Probability of Getting Struck

Thunderstorms and lightning flashes do not occur with uniform frequency throughout the world, but vary instead with the climate and topology of particular locations. The only parameter related to lightning incidence for which world-wide data accumulated over many years exists is the *thunderstorm day*. This data is accumulated by the World Meteorological Association 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 map of Figure 2. When used in the analysis that follows, this parameter is designated T_y.

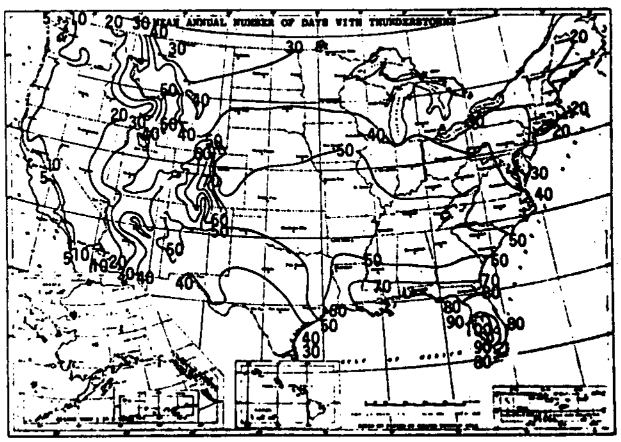


Figure 2—Isokeraunic Map of the United States. Numerals indicate number of thunderstorm days per year (from Reference 1)

Most observers agree that there are about 3 lightning flashes per minute in the average thunderstorm cell, and that a cell covers around 500 square kilometers 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 per thunderstorm day. Actually flash density is related more closely to the square of the isokeraunic level, as follows:

$$\tau_y = 0.2T_y^{1.7} \text{ flashes/km}^2\text{/year} \quad (1)$$

The flash density of equation (1) includes flashes between clouds and flashes to ground. Both are of concern to aircraft which may be struck aloft but only those that go to ground are of great concern to other systems. Pierce (Reference 2) has noted that the percentage, P, of flashes to ground increases with geographical latitude and he has represented the latitudinal variation in equation (2):

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

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).

Equations (1) and (2), can be used to estimate the average number of times lightning may be expected to strike the ground within one square kilometer, based on the number of thunderstorm days per year and the geographical latitude of the location.

and,

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

An example of such a calculation for an 80′ high rectangular building covering 23,940 square feet at Newport, R.I. is shown in Table I. The isokeraunic level at Newport is 20 thunderstorm days per year, resulting in a ground flash density of 0.625 strikes within each square kilometer each year.

This resulted in a prediction of 3.122×10^{-2} strikes to the building each year, or about one strike every 30 years. Thus the probability of a direct strike to this particular building, and resultant physical damage to it, is low.

One might thus conclude that lightning effects are of even less concern to equipment inside, but as we shall see, lightning need not strike the building itself for damaging surges to enter and play havoc with electronics housed within it. There are frequent reports of nearby strikes having damaged electronics contained within a building, and quite often the strike has been several kilometers away.

Within a one kilometer radius of the building at Newport, about:

$$(3.14 \text{ km}^2)(0.625 \text{ F/km}^2\text{/yr}) \sim \underline{2 \text{ strikes}}$$

reach the ground each year. This is enough to be of concern.

Lightning Effects

The physical damage effects produced at the point where the strike occurs are called the *direct effects* and include holes punctured in non-conducting materials during the attachment process, and burning and blasting produced by the high temperatures and pressures associated with the lightning arc. Much has been written about protection against these direct effects, and this subject will not be discussed further here.

Of greater concern, perhaps, to the EMC engineer are the *indirect effects*. These are caused, primarily, by earth voltage rises which occur when the flash dumps charge into the earth and by electromagnetic fields associated with the

TABLE I—Calculation of Direct Strikes to an 80 ft. High, 23,940 sq. ft. Building at Newport, R.I.

Stroke Amplitude Range:	Prob. of Occurrence (fr. Fig. 4)	Attraction Distance (fr. Fig. 4) (nH)	(ft.)	Attraction Area (from Eq. 3) (ft²)	(km²)	Ground Flash Density (fr. Figs. 1 & 2) F/km²/yr.	Number of Strikes to Shelter/year (prob. × area × density)
0- 20 kA	0.5	2H	160	222,445	2.06×10^{-2}	0.625	0.644×10^{-2}
20- 40 KA	0.3	4H	320	581,799	5.40×10^{-2}	0.625	7.013×10^{-2}
40- 65 kA	0.1	6H	480	1,102,003	10.20×10^{-2}	0.625	0.638×10^{-2}
65-140 kA	0.08	8H	640	1,783,056	16.54×10^{-2}	0.625	0.827×10^{-2}
							3.122×10^{-2} strikes per year

lightning flash. There are broad-band radiated fields produced by the many sparks which occur during the flash formation process, and there are inductive fields produced by the stroke currents flowing in the flash. The former are sometimes called *spherics* and produce noise in communications equipment and interference in digital systems, but rarely have the energy to damage components.

The fields produced by return stroke currents do have enough energy to cause burnouts and so do the earth voltage rises. All of these are complex phenomena about which there has been a considerable amount of research, but the engineer concerned with protection against these effects need not delve deeply into this research to estimate the order-of-magnitudes of the fields and voltages he must deal with.

Figure 5, for example, shows how the magnetic fields and earth voltages at various distances, D, from the strike point can be estimated. The example is of a 140 kA stroke entering earth of 1,000 ohm-meters resistivity.

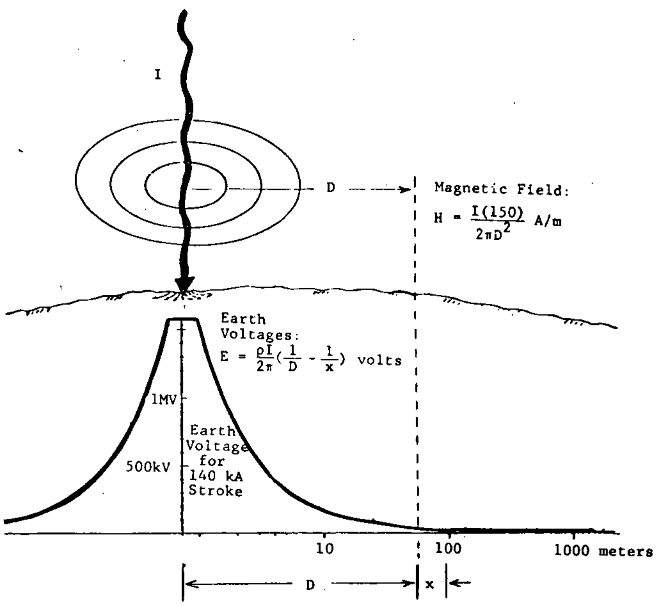


Figure 5—Magnetic Fields and Earth Voltages
•Earth voltage profile is shown for a 140 kA stroke into soil of 1,000 ohm-meters resistivity.

The expression for the magnetic field intensity is:

$$H = \frac{I\,(150)}{2\pi D^2} A/m \tag{4}$$

where

H = Magnetic field intensity a distance, D, away from the flash channel due to current I in the channel (amps/meter)

D = Distance away from the flash channel (meters)

I = Lightning current (amperes)

The expression governing the earth voltage is:

$$E = \frac{\rho I}{2\pi}\left(\frac{1}{D} - \frac{1}{D + x}\right) \text{ volts} \tag{5}$$

where

E = Voltage between two points x meters apart on the earth surface due to Current, I, entering the earth at an average distance, D, away from the point of interest (volts)

x = Radial distance outward to another point of interest from the reference point (meters)

Table III shows examples of the magnetic field intensities and earth voltages determined from expressions (4) and (5) which would appear at three different distances, D, away from where a 140 kA stroke entered earth of resistivity 1,000 ohm-meters.

TABLE III—Typical Magnetic Fields and Earth Voltages Produced by a 140 kA Stroke

Distance, D, from Flash	Magnetic Fields A/m	Earth Voltages for $\rho = 1000\Omega - m$, $x = 150$ m
100 m	3.3×10^2	134 kV
1 km	3.3×10^0	2.9 kV
10 km	3.3×10^{-2}	33 volts

Whether the magnetic fields and earth voltages can directly penetrate a building or other enclosure depends, of course, upon how it is constructed. But even if the enclosure is shielded, surges may be induced on exterior power or signal cables and conducted by them into the building.

Consider, for example, a cable extending between two buildings as shown in Figure 6.

Here the magnetic field, H, from the lightning stroke passes through the loop formed by the cable and the earth, inducing a current in this loop. The earth is represented by a distributed resistance, R, at some finite distance below the actual surface. In reality, the induced current flows throughout a wide volume between the two shelters, but it will be sufficient to lump this into a single resistance for the purpose of analysis.

The voltage induced by the magnetic field is:

$$e(t) = \frac{d\phi}{dt} = \mu_o S \frac{dH}{dt} \quad \text{volts per meter of cable length} \tag{6}$$

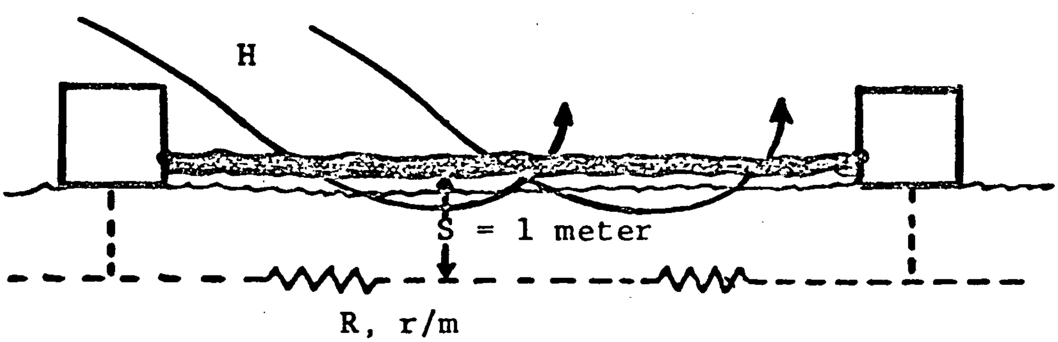


Figure 6—Magnetic Fields Link a Cable between Two Buildings.

where:

$e(t)$ = induced voltage in the cable—earth loop (volts/meter of cable length)

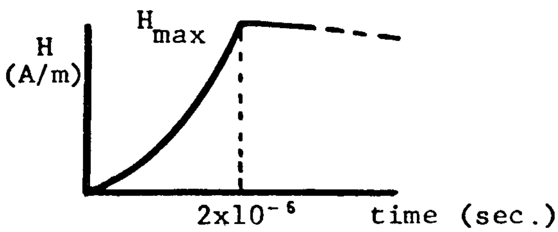
ϕ = magnetic flux passing through the loop (Webers)

H = magnetic flux density (amperes/meter)

μ_o = permeability of free space—$4\pi 10^{-7}$henrys/meter

S = spacing between cable and earth return (meters)

The magnetic flux, H, follows the same waveform as the lightning stroke current that produces it. Most natural lightning stroke currents are concave and can be represented best by a $(1-\cos)$ function reaching its peak (at $\pi/2$ radians) in 2 microseconds to represent a moderately severe rise time, as shown in Figure 7.



$$\omega = 2\pi \frac{1}{T} = 0.79 \times 10^{6} \text{sec.}$$

Figure 7—Mathematical Representation of Return Stroke and Magnetic Field Wavefront.

If

$$H = H_{max}(1-\cos\omega t) \tag{7}$$

then:

$$\frac{dH}{dt} = \omega H_{max} \sin \omega t \tag{8}$$

Inserting this expression into equation (6) for the voltage induced in the cable-earth loop and letting S = 1 meter gives:

$$e(t) = \mu_o \omega H_{max} \sin\omega t \quad \text{volts per meter of distance between the two buildings} \tag{9}$$

This voltage would be available to drive currents through the cable shield if it is a shielded cable, or through the cable conductors if they are unshielded. The current is limited by the earth resistance and the loop inductance. The equivalent loop circuit is shown in Figure 8.

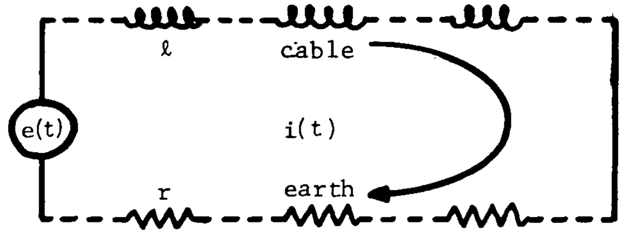


Figure 8—Equivalent Circuit of Cable and Earth Return.

$$i(t) = \frac{e(t)}{r}\left(1-\varepsilon^{-\frac{rt}{\iota}}\right)\text{amperes} \tag{10}$$

where:

r = resistance per unit length of cable (ohms/meter)

ι = inductance per unit length of cable (henrys/meter)

$e(t)$ = volts per unit length of cable (volts/meter)

$i(t)$ = loop current flowing in cable (amperes)

Substituting expression (6) for e(t) in equation 7 gives:

$$i(t) = \frac{\mu_o \omega H_{max} \sin\omega t}{r}\left(1-\varepsilon^{-\frac{rt}{\iota}}\right) \tag{11}$$

This expression and those that preceded it are valid until the stroke current reaches its crest ($\cos\omega t = \pi/2$), assumed to be 2 μs for these calculations. ω is available from Figure 7 and the peak magnetic field strength, H_{max}, was calculated in Table III for a 140 kA flash striking the earth at several distances, D, away from the buildings. r depends on the soil resistivity at the particular location, but ι is less dependent on such site factors and can be assumed to be 1 microhenry per meter of cable length. Values of i(t) therefore can be calculated in equation 11 for various combinations of D and r. Peak currents for several combinations of D and r are presented in Table IV.

TABLE IV—Peak Currents Induced in Cables by Magnetic Fields Passing between a Cable and Earth Return

Distance, D, from Flash	Return Path Resistance (ohms/meter)		
	0.5	1.0	10.0
	Peak Currents (amperes)		
100 m	413	282	16.3
1 km	4.1	2.8	0.16
10 km	0.04	0.03	0.002

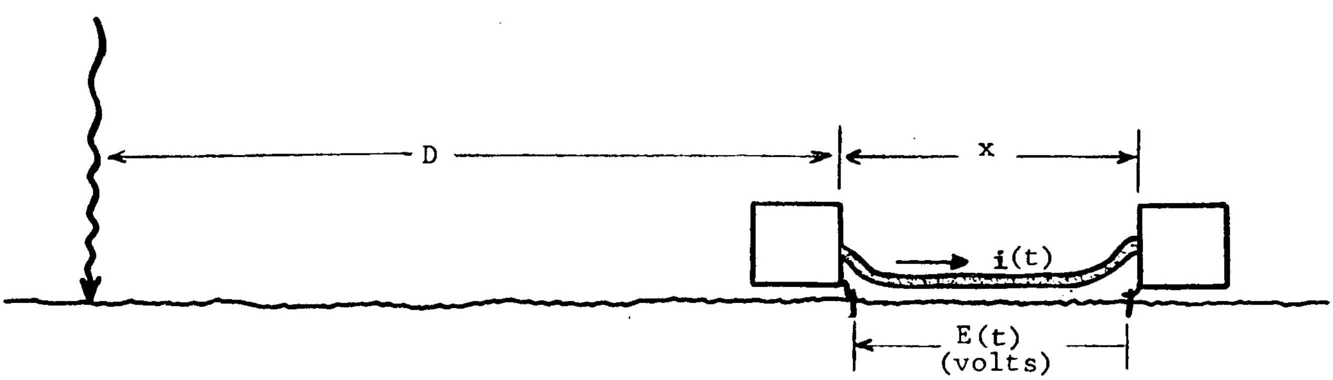


Figure 9—Earth Voltage Drives Current through Cables.

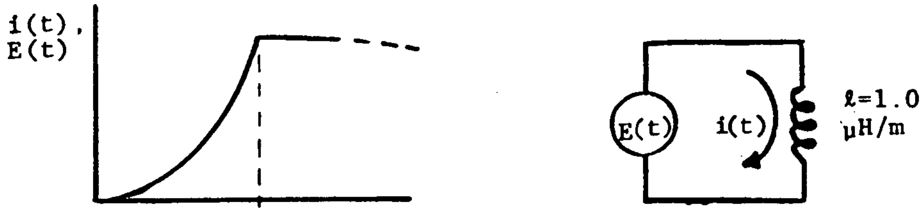


Figure 10—Earth Voltage Waveform and Equivalent Circuit

Table IV shows that the greater the return path resistance through the earth, the lower the currents which may be induced in the cable. This result illustrates the possibility that a low ground resistance (i.e. resistance between the building and "earth") may sometimes aggravate lightning effects instead of mitigating them. While "grounding" has an important role to play in lightning protection, much of the lightning protection literature to date has been excessively preoccupied with grounding, while overlooking inductive effects which are at least as significant.

Induced Effects from Earth Voltages

The other indirect effect which may cause currents to circulate in cables is the earth voltage rise.

The voltage, E(t), between two shelters a distance, x, apart drives a current, i(t), through any cable(s) that extend between them. This situation is shown in Figure 9.

Assuming that the lightning current wavefront is a (1 − cos) function as before, the earth voltage will follow and drive a current through the cable inductance, as shown in equivalent circuit of Figure 10.

The earth voltage is given by equation (5) and is:

$$E(t) = \frac{pI(t)}{2\pi}\left(\frac{1}{D} - \frac{1}{D+x}\right) \qquad (12)$$

Let e(t) be the average earth voltage per meter of cable length between the two shelters, then:

$$e(t) = \frac{E(t)}{x}\,(1 - \cos\omega t),\ \text{for } 0<t<2\,\mu s \qquad (13)$$

and

$$i(t) = \frac{1}{\ell}\int_0^{2\mu s} e(t)\,dt \qquad (14)$$

$$= \frac{1}{\ell}\int_0^{2\mu s} \frac{E_{max}}{x}(1 - \cos 0.79\times 10^6 t)dt \qquad (15)$$

$$= \frac{E_{max}}{\ell x}\left[t - \frac{1}{0.79\times 10^6}\sin 0.79\times 10^6 t\right] \qquad (16)$$

If the cable inductance, ℓ, is again assumed to be 1 μH/meter and the cable length, x, is assumed to be 150 meters, the peak cable current, i_{max}, can be calculated for various combinations of p and D by substituting the appropriate value of E_{max} obtained from equation 5 into equation 16. Peak cable currents resulting from a 140 kA stroke are presented in Table V.

TABLE V—Peak Currents in Cables as a Result of Earth Voltages

Soil Resistivity (Ω – m)	Stroke Distance from Buildings D =	100 m	1 km	10 km
	Peak Cable Current i_{max}			
p = 10		6.4	0.16	Insignificant
p = 100		64.0	1.4	"
p = 1000		640.0	14.0	"

Table V shows that there are conditions under which earth voltages from a nearby flash can drive up to several hundred amperes through cables. Thus, there are at least two mechanisms whereby nearby lightning strikes can cause surge voltages and currents to appear in interconnecting cables, even when neither of the buildings is directly struck.

If surges of this magnitude appear in unshielded cables they are likely to burn out electronics. If the cables are shielded, the induced currents will flow on the shields instead of the conductors. The shields will greatly attenuate the voltages that are induced upon the conductors, but some voltage will still appear on the conductors due to the shield resistance and to magnetic flux through the shield.

Component Vulnerability

If the transfer characteristics of the cable shields are known it will be possible to estimate the magnitude of voltages that electronics will be exposed to. A rough estimate of this can be obtained from cable shield resistance. For example, if shield resistance were one milliohm per meter, the total resistance of the cable in the example of Figure 6 would be 0.15 ohms. A surge current of 500 amperes in this cable would produce a surge voltage of

$$\begin{aligned} e &= (0.15 \text{ ohms})(500 \text{ amperes}) \qquad (17)\\ &= 75 \text{ volts} \end{aligned}$$

along the conductors. If the impedance at both ends were the same, half of this voltage would appear at each end. If the impedances are unequal, the voltages will divide proportionately.

A 75 volt surge of a few microseconds duration can be tolerated by most power supplies and electromechanical devices, but not by many microcircuits. The damage thresholds of typical TTL digital line drivers and receivers, for example, are shown in Figure 11.

The duration of most lightning-induced surges can be expected to fall in the range of 0.1 to 10 microseconds, and Figure 11 shows that surges as low as 20 volts are all that is necessary to damage some digital line receivers. Similar data is available for many other types of components.

Systems which are particularly prone to this type of interference are those where a central electronic package such as a computer, process controller or information center is connected by extended cables to outlying stations. Of course, the AC power lines themselves may be sources of interference and this makes nearly any electronic device that is powered from external power lines susceptible. Even though lightning arresters may be present at power distribution stations, these arresters are there to protect the distribution transformer and they do not necessarily protect the loads beyond. There are several mechanisms by which lightning surges may appear on incoming power distribution lines, and successful protection must take each of these mechanisms into account.

Protection Approaches

Protection of electronics against lightning effects involves applying, to some degree, each of the following two principles:

1. Control of lightning-induced surges in signal and

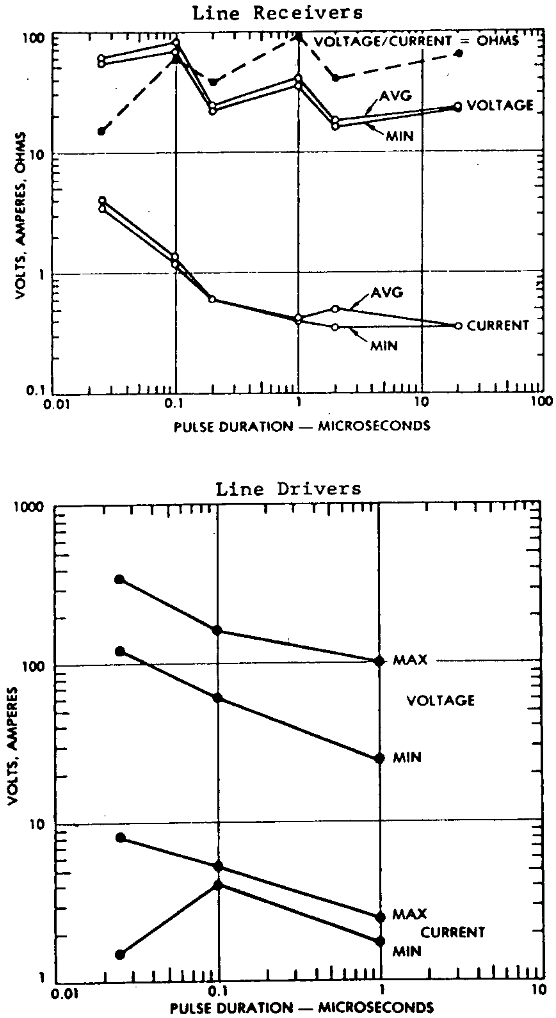


Figure 11—Damage Thresholds of Typical TTL Line Drivers and Receivers.

power cables to reasonable levels.

2. Design or hardening of electronics to withstand surges of reasonable levels.

The first principle is accomplished by routing of cables to reduce magnetic field interactions and shielding of them to further reduce these interactions. Rigid metal conduits or flexible foils and braids are commonly used as shields.

Hardening of electronics is accomplished by employing balanced input circuits with high common-mode rejection characteristics, input buffer resistance, shunt capacitance, series inductance or other types of filters or isolation transformers; and by design of the solid-state components themselves to tolerate higher surge voltages.

If the lightning problem is not recognized until after the equipment is *built* circuit design modifications are often impractical and the protection engineer is limited to consideration of shielding and suppressors to reduce the incoming surges to levels which can be tolerated by the equipment.

If the problem is not recognized until the equipment is *installed* (all too frequently the case), even shielding modifications may be difficult and surge suppressors alone may have to be relied upon to do the job. Surge suppressors include varistors, zener diodes, forward and reverse diodes, gas tubes, spark gaps, inductors, capacitors and hybrids made up of combinations of several of the above. There is no individual suppressor capable of protecting all types of electronics against all possible surges and prices range from a few cents to a few hundred dollars each (with performance not always related to cost). An investment, therefore, in careful selection of the right suppressor can eliminate excessive costs and assure the best possible protection.

Clearly, lightning protection is most effective and economical if designed into the system at the start, as this is the time when the greatest number of options are available. Some philosophical hints to keep in mind when designing protection into a system are as follows:

1. Start early!
2. Work as much as possible with conducting elements already being incorporated in a structure, installing conductors dedicated soley to lightning protection only when no others exist.
3. It is *usually* best, when system requirements permit, to connect all grounds (lightning, power, signal) together. If this can be done, do so at as many places as possible.
4. Try to achieve low *inductance* in ground connections.
5. Use inductance to advantage, by reducing it where preferred paths to earth are desired and increasing it where circuit isolation is desired.
6. Work on reducing incoming cable and power line susceptibility first, then protect the electronics against the transient levels that remain.

Ultimately, protection of electronics is likely to be organized around the *transient control levels* proposed by Fisher and Martzloff (Reference 4) or some similar concept in which the electronics engineer designs his equipment to tolerate transients up to an agreed-upon transient design level, and the user takes the responsibility of limiting transients induced in interconnecting wiring to a lower level. There would be a margin of safety between, and there would be different levels appropriate to different types of electronics. Thus, digital IC's would not be required to withstand the same transient levels as 115 VAC power supplies. Until a method such as this becomes common practice, it will be up to the system designer to work out his own set of criteria.

In the foregoing discussion we have attempted to explain what lightning is, how often it occurs and how it can interact with electronic systems. We have not recommended specific protective measures because treatment varies from one situation to another. We have instead identified some general guidelines in the hope they will be helpful.

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