

The Case for Using Blunt-Tipped Lightning Rods as Strike Receptors

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ABSTRACT

Conventional lightning rods used in the United States have sharp tips, a practice derived from Benjamin Franklin's discovery of a means to obtain protection from lightning. However, the virtue of sharp tips for strike reception has never been established. An examination of the relevant physics shows that very strong electric fields are required above the tips of rods in order that they function as strike receptors but that the gradients of the field strength over sharp-tipped rods are so great that, at distances of a few millimeters, the local fields are often too weak for the development of upward-going streamers. In field tests, rods with rounded tips have been found to be better strike receptors than were nearby sharp-tipped rods.

1. Introduction

Although many of the lightning rods currently in use have sharp tips, the virtue of sharpness as an aid in strike reception has never been established. This form of the lightning rod originated with Benjamin Franklin, who speculated around 1750 that the emissions from sharp-tipped rods would prevent lightning by discharging electrified clouds. When he erected an iron rod for this purpose, however, it did not prevent discharges but, instead, was struck by lightning; it served as a receptor rather than a preventer of lightning. Indeed, the modern understanding of the lightning-rod function is that they serve solely as receptors for lightning strikes in lightning protection systems that conduct the discharges to the earth, thus protecting the structures on which they are mounted. Nevertheless, sharp-tipped rods are still commonly used. The purpose of this paper is to report on an examination into the role that rod-tip curvature has on the effectiveness of the rods as strike receptors and to provide the interested reader with relevant information that has been published in widely diverse journals (Franklin 1753; Loeb 1935; Kip 1938; Chapman 1967; and many others).

2. Historical background

Lightning's preference for striking elevated objects has long been known (Lucretius 55 B.C.), but no successful efforts using this knowledge for lightning protection were recorded until Benjamin Franklin (1753)

announced that strikes to a tall metal rod could be conducted to the earth by a wire without damage to the structure on which the rod and connecting wire were installed. His discovery came after some parlor demonstrations with an electrostatic generator in which Franklin and his associates had found that they could discharge electrified objects silently, without any sparking, by approaching the object while holding a sharp-tipped needle in hand. This discovery led Franklin to speculate on how it might be possible to prevent lightning by discharging thunderclouds by the use of sharp-tipped metal rods on the earth. When he tried this idea by erecting an iron rod with a small brass wire inserted in its tip, instead of discharging a thundercloud that passed overhead, his rod was struck by lightning. Nevertheless, he held the idea thereafter that the primary function of his lightning rods was to prevent lightning, but, if that did not occur, he recognized that a rod could be used to conduct a discharge to the earth through a suitable wire terminated in the ground. His final guidance on the installation of lightning rods was given in a letter (Franklin 1767) written in Paris:

... we elevate the upper end of the rod six or eight feet above the highest part of the building, tapering it gradually to a fine sharp point, which is gilt to prevent its rusting. Thus the pointed rod either prevents a stroke from the cloud, or, if a stroke is made, conducts it to the earth with safety to the building. The lower end of the rod should enter the earth so deep as to come at the moist part, perhaps two or three feet; and if bent when under the surface so as to go in a horizontal line six or eight feet from the wall, and then bent again downwards three or four feet, it will prevent damage to any of the stones of the foundation.

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Modern lightning protection practices have followed and refined Franklin's instructions for the installation of lightning protection. The conventional lightning rods currently used in the United States have sharp tips as recommended by Franklin, although it is now recognized that the sole function of a lightning rod is to be the receptor or interceptor of strikes for a lightning protection system that conducts lightning discharges to the earth without damage to the structure on which the system is mounted.

The early successes in lightning protection came from sharp-tipped rods acting as strike receptors; these were exposed on tall structures, as Franklin recommended, well above any competing objects. In the years since Franklin announced his invention, no credible evidence has ever been presented demonstrating that lightning rods discharge thunderclouds or that they prevent the initiation of strikes within thunderclouds.

3. Scientific studies of lightning strikes and point discharges

The nature of lightning strikes was not known until Schonland and Collens (1934) reported on their photographs taken with a Boys camera. From these pictures, they discovered that most cloud-to-ground lightning starts with a negative stepped leader that descends from a thundercloud, provoking upwardly propagating positive leaders emitted by tall, exposed objects on the earth.

Schonland and Collens's discovery led to an understanding that the principal charge transfers and most of the damage caused by the usual negative cloud-to-ground lightning strikes occur during the development and propagation of the upward-going, positive "return strokes" that form after the positive leaders connect with the descending negative leaders. In the 1930s, however, there was no physical understanding of the role played by lightning rods during the initiation of lightning strikes. It was appreciated that the ambient electric fields at the tips of lightning rods exposed beneath thunderclouds were greatly intensified and that, as Franklin had inferred, electric currents flowed from the exposed tips into the air beneath storms. Warburg (1899) and Chapman (1967) had demonstrated that these currents, at the level of a few microamperes in laboratory studies, increased with the square of the applied electric fields, but there was no application of these findings to an understanding of lightning strike reception. (It is now known that the current dependence on the square of the electric field strength arises because the amount of charge in an emission "burst" depends on the field strength, as does the rate at which the charge from an emission is transported away from the source.)

An example of the currents emitted by a sharp-tipped Franklin rod mounted above the "Iron Kiva," our underground laboratory near the summit of the Magdalena Mountains in west-central New Mexico, during a nearby lightning strike is shown in Fig. 1. For an interval of

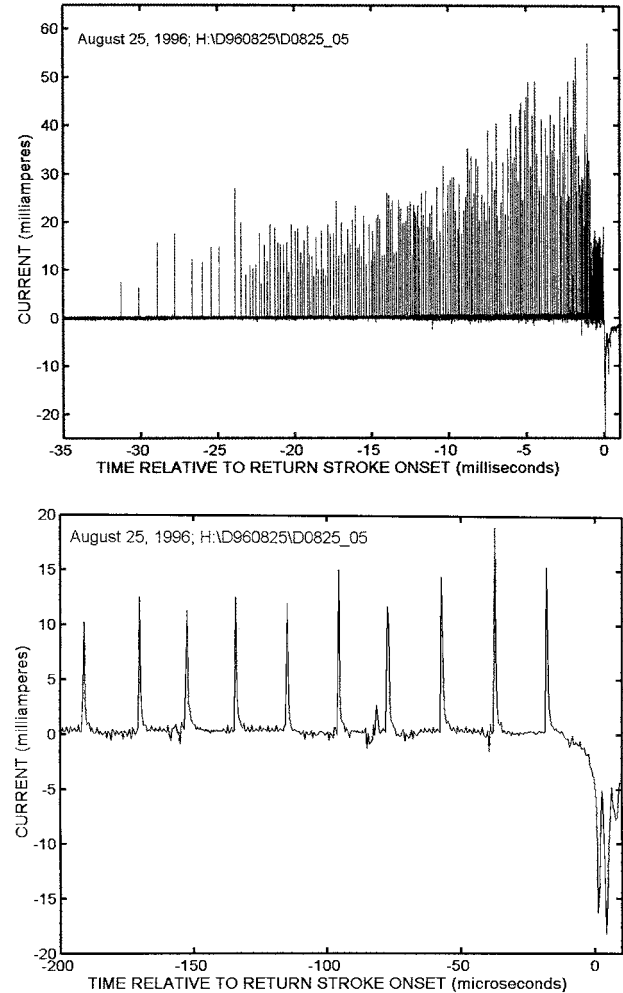


FIG. 1. A record of the corona current flow from the tip of a 12.7-mm- ($\frac{1}{2}$ in.)-diameter, sharp conically tipped Franklin rod exposed above a 6-m- (20 ft)-high mast on South Baldy Peak in the Magdalena Mountains of central NM just before lightning struck nearby on 25 Aug 1996. This record was obtained with the use of a computer-controlled digitizer that recorded the current at the rate of 4 million samples per second. The current flow was not continuous but consisted of repetitive bursts of charge liberated by electron avalanches from air molecules just above the tip of the rod. Lower plot is an expanded view of the time just prior to return-stroke onset.

about 30 ms immediately before the onset of a return stroke from some object nearby, the sharp rod emitted bursts of charge at the rate of about $50\,000\text{ s}^{-1}$. The amount of charge carried by each burst was on the order of 6 nC; the duration of each burst was about $2\ \mu\text{s}$. After the cessation of each burst, there was a pause of about $15\ \mu\text{s}$ before the onset of another burst. Note that over the past 48 years none of our sharp-tipped rods exposed under thunderclouds for measurements of their electric-field-induced emissions has been struck by lightning.

For comparison with Fig. 1, an example of a blunt-tipped rod's response to a nearby strike (to another blunt rod that was located 40 m to the northwest) is shown

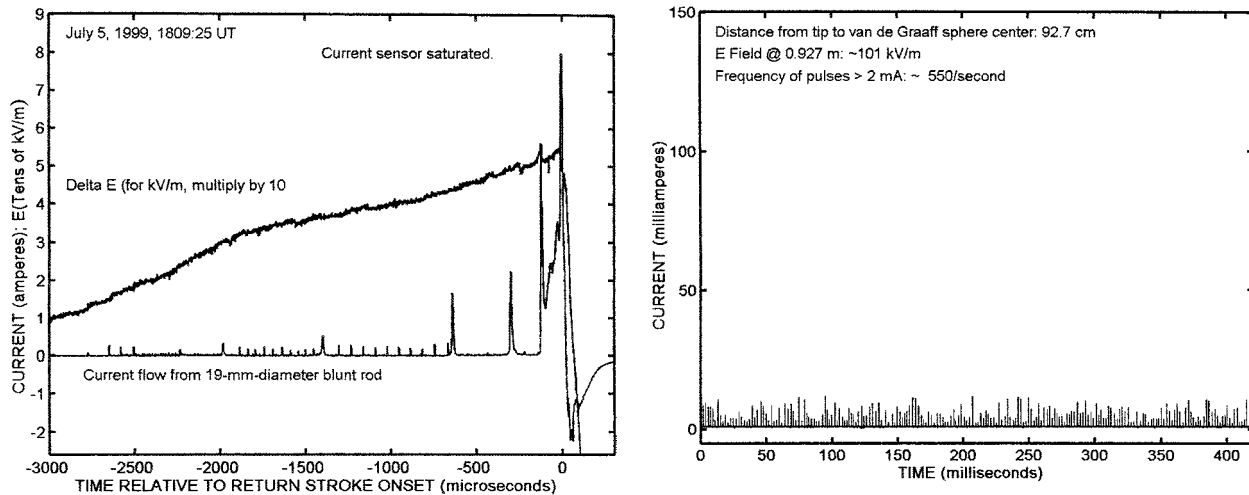


FIG. 2. Plots of the electric field change and of the current emitted by a 19-mm-diameter blunt rod on 5 Jul 1999 during a lightning strike to another blunt rod that was located 40 m distant.

in Fig. 2. This example is of interest because initially the instrumented blunt rod above the Iron Kiva responded to strong electric fields with transient bursts that were somewhat similar to those of the sharp-tipped rod shown in Fig. 1. As the electric field initially intensified, short-duration ($2 \mu\text{s}$), 600-nC bursts of charge were emitted by the blunt rod, but, as the negative leader approached and the electric field acting on the rod exceeded 40 kV m^{-1} , the amounts of charge carried by a burst increased to more than $15 \mu\text{C}$ and the duration of the bursts lengthened to about $20 \mu\text{s}$. Just before the onset of the return stroke from the nearby rod, the current from the blunt rod above the Iron Kiva increased to more than 8 A, the maximum current that our circuit could measure. Our subsequent examination of the rod tips indicates, however, that the instrumented rod above the Iron Kiva was not struck directly by this lightning that connected to the other blunt rod at a distance of 40 m.

4. Laboratory studies of discharges from exposed electrodes

Because lightning strikes to a given location are infrequent and field studies are time consuming, the responses of various electrodes to strong electric fields can be studied more readily in a laboratory with the use of a high-voltage generator. Figure 3 shows plots of the currents emitted by two Underwriters Laboratories, Inc.,-listed lightning rods that were exposed to strong electric fields created by a laboratory Van de Graaff generator. These recordings were made with a computer-controlled, 12-bit Gage Applied, Inc., GageScope digitizer taking 5 million samples each second. The potential of the Van de Graaff generator was measured by use of a calibrated electric field mill aimed at the generator electrode from a distance of 262 cm. The upper plot in Fig. 4 shows that a sharp, conically tipped Frank-

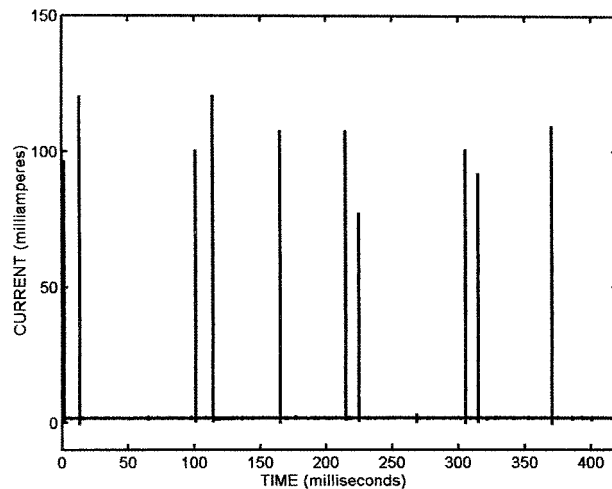


FIG. 3. A comparison of the responses of (top) a sharp, conically tipped and (bottom) a blunt, hemispherically tipped lightning rod (both 12.7 mm in diameter) exposed to strong electric fields near a laboratory Van de Graaff high-voltage generator, expressed as current emitted.

lin rod emitted nominal 0.7-nC bursts of positive charge at a rate of about 550 s^{-1} when exposed to ambient electric fields of about 100 kV m^{-1} . The duration of each pulse was on the order of $0.4 \mu\text{s}$, with short-term peak currents ranging from 2 to 13 mA.

The two plots in Fig. 5 show the current emitted from a 19-mm-diameter, hemispherically capped rod, the tip of which was located 52 cm from the center of the Van de Graaff generator's high-voltage electrode. The strength of the electric field at this distance from the center of the electrode in the absence of the rod was about 264 kV m^{-1} . During each of the experiments in which this rod was exposed to such electric fields, an initial burst of current on the order of 100 mA or greater occurred, followed a few microseconds later by a stronger, sparklike discharge with currents on the order of 800 mA and charge transfers of about $2 \mu\text{C}$ as shown in Fig. 6. The lower plot in Fig. 4 shows that, with

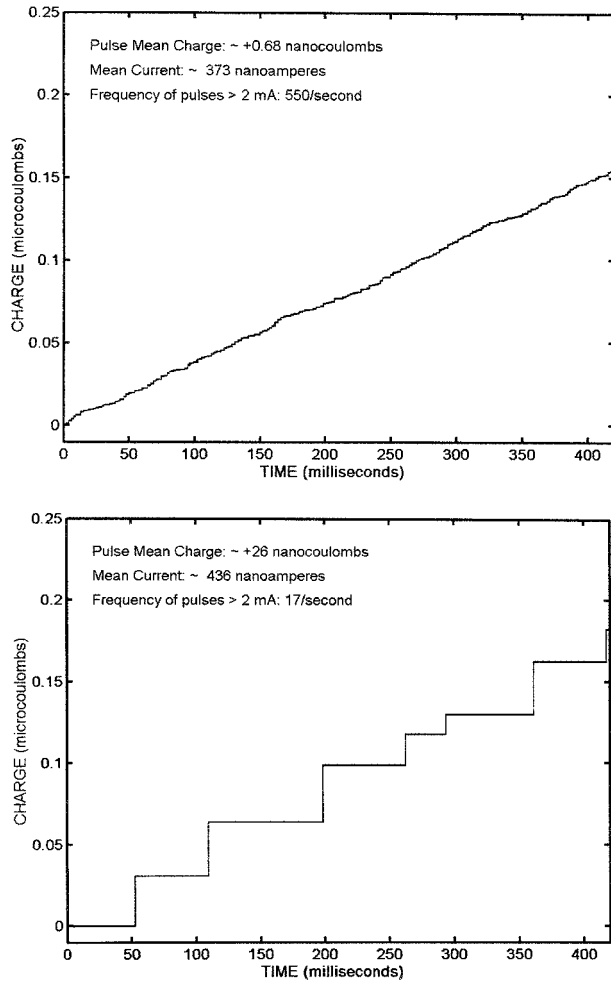


FIG. 4. Same as Fig. 3 but expressed as charge emitted (top, sharp; bottom, blunt).

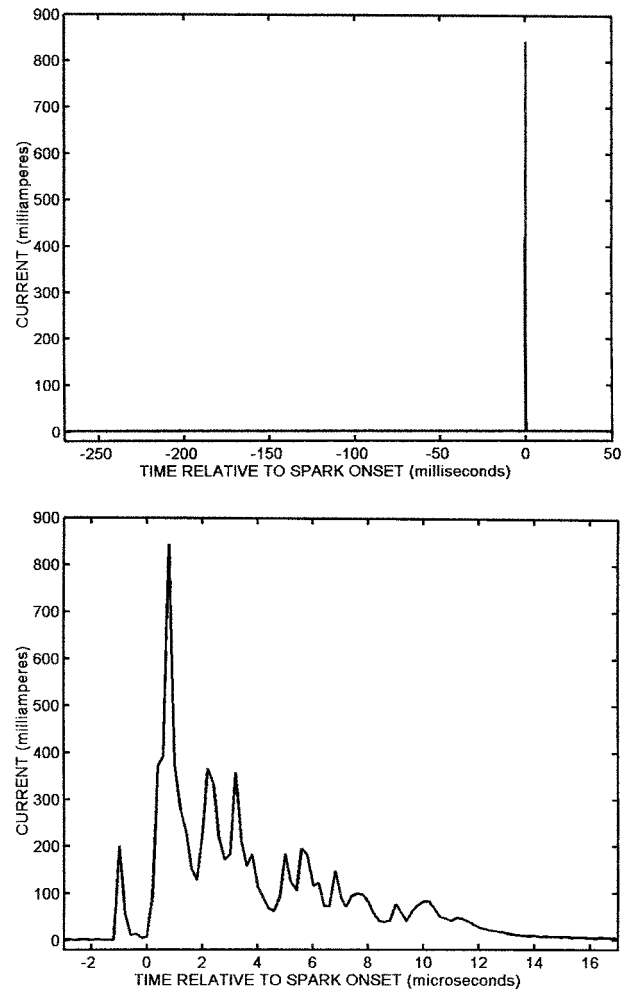


FIG. 5. The current emitted by a 19-mm- (3/4 in.)-diameter blunt, hemispherically tipped lightning rod exposed to strong electric fields near a laboratory Van de Graaff generator. Lower plot is an expanded view of the time just prior to spark onset.

stronger electric fields, a hemispherically tipped, 12.7-mm-diameter rod exposed to ambient electric fields of about 228 kV m^{-1} produced bursts of charge of about 26 nC with peak currents of about 100 mA at the rate of about 27 s^{-1} . No evidence of other precursor “corona” discharges was detected prior to the onset of the sparklike discharges.

A comparison of the responses of the sharp- and blunt-tipped rods to the same electric field strength was not possible. An ambient field strength of 100 kV m^{-1} was not sufficient for the initiation of discharges from the hemispherically tipped rod; field strengths in excess of 200 kV m^{-1} were required for the onset of avalanches. On the other hand, as the Van de Graaff generator belt speed was increased to the maximum possible, the emissions from the sharp-tipped rod increased to about $4 \mu\text{A}$ and negated all of the charge being carried by the belt without a significant increase in the generator potential. Hence, fields stronger than 100 kV m^{-1} could not be developed by the generator when it was exposed to a nearby sharp rod.

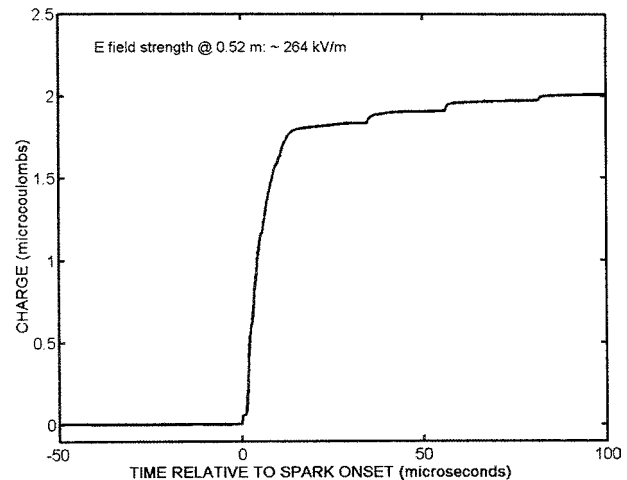


FIG. 6. Same as Fig. 5 but expressed as charge emitted.

When viewed in a darkened room, a faint nimbus of blue light extending for about 5–7 mm from the tips of the sharp-tipped electrodes exposed to the Van de Graaff generator could be seen by a dark-adapted observer. This blue luminosity presumably was emitted by excited nitrogen ions, N_2^+ , at a wavelength of about 428 nm (Herzberg 1950). When blunt-tipped rods replaced the sharp-tipped ones, the luminous nimbus extended as a spray to distances of about 70 mm but increased during sporadic streamers that propagated to the generator electrode 40 cm distant, and it was punctuated at intervals by bright blue sparks.

The luminosities created by the discharges from these electrodes were measured with an Electrical and Musical Industries, Ltd. (EMI) type 9524A photomultiplier tube having an S11 photocathode with a peak response to light with a wavelength of 420 nm and a nominal sensitivity of 200 A l m^{-1} under the conditions that we used. The source luminosity associated with a pulsed discharge from a very sharp needle and, later, from a conically tipped lightning rod at a distance of 40 cm from the Van de Graaff electrode was approximately $3 \mu\text{lm}$ that commenced about 40 ns after the onset of a current burst. The larger source luminosities associated with discharges from the hemispherical tip of a 12.7-mm-diameter rod were more difficult to measure precisely because of the electromagnetic disturbances associated with the greater bursts of current, but we estimated luminosities on the order of $60 \mu\text{lm}$ in the intervals between sparks.

5. An explanation of the repetitive charge bursts from a sharp-tipped rod

These bursts are a result of strong electric fields at the tips of electrodes acting on free electrons in their vicinity. Free electrons are normally scarce in the atmosphere because, after liberation from neutral air molecules by cosmic radiation or other energetic agents, they quickly attach to electronegative molecules such as oxygen or water vapor with which they collide, forming negative ions. At equilibrium, positive and negative ions exist in the free atmosphere in concentrations of several hundred per cubic centimeter, whereas free electrons have only a transient existence before colliding with neutral air molecules and attaching to electronegative oxygen or water vapor molecules. However, free electrons can appear after being liberated from negative ions in the air around the tips of electrodes exposed to strong electric fields.

Research by Kip (1938) showed that, under the influence of the strong fields directed away from a positive electrode, naturally existing negative ions in the air surrounding the tip are accelerated and acquire a velocity component inward, toward the tips. On collision with other air molecules in their paths, negative ions that have acquired kinetic energies greater than 0.65 eV (Loeb 1935) can lose their attached electrons (which

caused them to be *ions*). Loeb had discovered that the strength of the electric field E_i required to detach a “seed” electron from an already existing negative ion in the air varies with the atmospheric pressure p , which determines the mean free path traversed by a field-accelerated ion between collisions with neutral air molecules. He found the critical E_i/p ratio to be $90 \text{ V cm}^{-1} \text{ torr}^{-1}$ of pressure (about $67 \text{ V m}^{-1} \text{ Pa}^{-1}$). Kip (1938) found that this electric field–pressure ratio must be met or exceeded for the onset of electron avalanches around the tip of a positively charged electrode. From these studies, it appears that an electric field with a strength in excess of 6.8 MV m^{-1} under a pressure of one atmosphere is necessary to accelerate negative ions sufficiently to detach seed electrons.

These liberated electrons, in turn, can be accelerated by the local electric fields, acquiring kinetic energies sufficient to detach electrons on collisions with neutral air molecules in their paths. These new electrons can then migrate under the influence of the field toward the tip of a positive electrode, detaching more electrons as they, in turn, collide with other air molecules. This process creates “avalanches” of electrons “falling” into the tip but leaving in their wake “trails” of positive ions created from the impacted molecules, each of which has lost an electron. The process can continue until the electric field created by the positive ions reduces the field around the tip below the level required for electron avalanching, whereupon the ionization ceases until the relatively massive positive ions migrate away from the tip under the influence of the external electric field and the local winds.

After the positive ions migrate away from the vicinity of the tip, the local field caused by external charges such as those carried by an approaching lightning negative-stepped leader can again become sufficiently strong that a new seed electron is liberated, and the electron avalanching process repeats, causing another sequence of positive-ion creation around the exposed tip.

The amount of electronic charge Δq that flows into the tip during each burst is determined by the change in the displacement charge on the tip surface, which is a function of the change in the strength of the electric field E at the tip between avalanche initiation and its cessation and of the area of the tip:

$$\Delta q \approx \epsilon_0 (E_{\text{initiation}} - E_{\text{cessation}}) \times (\text{tip area}), \quad (1)$$

where ϵ_0 is the permittivity of the air, 8.85 pF m^{-1} . As is shown in Fig. 4, smaller bursts of charge are emitted by the sharp-tipped rod than by the larger, blunt one.

The time intervals between charge emission bursts are determined by the times required for the appearance of new seed electrons, which, in most cases, depend on the removal of the positive-ion space charge produced in the preceding avalanche sequence and on any intensification of the electric field in the vicinity of the tip to the strengths necessary for the detachment of a new

seed electron from an accelerated negative ion. The intensification of the ambient electric field depends on external factors such as the charges at the field source; it is not controlled primarily by the configuration of the lightning rod.

On the other hand, the durations of the bursts themselves are determined by the durations of the electron avalanches that are limited by their formation of positive-ion space charges and by the migrations of the positive-ion residues from around the tips under the influence of the locally strong electric fields outward to regions in which the electric fields are too weak to cause seed-electron liberation.

6. An analysis of the discharges from sharp-tipped rods

Because the discharges of interest are caused by the action of strong electric fields, we need first to examine the electric field distribution above these electrodes.

a. The strength of the electric field around the tip of an air terminal

When a tip of a conductor is exposed to an external electric field E_0 , the field strength at the conductor tip is intensified over that at locations far removed from the tip by the accumulation of “displacement charges” on its surface. The amount of intensification relative to that of the undisturbed field (E_{tip}/E_0) is known as the field enhancement factor k_e . It is possible to calculate k_e for some simple, symmetric conductor shapes such as a hemispherical boss protruding above a conducting plane (for which $k_e = 3.0$), but simple analytic solutions do not exist for vertical sections of cylinders. As a result, the lightning rods of interest cannot be treated analytically, but their geometry can be approximated by simulating a lightning rod with a conducting, vertical, prolate spheroid (a shape for which an analytic solution does exist) having the same radius of curvature for the tip and the same tip height. The surface of the prolate ellipsoid (that is equivalent to the lightning rod having a tip radius a and a tip height c rising above a flat, conducting plane) is defined by η_0 , where

$$\eta_0 = \left(1 - \frac{a}{c}\right)^{-1/2}. \tag{2}$$

With this assumption of the equivalent shape for the conductor tip, a useful value for k_e can be calculated by differentiating Smythe’s (1950, p. 169) prolate spheroid potential function described as in Moore (1983). This leads to a determination of the factor k_e for the intensification of a uniform, external electric field E_0 at the tip of the equivalent prolate ellipsoid in the absence of ionization and of any space charge as

$$k_e \equiv \frac{E_{tip}}{E_0} = \left[\eta_0(\eta_0^2 - 1) \left(\coth^{-1}\eta_0 - \frac{1}{\eta_0}\right)\right]^{-1}, \tag{3}$$

where

$$\coth^{-1}\eta_0 = 0.5 \ln[(\eta_0 + 1)/(\eta_0 - 1)]. \tag{4}$$

Although the ambient electric fields are greatly intensified around the tips of electrodes exposed to external electric fields, this intensification initially decreases with distance r from the center of the tip as a function of tip radius of curvature a ,

$$\frac{E(\text{at distance } r)}{E(\text{at tip})} \sim \frac{1}{2r/a - 1}. \tag{5}$$

At a distance of 10 radii above the tip of an exposed electrode, the strength of the electric field is less than 5% of that at the tip itself (Moore et al. 2000b). More general, the strength of the electric field E_η (in the absence of ionization and of any space charge) directly above the tip of an elliptical electrode exposed to an external electric field E_0 can be calculated by differentiating Smythe’s (1950, p. 169) potential function, which yields

$$E_\eta = E_0 \left\{ 1 - \frac{\coth^{-1}(\eta) - \frac{1}{\eta}}{\coth^{-1}(\eta_0) - \frac{1}{\eta_0}} + \frac{1}{[\eta(\eta^2 - 1)] \left[\coth(\eta_0) - \frac{1}{\eta_0}\right]} \right\}, \tag{6}$$

where

$$\eta = \eta_0(z/c), \tag{7}$$

and z is the height of the location of interest above the plane on which the prolate spheroid is mounted.

Plots of the calculated distances from the tips of various electrodes to the location of the 6.8 MV m⁻¹ contour above a 6-m-high electrode are shown in Fig. 7, which illustrates the increase, with intensifying ambient electric fields, in the size of the regions from which seed electrons may be liberated.

b. Electric field strengths necessary for the liberation of a seed electron in the vicinity of a lightning-rod tip

The plots in Fig. 7 show that, when the ambient electric fields are stronger than about 60 kV m⁻¹, the enhanced local electric fields at distances of a few millimeters above electrodes with tip radii of curvature ranging from 0.02 to 13 mm are initially stronger than 6.8 MV m⁻¹ so that negative ions in this region can readily furnish seed electrons for electron avalanching.

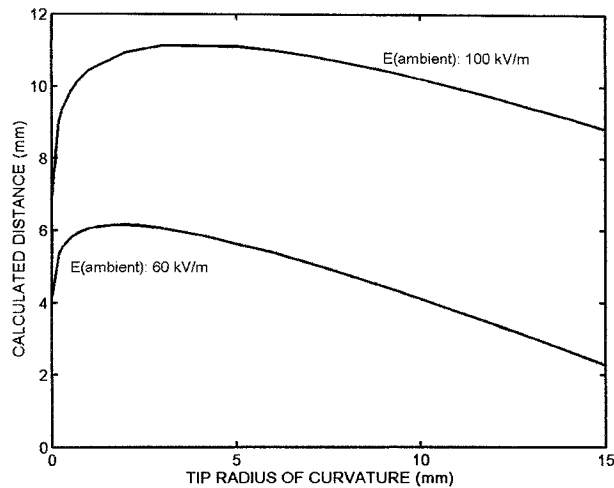


FIG. 7. Plots of the distances from the tips of simulated lightning rods mounted on top of a 6-m-high mast and exposed to the indicated, vertically directed ambient electric fields to the regions above the tips in which the strength of the local electric field is 6.8 MV m^{-1} .

c. Formation of a positive-ion streamer

The positive ions formed as the residue during electron avalanches around the tip of a lightning rod constitute “space charges” that act to limit the strength of the local electric field and to oppose the continuation of the electron avalanching. If, however, the electric field *above* the region containing the positive-ion space charge becomes sufficiently strong, any free electrons there, liberated either by photoionization or from negative ions, may accelerate inward, toward the electrode tip, creating new avalanches and a new positive-ion region farther from the tip. This extending process may continue, creating additional volumes with positive charges as long as the electric fields ahead of the last ion volume are sufficiently strong; this sequence can culminate in the formation of a “streamer zone” that propagates in the direction of the electric field.

Phelps (1971), Allen and Ghaffar (1995), and others have found that ambient electric field strengths in excess of about 450 kV m^{-1} under a pressure of 1 atmosphere are required for this streamer process to continue in air. If the field strengths are strong enough over an appreciable distance, the number of electrons falling into the tip of the streamer may be sufficient to increase the ionization within the streamer channel, making it so conductive that it acts as an extension of the initiating electrode.

For the initiation of a streamer, however, strong electric fields are required, and these fields are opposed by the space charges resulting from the formation and migration of the positive-ion residue from electron avalanches, which act to weaken the local electric fields. From Gauss’s law, we can estimate the rate dE/dt at which the electric field E at the tip of an electrode is weakened by the current i resulting from electron avalanches into the tip having a radius a ,

$$\frac{dE}{dt} \sim - \frac{i}{\epsilon_0 \pi a^2}. \quad (8)$$

For an avalanching electron current of $1 \mu\text{A}$ into a tip with a radius of curvature of 0.1 mm , the resulting formation of positive ions would, if the resulting ions were stationary, represent a field weakening rate of about $3.6 \times 10^{12} \text{ V m}^{-1} \text{ s}^{-1}$, whereas the same current into a 1-cm -radius tip would represent a weakening rate of about $3.6 \times 10^8 \text{ V m}^{-1} \text{ s}^{-1}$. In the real world, the migration of ions away from the tip under the influence of the local fields counteracts this weakening, but, as shown in Figs. 2 and 3, the pulsating nature of the charge bursts demonstrates that the average rates at which positive ions are created are limited by the time required for their migration away from the tips of the rods. The more rapid bursts associated with the sharp rod imply shorter ion removal times than do the less frequent bursts from a blunter tip.

d. Estimates of the times required for positive ions to “clear” the tip region

After the onset of an electron avalanche sequence, the positive ions that are created repel each other and migrate away from the tip of an electrode under the influence of the local electric field, which they tend to weaken. Any subsequent avalanches in the sequence depend on electron liberation from regions ahead of the ion residue, at greater distances from the tip. The time required for positive ions to clear the tip of an electrode and to terminate the avalanching, in the absence of photoionization, depends on the distances that the ions must travel to regions in which the local electric field is too weak for the liberation of more seed electrons, on the velocities of the ions that are controlled by the strength of the local electric field, and on the positive-ion mobility μ (typically about $2 \times 10^{-4} \text{ m s}^{-1} \text{ V}^{-1} \text{ m}^{-1}$). These ion migration time intervals Δt can be calculated from

$$\begin{aligned} \Delta t &\approx \int_a^{R(E < 6.8 \text{ MV m}^{-1})} \left(\frac{dr}{\text{ion velocity at } r} \right) \\ &\approx \sum_{r=a}^{R(E < 6.8 \text{ MV m}^{-1})} \left[\frac{\Delta r}{\mu E(r)} \right] \end{aligned} \quad (9)$$

(by ignoring, for these estimates, any effects that these ions may have on the local electric fields behind them). The calculated time intervals necessary for ion migrations from the vicinities of the lightning-rod tips out to the regions in which the strength of the local electric field is less than 6.8 MV m^{-1} are shown in Fig. 8 from which it appears that the ions from a burst from a blunt-tipped rod linger longer in the strong field regions than do those from sharp tips. The observed short durations of the current flows from a sharp-tipped rod shown in

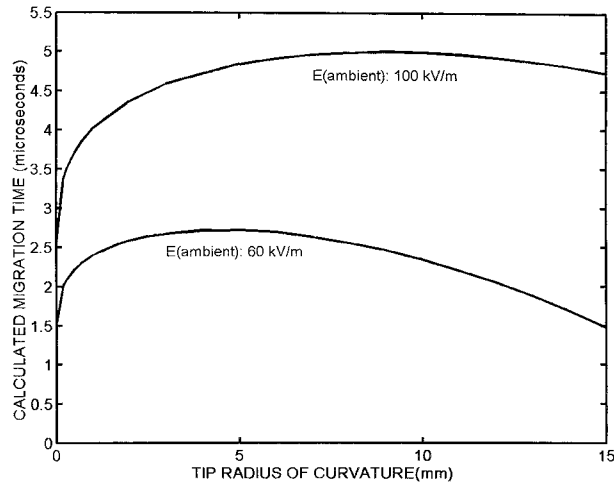


FIG. 8. Plot of the time required for ion migration from the tips of simulated lightning rods mounted on top of a 6-m-high mast to the 6.8 MV m^{-1} contour as a function of the tip radius of curvature in an axially directed, ambient electric field.

Fig. 1 are consistent with the ion migration times calculated with the use of Eq. (9).

Our calculations showing how limited in distance are the regions with strong electric fields around the sharp-tipped electrodes are supported by the observations of the observed small sizes of the luminosities around sharp-tipped electrodes. Further, the fact that these spatially limited luminosities do not commence until about 40 ns after the onset of a current burst arising from electron avalanches suggests that photoionization does not play a major role in the initiation or in the development of discharges from sharp-tipped electrodes. The positive ions that are created migrate quickly to regions in which the local electric fields are too weak to liberate new electrons; the limited size of the luminosity around a sharp tip shows that the ion excitation is limited to the vicinity of the tip. On the other hand, the more extensive luminosities associated with the larger, positive-ion charge transfers and the sparks from the blunt-tipped rods suggest that photoionization processes may play a significant role in the formation of streamers and sparks over the blunt-tipped electrodes. The luminosities in the 428-nm band result from transitions of excited N_2^+ ions with energies of 18.75 eV to the ground state at 15.58 eV for ionized nitrogen (Zaidel and Shreider 1970), indicating the occurrence of ionization processes.

Loeb (1965) reported that a larger number of electron avalanches, as occur over the blunt-tipped rods, can create a “sizable number of photons . . . that proceed outward and create photoelectrons in electric fields that are too weak to cause multiplication . . . [The increased electric field along the axis created by] very large avalanches at the anode [the positively-charged tip] or a convergence of many smaller avalanches at the same local area before the ion space charge can move away . . . may draw in the photoelectrons produced” in the

vicinity. “Once this occurs, the discharge will propagate as a breakdown streamer.” This process appears to operate at the tips of blunt rods exposed to strong electric fields, although Loeb did not necessarily have this situation in mind when he wrote his analysis; our observations of the blunt-rod responses to strong electric fields indicate many electron avalanches, extended luminosities suggesting appreciable photoexcitation, and the formation of streamers.

It appears, however, that, for streamer formation from a sharp-tipped rod, the ambient electric fields acting on an existing ion burst must intensify at rates that are orders of magnitude greater than for those rods with tip diameters in the range between 10 and 25 mm. The repeated occurrence of avalanches above a sharp-tipped rod will result in the successive formation of positive ions in the vicinity of the tip that limit the strength of the local field, but the motions of these ions prevent the electric fields at greater distances from reaching the level necessary for the development of streamers, until the rate of ambient field intensification exceeds the rate at which the field is weakened by the ion formation and migration processes.

It follows from this analysis that, although ionization processes begin in weaker ambient electric fields over sharp-tipped rods than over blunter ones, the lesser *gradients* of the electric field strength over the blunter rods are conducive to the earlier formation of upward-going streamers under more slowly intensifying electric fields than over the sharper tips. The question then arises, “What is the optimum configuration for a lightning-strike receptor?”

7. The optimum configuration for a lightning-strike receptor

From the preceding analysis, it follows that, despite their long usage, sharp-tipped lightning rods are not the best strike receptors possible. Although their shape is very effective in causing the ionization of the air when they are exposed to a strong electric field, the ions that are created migrate quickly to regions in which the electric fields are too weak for the development of upward-going streamers. As a result, sharp-tipped rods are not effective as strike receptors until the ambient electric fields become very strong. On the other hand, it is possible for a rod to be too blunt, so blunt that no ionization occurs around its tip with the electric fields that are developed under thunderstorms. The 51-mm-diameter rod that we exposed on a 6-m-high mast over a 3-yr period has never been struck by lightning. The strength of the electric field necessary to liberate an avalanche-initiating electron above a 51-mm- (2-in.)-diameter rod exposed on a 6-m-high mast is calculated to be in excess of 100 kV m^{-1} , a strength at which many other objects in the vicinity with enhanced local electric fields can have already formed streamers.

Choice of the optimum diameter for a strike receptor



FIG. 9. Photograph of six blunt aluminum rods, each of which has been struck by lightning on South Baldy Peak. The two rods on the left were 12.7 mm ($\frac{1}{2}$ in.) in diameter, the rod on the right was 25.4 mm (1 in.) in diameter, and the diameters of the other rods were 19 mm ($\frac{3}{4}$ in.).

depends on its exposure and on the strength of the electric field produced by a stepped leader descending from a thundercloud. To be a strike receptor, some ionization must occur at the tip of the rod under the electric field strengths experienced during the approach of a stepped leader. It is also necessary that the dwell time of the ions in the region of the tip be long enough that further ionization can develop at greater distances from the tip. These requirements rule out the use of both sharp-tipped rods and very blunt ones as favored lightning rods.

In our measurements of electric fields associated with nearby lightning, we have found values for the field strength in excess of 80 kV m^{-1} just prior to most nearby strikes, and peak values on occasion of as great as 400 kV m^{-1} . The lightning-rod configurations that seem to be to be most useful for installations with rod-tip heights ranging from 1 to 10 m are those with tip diameters ranging from $\frac{1}{2}$ (12.7 mm) to about $\frac{3}{4}$ in. (19 mm). If we consider practical concerns, such as strength and durability of the electrode, cost of the material, existing hardware, and similar matters, it appears that a choice of rods with diameters of about $\frac{5}{8}$ in. (16 mm) may be desirable as a standard [as in National Fire Protection Association (2000)].

8. Field tests

Competitive tests for strike reception between sharp-tipped and blunt rods mounted on 6-m-high masts on

South Baldy Peak in New Mexico over the past 7 yr (Moore et al. 2000a) have yielded the following results: 13 blunt-tipped rods with diameters ranging from 12.7 to 25.4 mm have been “struck” by lightning, whereas none of the nearby sharp-tipped rods (all of which were at distances of about 5.3 m from the blunt ones) have taken a strike. Figure 9 is a photograph of six of the blunt rods that were struck by lightning during these experiments. Most of the blunt rods that were struck were 19 mm in diameter; the 12.7-mm rods were the next most frequent in the reception of strikes.

These experimental results and the laboratory demonstrations with the Van de Graaff generator are consistent with the preceding analysis; they all indicate that blunter rods are better candidates for strike reception than are very sharp ones.

9. Conclusions

The field tests and the analyses described here support the idea that improvements can be made in the present choice of shape for lightning rods. Although Franklin’s sharp-tipped rods are very effective in causing ionization of the air when they are exposed to strong electric fields and are useful as strike receptors when they are tall (with no nearby competitors), rods with this design are found to be less effective as strike receptors when they compete for strike reception with blunter objects

in their vicinity. This difference is caused by the rapid weakening with distance of the electric fields around the tips of sharp rods; at distances of a few millimeters from the tips the fields can be too weak for the development of streamers. As a result of the rapid clearing of ions from around the tips and of the weaker electric fields ahead of the local ions in those regions, streamer development over sharp rods requires more rapidly intensifying fields than is required above blunter rods.

Somewhat similar conclusions have recently been published by Aleksandrov et al. (2001) who wrote in a paper with a different aim, "It is shown that the electric field distribution due to the space charge released by the long corona discharge near the top of a high object hinders the initiation and development of an upward leader from the object in a thunderstorm electric field."

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