is more likely to attract flashover than is the nonionized air terminal. Radium sources of ionization are more effective than other available and permitted sources because of the high radioactive rate. Outdoor field tests have been conducted in western New York State and in Australia, and show the same results, that ionized air terminals are more effective in attracting lightning strikes than were the nonionized Franklin Air Terminals. The outdoor testing is continuing.

The field tests are more indicative than the controlled short distance between the terminals and the overhead mesh laboratory tests. As cited above, the negative step leader advances in steps of tens of meters, and the downward leader meets the upward leader some tens of meters above the ground. Wind will blow the ion stream, affecting the height that the ion stream can obtain [15]. With the testing that has been performed, the NFPA is now considering adopting Standard No. 781 entitled, "Lightning Protection System Using Early Streamer Emission Air Terminal."

B. The Triax Downconductor

The conductor connecting the early emissions air terminal and carrying the discharge current to the earth connection is specially constructed. The advantages of the construction are the prevention of any side flashes to the structure under protection and the safe conductance of the lightning current to ground.

The triax cable concentric construction consists of a center strain cord surrounded by a plastic filler. The third layer is a 50 mm (slightly less than 1/0, 98.7 kcmil) helix wound copper conductor, covered by primary insulation. Copper tape shielding tape is over the primary insulation, and it is covered by secondary insulation. The secondary insulation is covered by a metal foil with an outer conductive sheath. If one were to exclude the center strain cord and plastic filler, the construction would resemble a medium voltage conductor. See Fig. 3.

The application of the triax conductor is similar to the recommended method for the installation of instrumentation and control, single signal cable. The interior conductor is the current (signal)-carrying conductor. It appears that the inner shield is floated at the top. (With instrument cable, the interior shield is connected at only one location, usually the control room.) Like instrumentation cable, the outer shield, metal jacket, is connected, bonded, at every convenient location to the building metal structure.

The downconductors used in the Franklin Air Terminal and Faraday Cage construction must maintain a very wide sweep to prevent side flashes from occurring. The triax design cable eliminates the problem of side flashes. The downconductor can be run inside the building in relative safety. The structure will carry the capacitive charging current.

The object of the center filler is to produce a large-diameter current-carrying conductor to compensate for the skin effect.

The mathematics that have been developed leave no question unanswered as to the functioning of the triax downconductor. The triax downconductor concept is viable. Installation data detailing the number of installed feet and the sizes are not available. Testing on the downconductor needs to be made available.

VI. MULTIPPOINT DISCHARGE SYSTEMS

The multipoint discharge system is an extremely controversial subject. It is difficult to obtain data-driven information on the ability of the system to function as advertised. There are other manufacturers and installers of the multipoint discharge systems. However, only the major patent-holding manufacturer's system has come under scrutiny. (For details, see the Appendix.) The information presented is not meant as an endorsement of the system.

A. Concept

When a thundercloud passes overhead and the field strength is greater than $2 \text{ kV} \cdot \text{m}^{-2}$, point discharge cur-

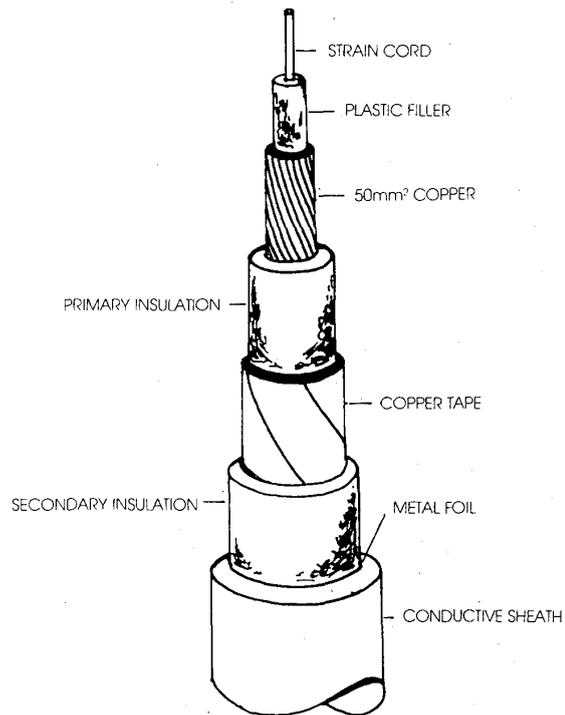


Fig. 3. Triax downconductor cable construction.

rent are generated. Any natural occurring sharp point, such as trees, blades of grass on flat plains, or pointed rocks on mountain tops, will generate corona discharge. As discussed above, Wilson showed in 1925 that point discharge currents act to limit the electric field strength.

B. Design Considerations and Method of Operation

The system consists of three elements: 1) the dissipator or ionizer, 2) the ground current collector, and 3) the conductors connecting the dissipator and the ground current collector.

1) *Grounding*: The earthing method used consists of ground rods about 1 m long (40 in). Chemical ground rods are used sometimes, depending on the soil resistivity. The ground rods are spaced about 10 m (33 ft) apart. If available, other grounding objects are interconnected, such as utility systems building electrical ground systems, etc. The object is to have an extremely low earth connection. Extensive testing of the soil resistivity is conducted before a system is installed.

2) *Conductor*: The earthing connection is connected to the dissipator by conductors buried 25 cm (9.8 in) deep.

3) *Dissipator*: There are many shapes and forms for the dissipator. It is reported by one manufacturer that the competition had four (4) similar dissipator designs with a multiplicity of points, which had too many points, too close together, making them ineffective [16].

The configuration depends on the size and height of the structure to be protected, soil conditions, prevailing wind conditions, storm patterns, altitude, and Keraunic Num-

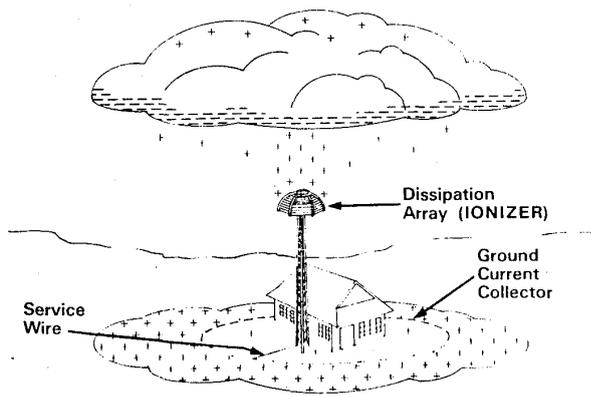


Fig. 4. Multipoint dissipation system.

ber. The basic configuration consists of a conductor with two (2) sharp-pointed "rods" connected at right angles to each other, and the right angle "rods" are spaced along the conductor. The configuration looks like barbed wire. This conductor with the multiple sets of two (2) "rods" spaced periodically along the length of the conductor is referred to as the "dissipating medium."

Using this "dissipating medium," several array configurations can be formed. The "Hemisphere Array" is shaped like an umbrella. The "dissipating medium" is wound around the umbrella. It is applied to towers up to 100 m (328 ft) in height.

The "Trapezoid Array" is similar to the umbrella, except that it is flat and at a 90° angle to the tower. Compared to the "Hemisphere Array," it offers less resistance to any wind loading. The "Trapezoid Array" is to protect very high towers where some protrusion such as a radio transmitter must be above the array. This configuration purports to protect against lightning side strokes.

The "Conic Array" looks like a "May Pole" with the "dissipating medium" attached at a point below the top of the tower or pole. Each conductor containing the "dissipating medium" is separately connected to the earth.

The "Roof Array" is used to protect a building. "The Array is fitted to the building so the dissipating medium is parallel with the lines of equal potential as formed by the building," as stated in an advertising brochure. The installation appears to be the same as the Franklin Rod installation, except that there are many more sharp protruding points.

The "Perimeter Array" is similar to the "Roof Array" and is used to protect tanks.

C. Testing and Effectiveness

Two extensive investigations of the multipoint discharge system have been conducted by organizations other than the manufacturers. J. Hughes organized the first investigation, "Review of Lightning Protection Technology for Tall Structures," which was held at the Lyndon B. Johnson Space Flight Center in Clear Lake City (Houston), TX on November 6, 1976. The agenda had R. B. Carpenter presenting "170 System Years of Lightning Prevention."

Twelve distinguished experts presented a different view of the efficiency of the multipoint discharge system. Over 250 pages of discussion are contained in the report.

The conclusions reached by Dr. R. B. Bent and S. K. Llewellyn [15] summarize the conference conclusions.

1) History shows that single-point corona currents exceed multipoint current.

2) History also shows that currents of a few tens of microampere are the maximum one can expect from arrays atop towers of the order of a hundred feet.

3) Corona discharge from beneath a thunder cell will not influence the cells' electrical charge due to recombination of the corona ions and an excessive time for them to reach the charge centers of the cloud.

4) The maximum current recorded from a large array at 100 feet under a severe storm was under 40 A.

5) A single point at 50 feet always gave more corona than a dissipation array at the same height.

6) Corona current from natural sources such as a few trees will often exceed that of a dissipation array.

7) Corona current cannot provide a protective ion cloud for a large area to prevent lightning already in motion from striking. If such a cloud existed it would be more dangerous than the initial lightning stroke.

8) The dissipation arrays do not eliminate lightning. Lightning has been photographed striking an array many times and the currents measured were of the order of 30–50 kA.

9) Improvements of grounding systems or introduction of RF chokes were the major reason for the success claimed for the dissipation arrays.

10) The reported data and success claims have been critically analyzed and been found to be grossly in error."

The second main scientifically conducted testing of these systems was directed by the Federal Aviation Administration in 1989 at Orlando, Sarasota, and Tampa, FL airports [17]. Two manufacturers' multipoint discharge systems were installed. The lightning dissipation systems supplied by Lightning Eliminators & Consultants, Inc. were installed at the Tampa airport, and the lightning deterrent systems, supplied by Verda Industries, at the Orlando airport.

This test was prompted by the FAA Administrator. Prior to his assuming the post, he was instrumental in the installation of the multipoint discharge system at the Federal Express facility at the Memphis, TN airport. The vendor reports 22 years of history at the Federal Express installation.

The FAA's major requirements were:

"The contractor would be required to utilize the FAA's installed buried earth electrode system (counterpoise)."

"The installation would use the FAA's down conductors and counterpoise system."

The Sarasota airport was used as a control.

A lightning storm tracking system was used to activate a video recording system. Premagnetized audio recording tape was installed on the down conductors to measure the magnitude of any current flow in the event a strike to the

multipoint discharge systems occurred. (A tone is deposited on a straight length audio tape. The length audio tape is placed perpendicular to a down conductor. The magnetic field associated with the lightning current traveling down the conductor will erase the tone placed on the tape. The distance the tape will be erased is a function of the magnitude of the current.)

It is interesting to note what one vendor has stated about the other vendors: "The limited history available to date reveals that they do reduce the number of strikes to the towers they are to protect; but despite their claims, they do not prevent all strikes, or even more than about 50% of the potential strikes to the given structure. When they fail, they act as an air terminal, similar to the lightning rod and attract the more damaging strokes" [16].

At the control site, Sarasota, on June 25, 1988, a lightning strike was recorded striking the air traffic control tower. The equipment within the air traffic control tower suffered no damage. The conclusion reached by the FAA was that with a properly installed lightning protection system, per the National Fire Protection Association's Standard 78, the FAA's Standard 019, and the Underwriters Laboratory 96, lightning will not cause any damage to the equipment. There was no instrumentation in place at the time of the lightning strike to record the current flow.

"On August 27, 1989, the Tampa air traffic control tower received a lightning strike. This event was witnessed by air traffic controllers and at least two technicians at the tower cab during the lightning storm. Examination of the magnetic tapes by Emmorton Electrical Testing Co. of Bel Air, MD showed there was a current flow of 8000 to 10 000 amperes per conductor on the down conductors connected between the dissipation arrays and the earth electrode system. Several systems suffered outages as a result of this incident." (Robert J. Hopkins, P.E., Vice President of Emmorton Electrical Testing Company is deceased, and the company is no longer in existence.)

Additional investigation raised the question of calibration of the magnetic audio tape instrument. The strike could have been in the range of 100 kA.

"Because of numerous congressional inquiries which resulted from complaints by a lightning protection system vendor, FAA secured the services of nongovernment experts in the field of lightning phenomena to provide independent analysis on the suspected lightning strike at the Tampa ATCT during the tests" [17]. The experts confirmed that lightning did strike the lightning multipoint discharge array on the Tampa tower.

About six (6) air control electronic systems were out of service due to the lightning strike. It is believed that the current in the downconductor induced excessive voltage in the adjacent interior unshielded cables connected to the electronic equipment or a side flash occurred to the interior grounded metal. The failure of the equipment would no doubt have occurred regardless of which lightning system was installed.

Examination of the multipoint discharge arrays mounted on each corner of the tower roof revealed that four (4)

spikes were missing from one of the arrays. The downconductor was expanded as if it had conducted a large current flow.

The multipoint discharge systems were removed from both airports and the rods were reinstalled.

Many locations have installed the multipoint discharge lightning protection systems. The opinion of the owners of the systems is that the systems work as there are fewer or no reports of strikes after installation. When questioned if the system have been inspected to ascertain that the arrays have not been hit, no one has performed such an inspection. When asked if instrumentation was installed to record current in the downconductor, again the reply was negative. It is believed that the extensive earthing system discharges the strikes without damage to nearby electrical systems. One can also conclude that the failure of the FAA's test was the requirement to utilize the existing downconductors and earthing system, which no doubt were inferior to installations by the manufacturers.

The problem with accepting the multipoint dissipation systems is the lack of valid testing to disprove the extensive negative comments and studies.

VII. OTHER EXPERIMENTAL SYSTEMS

A. Rocket Initiated Lightning

Accidents involving aircraft and spacecraft have prompted research into the interaction of rockets and lightning. Rockets have been used to initiate lightning discharges. By trailing a grounded wire, a discharge to earth can occur. This usually results in an upward leader with no first return stroke. With a short conductor, an intracloud discharge can be triggered. Extensive studies are being conducted.

The use of rocket triggered lightning strokes can be used to verify the ability of a lightning protection system to protect a facility. The overall effectiveness of a lightning protection system for explosive handling and storage sites were tested using rocket-triggered lightning. The test data are contained in a paper presented at the Industrial and Commercial Power Systems Department Technical Conference in May 1993 [18].

Extensive measurements were made. Measurements included the short-circuit current between exposed metal parts, the open-circuit voltage between metal connected to the building grounding system and rebar of the walls and floor, electromagnetic fields, coupling-to-connector pins and other short exposed metal-like antennas, current flowing in the counterpoise system, etc. The importance of the counterpoise system in an earth-covered explosive storage structure as compared to the concrete-encased rebar, to dissipate the current into the earth, indicated a relative small amount of current flows over the counterpoise system. "Presumably the remainder of the current flows through the rebar, into the concrete, and into the soil directly and also into conduits and buried cables, thereby bypassing the counterpoise system" [18].

A pseudometal building has been constructed with extensive instrumentation installed on steel columns, piping,

sidewalls, etc. This instrumentation will measure the flow of lightning current with a building after it is struck. Additional tests of this building are currently being conducted. The results of this test will be of interest to all owners of metal frame buildings, and should be available by the end of 1994.

B. Lasers

Ball proposed in 1974 the use of lasers to discharge thunderstorms. The laser would produce multiphoton ionization. With the use of computers, the firing time could be determined from input measurements from the electrical field developed and from the thermodynamics of a thunderstorm. The laser beam could intercept a leader as it developed toward the earth. The laser beam would act as a conductor from the cloud to the ground and would be terminated by a downconductor and an earthing system.

VIII. COST COMPARISON

Cost comparisons of the three methods of lightning protection were made by soliciting bids for the protection of a new 35 kV, 7.5 MVA substation. The substation consisted of an underground 35 kV feeder, 7.5 MVA top-mounted bushings, with 30 ft pole construction. Drawings of the substation, showing the plan and elevation views, were made. Pictures of the installation under construction were included in the bid package.

A. Franklin Air Terminal Costs

The least costly was the Franklin Air Terminal mounted on two (2) existing 30 ft lighting poles located on the perimeter of the yard. Vendor A planned to use the existing substation ground grid, which the owner was to expose. The bid lacked any detail as to the height of the rods, downconductor size, etc. The cost from Vendor A was \$1540.00.

Vendor B supplied a very detailed form letter. The letter covered protection against surges, eliminating earth loops, details as to the electrical contractor responsibilities, roof repair, etc. This vendor will perform detailed engineering before selling a system. Their cost to protect the substation was \$14 000.00, supplying their own "poles."

B. Ionized Air Terminal Costs

Vendor B also supplied a quotation for an ionization air terminal system. The same detailed form letter citing the additional actions one needs to take to completely protect the site from secondary effects from a lightning strike were included. The costs was \$12 000.00 or \$2000.00 less than the Franklin Air Terminal system.

Vendor C, who supplies multipoint discharge systems, did not respond.

IX. CONCLUSIONS

The combined Franklin Air Terminal (rod) and modified Faraday Cage method of lightning protection has proven, over the intervening 200 years, to afford an economical and reliable method of intercepting, controlling,

and equalizing the charge, of the awesome and destructive power of lightning. Standards have been developed and the installation methods codified.

Modern steel-frame buildings or an open steel box-type of construction used in chemical and petroleum facilities, with a reinforcing bar in the concrete foundation tied into the building steel, approach the Faraday Cage concept. The width of the "mesh" of this type of construction was examined by Schwab [11], and he concluded that the risk of a lightning stroke penetrating the "mesh" was extremely small. If one is uneasy and a comfort factor is needed, rods can be attached to the topmost steel.

It is apparent from the two extensive tests of the expensive multipoint discharge systems that they function like an inexpensive Franklin Rod system. The manufacturer's insistence on an extremely low resistance connection to earth contributes to their effectiveness in conducting lightning strokes to earth where the charge is equalized. The claims of being able to dissipate any and all lightning strokes have been shown to be untrue.

Extensive testing in open fields, like the early streamer emission-enhanced ionizing air terminal systems can lead to acceptance. Instrumentation of existing systems will verify exactly how the questionable systems function.

The early streamer emission-enhanced ionizing air terminal systems has gained credibility. The field tests that are being conducted appear to substantiate the claims, whereas the open-air laboratory test results are dubious due to the lack of adequate height. The effect of wind on the ion stream needs to be quantified. The use of the rocket triggered lightning should be considered for comparison testing.

The work of Morris *et al.* confirms the efficiency of the concrete-encased rebar for grounding not only electrical systems, but earthing of lightning discharges. This confirms the use of rebar for grounding as presented by Fagan and Lee 20 years ago.

APPENDIX

The Lightning Eliminator System or the Dissipation Array® System is an extremely controversial subject. It is difficult to obtain factual information on the ability of the system to function as advertised. There are other manufacturers and installers of the multipoint discharge systems. However, only the major patent-holding manufacturer's system has come under scrutiny. The information presented is not meant as an endorsement of the system, but information is supplied in order to inform the reader.

A. Background

In 1930, J. M. Cage, a California resident, patented a multipoint discharge system to prevent lightning. In 1971, the application of this concept began to be marketed by Roy B. Carpenter, Jr.

There are conflicting documents about R. B. Carpenter, Jr. and his association with the four companies marketing this lightning method. One report, dated 1987, lists the following details [16].

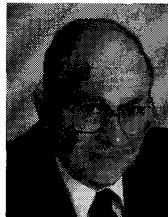
R. B. Carpenter, Jr. in 1971 formed a company, Lightning Elimination Associates, Inc. (LEA), now known as LEA Dynatech Inc. Since June 1971, the Dissipation Array[®] System (DAS) has been marketed. The Dissipation Array[®] System has been patented in the U.S. and in many foreign countries. Lightning Eliminators and Consultants (LEA) bought the Dissipation Array[®] System in 1985. R. B. Carpenter, Jr. is CEO and Consultant for LEA.

A letter sent to Daniel J. Love from R. B. Carpenter, Jr., dated December 20, 1991, lists the following. "In mid 1971, Mr Carpenter formed the firm now known as LEA Dynatech, Inc. of Santa Fe Springs, CA, formerly known as Lightning Elimination Associates. In 1982 it was sold to Dynatech Corporation, a 'high tech' conglomerate. He operated the company for 2 years; then in 1984, he purchased the Lightning Warning and Strike Prevention Systems back and formed a new company called Lightning Eliminators & Consultants, Inc. in Santa Fe Springs, CA."

As stated above, there is little factual data available to substantiate the claims being made for the system. Many installations have been made. The owners have not inspected the systems for direct strikes, nor have any of the systems been instrumented. The lack of viable and repeatable testing, when compared to the NASA and FAA studies and the multitude of experts in the lightning field who claim the system fails to function as advertised, casts doubts on the effectiveness of the multipoint discharge system to prevent lightning strikes.

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