FEATURE ARTICLE

Early Streamer Emission Lightning Protection Systems: An Overview

Key Words: Air terminal, early streamer emission, Franklin rod, lightning protection, lightning rod

R. J. Van Brunt, T. L. Nelson, and K. L. Stricklett
National Institute of Standards and Technology

Early streamer emission (ESE) lightning protection systems are a relatively new approach to the perennial problem of lightning damage, and these systems may hold promise for a more effective protection against lightning. However, the scientific and technical basis for this improved performance is far from certain and the efficacy of these technologies remains open to question. In this paper we examine the physical basis for ESE devices and identify areas of controversy and gaps in our knowledge of lightning and lightning protection that need to be considered in assessing ESE devices and in their future development.

The ESE devices considered here are lightning attractors, and in that sense, their purpose is the same as that of conventional "lightning rods." ESE devices, however, differ from conventional lightning rods in that they are equipped in some fashion to increase the efficiency of lightning attraction and thereby to extend the effective range of protection over and above that of conventional lightning rods.

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This article is based on a comprehensive bibliography of ESE lightning protection systems that was prepared at the request of the National Fire Protection Research Foundation [1]; the reader is referred to that report for a critical analysis of the published literature. Most of the papers on ESE terminals have been published within the last 30 years, and bibliographies covering the years before 1980 [2, 3] reveal very little work directly concerned with ESE terminals.

Definitions

As an aid to the reader, commonly used terms are defined below. It should be cautioned, however, that there is little consensus on the meaning of these terms. For example, the terms "streamer" and "leader" are often used interchangeably. There are also cases where different words are used to denote the same phenomenon. For example, a "corona discharge" is sometimes called a "point discharge" or a "partial discharge." The following definitions are used in this report:

Lightning rod—A vertical conducting rod used to attract (or intercept) a lightning strike by producing a local enhancement of the electric field strength in air. It is sometimes called a *Franklin rod, conventional air terminal*, or *lightning conductor.*

Early streamer emission air terminal—An air terminal equipped with a device that triggers the early initiation of the upward connecting streamer-leader discharge, when compared with a conventional air terminal under the same conditions.

Primary cloud-to-ground (CG) *lightning stroke*—The initial discharge between a thundercloud and ground that is generally associated with the propagation of a stepped leader. Four types of primary strokes are distinguished: 1) downward propagating negative stroke from a cloud negatively charged relative to ground (often referred to as normal lightning); 2) downward propagating positive stroke originating from that part of a thundercloud positively charged relative to ground; 3) upward propagating negative stroke; and 4) upward propagating positive stroke. The primary CG lightning stroke is also referred to as the *initial stroke* or as simply a *lightning flash.*

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Stepped leader—Intense spark or plasma channel of finite but variable length in air corresponding to the observed individual steps in a lightning stroke. This is considered to be a relatively high-temperature discharge stage heated by the passage of an electrical current pulse of high magnitude [4-6].

Streamer—A narrow, highly directed, and self-propagating discharge in air. A streamer develops from an electron avalanche when the local space charge becomes of sufficient density to produce an electric-field strength comparable to or greater than the external field. It is believed to propagate at a high velocity by the mechanism of photoionization in high-field regions produced ahead of the discharge. This is a relatively cold discharge phenomenon that can be the precursor to the formation of a leader step [4-6].

Return stroke—This is a discharge that propagates upward from the ground (or lightning rod) in the channel formed by the primary downward stroke. An individual lightning event may exhibit one or more return strokes [9, 10]. The return stroke should not be confused with the streamer-leader initiated at a terminal by the advancing primary lightning stroke.

Striking distance—The distance covered by the last leader step of a downward propagating primary lightning stroke in making contact with a grounded object (lightning rod). This is sometimes called the *final jump* and it is expected to follow the path of an upward propagating streamer if such a streamer occurs. This distance varies with type and intensity of the lightning stroke.

Corona discharge—A localized, cold discharge in air that forms around objects such as sharp conducting points or wires that produce an enhancement in electric-field strength sufficient to allow ionization growth. Corona is also believed to form around leader channels. Corona is an important source of space charge at ground level and is sometimes called a *point discharge*, or *partial discharge*. Under some conditions it is the precursor to streamer formation [11].

Zone of protection—The volume surrounding or adjacent to a lightning protection system that is presumed to be substantially immune to direct lightning strikes. In the case of air terminals, this could be defined as the volume in which an acceptably high percentage of lightning strokes will attach to the rod as opposed to other locations upon entering this volume. A precise definition of the zone of protection and the methods to be used for its determination are subjects of debate [12-14]

Cone of protection—A conic volume around a vertical lightning rod used to define a region of protection. This is a cone whose height equals the height of the rod and whose base has a radius centered at the rod and equal in length to the height of the rod. The cone-of-protection concept is based on an electrostatic field [15].

Rolling sphere method—A method that enables identification of possible lightning attachment points by imaging a sphere of radius equal to the assumed striking distance that is rolled over the exposed surface area surrounding a structure (lightning rod) [14]. Points contacted by the sphere on the surface identify possible lightning attachment locations. It should be noted that, although the method identifies possible attachment points, it does not give information about the probability of attachment to these points [16].

Lightning attraction efficiency—A measure of the probability that a lightning stroke will attach to an air terminal if it enters its zone of protection, e.g., a 90% efficiency implies that 90% of all strokes that enter the zone will attach, independent of parameters such as current and angle of approach. There seems to be no clear consensus on this definition; however, the above definition will be used in this report.

Onset field—The electric-field strength above which ionization growth (electron-avalanche formation) is possible in air. This is approximately 2.6 MV/m in dry air at standard temperature and pressure [17].

Time lag—The time between when the field strength first exceeds the onset field and when a discharge is initiated. A distinction is usually made between the statistical time lag (t_s) corresponding to time of electron-avalanche initiation and the formative time lag (τ_f) corresponding to the time for complete discharge (streamer or leader) formation. Usually (τ_f) is much less than (τ_s) [17].

Space charge—Density of charged particles (ions) in air that modifies the local electric field. The existence of space charge can have a significant influence on lightning propagation.

Thundercloud—A cloud containing a charge density sufficiently high to allow formation of a lightning stroke.

Cloud-to-cloud (CC) *lightning stroke*—A lightning stroke between thunderclouds that may or may not be related to a cloud-to-ground stroke.

Lightning dissipater array—A system that supposedly repels or diverts lightning by formation of space charge such as from corona discharge generated by an array of sharp metal rods [20, 21].

Electron avalanche—An electron multiplication process due to electron-impact ionization of gas molecules. This is the initial stage in the development of an electrical discharge in air, e.g., a corona or streamer.

Discussion

Characteristics of Lightning

In the discussion that follows, we highlight some of the properties of lightning to which particular attention should be paid in the evaluation of lightning-attractor-type protection systems. A complete treatment of the state-of-knowledge of lightning can be found in other published reviews [3, 22-26].

Perhaps the most significant property of lightning that should be kept in mind is its complex, stochastic, and fractal character. These properties make it impossible to predict precisely how a lightning stroke will develop. Indeed, the behavior of lightning phenomena is best described in statistical terms, e.g., by giving probability distributions for stepped leader lengths, striking distances, currents, number of return strokes, angle of approach, etc. as are often found in the literature [27-36]. It may be noted that even low-level corona discharge phenomena can exhibit complex stochastic and multi-modal behavior that is not easily predicted or understood [11, 37, 38].

Two types of cloud-to-ground lightning discharges are identified, namely, positive and negative, where the sign refers to the charge at the base of the cloud relative to the charge at ground level. Upward propagating discharges, which apparently originate at ground level, of both polarities are also observed. In most locations, negative downward strokes are by far the predominant form of lightning. However, recent surveys show that the proportion of positive strokes can be greater than 25% in some locations, especially in mountainous areas or high latitudes in the northern hemisphere where thunderstorms associated with frontal zones predominate [28, 39, 40]. The occurrence of positive lightning also varies significantly with season, generally being most common in winter [32, 39, 41].

In general, the statistical distributions of lightning characteristics vary with terrain, altitude, latitude, and time of year [42]. These variations need to be considered in evaluating or designing a lightning protection system for a particular location. Evidence for significant variability in the behavior of lightning is found not only from geographical surveys [40, 43], but also from numerous observations and recordings at sites frequently hit by lightning, such as the CN tower in Toronto, Canada [44], the Empire State Building in New York [28, 31, 34, 45], Mount San Salvatore near Lugano, Switzerland [27, 46], and other locations [30, 47, 48]. Observations at such locations reveal unusual and unexpected behavior of lightning propagation [49]. Although it is known, for example, that lightning often propagates horizontally with respect to ground level within a cloud [50], there are also unexpected recordings of nearly horizontal propagation over considerable distances at sub-cloud levels [46, 51-54]. The phenomenon of "ball lightning" [55-58] may correspond, in some instances, to a type of horizontally propagating lightning near ground level.

Lightning is generally believed to propagate in the atmosphere by a streamer-leader mechanism [4, 5, 35, 59-66]. Leaders are highly conductive, luminous plasma channels that typically vary in length between 3 m and 200 m. The initial lightning stroke is composed of connected leaders or leader steps. The average velocity of propagation of a stepped leader generally fits a log-normal distribution and typically lies within the range of 1.0×10^5 m/s to 2.7×10^6 m/s [36, 67], and the electric charge deposited in the leader channel is within the range of 3 °C to 20 °C.

Because of the high concentration of charge in the channel, the electric-field strength produced by the leader can be sufficient to allow electrical breakdown (ionization) of the air at distances greater than 10 m from the tip of the leader. Corona-type discharges develop in the intense field region at the end of the leader from which fast streamers emanate and prepare the path for the next leader step [4, 61, 64]. When a leader approaches ground level, it can, given a sufficiently high charge concentration in the channel, cause the field strength at grounded conductors such as a lightning rod to become great enough for the initiation and development of a discharge at the grounded site. If a discharge is initiated at ground level, it is likely to propagate upward in the high-field region produced by the leader channel [68]. This is usually the process by which the initial lightning stroke completes its path to ground. The existence of upward propagating discharges that connect with a downward propagating leader has been clearly established from observations in the laboratory of discharges generated under impulse voltage conditions in long air gaps [69, 70] as well as from observations of natural lightning [46, 68, 71]. It should be noted, however, that upward connecting streamers are not always observed during a lightning strike to ground [25, 71]. Considering the probabilistic nature of the streamer initiation process, it is not surprising that the upward streamer may not always occur, or may be too weak to observe. Moreover, the advancing leader can initiate more than one upward streamer at different ground-level locations [25, 72], but only one is likely to connect.

The probability that an upward streamer will be initiated at a ground site increases with the local electric-field strength produced by the leader. The instantaneous field produced by the leader in turn increases with the instantaneous charge and therefore the current in the leader channel at any given time. It can thus be expected, as observed, that for a fixed striking distance from a grounded object, the probability that an upward streamer will be launched should increase with increasing current in the final leader step of the lightning stroke [68]. Also, the mean striking distance to a grounded object should increase with increasing stroke current [22, 73].

A typical lightning stroke exhibits a complex branching structure [3, 45, 48]. This branching comes about in part because of the possibility that, at the end of a stepped leader channel, more than one path may be prepared by different streamers [63]. If this happens, the subsequent leader step can divide and propagate simultaneously in two or more different directions. Only one of the leader channel branches is likely to connect to ground. Cases have been recorded, however, where two or more stepped leader branches simultaneously propagate to ground. In such cases, questions arise about the mutual interaction between branches and the minimum likely branch separation. The theory of lightning is not sufficiently advanced at the present time to account for branching behavior and the general fractal dimensions of lightning. The space-charge distribution in the atmosphere below the cloud is also likely to influence the branching characteristic [13]. It is only relatively recently that fractal models of electrical-discharge phenomena have been introduced that deal with the branching characteristics [30, 74].

There is still much that we do not understand about the behavior of lightning, and the physics of lightning remains a topic of intensive scientific investigation at research laboratories around the world [75-78]. Little is known, for example, about the mechanisms by which a lightning discharge is initiated within a thundercloud [79, 80]. The average electric-field strength in a cloud generally lies far below the breakdown strength of air. The initiation of lightning is possibly associated with local enhancements in the charge density within the cloud. In any case, there is reason to believe from observations of lightning propagation within clouds [54, 81] that a cloud from which lightning originates cannot be treated as a uniformly charged equipotential region. Moreover, it has been argued that objects at ground level cannot influence the triggering of lightning in a cloud [82, 83]. This is a reasonable expectation because the region of a cloud from which lightning originates is likely to be at an altitude of 3 km to 4 km above ground level, which is one to two orders of magnitude higher than most grounded objects. Thus, any claims made about the ability of a ground-based lightning protection system to trigger or attract lightning strikes from a cloud should be viewed with skepticism. An exception, of course, is the use of ground-launched objects such as aircraft or rockets that are known to trigger lightning [84, 85].

Another area of active lightning research that deserves special attention is that concerned with the influence of local space charge on the path of a lightning stroke. It has already been shown from laboratory simulations [54, 86, 87] that discharge propagation can be affected significantly by the presence of space charge associated with ions or charged particles. Space-charge effects are expected to be significant within a thundercloud, but may also be important at ground level where ions can be produced by corona or point discharges that occur in advance of a lightning strike [23, 82, 88-91]. The presence of space charge could influence the performance of a lightning protection system and may explain the occurrence of horizontal or other unusual forms of lightning [13]. Research is needed on factors that influence the electric-field distribution at ground level under a thundercloud [81, 92-95].

ESE Air Terminals

An early streamer emission air terminal differs from a conventional air terminal or lightning rod in that it is equipped with a device that supposedly enhances the probability of initiating an upward propagating discharge (streamer) to connect with the downward propagating leader of a lightning stroke [96]. Presumably, this enhancement applies for both polarities of natural lightning, although discussion of the polarity dependence of ESE systems is noticeably absent from the literature. An ESE terminal can often be distinguished from an ordinary lightning rod by the presence of a small object near the top of the rod that serves as a discharge trigger [97]. The geometrical configuration of the rod tip for ESE rods can also be more complex than that of a conventional rod [97].

There are different types or designs for ESE terminals. A common feature in their operation is the use of a discharge triggering device to increase the probability for initiating a streamer discharge at or near the rod tip upon the approach of a descending leader. Contrary to some misconceptions, ESE terminals do not significantly increase the conductivity of air at a distance greater than 10 cm beyond the tip of the rod [98, 99]. Possible exceptions are systems that utilize intense laser beams to "guide" a leader discharge. However, such devices are considered to be experimental and are not presently used for practical lightning protection. The main attracting effect of an ESE terminal is undoubtedly due to the metal conductor itself that introduces a significant enhancement of the electric-field strength which, in turn, increases the rate of ionization in the air around the rod above that at other nearby locations. In so doing, it increases the probability of discharge initiation and perhaps also the speed with which the discharge can propagate compared to surrounding areas that are at a lower field. A tall lightning conductor can therefore compete more favorably in attracting a lightning discharge than conductors in the same vicinity of smaller height [100, 101]. Like conventional terminals, the attraction efficiency of an ESE terminal should increase with its height above the ground up to a limit determined by the maximum striking distance.

Three general types of ESE devices have been identified, namely: 1) rods to which a radioactive source is attached, also referred to as *ionizing* or *radioactive air terminals* [102-104]; 2) rods equipped with an electrical triggering device [97, 105]; and 3) systems that use laser beams [106-109]. Of these only the first two types are currently in use. The third type is still under development and its effectiveness, although promising, has not yet been demonstrated outside of the laboratory.

The most widely used, and perhaps most controversial ESE device is that equipped with a radioactive source positioned near the top of the terminal [102, 110, 111]. The radioactive materials employed are weak alpha particle emitters with relatively long lifetimes such as ^{241}Am (half-life of 433 years), which is also used in some smoke detectors. Other types of radioactive materials have also been used, including ^{210}Po, ^{226}Ra, ^{85}Kr, and ^{60}Co [112]. The products from radioactive decay of these materials ionize the air in the immediate vicinity of the terminal, typically within a radius of 1 cm to 3 cm. The ion-pair production rate can be as high as 10^{12}/s. It has been argued that, outside of a small region near the terminal, the ion pair formation rate in the atmosphere from the radioactive source will fall significantly below the rate from natural background radiation [99]. Evidence that radioactive air terminals are superior to conventional Franklin rods has been reported based on interpretation of results from outdoor tests using impulse breakdown of rod-plane gaps [113-117]. However, many questions have been raised in the literature both about the effectiveness of radioactive air terminals [12, 16, 90, 98, 99, 118-129] and about the potential hazards they pose due to possible human exposure to harmful radiation

[112, 129-135]. Indeed their use is prohibited in some countries [105].

In recent years, ESE terminals that use electrical triggering devices have been introduced. In principle, their purpose is the same as a radioactive source, and there is no reason to believe that electrically triggered systems could not be at least as effective as a radioactive air terminal. They offer the potential advantage of more control over ion production at the tip of the terminal and thus would appear to be more effective in avoiding unwanted continuous corona discharge formation in advance of a lightning strike. They also avoid the health and environmental issues that are associated with radioactive devices. Nevertheless, very little information could be found about electrically triggered ESE systems in the archival literature. Most of the discussion about these devices is confined to patent documents [105] and to relatively recent conference papers [97, 136-140]. The available information is usually both of a preliminary nature and lacking in technical details. Consequently it is impossible at this time to make a complete, independent assessment of the performance of ESE terminals that employ electrical triggering.

From the limited information published about such devices, it appears that they employ a detector that senses the approach of a downward propagating leader by producing an electrical signal proportional either to the electric field or the rate-of-change of the electric field produced by the approaching leader [97, 105]. When the output signal of the detector reaches a certain level, it triggers a circuit that then applies a fast, high-voltage pulse or pulses either directly to the rod or to a spark gap electrode arrangement positioned at the top of the rod. The application of the electrical pulses enhances the field enough to create a local discharge or ionization at the most opportune time to initiate an upward propagating streamer. Thus, unlike a rod equipped with a radioactive source that causes continuous ionization in the surrounding air, the electrically triggered ESE device produces ionization only during a brief period prior to the lightning strike. Information about the duration and extent of this ionization could not be found.

There are other types of recently developed ESE terminals that utilize the piezoelectric effect for electrical triggering. Although this type of terminal is now available commercially, only scant mention of it is made in the archival literature [105, 141]. From an examination of the literature, we decided that there is insufficient published information about the operating principles and performance of the piezoelectric devices to enable an independent appraisal of their performance. It is presumed that the function of a piezoelectric trigger is the same as other ESE devices, namely, to enhance ionization and thereby increase the probability (reduce the time lag) for initiation of an upward propagating streamer.

As mentioned above, lightning protection systems that utilize laser beams to trigger and/or guide a lightning discharge, or to assist in launching an upward streamer are considered to be experimental. At the present time, there are no known commercial systems that employ lasers. Laboratory studies have shown, however, that laser beams can be effective in initiating and controlling the path of an electrical discharge in long air gaps [108, 142-158].

The comparative advantages and disadvantages of the different types of ESE devices in terms of their cost, size, reliability, etc. have not been examined in this investigation. The fact that there are competitive ESE devices available with differing configurations and operating principles should be of concern in proposing new standards for lightning protection systems. It is doubtful that the efficiency and reliability of performance is the same for all types of ESE terminals.

In the following three sections the physical bases for ESE devices are examined and issues related to the validation or verification of ESE device performance are discussed.

Physical Bases for ESE Air Terminals

A complete assessment of ESE air-terminal performance requires an understanding of the basic physical mechanisms responsible for their operation. It is not clear from an examination of the relevant literature that there is a complete and universally agreed upon understanding of how or why these devices work. In the case of ESE terminals that use radioactive sources, arguments are made in the literature that they simply do not work, or are at best relatively ineffective [16, 118, 120, 122, 124-129]. These negative opinions are usually based on a lack of evidence that could be found in the literature about the performance of radioactive terminals, and are seldom based on results of independent tests. Reliable quantitative data about the relative performance of ESE versus conventional devices under relevant conditions are definitely lacking. However, the lack of data does not necessarily prove that ESE devices do not work. The questions that should be asked are, how do they work and how much better do they work, or could they work than conventional terminals, i.e., what is the gain, if anything, in lightning attraction efficiency? Indisputable results were not found to answer these questions.

Taking into consideration what is presently known from laboratory studies of relevant electrical-discharge phenomena, reasonable speculation is possible about the important processes that can account for ESE device operation. Unfortunately one must resort to speculation or extrapolations from laboratory scale experiments because there is a dearth of detailed information from observations made during lightning strikes in the natural environment.

The one characteristic that appears common to all types of ESE devices is that they enhance ionization of the air in the immediate vicinity of the terminal tip prior to an approaching lightning stroke. This additional ionization presumably enhances the probability that an upward propagating streamer will be launched from the terminal tip. A legitimate question that could then be asked is, how does this additional ionization act to enhance streamer formation?

The answer to this question is not obvious but would appear to be found from a consideration of the *time lag* to electrical breakdown. This topic has been the subject of numerous laboratory investigations [19]. In order for an electrical discharge (streamer) to be initiated after a rapidly rising voltage has been applied—for example, to a point-sphere or sphere-sphere electrode gap in air—so that the electric-field strength exceeds the breakdown strength of air, there must be at least one free electron available to initiate the electron avalanche process, which is the precursor to streamer formation [4, 7, 19, 159, 160]. In the case of a positive point electrode, which approximates the conditions of a normal negative lightning stroke, the initial electron release mechanism is thought primarily to be collisional electron detachment from negative ions [19, 161]. The rate of collisional detachment depends both on the anion species and on the strength of the electric field in which it moves.

In the case of air, the types of negative ions that can be formed depend significantly on water-vapor content (humidity), which appears to account for the observed large difference in laboratory measured time lags for dry and humid air under positive impulse conditions [162-166]. From laboratory experiments on positive impulse breakdown in air, it is usually found that measured time lags exhibit a pronounced decrease with increasing humidity, i.e., the discharge initiation probability is enhanced by the presence of water vapor [19, 167]. Negative ions in the atmosphere are formed by attachment of low-energy electrons to electro-negative gas molecules such as O_2 and H_2O. Initially formed negative ions such as O^-, O_2^- and OH^-, can undergo transformations into other types of negative ions such as O_3^- and $OH^- \cdot H_2O$ through a complex sequence of ion-molecule reactions [11].

The presence of negative ions in an electrode gap prior to the application of an impulse voltage (simulating an approaching leader) does not guarantee that a discharge will be initiated. For example, if the rate of voltage rise is too slow, the ions may simply be swept out of the gap before undergoing detachment. Moreover, the field strength at which a negative ion can detach an electron may, depending on the type of ion, lie above or below the breakdown field strength of air and this will determine its effectiveness in initiating a discharge. If the ESE device helps ensure the presence of negative ions near the terminal during the approach of a lightning stroke, then it could be effective in reducing the time lag for streamer initiation. However, its effectiveness must be measured against naturally occurring time lags and might depend significantly on such conditions as relative humidity and total charge (strength) of the oncoming leader in the lightning stroke.

In the case of a negative point electrode, as occurs for positive lightning, the mechanism for discharge initiation can be quite different. Near a negative point, detachment of negative ions may still play a role; however, these ions will be forced to move into the lower field region away from the electrode tip where electron detachment by collision with air molecules becomes less probable. For negative points, electrons can also be released by collision of positive ions with the electrode surface. The effectiveness of preleader ionization in enhancing streamer initiation at the tip of an air terminal can be expected, therefore, to depend on polarity. The extent to which the probability of streamer initiation depends on polarity for a given ESE or conventional terminal is generally not known, or at least there is no evidence in the archival literature that the effect of polarity has been investigated thoroughly.

The presence of ionization at the terminal tip in advance of a lightning stroke can also act to undermine the effectiveness of an ESE device if this ionization can occur under high enough field strength to allow formation of a corona discharge [42, 113, 160, 168, 169]. Once a corona forms it produces orders of magnitude more ions than can be generated, for example, from alpha particle emission from a radioactive source. The presence of ion space charge can significantly reduce the electric-field strength near the top of an air terminal and may thereby act to inhibit streamer initiation [37, 170]. The possibility of corona formation depends on factors such as the geometry of the terminal [171]. It has also been shown conclusively by experiments performed in the atmosphere that the intensity of a corona discharge and the density of space charge associated with it depends significantly on local wind velocity [94, 172].

Laboratory experiments performed to determine the influence of radiation on the initiation of air discharges in large sphere-plane gaps have shown that the presence of radiation increases the likelihood of discharge formation for impulse voltages with steep wavefronts, but decreases the likelihood for breakdown at longer wavefronts (1 μs compared to 180 μs) [173]. For steep wavefronts the breakdown voltage is therefore effectively lower than it is for longer wavefronts. This experiment seems to show that the presence of radiation enhances discharge initiation provided there is insufficient time for corona space-charge formation. However, the effect of the radiation was, in either case, relatively small and the source and role of corona generated space charge were not quantified or even clearly identified. One of the conclusions given in this work is that the major effect of the radiation and corresponding ionization of the air is to eliminate very long time lags to spark-over. It should be kept in mind that time lag is a statistical variable, and for a given well-defined set of discharge gap conditions there will exist a distribution in time lags that can be determined experimentally [19, 161].

It should also be noted that corona discharge formation is invoked to account for the effectiveness of supposed lightning dissipaters [20, 12, 121, 163]. In this case, corona discharges presumably form at a multitude of sharp conductors positioned around the area to be protected and thereby produce enough space charge to reduce the electric field and deflect the path of oncoming lightning. The formation of corona can depend significantly on the water vapor content of the air around the terminal [164, 174]. The issue of corona formation is also central to the debate about the most desirable shape for the end of a conventional lightning rod [21, 83, 175-178]. Blunt rods are reported to perform better than sharp rods in attracting lightning, supposedly because corona forms less readily around blunt rods than around sharp rods [178]. The issue of corona formation is also relevant to the operation of ESE devices and is presumably a factor that is considered in the design of ESE terminals. Details of how ESE devices are designed to avoid corona formation prior to a lightning strike are not discussed in the archival literature.

In addition to ion formation that occurs during discharge activity near the tip of a lightning rod, electron and ion collisions with atmospheric molecules can form relatively long-lived metastable excited neutral species such as the $a^1\Delta g$ electronic state of the oxygen molecule or the $A^3\Sigma_u^+$ electronic state of the nitrogen molecule. Additionally, vibrationally excited metastable molecular species are produced in a gas discharge. The presence of these metastable species can have a significant influence on streamer-discharge propagation because they are more readily ionized than air molecules in the ground state and because they can supply energy to electrons by super-elastic collisions, the overall effect of which is to provide a path of lower resistance to an oncoming discharge [179-181]. The quenching of metastable species through collisions with other molecules or with surfaces can also be a source of discharge initiating electrons, i.e., their presence under some conditions might be effective in enhancing the probability of discharge inception [38].

Unlike ions, neutral metastable species do not contribute to modification of the local electric-field strength and their motion is also not significantly influenced by the presence of a field. They tend to diffuse away from their point of origin, and their effectiveness in modifying a discharge path and their range of influence depends on their excitation energy and density distribution at any given time. The density of metastable species depends, in turn, on the relative rates of formation, quenching, and diffusion of these species. Although the influence of metastable species on discharge development has been established from laboratory investigations [180], considerably less is known about the dynamics and interactions of these species in a discharge compared to what is known about ions. In particular, very little is known about how they contribute to lightning discharge initiation or propagation under relevant atmospheric conditions. As with negative ions, the metastable content of the air around a lightning terminal will be affected by relative humidity and general air contamination. The influence of metastable species should not extend significantly beyond the end of a lightning rod. Their role, if anything, will be to enhance initial development of a streamer at the rod tip.

In summary, it would appear that enhancement of upward streamer initiation from an ESE terminal (compared to a conventional terminal) has a plausible physical basis. However, it would also appear that a complete and universally accepted understanding of how all ESE devices work has not yet been achieved, and it can be argued that a better understanding is needed to make meaningful quantitative comparisons between the performances of ESE and conventional devices. To reach such an understanding it will undoubtedly be necessary to address numerous basic questions such as:

1. What are the predominant streamer initiation mechanisms under different conditions of polarity, atmospheric humidity, air contamination, and terminal geometry?

2. What are the relative roles of ions, electrons, and metastable species on the development and propagation of a streamer discharge from a terminal for different conditions?

3. What is the likelihood of corona formation around a terminal and how will the presence of corona affect the ability of the terminal to launch a streamer upon approach of a lightning stroke?

4. In the case of radioactive terminals, what is the dependence of the streamer initiation probability on the intensity and type of radiation source?

5. In the case of electrically triggered devices, how does the streamer initiation probability depend on the timing and magnitude of the electrically triggered spark?

6. Also for electrically triggered devices, how reliable is the field sensor that controls the triggering, and can its performance be affected by local space charge?

Attempts to find answers to questions like these are the focus of much ongoing experimental and theoretical research, not only on lightning, but also on electrical discharge phenomena in general.

Validation of ESE System Performance

Three general methods have been used to evaluate and test the performance of lightning protection systems, namely: 1) small-scale laboratory or outdoor tests in which lightning, or the effects of lightning, are simulated by applying high-voltage impulses to widely separated electrodes; 2) theoretical simulations of lightning strokes that predict propagation behavior and striking distance; and 3) outdoor tests involving observations of artificially triggered or naturally occurring cloud-to-ground lightning strikes. In this section we briefly examine the advantages, disadvantages and issues that have been raised concerning the use and validity of these methods.

LABORATORY AND SMALL-SCALE TESTS

Considerable insight has been gained about the physical nature of lightning from laboratory-scale studies of electrical breakdown and spark formation in "long" air gaps, with typical gap spacing of 2 m to 15 m [69, 136, 166, 173, 182-188]. Long air gaps have also been used to test the performance of lightning rods, including ESE devices, both in enclosed laboratory space and in the open outdoor environment [72, 113-117, 137-139, 189]. An obvious criticism of such tests is that even a 15-m gap is at least two orders of magnitude smaller than the height of a cloud above ground from which a typical lightning stroke originates. Such a large extrapolation has been considered by some to be unacceptable and essentially renders laboratory-scale tests useless in evaluating the performance of a lightning rod [190, 191].

It can be argued, however, that for the purposes of testing and research on lightning rod performance, it is probably not necessary to simulate an entire cloud-to-ground lightning stroke in the laboratory. It is only required that a realistic simulation be made of the final leader step in the stroke that approaches a lightning rod [189, 191]. This reduces the scale and simplifies the problem enormously, but still leaves a task that taxes the limitations of present day laboratory facilities. For example, to simulate the entire range of striking distances likely to occur in the natural environment, it would be necessary to perform tests using electrode gaps in excess of 100 m. The gaps presently available in the largest laboratories are smaller than this by roughly an order of magnitude. Although some gain in gap spacing can be achieved by going to the outdoor environment [188], one still encounters the limitations on voltage imposed by existing impulse generators. Even in the largest laboratories in which ESE devices have been tested there is no provision to simulate all of the conditions under which lightning occurs in the natural environment. It will be recalled that natural lightning exhibits significant statistical variability in such parameters as current, mean striking distance, and angle of approach with respect to any vertical lightning conductor. It also usually occurs under conditions where significant space charge may be present due to local point discharges and where humidity and surface moisture levels are relatively high. Moreover, high winds also tend to be associated with the occurrence of lightning. It must be recognized that such parameters as humidity, space charge, and wind are not independent. For example, the rate of space charge development is expected to depend on humidity and the wind will be effective in redistributing the space charge once it is formed [94]. Although the influence of factors such as space charge [192] and humidity [166] have been investigated in the laboratory tests, it is not clear that the myriad conditions that can exist in the natural atmosphere during a thunderstorm can be adequately simulated in present laboratory facilities. The extent to which it may be necessary to simulate all conditions is certainly a subject for debate.

Another concern about the validity of small-scale simulations is the degree to which the discharge produced is like lightning. There is evidence, for example, that the current and propagation velocities of laboratory-generated leaders differ considerably from those associated with natural lightning. It would appear that more investigations into comparisons between the properties of simulated and natural discharges may be required before more reliance is placed on laboratory scale testing to evaluate the performance of air terminals. The adjustment of laboratory parameters to produce long sparks that match the characteristics of natural lightning assumes a complete knowledge about the characteristics of natural lightning. The extent to which our knowledge of lightning is sufficiently complete is still open to debate. The similarities and differences between natural lightning and long sparks produced in the laboratory have been extensively discussed [66, 113, 176, 190, 191, 193-206].

Despite the present limitations, laboratory tests coupled with fast electrical and optical diagnostics probably offer the best means for learning about the physical mechanisms, operation, and performance of lightning protection devices in a reasonable time frame. Laboratory tests are especially useful for investigating factors that influence streamer initiation from an air terminal, and there seems to be much that can be learned about the initial discharge growth process for both conventional and ESE terminals. Many laboratories have been set up to simulate different aspects of lightning [92, 207-217], and even though most of them are not designed specifically for testing lightning protection devices, some of the advanced diagnostic methods developed in these laboratories might find application in air terminal testing.

Because of the large statistical variability in lightning behavior, it is unlikely that a single test configuration can be used to completely characterize the performance of all lightning protection devices. In the future, it will probably be necessary to consider a set of laboratory test configurations that represent the range of lightning behavior likely to be encountered in the environment. At present it would seem that we are a long way from having a standard laboratory test procedure for lightning protection systems. The influences of such parameters as moisture, space charge, and wind are still topics for research.

It is recommended that caution be exercised in drawing significant quantitative conclusions about the comparative performances of different lightning protection systems in the natural environment from small-scale tests. There would especially be reason to doubt results from simultaneous tests of two or more devices that are placed in close enough proximity to be within each others supposed range of protection. Under such conditions, the presence of one device can significantly modify the electric field configuration of another device (and vice-versa) and thereby affect its performance.

SIMULATIONS USING THEORETICAL MODELS

With the advent of high-speed computing, it has become feasible to consider the use of theoretical simulations of lightning as a tool in evaluating the performance of a lightning protection system. In the past 20 years, considerable progress has been made in understanding the mechanisms of electrical discharge initiation [17, 67, 169, 170, 218-222] and in the modeling of corona streamer-leader discharge propagation in both small and long air gaps [3, 59, 223-233]. Nevertheless, the theory of lightning is still in the developmental stage and new results continue to appear in the literature. At present, a "standard" model for the lightning discharge does not exist. The existing models employ many simplifications and approximations that cannot be examined or critiqued in this report. It suffices to say that they are generally designed to account best for laboratory-scale observations of long-gap spark development in air and have not reached the level of sophistication required to account for the broad range of complex statistical and fractal behavior characteristic of natural lightning. The stochastic behavior of relatively simple phenomena such as electron-avalanche development and corona has only recently been dealt with in theoretical models [11, 38, 222].

In as much as the effectiveness of ESE devices is attributable to their ability to enhance initiation of an upward streamer in the field of an advancing leader, models used to estimate their performance compared with conventional terminals must deal with the statistics of discharge initiation, i.e., they must be capable of predicting time lags applicable to environmental conditions of the terminal. Unfortunately, the problem of statistical time lags is very complex and is generally avoided in existing computer models of discharges. The complexity of the problem is due in part to a lack of knowledge about microscopic processes of electron release and the statistical behavior of electron-avalanche growth in nonuniform electric fields, particularly under the multitude of conditions that could be encountered at the tip of a lightning terminal.

One area where theory shows promise for evaluation of lightning terminals is in the prediction of striking distances [73, 186, 193, 234-246]. Assuming that the electric-charge distribution within the approaching leader step is known, estimates can be made from electrostatic-field calculations of the instantaneous field at a nearby conductor, e.g., a vertical conducting rod. Assuming a relatively simple charge distribution in the leader channel, e.g., a linearly uniform cylindrical distribution, it is often possible to express the field at the terminal due to the leader in closed form [240]. Calculations of this type which take into consideration the wide range of possible leader conditions (defined by such parameters as charge, length, and position) could be useful in estimating the maximum ranges of protection [68]. In essence, such calculations, when coupled to the streamer inception criterion [8, 111, 137, 159, 223, 225, 247, 248], determine the locations where an advancing leader produces an electric-field strength at the terminal tip sufficient to allow streamer development. It must be understood, however, that such calculations supply geometrical information that is applicable to all terminals of the same general geometrical configuration independent of whether or not they are equipped with an ESE device. In this respect, they do not yield specific information about performance of the ESE device itself unless the device operates in such a manner that an impulse voltage is applied to increase the potential of the terminal conductor tip relative to ground during the approach of a lightning stroke. Such a voltage would create a field that adds to the leader field thereby increasing the presumed maximum range of protection. (It is not clear that any electrically triggered ESE devices actually do this, and if they do, no information could be found in the literature to indicate that calculations of the type mentioned above have ever been performed.)

Criticisms that can be raised about present striking distance calculations relate to their semi-empirical nature and the fact they assume leader charge distributions that may be unrealistic or have not been confirmed by observations of actual lightning discharges. Moreover, these calculations have not dealt with effects of atmospheric space charge near ground level.

Validation of lightning models by comparison of calculated results with observations made during natural lightning strikes presents a major challenge to theorists. A complete model should account for all observed properties of lightning such as measured current, optical and radio-frequency emission spectra, propagation velocity, etc. The challenge is made especially difficult by the broad statistical variability in lightning behavior and the paucity of complete sets of observations on single lightning strokes. Nevertheless, it would appear that the method of predicting striking distances by simulating the effect of an approaching leader shows great promise and it should be pursued and improved upon. It possibly offers the best approach to answering some of the difficult and controversial questions associated with realistic determinations of protection zones that will be discussed later in this report.

TESTS USING NATURAL OR ARTIFICIALLY TRIGGERED LIGHTNING

Perhaps the easiest and least controversial method of testing lightning protection systems is to observe their performance in the natural environment during actual thunderstorms. However, this approach is neither as easy nor as lacking in controversy as it may first seem. First of all, with the exception of unusually high towers such as the Empire State Building, lightning strikes to any given location in relatively flat terrain where a lightning rod is positioned are likely to be extremely infrequent [249]. Even in places that experience a high rate of lightning strikes such as in some parts of central Florida, the number of recorded cloud-to-ground strokes within a square kilometer is likely to be less than five per month on average [40, 250] during the peak of the thunderstorm season. Clearly, if natural lightning strikes a terminal only one or two times per year, it takes an extremely long time to acquire enough data on its performance to be statistically meaningful.

Recent attempts to test air terminals positioned at high elevations on mountain tops in New Mexico where there is a known high frequency of lightning have shown that lightning seldom hits a terminal regardless of whether or not it is equipped with an ESE device [126, 177, 251]. Although a few isolated strikes to the mountain were reported to have occurred within the supposed zones of protection of ESE terminals [126, 177], it would appear that the overwhelming majority of strikes to the mountain were at considerable distance from any terminal. In any case, the failure of air terminals to attract lightning on mountain tops at elevations of 3000 m (9843 feet) or more is obviously disturbing and raises questions about the interpretation of such observations. Before any serious conclusions are drawn about the performance of lightning attractors from tests performed on mountain tops, it may be necessary to consider the perturbing effect of the mountain itself on such parameters as the surface charge distribution and electric-field profile under a thundercloud, as well as the extent that lightning strokes at such high elevations differ from those that normally occur in lower, flatter locations. It would appear that the answers to some of these questions might already be found in the literature.

It is noted in some papers that lightning that occurs at high elevations generally differs on average from that which occurs at sea level, if in no other respect than that it has less distance to cover in going from the cloud to the ground [27]. At an elevation of 3000 m, the ground can be quite close to or even engulfed by the base of a storm cloud. Certainly the results from high mountain tests cannot be dismissed, and such tests should continue, as should similar tests underway at other locations [176]. The problem is how to interpret the results of these tests and infer what they might imply about air terminal performance at lower elevations, and what they indicate about the influence of mountainous or rocky terrain on the effective zone of protection of an air terminal.

The unfavorable statistical odds associated with natural lightning can be partially overcome by using artificially triggered lightning. Tests have shown that lightning can be triggered with reasonably high probability by a rocket launched into a thundercloud [85, 252-254]. A long trailing wire is usually attached to the rocket, which provides a low resistance path to guide the initial discharge and define its direction of propagation [85, 255, 256]. Transportable facilities have been developed for rocket triggering of lightning that can be used for testing at nearly any location [257]. Although tests of air terminals are being made using triggered lightning, there are questions that can be raised about the meaning of such tests. There is evidence that triggered lightning is unlike natural lightning both in its intensity and propagation characteristics. In particular, it has been noted that triggered lightning is of lower current than natural lightning and exhibits characteristics more like those of return strokes observed in natural lightning [258, 259]. It has also been argued that triggered lightning does not satisfactorily mimic the primary stroke and is therefore unsuited for investigation of the attachment to a grounded lightning conductors, i.e., its use in evaluating air terminals would appear to be questionable [258]. The extent to which rocket-triggered lightning behaves like natural lightning seems to depend on the length of the trailing wire and the distance of the bottom end of the wire above ground when the discharge occurs. Notwithstanding valid criticisms, essentially no quantitative information could be found in the literature about results from tests performed on air terminals using artificially triggered lightning [260].

Even though testing of air terminals using natural lightning has obvious limitations, we would recommend long-term or continuous monitoring of lightning around air terminals during thunderstorm activity. Data from such monitoring could prove valuable in identifying conditions under which lightning protection devices are likely to fail. Admittedly it is difficult to draw meaningful conclusions from isolated events. However, it can be argued that previous lightning records [36, 43, 51, 176] have proven useful in revealing unusual forms of lightning behavior that ought to be considered in designing laboratory methods or computer simulations for use in evaluating lightning rods.

ISSUES TO BE ADDRESSED

In concluding this discussion we draw attention to four specific issues: 1) the zone of protection, 2) uncontrollable factors, 3) radiation hazards, and 4) damage and maintenance. For purposes of evaluating the relative performance of ESE and conventional air terminals, the zone of protection is by far the most important. The second issue is connected with the first in the sense that there may exist uncontrollable factors that affect the zone of protection offered by a terminal regardless of whether or not it is equipped with an ESE device.

Zone of Protection

The classical "cone-of-protection" concept is often used to specify the region of space that is "protected" by a lightning conductor. This concept was first introduced in the nineteenth century and is based on rather simplistic electrostatic field analysis using a rod-plane type geometry in which the base of the thundercloud is assumed to have a uniform charge distribution [15, 261]. More recently the "rolling sphere" method has been introduced [14, 16, 122, 178, 258] to estimate protection zones. Although this method can be viewed as an extension of the cone-of-protection concept, it goes beyond this concept in providing identification of possible attachment points within the cone. The rolling sphere method allows for possible lightning strikes to the side of the Empire State Building, whereas the cone-of-protection does not.

Despite their simplicity, these concepts can be used to make first order estimates of protection zones around a lightning rod or an array of lightning rods [12, 122, 178, 262-264]. However, we would judge that zone-of-protection estimates that are derived from electrostatic field calculations are easily misinterpreted and can lead to exaggerated or unrealistic claims about the protection capabilities of air terminals (regardless of whether or not they are equipped with an ESE device).

Recognizing that lightning is a stochastic process that exhibits a broad range of behavior, it has been recommended that the simplistic zone-of-protection concept be replaced with a more realistic statistical description in which, for example, the most probable (or maximum) striking distance is displayed graphically as a function of leader or primary stroke current [22, 239, 265, 266]. It has been noted that striking distances for positive discharges will differ from those for negative discharges, and that the knowledge about positive striking distances is inadequate [13].

Nevertheless, enough may now be known about the behavior of lightning and the lightning attachment process that more sophisticated and statistically meaningful statements can be made about protection zones than are used presently [68, 193, 258, 267].

Recently developed models for calculating striking distances [73, 111, 186, 235, 237, 239-246, 268] could prove useful, for example, in determining the maximum distances from a terminal at which leaders with particular characteristics (length, charge distribution, and velocity) could enhance the local electric-field strength enough to allow development of an upward streamer. Such calculations place an upper bound on the size of the protection zone for a terminal with a given geometry (height) independent of its ESE characteristics [269]. Given knowledge (or assumptions) about enhancement of streamer initiation probability at an ESE terminal for a particular local field strength, it is conceivable that reasonable quantitative estimates could be made of the incremental increase in lightning attraction efficiency of ESE terminals over conventional terminals. No evidence could be found that this type of analysis has ever been attempted for ESE terminals. Most of the theoretical work on striking distance has been motivated by the concerns of electric-power utilities about lightning strikes to power transmission systems [14, 23, 236, 239-244, 269]. Much of what has been learned from the utility work can undoubtedly be applied to an evaluation of air terminals.

Uncontrollable Factors

One of the most difficult problems faced in the design of air terminals is associated with assessing the influence of uncontrollable factors. Included here are the effects of nearby objects such as trees, buildings, smoke stacks, etc. Such objects may not only be sources of corona and therefore space charge [94, 270]; they may also significantly perturb the electric field within the specified zone-of-protection. In addition to nearby objects, the terrain itself can also be a factor in determining realistic zones of protection. If the effective zone of protection is extended through the use of an ESE device, then problems of assessing the influence of other objects and variations in terrain are also extended.

Flying debris in the vicinity of an air terminal (dust, leaves, sticks, paper, etc.) may also be of concern, particularly if it can somehow attach to the terminal. This concern is justified because high winds often associated with thunderstorms stir up and elevate ground matter and because the more complex geometries used in the construction of ESE devices may offer greater opportunities for trapping ground matter. The effect of flying debris is an issue that seems to be ignored in the literature. On the other hand, no evidence could be found to suggest that this effect is responsible for any failures of air terminals to attract lightning.

Radiation Hazards

In the case of ESE devices employing radioactive materials, issues have been raised about the possible radiation hazards to humans that the use of these devices present [112, 129-132, 135, 271]. As noted above, radioactive air terminals are banned in some countries, presumably because of perceived health hazards. It has been noted that ^{241}Am sources used in lightning protection devices are not any more hazardous than similar sources approved for use in smoke detectors or static eliminators [104, 112, 134]. Nevertheless, there are those who argue that the public may be placed at risk from a proliferation of radioactive materials in devices that can enter the environment without adequate controls [112, 131, 271].

Damage and Maintenance

Given that ESE devices likely have a structure and associated instrumentation that are more complex than conventional air terminals, questions can be raised about their susceptibility to damage during a lightning strike. The electric current and energy deposited by a lightning stroke can be sufficiently high to actually melt metallic structures and destroy electronic components. There are numerous reports of damage inflicted by the primary lightning stroke to metal parts on aircraft, etc. [211, 272-276]. The possibility of damage means that a lightning protection device may require periodic inspection and/or maintenance that is generally not required for conventional terminals. Although this problem is pointed out [105], there seems to be very little discussion about it in the open literature.

Conclusions

The possible conclusions that can be drawn from an examination of the literature are discussed in this section. The main conclusions of this report are briefly summarized in the Summary of Conclusions.

Due to the paucity of reliable quantitative data from tests of ESE air terminals that can be found in the peer-reviewed literature, it is nearly impossible to make quantitatively meaningful statements on the relative performance of ESE devices and conventional Franklin rods. In fact, sufficient reliable quantitative data on the performance of conventional rods seem not to exist. There is, for conventional terminals, ongoing debate about the best geometry for optimal lightning attraction efficiency, for example.

Nearly all of the data found on ESE device performance resulted either from tests performed by manufacturers of lightning protection systems or by those directly or indirectly employed by such manufacturers. Although criticism is published by non-manufacturers about the performance of ESE devices, especially radioactive air terminals, it is seldom based on actual test data. Those on both sides of the issue invoke lack of evidence in making their case about the performance of ESE terminals. Proponents of these devices claim that a lack of credible statistical data on failure of ESE terminals proves their effectiveness, while critics of these terminals argue that a lack of evidence about the improved performance of ESE terminals over conventional terminals proves their ineffectiveness. In either case, one must beware of faulty logic, in as much as a lack of evidence never proves the lack of something.

There are reports of incidents where ESE devices failed to provide the protection specified by the manufacturer [16, 126, 277, 278]. Statistics on the failure of conventional systems have also been documented [104]. When examining reports of "failures," one can always raise questions about their cause, e.g., whether they are primarily a consequence of exaggerated claims made by the manufacturer or a consequence of misuse (faulty installation) of the device. Reports of isolated failures raise legitimate concerns, but are seldom accompanied by enough supporting data about the event to enable a determination of why the failure occurred. Generally it is difficult to draw significant conclusions from single events that can be used to improve system design or evaluate system performance. There is no reason to believe that an air terminal is 100% efficient in attracting lightning, regardless of what kind of ESE device it uses, if any. Considering the wide range of possible atmospheric conditions and types of lightning behavior that have been recorded, it is not surprising that air terminals of all types will sometimes fail [46, 49, 53]. Tall structures are reported to be struck occasionally by lightning at points far below the top, i.e., outside of the "protection zone" [45, 52, 279]. Any claims of 100% efficiency in the performance of a lightning attractor should be viewed with skepticism. In any case, the meaning of the term "efficiency," when specified for an air terminal, should be clearly defined and understood.

A reasonable physical basis for the operation of an ESE device appears to exist in the sense that there is good evidence from laboratory investigations that the probability of initiating a streamer discharge from an electrode can be increased significantly by irradiation or electrical triggering. However, the precise amount by which this enhancement in streamer initiation improves the lightning attraction efficiency of an air terminal remains questionable. There is reason to doubt that it significantly extends the maximum range of protection. A lightning stroke that would not hit a conventional terminal because of the fact that it does not enhance the field at the terminal tip enough to allow streamer formation will also not likely hit a terminal equipped with an ESE device. (The exception would be an ESE device that significantly increases the terminal potential during the approach of a lightning stroke.) In our view, the possible advantage offered by an ESE device, if operated properly, is that it helps to insure that a streamer will be initiated if the field produced by the oncoming stroke at the terminal becomes sufficiently great to allow streamer propagation. When comparing ESE and conventional terminals, it is probably preferable to consider efficiency rather than zone of protection as a measure of performance.

It is possible that the increase in lightning attraction efficiency gained from using an ESE device can also be achieved by simply using a conventional terminal of greater height [113]. There is no indisputable evidence from the literature that the range of protection offered by a single ESE terminal can be greater than or necessarily the same as the range provided by two or more conventional terminals of the same height with overlapping zones of protection. On the other hand, an array of ESE terminals may provide better protection than a similar array of conventional devices. Although the precise amount by which the ESE device extends or improves the performance of a conventional terminal is generally not known or easily measured; there is no reason to believe that an ESE array will have an inferior performance. We would argue that until issues concerning the relative performances of single ESE and conventional terminals are settled meaningful statements cannot be made about the comparative performances of arrays of these terminals.

In general, it can be presumed that ESE terminals perform at least as well as conventional terminals with the same geometrical configuration provided, of course, that they are properly designed to avoid significant corona formation during a thunderstorm. In the event that an ESE device fails or becomes inoperative for some reason, the ESE terminal should revert in its characteristics and performance to that of a conventional terminal with the same height, geometrical configuration, and connection to ground.

Much has been learned about the operation of ESE terminals from laboratory-scale tests to suggest that ESE devices do indeed enhance streamer emission compared to conventional terminals. However, these results have not been, and probably cannot be, used to make quantitative determinations of the relative efficiencies of these terminals for atmospheric conditions under a thunderstorm. At the present time, the results from a limited number of field tests with natural lightning are inconclusive with respect to providing estimates of relative efficiencies. It is not clear that enough data can ever be acquired from such tests to draw quantitative conclusions about attraction efficiency. Tests in the natural environment appear to be most useful in identifying and documenting conditions under which air terminals fail.

Semi-empirical models have recently been developed to calculate striking distances to lightning conductors. These models show promise in providing a method for making realistic estimates of maximum protection range for air terminals. The maximum extent to which ESE devices enhance the attraction efficiency or increase the effective range of protection of a terminal could conceivably be investigated with these models.

Recommendations

Until recently, because there is not much that can be done to improve the design of a conventional lightning rod, there was little motivation to perform complicated tests to evaluate the efficiency of these rods as lightning attractors. It has always been recognized that conventional rods sometimes failed and that the reasons for failure were usually attributable to the complex and unpredictable nature of the lightning discharge. With the appearance on the market of competing products (ESE devices that supposedly improve the attraction efficiency of a rod) have come questions about how these new devices work and how they can be tested to verify their performance. Lightning, in the meantime, remains as complicated as ever, and our understanding of lightning seems to progress only very slowly. Given this situation, it is not clear that we can find quantitatively acceptable answers to questions about the performance of lightning protection systems any time soon.

Considering the difficulty of the task, we offer the following recommendations for future work without being specific about realistic timetables and expectations:

1. Give priority to developing new methods for calculating or otherwise determining striking distances and related zones of protection that are more meaningful from a statistical point of view.

2. Continue and extend laboratory tests to investigate the effects of relevant parameters such as polarity, space charge, wind, and humidity on the streamer initiation probabilities and propagation from ESE and conventional terminals.

3. Continue observations of natural lightning in and around test sites setup with different air terminals in various locations where the frequency of lightning is known to be high.

4. Compile and analyze existing and newly acquired statistical data on the behavior of lightning from different locations and different sources in a central location.

To enhance credibility, more of the testing and data evaluation should be performed by individuals or organizations not identified with manufacturers of lightning protection systems.

Summary of Conclusions

The main conclusions of this report can be summarized in the following statements:

1. Lightning is a complex, chaotic phenomenon that exhibits a broad range of behavior and characteristics that are unpredictable. Any theory or assessment of lightning protection devices must take this fact into account.

2. A plausible physical basis exists for ESE devices, in the sense that they can enhance the probability for initiating an upward propagating streamer, which is directed at an oncoming lightning stroke, from an air terminal.

3. Insufficient information could be found about both ESE and conventional air terminals to allow a meaningful comparison of their relative performance in a natural environment.

In conclusion, it could be said that there is yet more to be learned about lightning and about how lightning protection devices work or do not work. The road to better lightning protection is obviously strewn with controversy and it would appear that the path to resolution requires more enlightenment and less thunder.

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Richard J. Van Brunt received his B.Sc. in physics from the University of Florida in 1961 and Ph.D. in physics from the University of Colorado—Joint Institute for Laboratory Astrophysics in 1969. He joined the National Institute of Standards and Technology in 1978 as a researcher. Upon his retirement in 1997, he was a NIST fellow in the Electrical Systems Group of the Electricity Division. He is an IEEE fellow and was the IEEE Whitehead Memorial Lecturer in 1994. He has conducted extensive research in atomic and molecular physics, with an emphasis on gaseous dielectrics, plasma processing, and partial discharge detection.

Tom L. Nelson received a B.Sc. in electrical engineering from North Dakota State University in 1988. In 1988 he joined the Electrical Systems Group of the National Institute of Standards and Technology, Gaithersburg, MD, where he has been working in the areas of precision power and energy measurements.

Kenneth L. Stricklett received his B.Sc. in mathematics from the University of Nebraska-Lincoln in 1979, and a M.Sc. and Ph.D. in physics from the University of Nebraska-Lincoln in 1981 and 1987, respectively. He then was a NORCUS post-doctoral Fellow at the Pacific Northwest Laboratories. He has been a researcher at the National Institute of Standards and Technology in the Electrical Systems Group of the Electricity Division since 1989. He is an IEEE member. He has conducted research in atomic and molecular physics and in electrical breakdown and partial discharge detection in fluids.

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Correction

The term "LC Shield," used in the November/December 1999 feature, "Technical Advances in the Underground Medium-Voltage Cable Specification of the Largest Investor-Owned Utilities in the U.S.," is a registered trademark owned by the Pirelli Cable Co. In the use of the term in the section on Metallic Shielding and the section on Protective Jackets, there should have been a trademark symbol (®) following the term whenever it occurred with a footnote indicating that it is a Pirelli trade mark. The editors regret that this omission occurred.