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LIGHTNING PROTECTION FOR TRAFFIC CONTROL SYSTEMS

Prepared with support from the

National Aeronautics and Space Administration

by Lightning Technologies, Inc.
for Public Technology, Inc.

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by

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Lightning Technologies, Inc.
Pittsfield, Massachusetts

for

Public Technology, Inc.
Washington, D.C. and Pasadena, CA

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Introduction

This handbook presents guidelines for improvement of lightning protection for highway traffic control systems. It is intended for use by traffic engineers and others concerned with elimination of troublesome lightning problems in existing systems, and by the designer and procurer of new systems.

The need for such a handbook stems from the expanded use of sophisticated electronics which are more sensitive to the electrical transients produced by lightning than earlier electromechanical systems. Other users of solid-state electronics have also had to deal with problems due to lightning strikes. It was learned early in the space program, for example, that the electronics necessary to launch a space vehicle could be vulnerable to upset or damage from nearby lightning strikes, as might the sensitive electronic controls and flight instruments being incorporated into modern aircraft. Since safety of flight depends on proper operation of this equipment, the consequences of failure due to lightning might be very serious.

Thus, protection of aerospace electronics against failure due to lightning has been the subject of National Aeronautics and Space Administration (NASA) research into the nature of lightning and the ways it interacts with sophisticated electronic systems. This research, which began in the early 1960's, has continued until the present and represents the most thorough analysis of lightning effects yet conducted. This research has led to a clearer understanding of the *indirect* effects of lightning; that is, the ways in which a nearby lightning strike (as well as a direct hit) can cause damage to solid-state electronics. Protective measures derived from this research have been incorporated into the design of aerospace electronics and have contributed to the extreme reliability and safety of all of the U.S. space missions. This technology has also made its way into modern commercial airliners, where reliance upon electronics for safe flight under adverse weather conditions has become routine.

Under the NASA Technology Spinoff program, Public Technology, Inc. (PTI) has been involved in identifying technology needs in municipalities that can benefit from NASA experience. As part of that program, PTI arranged with the authors to diagnose lightning problems in traffic control systems and apply technology derived from the NASA research to solve these problems. To focus the project on the most important problems, a User Requirements Committee (URC) of municipal traffic personnel from nine cities and one representative each from the National Electrical Manufacturers' Association (NEMA) and the International Municipal Signal Association (IMSA) was formed.

With participants from the URC and PTI, the authors visited six representative municipalities to study traffic system lightning problems and electrical practices. These site inspections indicated that lightning protection ranged from adequate to none at various locations. More significantly, the survey also revealed that in this industry there are no well-defined requirements or *standards* for lightning protection, and no criteria defining the responsibilities of equipment manufacturer and user.

Using the information gathered from the fact-finding inspections and experience developed from NASA research, the authors determined the probable cause of the several types of problems found to be related to lightning. Protective measures were then selected for each type of problem. The results of this project are presented in the following four chapters.

Chapter 1 contains a brief discussion of natural lightning, along with the necessary data to estimate the number of lightning flashes to hit a given structure or geographical area at various locations in the U.S. Additional strike data is presented in the Appendix.

Chapter 2 describes the ways that lightning interacts with highway traffic control systems, and the mechanisms by which the most common problems occur. An understanding of these mechanisms will be helpful to the traffic engineer who must decide where to apply protective measures and the designer of a new controller, who must know what magnitude of surges to expect on incoming power and signal lines.

In Chapter 3, guidelines are presented for protecting specific parts of traffic control systems that are already in existence. Chapter 3 begins with a review of protection *approaches* by defining the roles of surge suppression, shielding and grounding. Specific recommendations for adding lightning protection to each of the elements of a typical system follow.

Chapter 4 presents specifications covering the procurement of new equipment. The Transient Control Level (TCL) philosophy is introduced as a means of defining and specifying expected transients for specific types of equipment. Recommended test procedures and test levels are given for each type.

To some extent each chapter stands alone and may be utilized by itself in designing protection. However, for the greatest probability of success, the user is encouraged to read each of the chapters. The authors will welcome comments and reports of experiences from those who utilize these guidelines, or notification of any errors that may have been overlooked in the text.

An *Executive Summary* to this publication, written for elected officials and appointed administrators, is available from Public Technology, Inc. The *Summary* provides a brief general overview of the NASA/PTI Technology Applications Program, the contents of this publication, and an order form.

LIGHTNING PROTECTION
FOR TRAFFIC CONTROL SYSTEMS

CHAPTER 1 Natural Lightning

1.1 LIGHTNING FORMATION

A lightning flash is a very long electrical spark which extends between one center of electrical charge in a cloud and another center of opposite polarity charge in the ground, in another cloud, or sometimes even in the same cloud.

The energy that produces lightning is provided by warm air rising upwards into a developing cloud. As the air rises, it becomes cooler and its water vapor condenses into droplets which then freeze into hailstones which are heavy enough to fall through the cloud, gathering water droplets as they do so. According to one theory, as these droplets freeze onto a falling hailstone, small splinters of ice chip off, carrying away with them a positive charge and leaving the hailstone with a negative charge. The vertical air currents carry the positively charged ice splinters to the upward part of the cloud, while the negative hailstones fall toward the base of the cloud. The cloud-base therefore acquires a negative charge and the top, a positive charge. The air currents and electrical charges tend to be contained in localized cells, and there may be several such cells in a single cloud. This charging process may take only a few minutes after the birth of the active cloud, and the total life of the cloud may be only 20 minutes or so.

The electric field around these charge cells is very intense and when sufficient charge has accumulated, this field may be strong enough to *ionize* the air, creating a luminous spark which jumps outward in a zig-zagging luminous column of ionized air called the *stepped leader.* Some of the charge from the cloud flows into this leader and when it begins, the leader moves in the general direction of the ground, but it does not "know" where it will finally strike. There may be several possibilities, and the leader frequently splits into several *branches* on its way, as happened in the flash of Figure 1.

As the leader approaches the ground, the electric field at the ground is intensified and sparks called *streamers* emanate from protruding objects

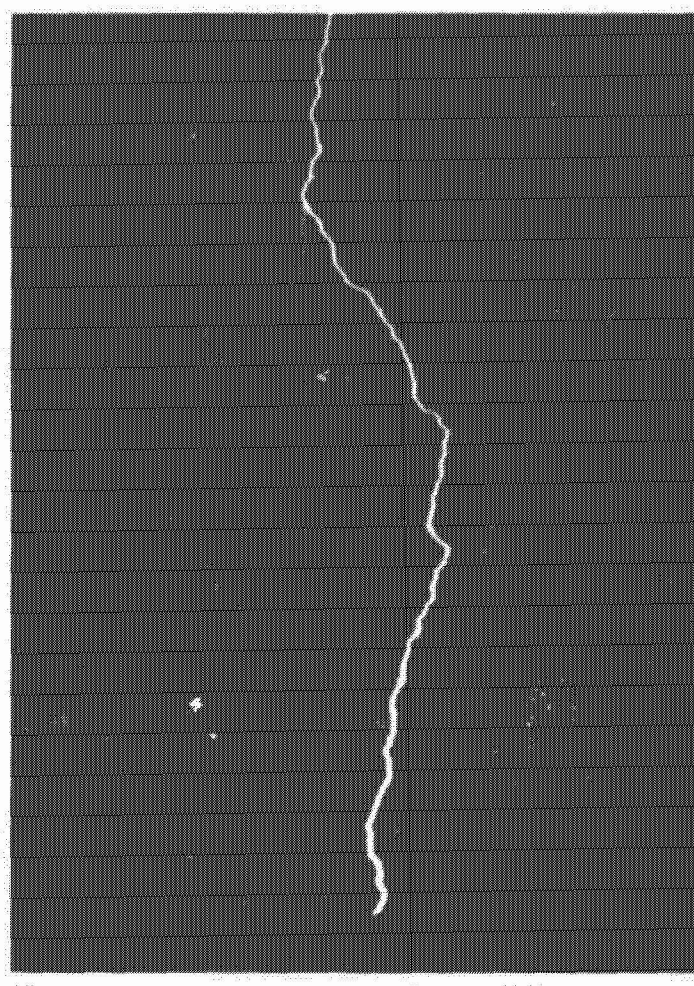


Figure 1. *Photograph of a Cloud-to-Ground Lightning Flash.*

such as utility poles, trees and buildings, and propagate upward to meet the downcoming leader. When they meet, opposite polarity charges from the earth rush into the leader, neutralizing the charge in it from the ground up. This surge of current is called the *return stroke* and it creates the bright flash and loud noise associated with lightning. Figure 2 illustrates the process just described.

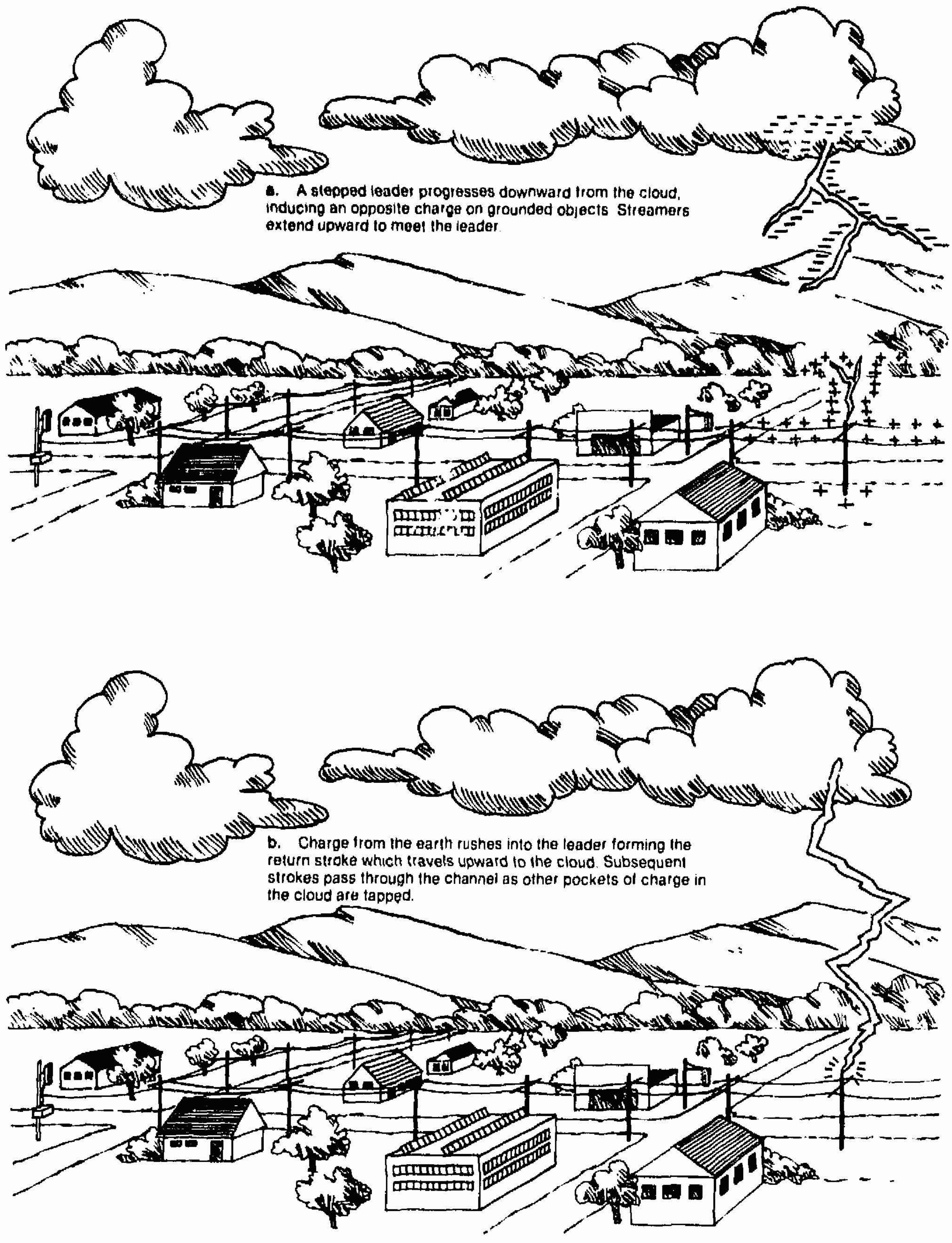


Figure 2. *Development of a Lightning Stroke.*

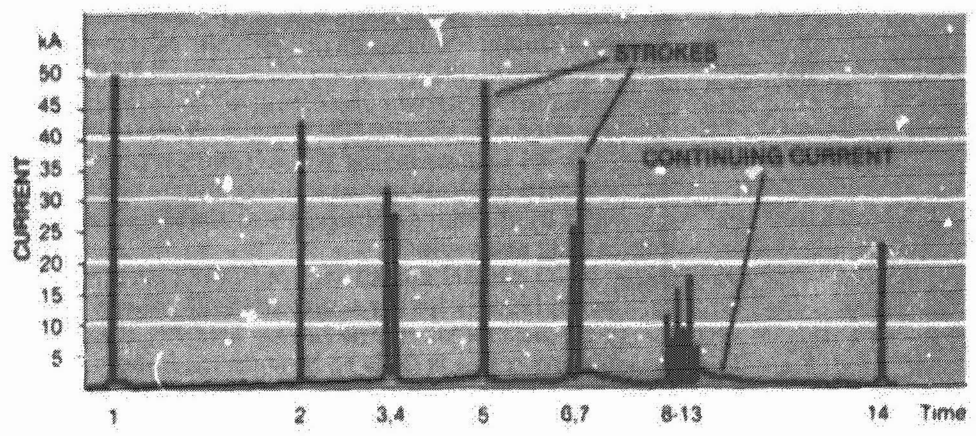


Figure 3. *Currents in a Multiple-Stroke Lightning Flash.*
- *14 Individual Strokes (numbered above)*
- *Total Flash Duration ~0.7 second*

When the return stroke is complete the original charge center in the cloud is connected to the earth by the conductive channel. Other pockets of charge located in the same cloud (or in a nearby cloud) jump to the first center and follow the established channel to earth. Subsequent discharges like this are very common and are called *restrikes*. Between successive strokes the channel is kept alive by drainoff of residual charges from the cloud. The currents that flow during this period are called *continuing currents*. The whole event may last up to one second and is referred to as the *lightning flash*.

If recorded on a linear time scale, the currents in a flash would appear as shown in Figure 3. The individual strokes may reach hundreds of thousands of amperes but last for less than one thousandths of a second, whereas the continuing currents reach only a few hundred amperes, but persist for nearly the entire life of the flash.

Much has been learned about lightning flashes from measurement of currents and photography of strikes to tall objects. Figure 4 shows a typical photograph of a multiple-stroke flash to the Empire State Building. In this picture, called a *Boys camera* photograph two lenses are employed. One lens is stationary and the other is rotated at one revolution per second, thus spreading out the flash to enable each of the short-duration strokes to appear separately on the film. An important implication of this is that objects "struck by lightning" are subjected not just to one stroke but to a series of strokes in rapid succession.

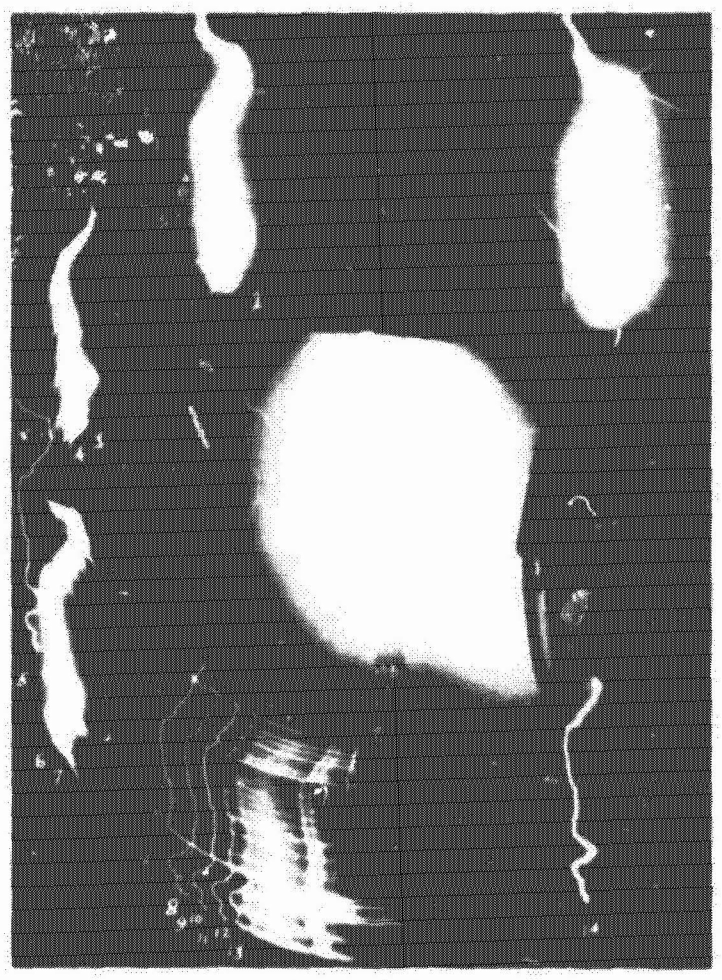


Figure 4. *Boys camera photograph of a lightning stroke to the Empire State Building. At the center is a still picture of all components of the flash superimposed on each other. The outside images are produced by a rotating lens and show the successive strokes (Nos. 1-14) separately. The blur between strokes is the continuing current. This is how the flash of Figure 3 might appear.*

1.2 ELECTRICAL CHARACTERISTICS OF LIGHTNING FLASHES

Most of the destructive energy produced in a lightning flash is delivered by the stroke current. The intense currents produce high overpressures

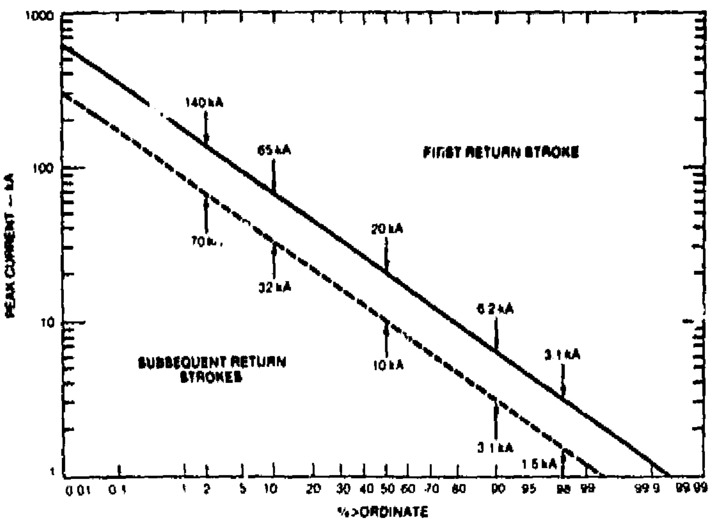


Figure 5. *Distribution of Peak Currents for First Return Stroke and Subsequent Strokes.* (from Cianos & Pierce—Ref. 1)

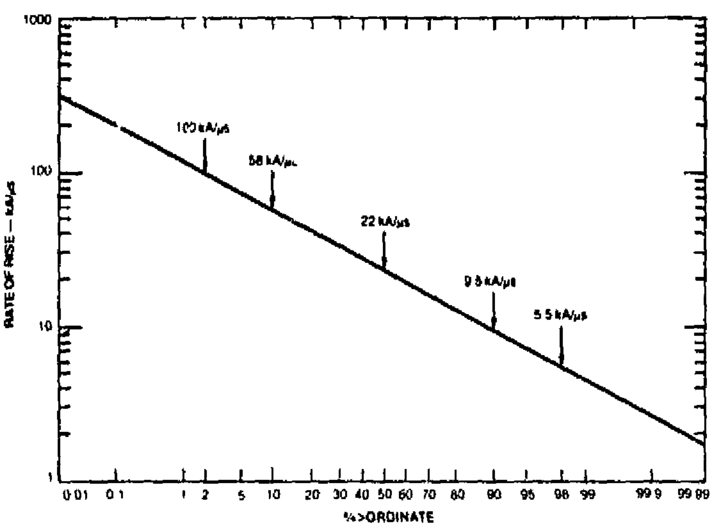


Figure 6. *Distribution of Rates of Rise* (from Cianos & Pierce—Ref. 1)

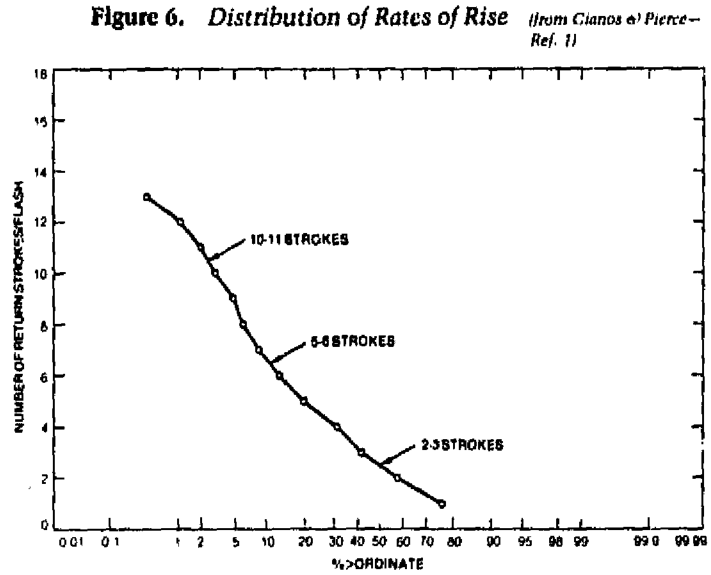


Figure 7. *Distribution of the Number of Return Strokes/Flash.* (from Cianos & Pierce—Ref. 1)

which may shatter concrete, glass, wood or other non-conductors, and their rapid rate of rise may cause high voltages to appear along conductors carrying these currents, resulting in "side flashes" to other objects nearby. The rapidly changing magnetic fields accompanying these strokes are also of concern to electronic systems which may be damaged by the surge voltages these fields induce in wiring and cables.

The lower amplitude continuing currents convey relatively little energy, and aside from localized melting where the hot arc attaches to metallic objects, there is little to be concerned about. Thus, the lightning parameters of most importance to traffic control equipment are **stroke amplitude** and **rate of rise**.

Many studies have been performed to measure the electrical characteristics of lightning. Cianos and Pierce (Reference 1) have collected much of the information from these studies into a complete set of statistics for use by the person concerned with protection of equipment on the ground. As with most other natural phenomena, they found a wide statistical distribution of magnitudes of these parameters. The distributions presented by Cianos and Pierce for stroke current amplitudes, rate of rise and the numbers of strokes per flash are reproduced in Figures 5, 6 and 7.

1.3 PROBABILITY OF GETTING STRUCK

Thunderstorms and lightning flashes do not occur with uniform frequency throughout the world, but vary instead with the climate and topography of particular locations. The only parameter related to lightning incidence for which world-wide data (Reference 2) accumulated over many years exists is the *thunderstorm day*. This data is accumulated by the World Meteorological Organization and is called the *isokeraunic* level. A thunderstorm day is defined as a 24 hour day on which thunder is heard. Thus, the parameter does not give information on the duration or intensity of the storm. For the United States, the isokeraunic level ranges between a low of 5 thunderstorm-days per year along the West Coast, to a high of 100 days on which thunder is heard in central Florida, as shown on the isokeraunic map of Figure 8. When used in the analysis that follows, this parameter is designated at T_y. Isokeraunic data for a large number of specific locations in the U.S. are presented in the Appendix.

Most observers agree that there are about 3 lightning flashes per minute in the average thundercloud and that a cloud covers about 500 square kilometers of ground for an average of between 1 and 3 hours. This works out to a *flash density*, τ_y, of between 0.3 and 1.0 flashes per square kilometer on each thunderstorm day. Actually, flash density

MEAN ANNUAL NUMBER OF DAYS WITH THUNDERSTORMS

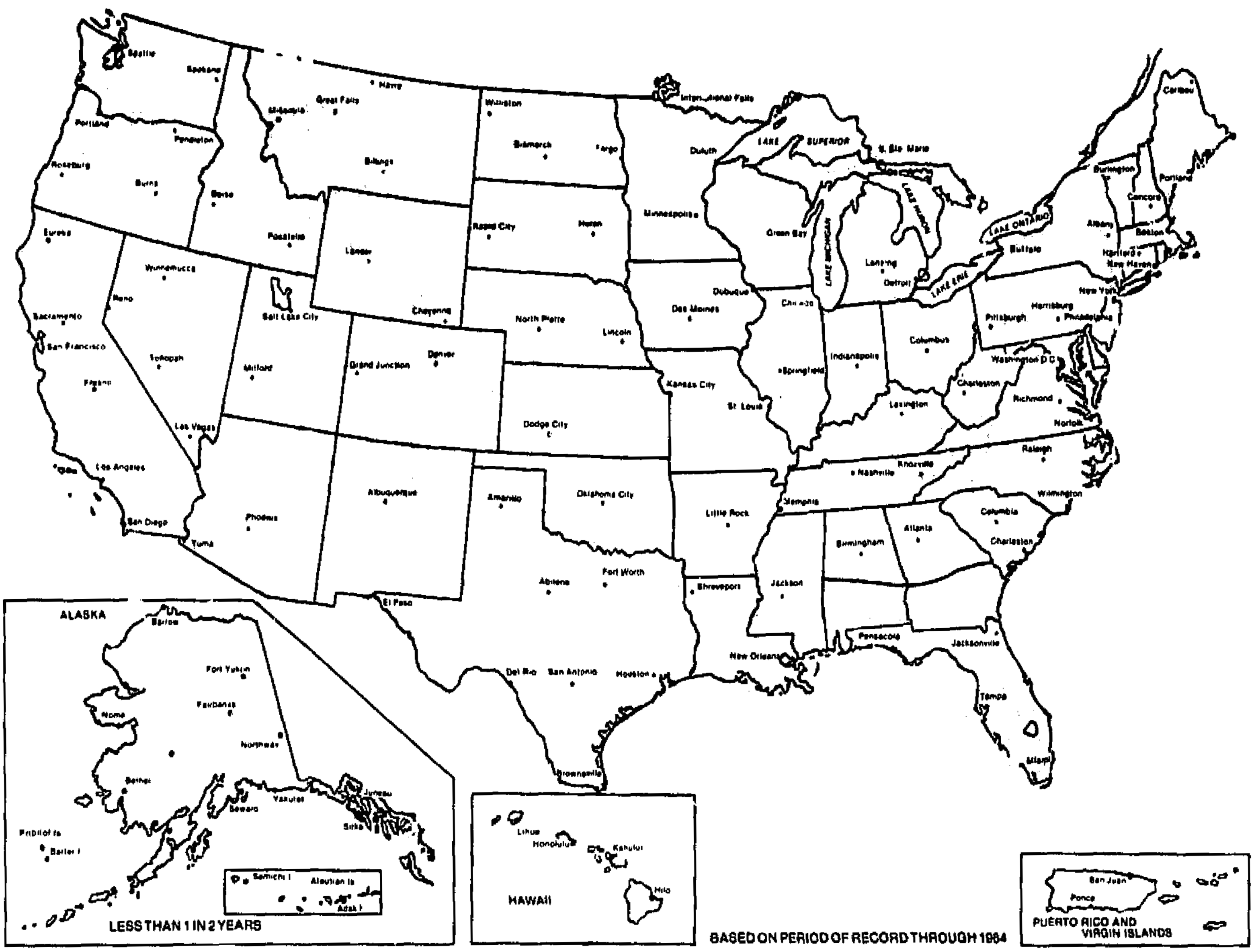


Figure 8. *Isokeraunic Map of the United States*
- *Annual number of thunderstorm days (T_y).*

City	Isokeraunic Level	Latitude	Total Flashes per Year per kM²		Flashes to Ground per Year per kM²	
			per kM²	per mi²	per kM²	per mi²
Miami, FL	70	26°	27.4	71.0	4.8	12.4
St. Petersburg, FL	85	28°	38.0	98.7	7.1	18.5
Montgomery, AL	54	32°	17.6	45.6	3.8	9.8
Savannah, GA	53	32°	17.1	44.2	3.7	9.5
Arlington, TX	48	33°	14.4	37.4	3.2	8.3
Oklahoma City, OK	45	35°	12.9	33.5	3.1	7.9
Raleigh, NC	41	36°	11.0	28.6	2.7	7.0
Washington, DC	35	39°	8.4	21.8	2.3	5.9
Lower Merion, PA	27	40°	5.4	14.0	1.5	3.9
Pittsfield, MA	29	42°	6.1	15.9	1.8	4.7
Albany, NY	2[illegible]	43°	4.1	10.7	1.3	3.3
Syracuse, NY	30	43°	6.5	16.8	2.0	5.1
Grand Rapids, MI	39	43°	10.1	26.3	3.1	8.0
Portland, OR	27	44°	5.4	14.0	1.7	4.4

Table I. *Lightning Flashes per Square Mile at Typical Cities in the U.S.*
(Note: Data for other cities in the U.S. are presented in the Appendix)

is related more closely to the square of the isokeraunic level, as follows:

$$\tau_y = 0.02 T_y^{1.7} \text{ flashes/km}^2\text{/year} \qquad (1)$$

Isokeraunic levels and lightning flash densities calculated from this equation for a number of typical cities in the U.S. are presented in Table I, expressed in flashes per square kilometer and flashes per square mile. Data for additional cities are presented in the Appendix.

The flash density of equation (1) includes flashes between clouds and flashes to ground. Both are of concern to traffic control equipment because changes in the potential of a cloud overhead may induce surges in power and signal lines beneath.

On the other hand, only those that reach the ground would be of concern with respect to physical damage to structures. Pierce (Reference 1) has noted that the percentage, P, of flashes to ground increases with geographical latitude and he has represented the latitudinal variation in equation (2) as follows:

$$P = 0.1[1 + (\lambda/30)^2] \qquad (2)$$

where λ is the geographical latitude in degrees. For the U.S., the percentage of earth-bound flashes ranges between 20% (in the South) to 36% (in the North). Equation 2 may be used to estimate the average number of times lightning may be expected to strike the ground within a given area.

Within a large area, lightning will strike higher objects such as radio towers, utility poles and rooftops much more frequently than objects that are shorter than these. It is well established, for example, that a conducting structure will divert the flashes to itself and keep objects within a radius equal to twice the height of this conductor from being struck if their own height does not penetrate the imaginary surface scribed between the tip of the structure and the ground twice the conductor-height away. This is the familiar *cone of protection* and is illustrated in Figure 9.

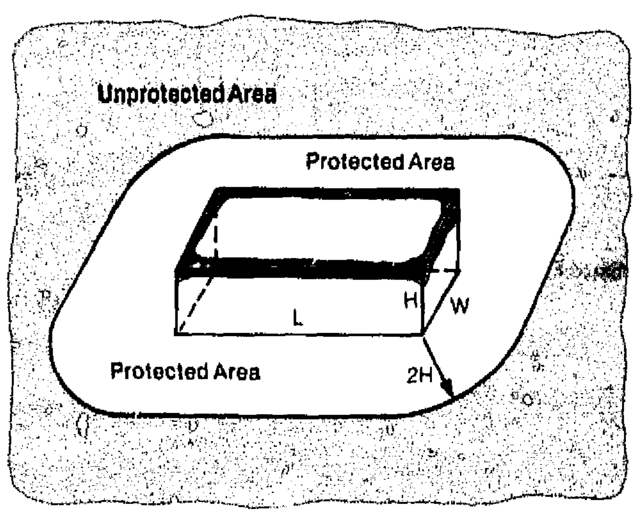


Figure 9. *Protected Area*

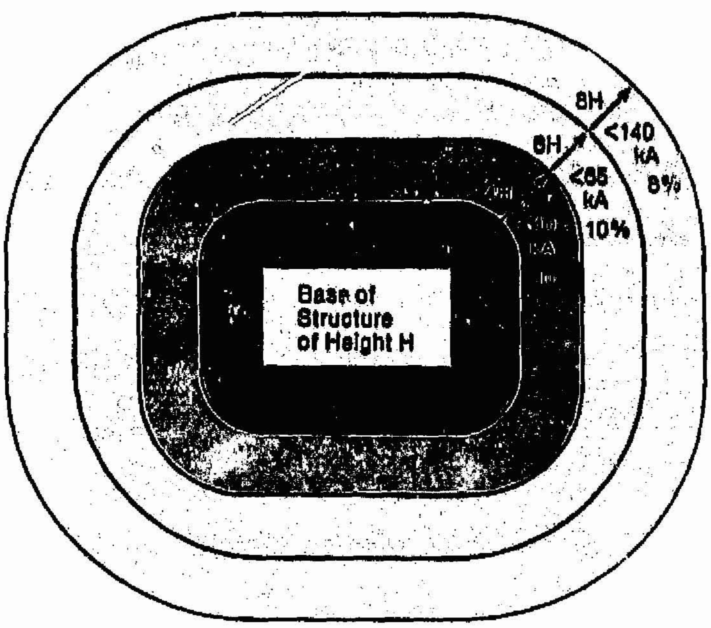


Figure 10. *Areas of Attraction, A, of a Structure of Height, H, as a Function of Stroke Intensity.* (Reference 3)

The upper edges of the structure in Figure 9 will intercept all of the flashes that would have struck the earth somewhere within the protected area, had the structure not been there. Since all flashes that approach the protected area will hit the structure, the protected area (with the area of the structure added) may also be considered the *attractive area* of the structure. Thus the probability of a particular structure being hit is determined, in part, by its size.

Whereas very nearly all flashes that approach a 2:1 cone protected area such as that of Figure 9 will be diverted to the structure, there is no assurance that all flashes approaching *outside* the 2:1 cone area will stay away from the structure. It is well established, in fact, (Reference 3) that a vertical structure of height, H, attracts to itself lightning flashes approaching an area out to 4H, 6H or more, as the stroke severity increases. The attraction areas under these conditions are shown in Figure 10.

The attraction area, A, is given by:

$$A_{nH} = LW + 2nH(L + W) + \pi(nH)^2 \qquad (3)$$

where,

nH = the attraction distance for strokes of various intensities, from Figure 10, where n = 2, 4, 6 and 8.

If the object is a thin tower or pole, the L and W terms approach zero and equation (3) becomes:

$$A_{nH} = \pi(nH)^2 \qquad (4)$$

The probability of a strike to a particular structure can be determined by the following steps:

1. Determine the **isokeraunic level**, T_y, of the city in question.
2. Calculate the **flash density** as a function of T_y with equation (1).
3. Calculate the **ground flash density** from equation (2).
   Note: Isokeraunic levels and flash densities calculated in accordance with steps 2 and 3 above for 266 U.S. cities are given in the Appendix.
4. Determine the **attraction areas** for each of the flash severity ranges shown on Figure 10 from equation 3. Note that if the structure is a single pole, L and W approach zero and equation (3) reduces to $A_{nH} = \pi(nH)^2$
5. For each flash severity range, multiply the **probability of occurrence** times the **attraction area** times the **ground flash density** to obtain the **number of strikes within each amplitude range** to the structure each year.
6. Add the strikes within each range to obtain the **total number of strikes** to the structure per year.

An example of such a calculation for an 80 foot high utility pole standing by itself in an exposed location at Raleigh, North Carolina is shown in Table II. From Table I (or the Appendix) the isoker-

Stroke Amplitude Range:	Prob. of Occurrence (fr. Fig 10)	Attraction Distance (fr. Fig 10) (nH)	(ft.)	Attraction Area (from Eq. 4) (ft^2)	(km^2)	Ground Flash Density (fr. Table I) $F/km^2/yr.$	Number of Strikes to Utility Pole/year (prob. x area x density)
0- 20 kA	0.5	2H	160	80,424	7.46×10^{-3}	2.7	1.01×10^{-2}
20- 40 kA	0.3	4H	320	321,699	29.84×10^{-3}	2.7	2.42×10^{-2}
40- 65 kA	0.1	6H	480	723,822	67.15×10^{-3}	2.7	1.81×10^{-2}
65-140 kA	0.08	8H	640	1,286,796	119.37×10^{-3}	2.7	2.58×10^{-2}
							7.82×10^{-2} strikes per year

Table II. *Calculation of Direct Strikes to an 80 ft. High Utility Pole at Raleigh, N.C.*

aunic level at Raleigh is 41 thunderstorm days per year, resulting in a ground flash density of 2.7 strikes within each square kilometer each year. This resu! in a prediction of 7.82×10^{-2} strikes to the pole ea... year, or about one strike every 13 years. Thus the probability of a direct strike to one particular pole (and resultant physical damage to the pole or to things attached to it) is low.

Because of this low probability, one might conclude that lightning is of little concern to signal lines or equipment attached to the pole. Lightning need not strike the pole itself, however, for damaging surges to be coupled into power or signal lines extending away from it. These surges can play havoc with electronics located a long way from the strike, and there are frequent complaints of signal outages when thunderstorms are simply "in the area."

Within a one kilometer radius of the pole at Raleigh, about:

$$(3.4\ \text{km}^2)(2.7\ \text{F/km}^2/\text{yr}) = \underline{\underline{8.5\ \text{strikes}}}$$

reach the ground each year, and nearly twice as many more occur overhead. This is enough to be of concern. The next chapter describes the mechanisms whereby lightning effects couple into municipal power and signal systems and the ways these systems may be damaged.

CHAPTER 2 Lightning Effects

2.1 INTRODUCTION

The physical damage effects produced at the point where a lightning strike occurs are called the *direct effects* and include holes punctured in insulating materials during the attachment process, and melting and burning of conductors caused by high temperatures associated with the lightning arc. In the vast majority of cases traffic signal lines and equipment are shielded from direct strikes by power lines suspended above, or by virtue of being located within a metallic enclosure or underground.

Of more concern to the traffic signal engineer is electrical damage to equipment from lightning-induced transient surge voltages and currents. These surges are termed *indirect effects* of lightning. They are the result of strikes to overhead wires, earth voltage rises, magnetic field coupling and capacitive coupling.

In this chapter the basic mechanisms which cause transient surges in traffic signal systems are discussed and estimates of their magnitudes are made. Succeeding chapters provide methods of minimizing damage and protecting equipment against these surges.

2.2 STRIKES TO WIRES AND CABLES

Exposed overhead wires and cables are subjected to severe transient surges when struck directly by a lightning flash. As lightning current enters a wire, the wire rises to a very high voltage, causing a flashover to ground to occur somewhere along the wire. On power lines, lightning arresters provide controlled discharge paths for the lightning currents to go to ground. When no arresters are provided, the lightning leaves the wires at supporting insulators or equipment terminals. During either process, high voltage and current surges are impressed on equipment connected to the wire.

These surges can be reduced considerably by shielding the wire, either by suspending a grounded conductor over the wire or by surrounding the wire with a grounded metal foil. The lightning currents will then be conducted through the shields. Such practices are very common in power and telephone systems.

The addition of shield wires or cable shields will greatly reduce the magnitude of the transient surges but will not completely eliminate them. The remaining transient surges can and do damage sensitive electronics connected to shielded wires. The causes of transient surges in shielded wires are illustrated in Figure 11. The voltage between the shield wire and the signal wire will be equal to the sum of the voltages around the loop formed by the two wires.

As lightning current passes through the shield wire, a resistive voltage along its length is established, equal to the lightning current times the wire resistance. A magnetic field around the shield wire is also established.

Part of the magnetic field will pass through the loop formed by the shield wire, the signal wire

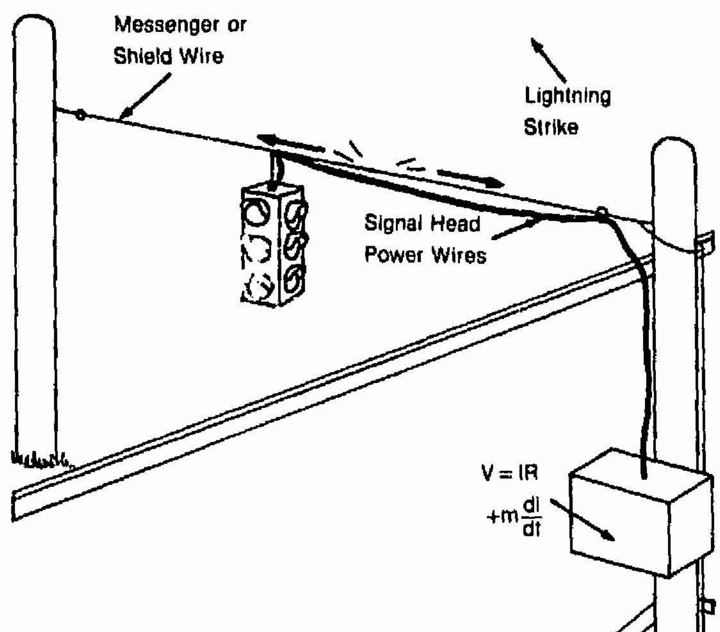


Figure 11. *Induced Voltages from Shielded Wires.*

and the terminations. This magnetic field will change in accordance with the lightning current and induce a voltage in the loop. This voltage is related to the lightning current rate of change (di/dt) and the amount of the magnetic field which can pass through the loop.

The voltages lightning may induce in signal wires contained within overall shields have been studied extensively at the NASA Kennedy Space Center (KSC) launch facilities (References 4 and 5). Protection for launch critical circuits required a knowledge of the magnitudes of the surges induced by lightning and the mechanisms relating shield currents to induced voltages. Research into these mechanisms and development of analytical techniques to predict the surges was carried out and verified.

The voltage induced on a conductor contained within a shield is shown in Figure 12. As the lightning current passes through the shield material, an electric field voltage is developed along the shield. If one end of the conductor is connected to the shield, the voltage at the other end will be equal to the sum of the electric fields around the loop formed by the signal conductor and the shield wall. If the shield is not solid, then magnetic fields can enter through holes and a magnetically induced voltage will also appear.

For thin (0.005" to 0.01") solid copper shields, the lightning current rise time is long compared to the time it takes for the current to diffuse to the inside surface of the shield. The internal electric field will therefore have the same

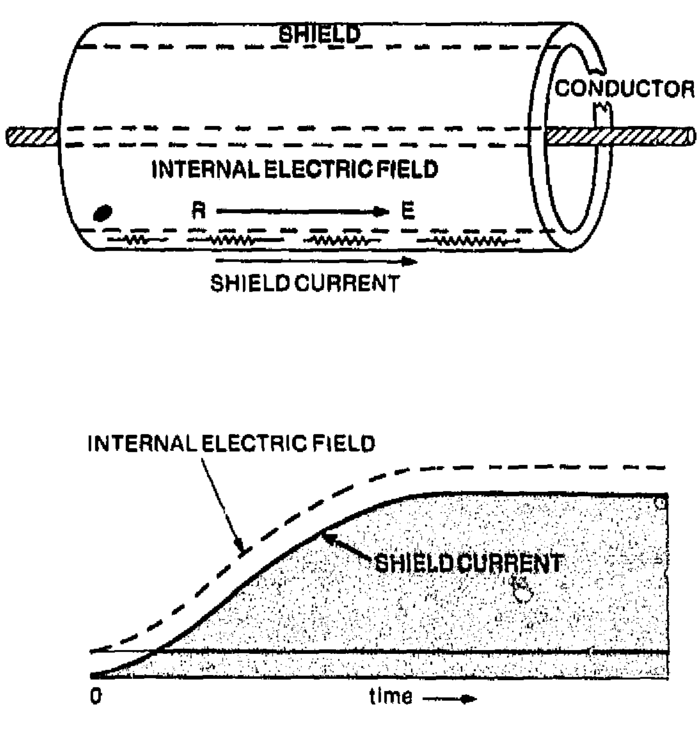


Figure 12. *Cable Coupling Mechanism.*

waveshape as the current and the induced voltage will be equal to the current times the shield resistance, or

$$v = iR \tag{5}$$

where,

v = the voltage along the shield (volts/meter of cable length)
i = lightning current in the shield (amperes)
R = the shield resistance (ohms/meter of cable length)

Typical telephone cables have shield resistances of between 3 and 6 ohms per mile. With the aid of the NASA-developed analysis techniques referred to earlier, calculations have been made (Reference 6) of the lightning-induced voltages and currents which may be coupled into the conductors of typical signal cables, as a function of lightning current amplitude and the distance along the cable of the strike from the signal controller.

Typical induced voltages and currents calculated by the NASA techniques are presented in Figure 13 a, b, and c. Figure 13a shows the waveform of the surge current that was assumed to enter the cable shield at the strike point. Figure 13b shows the voltage arriving at a controller 2.75 miles away. Figure 13c shows the maximum current that this voltage would drive through a suppressor (if present) at the controller end of the cable.

This analysis shows that if a severe (100 kA) lightning stroke enters a power line or utility pole and causes a surge of 25 kiloamperes to flow on the signal cable shield, a voltage surge reaching a peak of over 18 kilovolts can be induced in the signal conductors and transmitted to a controller 2.75 miles away. It also shows that over 300 amperes of surge current could flow into the electronics, or through a suppressor, if present at the ends of the cable.

Since 18 kV far exceeds the withstand capability of controller electronics, suppressors must usually be installed where signal cables interface with controller electronics, and it is necessary that the suppressors be able to conduct the available surge current. Table III gives the surge currents predicted in the preceding analysis for strikes at various distances from a controller.

2.3 EARTH VOLTAGES

When lightning currents reach the ground they enter the earth at one or two concentrated points and fan out from these points in all directions, toward far-away regions of lower potential. Near the point(s) of entry, the concentrated lightning currents of many kiloamperes flowing in resistive earth give rise to *earth voltages* of many thousands

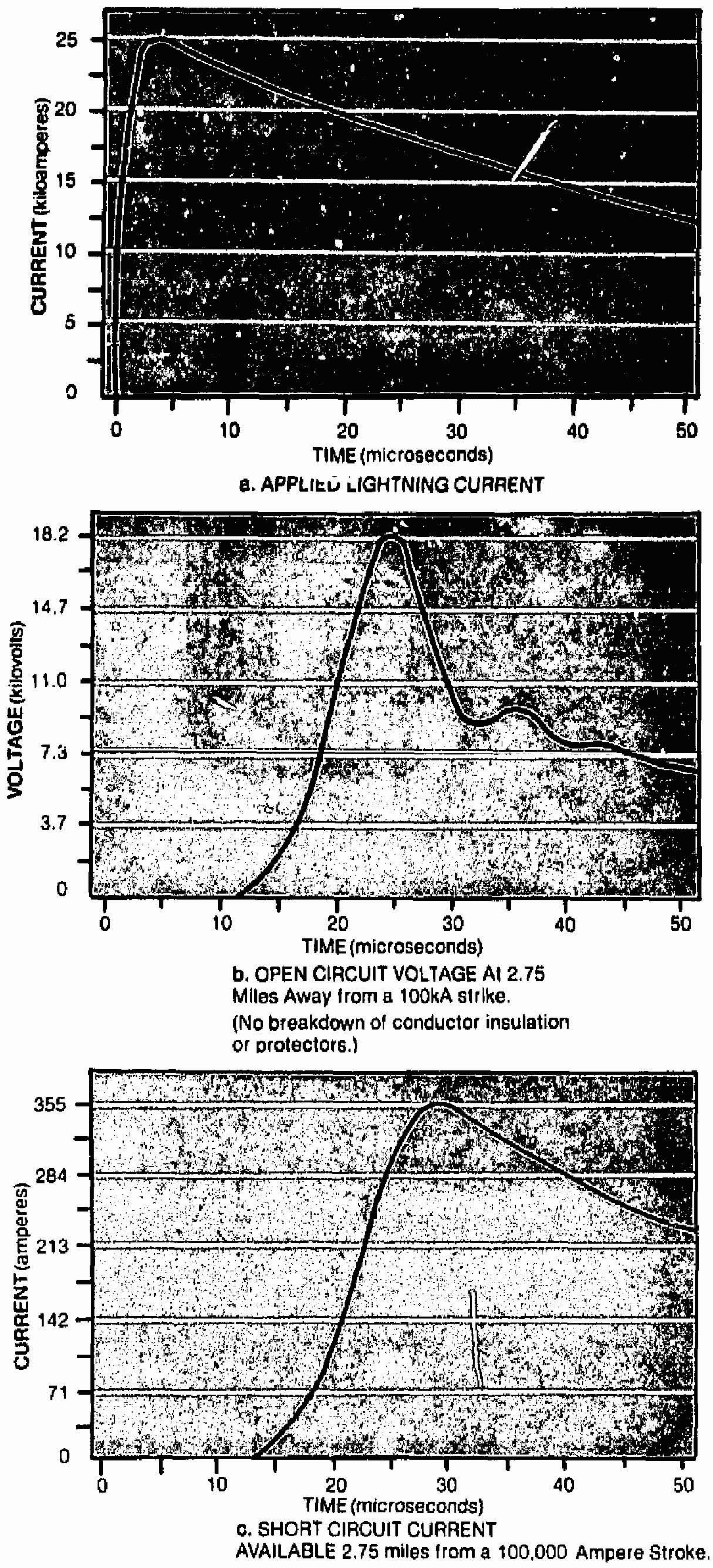


Figure 13. *Examples of Lightning-Induced Voltages and Currents in Signal Cables.*

Distance from Controller to Strike (Miles)	Peak Induced Currents (Amperes)
2.75	355
1.50	637
1.00	799
0.50	1120
0.25	1480

Table III. *Peak Lightning Induced Currents in Signal Cable Conductors (for a 100 kA lightning strike at various distances away)*

of volts. These voltages appear between the point(s) where the lightning current enters the earth and places farther away where the current concentration is much less. The earth voltage is therefore highest at the strike point, falling off inversely with distance from this point. For example, the earth voltage surrounding a utility pole which is carrying some lightning current to earth after a power line has been struck is shown on Figure 14. The magnitudes shown are for 20 kiloamperes of current (i) entering earth of typical 100 ohm-meters resistivity (ρ).

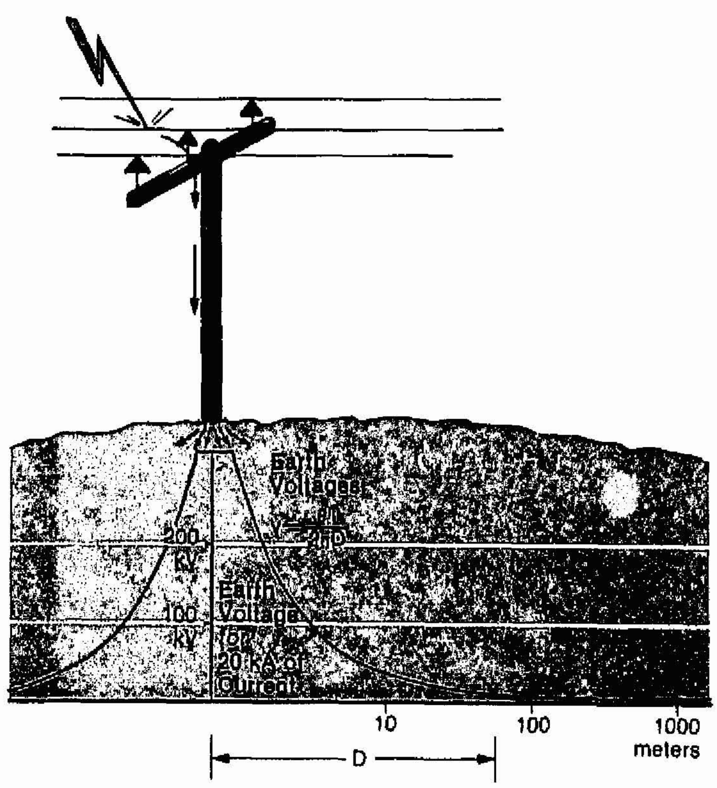


Figure 14. *Earth Voltage Profile for 20 kA of Lightning Current Entering Soil of 100 ohm-meters Resistivity.*

Higher (or lower) currents and/or higher (or lower) earth resistivities would create correspondingly higher (or lower) earth voltages.

These earth voltages will appear in signal control cabinets when there are circuits leading from this cabinet to a cabinet at lower potential. If the signal wires are contained in shielded cables, then the earth voltages will drive currents through the cable shields and these currents will induce voltages in the signal conductors, as described in Para. 2.2. This situation is illustrated in Figure 15.

If the same lightning current and earth resistivity as in the example of Figure 14 are assumed, the first control cabinet will rise to a potential close to that of the pole ground—about 300 kilovolts. Meanwhile, the second cabinet a block away

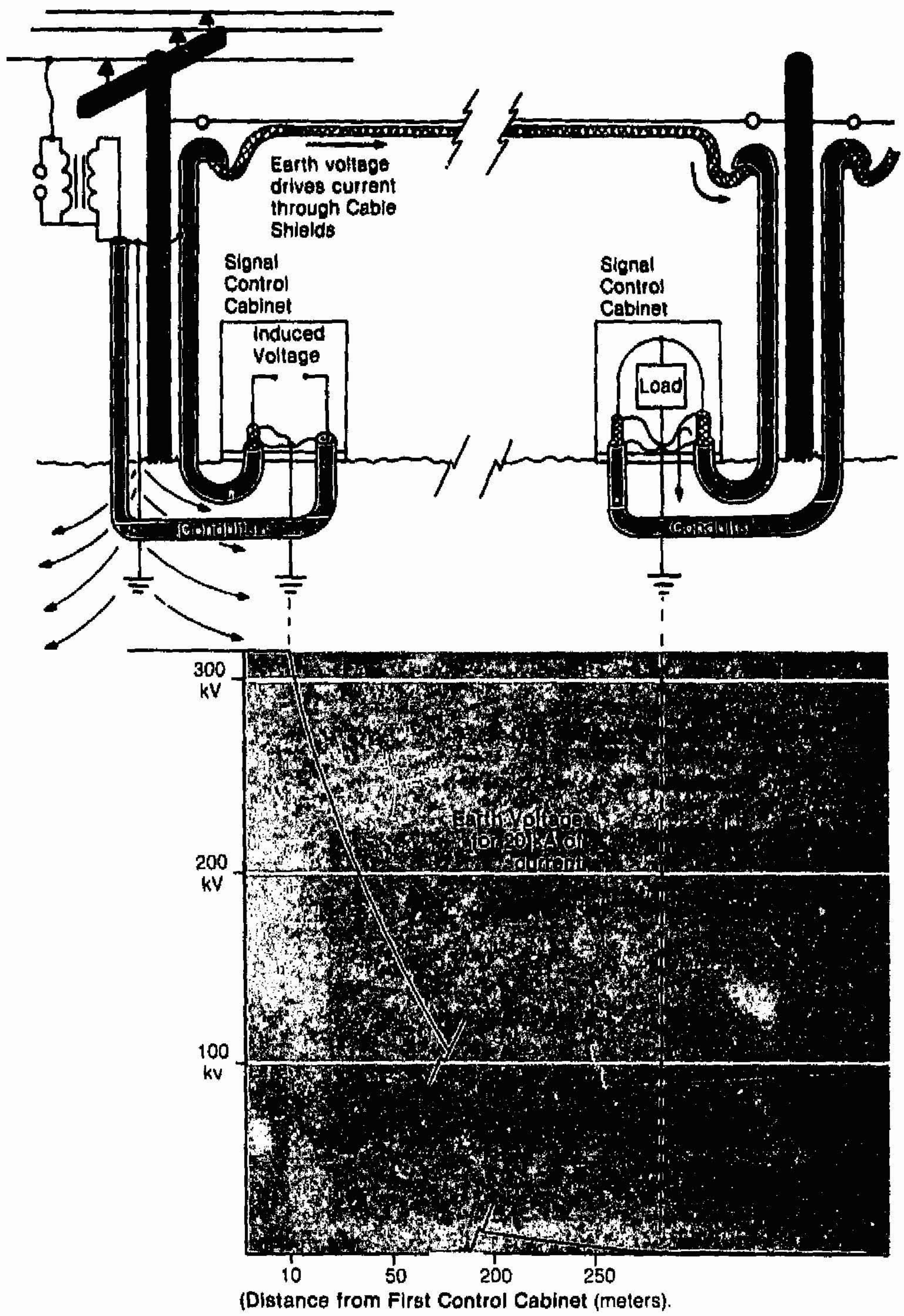


Figure 15. *How Earth Voltages Appear in Signal Controllers.*

remains near "true" ground potential—near zero volts, and the earth voltages show up wherever circuits connecting the two cabinets come together.

2.4 INDUCTIVE VOLTAGES

Due to the earth voltages just described, emphasis is usually placed upon achievement of low resistance earth grounds for municipal signal installations. Low-resistance grounds are preferred, of course, for two reasons,

1. to provide a direct path for lightning currents to flow into the earth, and
2. to minimize voltages that arise during lightning current flow along this path.

Provision of a low *resistance* ground by itself, however, will not assure that the above two objectives will be met, because significant voltage rises and impedances to lightning current flow may occur along low resistance ground paths if the *inductance* of these paths is not also low. Inductance is the property of a conductor that allows energy to be stored in a magnetic field, and because these magnetic fields are invisible, this property is frequently overlooked.

Surrounding any electric current is a magnetic field, as shown in Figure 16.

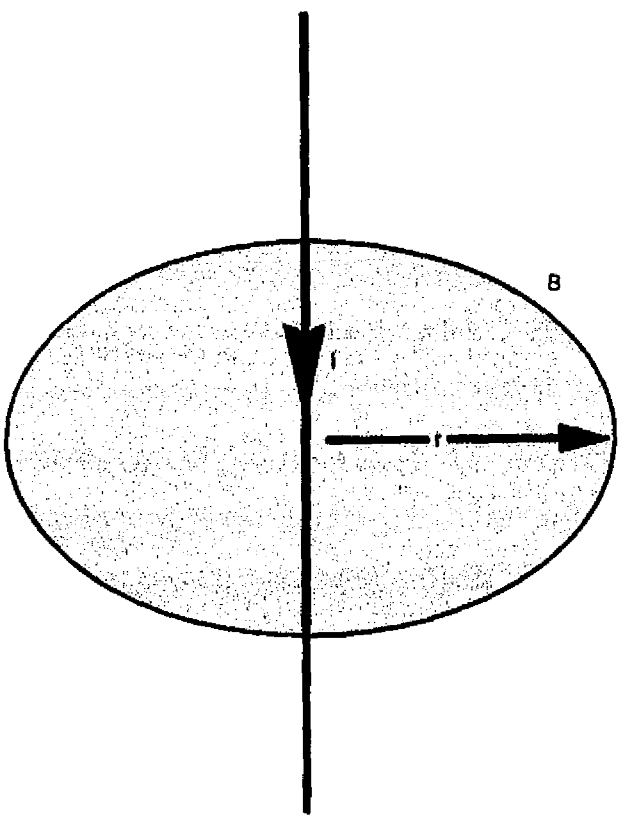


Figure 16. *Magnetic Field around a Single Conductor.*

The magnetic field *intensity*, B, at any point a distance, r, away from the conductor is proportional to the current amplitude and diminishes inversely with distance from the outside surface of the conductor as follows:

$$B = \frac{\mu I}{2\pi r} \tag{6}$$

where:

B = the magnetic flux density (webers/meter²)

μ = the permeability of the medium (henrys/meter)
$= 4\pi \times 10^{-7}$ H/m for air

I = the current in the conductor (amperes)

r = the radial distance from the conductor (meters)

The total magnetic field around the unit length of this wire is equal to the integral of the flux density from the surface of the conductor (where the flux density is very intense) out to where its value is insignificant. This may be expressed per meter of conductor length as:

$$\phi = \int_{r_1}^{R} \frac{\mu I}{2\pi r} dr = \frac{\mu I}{2\pi} \int_{r_1}^{R} \frac{dr}{r} \text{ webers/meter} \tag{7}$$

where:

ϕ = magnetic flux linkages (webers)

r_1 = the radius of the conductor (meters)

R = the radius of a typical thunderstorm (one thousand meters)

For example, the magnetic flux surrounding an AWG 4/0 ground conductor with a radius, r_1, of 0.66 cm is:

$$\begin{aligned}\phi &= \frac{\mu I}{2\pi} \ln\left(\frac{R}{r_1}\right) = 2 \times 10^{-7} \ln\left(\frac{1000\text{m}}{0.0066\text{m}}\right) I \text{ webers/meter} \\ &= 2 \times 10^{-7}(11.93) I = 2.4 \times 10^{-6} I \text{ webers per ampere of current, per meter of conductor length}\end{aligned} \tag{8}$$

The *inductance*, L, of a conductor is defined as the ratio of the magnetic field surrounding a conductor to the current that produces it and is measured in *henrys*. Thus:

$$L = \frac{\phi}{I} = \frac{\text{webers/meter}}{\text{ampere}} = \text{henrys/meter} \tag{9}$$

thus,

$$\text{henrys} = \frac{\text{webers}}{\text{ampere}} \tag{10}$$

and the inductance of the 4/0 conductor mentioned above is:

$$\begin{aligned}L &= \frac{2.4 \times 10^{-6} I}{I} = 2.4 \times 10^{-6} \text{ henrys/meter} \\ &= 2.4 \text{ microhenrys/meter}\end{aligned} \tag{11}$$

When currents pass through an inductor, the voltage across the inductor is given by:

$$v = L\frac{di}{dt} \qquad (12)$$

where,

v = inductor voltage (volts)
di/dt = rate of change of current (amps/second)

The rate at which current can build up($\Delta i/\Delta t$) is directly proportional to the electrical force (voltage, v) behind the current, and inversely proportional to the inductance (ability to store energy) of the conductor, or:

$$\frac{\Delta i}{\Delta t} = \frac{v}{L} \text{amperes/second} \qquad (13)$$

where:

v = the driving voltage (volts)
t = time (seconds)

In the case of a lightning strike, the rate at which current builds up ($\Delta i/\Delta t$) is governed by the lightning flash and the voltage along the conductor must increase to a level sufficent to allow the lightning current to enter the inductor at the predetermined rate.

Equation 12 is very important because it shows that voltage can arise along a conductor which has no resistance, and that this voltage is proportional to both the inductance of the conductor and to the rate of change of current flowing through it.

The high amplitude strokes associated with a lightning flash have very fast rates of change as shown in Figure 6 of Chapter 1. These are the rates at which lightning currents may be injected into a ground conductor such as the one running down the utility pole in Figure 15.

The maximum rate of rise of current flowing down any utility pole probably does not exceed 100 kiloamperes per microsecond since it is rare that all of the lightning current would go down a single pole. In fundamental units this is 10^{11} amperes per second. A lightning current entering the 4/0 conductor discussed earlier and rising to its peak at a rate of 10^{11} amps/sec would create a voltage of (from equations 8 and 13):

$$v = L\frac{di}{dt} \qquad (14)$$

$$= (2.4 \times 10^{-6} \text{henrys/meter}) (1 \times 10^{11} \text{ amps/sec})$$

$$= 240{,}000 \text{ volts per meter of conductor length}$$

This voltage would appear along the conductor while the lightning current is rising to its peak. When the current reaches its peak, it would cease to change and for a moment the inductive voltage would be zero. Then, as the stroke current decays, the inductive voltage would increase again but in the opposite direction as the magnetic field

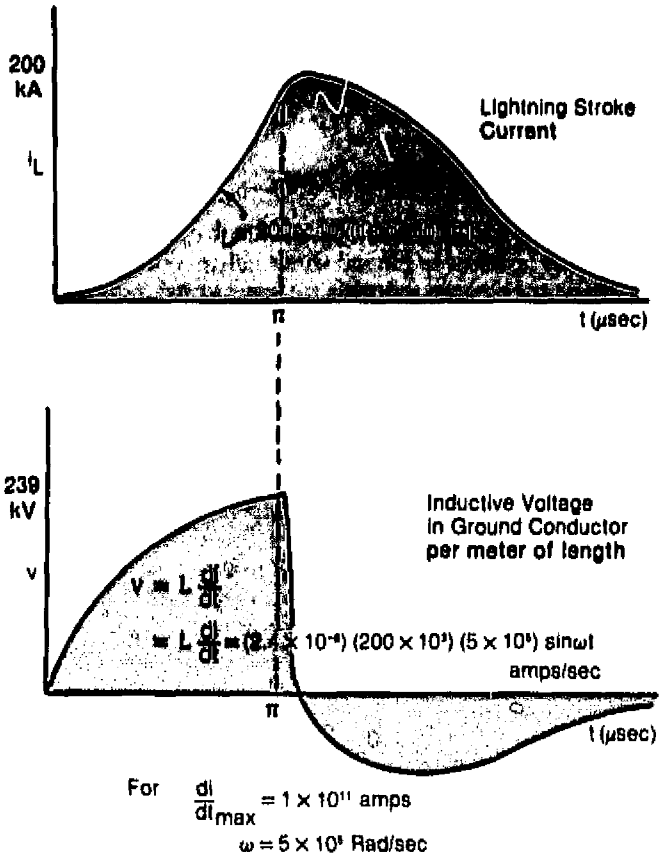


Figure 17. *Severe Lightning Stroke and Inductive Voltage in Ground Conductor.*

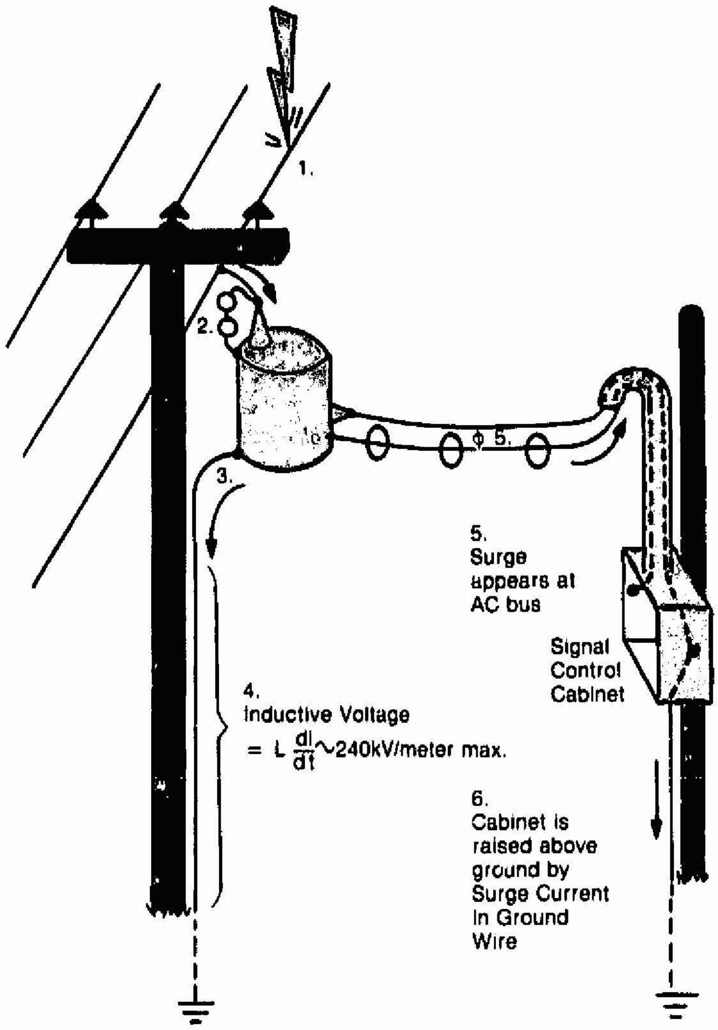
diminishes and energy begins to leave. Using a (1-cos) expression to represent a typical stroke wavefront, the stroke current and the inductive voltage that it would produce along the 4/0 ground conductor would appear as shown in Figure 17.

This inductive voltage will add to the earth resistive voltage described earlier. In most cases the resistance will be associated with the earth connection (ground rod) whereas the inductive voltage will be distributed along the entire ground conductor.

Inductive voltages are a frequent cause of damage to signal equipment. A very common example of how this occurs is shown in Figure 18.

In Figure 18, the distribution lightning arrester on the transformer primary sparks to protect the transformer. The lightning current is carried to ground on the pole ground wire, but the inductive voltage in the ground wire can be as high as 240 kV/meter. This voltage forces current along the neutral to the controller cabinet. As discussed in Paragraph 2.2, these currents will induce surge voltages in neighboring power wires, and these surges, which may reach many thousands of volts, must be suppressed inside the cabinet.

As a result of the above mechanisms, surge suppressors have been installed in many signal control cabinets, but their effectiveness is frequent-



1. Lightning strikes the power line.
2. The arrester sparks and protects the transformer.
3. Most lightning current flows to ground via transformer ground wire.
4. Inductive voltage in the ground wire raises transformer to a high voltage.
5. Some lightning current enters the secondary neutral and the magnetic field produced by this current induces a voltage surge into the secondary circuit.
6. The signal controller cabinet is also raised above ground by the neutral current flowing in the cabinet ground wire.

Figure 18. *Inductive Voltage Surge in a Power Distribution Circuit.*

ly diminished by the inductance associated with long leads. Figure 19 shows a typical installation of a power line surge suppressor intended to clamp surges appearing at the AC bus. For convenience, the suppressor is often mounted at a spot on the cabinet wall, out of the way of other equipment. The leads necessitated by this arrangement frequently insert one or two microhenrys of inductance between the suppressor and the bus.

If the maximum surge current rate of rise produced by lightning in secondary power distribution systems is taken as 500 amps/microseconds the voltage produced by this current along the suppressor leads would be:

$$v = L\frac{dI}{dt} \qquad (15)$$

$$= (1 \times 10^{-6}\text{H})(5 \times 10^{8}\text{ amps/sec})$$

$$= 500 \text{ volts per microhenry of inductance}$$

The inductance of the suppressor circuit may be assumed to be 1 microhenry per meter of lead length. Thus, for an installation requiring leads 1 meter in length the inductance would be 2 microhenrys. The surge voltage appearing across the loads in the controller (bus-to-ground) in Figure 19 would be the sum of the suppressor clamp voltage (e_C) and the inductive voltage in the leads. If for example, the suppressor in Figure 19 were capable of clamping a surge to 600 volts, the surge voltage appearing across the loads would reach **1600 volts** and protection thought to be achieved by installation of the suppressor would not be obtained. Situations like this appear very often because the role of inductance in lightning protection is not well understood by many users of protective devices.

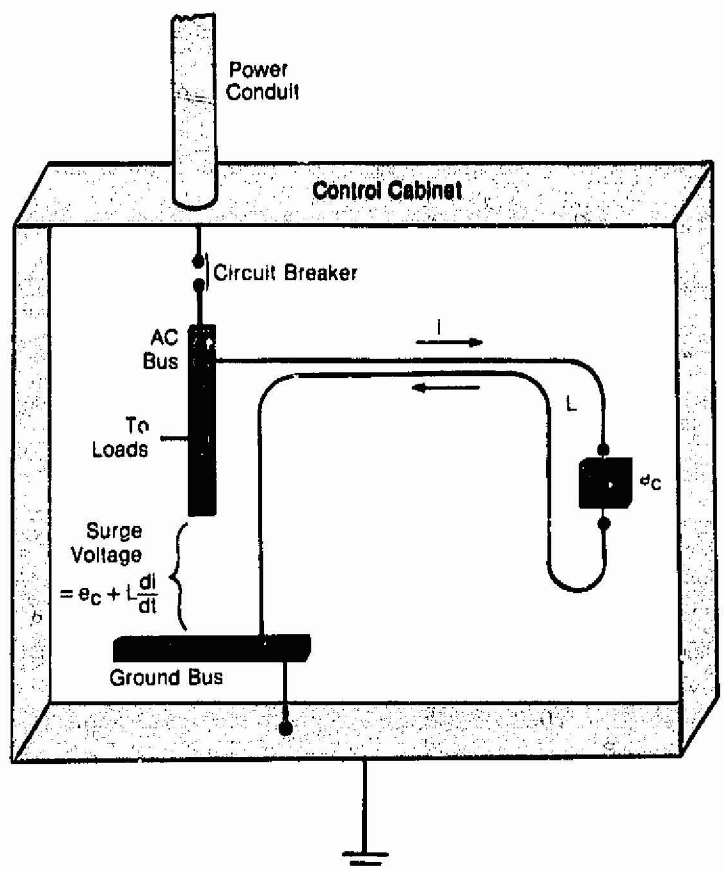


Figure 19. *Effect of Long Suppressor Leads*

2.5 CAPACITIVE VOLTAGES

In addition to the resistive and inductive mechanisms described in the previous paragraphs, voltage and current surges may arise in traffic signal installations via *capacitive coupling.*

If two (or more) conductors are in proximity to each other and an electrical charge of either polarity is placed upon one of them, an electric field is established by the charge and will attract a charge of opposite polarity to the other conductor. If additional charge of the original polarity is applied to the first conductor, a similar amount of opposite polarity charge will be drawn to the other. This phenomenon is know as *capacitive charging* and the charge flow to or from one conductor caused by a change in the amount of charge on the other is called *capacitive charging current.* These currents are proportional to the amount of capacitance and the difference in charge potential (voltage) between the two conductors.

Due to the relatively large area they cover and their proximity to the ground, vehicle detector loops are prone to receiving capacitive charging currents from the earth when lightning currents raise the earth voltage above zero potential. The process is pictured in Figure 20.

The input circuitry of most loop detectors contains solid-state components which are sensitive to these surge currents, and burnouts frequently occur.

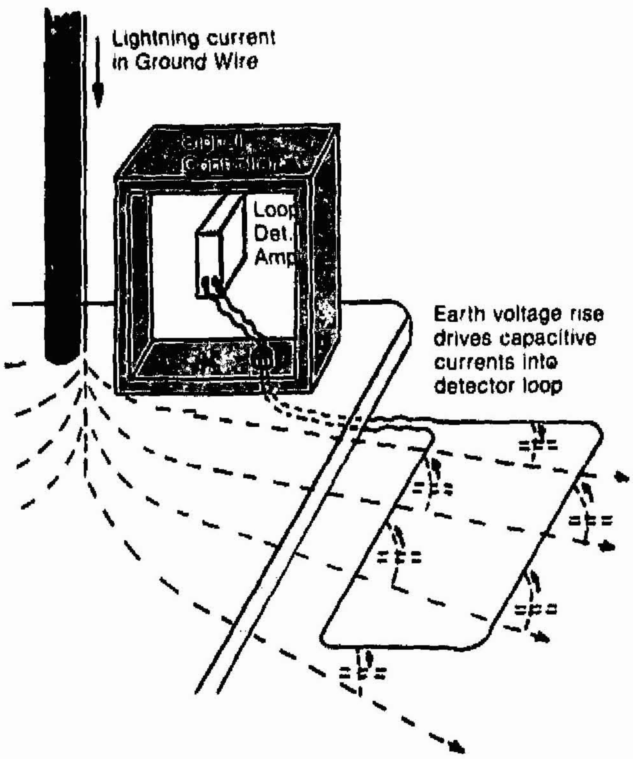


Figure 20. *Capacitive Charging Currents Enter Vehicle Detector Loop when Lightning Current Enters Ground Nearby.*

Figure 21 shows the input circuit of one loop detector in which burnouts have occurred. In this case, capacitive charging currents elevate the detector loop and winding T1A of the coupling transformer to the earth potential, which is usually different from the electronics ground to which windings T1B and T1C are referenced. The resulting difference of potential appears as a voltage surge on the insulation between transformer windings, causing breakdown. Typically, the insulation of miniature transformers like this can tolerate no more than 1 kilovolt, and capacitive voltage surges in loops like this may reach several 10's of kilovolts.

Since capacitive charging currents are likely to enter all sides of a vehicle detector loop, the entire loop and both of its connecting wires receive the same surge at once. Surges which appear on both conductors at once (with respect to some other reference) like this are called *common mode* (sometimes called transverse) surges, in contrast to *differential* (sometimes called metallic) surges in which one wire of a circuit is elevated to a much higher potential than the other (or in which surge current flows in only one of the two wires). There are other effects such as magnetic field coupling, which are capable of inducing a voltage around the loop such that one end would be at a higher potential than the other. The failure modes observed in most detector-amplifier units, however, indicate that the common-mode, capacitively coupled surges predominate.

2.6 SUMMARY OF LIGHTNING-INDUCED SURGES

From the preceding discussions it should be clear that lightning damage to traffic signal systems results from voltage and current surges induced, by one mechanism or another, into wires and cables that feed into the signal controls from outside places. If no wires entered a controller cabinet there would very likely be no lightning-related damage to controller electronics. Unfortunately, it is not yet possible to design a useful traffic control device without interconnecting wires. Every wire, therefore, that is brought into a controller cabinet must be considered a source of lightning-induced transients. This includes the 115V AC power, vehicle detector loops, pedestrian controls, interconnect cables and others.

The magnitudes of the lightning-induced surges appearing on these wires depend on their length, their degree of shielding, and their routing. For example, a wire that goes directly from a controller cabinet to an overhead span where it can be struck directly by a lightning flash could receive surges approaching natural lightning current levels. If the wire were routed underground for some distance before rising to an overhead span, the surge

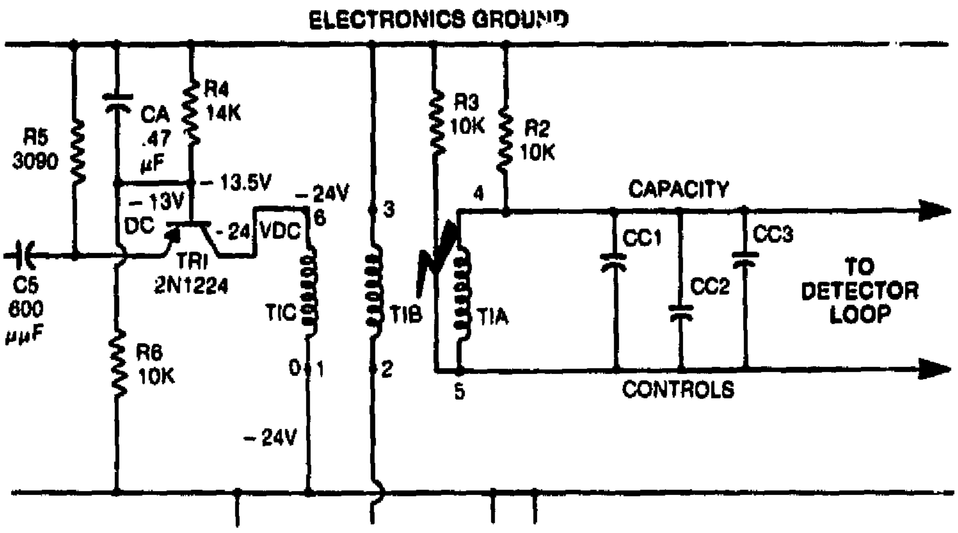


Figure 21. *Input Circuitry of One Loop-Detector Unit in which Lightning-Induced Failures Have Occurred. Earth Voltages Enter Detector Loop, Elevating Potential of Winding T1A with Respect to Other Windings, Causing Insulation Failure.*

Typical Wire Configuration	Peak Voltage (Volts)	Peak Current (Amps)	Peak Energy (Joules)
Cables Exposed to Direct Strikes			
Unshielded, aerial with strike nearby*	10^4	10^5	10^3
Unshielded, aerial with strike far away†	10^4	10^4	10^2
Unshielded, buried	10^4	10^4	10^2
Shielded, buried or aerial	10^4	10^3	10^2
Cables Exposed only to Partial Amounts of Lightning Current			
Unshielded, single wire	10^3	10^3	10^3
Unshielded pair—wire to wire	10^3	10^2	10^1
—wire to ground	10^2	10^2	10
Shielded wire	10^2	10^2	1
Shielded pair—wire to wire	10	10^1	10^{-1}
—wire to ground	10^2	10^1	1

* i.e. within a block or two
† i.e. within a mile or two

Table IV. *Estimated Lightning-Induced Surges in Traffic Control Systems*

magnitudes would be reduced due to insulation sparkover where the wires enter an underground conduit. On the other hand, if the signal wires were accompanied by dedicated return wires, if both are contained within double shields, if these shields are grounded at both ends, and if this shielded cable is a continuous iron conduit, the lightning-induced surges will be very small. Neither of these situations, however, is found very often in traffic signal systems.

Engineering estimates of lightning-induced transients occurring in the types of cables that are used most often are given in Table IV. These estimates are based on severe lightning flash levels and include peak values rounded off to the nearest power of 10.

The estimates of Table IV have been used to determine the performance required of the suppressors recommended for specific applications in Chapter 3.

CHAPTER 3 **Protection of Existing Systems**

3.1 BASIC APPROACHES

The necessity for adding protection to an existing traffic control system is dictated by the level of lightning-related problems being experienced. The *amount* of protection to be added to minimize future problems may not be as evident, since in some cases, the electronic components that fail are themselves suppressing transients that would cause failure of other devices located further inside the electronics. Therefore, if the components that are failing are simply replaced with components able to withstand higher surge levels, other components (including the protective devices themselves) may begin to fail. In one case, for example, buffer relays were added between the incoming signal cables and the traffic controller to protect against surge damage to the controller. These prevented further controller failures, but the relays themselves began to fail and the traffic control system was "down" about as often as before.

To preclude such unfortunate results, the lightning transient source and system entry point(s) must be identified, the transient magnitude estimated and protective devices applied which are capable of suppressing the surge voltage and withstanding the surge current.

It may be possible to achieve acceptable performance by protecting only that part of the system in which past failures have occurred. If loop detector failures comprise essentially all of the lightning-related problems on a system, then protection of loop detectors may be all that is required. However, in many systems lightning causes damage to more than one part of the system and in these cases, over-all protection should be considered.

Two basic approaches to protection are available. The first approach is to minimize the incoming surges by *shielding* interconnecting cables. This is accomplished by placing these cables within conductive conduits or wire braids: or by including an extra wire grounded at each end. The shields or grounded wires provide alternate paths for lightning-induced surges to flow on, thereby reducing the level of surges that are induced in the signal conductors.

In the second approach, lightning-induced voltages are clamped or *suppressed* to harmless levels by installation of *surge suppressors* where these cables enter the electronics. Surge suppressors fall into three general categories: nonlinear devices, switching protectors and hybrid assemblies.

3.1.1 Nonlinear Suppressors

Zener diodes and varistors are the most common examples of nonlinear suppressors. At normal operating voltages these solid-state devices draw extremely low current but at higher voltages they begin to conduct and draw a much larger amount of current, thereby draining energy from the surge. This energy is transformed into heat in the device. Typical nonlinear suppressors are pictured in Figure 22.

The relationship between the voltage applied to such a device and the current through it is expressed as:

$$i = kv^{\alpha} \tag{16}$$

where,

i = current through the device (amperes)
k = a device constant
v = voltage across the device (volts)
α = the nonlinear exponent

Silicon carbide varistors exhibit nonlinear exponents of 3 to 7, zinc oxide varistors (MOV's) exhibit exponents of 20 to 70, and silicon zener diodes exhibit exponents of 100 to 500.

Nonlinear suppressors absorb the surge energy within themselves, transforming it into heat. Zener diodes can absorb up to 1 joule (watt-sec) of energy, whereas silicon-carbide and zinc-oxide varistors can absorb from 1 to 100 joules, depending upon their physical size.

3.1.2. Switching Protectors

Switching protectors consist of various types of spark gaps and other devices that switch from a very high impedance to a low impedance (i.e. short circuit) state. The most commonly used switching

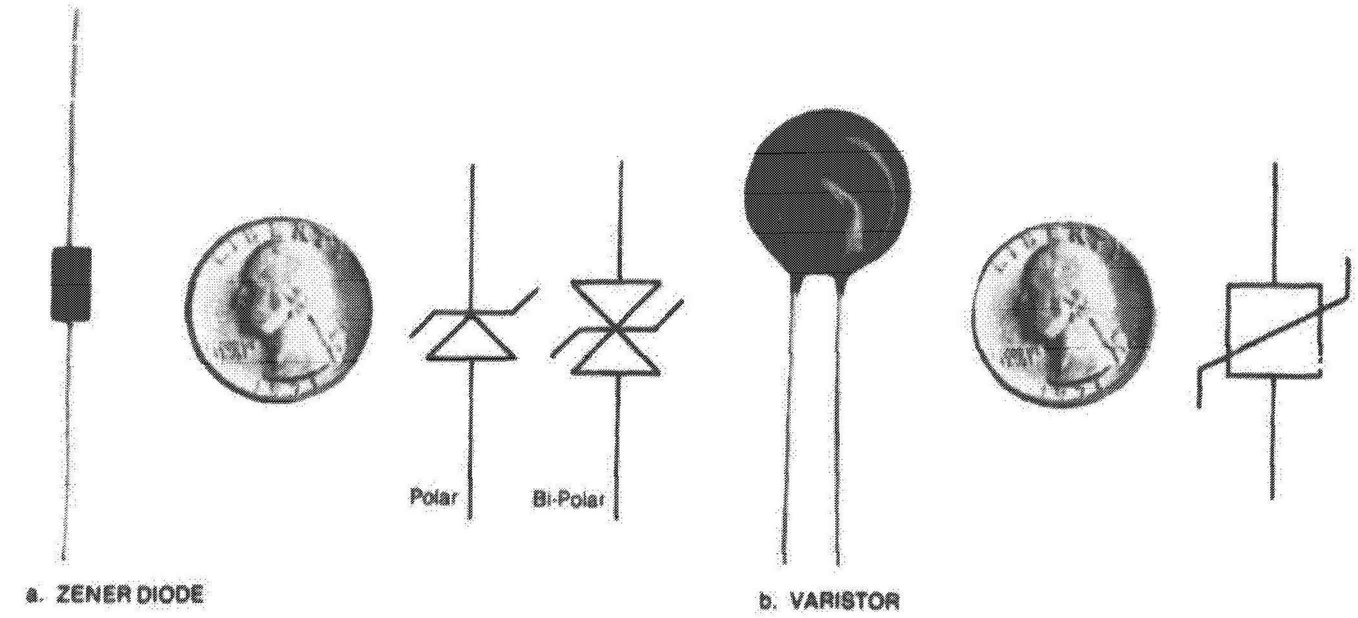


Figure 22. *Typical Nonlinear Suppressors.*

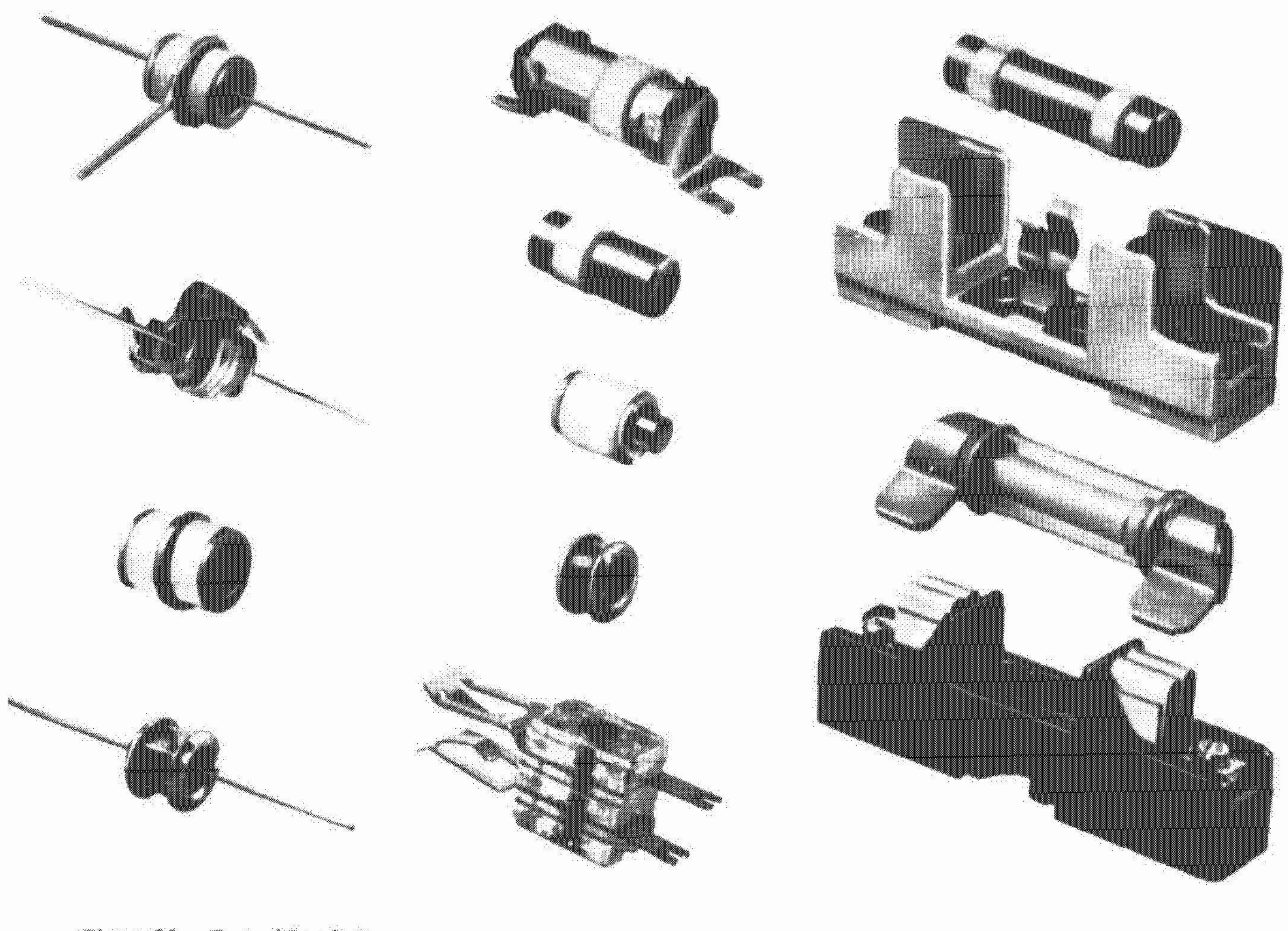


Figure 23. *Typical Spark Gaps.*

Siemens Corp. Photograph

protectors are spark gaps, shown in Figure 23. A spark gap is made up of electrodes closely spaced in a gas atmosphere. When the applied voltage exceeds the dielectric strength of the gas an electrical spark is formed and the gas abruptly changes from an insulator to a conductor. At this point, the voltage across the gap drops from an open-circuit voltage of 100's of volts to nearly zero.

Because the conducting voltage is low, spark gaps do not dissipate very much of the surge energy. Instead, the surge is reflected and dissipated in the resistance of the wires. Several passages of the surge back and forth along the line may be required before the energy is fully dissipated. Since spark gaps do not dissipate energy, they are rated in terms of the amount of voltage required to cause them to spark, and the maximum amount of surge current they can sustain after sparkover occurs.

Because a finite amount of time is required to form the spark, the first part or *front* of the transient may pass through a spark gap before the spark is formed and the voltage is clamped. This is called the *time-lag* characteristic and results in an upturn in spark-gap breakdown voltages at early times, as shown in the voltage breakdown curve for typical spark gaps of Figure 24.

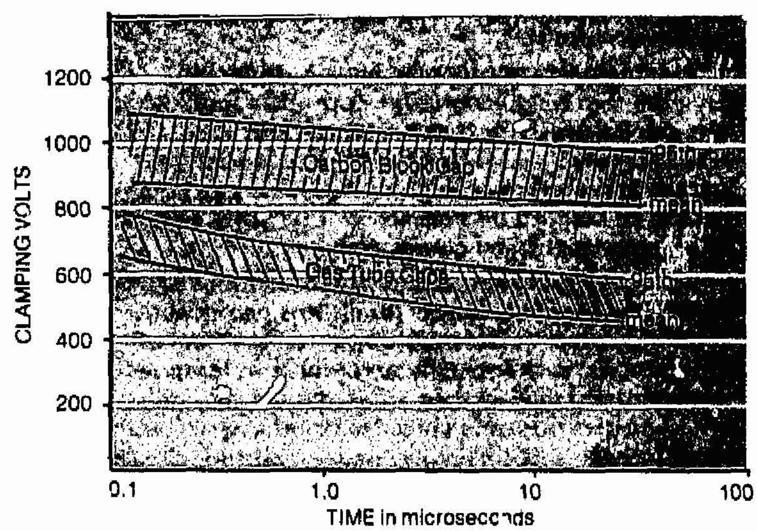


Figure 24. *Breakdown Voltage vs Time for Typical Spark Gaps.*

Frequently a switching-type protector and a nonlinear suppressor are used together, with the switching protector used as *primary* protection to deal with high surge currents, and the non-linear suppressor used as *secondary* protection to clamp the surge to a lower level. The concept is illustrated in Figure 25.

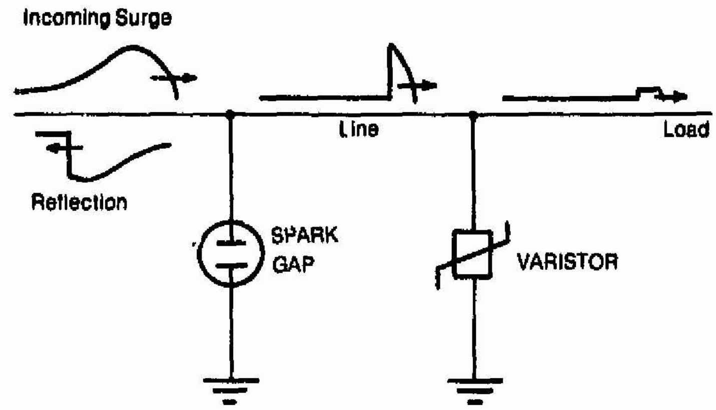


Figure 25. *Performance of Switching-type (spark gap) and Nonlinear Suppressor (varistor).*

When connected across AC or DC power lines which can deliver large short circuit currents, current-limiting impedances usually have to be inserted in series with the spark gap to help the spark extinguish when the transient is over. Varistors are often used for this purpose, as shown in Figure 26.

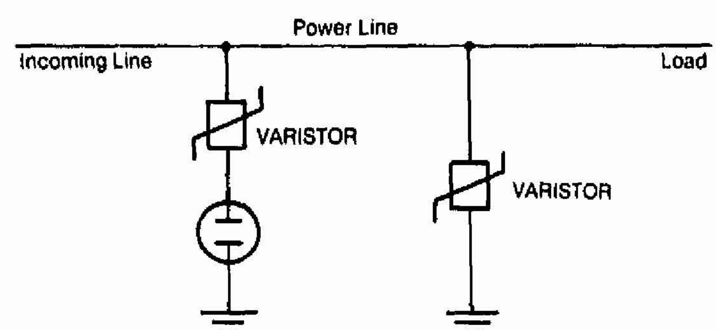


Figure 26. *Use of a Spark Gap Across a Power Line.*

To be successful, the primary and secondary protectors must be separated enough so that the surge reaches the primary protector before appearing at the secondary protector. If not, the secondary protector, which clamps at a lower voltage, will operate first and be exposed to the full surge current and resultant damage. This may require that additional *inductance* or *resistance* be inserted in the line between the primary and secondary protectors as shown in Figure 27.

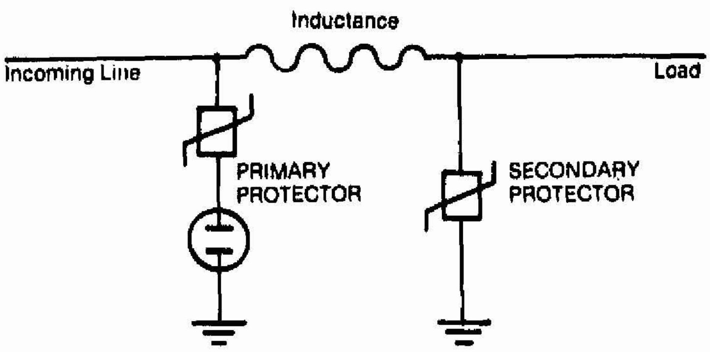
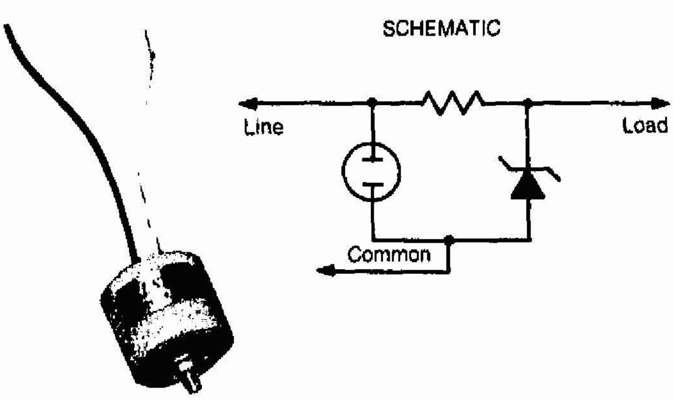


Figure 27. *Primary and Secondary Protectors.*

The three or four components involved in the protection circuitry of Figures 26 and 27 are sometimes packaged and marketed as a single protector. Such products are often referred to as *hybrid protectors.* Line, loa and ground (common) leads are brought out of the package as shown in Figure 28. All other connections are made within the sealed unit. By packaging several components together, hybrid protectors may require less labor from those who must design and install protection—particularly for existing systems.

In the example of Figure 28 a resistor is used to separate the primary and secondary protectors. The upper limit of this resistance is the amount that can be tolerated in the signal circuit without degrading its performance. The lower limit is the amount necessary to limit the current through the zener diode to a tolerable level.

It is possible for the users to install their own primary and secondary protectors and, by installing them at different places in the system, utilize the inductance already present in the system between these places to separate the two protectors.



EDCO Inc of Florida Photograph

Figure 28. *Typical Three-Terminal Hybrid Protector.*

3.2 PROTECTIVE MEASURES

In this section we present guidelines for protection of the various parts of a traffic control system. Unless otherwise noted, each of the following protective measures should be implemented when improved protection is desired.

3.2.1 Controller Cabinets

A. Metal controller cabinets, whether mounted on a pad or a utility pole, should be grounded to earth via a ground connection at the base of the cabinet as shown in Figure 29.

B. Many cabinets are already grounded as shown in Figure 29. If the ground wires are longer and less direct than those shown, they should be shortened to appear as shown in Figure 29. This will remove unnecessary inductance from these wires. Tight, bare-metal connections should be used throughout.

C. Lightning protectors and all other components that may carry surge currents should be grounded directly to the nearest cabinet wall, since the wide metal sheets offer the lowest inductance paths between ground points. The paint should be scraped off beneath ground studs to provide a good electrical connection.

D. It is important to have low resistance to earth, but improvement is much less practical to come by as it requires addition or replacement of ground rods. It is normally acceptable to leave existing ground rods as they are, provided they do not appear excessively corroded or otherwise badly damaged.

E. *Non-metallic cabinets* made of fiberglass or other nonconducting materials are beginning to be offered by some manufacturers. Such cabinets should be equipped with conducting plates or shelves to provide a low-inductance path among grounded components, as shown in Figure 30.

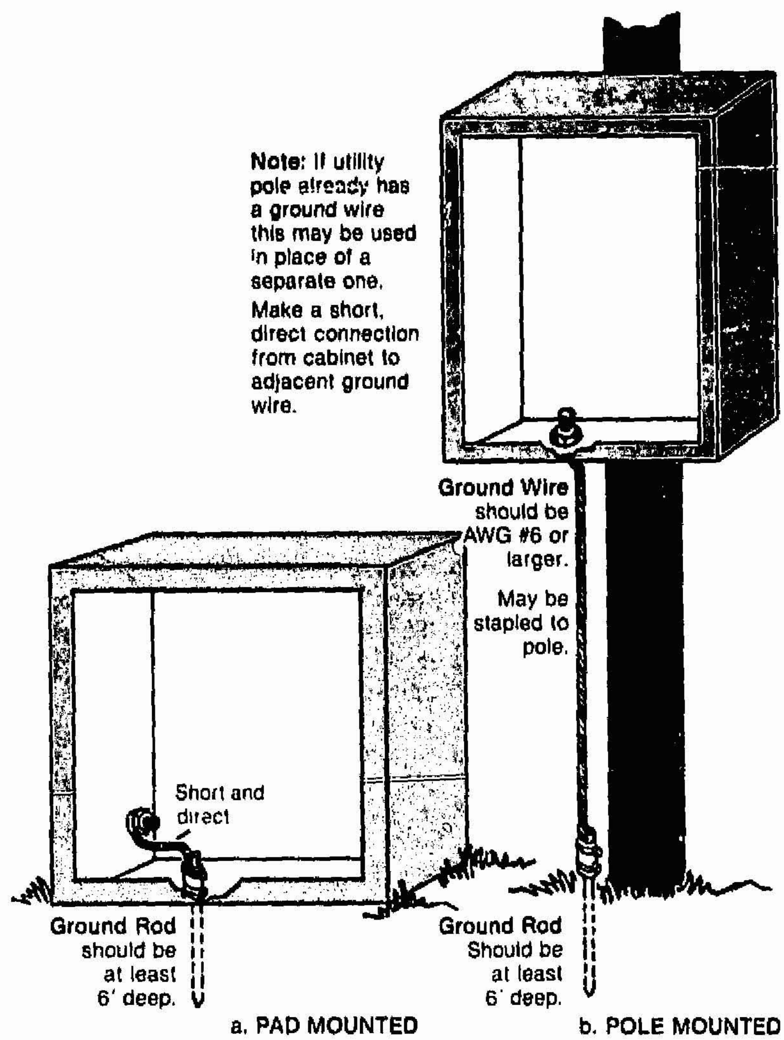


Figure 29. *Grounding of Control Cabinets.*

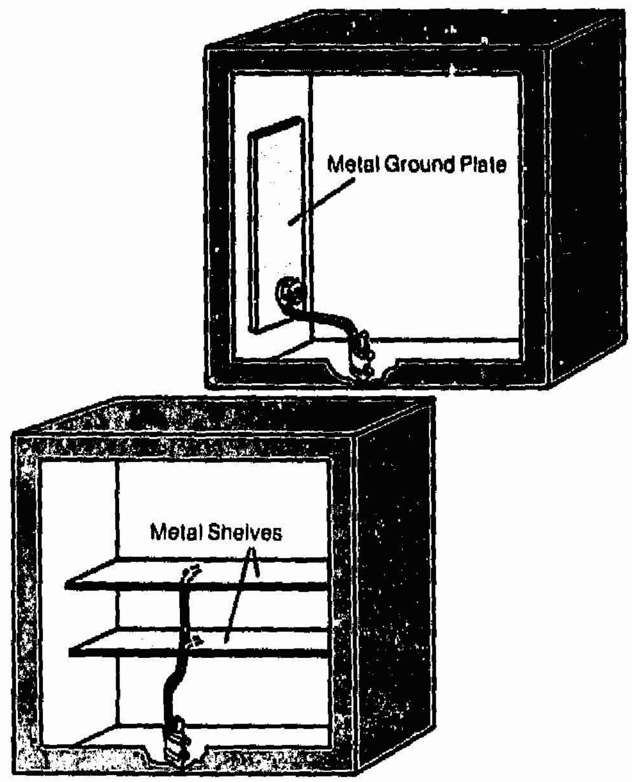


Figure 30. *Ground Plates or Shelves for Non-metallic Cabinets.*

Any sheet-metal that has adequate mechanical strength and anti-corrosive properties will be adequate for the grounding plates. All electrical connections should be made to bare metal.

All incoming conduits must be grounded to the plate or shelves. Thus, if the conduits arrive at a wall the ground plate should be fastened to the same wall so that the conduits will be grounded to it by their retaining nuts as shown in Figure 31.

3.2.2 Wires Entering Controller Cabinets

Since all wires extending away from a control cabinet are potential sources of lightning-induced surges, methods for suppressing these surges to tolerable levels are now described.

If it can be established that some incoming lines are not sources of damaging surges, these

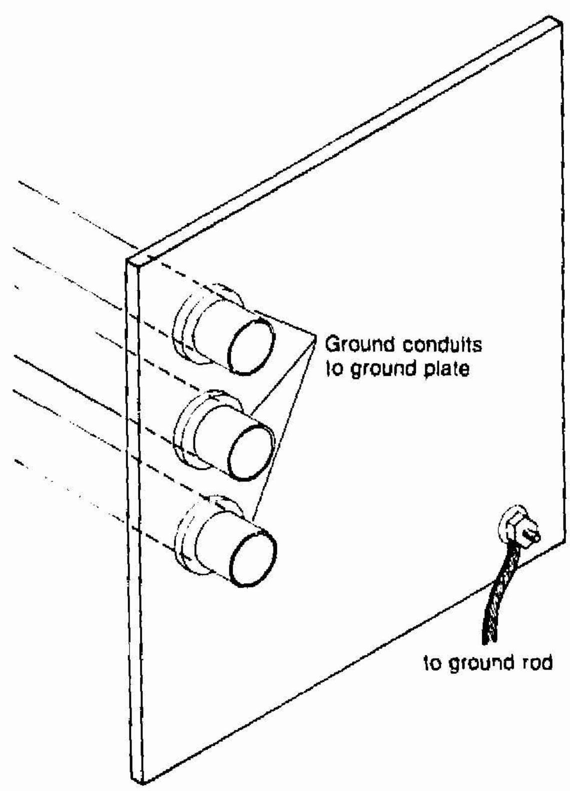


Figure 31. *Incoming Conduits Should be Grounded to Ground Plate Inside Controller Cabinet.*

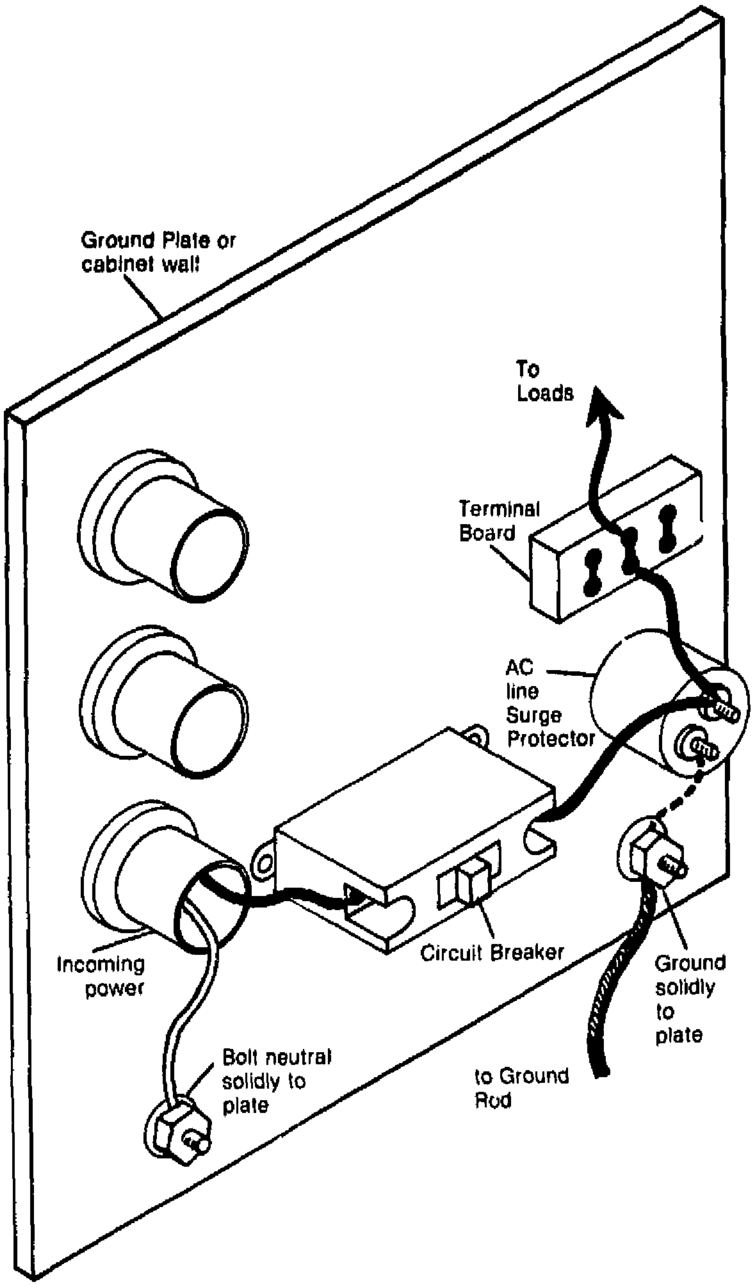


Figure 32. *Installation of AC Line Surge Protector.*

lines need not be protected. If, for example, only power-supply components in loop detectors and controllers have burned out and no other components in these units have been damaged, it is probably sufficient to protect only the incoming 115 VAC power lines and leave detector and control circuits unprotected. On the other hand, if no clear pattern exists, it is better to protect all of the incoming lines. Methods for protecting each type are given in the following paragraphs.

3.2.2.1 AC Power

A. AC power is normally supplied by the power company from overhead distribution wires. These overhead lines are subject to direct lightning strokes and are a frequent source of damaging surges, as described in Para 2.4. Since the power distribution system is outside of the traffic engineer's control, there is no practical method of controlling the incoming surges. Instead, these surges must be suppressed where they enter the controller cabinet.

Suppression may be accomplished by installing AC line surge protectors (also referred to as a "home lightning arrester," "lightning surge arrester," "power line protector," "secondary power arrester," etc.) between the 115 VAC incoming line and cabinet ground. The protector should be capable of:

- limiting the surge voltage to 3 kV peak, while
- conducting surge currents of at least 10 kA with an 8 x 20 μs (time to crest x time to second half-crest) waveform, and
- recovering to its former state after the surge is over with AC power applied, and
- the manufacturer of the AC suppressor shall certify that the suppressor meets the requirements of ANSI C62.1-1975/ IEEE Std. 28-1974 Para. 7.1 and 7.6 (Reference 7). The suppressor peak voltage shall not exceed 3 kV when tested per Para 7.3 and 7.5 of the ANSI/ IEEE specification.

Normally, a hybrid-type protector containing a spark gap and non-linear device must be utilized to meet these requirements, but some larger sized varistors that are capable of meeting this requirement have recently become available.

B. The AC line surge protector should be installed on the load side of the circuit breaker, so that if the protector should fail short, the circuit breaker will open to give maximum protection. The arrester leads should be kept as short as possible. Grounds should be made directly to the cabinet wall (or ground plate) as near as possible to the object being grounded. An acceptable arrangement is shown on Figure 32.

C. If the AC power is brought into the cabinet via an underground conduit, a similar arrangement should be followed, as shown in Figure 33. If the conduit is metallic, it should be connected to the ground rod as shown.

D. Connections from the ground rod to other objects inside the controller cabinet should be made with AWG No. 8 (or larger) copper wire. It may be stranded or solid.

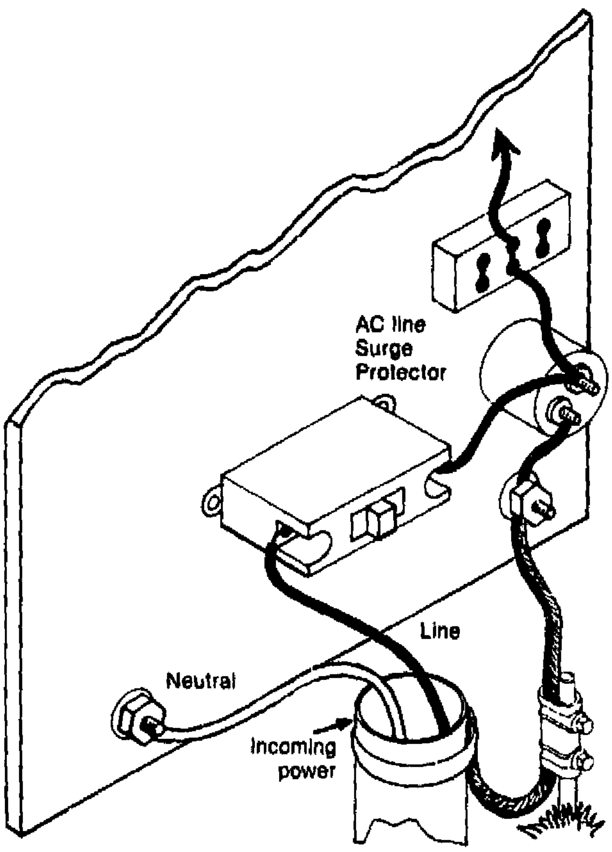


Figure 33. *Installation of Line Surge Protector when AC Power Is Fed through Underground Conduit.*

3.2.2.2. **Interconnecting Signal Wires** When several intersections on a main thoroughfare are synchronized together, the intersections must be interconnected by signal wires. These wires may be shielded or unshielded, and suspended overhead or buried in a conduit. Operating voltage levels of these circuits range from a few volts DC to 120 volts AC.

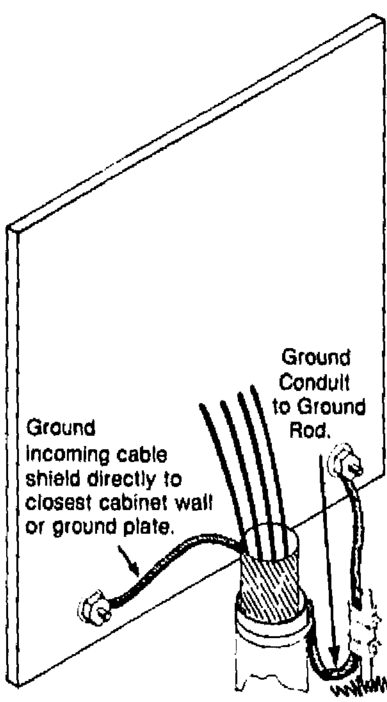
A. Wherever possible, it is recommended that signal lines be carried in shielded cables, with the shields grounded at both ends.
It may be impractical to provide a shield for signal lines already in existence. In these cases, protection will have to be provided by surge suppressors installed in the cabinets at each end of the line.

If a shield is already present, it should be inspected to determine if:

1. it is continuous along the entire length of the line
2. each end of the shield is grounded to the controller cabinet

If, as is often the case, either of the above conditions are not met, the shield will offer little or no protection. If cases like this are found, they should be corrected before additional protective measures (such as surge suppressors) are added.

B. The most effective shields are constructed of aluminum or copper foil which is folded around the circumference of the cable (as provided in telephone cables) such that the shield resistance does not exceed 4 ohms per mile. Some other types of shields, such as spiral-wrapped foils which do not make edge-to-edge contact around the spiral, are much less effective. Examples of how existing shields should (and should not) be grounded are shown in Figure 34.



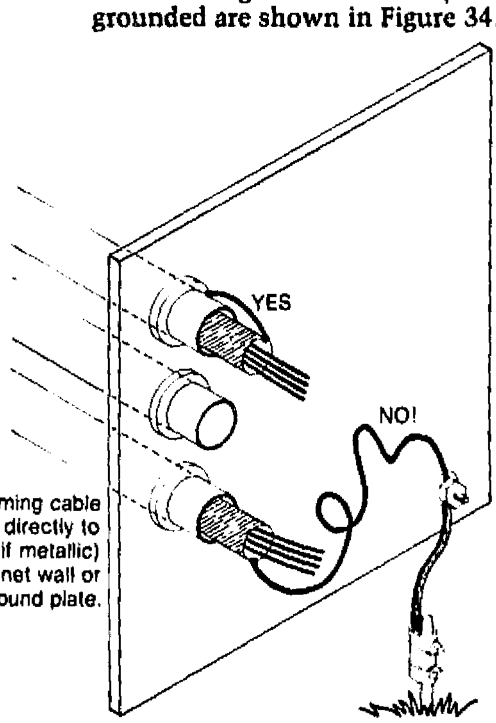


Figure 34. *Grounding of Signal Cable Shields.*

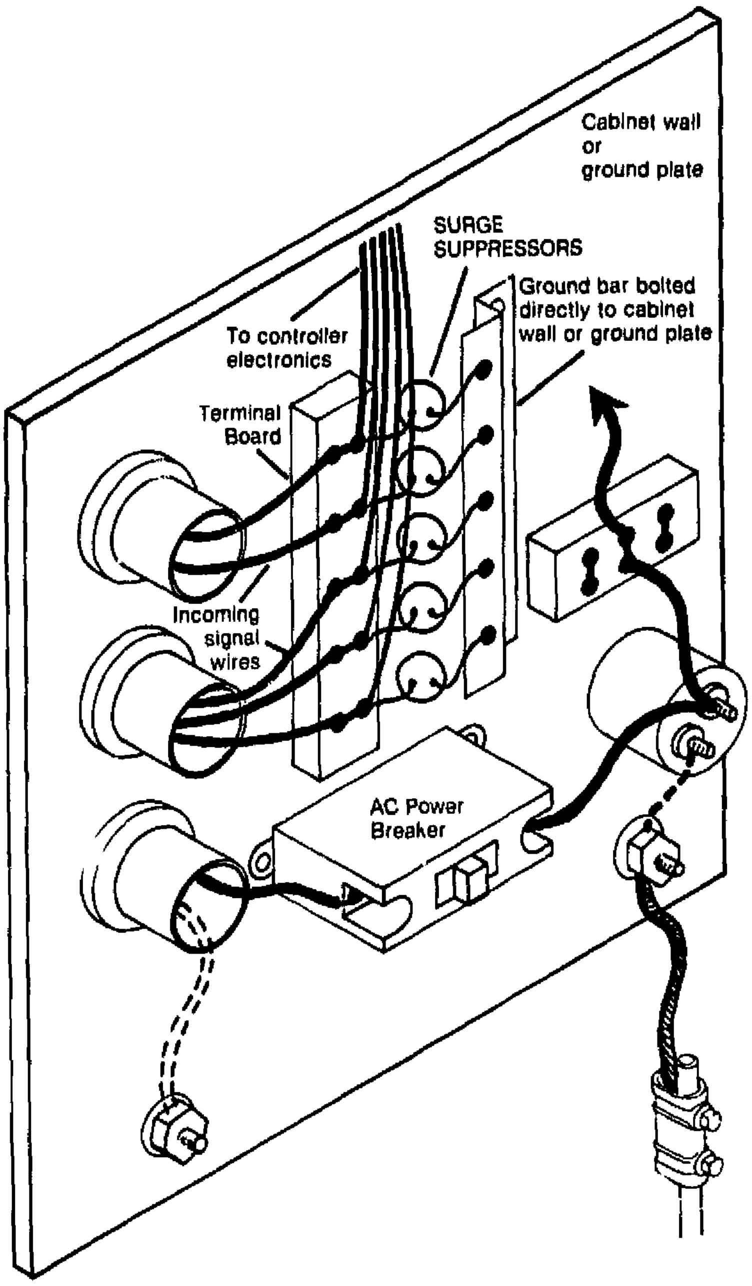


Figure 35. *Installation of Surge Suppressors on Incoming Signal Cable Conductors.*

If failures continue after the above shielding improvements have been made, or if no shielding improvements can be made, surge suppressors should be installed between each of the incoming signal conductors and ground. The suppressors utilized should have the following capability:

1. Clamp the surge to as low a voltage as possible, ideally to about twice the peak operating voltage of the circuit being protected, and
2. Be capable of conducting a surge current of at least 1,000 amperes at an $8 \times 20\ \mu s$ waveform without damage to itself, and
3. Be capable of dissipating at least 40 joules of energy without damage to itself, and
4. Be capable of suppressing 6 surges in rapid (1-second) succession as described in (1), (2) and (3) above without degradation of performance.

C. Signal-line suppressors should be installed as close as possible to the point where the lines enter the controller cabinet. A preferred arrangement is shown on Figure 35. Occasionally, a number of surge suppressors packaged in one unit are available. Such units may be utilized in place of the individual arrangement shown on Figure 35 if the suppressors contained within it meet the performance requirements listed above. In either case, *it is particularly important that suppressor leads be kept as short as possible.* The principle to follow is illustrated in Figure 36.

3.2.2.3 **Vehicle Detector Loops** Vehicle detector loops are unshielded, insulated wires buried in the street pavement. The two ends of this loop feed directly into solid state circuits in the loop detector units. As explained in Para. 2.5, the detector loops are capacitively coupled to the earth and receive a voltage surge whenever lightning currents enter the earth somewhere nearby and cause an earth voltage rise. Since it is impractical to modify detector loops already in existence, the surges must be suppressed where the detector loop wires enter the controller cabinet or where these circuits enter the loop detector units.

Because they are capacitively coupled, the induced-voltage surges contain comparatively little energy, and back-to-back zener diodes usually provide adequate protection. Some loop detector units are available with zener diodes already incorporated in them, and these have had a lower

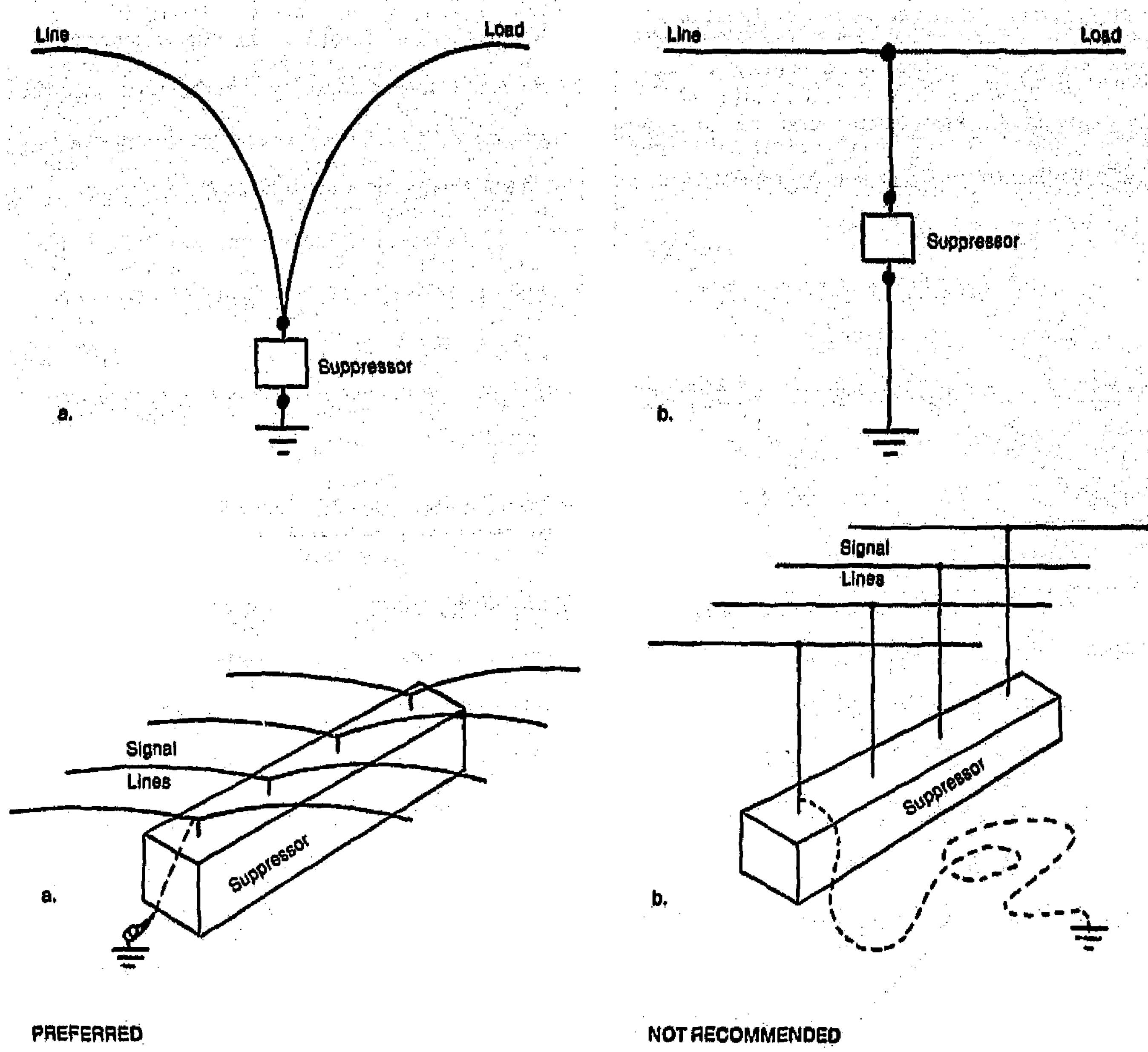


Figure 36. *Principle to Follow when Installing Suppressors: If long wires must be used to reach suppressor bring the protected line to the suppressor as in a) Do not use long suppressor leads as in b).*

lightning failure rate than unprotected units, but in some cases even "protected" units have failed. Protection can be improved as follows.

Where units without zener diode protection are present, zener diode protectors should be installed line-to-line and one line-to-ground where the loop circuits enter the controller cabinet. The diodes used should have the following capability:

1. be back-to-back or bipolar devices
2. be rated at 10 volts and 5 watts

A preferred installation arrangement is shown in Figure 37. As in protection of other circuits, the protector leads must be kept very short.

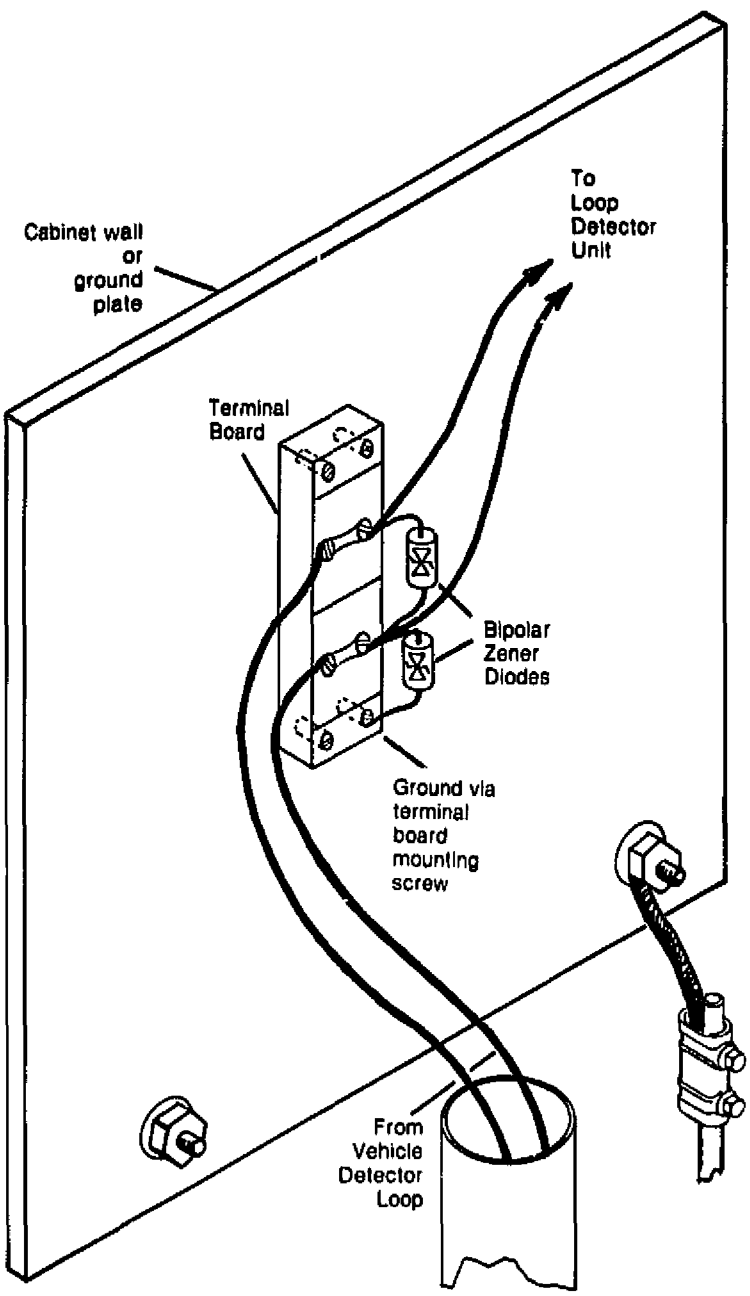


Figure 37. *Installation of Protection for Loop Detectors.*

3.2.2.4 **Signal Head Power Wires** Even though most signal lamp power is controlled by solid-state relays (using triacs), few lightning problems associated with the lamp circuits have been reported. The reason is that the triacs and other components in the lamp circuits are more rugged than most other components in the signal system because they must tolerate the surges that occur each time a light is switched on. When lightning-induced voltage surges appear in the more-sensitive triac trigger circuits, they may cause the triac to trigger, at which time the surge would pass back into the lamp power system. The triac would shut off again when the first AC zero-crossing occurs, resulting in no permanent effects.

In the few cases where lamp switching units have been damaged during thunderstorms, protection can be improved by installing AC line surge protectors between the 115 VAC lamp power wires and cabinet ground. The protector used should have the same capabilities as recommended for protection of incoming AC power circuits in Para. 3.2.2.1, and be installed in the controller cabinet near the place where the lamp wires enter.

3.2.2.5 **Telecommunication Lines** In some cases, central computer connections to individual intersections are provided via local telephone company lines. The telephone company usually provides carbon-block spark gap suppressors at both ends of their lines. These suppressors will generally limit surges between the telephone lines and ground to 1,000 volts or less. Conventional telephone relaying equipment can tolerate surges of this magnitude, but modern solid-state switching units or other equipment associated with the municipal signal system may be vulnerable to such surges. In these cases, secondary protectors, selected to clamp the surges to lower voltages, are required.

A. The secondary protectors should be capable of:

1. Clamping the surge to as low a voltage as possible; ideally to about twice the peak operating voltage of the equipment being protected.
2. Dissipating at least 20 joules of energy without damage to themselves.
3. Suppressing 6 surges in rapid (1 second) succession as described in (1) and (2) above without degradation of performance.

A varistor is most suitable for this application.

B. The secondary protectors should be isolated from the primary protectors by either:

1. at least 15 feet (4.5 meters) of circuit length, or
2. at least 10 microhenrys of lumped inductance, or
3. at least 10 ohms of resistance. If 50 ohms of resistance can be inserted in the line between primary and secondary protectors without degrading signal circuit operation, a 5-watt bipolar or back-to-back zener diode can be used as the secondary protector.

C. **Note:** Neither the primary nor secondary protection will function properly unless the suppressors (and cable shields, if present) are solidly grounded to the cabinet ground. *Short* suppressor leads are necessary to provide maximum protection.

3.2.2.6 **Pedestrian Signal Lines** Pushbuttons are present at some intersections for pedestrians' use in calling for a walk light. The wires running from the switches to the controller units are a source of lightning-induced surges, but the surges rarely reach the controller electronics due to the isolation provided by the coupling transformers or relays which are usually present.

A. In cases where burnouts of electronic components attached to these pedestrian signals do occur, varistors should be installed from each incoming line to cabinet ground where these circuits enter the cabinet. The varistors should have the following capability:

1. Clamp the surge to as low a voltage as possible, ideally to about twice the peak operating voltage of the circuit being protected, and
2. Be capable of dissipating at least 10 joules of energy without damage to itself, and
3. Be capable of suppressing at least 6 surges (within 1 second) as described in (1) and (2) above without degradation of performance.

B. The suppressors should be installed in the manner shown in Figure 35.

3.2.3. CENTRAL COMPUTERS

In some jurisdictions the operation (and monitoring) of a number of intersections is controlled from a centrally located computer. Control and monitor signals travel between this computer and the intersections on aerial or buried cables installed expressly for this purpose, or via leased telephone lines. Lightning-induced surges on these lines may damage computer electronics.

Lightning surges, of course, may also enter a computer via power distribution lines. As discussed in Para. 2.4, surges of up to 10 kilovolts may appear at unprotected service entrances, and even with a power line surge protector present, up to 3000 volts or so may pass on into the computer. Since some computer power supplies cannot tolerate surges of this magnitude, it may be necessary to apply secondary protection at the computer power supply. Protection against surges originating from both sources may be accomplished as follows:

A. Surges originating in **signal** lines may be suppressed by installation of suppressors between each incoming line and ground. The suppressors utilized should have the following capability:

1. Clamp the surge to as low a voltage as possible, ideally to about twice the peak operating voltage of the circuit being protected, and
2. Be capable of conducting a surge current of at least 1,000 amperes at an $8 \times 10\ \mu s$ waveform without damage to itself, and
3. Be capable of dissipating at least 40 joules of energy without damage to itself, and
4. Be capable of suppressing 6 surges in rapid succession as described in (1), (2) and (3) above without degradation of performance.

A varistor or back-to-back zener diode device is most suitable for this application.

These secondary protectors should be installed as far from the primary protectors (if present) as possible. This idea is illustrated in Figure 38. If the signal cables running between the primary and secondary protectors are shielded, the cable shields should be grounded at each end. If the signal cables running between the primary and secondary protectors are **not** shielded, a ground wire should be run along with each cable. This may be a presently unused wire, with its ends grounded at the same places the primary and secondary protectors are grounded.

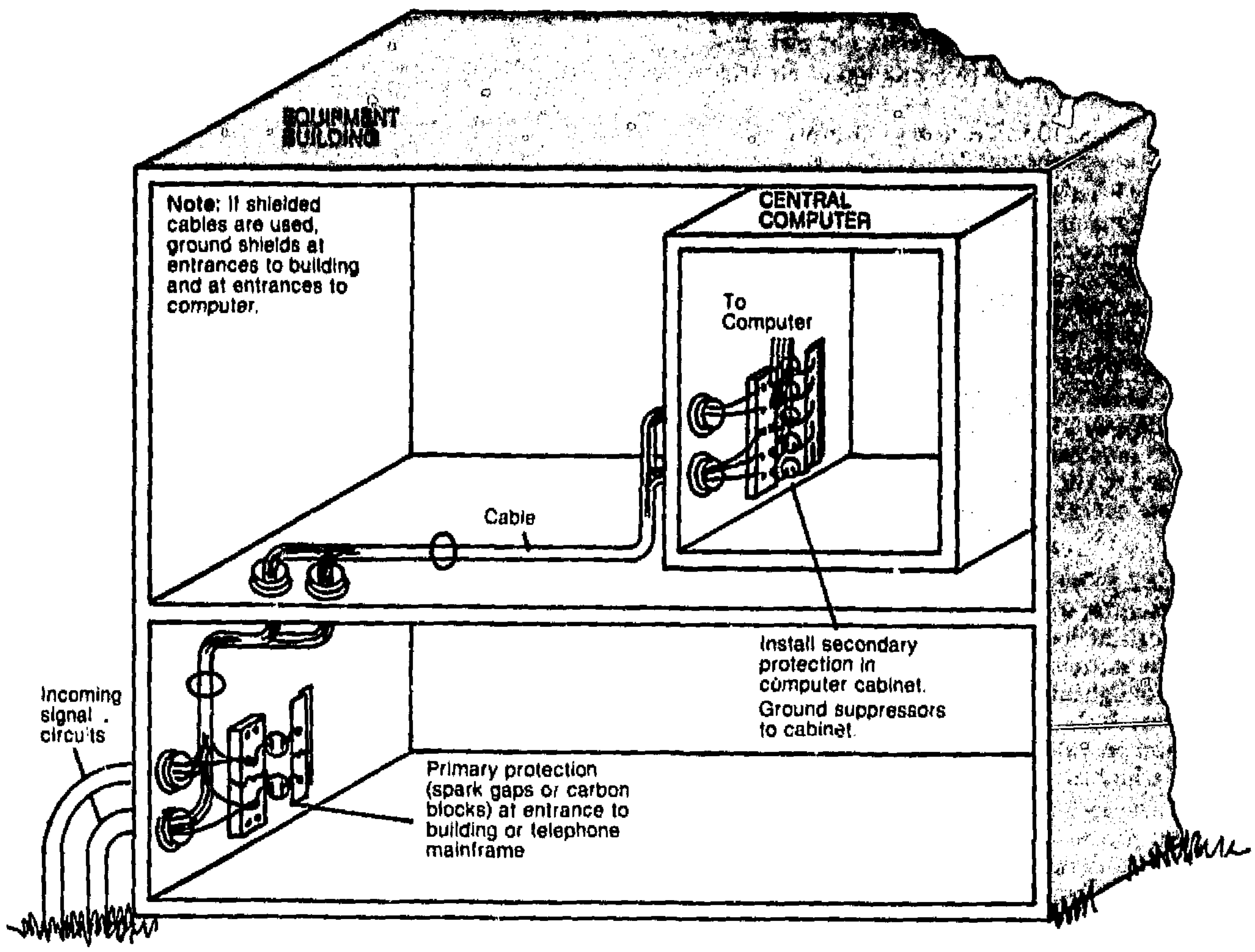


Figure 38. *Protection for Central Computer Signal Circuits*

B. Surges originating in **power** lines may be suppressed by installation of secondary suppressors between each incoming power line and ground. When a primary protector (AC line surge protector) meeting the requirements of Para. 3.2.2.1 is present, the secondary suppressors should have the following capability:

1. Clamp the surge to 600 volts (for 115 VAC lines) while conducting a surge current of 100 amperes, and
2. Be capable of dissipating at least 20 joules of energy without damage to itself, and
3. Be capable of suppressing 6 surges in rapid succession as described in (1) and (2) above without degradation of performance.

A varistor is most suitable for this application.

Note: If no primary protector is present at the AC power service entrance to the buildin: primary protectors having the capabilities listed in Para. 3.2.2.1 should also be provided. The locations of primary and secondary protectors for a central computer located within a building are shown in Figure 39.

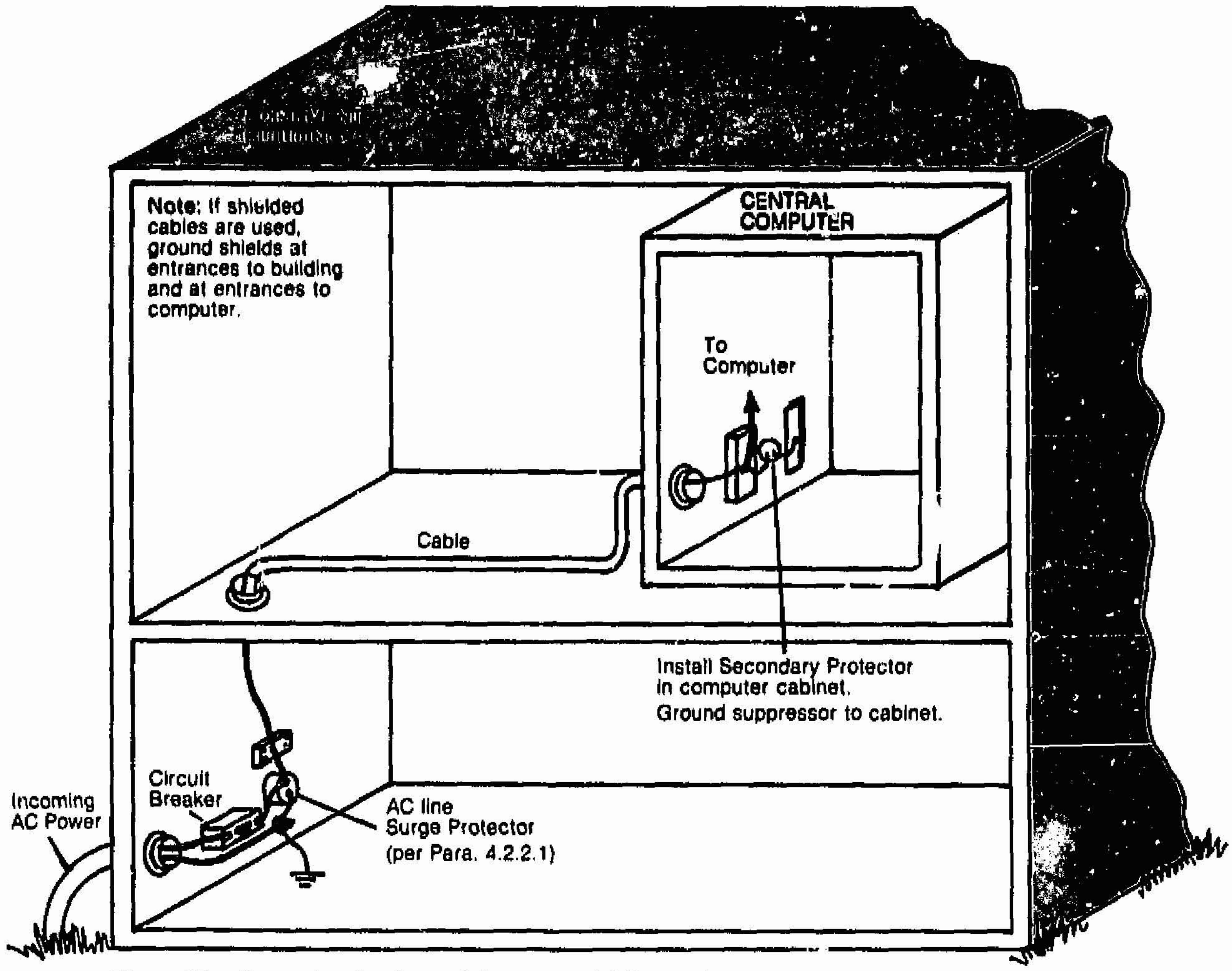


Figure 39. *Protection for Central Computer AC Power Circuits.*

CHAPTER 4 Protection of New Systems

4.1 INTRODUCTION

The protection techniques suggested in Chapter 3 are applicable for new systems. However, shielding to reduce the transient susceptibility and suppression to reduce equipment vulnerability can be considered and incorporated during the design stage. This way, the cost of the lightning protection will be minimized and its effectiveness improved.

4.2. TRANSIENT CONTROL LEVEL PHILOSOPHY

At the present time, industry standards do not offer sufficient guidance to the designers and manufacturers of most electronic equipment as to what types of transients to consider and how to prove that equipment works in the presence of these transients. The situation is under some control in the electric power field where the Institute of Electrical and Electronics Engineers (IEEE) Surge Protective Devices Committee has a Working Group on Surge Voltages in AC Power Circuits Rated 600 Volts and Less which has been gathering data on surges for the past several years. The working group is now in the process of preparing a guideline document describing the transient environment (Reference 8). Also the IEEE Power System Relaying Committee, after collecting information on power substation transients, has issued a test standard called the Surge Withstand Capability (SWC) test (Reference 9). High voltage transmission apparatus has long been designed to meet standard insulation levels called Basic Insulation Levels (BIL's). The equipment system insulation is designed to meet specific BIL's and the equipment is subjected to proof tests.

In an attempt to provide similar standards for electronic equipment, discussion has been initiated to establish low voltage industry standards for transient protection similar to the BIL system (References 11, 12, 13). The newly proposed levels for electronics have been termed Transient Control Levels (TCL's).

The objective of the TCL proposal as illustrated in Figure 40 is to establish transient levels that electronic equipment manufacturers must withstand at their equipment terminals. The proposal applies also to the cable system designer who must insure that the actual transients on the cables do not exceed the TCL levels. The designated TCL's must therefore be a compromise since, if no protection was provided by the cables, the electronics would have to withstand overly severe transients or if the cables were heavily shielded to eliminate transients, the electronics might need no protection at all. The TCL system therefore implies a role for the cable system designer as well as the designer of the electronics. The cable system designer's job is to ensure that actual transients do not exceed the transient control level, whereas the electronics designers must ensure that the electronics can withstand voltages higher than the transient control level.

The degree of protection which can be afforded by the cable system will usually determine the

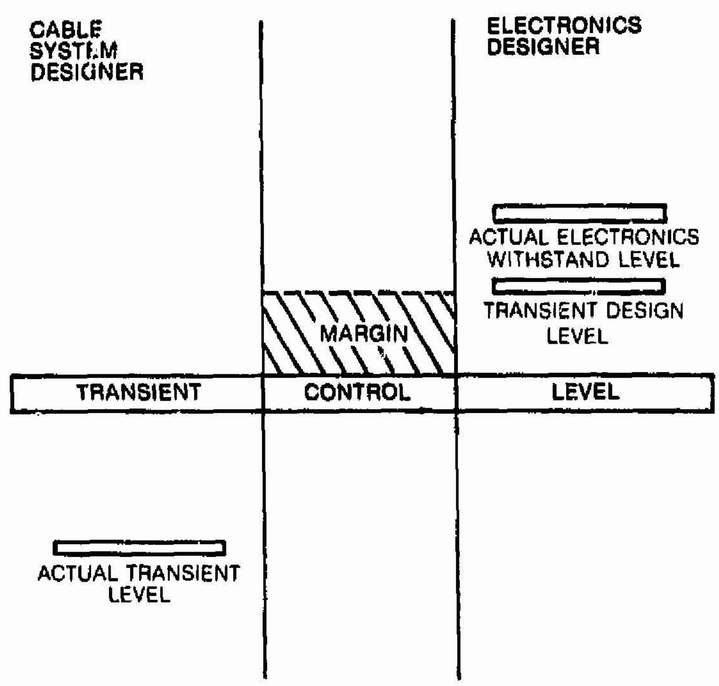


Figure 40. *The Transient Control Level Philosophy*

Proposed Transient Control Level Number	Open Circuit Voltage Level (volts)	Short Circuit Current Level (amperes)
1	15	1
2	30	2
3	60	4
4	150	10
5	300	20
6	600	40
7	1500	100
8	3000	200
9	6000	400
10	15000	1000

Table V. *Proposed Transient Control Levels*

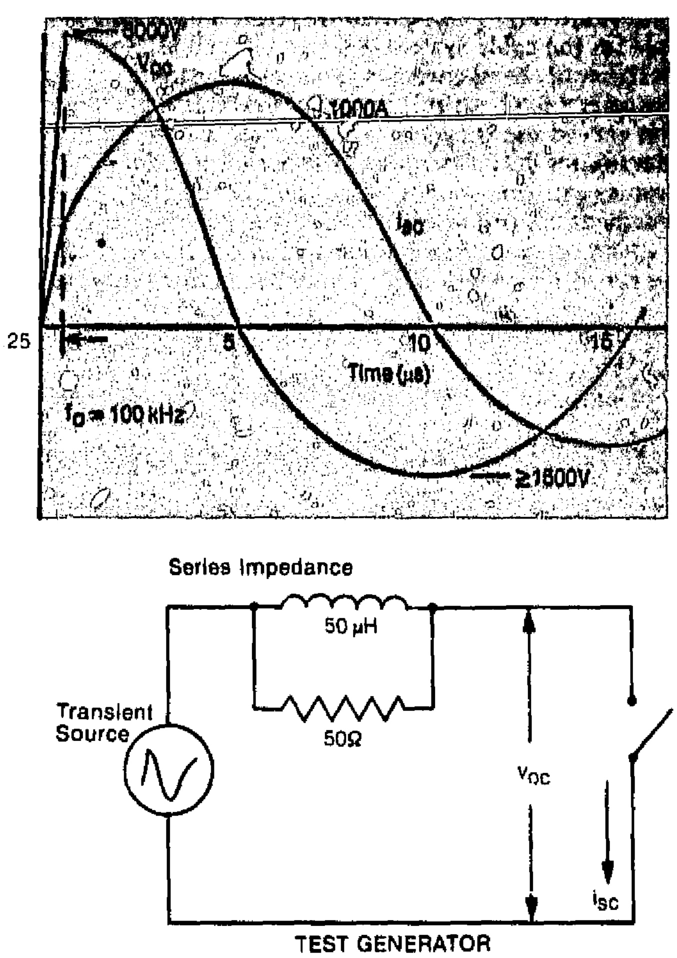


Figure 41. *Short Circuit Current (I_{SC}) and Open Circuit Voltage (V_{OC}) from a Test Generator with a 50Ω/50μH Source Impedance.*

TCL level. The signal cables described in Chapter 2 will deliver transients which can be assigned a level, such as 9. The addition of a second shield to the cable, grounded at both ends, will reduce the delivered transient to a lower level such as 6. However, the cost of a double-shielded cable will often be higher than the cost of designing the equipment to accept the higher transients.

To implement the TCL concept, testing of the electronics is required. The tests may be performed either by the manufacturer appropriately witnessed or certified, or by the user upon receipt of the equipment. Either way, acceptance tests to prove that the equipment will withstand the specified TCL tests must be made. Table V presents a set of Transient Control Levels proposed by Fisher and Plumer (Reference 10). The TCL's are presented in terms of open circuit test generator voltage and the current which this voltage surge will drive into a short circuit. This is the maximum current available from the test generator. Figure 41 shows a proposed test generator and its open circuit voltage and short circuit current waveforms. The waveforms shown are representative of lightning-induced transients. The test generator source impedance necessary to achieve the proper relationship between generator open circuit voltage and short circuit current has been the subject of much discussion and a 50 ohm/50 microhenry value has been suggested by Fisher and Martzloff in Reference 11.

For tests of traffic control equipment, an increase in the short circuit current associated with each voltage level is needed. This is because traffic control systems are more exposed to lightning effects than most other electronics. Table VI and Figure 42 show TCL levels and a generator which will produce more severe short circuit currents. These tests would be applied to all electronic components, with the exception of the loop detector amplifier where the higher impedance (50 ohm) generator would be adequate.

4.3 TRANSIENT CONTROL LEVEL TESTING

It should be understood that the TCL philosophy is not written around any particular surge generator. Any surge generator that will produce the specified open-circuit voltage and short-circuit current will be satisfactory.

4.3.1 Types of Tests

Experience has shown that much confusion can surround two seemingly simple questions:

1. Why is the test being made? and
2. How severe should the test be?

There are two reasons for performing TCL tests, as illustrated in Figures 43 and 44. Tests are performed to determine which level a piece of

Proposed Transient Control Level Number	Open Circuit Voltage Level (volts)	Short Circuit Current Level (amperes)
1	15	5
2	30	10
3	60	20
4	150	50
5	300	100
6	600	200
7	1500	500
8	3000	1000
9	6000	2000
10	15000	5000

Table VI. *Proposed Transient Control Levels for Traffic Control Equipment*

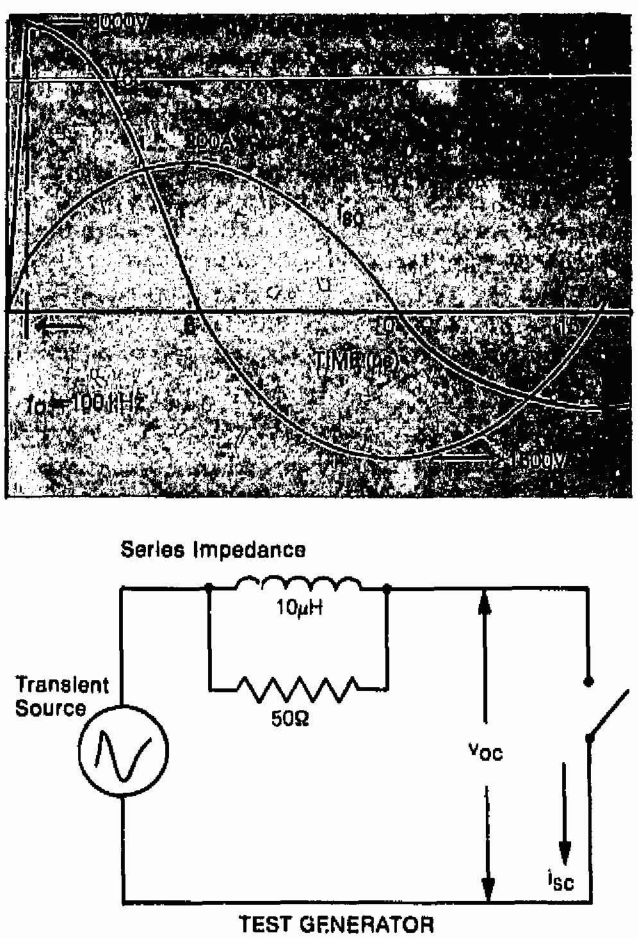


Figure 42. *Proposed Test Generator and Waveforms for Traffic Control Equipment.*

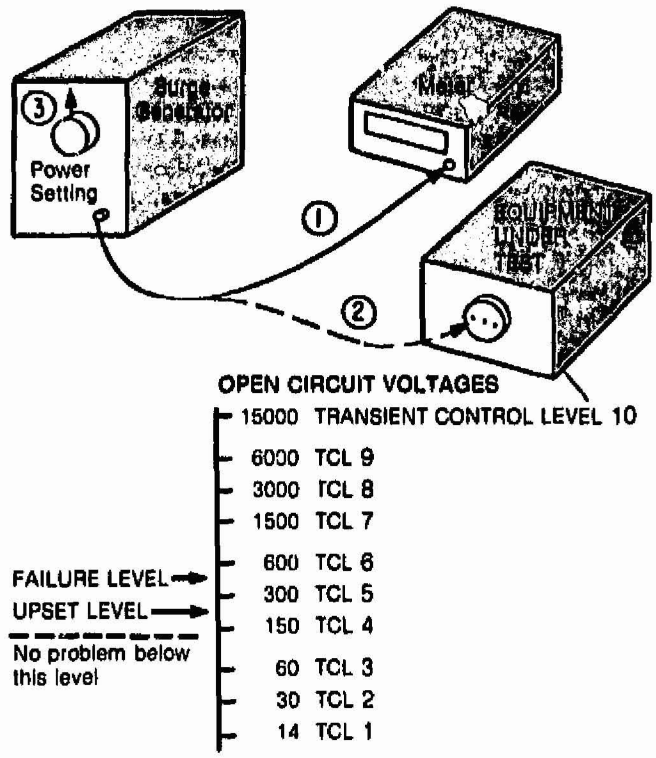


Figure 43. *Determining Upset or Failure Levels of a Piece of Equipment.*

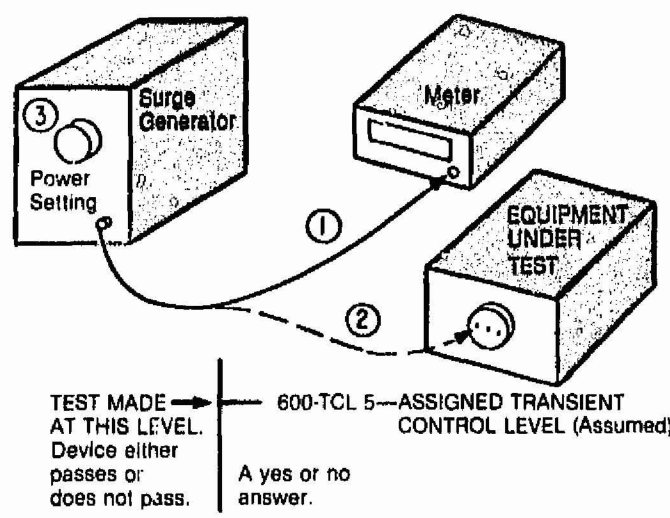


Figure 44. *Acceptance Tests on a Piece of Equipment.*

equipment can withstand as in Figure 43, and to determine if the equipment meets a required level as in Figure 44. In the first type of test, increasing test voltage levels are applied and the equipment performance is monitored to determine when malfunctions begin. When the malfunction voltage level has been determined, without making any changes in the generator setting, the generator is disconnected and the **open circuit voltage level** is measured. The next lower TCL voltage level is then taken to be the equipment capability.

In the second type of test, the generator settings are adjusted until the specified TCL open circuit voltage level has been attained. The equipment is then connected and the test applied. If the equipment is undamaged, it has passed the test, if damaged, it failed. Damage is defined as acceptable equipment behavior (within the manufacturer's specification) during and after the test.

Test severity, the second question, has been addressed indirectly in answering the first question. If the test levels were defined only in terms of the voltage applied to equipment terminals, then unduly high *currents* would be required in an attempt to apply that voltage level to a piece of equipment with a suppressor on its input. If the transient were defined only in terms of surge current, unduly high *voltages* would be required to force that current into a high impedance circuit.

Hence, the TCL levels are defined in terms of generator open-circuit voltage and short circuit current.

4.3.2 Test Equipment

Surge generators capable of producing the required open circuit voltages and short circuit currents generally employ capacitors that are discharged into waveshaping circuits.

A typical surge generator circuit is shown in Figure 45. The generator is configured to superimpose the transient on a live AC power line. The isolation transformer prevents inadvertent grounding of the hot line and allows the neutral side of the power circuit to be grounded. The switch (SW) can be electronically controlled to apply the test surge at a predetermined time on the 60 Hz power wave. Spark gap switches are generally used in generators with charging voltages above 2000 volts. Components should be chosen and laid out in such a manner as to minimize undesired inductance and radiated interference. Circuit voltages are high enough to be hazardous so appropriate safety precautions are required.

4.3.3 Acceptance Test Procedures

Acceptance or proof tests performed on traffic control equipment should be carried out as follows:

a) The equipment shall be energized and its functional operation demonstrated in accordance with manufacturing instructions. The demonstration shall cover all features.

b) The surge generator shall be set to provide the specified TCL open-circuit (OC) voltage and short-circuit (SC) current. These levels shall be verified by open-circuit and short-circuit tests prior to testing the equipment. **Note:** Where the TCL is to be superimposed on power or signal voltage, this voltage will be deenergized **prior** to open-circuit and short-circuit current tests.

c) Without changing the surge generator settings, the generator shall be connected to the equipment input terminals. The equipment shall be energized and connected to its normal loads (real or simulated). Twelve (12) test surges shall be applied, 6 of positive polarity and 6 of negative polarity. Tests shall be applied between each input terminal and ground as well as between the two input terminals of a circuit pair.

When the TCL surges are superimposed on 60 Hz power, the application of the waves shall be timed so that two (2) surges occur at the zero cross-

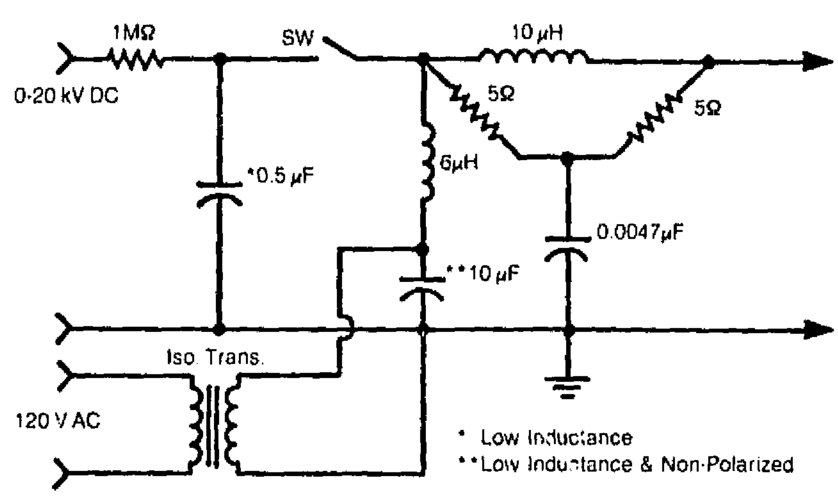


Figure 45. *Schematic Diagram for a Transient Surge Generator for Testing Traffic Control Equipment.*

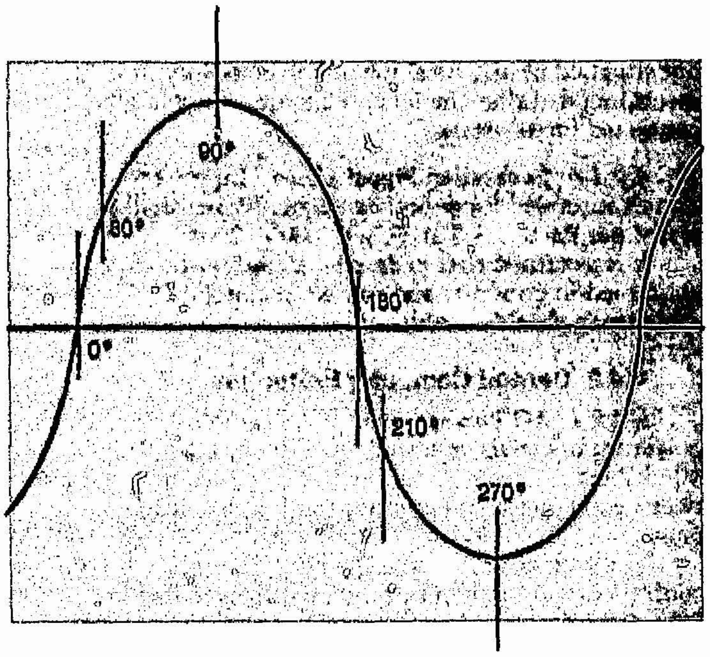


Figure 46. *Timing of Applied TCL Test Surges on 60 Hz Power Lines.*

ing, two (2) at ½ peak voltage (30° electrical) and two (2) at peak voltage (90° electrical) as shown in Figure 46.

d) The equipment shall be monitored for improper operation during the tests and shall perform in accordance with its specifications after test as evidenced by repeating the same functional tests as in step (a) above.

4.4 TYPICAL LIGHTNING PROTECTION SPECIFICATIONS FOR TRAFFIC CONTROL EQUIPMENT

The following TCL test levels are recommended for traffic control equipment by the authors and are based on present, customary wiring practices. A description of the wiring practices accompanies each recommendation. If other wiring practices are used, the recommended TCL does not apply and another level, either higher or lower, must be selected.

If a piece of equipment is procured according to the TCL standards recommended below and fails in service, it means that (1) the recommended TCL was in error, or (2) the cabling practice was not followed or properly installed.

4.4.1 Controller Cabinets at Intersections

Intersection controller cabinets may be purchased either complete with all electronic components already installed, or as separate components with the system assembled by the user on site.

When a pre-assembled cabinet is procured, terminals common to several electronic components may be tested at once. Thus a TCL test must be applied to the control signal and AC power line input to the *cabinet* with all components installed; but need not be applied to each individual component within the cabinet.

Since some controllers are procured as separate components, most manufacturers will want to test their equipment on an individual component (i.e., loop detector-amplifier, contro' er, etc.) basis. The following specifications, therefore, are written as though the equipment was being procured separately and assembled by the user on site.

4.4.1.1 **AC Power Terminals** Input power terminals of controller cabinets or other complete assemblies shall be tested in accordance with Para. 4.3.3 at TCL 10 (15 kV OC, 5 kA SC). In addition, the manufacturer of any lightning protectors incorporated in the equipment (or in the cabinet) shall certify that the protector meets the requirements of ANSI C62.1-1975/IEEE Std. 28-1974 Para. 7.1 and 7.6 (Reference 7). The suppressor peak voltage shall not exceed 3 kV when tested per Para. 7.3 and 7.5 of the ANSI/IEEE specification.

Input power terminals of equipment contained within a controller cabinet which is protected by a protector which meets the above requirements shall be subjected to TCL 8 (3kV OC, 1kA SC). If no such protection is provided, the equipment must be tested at TCL 10.

Since the local power company determines the type of power distribution wiring used to feed the controller cabinet, open and unshielded AC power distribution wiring configurations were assumed for the above recommendations.

4.4.1.2 **Control Signal Terminals** Terminals connected to interconnect wires placed between coordinated intersections shall be tested per Para. 5.2.3. at TCL 9 (6 kV OC, 2 kA SC). The equipment shall be tested with normal signal voltages on the terminals.

The signal cables between intersections should be shielded as described in 3.2.2.2B. The shield must be electrically continuous from end to end. If the shield is broken between the ends, at a junction for example, a lo· · inductance connection across the junction must be provided. It is preferable to enclose the entire junction in a conducting, metal enclosure connected to both ends of the opened shield.

4.4.1.3 **Detector Loops** Amplifier terminals to be connected to wire loops buried in the roadway shall be tested per Para. 4.3.3. at TCL 7 using the 50-ohm TCL generator (1.5 kV, OC, 100 A SC). An air core inductor representing the average loop inductance specified by the manufacturer shall be connected between the loop input terminals during tests.

The sensor loop wires are to be shielded to reduce lightning induced transients. As shown in Figure 47, after inserting the loop wires into the pavement, a single AWG #14 insulated wire is placed over the loop and lead-in wires to the controller cabinet. This shield wire protects the loop from capacitive (E-field) induced voltages. In this particular instance, only one end of the wire is to be grounded, the opposite end must be left floating (ungrounded). If it is grounded at both ends the loop detector amplifier will not operate since the detector loop will be shorted.

4.4.1.4 **Signal Head AC Power** The terminals which supply AC power to the signal head shall be tested per Para. 4.3.3 at TCL 7 (1.5 kV OC, 500A SC).

It is assumed that signal head power wires are routed next to or inside grounded structures, such as conductive standards or conduits on wooden poles, such that they are well shielded from direct lightning strikes. If the signal power wires are exposed to direct lightning strikes, then TCL 10 must be applied.

4.4.1.5 **Telecommunication Lines** Terminals on interface equipment connected to telecommunication type lines, computer date links, etc., shall be tested per Para. 4.3.3 at TCL 7 (1.5 kV OC, 500 A SC).

It is assumed that telecommunications cables will be shielded and protected in accordance with standard telephone practice. Where the lines are not supplied by the local telephone company, it is recommended that the local telephone company be contacted for assistance.

4.4.1.6 **Pedestrian Signal Lines** Input terminals intended for pedestrian signal wires shall be tested per Para. 4.3.3 at TCL 6 (600V, 200A).

It is assumed that pedestrial signal wires are contained in conduits and routed to control cabinets in shielded cables.

4.4.2 Central Computer Protection

4.4.2.1 **AC Power** Central computer AC power inputs shall be tested per Para. 4.3.3 at TCL 9 (6 kV OC, 2 kA SC). Tests will be applied between each phase and ground, and between each phase.

The service entrance AC power leading to the central computer shall be protected as specified in Para. 3.2.3B.

4.4.2.2 **Telecommunication Lines** Each pair of input telecommunication lines shall be tested per Para. 4.3.3 at TCL 7 (1.5 kV OC, 500A SC).

Telecommunication cables shall be shielded and protected in accordance with standard telephone practice at the entrance to the building or structure housing the central computer.

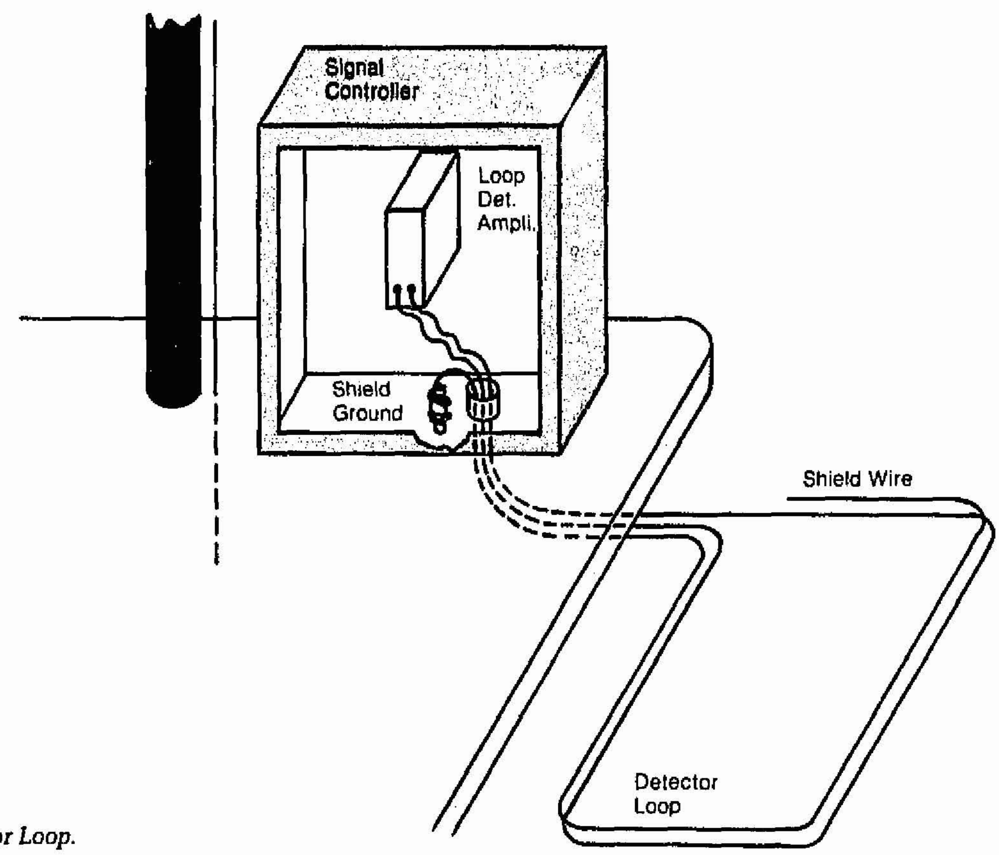


Figure 47. *Shielded Sensor Loop.*

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APPENDIX

Lightning Activity at Cities in the United States

The following data is for use in estimating the number of lightning-related problems to be expected in particular cities. Included are:

1. The **Isokeraunic Level** which is the average number of days on which thunder is heard in a year.
2. The **Total Flashes per Year** which is the total number of lightning flashes to be expected over areas of 1 square kilometer at one square mile during a year.
3. The **Flashes to Ground** which is the total number of lightning strikes expected to reach the ground in a year.

This data has been derived from statistics gathered by the World Meteorological Organization (WMO) over many years (Reference 2). As such, it is average data and the experience in any individual year may differ somewhat from that predicted.

City	Isokeraunic Level	Latitude	Total Flashes per Year per kM²	per mi²	Flashes to Ground per Year per kM²	per mi²
ALABAMA						
Anniston	60	33°40'N	21.1	54.6	4.7	12.3
Birmingham	67	33°34'N	25.4	65.9	5.7	14.8
Mobile	64	30°41'N	23.5	60.9	4.8	12.4
Montgomery	54	32°18'N	17.6	45.6	3.8	9.9
ARIZONA						
Flagstaff	35	35°12'N	8.4	21.8	2.0	5.2
Phoenix	26	33°26'N	5.1	13.2	1.2	3.0
Prescott	43	34°39'N	12.0	31.0	2.8	7.2
Tucson	35	32°07'N	8.4	21.8	1.8	4.7
Winslow	34	35°01'N	8.0	20.8	1.9	4.9
Yuma	10	32°45'N	1.0	2.6	.23	0.6
ARKANSAS						
Fort Smith	53	35°22'N	17.1	44.2	4.2	11.0
Little Rock	58	34°44'N	19.9	51.5	4.7	12.1
Texarkana	71	33°00'N	28.1	[illegible]7	6.2	16.1
CALIFORNIA						
Bakersfield	3	35°25'N	0.1	0.3	0.04	0.1
Beaumont	9	33°56'N	0.8	2.2	0.2	0.5
Eureka	3	40°48'N	0.1	0.3	0.04	0.1
Fresno	4	36°46'N	0.2	0.5	0.04	0.1
Los Angeles	3	33°56'N	0.1	0.3	0.04	0.1
Mount Shasta	14	41°17'N	1.8	4.6	0.5	1.3
Oakland	2	37°44'N	0.1	0.2	0.02	0.04
Red Bluff	9	40°09'N	0.8	2.2	0.2	0.6
Sacramento	4	38°31'N	0.2	0.5	0.04	0.1
San Diego	3	32°44'N	0.1	0.3	.04	0.1
San Francisco	2	37°45'N	0.1	0.2	0.02	0.04

City	Isokeraunic Level	Latitude	Total Flashes per Year per kM²	Total Flashes per Year per mi²	Flashes to Ground per Year per kM²	Flashes to Ground per Year per mi²
COLORADO						
Alamosa	51	37°26'N	16.0	41.4	4.1	10.6
Colorado Springs	68	38°49'N	26.1	67.5	7.0	18.2
Denver	44	39°46'N	12.4	32.2	3.4	8.9
Grand Junction	41	39°06'N	11.0	28.6	3.0	7.7
Pueblo	42	38°14'N	11.5	29.8	3.0	7.8
CONNECTICUT						
Hartford	27	41°44'N	5.4	14.0	1.6	4.1
New Haven	24	41°16'N	4.4	11.5	1.3	3.3
DELAWARE						
Wilmington	33	39°48'N	7.6	19.8	2.1	5.4
DISTRICT OF COLUMBIA						
Washington	35	38°51'N	8.4	21.8	2.3	5.9
FLORIDA						
Apalachicola	74	29°44'N	30.1	78.0	6.0	15.5
Daytona Beach	93	29°20'N	44.4	115.0	8.7	22.5
Fort Myers	91	26°35'N	42.8	110.8	7.6	19.7
Key West	57	24°35'N	19.3	50.0	3.2	8.3
Melbourne	88	28°06'N	40.4	104.7	7.6	19.7
Miami	70	25°49'N	27.4	71.0	4.8	12.4
Orlando	91	28°33'N	42.8	110.8	8.1	21.1
Pensacola	70	30°21'N	27.4	71.0	5.5	14.3
Tallahassee	78	30°26'N	32.9	85.3	6.7	17.3
Tampa	85	27°58'N	38.1	98.7	7.1	18.5
West Palm Beach	79	26°41'N	33.7	87.2	6.0	15.6
GEORGIA						
Albany	66	31°32'N	24.8	64.2	5.2	13.5
Athens	49	33°50'N	14.9	38.7	3.4	8.8
Atlanta	50	33°39'N	15.5	40.0	3.5	9.0
Augusta	41	33°28'N	11.0	28.6	2.5	6.4
Columbus	64	32°30'N	23.5	60.9	5.1	13.2
Macon	59	32°50'N	20.5	53.1	4.51	11.7
Rome	65	34°15'N	24.2	63.0	5.6	14.4
Savannah	53	32°01'N	17.1	44.2	3.7	9.5
Valdosta	69	30°53'N	26.7	69.2	5.5	14.3
IDAHO						
Boise	18	43°34'N	2.7	7.1	1.1	2.9
Lewiston	17	45°58'N	2.5	6.4	0.8	2.1
Pocatello	27	42°55'N	5.4	14.0	1.7	4.3
ILLINOIS						
Cairo	58	37°00'N	19.9	51.5	5.0	13.0
Chicago	37	41°47'N	9.3	24.0	2.7	7.1
Joliet	41	41°38'N	11.0	28.6	3.2	8.4
Moline	47	41°27'N	13.9	36.0	4.1	10.5
Peoria	47	40°40'N	13.9	36.0	3.9	10.2
Springfield	49	39°50'N	14.9	38.7	4.1	10.7

City	Isokeraunic Level	Latitude	Total Flashes per Year per kM^2	Total Flashes per Year per mi^2	Flashes to Ground per Year per kM^2	Flashes to Ground per Year per mi^2
INDIANA						
Evansville	50	38°02'N	15.5	40.0	4.0	10.4
Fort Wayne	41	41°10'N	11.0	28.6	3.7	8.2
Indianapolis	42	39°44'N	11.5	29.8	3.2	8.2
South Bend	48	41°42'N	14.4	37.4	4.2	11.0
Terre Haute	49	39°27'N	14.9	38.7	4.1	10.5
IOWA						
Burlington	56	40°47'N	18.7	48.6	5 3	13.8
Davenport	42	41°30'N	11.5	29.8	3.4	8.7
Des Moines	46	41°32'N	13.4	34.8	3.9	10.1
Dubuque	39	42°24'N	10.1	26.3	3.1	7.9
Sioux City	42	42°23'N	11.5	29.8	3.4	8.9
Sioux Falls	46	43°34'N	13.4	34.8	4.2	10.8
KANSAS						
Concordia	45	39°35'N	12.9	33.5	3.6	9.2
Dodge City	39	37°46'N	10.1	26.3	2.6	6.8
Goodland	44	39°21'N	12.4	32.2	3.4	8.8
Topeka	51	39°04'N	16.0	41.4	4.3	11.2
Wichita	54	37°38'N	17.6	45.6	0.5	11.7
KENTUCKY						
Lexington	44	38°02'N	12.4	32.2	3.2	8.4
Louisville	46	38°11'N	13.4	34.8	3.5	9.1
LOUISIANA						
Baton Rouge	78	30°25'N	32.9	85.3	6.7	17.3
Lake Charles	78	30°13'N	32.9	85.3	6.6	17.1
New Orleans	75	30°00'N	6.5	16.8	1.3	3.4
Shreveport	50	32°33'N	15.5	40.0	3.4	8.7
MAINE						
Caribou	21	46°52'N	3.5	9.2	1.2	3.2
Eastport	13	44°54'N	1.6	4.1	0.5	1.3
Portland	27	43°39'N	5.4	14.0	1.7	4.4
MARYLAND						
Baltimore	32	39°11'N	7.2	18.8	2.0	5.1
Frederick	24	39°20'N	4.4	11.5	1.2	3.1
MASSACHUSETTS						
Boston	20	42°22'N	3.3	8.4	1.0	2.5
Concord	24	43°12'N	4.4	11.5	1.4	3.5
Nantucket	15	41°15'N	2.0	5.2	0.6	1.5
Pittsfield	29	42°25'N	6.1	15.9	1.9	4.8
Salem	5	42°28'N	0.3	0.8	0.1	0.2
MICHIGAN						
Alpena	24	45°04'N	4.4	11.5	1.4	3.7
Detroit	32	42°24'N	7.2	18.8	2.2	5.6
Escanaba	33	45°48'N	7.6	19.8	2.5	6.6
Grand Rapids	39	42°54'N	10.1	26.3	3.1	8.0
Lansing	40	42°47'N	10.6	27.4	3.2	8.3
Marquette	25	46°34'N	4.8	12.3	1.6	4.2
Muskegon	33	43°10'N	7.6	19.8	2.4	6.1
Sault Ste. Marie	24	46°25'N	4.4	11.5	1.5	3.9

City	Isokeraunic Level	Latitude	Total Flashes per Year per kM²	Total Flashes per Year per mi²	Flashes to Ground per Year per kM²	Flashes to Ground per Year per mi²
MINNESOTA						
Duluth	29	46°50'N	6.1	15.9	2.1	5.5
International Falls	28	48°36'N	5.8	14.9	2.1	5.4
Minneapolis	39	44°53'N	10.1	26.3	3.3	8.5
Rochester	40	44°00'N	11.0	27.4	3.3	8.6
St. Cloud	36	45°35'N	8.8	22.9	2.9	7.6
St. Paul	34	44°56'N	8.0	20.8	2.6	6.8
MISSISSIPPI						
Jackson	64	32°20'N	23.5	60.9	5.1	13.2
Meridian	64	32°20'N	23.5	60.9	5.1	13.2
Vicksburg	62	32°24'N	22.3	57.7	4.8	12.5
MISSOURI						
Columbia	58	38°58'N	19.9	51.5	5.4	13.9
Kansas City	55	39°07'N	18.2	47.1	4.9	12.7
Springfield	59	37°14'N	20.5	53.1	5.2	13.5
St. Joseph	54	39°46'N	17.6	45.6	4.9	12.6
St. Louis	49	38°45'N	14.9	38.7	4.0	10.3
MONTANA						
Billings	33	45°47'N	7.6	19.8	2.5	6.6
Butte	43	46°00'N	12.0	31.0	4.0	10.4
Glasgow	27	48°11'N	5.4	14.0	1.9	5.0
Great Falls	29	47°30'N	6.1	15.9	2.2	5.6
Havre	23	48°31'N	4.1	10.7	1.5	3.9
Helena	31	46°36'N	6.9	17.8	2.4	6.1
Kalispell	22	48°11'N	3.8	9.9	1.4	3.5
Missoula	27	46°55'N	5.4	14.0	1.9	4.9
NEBRASKA						
Grand Island	50	40°58'N	15.5	40.0	4.4	11.5
Lincoln	47	40°52'N	13.9	36.0	4.0	10.3
Norfolk	53	41°59'N	17.0	44.2	5.1	13.1
North Platte	38	41°08'N	9.7	25.1	2.8	7.2
Omaha	39	41°18'N	10.1	26.3	2.9	7.6
Scottsbluff	48	41°50'N	14.4	37.4	4.3	11.1
Valentine	39	42°53'N	10.1	26.3	3.1	8.0
NEVADA						
Ely	31	39°17'N	6.9	17.8	1.9	4.9
Las Vegas	13	36°05'N	1.6	4.1	0.4	1.0
Reno	14	39°30'N	1.8	4.6	0.5	1.3
Winnemucca	11	40°54'N	1.2	3.1	0.03	0.9
NEW HAMPSHIRE						
Mount Washington	16	44°16'N	2.2	5.8	0.7	1.8
NEW JERSEY						
Atlantic City	23	39°22'N	4.1	10.7	1.1	2.9
Newark	27	40°42'N	5.4	14.0	1.5	4.0
Trenton	35	40°13'N	8.4	21.8	2.4	6.1

City	Isokeraunic Level	Latitude	Total Flashes per Year per kM²	Total Flashes per Year per mi²	Flashes to Ground per Year per kM²	Flashes to Ground per Year per mi²
NEW MEXICO						
Albuquerque	47	35°03'N	13.9	36.0	3.3	8.5
Clayton	63	36°27'N	22.9	59.3	5.7	14.7
Raton	75	36°58'N	30.8	79.8	7.8	20.1
Roswell	45	33°24'N	12.9	33.5	2.9	7.5
NEW YORK						
Albany	23	42°45'N	4.1	10.7	5.4	3.2
Bear Mountain	28	41°50'N	5.8	14.9	1.7	4.4
Binghampton	31	42°05'N	6.9	17.8	2.0	5.3
Buffalo	29	42°56'N	6.1	15.9	1.9	4.8
New York City	31	40°46'N	6.9	17.8	2.0	5.1
Oswego	25	43°25'N	4.8	12.3	1.5	3.8
Rochester	27	43°07'N	5.4	14.0	1.7	4.3
Syracuse	30	43°07'N	6.5	16.8	2.0	5.1
NORTH CAROLINA						
Asheville	53	35°36'N	17.1	44.2	4.1	10.6
Cape Hatteras	40	35°15'N	10.6	27.4	2.5	6.5
Charlotte	46	35°14'N	13.4	34.8	3.2	8.2
Greensboro	50	36°05'N	15.5	40.0	3.8	9.8
Raleigh	41	35°52'N	11.0	28.6	2.7	7.0
Wilmington	46	34°14'N	13.4	34.8	3.1	8.0
Winston-Salem	46	36°07'N	13.4	34.8	3.3	8.5
NORTH DAKOTA						
Bismark	31	46°46'N	6.9	17.8	2.4	6.1
Devil's Lake	30	48°07'N	6.5	16.8	2.3	6.0
Fargo	29	46°54'N	6.1	15.9	2.1	5.5
Williston	25	48°09'N	4.8	12.3	1.7	4.4
OHIO						
Akron	38	41°02'N	9.7	25.1	2.8	7.2
Cleveland	35	41°24'N	8.4	21.9	2.4	6.3
Cincinnati	53	39°04'N	17.1	44.2	4.6	11.9
Columbus	40	40°00'N	10.6	27.4	2.7	7.6
Dayton	48	39°49'N	14.4	37.4	4.0	10.3
Sandusky	31	41°25'N	6.9	17.8	2.0	5.2
Toledo	35	41°34'N	8.4	21.8	2.5	6.4
Youngstown	36	41°16'N	8.8	22.9	2.5	6.6
OKLAHOMA						
Oklahoma City	45	35°24'N	12.9	33.5	3.1	8.0
Tulsa	58	36°11'N	19.9	51.5	4.9	12.6
OREGON						
Baker	16	44°50'N	2.2	5.8	0.7	1.9
Burns	14	43°35'N	1.8	5.0	0.5	1.4
Eugene	5	44°07'N	0.3	0.8	0.1	0.3
Medford	9	42°23'N	0.8	2.2	0.3	0.7
Pendleton	12	45°41'N	1.4	3.5	0.5	1.2
Portland	6	45°36'N	0.4	1.1	0.2	0.4
Roseburg	5	43°13'N	0.3	0.8	0.1	0.2
Troutdale	12	45°35'N	1.4	3.5	0.5	1.2

City	Isokeraunic Level	Latitude	Total Flashes per Year per kM^2	Total Flashes per Year per mi^2	Flashes to Ground per Year per kM^2	Flashes to Ground per Year per mi^2
PENNSYLVANIA						
Allentown	36	40°39'N	8.8	22.9	2.5	6.5
Curwensville	47	40°59'N	13.9	36.0	4.0	10.3
Erie	33	42°05'N	7.6	19.8	2.3	5.9
Harrisburg	33	40°13'N	7.6	19.8	2.1	5.5
Philadelphia	27	39°53'N	5.4	14.0	1.5	3.9
Pittsburgh	40	40°21'N	10.6	27.4	3.0	7.7
Reading	33	40°23'N	7.6	19.8	2.2	5.6
Scranton	32	41°24'N	7.2	18.8	2.1	5.4
Williamsport	20	41°15'N	3.3	8.4	0.9	2.4
RHODE ISLAND						
Block Island	17	41°10'N	2.5	6.4	0.7	1.8
Providence	21	41°44'N	3.5	9.2	1.0	2.7
SOUTH CAROLINA						
Charleston	56	32°54'N	18.7	48.6	4.13	10.7
Columbia	47	33°57'N	13.9	36.0	3.2	8.2
Florence	56	34°11'N	18.7	48.6	4.3	11.1
Greenville	52	34°51'N	16.5	42.8	3.9	10.0
Spartanburg	49	34°58'N	14.9	38.7	3.5	9.1
SOUTH DAKOTA						
Huron	38	44°23'N	9.7	25.1	3.1	8.0
Rapid City	41	44°09'N	11.0	28.6	3.5	9.0
TENNESSEE						
Bristol	53	36°29'N	17.1	44.2	4.2	11.0
Chattanooga	58	35°02'N	19.9	51.5	4.7	12.2
Knoxville	48	35°49'N	14.4	37.4	3.5	9.0
Memphis	51	35°03'N	16.0	41.4	3.9	10.0
Nashville	52	36°07'N	16.5	42.8	4.1	10.5
TEXAS						
Abilene	38	32°26'N	9.7	25.1	2.1	5.4
Amarillo	38	35°14'N	9.7	25.1	2.3	5.9
Austin	42	30°18'N	11.5	29.8	2.3	6.0
Brownsville	28	25°55'N	5.8	14.9	1.0	2.6
Corpus Christi	33	27°46'N	7.6	19.8	1.4	3.7
Dallas	51	32°51'N	16.0	41.4	3.6	9.2
Del Rio	27	29°20'N	5.4	14.0	1.0	2.7
El Paso	28	31°48'N	5.8	14.9	1.2	3.2
Fort Worth	46	32°49'N	13.4	34.8	3.0	7.7
Galveston	49	29°16'N	14.9	38.7	2.9	7.5
Houston	57	29°39'N	19.3	50.0	3.8	9.9
Laredo	36	27°32'N	8.8	22.9	1.6	4.2
Lubbock	52	33°36'N	16.5	42.8	3.7	9.7
Palestine	46	31°45'N	13.4	34.8	1.6	4.2
Port Arthur	72	29°58'N	28.7	74.4	5.8	14.9
San Angelo	45	31°22'N	12.9	33.5	2.7	7.0
San Antonio	37	29°32'N	9.3	24.0	1.8	4.7
Victoria	49	28°47'N	14.9	38.7	2.9	7.4
Waco	35	31°37'N	8.4	21.8	1.8	4.6
Wichita Falls	52	33°59'N	16.5	42.8	3.8	9.8

City	Isokeraunic Level	Latitude	Total Flashes per Year per kM^2	Total Flashes per Year per mi^2	Flashes to Ground per Year per kM^2	Flashes to Ground per Year per mi^2
UTAH						
Milford	28	38°24'N	5.8	17.9	1.5	3.9
Salt Lake City	35	40°46'N	8.4	21.8	2.4	6.2
VERMONT						
Burlington	28	44°28'N	5.8	14.9	1.9	4.8
VIRGINIA						
Cape Henry	39	36°56'N	10.1	26.3	2.5	6.6
Lynchburg	35	37°20'N	8.4	21.8	2.2	5.6
Norfolk	38	36°53'N	9.7	25.1	2.4	6.3
Petersburg	41	37°14'N	11.0	28.6	2.8	7.3
Richmond	40	37°30'N	10.6	27.4	2.7	7.0
Roanoke	42	37°19'N	11.5	29.8	2.9	7.6
WASHINGTON						
Ellensburg	11	47°02'N	1.2	3.1	0.4	1.1
Olympia	3	47°00'N	0.1	0.3	0.04	0.1
Port Angeles	4	48°08'N	0.2	0.5	0.1	0.2
Seattle	5	47°31'N	0.3	0.8	0.1	0.3
Spokane	11	47°33'N	1.2	3.1	0.4	1.1
Stampede Pass	8	47°17'N	0.7	1.8	0.2	0.6
Stevenson	10	45°40'N	1.0	2.6	0.3	0.9
Tacoma	6	47°09'N	0.4	1.1	0.2	0.4
Tatoosh Island	3	48°23'N	0.1	0.3	0.03	0.1
Walla Walla	9	46°06'N	0.8	2.2	0.3	0.7
Yakima	5	46°34'N	0.3	0.8	0.1	0.3
WEST VIRGINIA						
Charleston	47	38°22'N	13.9	36.0	3.7	9.5
Elkins	46	38°53'N	13.4	34.8	3.6	9.3
Parkersburg	43	39°21'N	12.0	31.0	3.2	8.4
WISCONSIN						
Green Bay	32	44°29'N	7.2	18.8	2.3	6.0
La Crosse	36	42°47'N	8.8	22.9	2.7	7.0
Madison	41	43°08'N	11.0	28.6	3.4	8.8
Milwaukee	33	42°57'N	7.6	19.8	2.3	6.0
WYOMING						
Casper	39	42°54'N	10.1	26.3	3.1	8.0
Cheyenne	46	41°09'N	13.4	34.8	3.9	10.0
Lander	22	42°48'N	3.8	10.0	1.2	3.0
Rock Springs	40	41°36'N	10.6	27.4	3.1	8.0
Sheridan	35	44°46'N	8.4	21.8	2.7	6.9