A STUDY OF LIGHTNING PROTECTION SYSTEMS

prepared for

The Atmospheric Science Program
of
The Office of Naval Research

by

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ABSTRACT

Lightning continues to be a severe hazard to explosives manufacturing and handling operations. As part of an effort to minimize these problems, the authors have studied the lightning protection standards and practices currently used. We find that some significant improvements in present practices could be made to reduce the severity and frequency of lightning-induced problems.

Our recommendations include:

1. More general installation and use of lightning surge suppressors and transient barriers on all power, signal and control lines attached to buildings in which explosives are handled or stored.

2. Development and testing of the improved air terminals and overhead wires that are to be used for protection of ordnance facilities.

3. Improvements in the connections between air terminals and the earth.

4. Use of lightning warning instruments and termination of all operations with explosives whenever lightning occurs within 8 km (5 miles or flash-to-thunder times of less than 24 sec). If the time required to secure operations with sensitive ordnance is more than about 3 minutes, the occurrence of lightning at correspondingly greater ranges should be used to signal the onset of hazardous conditions. It should be noted that the greater the range criterion, the greater will be the incidence of "false" alarms with subsequent work losses and the development of a tendency to ignore the hazards. An appropriate range criterion needs to be developed and reviewed for each site where explosive operations are conducted in exposed structures above the earth.

5. Construction of Faraday-cage, multiple shields for protection of especially sensitive systems.

6. Development of new standards for lightning protection that incorporate these recommendations.

7. Establishment of a lightning review board to ensure user adherence to the improved procedures and to investigate accidents caused by lightning.

A STUDY OF LIGHTNING PROTECTION SYSTEMS

I. INTRODUCTION

The purpose of this study was to examine present Department of Defense (DOD) practices relating to lightning protection systems for critical installations, where maximum protection against lightning damage is mandatory. There are at least three sets of guidelines for lightning protection systems presently used by the Navy, Army, and Air Force. Although essentially similar in many respects, the recommended procedures and hardware implementations differ considerably. Not infrequently, the need for augmented lightning protection in existing, old facilities is difficult to implement because the requirements are often contradictory and confusing to the safety officers involved. We attempt in this report to address these and other problems associated with lightning protection for new installations, as well as for existing areas and buildings not now optimally protected.

In addition to hardware and its optimum utilization in building design and construction, we are concerned with questions of surveillance and the generation of reliable warning signals for approaching situations of hazardous weather. Plant or operations shutdown involves judgements made by supervisory personnel. Ideally, such judgements should be made on the basis of firm information and technical grounds, but ultimately the choice between plant shutdown costs and personnel safety becomes a moral judgement weighing operational costs (which can be estimated) against the value of human life (which we do not normally list in cost-pricing handbooks). An approach to solving this dilemma is to provide those who must make such decisions with the best possible background information. Another purpose of this study was to provide a palatable review of the appropriate lightning phenomena which should be helpful in understanding the origins, reasons, and motivations for some of the discussion made and the recommended techniques.

II. NATURE OF LIGHTNING

A. The Environment of Lightning

1. Winter and summer storms, tall and shallow clouds, volcanoes, and forest fires. Lightning is most frequently a feature of summertime convective clouds. Generally, summer thunderstorm cloud-tops reach up to between 10 and 16 km (30,000 to 50,000 feet), and the more vigorous storms have been observed to penetrate the stratosphere to 20 km and higher. These clouds extend well above the freezing level, which in the temperate U.S. is usually located between 4.5 and 5.5 km mean sea level(msl).

Summer orographic clouds form predictably over terrain features which, through solar heating, provide energy to the local air mass, and thus give rise to "local air mass" storms. These storms, usually over mountain ranges and peaks which provide high level heating as the source of dynamical instability, are mostly small in horizontal extent, perhaps not more than a few kilometers in radius, and are born early in the storm day. Mountains provide a "heat leak" to the atmosphere, thereby preventing the buildup of large instabilities.

Large storm systems are produced by squall lines, systems which are often hundreds of miles in horizontal extent. These large storms derive their energy from the latent heat of water and from large scale pressure gradients.

Both large and small scale storms produce vigorous lightning activity. In addition to the necessary moisture, key ingredients are strong, vertical convection coupled with a mix of solid and liquid precipitation. Although flashing rates may be higher for the larger storms, there is presently little evidence, except for some special winter situations, that the physical characteristics of lightning are different for different sized storms or for different geographical locations.

Regarded as a rare occurrence is lightning which has been seen to originate in shallow clouds with tops everywhere warmer than freezing. More common, although also relatively rare, is the lightning present in winter snowstorms, such as occur off the Great Lakes (e.g., Buffalo, N.Y.). Lightning in winter storms is difficult to anticipate because the discharge rate is very low, perhaps only one or two flashes per hour. The relative unpredictability of lightning occurrence in these storms make them a severe hazard, especially for the situations which may require decisions involving plant or operations shutdown.

Another type of rare lightning occurrence is associated with the more violent stages of volcanic eruptions. Recent good examples are Surtsey and Heimey in Iceland, Sakurajima and Aso in Japan, and Mt. St. Helens in Washington State. In the case of Mt. St. Helens, lightning from the drifting ash cloud was reported to occur five hours after the explosion and more than one hundred miles downwind of the volcano. Lightning occurred repeatedly even though the initial turbulent motions in the cloud had subsided.

Lightning has also been reported to accompany the vigorous cumulus clouds which are produced by the intense heat released by forest fires and burning oil-storage tanks.

2. The cellular nature of stormclouds. Radar pictures and time-lapse movies show that cumulus clouds are cellular in nature, and that lightning activity is strongly associated with the cloud's updraft structure. Vigorously growing cells produce high lightning discharge rates, and vertical cell growth exceeding 30m/sec is not uncommon. In summer convective storms, lightning from a new growing cell can be expected to first appear as the cell top approaches about 8500m (28,000 ft) (msl). Aircraft and radar measurements indicate that minimum cell sizes are about 100m (300 ft) in diameter, but cells exceeding 10km (30,000 ft) in diameter are often seen by radar. Several growing cells may be active simultaneously, each producing lightning at its own rate. Indeed, most large storms produce lightning from a multitude of cells active simultaneously over a large area.

3. Lightning flash density. The most intense lightning activity in the U.S. occurs in the midwest and is usually associated with the passage of a squall line. Spectacular displays with almost continuous lightning accompanied by golfball or grapefruit sized hail have been reported. Frequently, these storms spawn tornadoes and devastating winds.

The highest frequency of lightning occurrence, as opposed to the "most active" storms, is found in Florida, and the adjacent Gulf coast of Louisiana, Mississippi, and Alabama. Surprisingly, the next most "thundery" area is the semi-arid southwest, from central New Mexico north into southern Colorado. Although much lightning activity occurs in this region, the amount of rain which reaches the surface is small due to the evaporation of precipitation into the dry subcloud air. Other regions such as Arizona and Utah also exhibit frequent lightning activity with relatively small amounts of surface rainfall. In contrast, lightning is a rare event along the wet coastal areas of Oregon and Washington state. Obviously, rainfall does not always correlate well with lightning activity.

Lightning occurrence data are usually presented in the form of isoceraunic maps, such as Figure 1. Figure 1 shows the frequency of occurrence of "Thunderstorm Days" per year based on a thirty year average of U.S. Weather Bureau records. Isoceraunic maps are used in the design of lightning protection systems for power lines, telephones, and other exposed systems. A fuller discussion of lightning occurrence frequency and

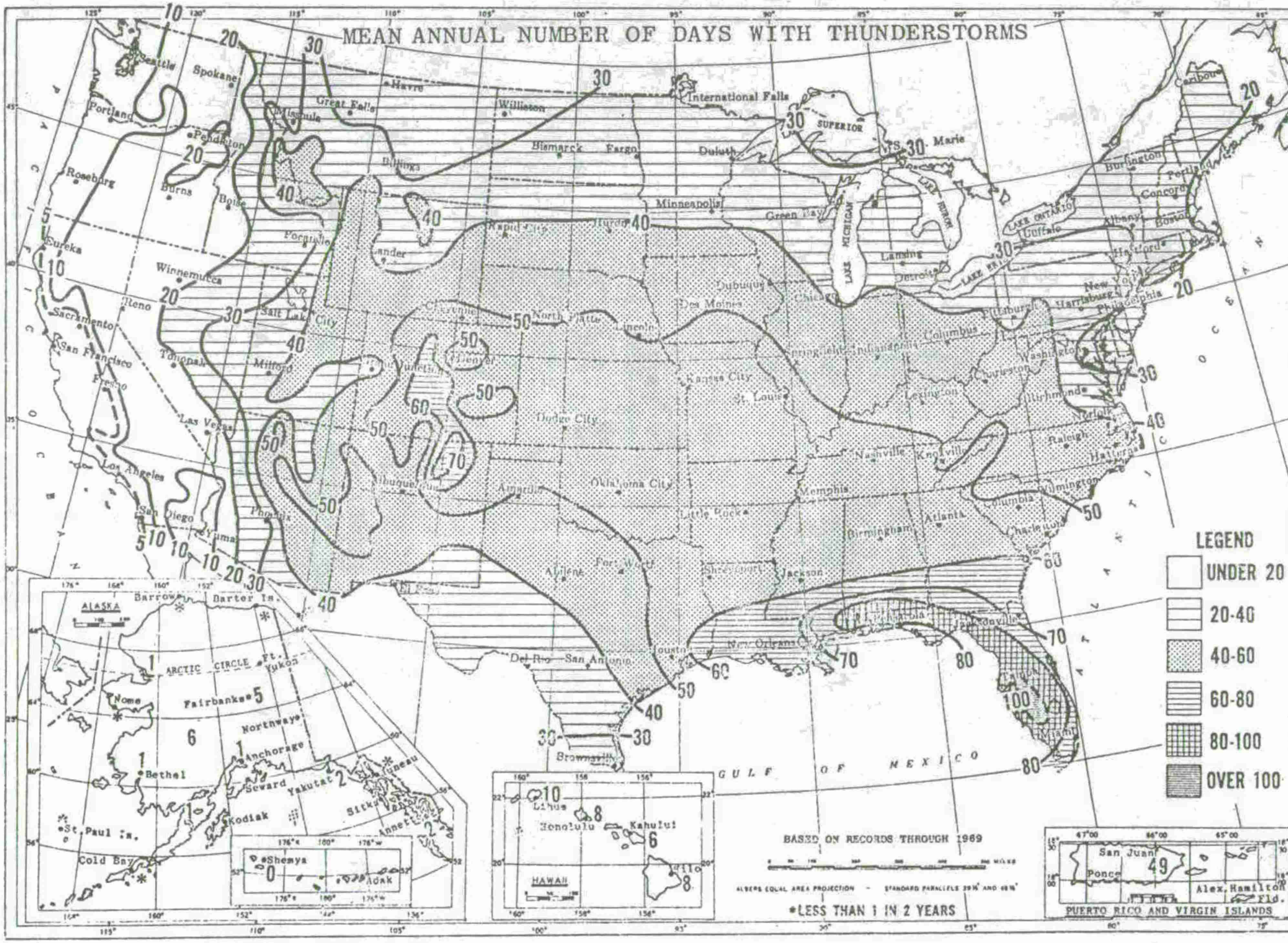


FIGURE 1. THUNDERSTORM DAYS PER YEAR IN THE U.S.

thunderstorm days as they might apply to munitions plant protection problems is given in Section IV.

B. The polarity of thunderclouds and lightning strokes

At this point it is well to emphasize the distinction between a lightning "flash" and a lightning "stroke". A "lightning flash" refers to the entire lightning discharge, lasting for about 0.4 or 0.5 seconds, and consisting of many short transient events, some confined entirely to the cloud while others emerging from the cloud and still others making their way to ground.

A "lightning stroke" is a specific event associated with a cloud-to-ground lightning flash. "Stroke" refers to the transient, high current, and highly luminous event which is generally seen as the bright lightning channel extending from cloud-to-ground. There are usually a number of lightning strokes traveling up the same path during a single lightning flash. This repetitive feature of lightning "return strokes" is responsible for the flickering appearance of many lightning channels.

Electrically, the thunderstorm may be approximated by a vertically oriented dipole with the positive charge uppermost (see Figure 2). The dominant mode of discharge to ground involves the lowering of negative charge to earth (or effectively raising positive charge to the cloud). In summer storms the negative charge brought to earth is located in the lower regions of the cloud, as shown in Figure 2a. The positive stroke (carrying positive charge) is rare, and usually occurs, if it does at all, in the dying phases as the last stroke(s) of the storm. In winter storms positive strokes are more common. They constitute, for example, 90% of all strokes in the Hokuriku winter storms off the Sea of Japan. The Japanese storms are of normal polarity, i.e., the positive charge of the dipole is still uppermost, and hence one concludes that the upper charge in this case is preferentially lowered to earth, (see Figure 2b). Presently, we have little information on the polarity of strokes from winter storms in the U.S. At any rate, the total number of ground strokes from winter storms is probably less than 0.1% of all lightning ground strokes, winter and summer combined. For this reason, we confine our attention to the predominant type of stroke which lowers negative charge to earth.

C. Charge Separation in Clouds

The mechanism by which clouds become electrified is a continuing subject of active research. Many theories have been proposed and advocated ever since man exercised his imagination. We shall make no attempt to catalogue the multitude of hypotheses in this brief introduction. We shall discuss the essence of two classes of explanations presently in vogue.

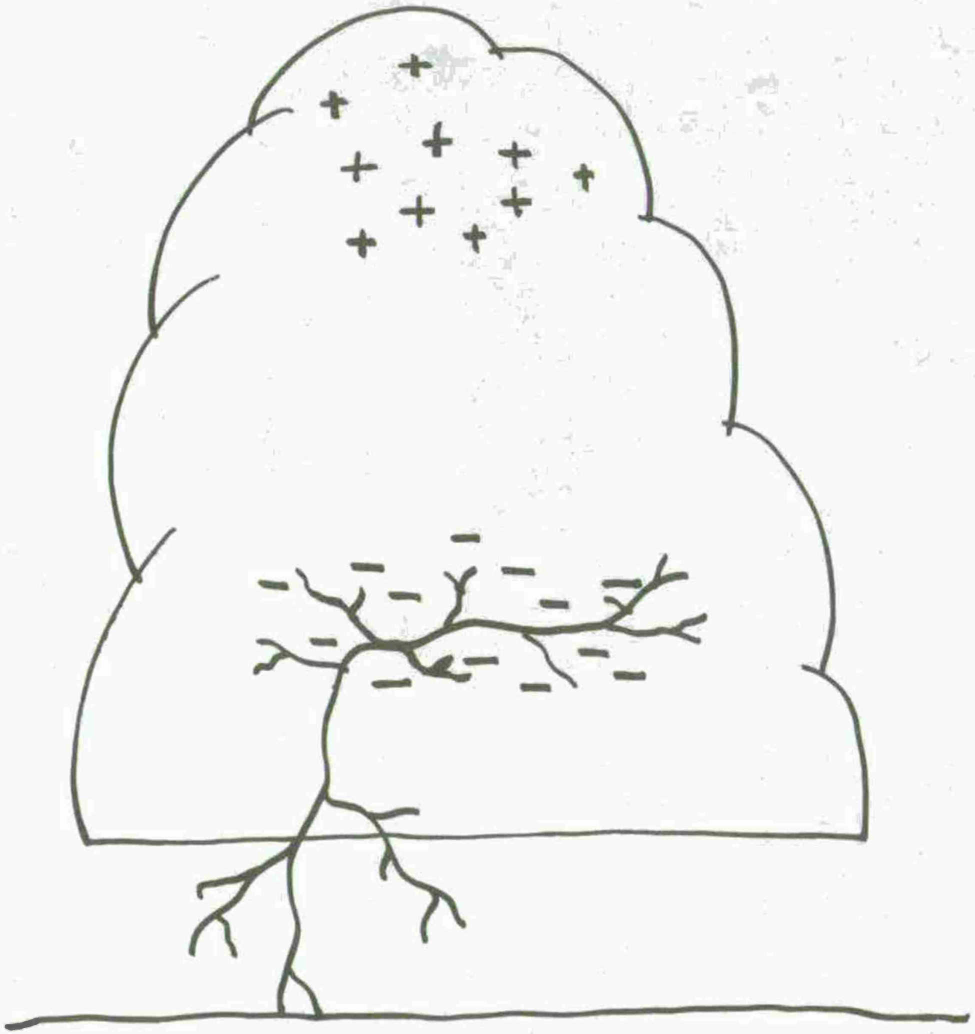


FIG 2a. TYPICAL MODE OF DISCHARGE
IN SUMMER STORMS-
NEGATIVE STROKE TO GROUND.

FIG 2b. TYPICAL DISCHARGE IN
WINTER STORMS-
POSITIVE STROKE.

Since no single hypothesis appears capable of explaining all the observational facts, several mechanisms may be operative simultaneously, the dominant one determined by the specific set of existing physical and cloud environmental conditions.

The first class of hypothesis we discuss all start with the earth's fine weather atmospheric fields and charges, and through a positive feedback mechanism (involving cloud and/or precipitation motion) separate charge in evergrowing amounts until electrical breakdown is reached. One such process is the induction mechanism which starts with an existing electric field in which large and small particles collide. The larger particles fall away from the smaller ones carrying predominantly one sign of charge, the smaller ones carrying the other. Another explanation in this first class is the convective mechanism which uses updrafts and downdrafts to transport charges in a somewhat organized fashion. If a cloud acquires a net charge in its upper regions, for example, charges of opposite sign will be attracted to the cloud by electrical forces. On arrival at the cloud boundary, these induced charges will become attached to the cloud droplets, and will then follow the cloud motions. In a convective cloud, an overturning motion occurs in which the air near the top is displaced to the side by the rising air from below. These overturning motions may be imagined to transport the immobilized induced charges downward, leading to an enhanced electric field at the surface which may eventually become strong enough to induce point discharge with the emission of ions of inverted polarity. The continued growth of the cloud will result in the entrainment of many of these new ions into the updraft, thus enhancing the initial electric field and leading to a further increase in the charges trapped and transported on the cloud boundary. In this process of cloud overturning, the system operates similar to a Wimshurst electrostatic generator with positive feedback.

Like most positive feedback systems, the process may be initiated through any number of effects which lead to a charge imbalance in the convective cloud. The imbalance may arise from charges carried on falling precipitation, or from the initial fine weather space charge existing in the subcloud air from which the cloud grows.

The second class of explanation involves the physical properties of cloud particles and precipitation in a direct way, and depends largely upon gravitational separation of small from large particles to accomplish the charge separation. One such hypothesis, known as the graupel-crystal collision mechanism, depends upon the coexistence of liquid and solid phases of water: supercooled cloud droplets, ice crystals, and soft hail (graupel). The graupel grows by falling through cloud and accreting the supercooled droplets, and becomes warmer than the ambient air due to the heat released as the droplets freeze to its surface. On falling, it also collides with crystals which, because of their low density and aerodynamic properties, move with approximately the updraft air velocity. Charge is separated as a result of the graupel-ice crystal collisions, the warmer particles (graupel) becoming negatively charged. Negative charge emerges from the bottom of the collision region and positive charge from the top.

As we indicated earlier, none of the existing hypotheses seem capable of accounting for all of the experimental facts, nor can they account for the electrification in the short time observed-approximately 10 to 12 minutes from clear sky to first lightning flash.

In recent years numerous attempts have been made to influence cloud growth, to make or inhibit rainfall, and to augment snowpack via cloud seeding activities. Many attempts have been made to control lightning by seeding clouds with silver iodide, dry ice and with conducting fibers, but at this time there is little evidence that lightning modification is a viable technique. In view of our ignorance of the exact nature of the charge separation process, it is not surprising that attempts to decrease lightning have not succeeded. On the other hand, modern "Benjamin Franklin" experiments have succeeded in triggering lightning strokes by firing small rockets with grounded wire attached. Though an initial controlled path for lightning is thus provided, the phenomenon of multiple cloud-to-ground strike paths (shown in Figure 3) has also been observed in these experiments.

D. Cloud-to-Ground Lightning

1. Some general characteristics. The duration of a lightning flash, intracloud or cloud-to-ground, is on the average about four tenths (0.4) seconds. This may vary from one tenth to several seconds, however, and depends on the level of lightning activity. In general, the flash duration is greater in storms where the flashing rate is high. An average level of thunderstorm activity is characterized by about two lightning flashes per minute while, in severe electrical storms, the flash rate may be as high as 25/min. For cloud-to-ground flashes, which lower about 20-30 Coulombs of charge per flash, this is equivalent to an average steady thunderstorm current of about one ampere of negative charge flowing from cloud-to-ground.

2. The leader-return-stroke sequence. A lightning flash to ground is initiated by a leader, called the stepped leader, which originates in the cloud and makes its way to earth in a series of tortuous steps. It is a streamer of negative polarity with jumps of about 100 ft in length and characteristically exhibits a bright tip at the end of each step. The time between steps is quite variable, but on the average is about 60 microseconds over the leader duration of between 5 to 30 milliseconds. The stepped leader is sometimes preceded by other electrical activity within the cloud which may last as long as 0.25 seconds. In general, the stepped leader in its initial

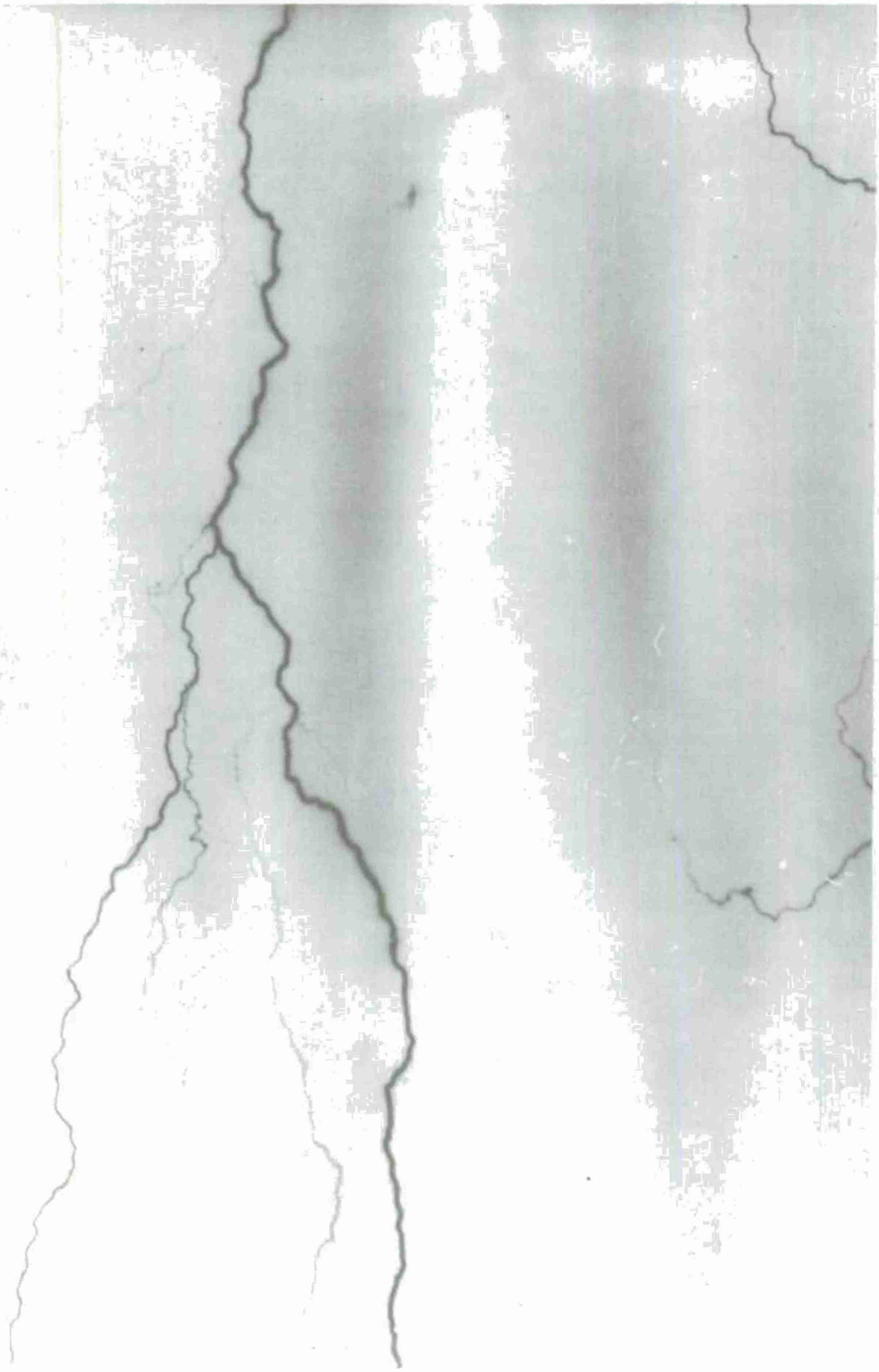


Figure 3. An example of a lightning flash with cloud-to-ground multiple-channel branching. Two strike points involving high current return strokes are easily recognizable.

stages is accompanied by strong radio emissions over a broad band of frequencies, an effect which has on occasion been used to build instruments to signal the imminent occurrence of a cloud-to-ground stroke. When the stepped leader comes to within about 100 ft of the surface, a multitude of positive streamers originate on the earth over a broad area and propagate upward to meet the leader. With this occurrence, the "return" stroke is initiated.

The return strokes are the major elements in the roughly one-half second long sequence of events which constitutes a lightning flash to ground. Figure 4 is a diagram giving the appropriate times of occurrence of the various events in a typical flash. The diagram simulates what a camera with a horizontally moving film would show for a ground flash with three return strokes.

On the average, lightning flashes consist of a sequence of four leader-return stroke pairs, although flashes containing only one stroke are common, and flashes consisting of more than 20 leader-return stroke pairs have been photographed with moving film cameras (see Figure 5).

Strokes subsequent to the first one which follow the same channel to ground are preceded by another, more rapidly moving leader called a dart leader. Unlike the stepped leader, which forges the initial ionized channel to ground, the dart leader travels without stepping down an already ionized path. The return strokes which follow the leaders travel back up the channel with a speed of about one-third the velocity of light, and leave a trail of almost completely ionized air at a temperature of about 25,000 degrees C. The current associated with the return stroke averages about 20,000 amperes, reaches peak value in a few microseconds, and decays to half value in about 40 microseconds. The intense heating of the air during the return stroke phase is the source of energy expended in the rapid expansion of the lightning channel; it produces the observed thunder which accompanies the strokes.

The average time between return strokes in a flash is 40 milliseconds, but here again the range of values is large and goes from about 3 milliseconds to greater than 100 milliseconds.

3. <u>Continuing current strokes.</u> Another kind of stroke which lowers negative charge to earth is the "continuing current" type. This return stroke does not exhibit the fast current rise of the ordinary discrete stroke referred to earlier, but instead involves a relatively steady current of about 175 amperes for a time of about 0.2 seconds. Although the currents are small compared to ordinary strokes, the heating effect of the relatively long-lasting current is significant. It has been shown to be a primary cause of lightning initiated forest fires. Continuing current strokes occur only about 20% of the time in multiple-stroke flashes to ground. On the other

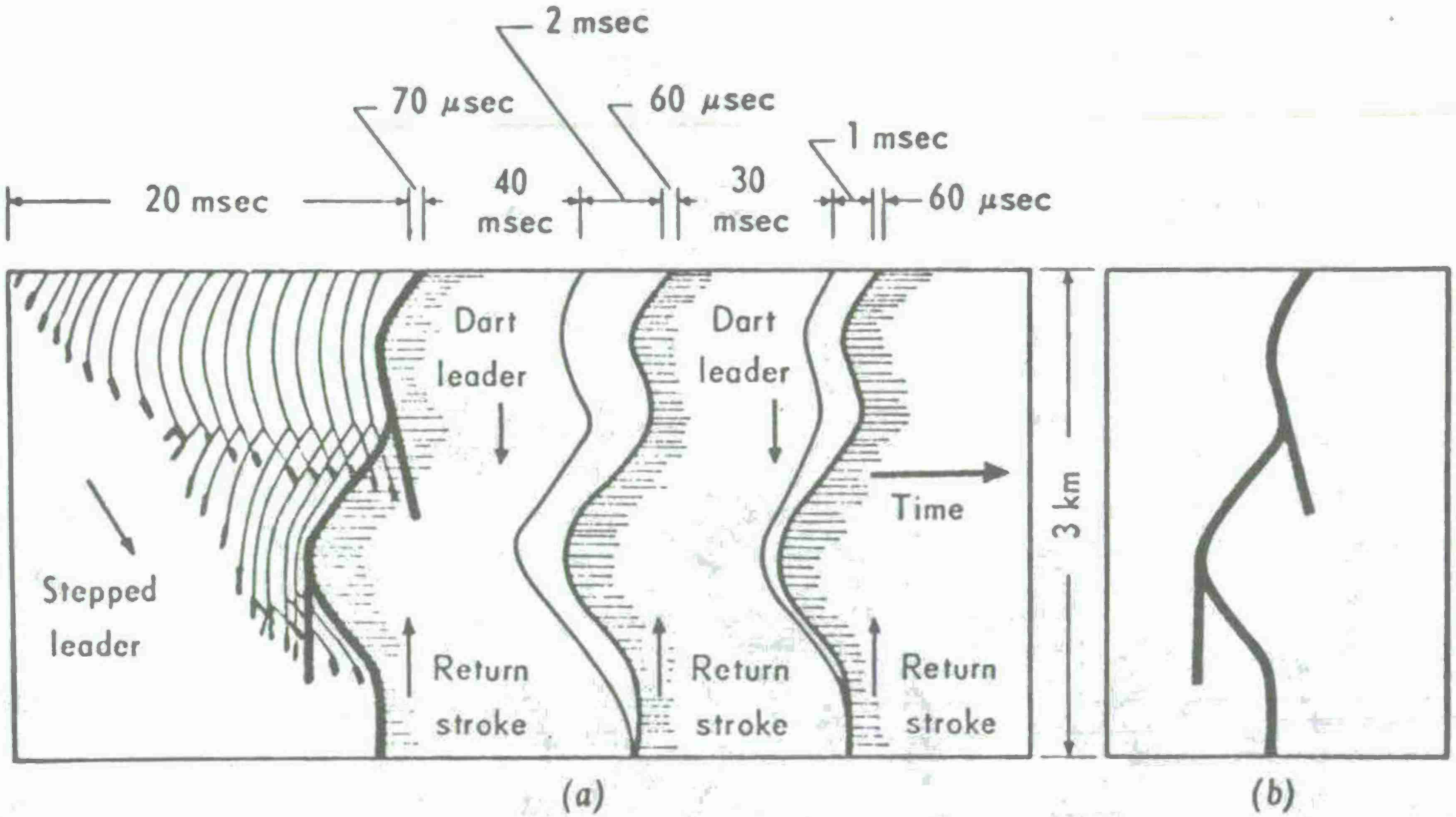


Figure 4. (a) The luminous features of a lightning flash as would be recorded by a camera with fixed lens and moving film. Increasing time is to the right. For clarity the time scale has been distorted. (b) The same lightning flash as recorded by a camera with stationary film.

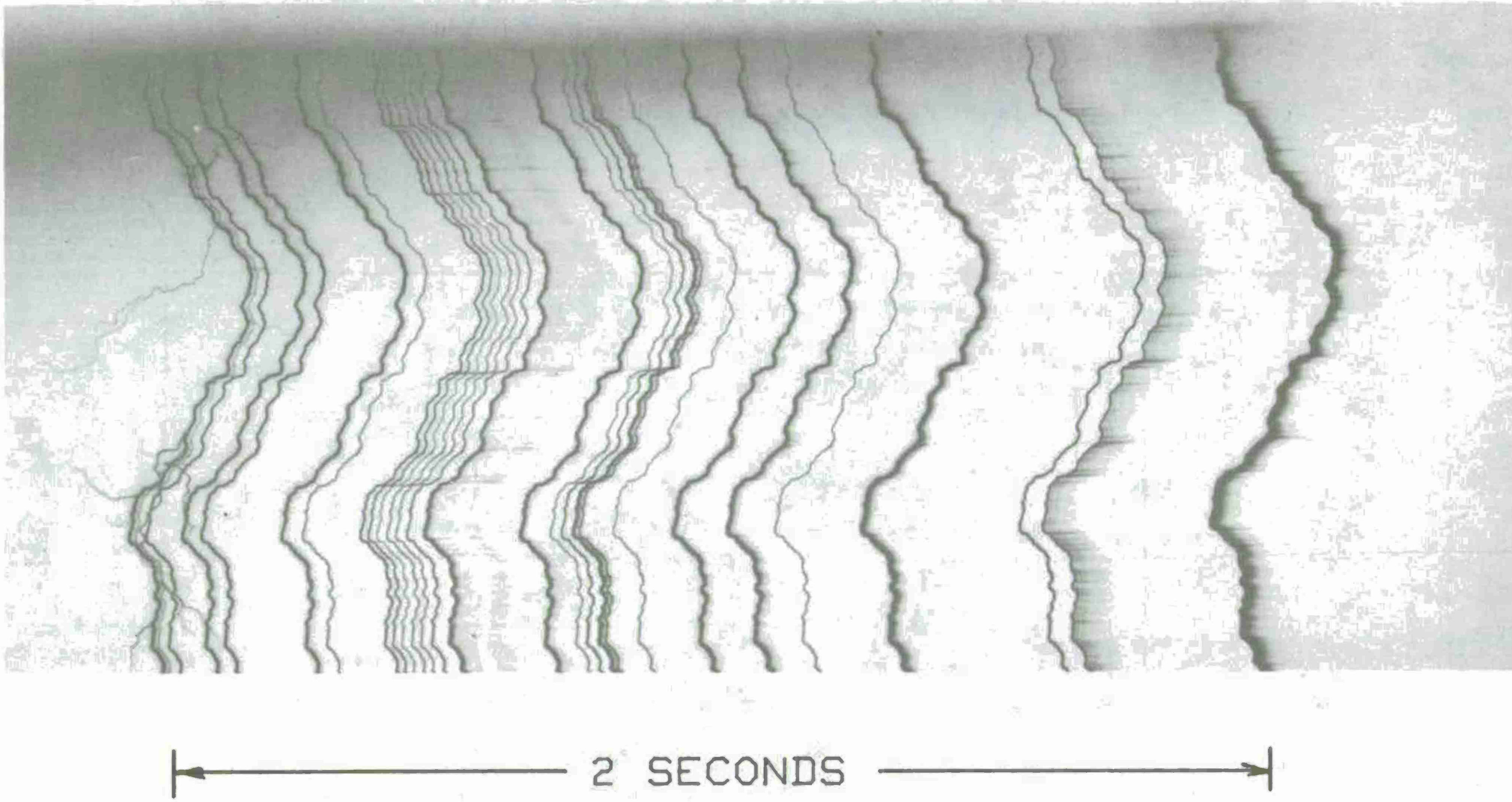


Figure 5. Multiple-stroke cloud-to-ground flash photographed with moving film camera.

hand, the charge lowered by a continuing current is of the order of 30 coulombs, or roughly six times as much charge as is carried by the ordinary discrete strokes.

4. Strokes with multiple strike points. The stepped leader produces many branching paths, each of which continues toward ground until one channel has made contact with one of the many positive streamers which rise to meet it. The origin of the positive streamers is attributed to the existence at the surface of a myriad of objects which behave like sharp points and go into corona as the leader tip approaches. The potential of the leader tip is of the order of 100 million volts, causing charge to be induced on all conducting (even poorly conducting) objects at ground potential. Thus trees, grass, poles, towers, etc. go into corona, emitting charge as a means of reducing the high electric field in their immediate vicinity. Usually, the ensuing return stroke localizes on one of the corona emitting objects, and it becomes a part of the return stroke channel.

But the first return stroke path does not always remain the unique and only channel for the duration of the flash. It happens reasonably often that the second or another subsequent stroke will not follow the original channel in its entirety: for one or more reasons the lower end of the channel cools rapidly, and the ionization decays to a level which will not support a dart leader in the original channel. At this point a new stepped leader forms to make a new channel, and another positive streamer connects with it to complete the channel to ground. Figure 3 is a photograph which shows a single channel for much of the lightning path, and three separate paths from there to earth. Emphasis is made here on the cloud-to-ground branching in order to underline the point that it is the lightning channel near the ground which can cool and as a result produce a second or even third ground strike point. A more complete discussion of this and other related considerations is given in Section IV.

A summary of cloud-to-ground lightning flash characteristics for strokes which bring negative charge to earth is given in Table 1. The data were collected from the work of many lightning investigators by Martin Uman and appear in his book "Lightning" published by the McGraw-Hill Book Co., New York, 1969. Another book on lightning and lightning protection which may be of use to the reader is the two volume work "Lightning", edited by R. Golde, and published by Academic Press, New York, 1977. In Section III, a more technical description of lightning, with references to original articles, is given.

5. Electric-Field changes associated with lightning. Most desirable for purposes of hazard detection and warning is the utilization of instruments which can sense lightning activity in clouds sufficiently distant to allow for the implementation of safety procedures. There are basically four techniques which can be utilized to detect or warn of the existence of lightning activity: (1) acoustic, (2) optical, (3) radiation (radio

noise), and (4) electric-field change. The first two listed techniques, which make use of thunder and light pulses are not very reliable because of the storm environment. Thunder is often muffled by the noisy wind background, and dense, black clouds can completely obscure the light, even with detectors which operate in full daylight. Radio noise emitted during the lightning flash has been used with success to detect and even pinpoint the strikes, but the instrumentation is expensive. Nevertheless, there may be situations where one, or even two instruments (for triangulation) may be fully justified.

TABLE 1

Data for a normal cloud-to-ground lightning discharge bringing negative charge to earth. The values listed are intended to convey a rough feeling for the various physical parameters of lightning.

	Minimum*	Representative	Maximum*
Stepped leader			
Length of step, m	3	50	200
Time interval between steps, microseconds	30	50	125
Average velocity of propagation of stepped leader, m/sec	1.0x10	1.5x10	2.6x10
Charge deposited on stepped leader channel, coul	3	5	20
Dart leader			
Velocity of propagation, m/sec	1.0x10	2.0x10	2.1x10
Charge deposited on dart leader channel, coul	0.2	1	6
Return stroke			
Velocity of propagation, m/sec	2.0x10	5.0x10	1.4x10
Current rate of increase, kA/microsec microsecond	<1	10	>80
Time to peak current, microseconds	<1	2	30
Peak current, kA		10-20	110
Time to fall to half of peak current, microseconds	10	40	250
Charge transferred excluding continuing current, coul	0.2	2.5	20
Channel length, km	2	5	14
Lightning flash			
Number of strokes per flash	1	3-4	26
Time interval between strokes in absence of continuing current, millisec	3	40	100
Time duration of flash, microseconds	10	0.2	2
Charge transferred including continuing current, coul	3	25	400

TABLE 1 - Continued

* The words maximum and minimum are used in the sense that most measured values fall between these limits.

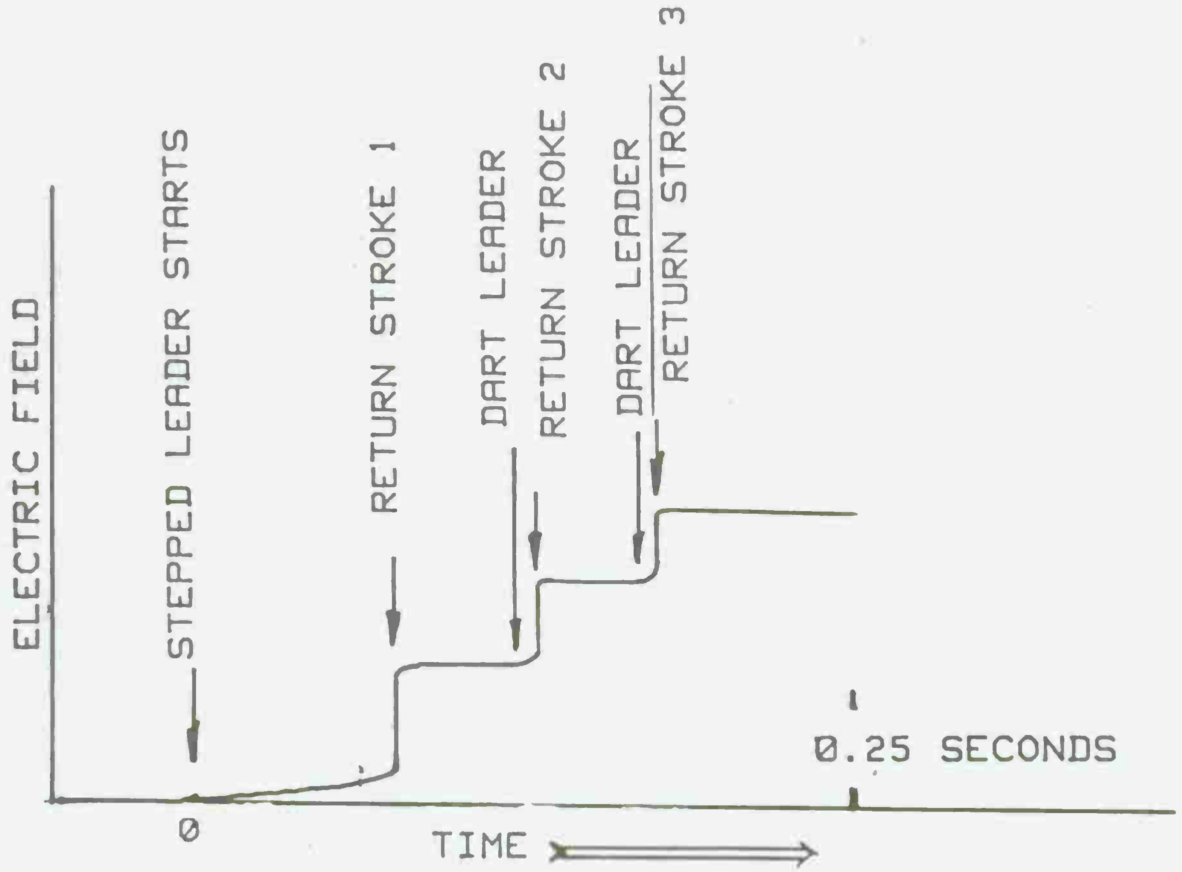
  Velocities of propagation are generally determined from photographic data and thus represent "two-dimensional" velocities. Since many lightning flashes are not vertical, values states are probably slight underestimates of actual values.

  First return strokes have slower average velocities of propagation, slower current rates of increase, longer times to current peak, and generaly larger charge transfer than subsequent return strokes in a flash.

  Current measurements are made, at the ground by direct measurement current (shunts or towers) and by indirect, remote sensing methods. The fourth technique utilizes the effect produced when electric charge is moved in or removed from the cloud. A change in the electric field occurs which is sufficiently abrupt in nature to be unique against background noise, and which can be sensed for distances up to 50 miles or more with confidence and reliability.

The electric field change which accompanies a typical cloud-to-ground flash is shown in Figure 6. Plotted on the vertical axis is the instantaneous value of the electric field referred to 0 volts per meter at time equals zero. This figure should be compared to Figure 5 which shows the same typical flash as recorded by the moving film camera. The reader should note that the cloud overhead becomes more positive as the flash progresses; this is, of course, a direct result of the removal of negative charge from the cloud (or the deposition of positive charge in the cloud) by the return stroke as well as by the leader strokes. Also note, the rapid or abrupt changes (jumps) in the field associated with the return strokes. The rapid electric field changes can be utilized to signal the occurrence of lightning, and warning instruments which operate on this principle are reasonably simple and economical to build and operate. They can be used with a bell to signal the occurrence of lightning, and through the use of a recorder, would provide a stroke vs. time record which can be helpful in deciding whether the storm is moving toward or away from the installation. Lightning flashes from an active cell occur with intervals which are more or less regular: this type of regularity can be used as a measure of lightning activity, and often provides a qualitative estimate of increasing or decreasing storm severity.

Instruments which make use of the electric field change, as well as others which may be used to warn of high electric field strengths for close-in storms will be discussed in Section VIII.



ELECTRIC FIELD CHANGE FOR
TYPICAL CLOUND-TO-GROUND FLASH
WITH 3 RETURN STROKES.

FIGURE 6.

III. THE PHYSICAL CHARACTERISTICS OF LIGHTNING

Lightning is a transient, high current electric discharge whose path length is measured in kilometers. The most common cause of lightning is the electric charge separated in ordinary thunderstorm clouds (cumulonimbus). Well over half of all flashes occur within the cloud (intracloud discharges), but it is cloud-to-ground lightning that is of primary interest in the protection of ordnance facilities.

The discussion of cloud-to-ground discharge components which follows is adapted from Uman (1969).

Although our primary interest is the individual lightning flash, it is worth noting the overall phenomenology of lightning in thunderstorms (e.g., the fraction of the total discharges which are to ground vs. storm phase, the number of lightnings vs. storm duration, the maximum and average flashing rates) is an area of current research (see, for example, Livingston and Krider, 1978). The question of whether lightning return stroke characteristics, and by implication lightning characteristics in general, are dependent on geographical location, season, or meteorological conditions is still not known. Thomson (1980) reports no significant correlation between the average number of return strokes per flash or the interstroke time intervals and the geographic latitude of the measurement. While average lightning flashes at various latitudes are probably similar, there are certainly differences within a given region: frontal storms produce a higher flashing rate and more strokes per flash than local convective storms (e.g., Schonland, 1956) topography affects the channel lengths to ground and other properties (e.g. McEachron, 1939; Winn et.al. 1973), and there are seasonal effects such as the positive discharges to ground produced by winter thunderstorms (Takeuti et.al., 1973, 1976, 1977, 1978, 1980).

A. Nature of a Cloud-to-Ground Flash

A typical discharge between cloud and ground is initiated in the cloud and neutralizes tens of coulombs of negative cloud charge in about 0.5 sec. The total discharge is called a <u>flash</u>. Among the various processes comprising a flash are typically 3 or 4 high-current pulses called <u>strokes</u>, each lasting about 1 millisecond with a separation time of typically 40 to 80 milliseconds. Lightning often appears to "flicker" because the eye resolves the individual light pulses associated with each stroke. In the idealized model of cloud charge shown in Figure 7, the primary dipole charges P and N are of the order of tens of coulombs or more of positive charge and negative charge, respectively, and p is a smaller positive charge. The <u>stepped leader</u> initiates the first stroke in a flash by moving charge from cloud-to-ground as sketched in Figures 7 and 8. The stepped leader is initiated by a <u>preliminary breakdown</u> within the cloud although there is still some disagreement about the

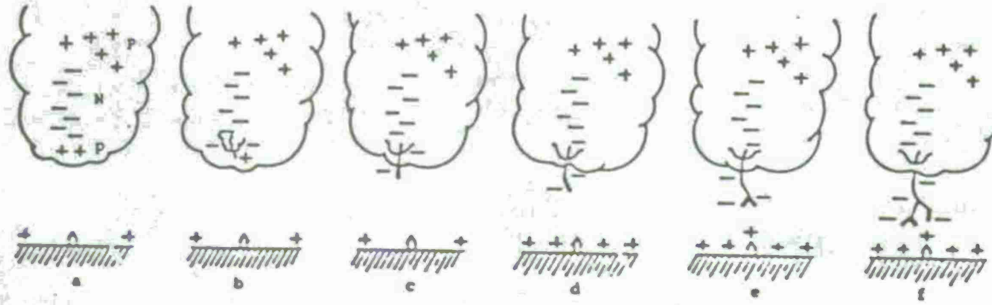


Figure 7. Stepped-leader initiation and propagation. (a) cloud charge distribution prior to lightning. (b) discharge called preliminary breakdown in lower cloud. (c)-(f) stepped-leader progression toward ground. Scale of drawing is distorted for illustrative purposes. Adapted from Uman (1971).

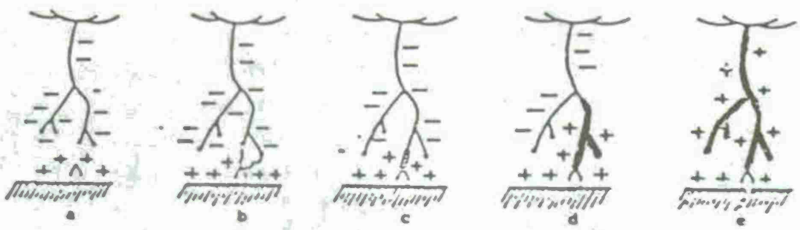


Figure 8. Return-stroke initiation and propagation. (a) final stage of stepped-leader decent. (b) initiation of upward moving discharges. (c)-(e) return-stroke propagation from ground to cloud. Scale of drawing is distorted for illustrative purposes. Adapted from Uman (1971).

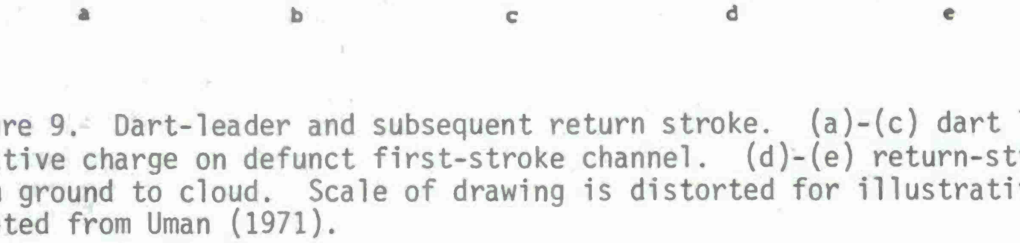


Figure 9. Dart-leader and subsequent return stroke. (a)-(c) dart leader deposits negative charge on defunct first-stroke channel. (d)-(e) return-stroke propagates from ground to cloud. Scale of drawing is distorted for illustrative purposes. Adapted from Uman (1971).

exact form and location of this process. In Figure 8(b) the preliminary breakdown is shown in the lower part of the cloud between the N and P regions. The preliminary breakdown sets the stage for negative charge (electrons) to be channeled toward ground in an intermittent series of short steps (hence the name stepped leader). Leader steps are typically 1 sec in duration and tens of meters in length, with a pause time between steps of about 50 microseconds (Figure 7(c)-(f), Figure 8(a). A fully developed stepped leader lowers about 5 coulombs of negative cloud charge toward ground in tens of milliseconds. The average downward velocity is about 2×10^5 m/sec, the average current is of the order of 100 A, and the electric potential of the leader channel with respect to ground is about -1×10^8 V. The intermittent leader steps have pulse currents of the order of 1 kA or more. Associated with these pulse currents are microsecond-scale electric and magnetic field changes. The stepped leader branches in a downward direction during its trip to ground. The preliminary breakdown, the subsequent lowering of negative charge toward ground by the stepped leader, and the resultant depletion of negative charge in the cloud combine to produce a total electric field change with a duration between a few and a few hundred milliseconds.

As the stepped leader nears ground, the electric field beneath it becomes very large and causes one or more upward-moving discharges to be initiated at the ground (Figure 8(b)), which starts the attachment process. When one of the upward-moving discharges from the ground contacts the downward-moving leader some tens of meters above the ground, the leader tip is connected to ground potential. The leader channel is then discharged by virtue of a ground potential wave, the return stroke, which propagates up the previously ionized path. The upward velocity of a return stroke is typically one-third the speed of light (Figure 8(c)-(e)) and the total transit time from ground to the top of the channel is typically about 100 microseconds. The return-stroke channel, at least its lower portion, carries a peak current of typically 20 kA, with a time from zero to peak of some microseconds. The maximum rate-of-change of the return stroke current is about 150 kA/microsecond or higher. Currents measured at the ground fall to half of peak value in about 50 microseconds, and currents of the order of hundreds of Amperes may flow for milliseconds or longer. The energy dissipated by the return-stroke current heats the channel to a temperature near 30,000°K and this in turn causes a high-pressure channel which expands and creates a shock wave which eventually becomes thunder. The return stroke lowers the charge originally deposited on the stepped leader to ground and in doing so produces an electric field change with time variations ranging from sub-microseconds to many milliseconds.

After the return stroke current has ceased to flow, the flash may end. On the other hand, if additional charge is made available to the top of the channel by discharges within the cloud known as K- and J-processes, a continuous or dart leader (Figure 9) may propagate down the decaying first return stroke channel at a velocity of about 3×10^6 m/sec. The dart leader lowers a charge of the order of 1 coulomb by virtue of a typical current of 500 A. The dart leader thus sets the stage for the second (or any subsequent) return stroke. Dart leaders and strokes subsequent to the first are usually not branched. Some leaders begin as dart leaders but end their trips toward ground as stepped-leaders. These are known as dart-stepped leaders. Dart leader electric field changes usually have a duration of about 1 millisecond. Subsequent-stroke electric field changes are similar to, but usually a factor of two or so smaller than, first-stroke field changes. Subsequent strokes have faster zero-to-peak current risetimes than first strokes but similar maximum rates-of-change of current.

The time between successive return strokes in the same channel is usually 40 to 80 millisecond but can be tenths of a second if a continuing current flows in the channel. A continuing current can also follow the final stroke in a flash. Continuing currents are of the order of 100 A and represent a direct transfer of charge from cloud-to-ground. The electric field change produced by a continuing current is linear for roughly 0.1 sec and is consistant with the lowering of about 10 coulombs of cloud charge to ground. Between one-quarter and one-half of all cloud-to-ground flashes contain a continuing current component.

In addition to the usual downward-moving negatively-charged stepped leader, lightning may also be initiated in the cloud by a positively charged downward-moving stepped leader, but this type of discharge is not common (Berger and Vogelsanger, 1966; Berger 1967, 1972; Takeuti et al., 1973, 1976, 1977, 1978, 1980). Furthermore, lightning can be initiated at the ground, usually from tall structures, by upward-going stepped-leaders which can be either positively or negatively charged (Berger and Vogelsanger, 1966; Berger, 1967, 1972). The upward-going leaders branch in an upward direction. In this review we will concentrate on the most common form of cloud-to-ground lightning, namely that which lowers negative charge from cloud-to-ground and is initiated by a downward-moving, negatively charged stepped leader.

B. Cloud Charges and Static Electric Fields

The most familiar lightning producing cloud is the cumulonimbus. Although some measurements have been made of the electrical properties of other types of clouds (Imyanitov et al., 1972; Imyanitov and Chubarina, 1967), the cumulonimbus is the most common lightning generator and is the cloud type about which the most is known.

By the early 1930's, a model for the charge structure of a thundercloud had emerged, primarily from ground-based electrostatic field measurements (Wilson, 1916, 1920; Appleton et al., 1920; Schonland and Craib, 1927). In this model the thundercloud charges form a positive electric dipole; that is, there is a positive charge located above a negative as shown in Figure 12. From in-cloud measurements Simpson and Scrase (1937) were able to verify this basic dipole structure, and they also found the small concentration of positive charge at the base of the cloud as shown in Figure 12. More recent measurements have confirmed the general validity of this model (e.g., Simpson and Robinson, 1941; Malan, 1952; and Huzita and Ogawa, 1976), although it is now recognized that there can be large horizontal displacements between the positive and the negative charge regions and that the positive charge may be highly diffuse.

Because of the remote (outside the cloud) nature of many of the measurements and the difficulty of interpreting these and the internal measurements in the presence of spatial and time-varying conductivities, the magnitudes and heights of the cloud charge distributions are still uncertain (see Kasemir, 1965; Moore and Vonnegut, 1977). For example, space-charge screening layers on the surface of the cloud (Brown et al., 1971; Hoppel and Phillips, 1971; Klett, 1972) can lead to a substantial underestimation of remotely-measured cloud charge magnitudes.

Although Figure 7 is generally valid, we now know that the overall charge associated with the major charge regions is not uniformly distributed, but rather is found in localized 'pockets' of high space-charge concentration. Evidence for this is found (1) in the fact that only occasionally are high values of electric field measured while randomly sampling the internal cloud fields (Winn et al., 1974) whereas if there were large charge regions there should be relatively large volumes of high field and (2) in the fact that individual return strokes in a multiple-stroke ground flash may tap different negative charge regions, the localized negative charge regions being displaced horizontally from each other.

Typical values given in the literature for the electric charge centers p, N, and P along with their mean observed altitudes above ground level are +4 C at 1.5 km, -24 C at 3 km and +24 C at 6 km in England, ground level being about 1 km above sea level (Simpson and Robinson, 1941); +10 C at 2 km, -40 C at 5 km, and +40 C at 10 km in South Africa, ground level being about 1.8 km above sea level (Malan, 1952); and +24 C at 3 km, -120 C at 6 km and +120 C at 8.5 km in Japan, ground level being about 1 km above sea level (Huzita and Ogawa, 1976). It is interesting to note that, while the absolute magnitudes of the charges in these models vary considerably, their proportions are relatively constant. Jacobson and Krider (1976) have summarized most available data for the location and size of the N charge neutralized by lightning, their results in Florida (at sea level) being -10 to -40 C at 6 to 9.5 km height.

C. Stepped Leader

A significant fraction of what is known today about stepped-leaders was determined photographically by Schonland and his co-workers (Schonland et al., 1938 a, b; Schonland, 1956) in South Africa using streak cameras. The photographic measurements were also supplemented by slow (millisecond scale) electrostatic field measurements at close range (e.g., Schonland et al., 1938; Malan and Schonland, 1947; Schonland, 1956). Recently measurements have been made with microsecond resolution of the electromagnetic fields due to individual leader steps (e.g. Weidman and Krider, 1980; Krider et al., 1977; Krider and Radda, 1975).

We now list some of the more important characteristics of stepped-leaders:

1. On the basis of step length and average earthward velocity, Schonland (1938) and Schonland et al. (1938 a,b) have divided leaders into two classes, and . The type leaders have a uniform earthward velocity of the order of 10^5 m/sec, have steps that are shorter and much less luminous than the steps, and do not vary appreciably in length or brightness. Type leaders begin with long, bright steps and a high average earthward velocity, of the order of 10^6 m/sec, exhibit extensive branching near the cloud base, and, as they approach the earth, they assume the . characteristics of leaders. Schonland (1956) states that the majority of photographed leaders are type , whereas the majority of electrical measurements indicate type . This fact and the fact that the non- characteristics of 's are photographed at high altitude suggests that the initial characteristics are probably associated with the preliminary breakdown process.

The step lengths of type leaders are typically 50 meters when the leader is relatively far above the ground, with a pause time between steps ranging from 40 to 100 microseconds (Schonland, 1956). Longer pause times are followed by longer step lengths. From time-resolved photographic records Schonland (1956) states that average two-dimensional stepped leader velocities are between 0.08 and 2.4 x 10^6 m/sec, the most often measured value being close to 2 x 10^5 m/sec. These values are not consistent with the value obtained by dividing the 50 m step length by pause times between 40 and 100 microseconds, 5 x 10^5 to 1 x 10^6 m/s. From electric field records Kitagawa (1957) observed a mean pause time of 50 microseconds for steps far above the ground, decreasing to 13 microseconds as the leader tip approached the ground. Recent work has verified that leader pulses on electric field records just before the return stroke occur at about 15 microseconds intervals (Krider and Radda, 1975; Krider et al., 1977). However, this may be due to the fact that there are steps in several branches radiating simultaneously, making the apparent time between leader pulses shorter than the time in any one branch.

2. The luminosity of the step rises to its peak in about 1 microsecond and falls to half this value in roughly the same time (Schonland et al., 1935; Schonland, 1956; Orville, 1968; Krider, 1974). Thus, for a 50 meter step the velocity of propagation of the light along the step must exceed 5 x 10^7 m/sec. Negatively charged leaders are photographically dark between steps, but positively charged leaders emit some light and have less distinct steps (Schonland, 1956; Berger and Vogelsanger, 1966).

3. Photographs (Schonland et al., 1935; Berger and Vogelsanger, 1966) show a faint corona discharge extending for about one step length in front of the bright leader step. The luminosity of this advance corona does not appear to develop between steps but rather occurs simultaneously with the creation of the bright step behind it. Luminous stepped leader diameters have been measured photographically to be between 1 and 10 meters with no central core apparent (Schonland, 1953). Expectation that there is a central current-carrying core follows from the spectral measurements of Orville (1968) and the fact that, for an arc of several hundred amperes in air, the average current needed to lower 5 coulombs of charge in 10 microseconds or so flows in a narrow channel some centimeters in diameter.

4. The time-varying electrostatic fields for the stepped leader are fairly well understood (Malan and Schonland, 1947), and hence, easily modeled by the lowering of negative charge along a vertical line. The field change is relatively smooth implying that the leader lowers charge continuously between steps and that the step process itself does not lower appreciable charge (Schonland, 1953; Krider et al., 1977).

5. Using measurements of the fields radiated by leader steps near the ground, Krider et al. (1977) infer that step currents are in the kA range or larger with submicrosecond rise times.

D. Attachment Process

When the stepped leader approaches any conducting object, such as a building or a power line, the electric field produced by the charge on the leader can be enhanced by the object to the point where discharges (called leaders, connecting leaders, or, sometimes, streamers) are emitted from the object. The characteristics of these discharges are not well understood, but have been the subject of considerable discussion in the context of modeling lightning strikes to power lines where the attachment process plays a significant role in the design of overhead ground wire protection.

An important parameter in lightning protection is the "striking distance": the distance between the object to be struck and the downward-moving leader tip at the instant that the connecting leader is initiated from the object. It is assumed that at this instant of time the point of strike is determined. It follows that the actual junction point is somewhere between the object and the tip of the last leader step, and it is often assumed to be midway between.

We now examine the attachment process as it relates to lightning strikes to ground or to objects on the ground. General reviews of this phenomenon have been given by Golde (1967, 1977) who outlines the following analytical approach: a reasonable charge distribution is assumed to be present on the leader channel, and the resultant fields on remote objects are calculated. The leader is assumed to be at the striking distance when the field at some point exceeds a critical breakdown value that is determined by laboratory tests. Various authors have derived relations between the striking distance and the leader charge (e.g., Golde, 1945). The relationship of more practical value in power line design, however, is that of striking distance to the peak current of the following return stroke. To make this connection, the peak current must be related to the leader charge distribution. It has not been proven that these two quantities are actually related, since the leader charge may be spread over a rather large volume in various leader branches, whereas the peak stroke current is determined in a few microseconds in a short channel section that is attached to ground. On the other hand, Berger (1972) shows that there is a correlation between the measured return stroke peak current at ground and the total charge transfer to ground in the first millisecond or so. The best fit relating peak current I to charge transfer Q for 89 negative strokes is

$$I = 10.6\ Q^{0.7}$$

with I measured in kA and Q in Coulombs. According to this expression, a typical peak current of 25 kA corresponds to a total leader charge of 3.3 C. When this expression is combined with the relation between charge and breakdown field, a relation for striking distance d_s can be found in terms of peak current. For example, one of several theoretical analyses reviewed by Golde (1977) yields

$$d_s = 10\ I^{0.65}$$

where d_s is in meters and I in kA. From the available experimental data and theory, it is possible to conclude that striking distances are generally between a few tens and a few hundred meters.

E. Return Strokes

The return stroke is probably the best understood lightning process because of the practical motivation (e.g. the need to reduce lightning damage and lightning caused outages on overhead power lines) and because of all the phases of lightning, the return stroke lends itself most easily to measurement.

Several types of experimental data are available which relate to the return stroke currents and fields: (a) Wideband (dc to some MHz) electric and magnetic fields at ground level (e.g., Tiller et al., 1976; Weidman and Krider, 1978; Lin et al., 1979; Weidman and Krider, 1980; Baum et al., 1980) and, to a very limited extent, above ground (Baum, 1980); (b) measured electric-field frequency spectra (e.g. Taylor 1963; Serhan et al., 1980); (c) current waveforms at ground level (e.g. Berger et al., 1975; Garbagnati et al., 1975) and, to a very limited extent, above ground (Petterson and Wood, 1968); and (d) return stroke velocities (e.g., Schonland et al., 1935; Boyle and Orville, 1976; Saint-Privat D'Allier Research Group, 1979; Hubert and Mouget, 1980). In order for any model of the return stroke and its possible effects to be valid, it must be capable of describing in a self-consistent way the above independently measurable fields, currents, and velocities. We now consider the above four types of experimental data in more detail.

1. The most complete description of return stroke electric and magnetic fields is given by Lin et al. (1979). The bandwidths of the electric field recording systems extended from near dc to over 1 MHz and for the magnetic field systems from 1 kHz to over 1 MHz. For both electric and magnetic fields, the system zero to peak rise times were about 0.3 microsecond. Measurements were made simultaneously at two Florida stations separated by either 50 or 200 km with the result that fields were obtained over a distance range from 0.2 to 200 km. Lin et al. (1979) present typical first and subsequent stroke waveform and statistical data on the salient characteristics of the waveforms.

Since Lin et al. (1979) and previous studies in the same experimental program (e.g. Fisher and Uman, 1972; Tiller et al., 1976; Uman et al., 1976a) focused primarily on the overall characteristics of the fields, Weidman and Krider (1978, 1980) have recently been examining the microsecond and submicrosecond structure of the waveforms. They find that the initial return stroke in a cloud-to-ground flash produces an electric field "front" which rises in 2 to 8 microseconds to about half of the peak field amplitude and is followed by a fast transition to peak whose 10 to 90 percent risetime is about 90 nsec. Subsequent stroke fields have fast transitions very similar to first strokes but fronts which last only 0.5 to 1 microseconds and which rise only to about 20% of the peak field.

To measure lightning field changes on a 20 nsec time scale accurately, it is essential that the field propagation from the lightning to the receiving antenna be over salt water; otherwise there will be a degradation in the high frequency content of the fields due to propagation over the poorly conducting earth (e.g., Uman et al., 1976b; Weidman and Krider, 1980). On the other hand, it is possible that lightning striking salt water could produce inherently faster risetimes than lightning striking ground. Weidman and Krider (1978) argue that this is probably not the case.

2. The most complete data on return stroke frequency spectra below 1 MHz are given by Serhan et al. (1980) and were obtained by Fourier analyzing the time-domain electric field waveforms of Lin et al. (1979) and Tiller et al. (1976). These spectra extend over a frequency range from 1 kHz to 700 kHz for lightning at distances between 1 km and 200 km. All of the other return stroke frequency spectra data in the literature (e.g., Taylor, 1963; eleven measurements discussed by Dennis and Pierce, 1964), with the exception of the narrow band measurements of Horner and Bradley (1964), are of distant lightning, and all have an upper frequency cutoff below 100 kHz.

3. The most complete description of lightning return stroke currents at the base of the channel is due to the work of Berger and co-workers in Switzerland, and is reviewed by Berger et al. (1975). These measurements were obtained at the top of a tower on a mountain as were all other current waveforms of statistical significance. Because of this, the published waveforms of the currents measured at these towers may well be different from those of strikes to low objects or the ground. Of particular interest is the early portion of the first stroke waveform, since this may partially be due to an upward-going leader and might be different for a tall structure than for normal ground or low objects. Also, first stroke currents striking tall objects are expected to be larger, on the average, than those to normal ground (Sargent, 1972). In any event, the measurements of Berger et al. (1975) are those that are summarized in Table 2. Other measurements of currents (e.g., Garbagnati et al., 1975, 1978; Eriksson, 1978) are, in general, consistent with those of Berger.

Subsequent strokes have risetimes for which the median value from 2 kA to peak is reported to be 1 microsecond. Berger et al. (1975) state that 5% of the 120 front times measured were less than 0.2 microsecond and 5% of the maximum rates-of-rise of current exceeded 120 kA/microsecond. Fieux et al. (1978) report that their 10 to 90% subsequent strokes risetime was less than 1 microsecond in 70 percent of 63 measurements.

Weidman and Krider (1980) have drived maximum rates of rise from first and subsequent stroke fields and find a mean of 100 to 150 kA/microsecond with maximum values about twice the mean. It should be noted that these recent derivative values are substantially larger than Berger's values given in Table 2. Peak currents for first strokes are generally thought to be in the 20 to 40 kA range with 200 kA occurring at about the 1% level although there is some argument about the exact statistics (Szpor, 1969; Sargent, 1972).

TABLE 2

LIGHTNING CURRENT PARAMETERS

Adapted from Berger et al. (1975)

Number of Events	Parameters	Unit	Percent of cases exceeding tabulated value		
			95%	50%	5%
	Peak current (minimum 2 kA)				
101	negative first strokes	kA	14	30	80
135	negative subsequent strokes	kA	4.6	12	30
26	positive first strokes (no subsequent strokes)	kA	4.6	35	250
	Charge				
93	negative first strokes	C	1.1	5.2	24
122	negative subsequent strokes	C	0.2	1.4	11
94	negative flashes	C	1.3	7.5	40
26	positive flashes	C	20	80	350
	Impulse charge				
90	negative first strokes	C	1.1	4.5	20
117	negative subsequent strokes	C	0.22	0.95	4.0
25	positive strokes (only one stroke per flash)	C	2.0	16	150
	Front duration				
89	negative first strokes	μsec	1.8	5.5	18
118	negative subsequent strokes	μsec	0.22	1.1	4.5
19	positive strokes	μsec	3.5	22	200
	Maximum di/dt				
92	negative first strokes	kA/μsec	5.5	12	32
122	negative subsequent strokes	kA/μsec	12	40	120
21	positive strokes	kA/μsec	0.20	2.4	32
	Stroke duration				
90	negative first strokes	μsec	30	75	200
115	negative subsequent strokes	μsec	6.5	32	140
16	positive strokes	μsec	25	230	2000
	Integral (i^2dt)				
91	negative first strokes	A^2 sec	6.0×10^3	5.5×10^4	5.5×10^5
88	negative subsequent strokes	A^2 sec	5.5×10^2	6.0×10^3	5.2×10^4
26	positive strokes	A^2 sec	2.5×10^4	6.5×10^5	1.5×10^7

(continued) page 2 of Table 2.

	Time				
133	between negative strokes	msec	7	33	150
	Flash duration				
94	negative (including single stroke flashes)	msec	0.15	13	1100
39	negative (excluding single stroke flashes)	msec	31	180	900
24	positive	msec	14	85	500

4. Return stroke velocities are important in interpreting lightning field measurements, but are difficult to measure since the luminosity of the return stroke wavefront at a given height in the channel has a risetime in the 1 to 10 microseconds range (Hubert and Mouget, 1980). First stroke velocities decrease with height as each major branch is passed; but subsequent stroke velocities are fairly constant with height (Schonland et al., 1934, 1935). All measurements obviously refer to the out-of-cloud portion of the lightning. Reviews of the relatively meager velocity data which are available (Boyle and Orville, 1976; Lin et al., 1979) show values which range from 2 x 10^7 to 2 x 10^8 m/sec. Typical values near the ground for both first and subsequent strokes are probably close to 1 x 10^8 m/sec.

Lin et al. (1980) have recently developed a model for the return stroke, based on the above physical characteristics, which describes most of the electric and magnetic field signatures produced by this process at near and intermediate distances. This model has been tested on subsequent strokes because these have a relatively constant velocity and no branches. The modeling of first strokes using the same technique produces reasonable fields but the inferred ground level currents do not look like the waveforms measured on towers. Inclusion of the upward-going leader in the modeling (e.g., Weidman and Krider, 1978) does not provide a solution to the problem since currents of the order of 10 kA would have to flow in the upward-going leader to produce the measured fields, and it is generally thought that these leader currents are much smaller.

The current distribution for the model of Lin et al. (1980) is divided into three components: (1) short-duration upward propagating pulse of current associated with the upward propagating breakdown at the return-stroke wavefront; (2) a uniform current that may already be flowing (e.g., the steady leader current) or may start to flow soon after the return stroke begins; and (3) a current called the "corona current" which is caused by a radially inward and then downward movement of the charge initially stored in the corona envelope around the leader channel. Statistics on the magnitude and waveshape of these three current components are given by Lin et al. (1980) from analysis of the two-station electric and magnetic field measurements for an assumed return stroke velocity of 10^8 m/sec. Lin et al. (1980) have assumed that the upward-propagating breakdown current pulse does not decay with height, an assumption that may well be reasonable for subsequent strokes.

F. Dart Leaders

Return strokes subsequent to the first in a flash to ground are usually initiated by dart leaders. Dart leaders are so named because they appear on streak camera photographs to be a 50 m long dart of light propagating toward earth. Dart leaders effectively carry cloud potential earthward via an ionizing wave of potential gradient (Loeb, 1966) and lower about 1C of negative charge (Brook et al., 1962) in about 1 millisecond. It follows that these leaders must have channel currents on the order of 1 kA. Dart leader velocities range from about 1 to 27 x 10^6 m/sec with the higher velocities being related to the shorter interstroke intervals and the lower velocities to longer intervals (Winn, 1965; Schonland et al., 1935; Schonland, 1956).

The electric field changes produced by dart leaders have been described by Malan and Schonland (1951). At a range of 5 to 8 km, the first dart leaders in multistroke flashes produce positive field changes and later ones have hook-shaped fields which begin with a negative polarity. The implications of this is that succeeding leaders originate from charge volumes higher in the cloud, the typical increase in height between successive leaders being about 0.7 km according to Malan and Schonland (1951) and about 0.3 km according to Brook et al., (1962). Apparent leader heights vary between 2 and 13 km according to Brook et al. (1962). Schonland et al. (1938) have inferred from the field ratios of 46 dart leaders and associated return strokes that the leader channel tends to be uniformly charged, although the charge removed by the subsequent return stroke is apparently not uniform.

If the time interval between strokes is long, the dart leader may change from a continuously moving leader to a stepped leader, a so-called dart-stepped leader. The stepped portion has a relatively high downward velocity (about 10^6 m/sec), short step lengths (about 10 m), and short time intervals between steps (about 10 microseconds) (Schonland, 1956; Krider et al., 1977). Dart-stepped-leaders probably initiate the multiple ground contacts such as are shown in Figure 3.

IV. LIGHTNING FLASHING RATES AND STRIKE PROBABILITIES

The "frequency of lightning occurrence" is not to be confused with the number of "thunderstorm days per year" shown in Figure 1. Given either of the above numbers, it would seem possible to calculate the other, since thunder is produced by lightning. But the exact relationship (if indeed one exists!) is not easily obtained from data such as Weather Bureau observations on how many days per year an observer hears thunder. In the context of the present report, a much more valuable parameter would be the lightning ground flash density (number of ground flashes per square km) plotted as a function of the month of the year. From such data one might try to calculate the strike probability for a given geographical area for a given time of year.

A number of empirical formulas has been suggested for converting thunderstorm days per year, T_y, to the number of ground flashes per square km, N_g. The utility of these relationships is questionable, considering the serious consequences which could result from assigning erroneous values to lightning strike probabilities. For example, one set of values is obtained from $N_g=.11T_y$ for northern U.S., and another set is obtained by using $N_g=.17T_y$ for southern U.S.; two other formulas each ostensibly valid for the whole U.S. are essentially the same. Thus, variations to be expected in the calculated probabilities are of the order of one hundred percent. In addition, regional factors as well as latitude factors may also cause errors. To illustrate how these values scatter and are subject to regional change, i.e., how the constant varies as a function of T, we note that for regions where the number of thunderstorm days is 10, N_g ranges from .2 to 2.9 flashes per square km, while for $T_y=30$, the values of N_g vary between 1.7 to 5.7.

In Figure 10 we show a set of observations of the horizontal separation of successive lightning flashes taken during two ten minute time periods of the same storm. This type of data is much more useful than the data which were used to construct the "Thunderstorm Days" map of Figure 1. For example, Figure 10 shows two groups of successive lightning flash locations plotted in plan view with successive strikes connected by a straight line, and with the locations numbered in succession. The first period (1815-1825 hrs) shows the "trajectory" of 11 successive flashes; the second period (1835-1845 hrs) is for 13 flashes. The scale is given in km, and a note indicates that the horizontal surface wind speed was 30 km/hr(8 m/s).

The reader should first note that the trajectories seem to be a reasonable approximation to a "random walk", and that the average distance between successive horizontal strikes is about 3 km. A plot of the distribution of distances between successive flashes is given at the bottom of Figure 10, from which strike probabilities may be estimated.

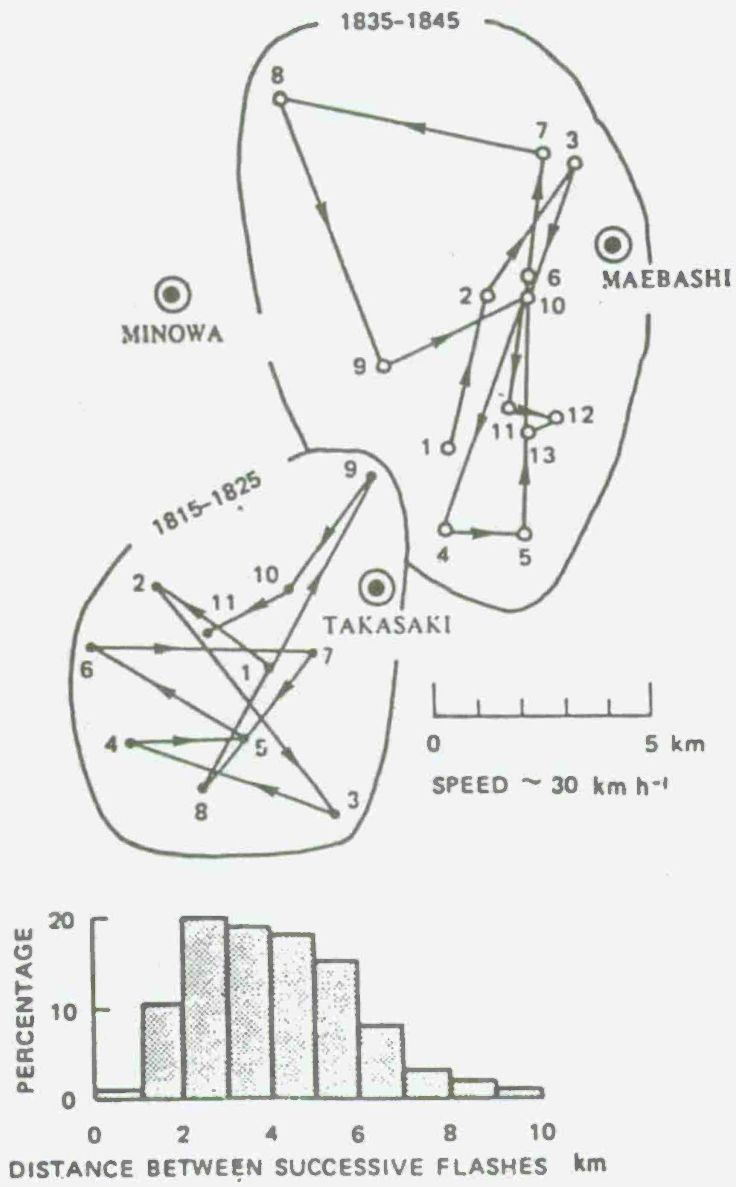


Figure 10. Horizontal separation between successive flashes.

The 3 km average spacing between successive strikes can be misleading however, because of the random-walk pattern. It is obvious that the drift velocity of the storm (storms move with the speed of the mean wind) and the progressional velocity of the lightning flashes are not related. In fact, the effective spacing between actual ground strike locations (not taken in time sequence) can be significantly less than 3 km, as examination of the figure will show.

A meaningful variation in the presentation of the same data is to calculate the areal density of strikes directly in terms of ground strikes per square km per storm. Using this approach, the first storm period in Figure 10 involved 11 flashes which occurred within an area of about 37 square km. Then 37/11=3.4 square km/flash implies an average linear strike distance of $\sqrt{3.4}$ or 1.8 km. This is less by almost a factor of 2 than the distance of 3 km between successive strikes, a reduction in distance brought about by the quasi-random occurrence of strike locations. Obviously, this linear strike distance will be influenced by the rate of flashing and by the speed with which the storm is moving through the area.

At this juncture in our discussion it is appropriate to re-examine the entire philosophy of using stroke occurrence probabilities as a basis for a) designing lightning protection specifications and hardware, and b) providing guidelines for procedures to be followed during times when lightning related hazards may exist. We emphasize the fact that our discussion relates specifically to lightning hazards at munitions manufacturing, assembly, and storage facilities. With this in mind, we question the basic approach, carried over from electric power transmission line practice, to the design and protection of munitions related operations.

The distinction we must make between our problems and those of the power generating companies is one of tolerance. Power line protection is designed to provide freedom from prolonged outages on the basis of a chosen percentage of time, let us say 95%. This figure is arrived at primarily by economic factors weighed against consumer annoyance tolerance levels. From the point of view of the electric power utilities, more protection in the sense of reduced outages is unnecessary. In the above application, the use of fuzzy strike probability numbers and concepts is justified, and in cases where the outages exceeded "good practice", additional protection appears to have been forthcoming.

In the case of lightning protection for munitions plants, we think it unacceptable to provide only "probabilistic" protection if and when "total" or near total protection is practicable and available. For example, an installation costing several million dollars might involve a direct cost for lightning protection of perhaps from one to ten percent of the total cost, using current standards. If the addition of equipment such as line filters, surge suppressors, and "Maypoles" of downconductors can be installed for another one or two percent, or even five percent, it is unthinkable not to do so. In fact, the issue of strike probability is almost irrelevant: when one stroke gets through, as in the Indian Head incident, it is of no concern whether that stroke was one in ten, one in a hundred, or even one in a million. The design of lightning protection for such plants must involve our best effort to prevent any lightning from getting through. In a number of instances outlined elsewhere in this report, the best technology available had not been implemented even though the additional cost burden would appear to have been slight.

V. MECHANISMS OF LIGHTNING DAMAGE

In this section, the term lightning damage will refer to any undesirable physical effect caused by any lightning process in the context of a military ordnance facility or an ordnance operation. These effects range in severity from the induction of a small spark across a pair of open switch contacts to the direct burn-through of a metal casing. Most lightning damage is electrical, although there can also be large mechanical forces caused by the channel shock wave or by the magnetic interactions of lightning currents.

We will first discuss the possible effects of a direct lightning strike and then consider the effects which might be induced by a nearby strike.

A. Direct Strikes

Most direct lightning strikes produce damage as a result of the electric current or the heat generated by this current. Side flashes to nearby objects can also cause damage similar to a direct strike.

1. Damage due to lightning current. Probably the most familiar form of lightning damage is that caused by the electric current. If lightning strikes a person, for example, the current can cause serious burns and damage the central nervous system, heart, lungs, etc. (Lee, 1977; Golde, 1975, Ch. 12). Many types of electronic circuits are damaged or destroyed if they are exposed to an excess current or to a current of the wrong polarity.

The detailed mechanisms of damage are often poorly understood and depend on the substance involved. In the case of human tissue, the electric current causes Joule heating and a variety of electrochemical reactions. In metals, large currents will heat the conductor by electron collisions with the metal lattice; and if this heat is large enough, the metal will melt or evaporate.

2. Damage due to electrical heating. Following Golde (1975, Ch. 5) we will examine the thermal effects of lightning under three headings: the temperature rise of a wire or a lightning conductor, the penetration of thin metal sheets, and the effects of a strike to a poor conductor or an insulator.

If a current of amplitude, i, is passed through a resistance R, the electrical heat deposited in the resistance will be proportional to the time-integral of the power dissipation, $\int i^2 R\, dt$. If we assume that R is independent of current and temperature, and if the duration of the current is short enough that the effects of thermal conduction can be neglected, then the temperature rise of a wire will be proportional to the "action integral", $\int i^2 dt$. In Table 2, we can see that maximum $\int i^2 dt$ which has been recorded for lightning is about $10^7 A^2 s$.

Calculations of the temperature rise of copper conductors of varying cross-sections are shown in Figure 11. For aluminum conductors the temperature rise will be about 1.5 times larger than the values for copper, and steel will be about 10 times larger than Figure 11. From these curves, we can conclude that even a $\int i^2 dt$ of $10^7 A^2 s$ will raise the temperature of a 56 mm^2 steel conductor only about 150°C, a value which is readily acceptable. Smaller steel conductors may not be acceptable, however, because of the larger thermal dissipation. If a metal conductor has a bond or joint with another conductor, it is important that there be good electrical contact or a low resistance between them. A high-resistance joint can produce substantial heating and/or sparking and must be avoided when using overlapping metal sheets, corrugated roofs, or similar constructions.

The penetration or burn-through of a metal sheet is important when considering a roofing or shielding material or the skin of an aircraft. If a lightning current, i, contacts a metal surface, the heat deposited at the point of the strike is approximately $\int v\, i\, dt = v\, Q$ where v is the surface potential of the metal, usually about 15V, and Q is the charge transferred by the lightning current. Therefore, we might expect that the amount of melting damage will be proportional to the charge transfer, at least to first order.

Figure 12 shows the relation between the size of holes burned in metal sheets and the total charge transfer, Q. In Table 2, we see that lightning can transfer hundreds of coulombs of charge and therefore we can certainly expect to have rather large holes burned in these metal sheets. If the duration of the charge transfer is long, the effects of thermal conduction will reduce the damage and increase the time required for a burn-through as shown in Figure 13.

If lightning strikes a relatively poor conductor or an insulator, the point of contact can be raised to a high temperature and result in a burn-through. There are numerous reports of centimeter-sized holes burned in glass windows, for example. If the insulator contains a trace of moisture, or some other conducting material, the current will tend to follow the path of least resistance. When the moisture is evaporated and converted to steam, the resulting pressure can cause explosive fractures which in some cases are said to be the equivalent of 250 kg of TNT (Golde, 1975, p. 55).

3. Damage due to mechanical effects. As mentioned previously, the shock wave produced by a lightning channel and the magnetic forces due to the lightning currents can cause mechanical damage. The shock wave is produced by the rapid heating of the channel by the return stroke (to temperatures on

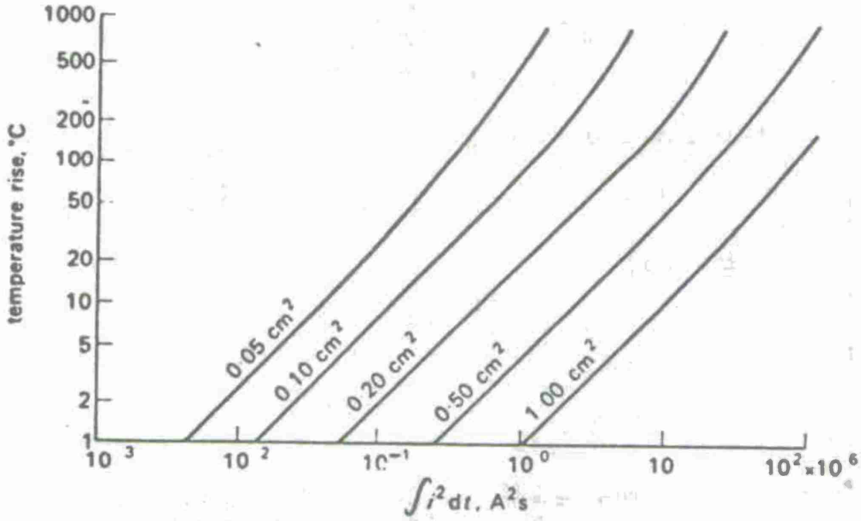


Fig. 11. Temperature rise of copper conductors of varying cross-sections as a function of $\int i^2 dt$. (Golde, 1975, Ch. 5, Fig. 23).

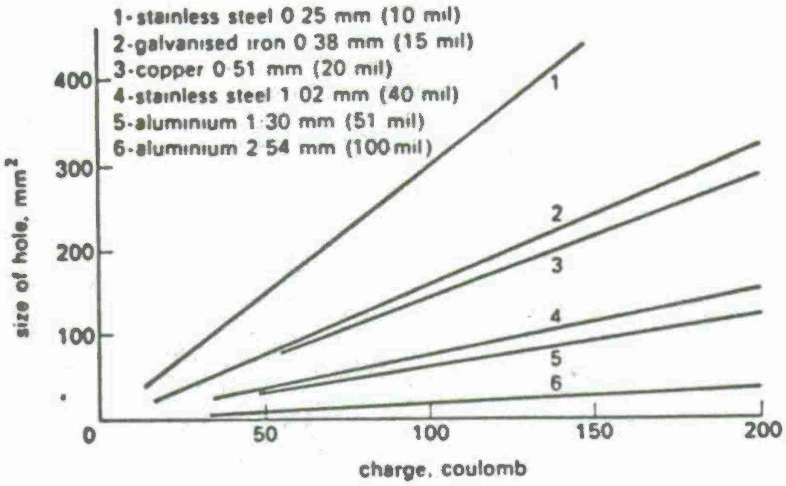


Fig. 12. The relation between charge and size of hole burned in metal sheets. (Golde, 1975, Ch. 5, Fig. 25).

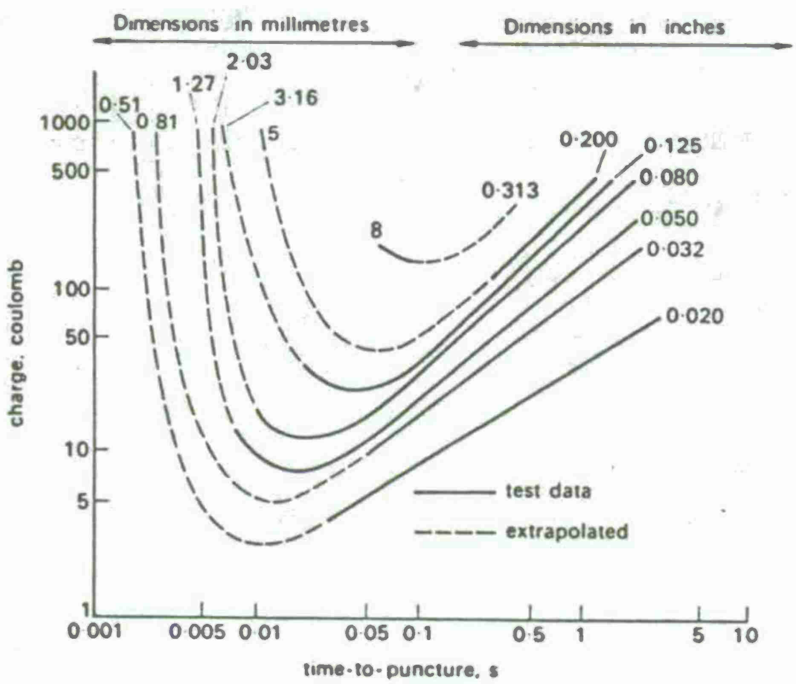


Fig. 13. Relation between charge and time-to-puncture, of aluminum sheets of different thicknesses. (Golde, 1975, Ch. 5, Fig. 26).

the order of 30,000°K), which produces a channel pressure of at least 30 atmospheres. The resulting expansion of the channel is very rapid and is sufficient to produce a strong cylindrical shock wave. (See Uman, 1969, Ch. 5). This shock wave relaxes to a sound wave at a distance of a few meters from the channel and eventually produces thunder (Hill, 1977). The shock wave heats the air nearby and can cause mechanical damage.

The magnetic forces produced by lightning currents can crush metal tubes, pull wires from walls (if they pass around sharp corners), and fuse stranded conductors (Humphreys, 1964, Ch. 18). Since the force between two parallel straight wires which share the lightning current is attractive, proportional to the square of the current, and inversely proportional to the distance between the conductors, the components of a system of lightning conductors should not be placed in close proximity to each other.

4. <u>The "Side Flash"</u>. When a large, rapidly varying current is injected into a lightning conductor (see for example, Figure 14), the inductance of the conductor and the resistance of the ground connection are often large enough to produce a "side flash", a discharge from the conductor to a nearby grounded object. A side flash occurs when the potential of the conductor is raised to a value which is large enough and of sufficient duration to initiate a spark and cause it to propagate to the nearby object. Normally, the dc resistance of the wires in a lightning protection system is much less than the inductive impedance or the ground resistance.

To illustrate this phenomenon, Figure 14a shows a sketch of a simple lightning conductor, and Figure 10b the equivalent electrical circuit. In this example, the voltage, V, at the tip of the conductor will be given by

$$V = i\,R_g + L\,\frac{di}{dt}$$

where i is the lightning current (a function of time), R_g is the ground resistance, and L is the total inductance of the wire. If we assume that the ground resistance is about 10 ohms, that the wire inductance is 15 micro H for a total length of 10 meters (1.5 micro H/m), and that the lightning current has a peak of 40 kA and a di/dt of 100 kA/microseconds, then the maximum V will be on the order of 2 million volts; that is

$$V_{max} = (4 \times 10^4)\,(10) + (15 \times 10^{-6})\,(10^{11}) \text{ Volts}$$

$$V_{max} = 1.9 \times 10^6 \text{ Volts}$$

This voltage will be present during the initial portion of each return stroke for only about 1 microsecond or less, but if there is a grounded object nearby, V can easily be large enough and present long enough to cause a flashover. Of course, a wide variety of other types of side flash phenomena can occur during

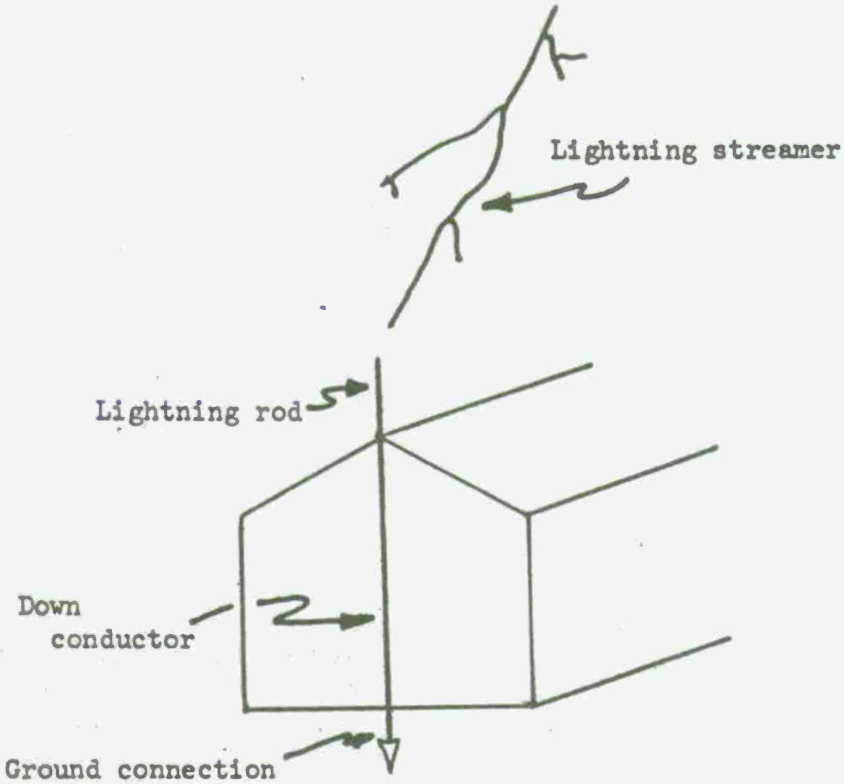


FIGURE 14a. A Simple Lightning Protection System Consisting Of A A Single Rod, A Down Conductor, And A Ground Connection.

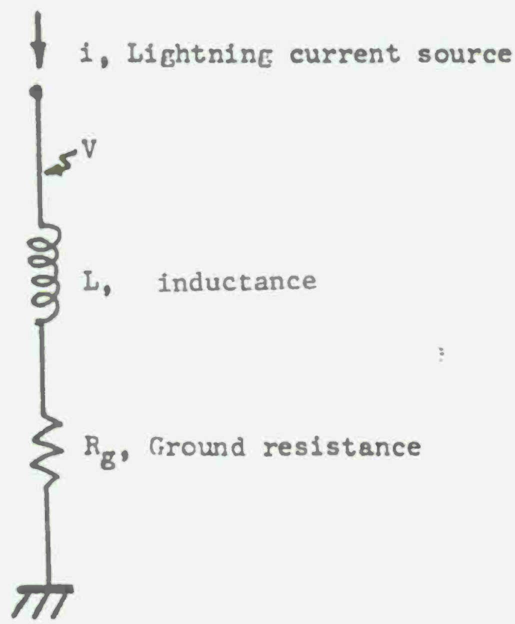


FIGURE 14b. Equivalent Circuit For System Shown Above

strikes to conducting materials or insulators. One of the biggest hazards of standing near an isolated tree or any other tall object during a thunderstorm is the exposure to a possible side flash.

B. Induced Effects

Nearby lightning flashes can cause damage to structures as a result of the large electric and magnetic fields and the effects of currents in the ground.

1. Magnetic Induction. If a closed loop of wire, or any other closed conducting path, is exposed to a time-varying magnetic field, a current will be induced to flow in the circuit. The magnitude of the current is proportional to the time-derivative of the magnetic flux density, and inversely proportional to the circuit impedance.

2. Electric Induction. Whenever a conductor is exposed to an external electric field, a surface charge is induced on the conductor which is proportional to the strength of the electric field. If the field varies with time, currents will flow in the conductor to keep the surface charge in balance with the field.

VI. BASIC PRINCIPLES OF PROTECTION

The protection of a building and its contents against lightning damage can be accomplished by (a) diverting the current produced by a direct strike away from the structure and letting it pass harmlessly to ground, and (b) shielding the structure and its contents against any lightning-caused transients. In Figure 14, we have seen a sketch of a simple current diversion system, a lightning rod, an appropriate down conductor, and a grounding system.

When lightning strikes a structure, the electric current behaves as if the channel is a pure current source; that is, the current that flows is essentially independent of the impedance of the structure. In the example given previously, the 2×10^6 volt potential at the top of the building is essentially independent of the physics of the discharge itself. If a 30 kA return stroke strikes a 200-ohms power line, the line potential will rise to 6 million volts if there are no lightning arrestors or insulator breakdowns.

All protection systems must be designed so that the large lightning-caused potentials are the <u>same</u> everywhere in the vicinity and so that there are <u>no</u> potential <u>differences</u> which can cause arcing. This practice is called <u>bonding</u>, but in practice it is usually very difficult to eliminate all potential differences within a structure because various conductors such as wires, plumbing pipes, etc. all have inductance and resistance. As we have seen previously, even one meter of wire with an inductance of only 1.5 μH is sufficient to produce a potential difference of 150,000 volts.

In places where lightning potential differences or over-voltages can occur, it is often necessary to utilize one or more voltage limiting devices to hold or clamp these transients to a harmless level. These devices are known by various names such as lightning arresters, surge arresters, surge suppressors, transient suppressors, etc. In all cases, they are basically just a resistance which decreases sharply when the voltage applied across them increases. This characteristic can be expressed in the following form

$$I = kV^n$$

where k is a constant and n provides a measure of the non-linear relationship between the current, I, and voltage, V. Silicon carbide, the material used in arresters for power systems, has a value for n that is in the range from 2 to 7. Zinc oxide varistors or MOV's (Metal Oxide Varistors) have values of n ranging from 20 to 70, and silicon zener diodes have n's ranging from 100 to 500. Nonlinear suppressors absorb the energy of the lightning surge within themselves by transforming it into heat. Zener diodes can absorb up to about 1 Joule (1 Watt-second) of energy, and silicon carbide and zinc oxide varistors can absorb from 1 to 100 Joules depending on their physical size.

There are also devices known as switching protectors which are essentially spark gaps that can switch rapidly from a very high impedance to a short circuit state. These devices do not absorb much energy but instead reflect it away from the short circuit. Frequently a switching-type protector and a non-linear suppressor are used together. Surge capacitors and other filters can also be used to reflect the lightning energy, but these devices must be carefully designed to avoid a flashover. For a more detailed discussion of lightning protection devices and installation practices, the reader should consult MIL-HDBK-419.

Ideally, if we eliminate all harmful potential differences within the building, there can be no arcing or equipment damage. This could be accomplished by completely enclosing the structure and all of its service wiring, plumbing, etc. within a perfectly conducting shield (a Faraday shield). With this, all lightning currents would flow on the low impedance outside surface of the shield rather than anywhere inside. In practice, such a shield is never possible because even an all metal building has windows, doors, and other apertures, and because power lines, telephone lines, pipes, etc., which must enter the structure are often poorly shielded or not shielded at all.

In practice, protection is obtained by combining what building shielding does exist with proper grounding and bonding to keep potential differences within the structure to a minimum. A good grounding system, for example, usually has sufficiently low resistance and inductance that lightning currents cannot produce potential differences large enough to cause a flash-over. Where power lines, communications lines, pipes, etc., enter the structure, they must be equipped with protectors, suppressors, filters, etc., to prevent any harmful voltages from entering the building.

Basically, a lightning ground system or earth-termination network provides a sink where the lightning current can be discharged harmlessly into the ground. In order to minimize any possible side flashes within the structure, the grounding impedance should be kept small as possible, and the geometry should be arranged so as to minimize potential differences on the surface of the ground.

Numerous technical articles and books (see, for example, MIL-HDBK-419) have been written about grounding electric power systems and associated equipment. Much of this information also applies to a lightning protection system, although the rapid lightning impulse sometimes poses special problems. For example, if a rapid current impulse is injected into a short ground rod, the soil surrounding the rod usually breaks down as though it were an insulator. However, if the current is injected into a long, buried conductor, the conductor will react with its surge impedance, usually about 150 ohms, rather then its steady-state ohmic resistance. As the front of the impulse propagates along the conductor, an increasing fraction of its length contributes to the discharge of the current into the surrounding soil and the effective impedance will decrease with time. Usually, the steady-state impedance will not be reached until there has been time for several reflections of the current pulse along the conductor.

VII. IMPROVED CONFIGURATIONS OF LIGHTNING RODS AND AIR TERMINALS

A. Introduction

The lightning rod was invented by Benjamin Franklin in 1750 as a result of his discovery of the point discharge phenomenon. In the course of his electrical experiments, he had found that electricity could be silently conducted away from a charged metal sphere by a nearby, sharp, iron needle. He suggested that thunderstorms might be discharged in the same manner with elevated and pointed, iron rods connected to the earth by a wire. After the first trials of this idea, he advanced another one: if the rods did not discharge an electrified cloud overhead, one of them might intercept a lightning stroke that it produced and conduct the lightning to earth, thereby shielding the buildings in the vicinity.

During his career as a scientist, Franklin thus proposed two quite, different modes by which elevated metal rods might provide protection against lightning, one acting to leak charge away from the storm so as to prevent lightning and the other intercepting lightning selectively and carrying the discharges to earth. Since these are quite different processes, it is unlikely that a lightning rod designed for one process will be the optimum one for the other. A study of lightning rods therefore seems worthwhile as a first step toward improving our protection against lightning.

B. Past Experience And Present Standards

Although his lightning rods have their greatest reported successes by being part of a lightning channel, Franklin did not explore the implications of his second idea. He remained enamoured of the ionizing power of a point in strong electric fields and recommended that all lightning rods be tipped with sharpened points for the prevention of lightning. An opposing view developed in England, leading George III to reject the American ideas and, later, to have his palace equipped with blunt rods on the basis that "sharpened rods might attract lightning and thus promote the mischief that it was hoped to prevent".

Franklin's views on this objection were stated in 1762 with a letter from London to his friend, Ebenezer Kinnersley, in Philadelphia: "Here are some electricians that recommend knobs instead of points on the upper ends of rods, from a supposition that the points invite a stroke. It is true that points draw electricity at greater distances in the gradual, silent way;--but knobs will draw at the greatest distance, a stroke". We have no record that Franklin ever expanded on this thought, which is similar to what we discuss later.

The relative merits of the two different rod configurations have continued to be controversial. By 1878, the lightning protection practices in vogue had become so varied that the

British Meteorological Society convened a lightning rod conference of scientists and engineers to formulate the existing knowledge and to prepare a general code of rules for the erection of lightning rods. This conference issued its report in Dec, 1881 and a copy is stored in the archives of the Royal Meteorological Society. The report indicates that the majority of the commercial lightning rod manufacturers in Britain supplied various forms of sharp cones or points as the upper termination of their lightning rods. On the other hand, the Royal Navy had been using the Harris system for protecting its wooden ships by surrounding the upper ends of the masts with copper bands, connected to the sea water by metallic cables. The damage to and loss of wooden ships caused by lightning strikes had decreased dramatically after the 1830-1840 era when the vessels were fitted with lightning conductors engineered by W. Snow Harris.

The report also covered the current American practices: Joseph Henry, a scientist, had prepared directions for constructing lightning rods in 1871. Among them is his specification that the upper end of the rod "should be terminated in a single point, the cone of which should be encased with platinum not less than 1/20 inch in thickness". Another of Henry's specifications will be of interest later: He recommended "the shorter and more direct the rod in its course to ground, the better; acute angles should be avoided".

An American writer of the 1880 period, John Phin, recommended strongly the use of lightning rods, but had "no faith in points, gilding or platinizing". He advocated the use of cast iron caps on the top of chimneys and other protuberances as the air terminal.

In a report to the British Association for the Advancement of Science, James Clerk Maxwell (1876) expressed his views concerning the use of sharpened lightning rods: "The electrical effect of such an arrangement is to tap, as it were, the gathering charge, by facilitating a quiet discharge between the atmospheric accumulation and the earth. The erection of the conductor will cause a somewhat greater number of discharges to occur at the place than would have occurred if it had not been erected, but each of these discharges will be smaller than those which would have occurred without the conductor. It is probable, also, that fewer discharges will occur in the region surrounding the conductor. It appears to me that these arrangements are calculated rather for the benefit of the surrounding country, and for the relief of clouds labouring under an accumulation of electricity, than for the protection of the building on which the conductor is erected."

"What we really wish is to prevent the possibility of an electric discharge taking place within a certain region, say, the inside of a gunpowder manufactory."

To accomplish this objective, Maxwell proposed enclosing the gun powder factory with a metallic, Faraday cage. We will return to this idea later in this study.

The formal position of the 1881 conference concerning the shape of the upper tips of the lightning rods is given in Section II of its report:

"SECTION II.--A Statement of those features in the construction and erection of Lightning Conductors, respecting which there has been, or is, a difference of opinion, and the final decision of the Conference thereupon.

Points.	Joints.	Height of Upper Terminal.
Material for Conductor.	Protection of Rod.	Testing Conductors.
Size of Rod.	Attachment to Building.	Internal Masses of Metal.
Shape of Rod.	Earth Plates.	External Masses of Metal."
(Rods, Tubes, Tape, Rope, Plait.)	Space Protected.	

"POINTS.--Starting with the extreme top, we have first to deal with the question of points. The utility of points was hotly contested rather more than a century since, and an abstract of the discussion will be found in Appendix F, page (79), and difference of opinion still exists as to their precise functions and value. The decision as to the best form of points is complicated by two opposing requirements (1), the sharper the point the more rapid the silent discharge of electricity, and therefore, the more effective the conductor; but (2) the sharper the point the more easily is it destroyed by oxidation, or fused, should a heavy disruptive discharge fall upon it."

"Attempts have been made by the use of gold, silver, and platinum, to obtain a sharp point which should not only be durable, but, owing to its high melting point, resist fusion by a disruptive discharge. But such metals are very expensive, and the statements in Appendix F, pages (67, 69, 73, 103, 123, 128, and 139) prove that even platinum points are often damaged. Copper points whose sectional area is less than .05 of a square inch are very liable to be melted. Lightning has even fused a copper rod .10 square inches in sectional area, i.e., 0.35 inches in diameter, and there are many rods still standing of which the extremity has been melted into a button or knob."

"For these reasons it seems best to separate the double functions of the point, prolonging the upper terminal to the very summit, and merely bevelling it off, so that, if a disruptive discharge does take place, the full conducting power of the rod may be ready to receive it, and, therefore, that there may be no risk of melted particles of metal setting fire to the building, as has occurred. [Appendix F, P.(93).]"

"At the same time, having regard to the importance of silent discharge from sharp points, we suggest that at one foot below the extreme top of the upper terminal there be firmly attached, by screws and solder, a copper ring, bearing three or four copper needles, each 6 inches long and tapering from 1/4 inch diameter to as fine a point as can be made; and with the object of rendering the sharpness as permanent as possible, we advise that they be platinized, gilded, or nickel plated."

These recommendations did not end the divergence of views concerning the best methods of protection against lightning: a new British Lightning Research Committee was formed in 1901 to urge the necessity of modified methods. This committee issued its report (Hedges, 1905) with major contributions by Oliver Lodge, a well known physicist of the period, who was one of the inventors of the electrostatic precipitator.

This committee addressed relatively little attention to the nature of the upper extremity of the lightning rod and to Maxwell's recommendations. Multiple, sharp points on vertical rods were considered acceptable but the expense of platinizing, gilding or electroplating them was found unnecessary. More attention was given to down-conductors and to the problems of making adequate contacts with the earth.

In his introduction to the 1905 Lightning Research Committee Report, Lodge wrote: "Since the report, many years ago, of the Lightning Rod Conference, knowledge of the subject has considerably increased, and the effect of self-induction, which then was completely ignored, has been taken into account and understood. The main difference between what is recommended to-day and what was considered sufficient then depends on the recognition of the influence of self-induction or electrical inertia. Then electricity was treated as if it had no inertia, and as if all that was necessary was to get it from the clouds to earth as quickly and easily as possible by the shortest path--which may be called the drain-pipe theory. It was supposed that it would always take the easiest path, and that the easiest path would protect all others. Attention was directed to the quantity of electricity which had to be conveyed down, and to nothing else...."

In a subsequent section, Lodge is quoted: "In protecting buildings from lightning, we must bear in mind that it does not follow the law of electric currents such as we are familiar with or those we read about as being employed for long distance power transmission.

1. Lightning shows a great tendency to distribute itself over such conductors as may be present on a building, and in doing so pays little heed to ohmic resistance.

2. It finds no great difficulty in making its way, often for a considerable distance, through the air or any other medium of rather better conductivity.

3. It prefers as much as possible to move in a straight line, and that therefore sharp turns, bends, or spiral windings in conductors present hindrances which readily lead to lateral discharges."

Another concept addressed in the 1905 report was that of the area of protection afforded by a lightning rod. On this subject, Hedges, the secretary to the Lightning Research Committee wrote:

"It is curious to note the growth of this fallacy (regarding the size of the protected area), which was first dispelled by Lodge at the Bath meeting of the British Association, and has received its death blow by the Report of the Lightning Research Committee, which contains many examples of buildings struck in the so-called protected area. Franklin does not mention the shielding effect of a lightning rod, but relies on its attraction, and it is probable that from his remarks the Academy of Science (in 1823) evolved the "protected space," to which they gave the name of the "double cone of Charles," in other words, a cone having for its apex the top of the lightning rod, and for its base a circle with a radius equal to twice its height. Later on Guy Lussac introduced M. Charles' single cone--ie, a similar cone having a base with a radius equal to only once the height--for church towers of ordinary height. In 1855 the double cone, which had meanwhile been found to be unsatisfactory in practice, was replaced by one having a base of 1-3/4 height radius. The Lightning Rod Conference in 1882 practically supported the rule that the base of the protected cone is assumed to have a radius equal to the height from the ground, but at the same time added, "though this may be sufficiently correct for practical purposes, it cannot always be relied on."

"Sir Oliver Lodge considered the term 'area of protection' meaningless, and stated:--"There is no space near a rod which can be definitely styled an area of protection, for it is possible to receive violent sparks and shocks from the conductor itself, not to speak of the innumerable secondary discharges that are liable to occur as secondary effects in the wake of the main flash."

"In the recently issued rules for the protection of Admiralty structures, the cone theory is dismissed with the following remark:--"This statement is not now generally accepted as true. Buildings protected on this principle would require very lofty lightning rods." It is considered that a number of smaller rods well connected together by conductors, carried along the salient features of a building, provide a more reliable protection than an equal amount of metal in higher rods spaced at greater intervals, and this is the system that has been adopted for the protection of all Admiralty structures...."

"The Elektrotechnische Verein issued in 1900 and 1901 two pamphlets on dangers from lightning, and do not even mention the idea of a protected area, which is practically abandoned. Dr. Van Gulik, in his report, 1905, to the Dutch Academy of Science, says:--"The days of the Lightning Rod Conference and Guy Lussac are past and gone; we no longer guarantee absolute security, but can only say that the protection afforded is more or less good according to whether the system adopted conforms with the principles which science has shown to be correct. The means by which protection is secured and the outlay required depends to a large degree on the value attached to the preservation of a building from damage great or little."

Despite the foregoing impeachment (and many subsequent reports of lightning strikes within the nominally protected regions) the concept of "a cone of protection" has continued to be highly regarded and is currently in wide use as a guide to define the necessary extent of a lightning protection system.

The recommended configurations of the upper terminals remain similarly diverse. The British standard (CP 326:1965) defines "the air termination as that part of a lightning protective system that is intended to intercept lightning discharges". This standard accepts vertical conductors for protection of a spire and single, horizontal conductors as on the ridge of a small dwelling but no consideration nor encouragement is given to sharpened points.

Most modern British systems follow the principles recommended by James Clerk Maxwell in 1876. He suggested that adequate protection could be obtained against thunderstorms in the British climate by carrying a #4 copper wire (6mm in diameter) "around the foundations of a house, up each of the corners and gables and along the ridges...The copper wire may be built into the wall to prevent theft but it should be connected to any outside metal such as lead or zinc on the roof, and to metal rain water pipes". He found no significant virtue in the use of pointed lightning rods.

The current American standards, on the other hand, specify pointed and vertical lightning rods.

Reliable and accepted data on the relative merits of the sharp and blunt rods are still not available, but it is now well recognized that sharpened lightning rods or points at the earth's surface cannot and do not dissipate the electrical charges in active thunderclouds overhead. In fact, wide spread and copious point discharge currents are emitted beneath thunderclouds from natural points - trees, shrubbery, and blades of grass - and these play a major role in limiting the strengths of the electric fields at the earth's surface without significantly weakening the electrical activity of thunderclouds overhead. For this reason, it appears that Franklin's first idea on the subject is not workable and that his second idea, the preferential interception of a lightning strike, is the way by which lightning rods may provide protection to structures in their vicinity.

The value of sharpening a rod to increase its chances of attracting or intercepting a lightning streamer has not been established but the present American lightning rod technology has maintained Franklin's views about the desirable configuration for the rods.

Despite the fears enunciated by Franklin's critic, Benjamin Wilson, that the use of sharpened lightning rods would increase the incidence of lightning, there is no evidence that the use of lightning rods of any configuration has increased the frequency of discharges. Lightning is almost invariably initiated by electrical breakdown processes that occur aloft in thunderclouds and therefore the nature of objects on the surface of the earth has little to do with the initiation of a discharge. This conclusion is not vitiated by observations that upward-going plasma streamers may sometimes be launched from very tall towers as an immediate result of sudden electric field changes caused by other, nearby lightning discharges.

Our concern with lightning rods and with tall towers has to do with how well they produce plasma streamers that intercept naturally-occurring, nearby lightning channels and connect them to earth, thus protecting structures in the vicinity.

C. Analysis of Lightning Rods

Theoretical analyses of lightning rods are difficult for many reasons. One of the significant difficulties arises from the changes in the local electric fields caused by the free charges in the form of point discharge ions emitted from the pointed end under strong electric fields. This emission occurs in fields far weaker than that required for the propagation of a lightning streamer but the presence and motions of these ions modify the local electric field in a non-linear manner so that it is difficult to treat the strong field conditions at top of the rod quantitatively.

The geometry with a vertical conducting rod and a randomly-positioned and oriented lightning plasma streamer, both having variable charge distributions, is also not tractable analytically but, by making some suitable approximations, we can at least place some bounds on the problem.

The first limitation that we accept for the analysis is an assumption of a uniform, vertically directed, electric field. While this is unrealistic, it permits us to model the responses of various configurations that enhance the local electric field and therefore we can compare various rods under similar, if idealized and unrealistic, conditions.

For this study, there are at least 3 configurations of interest:

1. A vertical, metallic rod with its upper end sharpened into a point and grounded at its lower end,

2. A similar rod with a smoothly rounded, upper end and,

3. An elevated, horizontal metallic wire connected appropriately to earth so as to maintain it also at earth potential.

Vertical metallic cylinders of finite length are difficult to treat analytically but they can be approximated as semi-prolate ellipsoids with a vertical, semi-major axis of length c, horizontal, semi-minor axes of length b and a tip radius of curvature of a (Larmor & Larmor, 1914). The radius of curvature, a, of the tip is related to b and c by $a = b^2/c$. Use of suitable c/a ratios permits a direct comparison between sharpened and the blunt rods under the same conditions.

The potential function for a conducting, semi-prolate vertical ellipsoid on a conducting plane under a uniform, vertically- directed electric field E is given by Smythe (1950, p.169) as

$$V = -E_o z\left[1- (\coth^{-1}\eta - 1/\eta) / (\coth^{-1}\eta_o - 1/\eta_o)\right]$$

where E_o is the ambient electric field strength away from the ellipsoid, η is the ellipsoidal coordinate in orthogonal, confocal, ellipsoidal and hyperbolic coordinates and z is the vertical height above the plane. η_o is the ellipsoidal coordinate of the conducting surface defined by:

$$\eta_o = (1- a/c)^{-1/2}$$

The focal height, h_f for the system is given by $h_f = c/\eta_o$.

We also use here a right handed, cartesian coordinate system with horizontal axes $\hat{x}$ and $\hat{y}$ and an upward-pointed $\hat{z}$ axis along that of the semimajor axis of the prolate ellipsoid. The x,y and z coordinates for a given location are measured from the center of the full ellipsoid. We take the cylindrical radius, ρ, for a given location as:

$$\rho = \sqrt{x^2+y^2}$$

The equation describing a family of ellipsoids in this mixed system of coordinates is:

$$\rho^2/(\eta^2-1) + z^2/\eta^2 = h_f^2$$

where η can have any value between 1 and infinity and a given value of η describes one specific ellipsoidal surface.

The conversion from the general cartesian coordinates for a location of interest into the equivalent confocal, ellipsoidal and hyperboloidal coordinates begins with the determination of η for the location:

$$\eta = \left\{\rho^2 + z^2 + h_f^2 + [(\rho^2 + z^2 + h_f^2)^2 - 4h_f^2 z^2]^{1/2}\right\}^{1/2} / (\sqrt{2}\, h_f).$$

The orthogonal component in hyperboloidal coordinates of ξ is given by $\xi = z/\eta h_f$.

The equations for the hyperboloidal surfaces have the form:

$$\rho^2/(\xi^2 - 1) + z^2/\xi^2 = h_f^2$$

where the value of ξ can vary between 0 and 1.0. These coordinates are shown in Figure 15.

The electric field components at location (η, ξ) are given by the negative of the spatial derivatives of the potential functions divided by the appropriate metrics:

$$E_\eta = (-1/h_f)\left[(\eta^2 - 1)/(\eta^2 - \xi^2)\right]^{1/2} \partial v/\partial \eta$$

and

$$E_\xi = (-1/h_f)\left[(1 - \xi^2)(\eta^2 - \xi^2)\right]^{1/2} \partial v/\partial \xi.$$

These convert into:

$$E_\eta = E_o \xi\left[(\eta^2 - 1)/(\eta^2 - \xi^2)\right]^{1/2}\left\{1 - (\coth^{-1}\eta - 1/\eta)/(\coth^{-1}\eta_o - 1/\eta_o) + 1/\left(\eta(\eta^2 - 1)[\coth^{-1}\eta_o - 1/\eta_o]\right)\right\}.$$

and

$$E_\xi = E_o \eta\left[(1 - \xi^2)/(\eta^2 - \xi^2)\right]\left\{1 - (\coth^{-1}\eta - 1/\eta)/(\coth^{-1}\eta_o - 1/\eta_o)\right\}.$$

A plot of the electric field lines around a grounded, vertical, conducting, semi-prolate ellipsoid in a vertical electric field is shown in Figure 16.

If we evaluate E_η at the tip of the ellipsoid where $\eta = \eta_o$ and $\xi = 1$.

$$E_{tip}/E_o = \left\{\eta_o(\eta_o^2 - 1)\left[0.5 \ln[(\eta_o + 1)/(\eta_o - 1)] - 1/\eta_o\right]\right\}^{-1}.$$

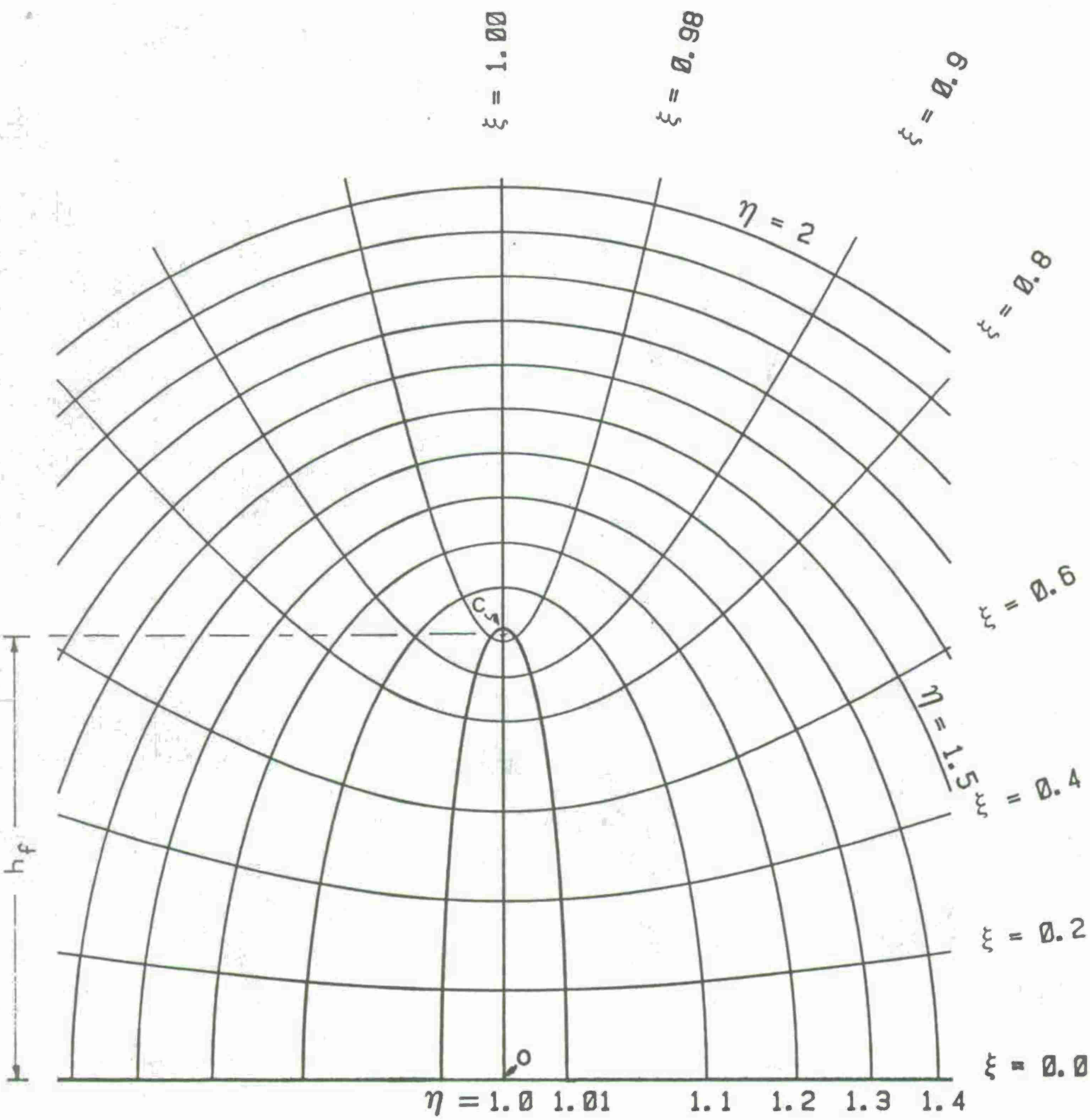


Figure 15.

Sections of Confocal Ellipses and Hyperbolae. These establish a coordinate system for calculations of the potential gradient above a conducting plane in the vicinity of a vertical, conducting, prolate half-ellipsoid whose major axis is in the direction of an external, uniform electric field.

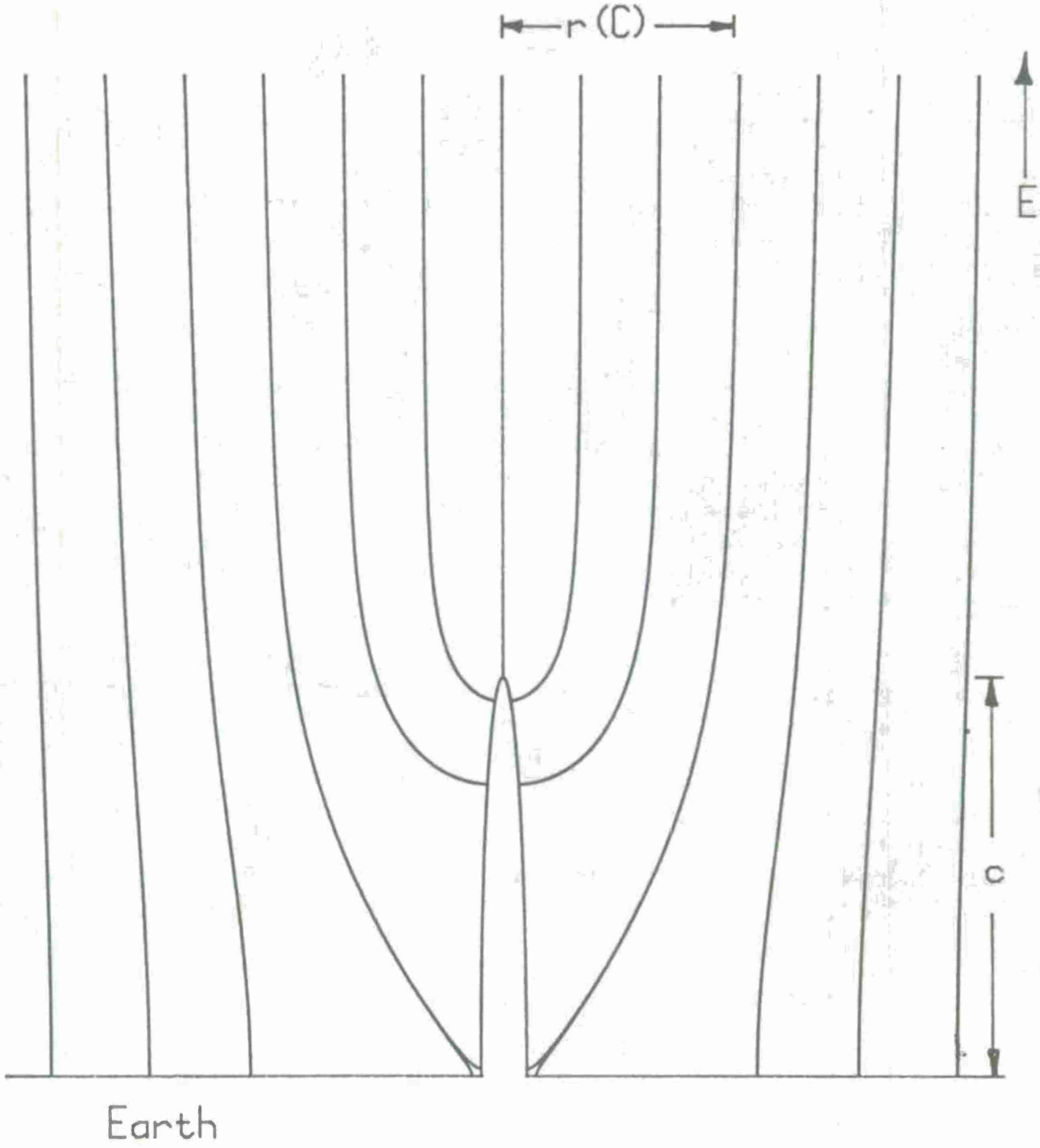


Figure 16.

Electric field lines around a grounded, vertical, conducting, prolate semi-ellipsoid. The height, c, of this semi-ellipsoid is 200 times the radius of curvature, a, of the tip. r(C) is the radius of the area through which pass the electric field lines that terminate on the ellipsoid.

For $c/a > 10$; $E_{tip}/E_o \leqslant c/a$.

Values of E_{tip}/E_o vs c/a are shown in Figure 17.

If we determine the rate of change of electric field strength with height above the tip of the ellipsoid, we find that, initially, it decreases as $1/r^2$ (with r measured from the center of curvature) but at $r > 3a$, the rate of decrease above the tip goes, thereafter, about as 1/r until the field strength approaches the ambient level.

Figure 18 is a normalized plot of this calculation for E along the vertical axis and in the absence of ions and free charge. It illustrates how the strength of the very strongly enhanced electric field at the tip decreases with height above the tip. As shown above, this rate of decrease is scaled relative to the radius of curvature of the tip: The field strength decreases more rapidly with distance over a sharp point than it does over a blunt one although, initially (in the absence of point discharge) the local field at the tip of a sharp rod is enhanced and is much stronger than that over a blunt one.

This effect is shown more clearly in Table 3 and in Figure 19 where the normalized field strengths above the tips of various ellipsoids (each with c = 2 meters) are plotted against the actual heights: At heights greater than about 1 cm, the fields above the blunter tips are as much as 1.5 to 2 times stronger than those above the sharper tips at the same distances. This relative enhancement is a geometric factor that occurs independently of point discharge effects and is important here because the electrical energy associated with an electric field varies with the square of the field strength. The application of this effect will be summarized after we discuss point discharge under strong fields and the nature of lightning strikes.

D. Point Discharge in Strong Electric Fields

Ionization of the air at the tip of a lightning rod exposed to strong electric field ultimately limits the field strength at the tip to that necessary for ionization (about 3MV/m at sea level) and thereafter, although the ambient electric field may strengthen, the flow of ions from the air near the tip absorbs and negates any local increase in field strength here, above the threshold level for ionization. A point thus protects itself effectively and rapidly from field strengths above the local threshold for ionization by the emission of point discharge ions that move upward and outward in the local electric field and act to decrease its strength.

As a result of the field enhancement factors, this limiting effect by point discharge occurs above sharpened rods in weaker ambient electric fields than is required for blunter rods but, under intensifying fields, the field strength above the blunt rod can reach the same limit as earlier developed over the sharp rod.

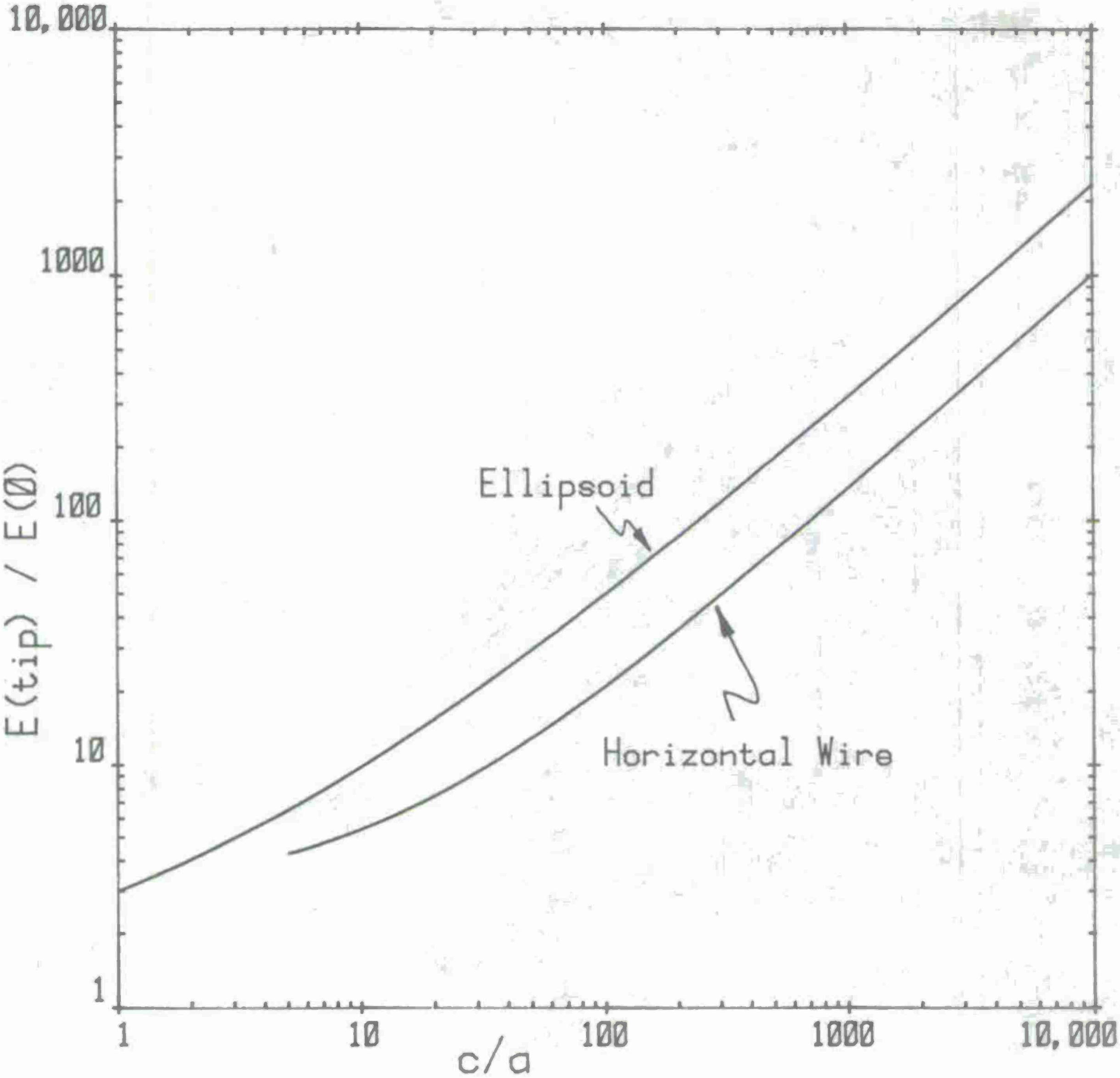


Figure 17.

The enhancement of the ambient electric field at the top of grounded conductors exposed to a uniform, vertically-directed, electric field.

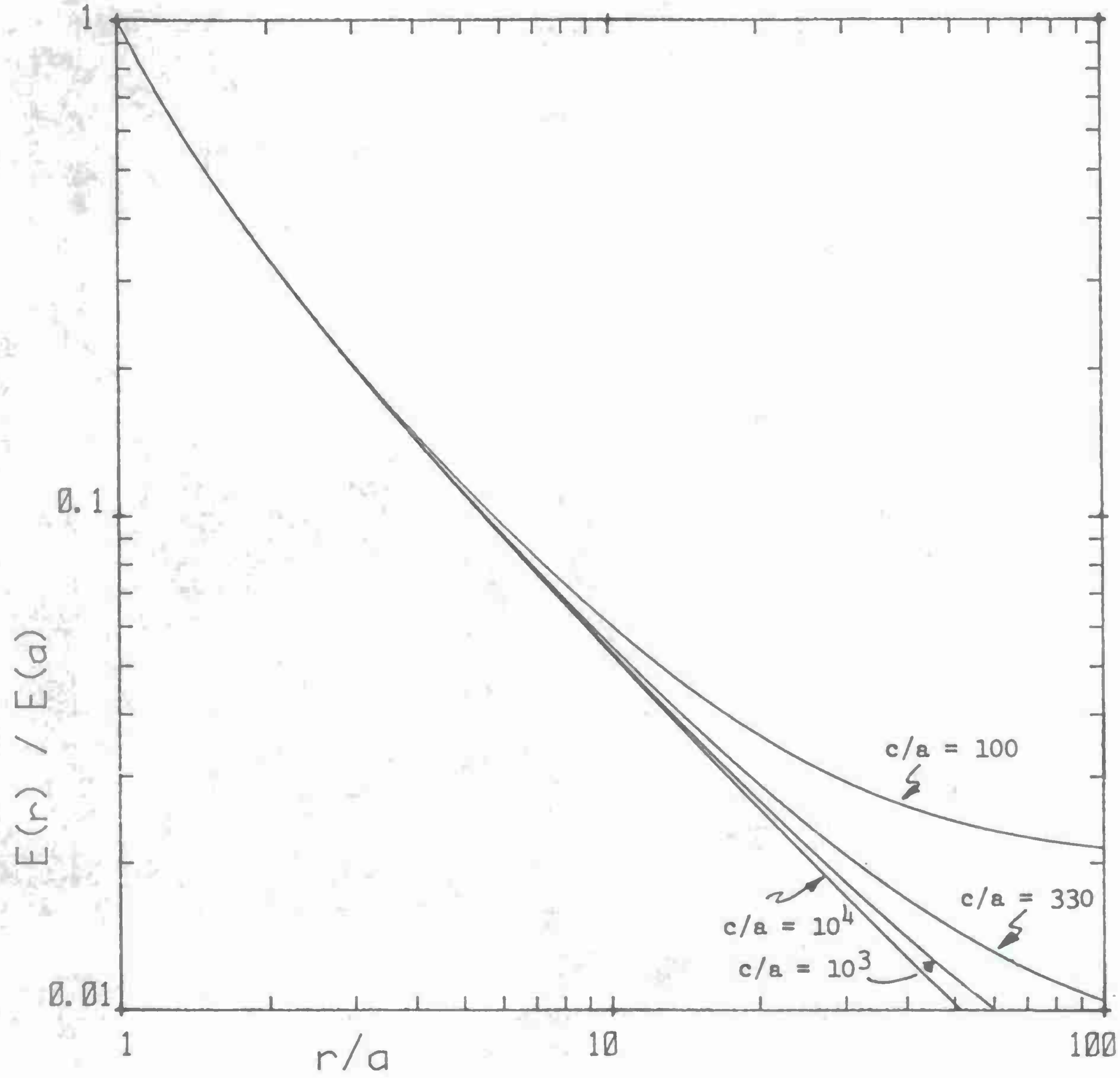


Figure 18.

The strength of the local electric field above the top of a grounded, conducting, prolate semi-ellipsoid exposed to a uniform, vertically-directed electric field relative to the field strength at the top. The radius of curvature of the top is a and the distance above the center of curvature is scaled in units of a. The ratio of tip height to tip radius of curvature is given by c/a. Initially, the field strength above the tip decreases according to $1/r^2$ but above 3a, the field strength decreases according to 1/r until it has decreased to that of the ambient level as shown on the lower right.

TABLE 3

A COMPARISON OF THE NORMALIZED ELECTRIC FIELD STRENGTHS ABOVE THE TIPS OF 2m HIGH SEMI-ELLIPSOIDS WITH VARIOUS TIP-HEIGHT TO TIP-RADIUS OF-CURVATURE RATIOS (c/a)

(E_o=ambient, undisturbed electric field strength)

c/a	$E(tip)/E_o$	$E(3cm)/E_o$	$E(10cm)/E_o$	height, h where $E(h)/E_o=3$	height, h where $E(h)/E_o=10$
1	3.0	2.91	2.73	0 cm	-
3	5.0	4.54	3.81	22.1	-
6.5	7.6	6.34	4.61	24.5*	-
10	9.8	7.55	4.94	24.2	0 cm
30	20.3	10.72	5.20*	21.3	3.45
80	42	12.30	4.86	18.4	4.00*
100	49	12.41*	4.74	17.8	3.98
300	117	11.92	4.17	15.0	3.66
1000	317	10.55	3.63	12.7	3.18
3000	811	9.32	3.26	11.1	2.78
10,000	2330	8.22	2.95	9.8	2.43
30,000	6190	7.41	2.73	8.8	2.17
100,000	18350	6.71	2.54	7.9	1.94

*maximum

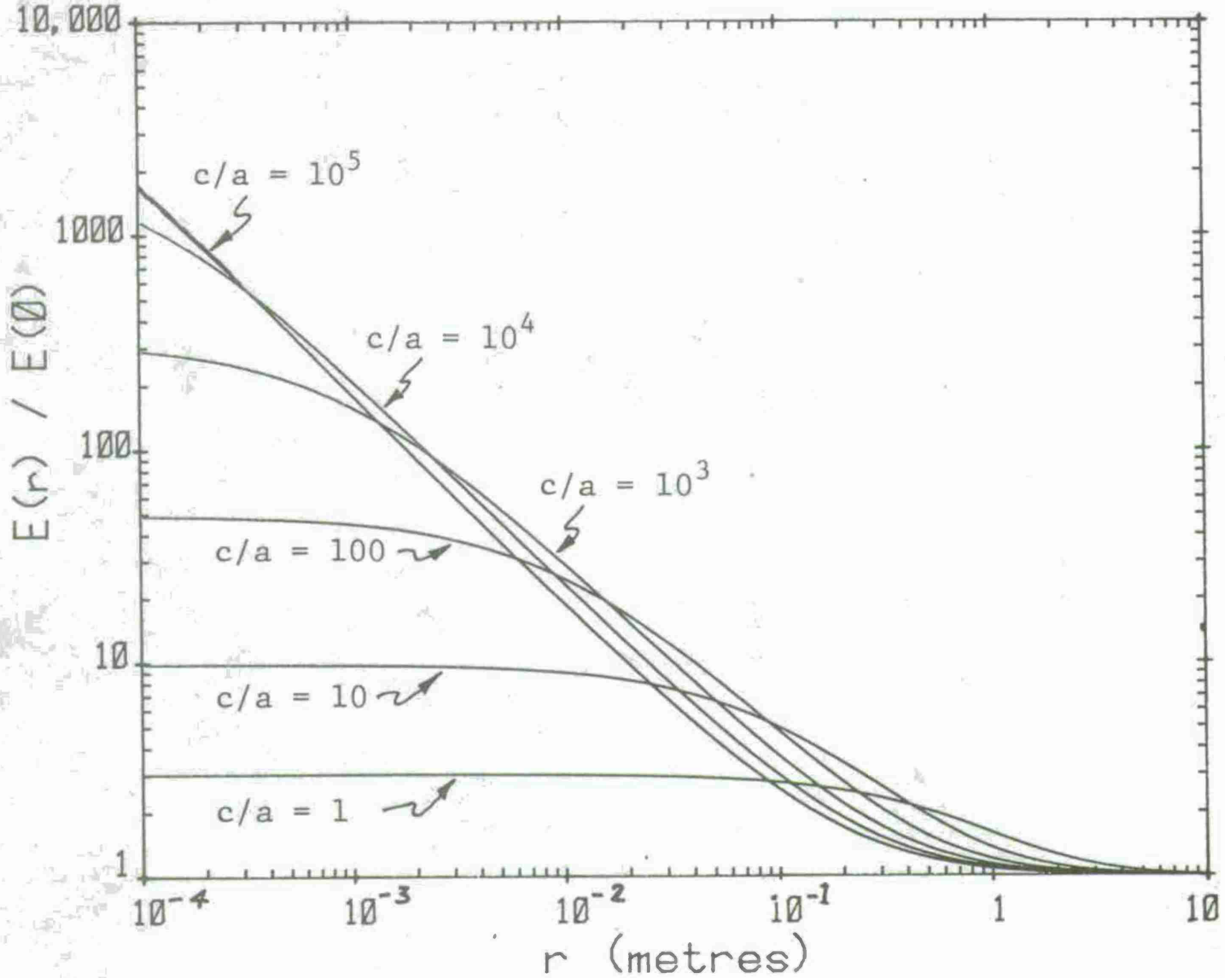


Figure 19.

The strength of the local electric field above the top of a grounded, conducting, prolate, semi-ellipsoid exposed to a uniform, vertically-directed electric field of ambient strength, Eo. These calculations assumed a 2 m high semi-ellipsoid. The tip-height to tip-radius-of-curvature-ratio is given by c/a.

At this time, the energy associated with the electric field over the blunt rod will be very much greater than that over the sharp rod and this, we think, can be significant in the possible interception of an approaching lightning streamer.

To pursue this idea, we turn now to an examination of the nature of lightning strikes to earth.

E. Lightning Strikes and Lightning Rods

Lightning strikes to earth generally occur after strong electric fields have developed within an electrified cloud and have caused local ionization aloft. This ionization often results in a plasma streamer that carries negative charge and propagates downward, toward the earth. The streamer, known as the "stepped leader" because of its discontinuous, stepping mode of downward propagation, intensifies the local electric fields at the earth's surface beneath. When these fields become sufficiently strong with the approach of the stepped leader, point discharges and plasma streamers carrying positive charge are launched from well-exposed conductors and propagate upward. Some of these positive streamers intercept and make an electrical connection with the approaching, stepped leader at heights of the order of 10 to 100 m above the earth. Thereafter, negative charge from aloft drains to earth through the conducting plasma channel as earth potential travels rapidly upward along the original, stepped-leader channel, producing a "return-stroke".

The object or location on the earth providing the positive streamer that intercepts the stepped leader thereafter has to carry the full return-stroke current that flows. It is, therefore, important for us to understand the conditions required for launching a successful streamer. As we discussed earlier, in strong electric fields, ionization and point discharges occur at a conducting point, forming plasma streamers that move rapidly away from the source and die out. They usually extinguish because the electric field decreases in strength with distance from the point due to both the geometry and to the presence of the ions.

Phelps (1971), and others have shown that sustained electric field strengths (at sea level) of the order of 400 kV/m are necessary for positive streamers to propagate through the air. At field strengths greater than this value, the energy given up by a charged, moving, streamer tip is sufficient to ionize air and to form a new charged tip; under these conditions, the tip will propagate in the direction of the field as a streamer. At field strengths below this critical value, streamers lose energy faster than they receive it from the field and so, they soon extinguish.

Field strengths of the order of 400 kV/m do not exist at steady state near the earth's surface because points on the earth readily emit ions that quickly reduce the fields to values near the threshold for point discharge. In strong ambient fields, the local fields around sharp, well-exposed points will remain near the 3MV/m level and a continuing emission of ions will flow from the plasma sheath around the point. If the ambient field intensifies, streamers in the plasma sheath will extend out to where the local electric field decreases below the 400 kV/m threshold for streamer-propagation and there die out, depositing an ionic space charge at this range. This process is very rapid and can counter most of the usual increases in field strength.

The situation becomes more exciting during the close approach of a stepped-leader streamer, for now, the local fields may intensify even more rapidly than the ion motions can counter-act. When this occurs, the plasma can propagate by photo-ionization and by electron acceleration, becoming an upwardly propagating streamer and a return stroke.

If an exposed structure is not initially emitting ions as the field intensifies, a meta-stable condition can develop: The field strength above a blunt conductor may increase above the streamer-propagation threshold for an appreciable distance into the air. Then, when the field strength at the tip exceeds the threshold for point discharge, ionization starts, followed by plasma streamers that propagate rapidly and vigorously over this region with strong fields, ionizing the air and raising earth potential toward the top of the ionized region. This may intensify the local field there so rapidly that further breakdown occurs. The streamer then propagates in the direction of the field as long as the energy given up by excluding the local field from the resulting plasma equals or exceeds that required to produce the ionization (and to compensate for the other losses).

When both sharp and blunt rods are exposed to an intensifying electric field, both will eventually emit point discharge ions and plasmas will form in the air above them. If the external field continues to intensify, upward going streamers can be launched from each of the points, but from which one will the first streamer come?

Standler (1975) modelled the breakdown process numerically in a cylinderical geometry with the inclusion of curvature and point discharge effects. He found that the sustained, critical electric field necessary for the launching of a return-stroke streamer could be developed around a large cylinder a significant time (of the order of 1/2 millisec) earlier than that developed around a small cylinder, as a result of the early emission of charge from the small cylinder. When his finding is extrapolated to the ellipsoidal geometry with an approaching streamer and with strong fields existing for appreciable distances above a blunt tipped conductor, it suggests that the blunt conductor may often win the competition to provide the first successful, upward-going streamer that connects the down-coming leader to earth.

F. Electric Field Collection by A Vertical Conductor

Yet another criterion by which various air terminals might be evaluated in a uniform, vertical, electric field is the radius or the half-width of their "collection area" for the electric field lines from overhead. This collection area S is defined as

$$S = \int_{surface} \underset{\sim}{E}_c \cdot d\underset{\sim}{S}/E_o$$

where E_c is the electric field vector normal to the surface of the conductor, and $d\underset{\sim}{S}$ is an infinitesimal area of the conductor surface. For the ellipsoid, $\underset{\sim}{E}_c = \underset{\sim}{E}\eta_o$ and

$$d\underset{\sim}{S} = h_f^2 \left[(\eta_o^2 - \xi^2)(\eta_o^2 - 1)\right]^{1/2} d\xi \, d\varphi \, \hat{\eta},$$

where φ is the usual horizontal azimuthal direction measured counter clockwise from a reference direction.

After integration over the ellipsoidal surface, we find that

$$S = \pi h^2{}_f \left[\eta_o \coth^{-1}\eta_o - 1\right]^{-1} \triangle \xi^2,$$

and the radius of the field collection area, r(C), is given by

$$r(C) = h_f \left[\eta_o \coth^{-1}\eta_o - 1\right]^{-1/2} \left[\triangle \xi^2\right]^{1/2}.$$

For integrations over the entire semi-ellipsoid, $\triangle \xi^2 = 1$.

Plots of the normalized radii, r(C)/c, for the field collection areas vs c/a and of the vertex half angles [given by 0.5 arc tan (r(C)/c)] are shown in Figures 20 and 21 for various portions of these ellipsoids. From these, it can be seen that the radii of the static "zones of field line collection" are less than 0.7 the ellipsoid heights for c/a ratios greater than 100.

This exercise also shows that, since the electric field lines are concentrated around the ellipsoidal tips, the radii of the electric field collection areas for ellipsoids with large values of c/a in a uniform field are much smaller than for blunter configurations. We may expect, therefore, that the same behavioural differences may exist in non-uniform fields and that blunt lightning rods should be able to furnish upward-going streamers that intercept approaching stepped leaders both more readily and over larger ranges than would sharp ones. This conclusion is independent of but in agreement with Franklin's 1762 suggestion that knobs on top of lightning rods will "draw" strokes from greater distance than will sharp rods.

G. Failures of Pointed Lightning Rods to Provide Protection

This view of the difference between sharpened and blunt rods is also supported by the repeated observations of lightning that strikes some conductor lower than an elevated and sharpened lightning rod in the vicinity:

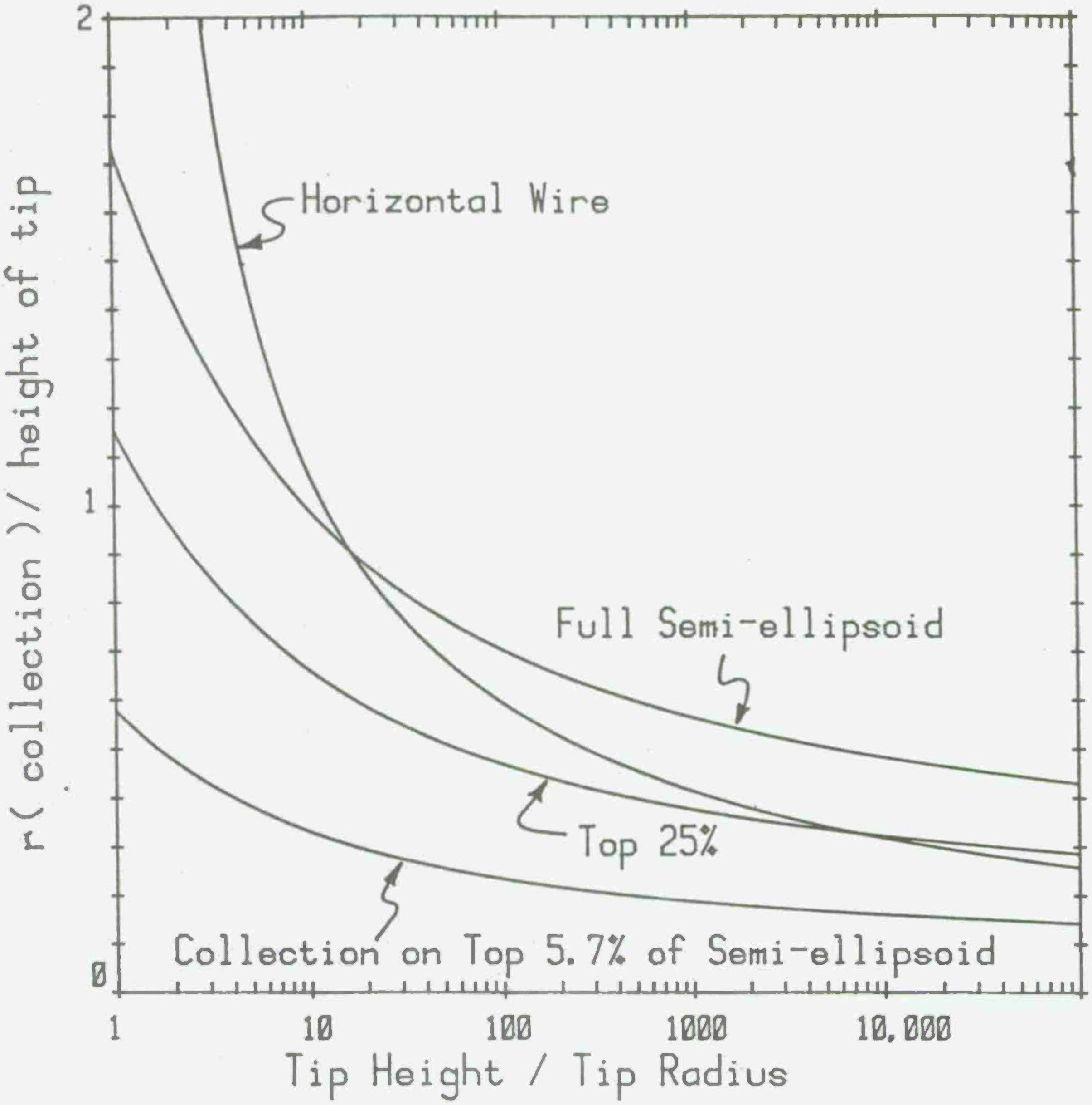


Figure 20.

The radius of the electric field collection zone as a function of tip height/tip radius. The top 25.4% of the ellipsoid collects 44% of the electric field lines over a radius of 2/3 that of the full, semi-ellipsoid zone of collection. The top 5.7% of the ellipsoid collects 11.1% of the electric field lines over a radius of 1/3 that of the full, semi-ellipsoid zone of collection.

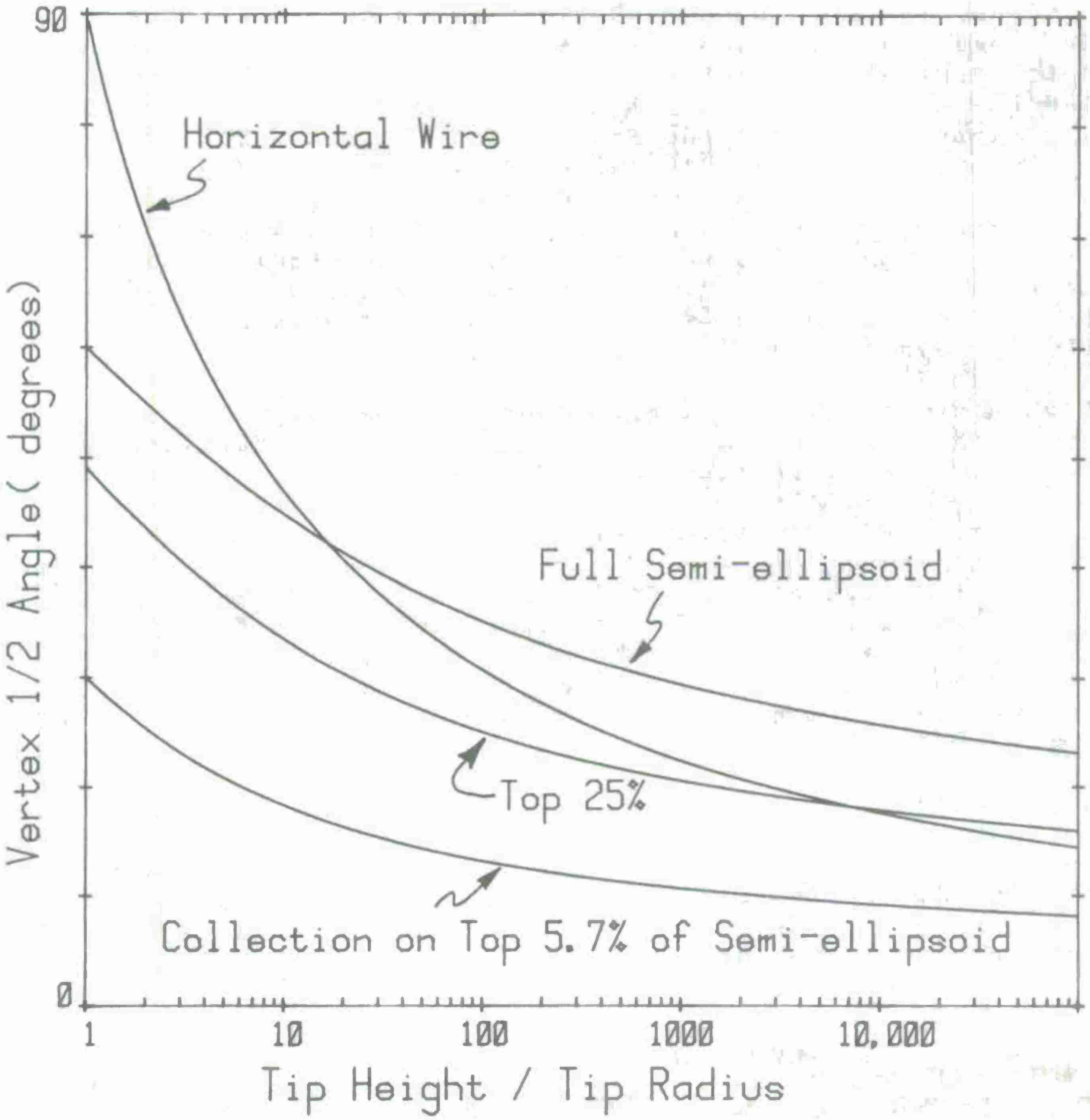


Figure 21

The angle subtended by edge of the electric field collection zone at earth as seen from tip of elevated conductor as a function of tip height/tip radius. The top 25.4% of the ellipsoid collects 44.4% of the electric field lines over a radius of 2/3 that of the full zone of collection. The top 5.7% of the ellipsoid collects 11.1% of the electric field lines over a radius of 1/3 that of the full zone of collection.

In his review of lightning strikes to sailing ships, Snow Harris (1843) reported on a number of lightning strikes to locations near but below an elevated lightning conductor and well within its nominal "cone of protection". Maksiejewski (1963) reported the observation of a lightning strike to the platform around a slender tower on the Palace of Culture and Science in Warsaw. The platform was 95m below the top of the 230m high tower and well within its nominal "cone of protection". Berger (1967) shows a picture of a discharge "which contacts the tower not at its tip (lightning rod) but just below, at the steel frame work". In another section (page 521), he attributes the presence of space charges as "the reason why so many downward strokes penetrate deep into the valleys between fairly high mountains".

Lightning struck a down-conductor that passed (with a 135° bend) over the corner of a building at Indianhead, Maryland during August 1974. The attachment point for this strike was near the base of a vertical, sharp lightning rod which showed no signs of having been struck (Plumer, 1974).

One of the lightning channels triggered by Apollo 12 at an altitude of about 2 km struck the high-pressure gas facility within 30 m of the base of the 160 m launch umbilical tower at LC-39A on Kennedy Space Center in Florida on Nov. 14, 1969. The launch tower was equipped with a sharpened corona point, mounted on its top.

The carefully sharpened points, used to study point discharge phenomena at Langmuir Laboratory in New Mexico, are elevated more than 10 m above the mountain summit. They have never been struck by lightning during 16 years of exposure to thunderstorms and with the close approach of hundreds of lightning discharges although lower objects in their nominal "cone of protection" have been struck repeatedly.

These and other reports lead us to conclude that conventional, sharply-pointed, lightning rods frequently fail to protect structures beneath them from lightning, and that they often do not provide the preferential path to ground for lightning currents in the vicinity. This conclusion, coupled with the preceding theoretical considerations, lead us to suggest that sharpened rods tend primarily to protect themselves by point discharge and that blunt lightning rods may be the more effective ones for lightning protection of structures by conducting lightning discharges directly to ground.

It also follows that the nominal "cone of protection" depends on the height, exposure and curvature of the air terminal. The concept is inexact and its use cannot be trusted to ensure protection from lightning.

H. Design of an Improved Lightning Rod

The question now arises as to what is the "optimum" blunt rod? There is insufficient information about the behavior of streamers near the earth for us to furnish a definitive answer but, from the foregoing approximations and from related approaches, we can furnish some criteria for an improved lightning rod configuration:

1. We wish to minimize point discharge under steady state electric fields beneath thunderstorms and this requires that the local field strength at the top not exceed 3 MV/m (at sea level) in ambient fields of the order of 15 kV/m. The local field enhancement at the tip therefore should not exceed a factor of about 200.

2. When a lightning streamer approaches the vicinity to be protected, we wish the chosen rod to cut across a potential difference of the order of 1 or 2 MV. This requirement makes the height of the rod important and suggests that, within limits, the higher the blunt rod, the more likely it is to furnish an upward going streamer to meet a leader streamer descending from the storm overhead. Field excursions of the order of 30 kV/m are frequently observed with lightning discharges at ranges of less than 1 km. We do not necessarily want our lightning rod to furnish upward-going streamers for such field enhancements, but if we did, rod heights in excess of 30 m might be required. On the other hand, we do want our rod responsive to stepped leaders that approach within 50 m.

Since, at the earth's surface, the vertical component of the electric field due to charge in an approaching leader varies about as the inverse cube of the slant range to the leader, the critical electric field for the propagation of an upward-going streamer may be first achieved at the tip of a vertical rod with a height of about 2 meters above a flat plane.

Our recommendation for a vertical lightning rod, designed to furnish streamers that intercept nearby lightning discharges and to conduct them preferentially to earth, would be for a rod:

(1) tall enough to cut across electrical potential differences of the order of 2 MV during the approach of a leader streamer,

(2) large enough at the tip to prevent point discharge under steady-state electric fields,

(3) large enough in cylindrical radius that the self-inductance is not dominant, and

(4) large enough in cross section to carry the main current of a discharge (sometimes in excess of 250 kA).

The desired rod height places yet another requirement on the diameter of the rod from mechanical strength considerations but guying, and curved sweeping connectors to horizontal ground leads, are both acceptable and desirable.

We, therefore, recommend an investigation of a prototype, vertical lightning rod at least 2 cm (or 3/4") in diameter with its top, blunt and at least 1.5 m high above any nearby conductor. This rod should be connected directly to earth through a low impedance path.

If the upper end of such a rod were finished smoothly as a hemisphere with the same radius as the rod, the c/a ratio for the rod would be of the order of 200 and the electric field enhancement at the tip would be approximately 100 fold. This should be insufficient to cause point discharge under ambient field strengths of up to 15 kV/m and therefore, point discharge should not occur under most steady-state thunderstorm electric fields. An approaching streamer should readily provoke a response from such an exposed conductor and there should be minimum interactions with local space charges emitted from the vertical rod.

The approximate distribution of electric field lines around such a vertical lightning rod 2 m high with a c/a ratio of 200 is shown to scale in Figure 22.

The transient response of such a lightning rod to an approaching, off-axis, stepped leader-streamer is not easily described analytically but, in view of its exposure, and its relative freedom from the self-protection effects caused by point discharge, we might expect that such a rod might provide the preferential lightning path-to-earth for all streamers within a radius equal to about 0.45 of its height.

I. Analysis of Elevated Horizontal Wires

We turn now from vertical rods to a consideration of elevated, horizontal wires that are connected appropriately to earth so that they remain at earth potential. The vertical electric field directly beneath such a wire at a height h above a conducting earth is given by

$$\underset{\sim}{E}_z = (\gamma / 2\pi\epsilon)\left[1/(h-z) + 1/(h+z) \right] (-\hat{z})$$

where γ is the induced charge per unit length on the wire (which is to be determined), ϵ is the permittivity of the air (8.854×10^{-12} F/m) and z is the height of the point of interest above the plane (but directly below the wire).

We choose the condition for the surface of the wire such that its potential is the same as that of the earth:

$$E_o h - \int_o^{h-a} \underset{\sim}{E}_z \cdot d\underset{\sim}{z} = 0$$

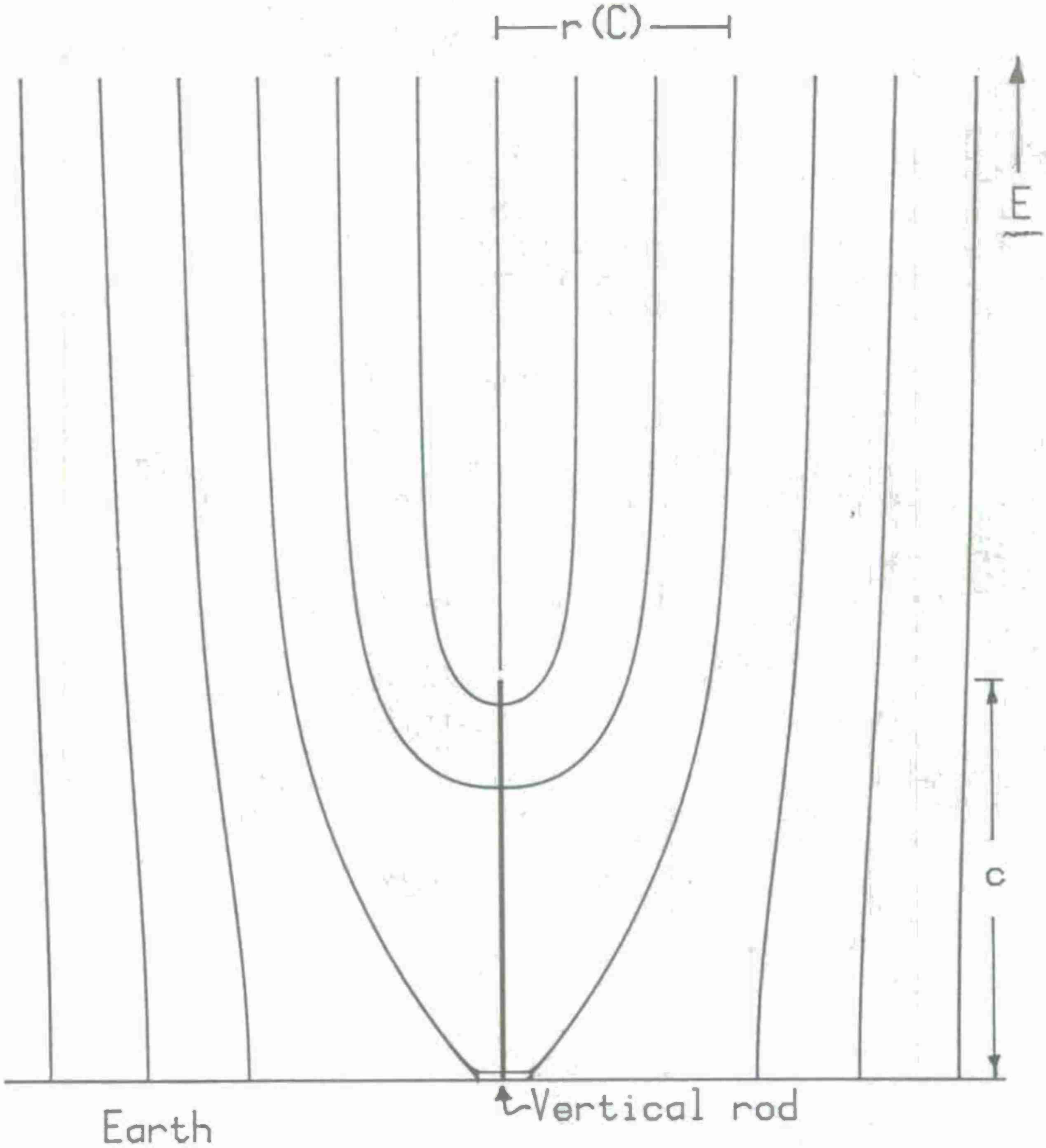


Figure 22.

The approximate distribution of electric field lines around a vertical lightning rod with a tip-height to tip-radius-of-curvature ratio of 200. These field lines were extrapolated from those around prolate, semi-ellipsoid with the same tip-height to tip-radius-of-curvature ratio.

where a is the radius of the wire. Solution of this relation gives

$$E_o h = \left[\gamma / z\, \pi \epsilon\right] \ln(2h/a - 1).$$

If we superpose the electric field around the wire due to the induced net charge γ with the polarization field around an isolated, conducting cylinder due to E_o, we get the radial field at the surface of the wire as

$$\underset{\sim}{E}_r = E_o \left\{ 2 \cos\theta + h/[a \ln(2h/a-1)] \right\} \hat{r}$$

where θ is the angle between zenith and the direction, $\hat{r}$. The maximum field strength occurs at the top of the wire where $\theta = 0$ and

$$E(\text{top of wire}) = E_o \left\{ 2 + h/[a \ln(2h/a-1)] \right\}.$$

A plot of E(top of wire)/E_o for various values of h/a (equivalent to c/a) is shown in Figure 17.

We can determine the width, w ,of the horizontal strip over the wire through which pass the electric field lines that terminate on the elevated wire from

$$w = \int_{\text{surface}} \underset{\sim}{E}_r \cdot d\underset{\sim}{S}/1$$

where $d\underset{\sim}{S}/1 = a\, d\theta\, \hat{r}$.

Solution of this relation gives

$$w = 2\pi h/[\ln(2h/a-1)].$$

A plot of the electric field lines above an elevated and grounded wire in a uniform, vertical, electric field is shown in Figure 23 and a plot of w/2h (the horizontal distance from the wire to the edge of the collection envelope, equivalent to r(C)/c) versus h/a is shown in Figure 20. The half angle subtended at the wire by the perpendicular distance, w/2, from the wire is shown in Figure 21.

In these figures, it can be seen that a semi-ellipsoid has a greater field collection radius than does a horizontal wire of the same tip-height to tip-radius ratio for all c/a or h/a ratios of interest in lightning protection. This is perhaps misleading for most of the electric field lines are collected below the tip of the ellipsoid in regions where the electric field strength is weaker than is required to initiate a return streamer. For example, the strength of the electric field at locations in the lower 14% of the ellipsoid height is even less than that of the ambient field as a result of the shielding provided by the upper

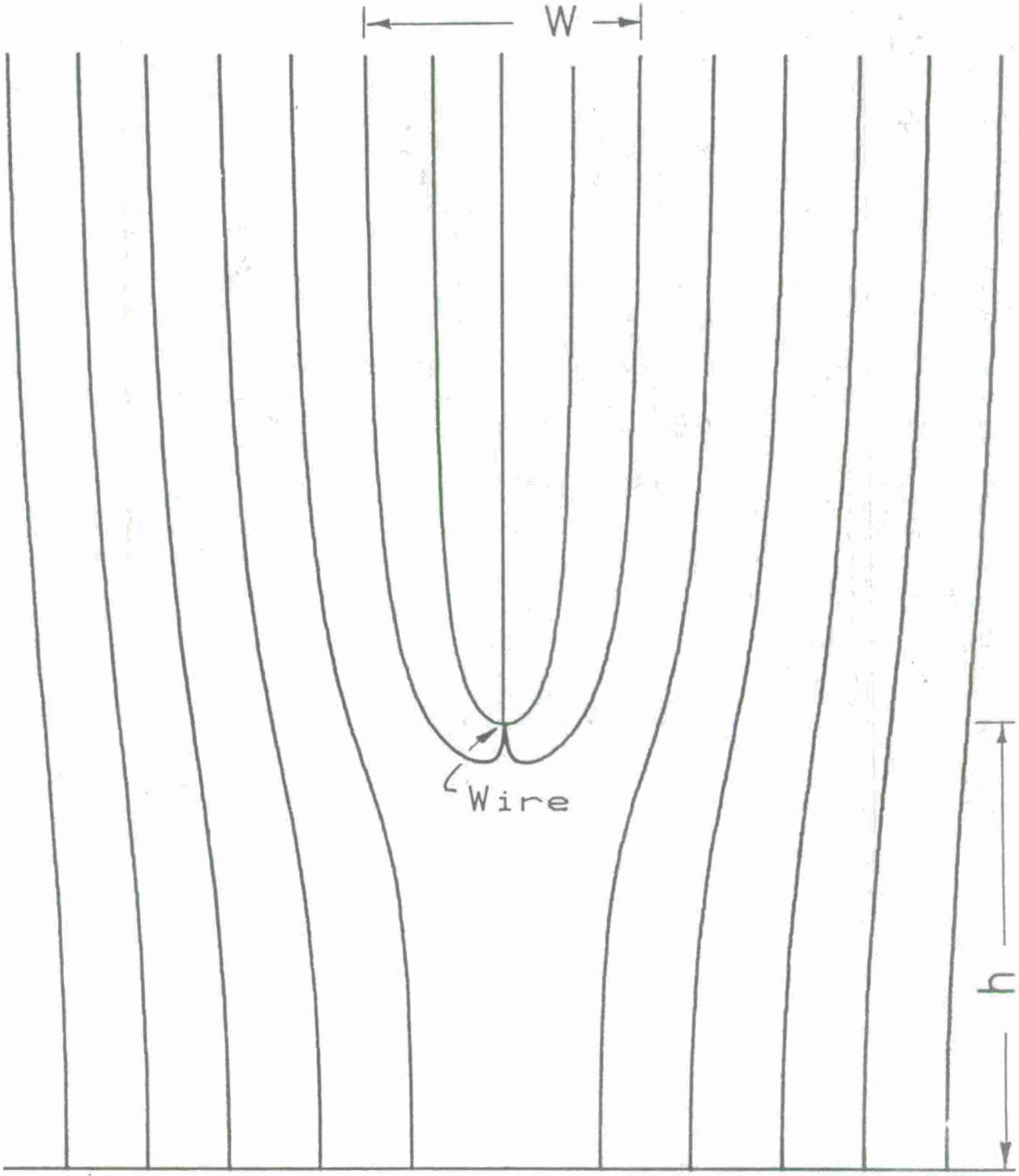


Figure 23.

The distribution of electric field lines around an elevated, grounded, horizontal wire at a height, h, above the earth and arranged to be perpendicular to the plane of the page. The width, w, of the zone through which pass the electric field lines that terminate on the elevated wire is shown at the top of the figure.

exposed conductor; we would not expect that a return stroke could be initiated in this region.

We are primarily interested in the regions of a lightning rod where the electric field is strongly enhanced and these, of course, are at the upper end of the conductor. In Figure 20, we have plotted the field collection radii for the zones shown in Figure 16. The inner zone has a radius of 1/3 the full collection radius: in it, 11.1% of the field lines terminate on the upper 5.7% of the ellipsoid. The middle zone has a radius of 2/3 the full collection radius: within it and the inner zone, 44.4% of the field lines terminate on the upper 25.4% of the ellipsoid.

Although the region most likely to initiate a return stroke lies within the upper 25% of a lightning rod, the radius of the field collection area for this region is less than that of the equivalent horizontal wire. To provide a better comparison of the collection areas of the two configurations, we have plotted, in Figure 24, the collection areas for a horizontal wire and for the regions on a vertical, prolate, semi-ellipsoid where the field strength is equal to or greater than that at the bottom of the horizontal wire. For the h/a and c/a ratios of interest ($h/a>100$), the horizontal wire collects electric field lines over a distance of more than 4 times those of the equivalent region of the ellipsoid. Accordingly, despite its larger total field collection area, the ellipsoid appears to have a smaller effective collection zone than does a horizontal wire.

We conclude, from all these considerations: the more uniform enhancement of the electric field, the larger effective field collection area and the greater ease of shielding an extended area, that properly arranged, elevated, horizontal wires will provide better lightning protection to structures below than can a row of vertical lightning rods.

J. Design Considerations

If elevated, horizontal wires are used for lightning protectors, the wires must be large enough to carry the peak currents. Consideration must be given to ensure that, if the wires are damaged by lightning (or by wind, weathering or corrosion), they do not create new hazards by falling into power lines or personnel below.

The major problem foreseen in optimizing the development of elevated grounded wires for lightning protection comes from the need to provide a low impedance path to earth. A system of wires elevated above the earth constitutes a network of transmission lines with local characteristic impedance, Z, to the conduction of lightning transients given approximately by

$$Z \simeq \left[\sqrt{\mu/\epsilon}\ \ln(h/a)\right]/2\pi n$$

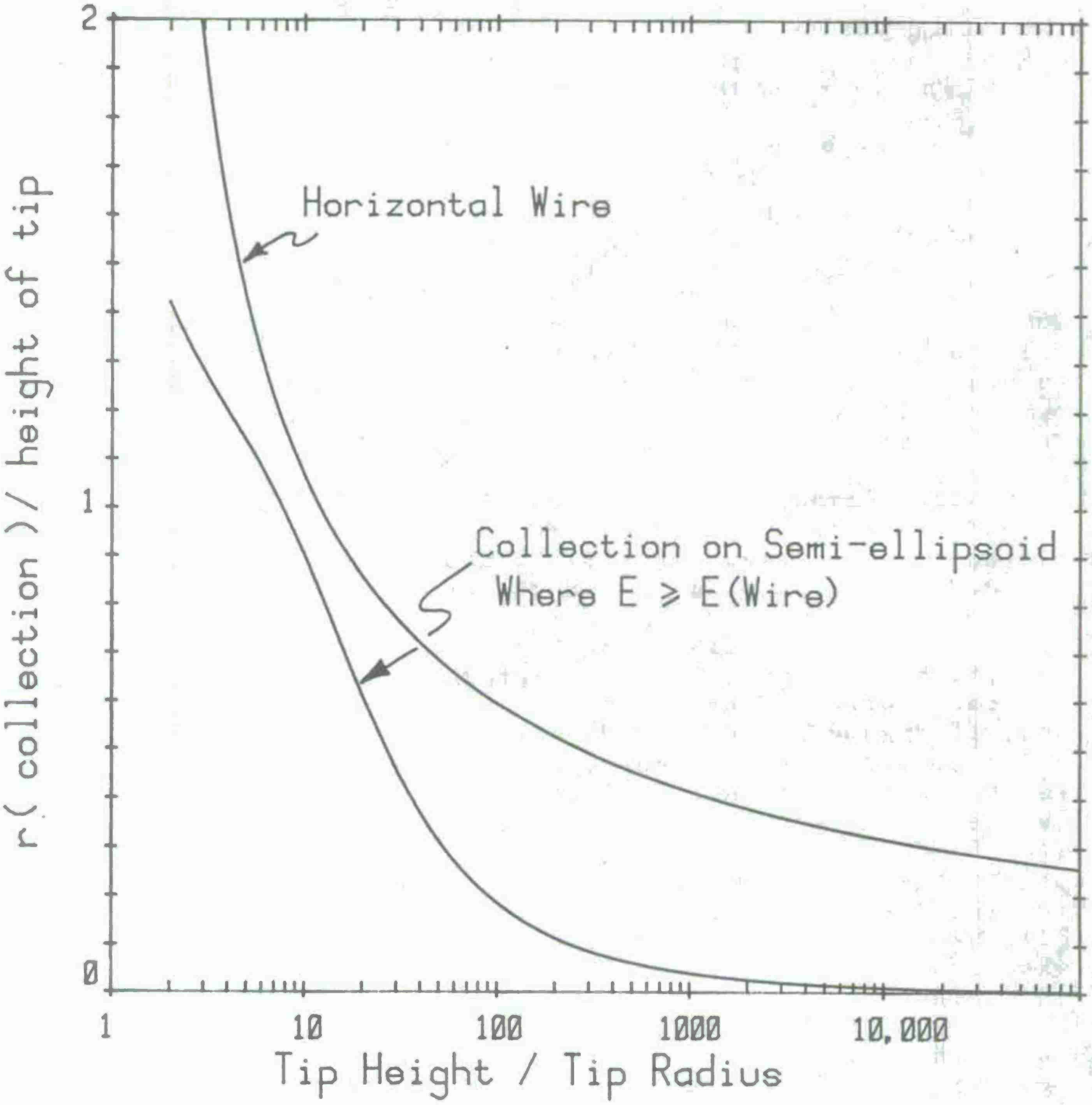


Figure 24.

A comparison of the dimensions of the electric field collection areas for elevated, horizontal, grounded wires and the portions of vertical, conducting, grounded, prolate semi-ellipsoids where the electric field is stronger than at the bottom of the horizontal wire with the height to top radius of curvature ratios.

where μ and ϵ are the permeability and the permittivity of the atmosphere respectively and n is the number of conductors leading from the lightning attachment point to earth. Evaluation of this relation yields

$$Z \simeq 60 \left[\ln(h/a) \right] / n \text{ ohms.}$$

For h/a values of the order of 1000, in a horizontal run of elevated cable,

$$Z \simeq 200 \text{ ohms}$$

which means that potential differences of many megavolts will be required to conduct lightning currents of the order of 50 kilo amperes down a cable. With potential differences of this order, local breakdown of the air may cause new streamers and side flashes to the structure that is to be protected.

An elevated "maypole" arrangement with a mast above the structure and connected to many down-conductors in a conical array will minimize these problems of side flashes to the protected building. Our view of one such arrangement is shown in Figure 25.

If the central supporting mast can be connected directly to the system ground, it may be made of metal, such as steel, and be allowed to carry part of the lightning current to earth. On the other hand, if a good connection to earth cannot be achieved or, if exclusion of all lightning currents from the protected structure is required, then a dielectric (a fiber glass or a treated wooden) mast should be employed.

This arrangement with a single elevated cable was employed successfully at Kennedy Space Center for the protection of the last Apollo vehicles against lightning at the launch pad. This scheme was first proposed by Regnier and was reviewed by Leroy, La Place and Coulomb in their report to the National Institute of France on Dec. 23, 1789. Regnier's method of protecting powder magazines is shown in Figure 26. Variations of this system were later suggested by Maxwell (1876) and by Golde (1967).

We think, however, that Regnier's upper point is not necessary; a blunt rod termination would better define the attachment point for any lightning. Discharge might be diverted from the magazine if a ring of tall grounded masts, tipped with blunt rods, were to surround the structure. This ring of blunt masts could produce the best, return-stroke candidates and thus provide even better protection to the contents of the magazine. In this case, the conical array of grounded wires would still be desireable as a second line of protection.

For the protection of an extended rectangular building, the arrangement shown in Figure 27 may be used. Here, a number of tall metal masts support the conducting guys.

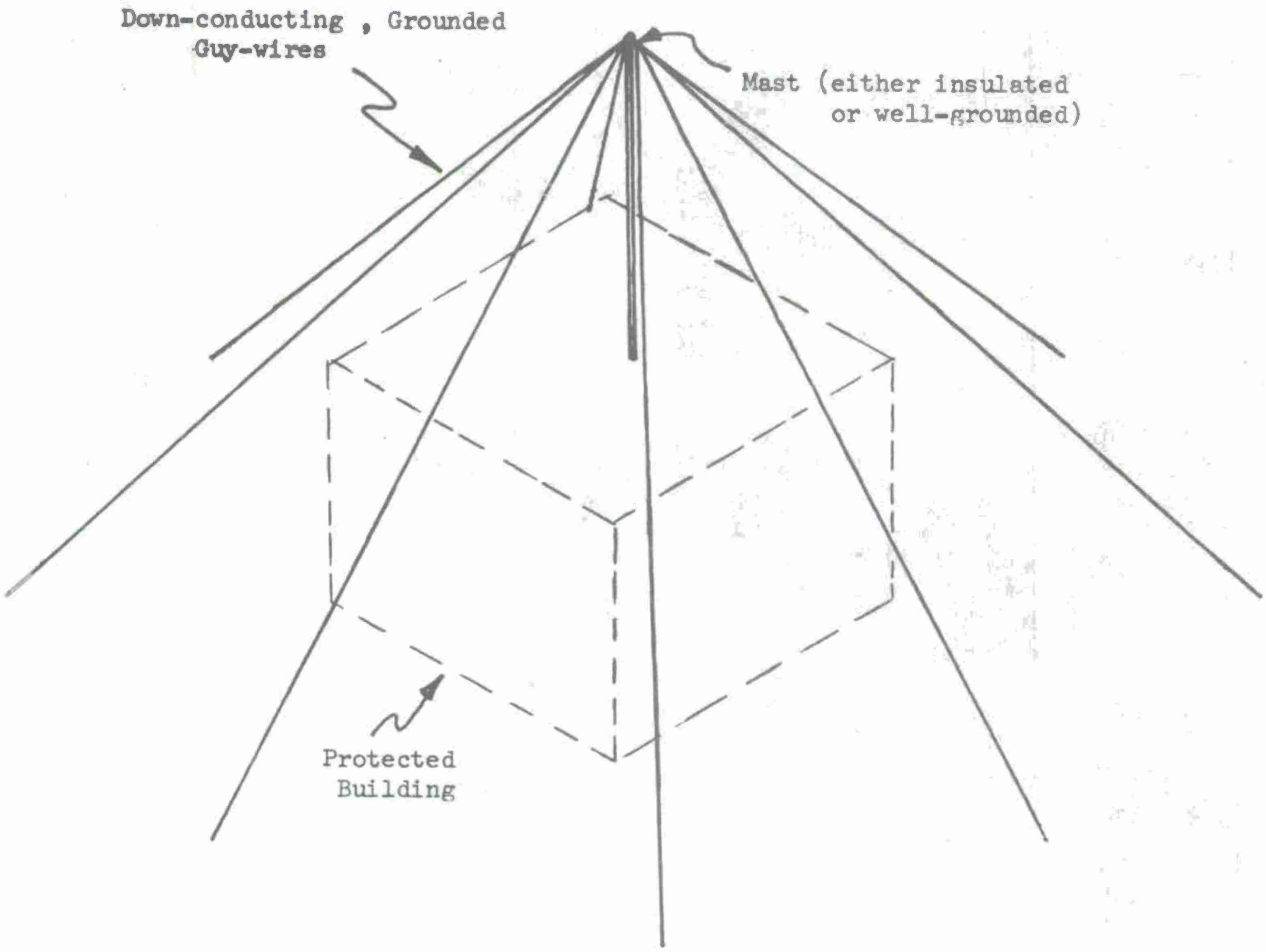


Figure 25

Proposed arrangement of lightning protection with the "maypole" concept that uses a mast over the structure to be protected and a conical array of down-conducting, guy wires.

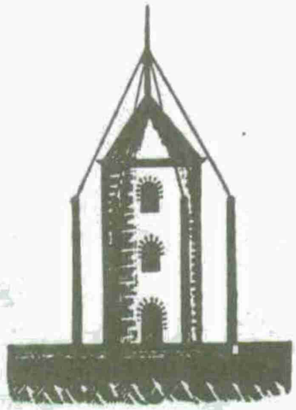


Figure 26

The lightning rod proposed by Regnier consisted of a piece of wood, coated with resin, rising 2 metres (6 feet 7 inches) above the roof, and having fixed on its top a sort of inverted funnel of copper, at the upper end of which was fixed the point. To the lower edge of the funnel were fastened ropes formed of twenty-seven annealed iron wires well bound together, which were, at a suitable distance, connected with iron bars, fastened to masts, and leading to moist earth. The point had a small piece of platinum at its upper end.

The reporters* observe that the wooden support may be employed by way of extra precaution, though there was no known instance of lightning leaving metal for wood; but it should be strong enough to resist the wind. They approve of the method proposed for connecting the point with the metal bars, metallic ropes being very suitable for this purpose, and keeping them well away from the building was quite right; but they add that the metallic bars should not only communicate with moist earth, but also with water in wells or otherwise.

*Leroy, La Place and Coulomb.

Gentle bends at all connections and straight runs of wire to ground electrode are recommended because sharp bends in down-conductors increase the conductor's local impedance to current surges thus causing it to act as a poorly-terminated transmission line. Surges on such lines are partially reflected at all impedance discontinuities and whenever the local impedance is greater than that of the straight line, the reflection has the same polarity as that of the incident surge. In this situation, the amplitude of the reflection superposed on that of the surge adds to and increases momentarily the local potential differences between the wire and its surroundings.

These reflections can, thus, cause "side flashes" to objects in the vicinity of a sharply bent conductor. All changes in the direction of a down-conductor should be gentle with the radii of curvature always exceeding 25 cm (8 inches). No changes in direction should exceed 90^{o} within distances of the order of 50 cm. These recommendations apply regardless of whether the air terminal is an overhead wire or a vertical lightning rod.

The need for gentle bends was recognized by Joseph Henry in 1871 and by Oliver Lodge in 1892. Despite their recommendations, right-angle bends in down-conductors are commonly shown in modern illustrations of lightning protection techniques.

K. Ultimate Lightning Protection

At this point, one might ask "what is necessary for complete lightning protection?". This question was answered by James Clerk Maxwell to 1876; He showed that it would be necessary to enclose a volume within a conducting, Faraday cage with no openings to protect it completely from lightning.

From Maxwell's equations, we can define the attenuation to lightning-induced and other electromagnetic signals as a function of the thickness and conductivity of the walls comprising the enclosure. A 2mm thick wall of continuous copper will attenuate the amplitude of incident electromagnetic signals due to lightning by a factor greater than 10^5. Such an enclosure, located beneath elevated lightning rods or wires that can withstand the direct heating effects at the lightning attachment point, should give essentially complete protection against terrestrial lightning. No apertures and no signal or power feed-throughs could be allowed in this ultimate protection scheme and therefore, it may have little utility for other than storage uses.

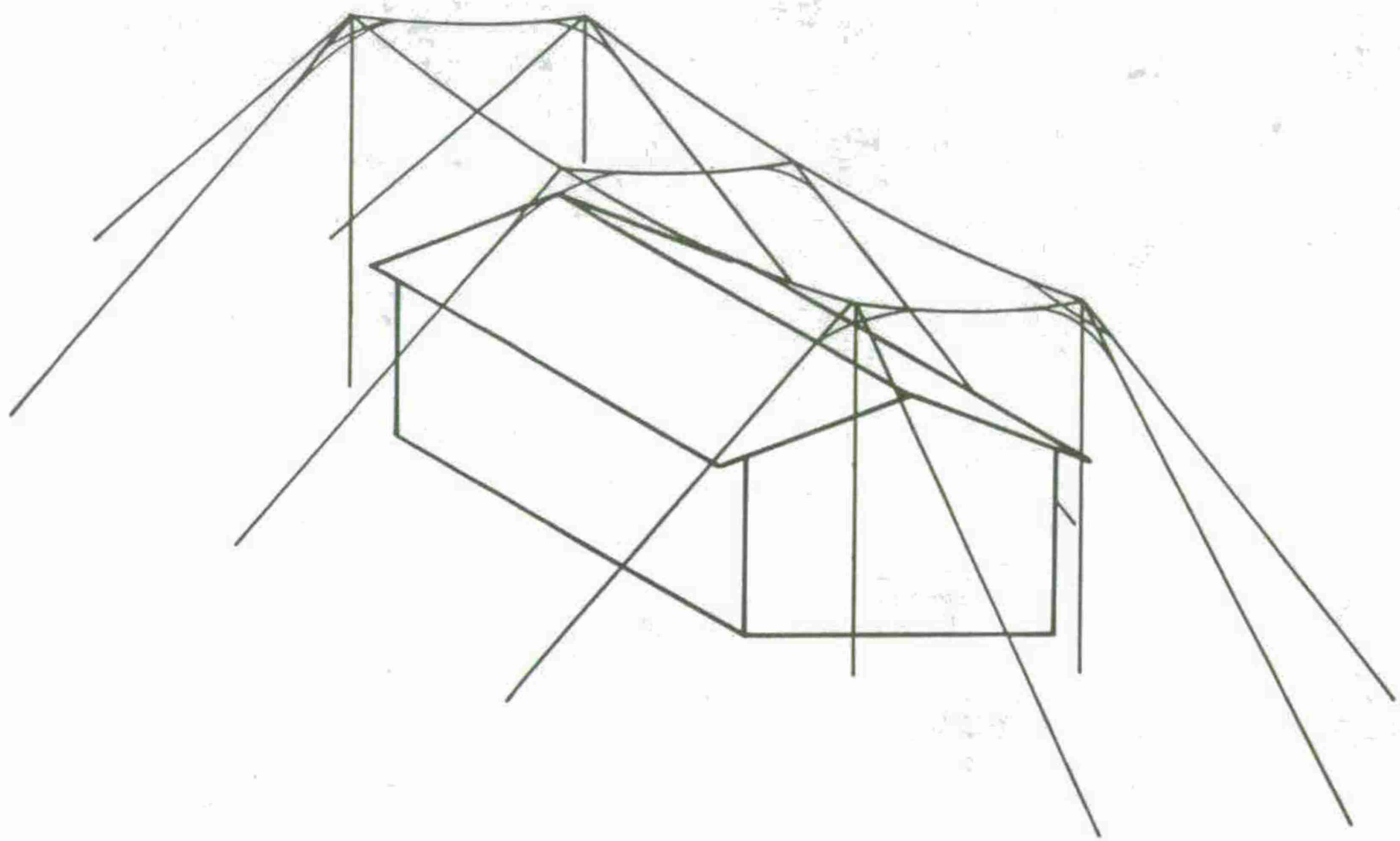


Figure 27

Sketch of the protection against lightning of an extended building with overhead grounded wires equipped with gently rounded connections across sharp angles in the conductors.

L. Concluding Remarks

Many of the ideas and views brought together and discussed above are well known; most of them have been reported in the scientific literature, and all of the well based ones we are pleased to acknowledge. Among these are:

1. Franklin's recommendation for the desired height of a lightning rod: 6 or 8 feet above the highest point to be protected (1753).

2. Franklin's view that lightning rods with knobs on them would attract a stroke from a greater distance than would a sharpened one (1762).

3. Regnier's (1789) scheme for powder magazine protection.

4. Henry's (1871) recommendation that no sharp bends be allowed in the down-conductors connecting the air terminals with the earth.

5. Overhead wires for protection against lightning The practice was begun in the 1890's by Reid, Stanley and others (McEachron, 1952) and is now widely used above high voltage transmission lines and less widely used in secondary power distribution systems.

Although, these ideas have been described in the scientific and technical literature, they are intermingled with other, less useful concepts. As a result, there is confusion in the protection techniques that are presently employed. It has been our purpose here to select, from the ideas available, those which have the best physical basis for lightning protection and to recommend that these be tested, optimized, and then adopted as standard techniques, even at this late date.

VIII. INSTRUMENTATION FOR DETECTING ATMOSPHERIC ELECTRICAL HAZARDS

Nearby lightning strikes cause most of the atmospheric electrical hazards of concern in ordnance operations, and therefore, the forecasting of an imminent strike can be of great importance to the safe conduct of these activities. At present, we cannot make accurate lightning forecasts for a given location, but we can reliably detect in advance the conditions that can lead to lightning and a nearby discharge. These conditions fall into two categories for our purposes: One set is associated with the approach of mature thunder clouds and the other with the initiation and development of cloud electrification nearby.

A. Detection Of Approaching Storms.

Most lightning is produced by electrified clouds that may be active for several hours. In the temperate zones of interest in North America, these storm clouds usually move toward the northeast or east under the influence of the westerly winds aloft and therefore, they can migrate appreciable distances during their active life.

Lightning flashes produce changes in the atmospheric electric field that can be detected at great distances ahead of the storm. Since these changes increase in intensity rapidly as a storm approaches, it is possible to measure the strength of the field change and thereby, to estimate the time of the arrival of a lightning producing storm well in advance of the time that it creates a local hazard. There are several devices that can be used to detect approaching thunderstorms. Among these are:

1. Various versions of the lightning counters developed by Pierce, Sullivan and Wells, Muller-Hillebrand, Kasemir and Krieg, CIGRE and others.

2. The Detector of Atmospheric Electric Disturbances developed for and adopted, with modification, by the U.S. Air Force. (Fougere et al, 1964).

3. The ground strike locator developed by Krider and his associates (Krider et al, 1980).

1. Lightning counters

As presently constituted, most of these are designed to sense the electric field changes caused by cloud-to-ground lightning. They operate with a fixed threshold for detection and are used to obtain an indication of all cloud-to-ground lightning within a preset range for the collection of lightning occurrence and flash flux density [flashes/sq km per unit time (month or year)] data. As such, these devices would be useful in characterizing the frequency of lightning in the vicinity of an ordnance plant, but most of them would require some modification for use in forecasting lightning hazards.

2. The present "Detector of Atmospheric Electrical Disturbances" also operates by sensing the low frequency electric field changes produced by lightning which vary approximately with the inverse cube of the distance to the discharge. It is arranged with four different levels of sensitivity for detecting and categorizing the electric field changes produced by lightning. To a first approximation, the electric field change ΔE is given, in mks units, by

$$\Delta E \simeq 2 \times 10^{+10} \, qh/r^3$$

where qh is the electric moment destroyed in a stroke and r is the slant range from the centroid of lightning charge change to the observer. Values for qh of the order of 10^5 coulomb meter may be expected for cloud-to-ground discharges.

The instrument is usually set so that the most sensitive channel detects all normal discharges within a distance of about 60 km (nominally 40 miles), the second channel detects discharges within 30 km (normally 20 miles) the third channel responds only to those discharges within 15 km (10 miles) and the fourth channel detects those flashes within 8 km or shorter range. No directional information on the discharges is produced by this device but, by noting the progressive activation of, more insensitive channels (as shown in Figure 28), an observer can extrapolate the intensification trend and forecast the approach or intensification of thunderstorm before it arrives over the station and before the lightning that it produces becomes a hazard to local operations. The detector also includes a sensor for detecting locally intense fields which will be discussed later.

3. Lightning location

A more sophisticated instrument (Krider et al, 1980) operates with two or more direction finding stations, preferably located with separations of the order of 40 km. When the characteristic waveform associated with the first portions of a return stroke is detected at a DF station, the azimuth angle to its source and its time of occurrence are recorded. When the two stations are connected by a communication link, it is possible to combine the two azimuths and to triangulate directly on the location of the ground strike position. The lightning "track" of a storm can thus be detected, located and followed well in advance of its arrival in the vicinity of interest. Its lightning activity can be monitored by observing the frequency and intensity of the discharges. The "false alarm rate" with this system can be lessened below that of the omnidirectional lightning counter by the ability to follo. storm tracks by their lightning "footprints".

The accuracy of ground strike location is estimated as being of the order of 2km @ 50km range. A discussion of the principles of operation of this system and examples of the outputs is given in Krider et al. (1980). It should be noted that there is already

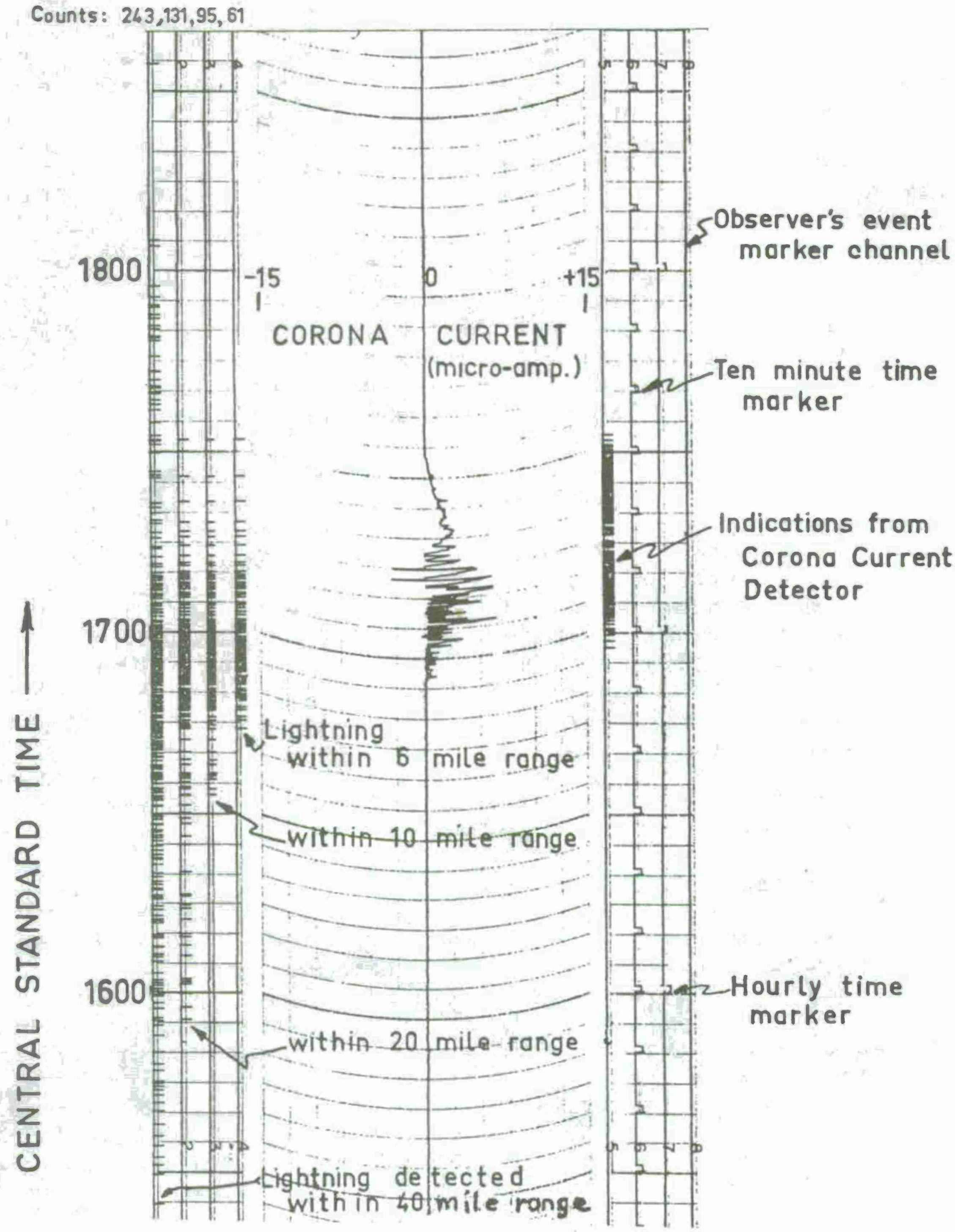


FIGURE 28. CHART RECORD FROM DETECTOR OF ATMOSPHERIC ELECTRIC DISTURBANCES AT SCOTT AIR FORCE BASE, ILLINOIS, FOR MAY 22, 1964, DURING PERIOD WHILE A DISTANT THUNDERSTORM DEVELOPED AND APPROACHED, PASSING OVER BELLEVILLE, ILLINOIS

a network of these detectors in place that cover about 40% of the total land area of the United States.

B. Detection of Locally Developing Storms

No helpful warnings are provided by a system that operates on the detection of distant lightning when a cloud directly over the site of interest becomes electrified and produces its first discharge overhead. For this circumstance, a different type of electrical detection instrument is needed. An acceptable device should measure some property of the local atmospheric electric field, should provide indications when hazardous conditions have developed and then should indicate how they are intensifying, all in advance of the first lightning discharge. There are at least three different types of instrumentation for detecting the onset of electrification in a nearby cloud:

1. Measurement of the local electric field by determining the displacement currents induced by a conductor moving in the electric field (e.g. an electric "field mill").

2. Measurement of the electrical potentials developed in the atmosphere by the electric fields.

3. Measurement of the point discharge currents induced by the electric fields.

We will discuss each of these briefly, but first we consider the electric fields in the lower atmosphere.

C. Electric Fields In The Lower Atmosphere

The earth carries a net negative charge of about -450,000 coulombs. In regions far from electrified clouds, this charge produces a downwardly-directed electric field of about 130V/m in the atmosphere just above the surface of the earth. (The direction of the electric field is defined as the direction in which a positive charge would move when placed in that field.) When electrified clouds develop, they usually have a net negative charge in their lower regions. The electric fields produced by this cloud charge often become so intense that they dominate the earth's field so that upwardly directed electric fields are usually observed at the earth beneath electrically active clouds.

The typical sequence of electric fields observed at the earth beneath a stationary thunderstorm is shown in Figure 29. With the development of electrification in the cloud, the field polarity reverses from the fine-weather, downwardly directed sense to the foul weather, upwardly-directed one. Initially, the foul weather field increases exponentially in strength, doubling its intensity every two minutes or so. When the field strength exceeds 3000 V/m or so, point discharge commences, causing an electric ion current to flow into the air from conductors exposed to the electric field. These ions constitute a space charge that opposes the

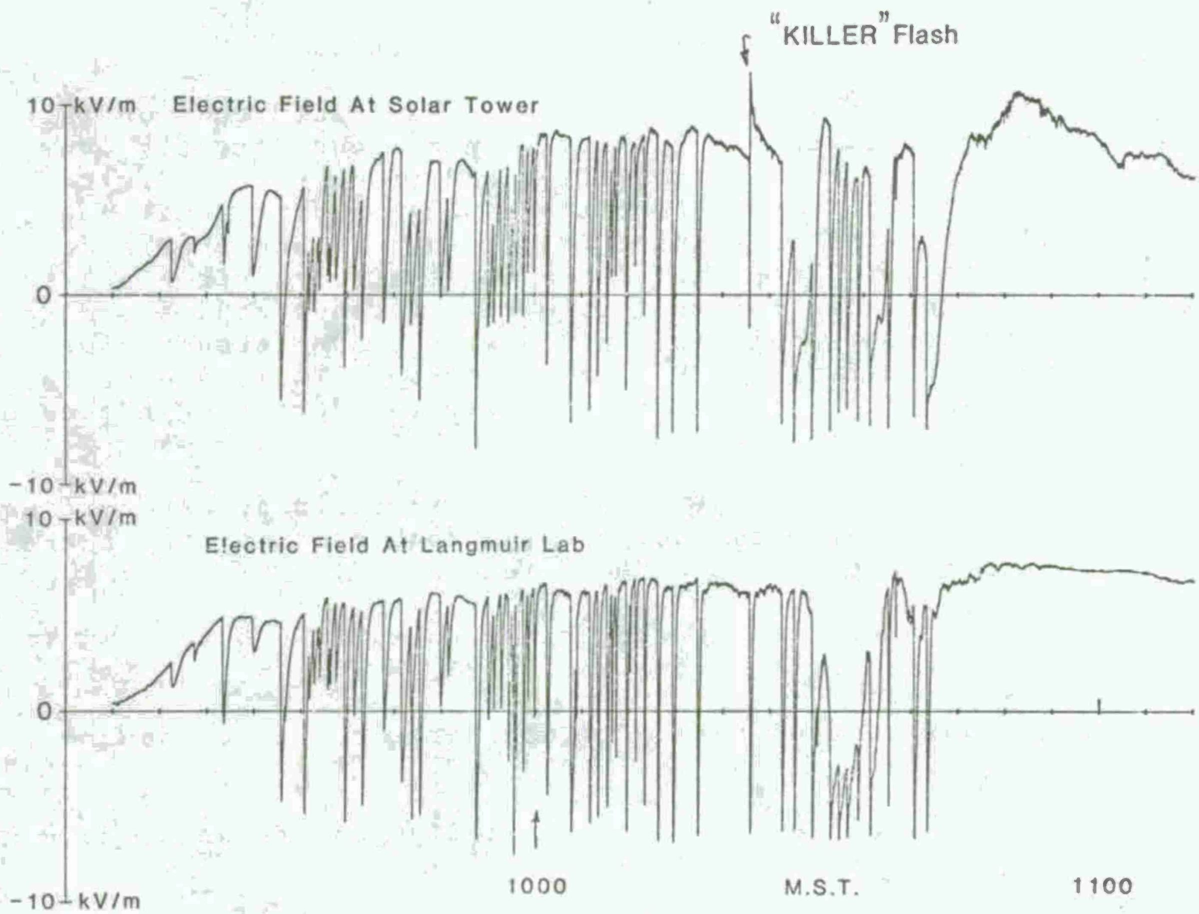


Figure 29

Electric field recordings at two stations separated by 1.8 km beneath a thundercloud on August 7, 1979.

An upward-directed electric field indicates an upward electric force on a positive charge in the field; this is the foul-weather polarity for the field. The discontinuities in the recordings are field changes due to lightning.

field intensification. Thereafter, the surface electric field intensifies more slowly than does the field aloft as more and more ions are emitted. Finally, a surface field strength is reached at which the resulting ion current just balances the increases in field strength aloft. The fields aloft may reach strengths in excess of 150 kV/m and often culminate in production of a lightning flash but the surface fields are usually limited to values of less than 15 kV/m by the space charges in the subcloud layer.

The sharp discontinuities shown in Figure 29 are the result of lightning transport of negative charge away from the cloud overhead. The electric field reverses polarity for a short time after each discharge, briefly showing the effect of the positive point discharge ions in the subcloud region. The field then rapidly recovers to its pre-discharge polarity and intensity as the electrification processes continues in the thundercloud.

The surface electric fields thus indicate the presence of electrified clouds aloft and the occurrence of lightning discharges but, after the fields become strong enough to induce point discharge, the measured surface fields may grossly under-estimate the strong electric fields aloft.

When a growing cloud becomes electrified, its electric field can be detected before the cloud produces its first lightning and we now turn to a discussion of suitable instruments for this purpose.

D. Electric Field Measurements

An instrument known as the "electric field mill" measures the strength and polarity of the local electric field by use of a periodically exposed, fixed electrode coupled to earth through a sensitive ammeter. The periodic exposure is provided by a grounded rotor that alternately shields, then uncovers a static fixed electrode, the "stator". The charge induced in the stator by the external electric field is released when the rotor shields the stator so that an alternating current flows between the stator and the earth. This current is often measured in an operational amplifier arranged as an ammeter. A comparison of the phase of the current maximum relative to the position of the rotor provides the field polarity information.

The data shown in Figure 29 were obtained with a field mill and a strip chart recorder. Interesting electric field sequences can be observed in these recordings during disturbed weather, with observations of the onset of electrification, the passage of storm cells, the field discontinuities caused by lightning and other electrical perturbations.

The presence of electrically disturbed weather patterns are clearly indicated with this instrument but, since point discharge effects limit the field strength at the earth, little information on the imminence of lightning can be extracted from surface measurements of the electric field, prior to the first flash.

Since an electric field mill has moving parts and exposed insulators, it requires maintenance, periodic cleaning of the insulators and replacement of the motor bearings.

Electric field meters are valuable scientific tools for the study of atmospheric processes and they would be useful to a Safety Director evaluating the development of a storm over an ordnance plant, but they may be too specialized and furnish more information than is needed in most industrial operations.

E. Electrical Potential Measuring Equipment

A less fundamental device for atmospheric electrical measurements consists of an exposed ionizer (such as a Staticmaster polonium source) suspended on a good insulator and connected to a high resistance voltmeter. The ions created at the surface of the exposed polonium source will allow any free charges there to be liberated and to flow into the air where they are carried away by the wind. As a result, the ionizer will come to the local potential of the surrounding air and this potential relative to the earth can be measured by a high resistance voltmeter.

Since the potential difference that is measured is the integral of the atmospheric electric field over a fixed geometry, the potential gives a measure of the average electric field existing between the earth and the ionizer. A schematic diagram of this system is shown in Figure 30. This system begins to depart from accurate representation of the field character when the potential differences exceed 10 kV or so. Local point-discharge effects in the measuring circuit then contribute more currents than the ionizer can liberate. The system is less reliable in dead calms than it is in strong winds, for similar charge transport reasons.

In the use of this system, it is imperative that the insulator used have resistances to leakage in the excess of 10^{13} ohms and the input resistance of the voltmeter should be at least 10^{12} ohms. The polonium probe needs to be renewed at least yearly for the half life of polonium is of the order of 120 days and it decreases its current-liberating ability by at least a factor of 8 each year. Suitable polonium sources are available commercially without requiring special licenses; these are not hazardous to humans in the proposed application as long as the source is not ingested by humans or held for long periods within 10 cm of skin tissue.

With this system, it is usually desirable to provide a periodic "electrical" short on the voltmeter input so that the zero field position on the recording can be known: The high-input resistance voltmeters needed here utilize high-gain amplifiers so that zero "offsets" often develop in their output.

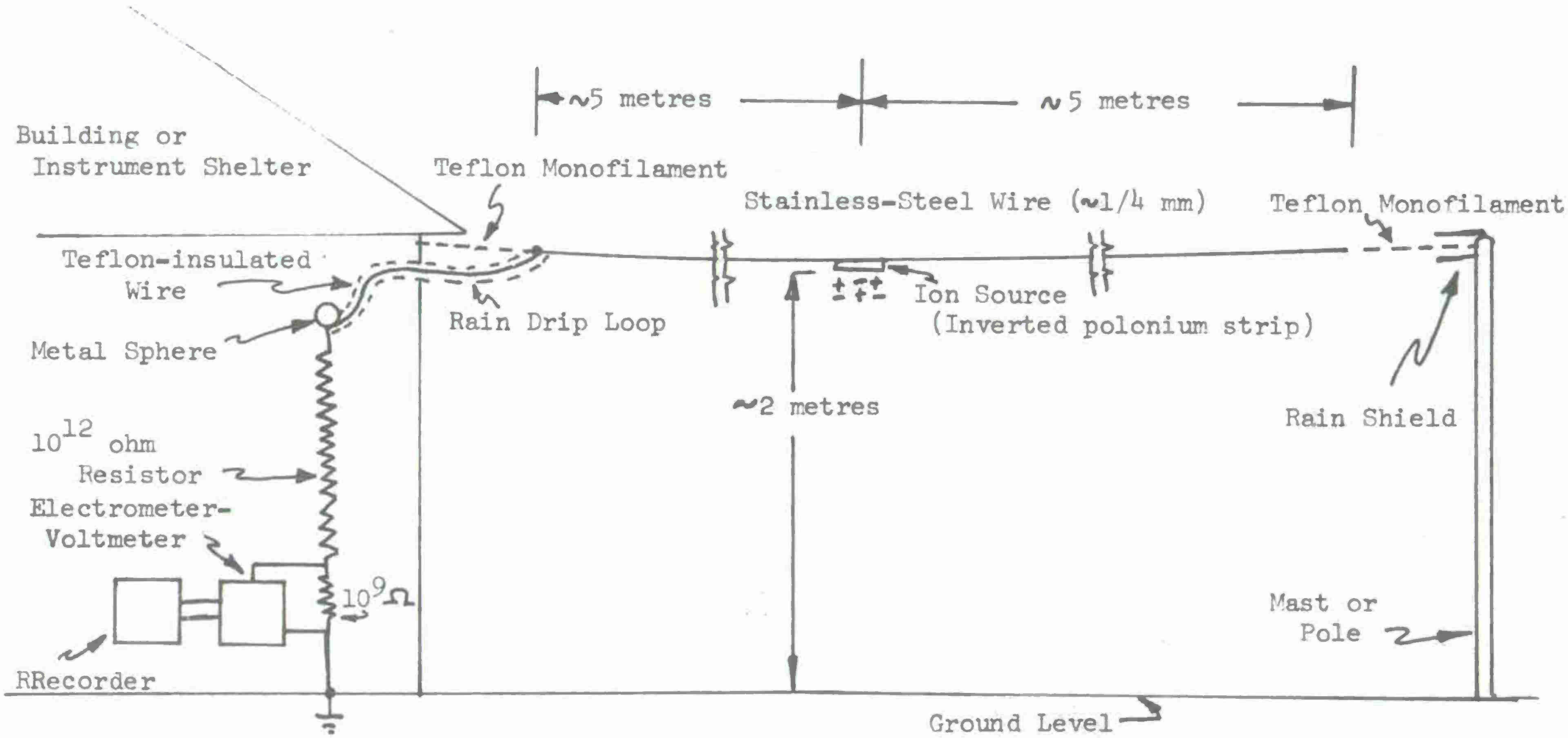


Figure 30

Illustration of technique for measuring the atmospheric electrical potential gradient near the surface of the earth. This technique produces recordings similar to those shown in Figure 31.

This system for observing the character of the earth's electric field has no moving parts other than the zeroing arrangement and is much less expensive to operate than is an electric field meter. A suitable electrometer-voltmeter can be arranged to provide a strip chart record that will be quite similar to the records provided by a field mill. The same interesting structures in the atmospheric electric fields can be observed with the potential measuring system as with the electric field mill and the limitations and interpretations of disturbed weather electrical phenomena are about the same, but the high impedance necessary is a definite drawback for an operational field instrument to be used by non-physicists.

F. Measurement of Point Discharge Currents

The electric fields at the top of a sharpened metal rod exposed to the atmosphere can become so intense that local ionization occurs and an electric current flows into the air. The value of the current depends on the strength of the atmospheric electric fields, on the exposure, height and tip curvature of the rod and on the speed of the local wind past the tip. The onset of current from a well-exposed, sharp rod located about 2 meters above surrounding objects occurs when the ambient electric fields exceed strengths of the order of 3000 V m^{-1}. This threshold provides a useful natural indication of the onset of potential electrical hazards. It is possible to use the onset of point discharge to sound an alert and to turn on recording equipment that displays the subsequent point discharge currents. An example is shown in Figures 28 and 31.

If a positive current flows (positive charge moving upward from the point) and if it continues to increase, the possibility of lightning in the vicinity increases and so, use of the value of the point discharge current may provide the simplest and most effective means of detecting and monitoring the local atmospheric electric hazards.

Negative current flowing from the point indicates the presence of positive charge overhead. This commonly occurs when an anvil cloud from a distant thundercloud moves over the observing site. Lightning strikes to earth occur less frequently from these clouds which are, therefore, less hazardous.

The use of point discharge currents over measurements of electric field strength or of electric potential has the advantage that when the electric fields aloft are intensifying toward electrical breakdown and production of lightning, the point discharge currents at the earth increase somewhat similarly and act to limit the field strength at the earth. For this reason, point discharge currents sometimes give a better indication of the imminence of lightning than can the measurements of the surface electric field.

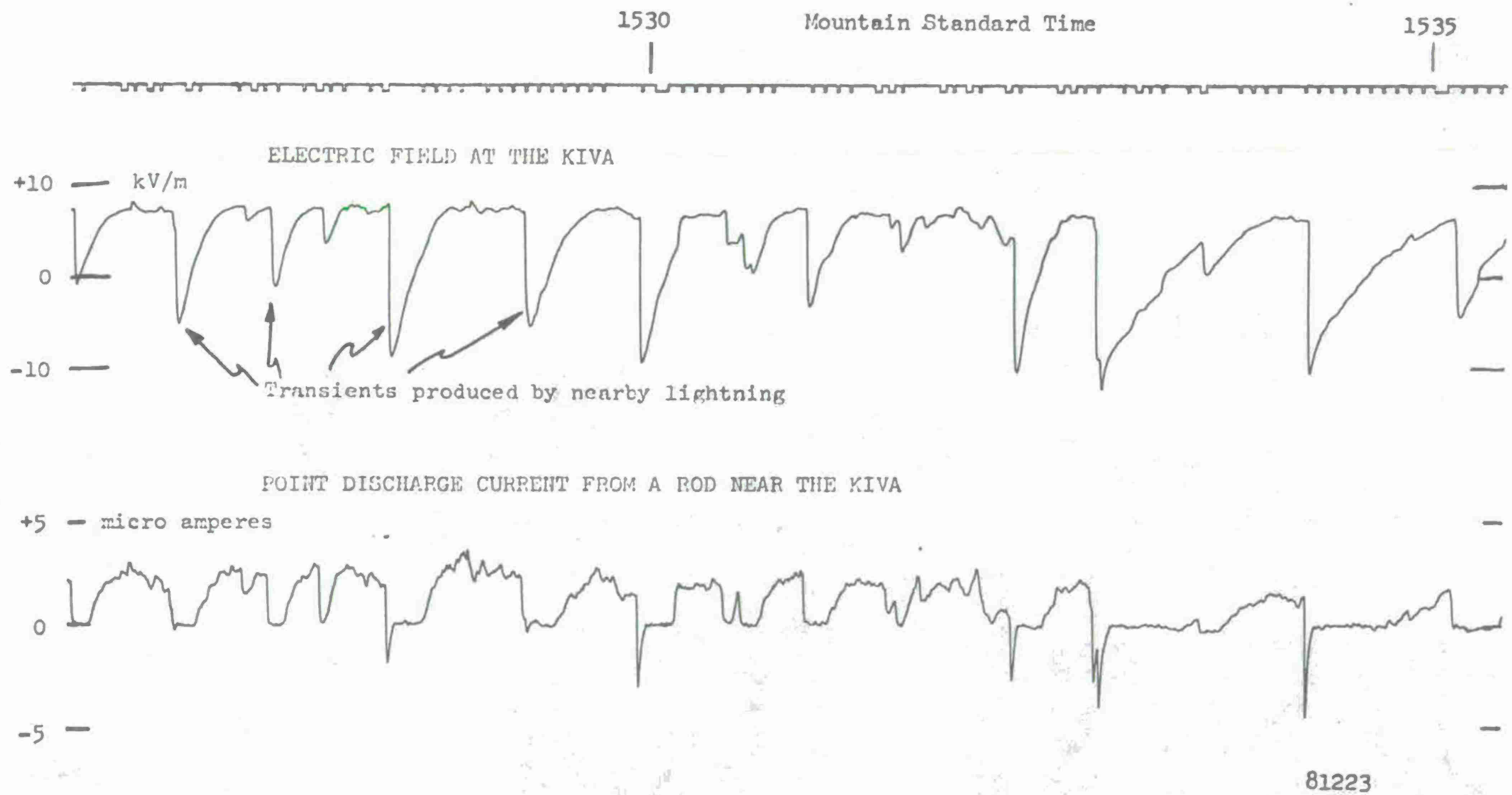
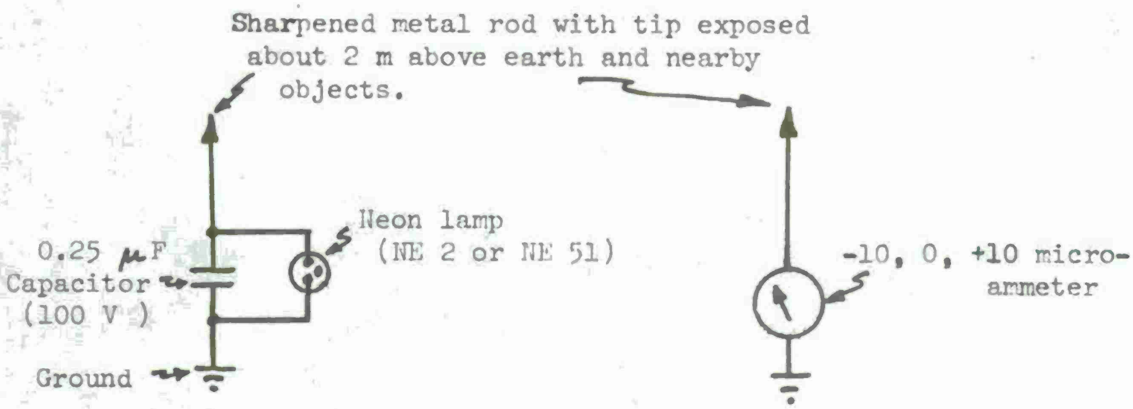


Figure 31

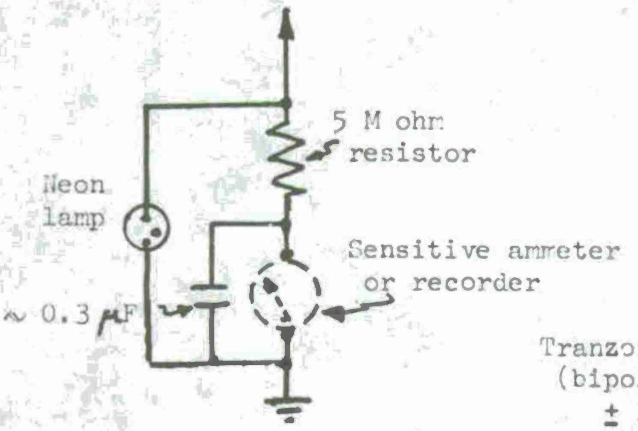
A comparison of simultaneous recordings of the atmospheric electric field strength and the induced point discharge current.
Note the period of zero current during the field recovery after each lightning when the field strength was below the point discharge threshold level. Note, also, the decrease in corona current as the recoveries after lightning became slower (as the storm vigor decreased).



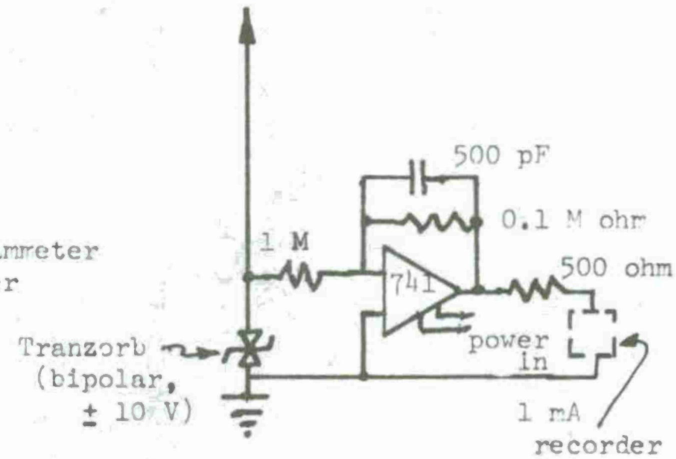
SIMPLE CIRCUIT FOR DETECTION OF STRONG ELECTRIC FIELDS.

The frequency of lamp flashing gives an indication of field strength.

SIMPLE CIRCUIT FOR DIRECT MEASUREMENT OF POINT DISCHARGE CURRENT AS AN INDICATOR OF STRONG FIELDS.



A SENSITIVE POINT DISCHARGE CURRENT METER OR RECORDER PROTECTED AGAINST LIGHTNING INDUCED TRANSIENTS.



CIRCUIT FOR AMPLIFICATION OF POINT DISCHARGE CURRENTS SO THAT THEY CAN BE RECORDED ON INEXPENSIVE, INSENSITIVE, MILLIAMPERE RECORDERS.

Figure 32 Circuits using point discharge to indicate occurrence of strong, atmospheric electric fields.

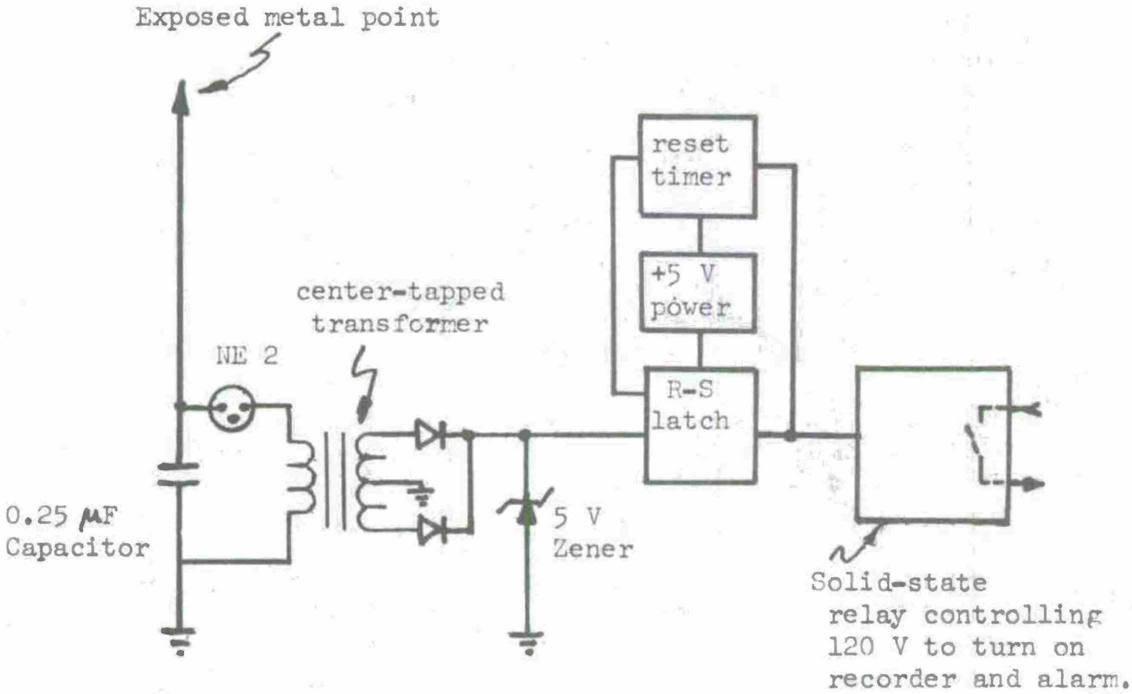


Figure 33

CIRCUIT FOR DEVICE TO ACTIVATE ALARM AND RECORDER UPON ONSET OF POINT DISCHARGE CURRENTS FROM THE EARTH UNDER INTENSIFYING ELECTRIC FIELDS. This device will give its first warning about 20 seconds after the onset of point discharge under a field strength of about 3 kV/m (depending on the height and exposure of the pointed rod). Soon thereafter, warning pulses will occur about every 5 seconds. The reset timer may be arranged to "stretch" the first warning and activate a recorder for a 10 or 15 minute period so that the trend of the storm can be studied. At the end of the reset period, the timer can rest and await another onset of point discharge. The timer, on the other hand, can be used to "stretch" the warning pulses just enough to activate a repetitive alarm that sounds once for each time the neon lamp flashes.

IX. GENERAL RECOMMENDATIONS

We believe that the lightning protection standards and practices in the Department of Defense Ordnance plants can be improved by the application of the following recommendations listed in approximate order of priority. In our view, all of these recommendations are worth implementing for achieving improved lightning protection of explosives handling facilities.

A. Installation of lightning protection, surge suppressors and transient barriers on all power, signal, control and communication lines coming from or going to each building where explosives are handled or stored. In installations involving computer control lines, optical isolators should be utilized on both ends of all lines going in and out of the facility. Examples of recommended installations are shown in Figures 34, 35, and 36.

B. Use of, suitably spaced, overhead grounded wires above all overhead wires entering or leaving each facility. Recommendation A and B are particularly appropriate for the protection of computer controlled facilities and for intruder alarm systems.

C. Development and testing of improved air terminals. We believe that the present hardware designs for conducting lightning strikes to earth can be improved and we recommmend that various air terminal configurations be investigated. It appears to us that adequate, overhead wires connected to earth through low impedance conductors may give better protection than do isolated, sharpened rods. Some optimum configurations for differing situations should be designed, tested, and specified as standards after their transient responses have been evaluated and optimized with modern instrumental techniques.

D. Improvement in the connections between air terminals and the earth. The 8 inch minimum radius of curvature rule and the prohibition against changes of more than 90° in down-conductor direction should be strictly enforced. Dynamic methods of testing the current-carrying abilities and the surge impedances of the connections from the air terminal to earth are greatly needed. Use of dendritic, "treed" grounds should be encouraged and every effort should be made to avoid turns and loops in down-conductors. Periodic testing, inspection and maintenance of ground connections should be emphasized.

E. Use of Lightning Warning Instruments

Devices that provide advance warnings of atmospheric electric hazards to operations involving explosives and volatile fuels should be developed, tested, standardized, installed, and used. Two different types of instruments should be developed:

1. A device that gives an indication of developing or existing local hazardous electrical conditions should be required at each potentially dangerous facility.

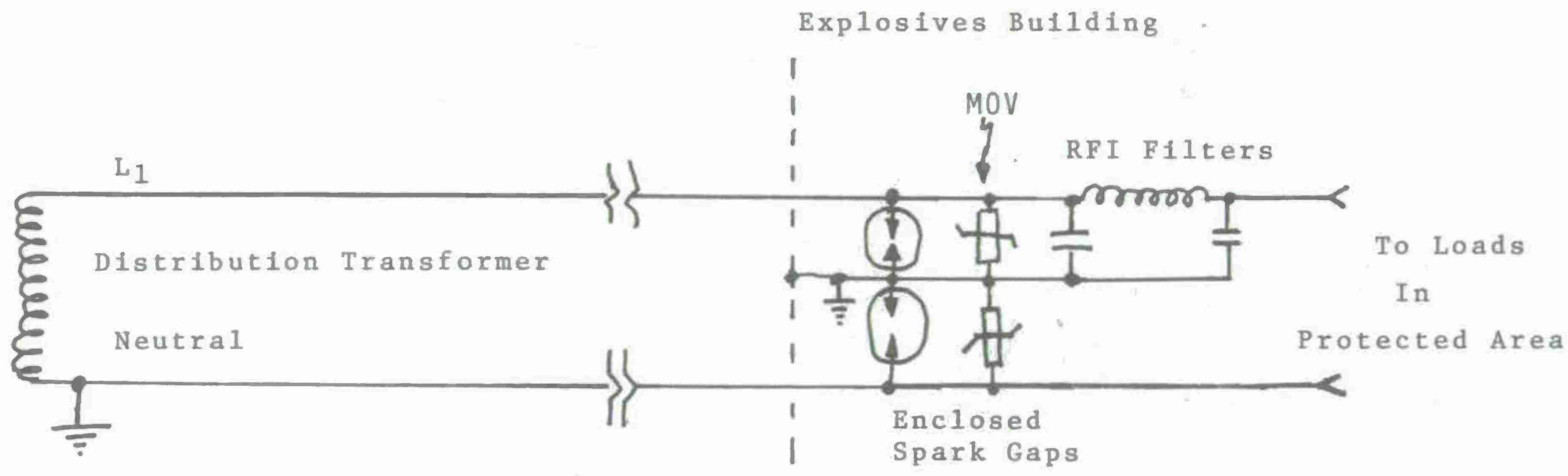


Figure 34 Minimum recommended transient suppression for secondary power distribution systems in explosives plants.

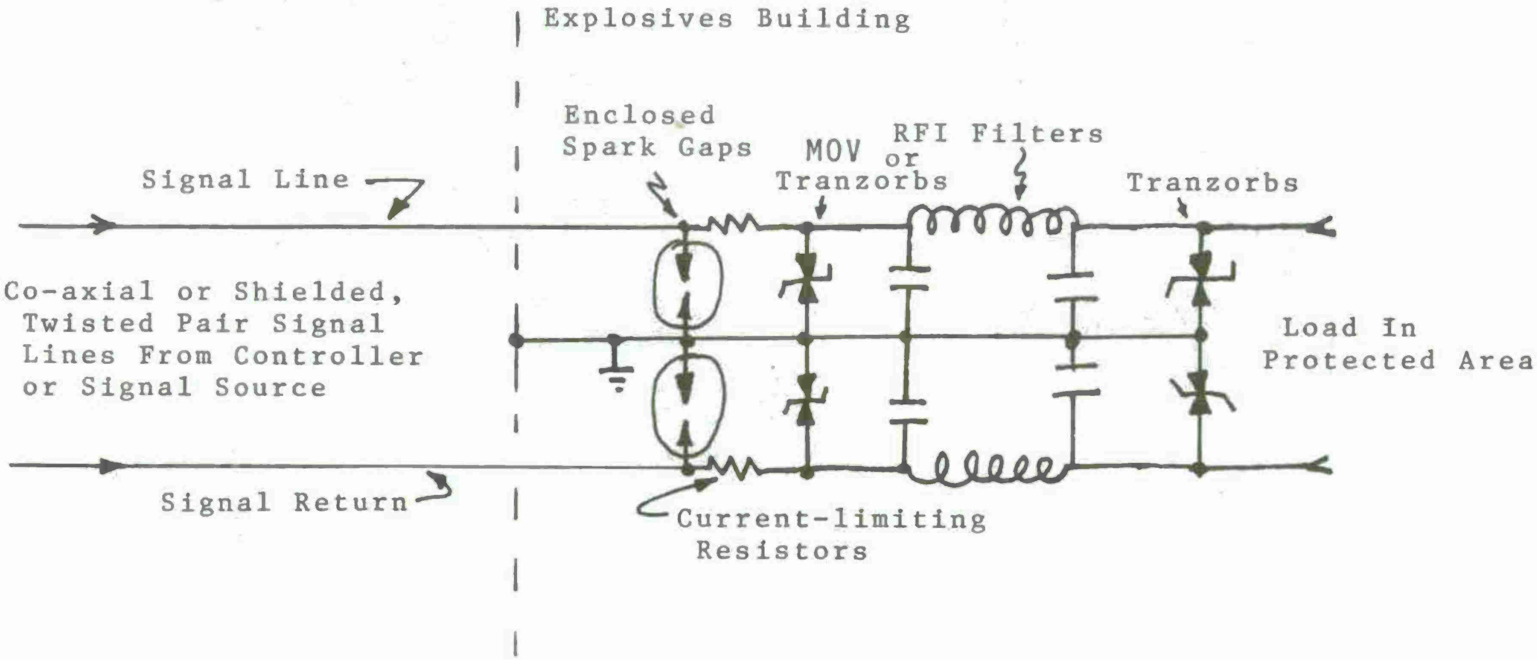


Figure 35 Recommended transient suppression for control signals entering explosives building.

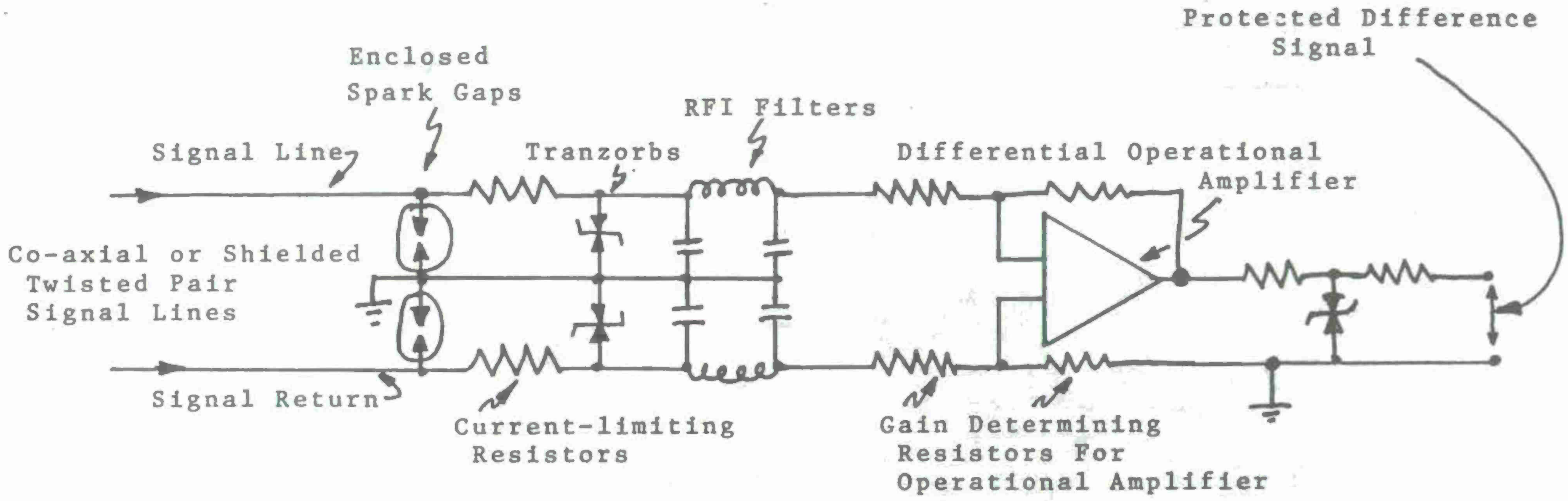


Figure 36 Recommended use of a differential amplifier to shift reference grounds and to avoid transient impacts by ground loops.

2. An electric field-change-sensing instrument for detecting, warning of, and counting, local lightning discharges.

Other devices that detect the approach of distant thunderstorms are recommended as optional, to be used when this information is needed and can be justified. A discussion of these warning instruments and techniques is included in Section VII.

Operations with explosives should be terminated whenever lightning occurs within a 8 km (5mi) range and the flash-to-thunder time is less than 24 sec.

F. Construction of Faraday-cage, multiple shields for protection against lightning for operations with sensitive electro-explosive and related devices. Procedures for essentially absolute protection are described in Section VII.

G. Testing of the effectiveness of various lightning protection systems and air terminals using fast response instrumentation and exposure to either a lightning simulator or to real lightning in an area with frequent thunderstorms.

H. Development of new standards for lightning protection

After these recommendations for improved lightning protection have been explored and implemented, we suggest that the present standards for lightning protection be extended to include the appropriate improvements, and after that, a new, unified DOD lightning protection code be adopted. Part of this unified code should specify the hazardous distances for lightning as a function of the lightning protection at a given operational site.

I. Set up review procedures to ensure adherence to the principles of lightning protection in all add-on wiring, telephone lines, power supplies, signal and central lines entering or leaving explosives facilities. (The Safety Officer should be in the "Work Order" loop).

We note that in general, lightning arresters in power distribution systems and in telephone lines are supplied by the utilities for the protection of their own equipment. No attempt by the utilities is made to protect the using subscriber. Surges in excess of 20 kV can pass into a facility serviced by some of these utilities and therefore, the responsibility for protection against the effects of lightning coming in on external wiring is the responsibility of the user.

For this reason, all modifications to the wiring to and from explosives facilities should be reviewed for lightning protection adequacy by an appropriately trained Safety Director.

J. Establishment of a Lightning Safety Review Board to visit explosives facilities, to serve as a Lightning Protection Quality

Assurance Review Body, and to evaluate accidents arising from lightning strikes.

K. Resuscitation

Since the Lightning Protection Standards specify procedures by which the harmful effects of lightning can be minimized, they should also include information on how humans exposed to electric shock may be revived. The cardiopulmonary resuscitation technique has been quite effective in reviving a large number of people whose heart has stopped as a result of lightning and other electrical shocks. The lightning protection standards should emphasize this procedure, safety seminars that demonstrate it should be held, the lead personnel and as many people involved as possible should be indoctrinated in it, and posters illustrating the technique should be prominently displayed in all locations where electric shock can occur.

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