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Responses of Lightning Rods to Nearby Lightning

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ABSTRACT

In an effort to determine the effectiveness of the sharp tipped lightning rods widely used in the U.S., we carried out a competition between sharp and blunt rods to determine which was preferentially struck by lightning. Over the past eight years, 12 blunt rods participated in cloud-to-ground discharges while none of the nearby rods with sharp tips were struck. Our analysis suggests that the emissions of point discharges from the tips of sharp rods associated with the rapid decrease of the electric field strength around the tips combine to make sharp rods poorer receptors for lightning than are moderately blunt rods.

INTRODUCTION

The use of lightning rods during the past 250 years has significantly limited the lightning-caused damage to structures but there is no consensus as to the optimal configuration of a lightning rod. In fact, the current American guides for lightning protection provide no specifications for the form and shape of lightning rods. Several illustrations in NFPA 780 [1], the U.S. National Fire Protection Fire Association's 1997 Standard for Installation of Lightning Protection Systems, depict rods with sharpened tips but NFPA 780 places no requirement on the size and shape of the rod tips. Nevertheless, sharpened rods are widely used in the United States. Their form is derived from Franklin's original idea that he could dissipate the electricity in thunderclouds by erecting sharpened rods which would conduct it away, thus preventing lightning. When he tried this idea out under a thundercloud, however, one of his first rods was struck by lightning. He then proposed a quite different use for the rod; if it did not prevent lightning (which, demonstrably, it never does), an elevated, grounded rod might provide a preferred path to Earth for the discharges that otherwise would strike and damage a vulnerable building. However, Franklin [2] continued to advocate that the tips of his lightning rods be sharp, a practice that has continued to modern times. In the years since Franklin invented them, many of his rods have reduced lightning damage to structures but it is widely recognized that objects in their vicinity are often struck and that there is still no clear understanding of how a rod connects to an approaching lightning discharge.

To complicate the matter further, in recent years several new devices have been offered for lightning protection with the claims that they emit upward-going, positive streamers earlier than possible from Franklin rods. Many of these devices employ sharp-tipped electrodes with a mechanism to produce a spark in a rapidly increasing electric field; others augment the sharp tips with radioactivity [3]. It has been asserted that these so-called "early-streamer-emitters" ("ESE" devices) have much greater "zones of protection" (with radii of up to 100 m) than those of Franklin rods and therefore that a single "ESE" device can provide better and less-expensive protection than can a large array of Franklin rods.

INVESTIGATIONS INTO LIGHTNING ROD BEHAVIOR

During the past eight years, we have made several different measurements to investigate the behavior of lightning rods that were exposed on a mountain ridge over which thunderclouds frequently formed. These investigations, which are discussed below, included:

(a) arranging a competition between sharp and blunt rods to determine which would be struck preferentially by lightning,

(b) high speed digitization and recording of these currents to selected rods.

A LIGHTNING-RECEPTION COMPETITION BETWEEN SHARP AND BLUNT LIGHTNING RODS

In an effort to compare the strike reception effectiveness of lightning rods with various tip configurations, we carried out an experiment around the 3287-m high summit of South Baldy Peak in the Magdalena Mountains of central New Mexico. Test rods were mounted in insulators on top of 6-m high pipe masts and connected to Earth by #10-wire "down conductors" that passed through nominal 2-A fuses. Adjacent to each sharp-tipped rod, at a distance of about 6 m, we mounted a similarly exposed, blunt, round metal rod (usually made of aluminum), the top of which had been turned into a smoothly-polished hemisphere. (Our calculations indicate that the perturbation in the field strengths at one of the tips produced by an adjacent, competing rod was about 1% of the ambient field strength, and therefore, the rods did not significantly interfere with each other.) The diameters of the blunt rods used in these tests were 9.5 mm, 12.7 mm, 19 mm and 51 mm. About ten such competitive setups were used each summer.

This competition between sharp and blunt tipped rods for receiving lightning strikes has been carried out during the past eight summer thunderstorm seasons with the results that none of the sharp-tipped rods have taken a strike whereas 12 of the adjacent blunt rods participated in discharges and acquired weld-marks on their tips. A photograph of six blunt rods that have been struck is shown in Figure 1. None of the exposed 9.5-mm or the 51-mm diameter rods was hit; most of the strikes have been to 19-mm diameter rods. Two different, sharp-tipped "ESE" devices were included in these tests but neither of them has been struck although other objects within their 100-m claimed zones of protection took strikes. Fifteen strikes were near a radioactive "ESE" device and two strikes were also adjacent to a sharp, sparking "ESE" device (which was tested for only a three year period).

DEVELOPMENT OF STREAMERS FROM A LIGHTNING ROD

Placing a conducting object in an otherwise uniform electric field changes the fields near the object. For example, the field at the tip of a 6 m tall rod with a 1 mm radius tip will be about 1,500 times stronger than the ambient field, and the field at the tip of a 6 m tall rod with a 10 mm radius tip will be about 230 times stronger than the ambient field. (See [4] for a method to calculate the fields near a lightning rod.) When the electric field is sufficiently strong (3×10^6 V/m at sea level) air will break down. The electric fields will cause the ions and free electrons to move, creating a low-current electrical breakdown called a streamer. The field at the tip of a 6 m tall rod with a 1 mm radius tip will equal the air breakdown field when the ambient field is about 2 kV/m, whereas the field at the tip of a 6 m tall rod with a 10 mm radius tip will not reach the breakdown value until the ambient field reaches 13 kV/m.

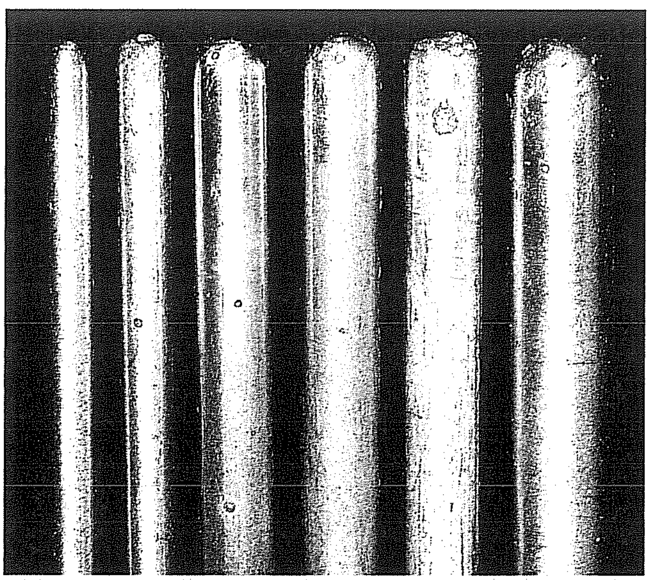

Figure 1. Photograph of six blunt aluminum lightning rods that were struck by lightning. The two rods on the left were 12.7-mm in diameter, the rod on the right was 25.4-mm in diameter and the diameters of the other rods were 19 mm.

In order for a streamer to continue to develop, the fields it propagates into must exceed 440 kV/m [5]. The ambient fields under a thunderstorm (with no approaching lightning leader) are about 5 kV/m. With this ambient field, the enhanced field at the tip of a sharp conducting object is is strong enough to produce a breakdown streamer. However, as the streamer moves away from the enhanced field at the tip into the ambient field, the field it encounters soon drops below the 440 kV/m needed to sustain the streamer, and the steamer dies out. The positive ions left by the aborted streamer reduce the field at the tip of the object, so a new streamer will not develop until this ion space charge is removed (by ion migration in the electric field or by wind), or the ambient field increases. Measurements of the currents from the tips of lightning rods under constant fields of about 5 kV/m show that the current in these short-lived streamers is a few milliamps, and the quiescent period between streamers is a few milliseconds [4].

As a negative lightning leader approaches the ground, the ambient electric fields on the ground intensify. The enhanced fields near the tips of conducting objects similarly intensify. As a leader approaches, the quiescent period between current bursts decreases to about 10 μs, and the peak current increases to about an amp. (Measurements showing this are presented in the next section.) When the leader reaches a critical distance, the field between the rod and the leader exceeds that needed to sustain the streamer, and the streamer transitions to an upward leader, with a sustained current exceeding several amps. The upward leader which first connects to the approaching lightning leader determines which object on the ground is struck.

DIGITIZED MEASUREMENTS OF STREAMERS FROM LIGHTNING RODS

In order to study the streamers coming off the tip of a lightning rod in response to an approaching lightning leader, we used high-speed digitizers to measure the currents flowing to the tips of three differently-shaped rods during lightning strikes near Kiva II, a buried steel instrumentation shelter on top of South Baldy Peak (Figure 2). We recorded four channels of data with a digitization rate of 5 MHz. The three rods included a sharp-pointed Franklin rod, a blunt rod (with a diameter of either 12.7 mm or 19 mm), and an "ESE" device. In addition to the three lightning rods, we recorded the electric field change induced by the approaching lightning leader. The three lightning rods used in this study were placed around the periphery of Kiva II and were arranged so as to be at the vertices of an equilateral triangle with legs 5.5 m long. The change in ambient electric field outside Kiva II was sensed by an isolated electrode that was mounted in an inverted housing about 1 meter above the earth. This

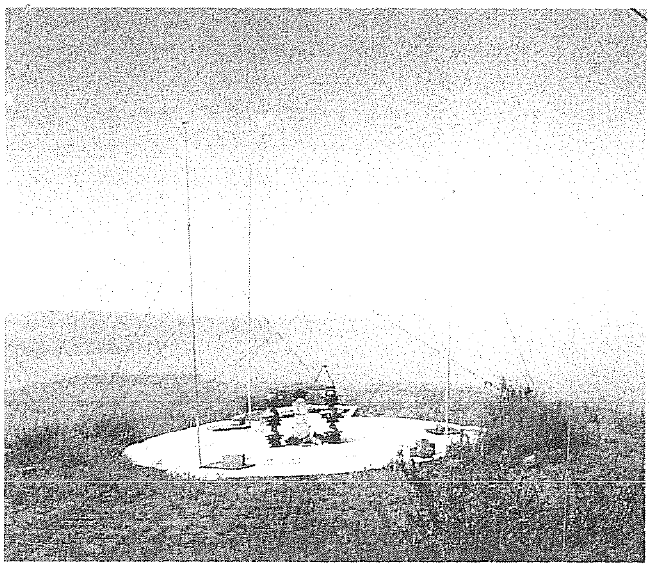

Figure 2. Three lightning rods around Kiva II used for high-speed current measurements. The digitizers and data storage computer are in an underground shielded metal building below the rods.

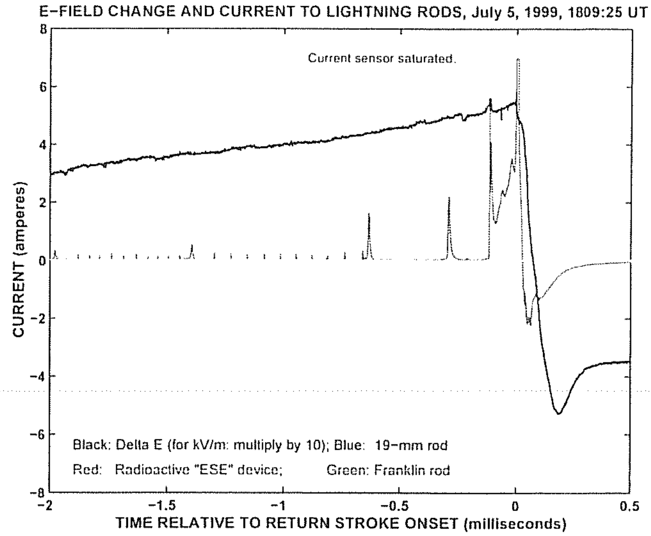

Figure 3. Plots of the electric field changes and of the currents that flowed from three lightning rods mounted on 6-m high masts above Kiva II on South Baldy Peak when lightning struck a 12.7-mm diameter blunt rod located 42-m WNW of Kiva II (July 5, 1999).

electrode was connected to earth through an operational amplifier that measured the displacement currents caused by changes in the local electric field. The signal from the field-change sensor fed a trigger generator consisting of a differentiator, a rectifier and a comparator with an adjustable threshold.

Whenever the time-rate-of change in the electric field signal exceeded the pre-set threshold, the generator provided a trigger to the digitizer that then stored four channels of digitized data for a one second period around the time of the trigger. The system was set up to record about 130 milliseconds of data from each channel prior to the trigger and about 900 milliseconds afterward. The system thus operated automatically in capturing data on the nearby lightnings that produced electric-field rates-of-change greater than the preset threshold.

During the four summers from 1996 to 2000 numerous data sets were recorded from lightning within about 2 km of the summit. During the periods digitized measurements were made, six discharges struck within a few hundred meters of the summit, and one of these discharges struck an instrumented blunt rod. Here we present data showing the response of the rods to three discharges of increasingly close distance.

NEARBY STRIKE ON JULY 5, 1999 – A widespread thunderstorm produced more than 50 lightning discharges, one of which struck a 12.7-mm diameter rod that was 6 m from a competing, sharp Franklin rod located 42 m west-northwest of the Kiva II center. The responses of the instrumented rods mounted above Kiva II are shown in Figure 3. Note that the red line plotting the small current from the "ESE" device is somewhat obscured by the other traces. Negligible amounts of charge (less than 5 microcoulomb each) were emitted from the Franklin rod above Kiva II and from the "ESE" device but the nearby 19-mm-diameter blunt rod emitted more than 452 microcoulomb of positive charge during the final 150 microseconds of the negative leader's descent. Despite the large emissions of positive charges from the Kiva-mounted blunt rod, its upwardly-going leader did not connect to the stepped leader; the successful positive leader was provided by the 12.7-mm-diameter blunt rod located 39 m to the west-northwest.

ROCKET-INITIATED LIGHTNING ON AUGUST 7, 1999 – A lightning discharge aloft was initiated when a small rocket, towing an 86-m length of 0.2-mm diameter steel wire, was launched into a thunderstorm over South Baldy Peak. An observer reported that an upward-going discharge developed above the top of the wire and a discharge went to Earth from the bottom of the wire when it was at a height approximately equal to the length of the wire. A later survey of the area indicated that the lower discharge struck a small pine tree, located about 33-m north-northeast of the center of Kiva II, and browned the tips of the needles on its west side.

Records of the currents emitted by the three instrumented rods installed above Kiva II are shown in Figure 4. Beginning at about 250 μs before the electric field sensor was triggered, all three rods emitted bursts of current in response to the approaching leader. It is of interest to note that, with a sudden increase in electric field (as the stepped leader made another step), all three rods emitted bursts of current at about the same time. The greatest current (about 3.7 A) was emitted by the Franklin rod which was the closest rod to the rocket launcher (about 10 m distant) and to the damaged pine tree (about 30 m distant). The Franklin rod appears to have emitted a sustain propagating streamer, although this streamer did not connect with the rocket-initiated negative leader. The integrated current from the Franklin rod during the last 100 microseconds before the strike to the tree amounted to 159 microcoulomb while those from the 19-mm blunt rod and the "ESE" device were both about 13 microcoulomb. The in-

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452/5 = 90.4

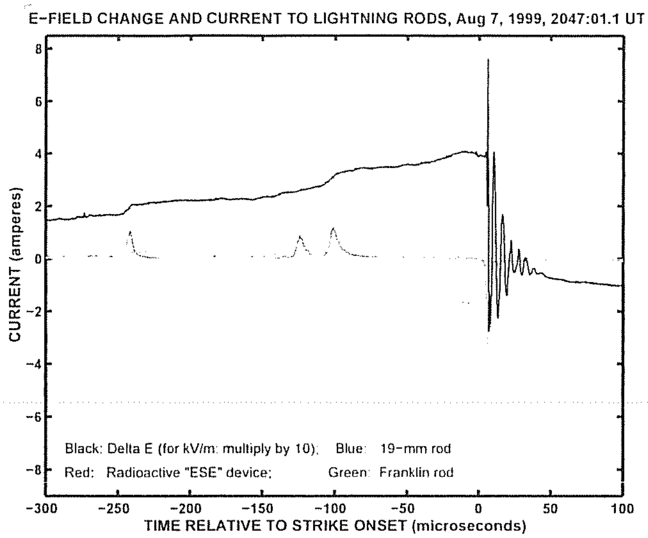

Figure 4. Plots of the electric field changes and of the currents that flowed from three lightning rods mounted on 6-m high masts above Kiva II on South Baldy Peak when rocket-initiated lightning struck a pine tree located 33-m NNE of Kiva II (August 7, 1999).

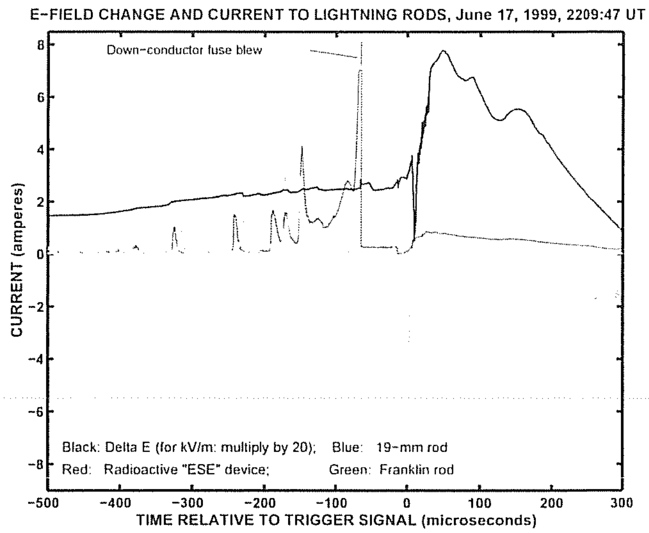

Figure 5. Plots of the early electric field changes and of the currents that flowed from three lightning rods mounted on 6-m high masts above Kiva II on South Baldy Peak when lightning struck the 19-mm diameter blunt rod (June 17, 1999).

teresting oscillation in the electric field change record was not a sensor artifact; it appears to have been real, with a 5 microsecond period and a quality factor for damped oscillation of about 4. This is probably due to ringing in the wire used to trigger the discharge.

STRIKE TO AN INSTRUMENTED BLUNT ROD ON JUNE 17, 1999 – On June 17, 1999, a 19-mm diameter aluminum rod above Kiva II was struck by a four stroke natural lightning discharge. The responses of the three instrumented lightning rods to the first stroke are given in Figure 5 in which it can be seen that, as the descending leader made a step downward, bursts of point discharge current were emitted from each of the three instrumented rods mounted above Kiva II. At about 150 microseconds before the electric field sensor triggered the digitizers, the 19-mm blunt rod emitted a burst of current that persisted and apparently grew into an upwardly-propagating leader with currents in excess of 8 A. A fuse that we had placed in the down-conductor lead (to protect the digitizer) exploded at this time and terminated the blunt-rod current measurement. It is of interest that, during the 70-microsecond burst of current from the blunt rod, the emissions from the two other rods declined, then ceased entirely. The integrated currents during this burst indicate that a positive charge of more than 199 microcoulomb was emitted by the blunt rod, 47 microcoulomb by the "ESE" device and 27 microcoulomb by the Franklin rod.

On lowering the mast supporting the 19-mm-diameter rod,, we saw four weld marks around the rod tip. A discharge had occurred inside the pipe mast near its top, presumably after the fuse in the down conductor failed early in the first strike. All of these indicated that the blunt rod had been struck repeatedly by lightning. On the other hand, there was no evidence of strikes to the tip of either the Franklin rod or to the "ESE" device; in addition, the fuses in their down conductors were intact.

CONCLUSIONS

We have found no evidence suggesting that sharp-tipped lightning rods are effective strike receptors when similarly-exposed, moderately blunt rods are in their vicinity. (For recommended tip-height to tip-diameter ratios, see Moore et al. [4].) While lightning does strike sharp rods when no competing receptors are nearby, we find that the rate of electric field intensification for return stroke leader formation must be much greater for sharp rods than for blunter ones. This is because the field enhancement for a sharp rod decreases much faster than for a blunt rod as the distance from the tip increases [4]. An initial streamer emitted by a sharp rod will soon enter into a field region away from the tip which is too low to sustain its propagation. For the same ambient field the field enhancement for a blunt rod decreases less rapidly, so the critical distance for the sustain propagation of a streamer will be larger for a blunt rod.

From this eight-year study, there are no indications that either of the so-called "early streamer emitting" devices created or emitted any effective early streamers or leaders. In our tests, two "ESE" devices responded to nearby lightning about as did the sharp Franklin rods, none of which took a strike during this study.

It is worth noting that, after a large current emission from one of the rods, the electric fields produced by the charges in that emission appear to suppress any competing emissions from nearby rods. This effect is shown in Figures 4 and 5 when the emissions from the 19-mm diameter rod were dominant and in Figure 3 when the charge transfer from the Franklin rod was 12-fold greater than that of both competing rods even though its streamers and leaders did not connect to the descending negative leader that struck a tree at a distance of 30 meters.

Since it is now well established that the emissions from sharp rods do not neutralize the electricity in thunderclouds and that they do not prevent the occurrence of lightning, the original reason for having sharp tips on lightning rods is demonstrably not valid. It appears that Benjamin Franklin's significant contribution to lightning protection was his suggestion for erecting grounded metal rods to provide preferential paths to Earth for lightning. In retrospect, Franklin's method for providing this protection has been made less effective than it could be by his urging that the tip of lightning rods be sharpened; our data show that his rods would provide better protection if they were not so effective in limiting the strength of the local electric fields.

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REFERENCES

[1] *NFPA 780*, National Fire Protection Association, 1 Batterymarch Park, Quincy, MA 02269, p.7, 1997.

[2] Franklin, B., *Experiments & observations on electricity*, 1774, reprinted by Harvard University Press, I. Bernard Cohen, editor, pp. 62, 374, 1941.

[3] Berio, G, "Use of ionization in air for lightning protection", *Isotopes and Radiation Technology*, **8**, 178-180, 1970.

[4] Moore, C. B., W. Rison, J. Mathis and G. Aulich, "Lightning Rod Improvement Studies", *J. Appl. Meteor.*, **39**, 593-609, 2000.

[5] Allen, N. L. and A. Ghaffar, The conditions required for the propagation of a cathode-directed positive streamer in air, *J. Phys. D*, **28**, 331-337, 1995.