LIGHTNING, LIGHTNING PROTECTION AND TEST STANDARDS

Lightning is a transient, high-current electric discharge whose path length is measured in kilometers. The most common source of lightning is the electric charge that is separated in thunderstorms, although lightning or lightning-like electrical discharges can also occur in volcanic plumes, snowstorms, and sand storms. On average, well over half of all lightning discharges occur inside thunderclouds and are called intracloud discharges. Intracloud discharges can pose a threat to aircraft or other airborne vehicles, but here our emphasis will be on flashes between cloud and ground. Cloud-to-ground lightning is obviously a hazard to humans and to ground-based structures and electronics, and the lightning test standards for aircraft are based primarily on the characteristics of cloud-to-ground discharges. Cloud-to-ground flashes are also the most severe in terms of peak current and are better characterized than cloud discharges.

Contours of the average number of cloud-to-ground flashes per square kilometer derived from measurements over four years are plotted in Fig. 1 with $60 \times 60\ \mathrm{km}^2$ spatial resolution. The state of Vermont is shown with $5\ \mathrm{km}^2$ resolution in the inset on the upper right-hand side of Fig. 1. Note that most of the continental United States experiences at least one cloud-to-ground flash per square kilometer per year and that about one-third of the United States has $4\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$ or more. The maximum area densities are found along the southeastern Gulf Coast and the Florida peninsula, where the values exceed $20\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$, or $50\ \mathrm{mi}^{-2}\ \mathrm{yr}^{-1}$, when viewed in $5\ \mathrm{km}^2$ squares. Roughly 20 to 30 million cloud-to-ground flashes strike the United States each year, and thus lightning is among the nation's most severe weather hazards, both to property and to life (1–3).

In the following, we will survey the development of a typical cloud-to-ground lightning flash, the currents and other

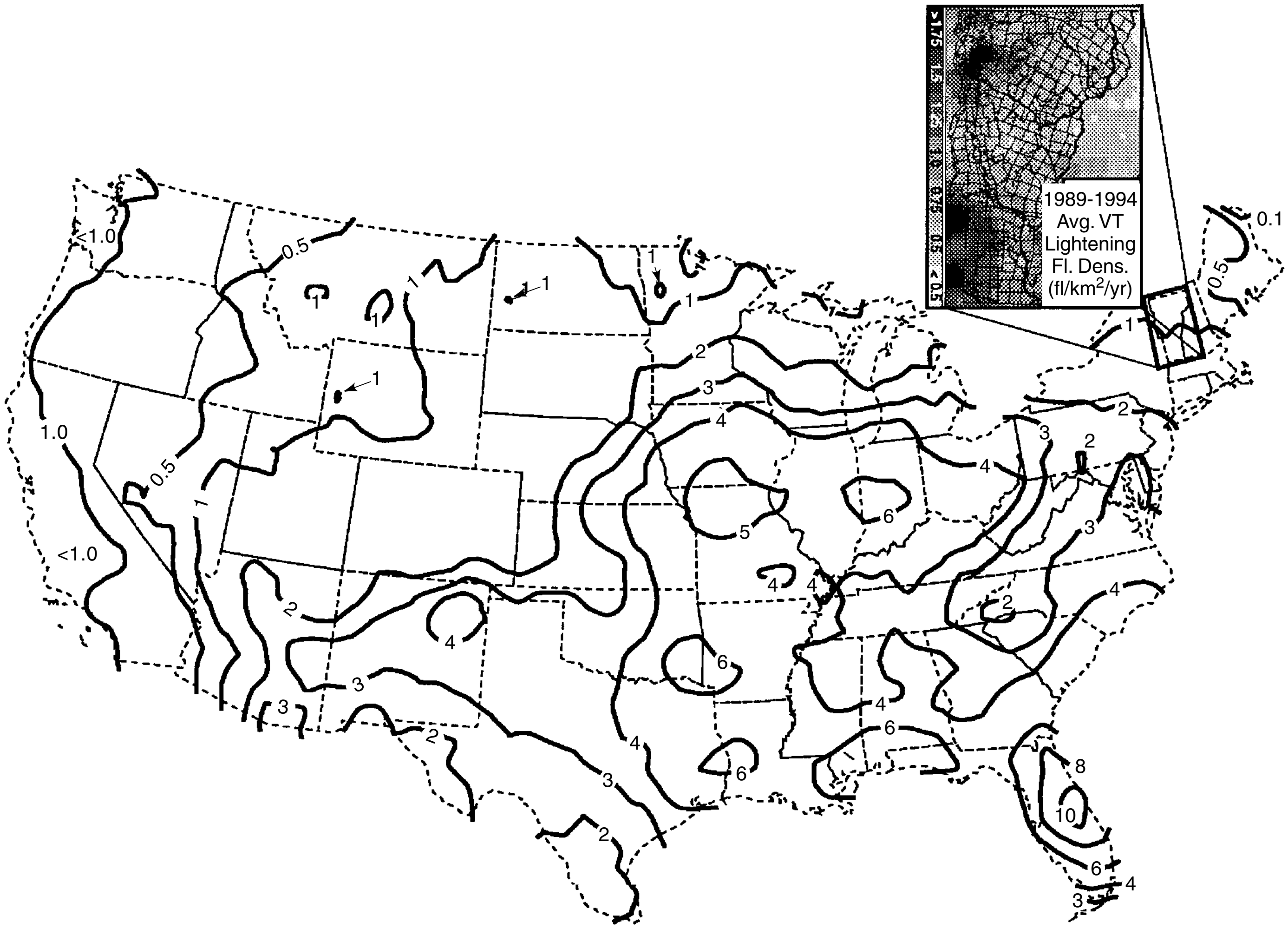

Figure 1. A low-resolution map of the average annual frequency of cloud-to-ground lightning in flashes/km^2 over the continental United States, in the years 1989 to 1993. A higher-resolution plot of Vermont is shown in the upper right-hand corner. (Courtesy of Global Atmospherics, Inc, Tucson, AZ.)

properties of such discharges, the mechanisms of lightning damage, the fundamentals of lightning protection, and lightning test standards. Although the phenomenology of a typical flash is discussed, it is worth noting that important parameters such as the total number of discharges in a storm, the fraction of discharges that strike the ground, the polarity of charge lowered by the flashes, the flashing rates, and even the characteristics of individual flashes vary widely and depend on the characteristics of the cloud and on the local meteorological environment. For example, frontal storms tend to produce higher flashing rates and more strokes per flash than local or air–mass storms, and there are important seasonal variations in the fraction of positive flashes to ground and in the amplitudes of the peak currents. For a discussion of the characteristics of lightning and thunderstorms that are beyond the scope of this review, the reader is referred to the books by Uman (4) and by MacGorman and Rust (5).

CLOUD-TO-GROUND LIGHTNING

The vast majority of cloud-to-ground (CG) discharges begins within the cloud near a negative charge region that is located near the -10°C temperature level (6). Most CG flashes transfer negative charge to the ground and are the primary type discussed here. A few percent of CG flashes originate in the upper regions of thunderclouds or within the trailing stratiform region of thunderstorm complexes, and lower positive charge. CG flashes begin with a *preliminary breakdown* process inside the cloud. Next, a highly branched discharge, the *stepped leader,* appears below cloud base and propagates downward in a series of intermittent steps, at an average speed of 10^5 m/s to 10^6 m/s. The leader effectively lowers the negative cloud potential, of the order of 10^8 V, downward toward ground. After a few tens of milliseconds, when the tip of the downward propagating leader gets to within some tens of meters of the ground, the electric field under the leader becomes large enough to initiate one or more upward *connecting discharges,* usually from the tallest object (or objects) in the "local vicinity," again within tens of meters, of the strike point. When an upward discharge contacts the leader, the first *return stroke* begins.

The return stroke is a very intense pulse of current and luminosity that propagates up the previously charged and ionized leader channel into the cloud at a speed comparable

Table 1. Properties of Return Strokes That Lower Negative Charge to Ground

Properties	Unit	Percentage of Cases Exceeding Tabulated Value		
		95%	50%	5%
Peak current (minimum 2 kA)				
First stroke	kA	14.0	30.0	80.0
Subsequent stroke	kA	4.6	12.0	30.0
Total charge				
First stroke	C	1.1	5.2	24.0
Subsequent	C	0.2	1.4	11.0
Entire flash	C	1.3	7.5	40.0
Impulse charge				
First stroke	C	1.1	4.5	20.0
Subsequent stroke	C	0.22	0.95	4.0
Stroke duration				
First stroke	μs	30.0	75.0	200.0
Subsequent stroke	μs	6.5	32.0	140.0
Action integral				
First strokes	A^2s	6.0×10^3	5.5×10^4	5.5×10^5
Subsequent strokes	A^2s	5.5×10^2	6.0×10^3	5.2×10^4
Interval between strokes	ms	7.0	33.0	150.0
Flash duration				
Including single stroke flashes	ms	0.15	13.0	1100.0
Excluding single stroke flashes	ms	31.0	180.0	900.0

Adapted from Berger et al. (36).

to the speed of light. After a pause of 40 ms to 80 ms, another leader, a *dart leader,* may propagate down the main part of the previous return-stroke channel (this time smoothly), recharge it negatively, and then initiate a *subsequent return stroke.* A typical cloud-to-ground flash contains several return strokes and has a total duration of about half a second. Lightning often appears to “flicker” because the human eye can sometimes just resolve the time interval between successive strokes. In roughly half of all flashes to ground, one or more of the dart leaders propagates down just a portion of the previous return-stroke channel and then forges a different path to ground. In these cases, the discharge usually strikes ground in two (or more) places, and the channel has the characteristic forked appearance that can be seen in many photographs.

Return stroke currents have been measured during direct strikes to instrumented towers and have been inferred from remote measurements of electromagnetic field changes. First stroke currents typically rise to a peak of 20 kA to 40 kA within a few microseconds and transfer several coulombs of negative charge to the ground. The maximum rate of rise of current during the initial onset can be of the order of 100 kA/μs or higher for tens of nanoseconds (7,8). The current falls to about half the peak value in about 50 μs. The peak currents in return strokes subsequent to the first are generally about half that of the first stroke but have about the same maximum rate of rise. Following subsequent strokes, there is often a *continuing current* of the order of hundreds of amperes for tens of milliseconds or more. Table 1 summarizes the characteristics of the currents in return strokes that lower negative charge to ground. Flashes that lower positive charge are much less frequent than those that lower negative charge, but positive flashes do tend to have large peak currents, sometimes exceeding 300 kA, and large charge transfers, sometimes exceeding hundreds of coulombs. A positive flash usually contains just a single return stroke followed by a long continuing current.

During its onset, a return stroke heats the leader channel to a peak temperature of about 30,000 K, roughly five times hotter than the surface of the sun. As a result of this heating, the channel pressure rises to tens of atmospheres, and then produces a rapid channel expansion behind a strong shock wave. The shock wave from each segment of the tortuous channel decays within meters to a weak shock wave that, in turn, decays into the acoustic wave that ultimately becomes thunder (9,10). Most of the energy input to a return stroke probably goes into heating the air and into the work of channel expansion.

LIGHTNING DAMAGE

At this point, it will be instructive to estimate how often a normal-sized structure, such as a house, will be struck by CG lightning. We assume that the house is located in a geographic region that has an average of about 4 CG flashes per square kilometer per year (see Fig. 1). We also assume that the area of the house is about 10×20 m^2 and that there will be a direct strike any time a stepped leader comes within 10 m of this area. In this case, the effective area of the house will be about 30×40 m^2, and the house will be struck, on average, $(1200)(4)(10^{-6}) = 4.8 \times 10^{-3}$ times a year, or about once every 200 years. Larger houses will be struck more often, smaller ones less often, and, of course, there can be serious damage from strikes that are further than 10 m from the structure. Another way to think of this hazard is that, in a region with 4 CG flashes per square kilometer per year (presuming a 10×20 m^2 house to be typical), an average of 1 out of every 200 houses will be struck directly each year.

Damage from the direct effects of lightning can usually be attributed to one of four measurable properties of the current, I: (1) the value of the peak, I_p, (2) the maximum rate of change of current, $dI/dt_{\max}$, (3) the integral of the current over time, $\int I\,dt$, or the value of the charge transfer, and (4) the integral of the current squared over time, the so-called "action integral," $\int I^2\,dt$, or the energy that would be transferred to a 1 Ω resistor.

1. For objects that offer a predominantly resistive impedance, R, such as a ground rod or the characteristic impedance of a long power line, the peak voltage on the object, V_p, will be given by Ohm's law, $V_p = I_pR$, where I_p is the peak current. For example, if a 30,000 A peak current is injected into an overhead power line with a 400 Ω characteristic impedance, an overvoltage of about 12 million volts will be produced in the absence of flashovers. Such large voltages frequently cause secondary discharges between the object that is struck and nearby objects that are grounded. These so-called "side-flashes" are one of the greatest hazards to humans or animals who are standing near a tree or any other tall object that is being struck by lightning. The damage produced by a side-flash is usually very similar to that of a direct strike.
2. For objects whose impedance can be represented by a lumped inductance, L, such as the wires in an electrical circuit, the peak voltage produced by the lightning current will be proportional to the maximum rate of change of current, dI/dt, multiplied by the inductance, $V = L\,dI/dt$. For example, 1 m of wire has a self-inductance that is of the order of 10^{-6} H. The peak dI/dt in a return stroke is of the order of 100 kA/μs; therefore, about 100 kV will appear on this length of conductor for the duration of the large dI/dt, typically some tens of nanoseconds.

   Figure 2 shows how the resistance and inductance of a grounding system can cause large differences in the "earth" potential between two adjacent structures. The potential V of the transmitter in Fig. 2 is $V_0 + IR + L\,dI/dt$, where R and L are the resistance and inductance of the grounding system and V_0 is the true earth potential. The potential of the receiver is at true earth potential because no lightning current is flowing in its grounding system. Transient voltage differences such as these can ultimately appear on signal cables that are routed between the transmitter and receiver.
3. The heating and potential burn-through of thin metal sheets, such as a metal roof or an airplane wing, are to a first approximation proportional to the total charge that is injected into the metal at the air–arc interface. Generally, large charge transfers are produced by long-duration (tenths of a second to seconds) continuing currents that are in the range of 100 A to 1000 A, rather than by the peak currents, which have a relatively short duration. A typical CG flash transfers 20 C to 30 C of charge to ground, and extreme flashes transfer hundreds and occasionally thousands of coulombs.
4. The heating of resistive loads or relatively poor conductors to the point of melting or evaporation is, to a first approximation, proportional to the action integral. About 1% of negative return strokes have action integrals that exceed 10^6 A^{2}s. In the case of a tree, the heat created by the action integral vaporizes the internal moisture of the wood, and the resulting high-pressure steam causes an explosive fracture.

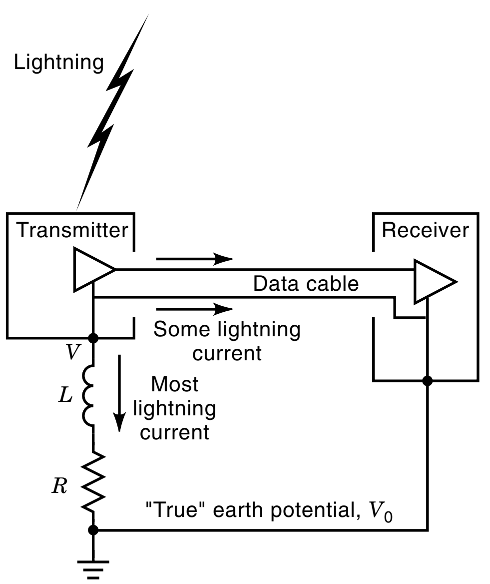

Figure 2. Path of the lightning current may flow in data cables because of the potential differences that are produced between two structures that are "grounded." (Adapted from Ref. 16.)

The electromagnetic fields from nearby lightning can induce damage, and such damage tends to depend on two parameters: (a) the peak value of the field and (b) the maximum rate of rise to this peak. Damage due to electromagnetic coupling is usually termed an "indirect" effect. For antennas or metallic structures that are capacitively coupled, the peak voltage on the structure is proportional to the peak amplitude of the field. For loops of wire or other conductors, the peak voltage is proportional to the maximum rate of change of the field.

Finally, it is appropriate to say a few words about the effects of lightning on humans. A direct strike will inject current that can damage a person's central nervous system, including stopping cardiac and pulmonary activity, burn the skin, and damage internal organs. Details of the consequences of lightning strikes to humans and methods of treatment can be found in Andrews et al. (11), Golde (12), and Lee (13).

PROTECTION TECHNIQUES

There are two basic methods of lightning protection: (a) diverting the current away from the structure so that it passes harmlessly to ground and (b) shielding the structure and its contents from any lightning-caused transients. On residential or commercial buildings, the diversion of lightning currents to ground can be accomplished by a system of lightning rods, down conductors, and grounds, as shown in Fig. 3. Such a system is usually sufficient to protect the structure from damage and to reduce (by imperfect shielding) the damage to any electronic equipment that is inside the structure [NFPA (14)].

The function of the lightning rod or "air terminal" is to initiate an upward connecting discharge that will intercept the downward-moving leader and thereby define and control

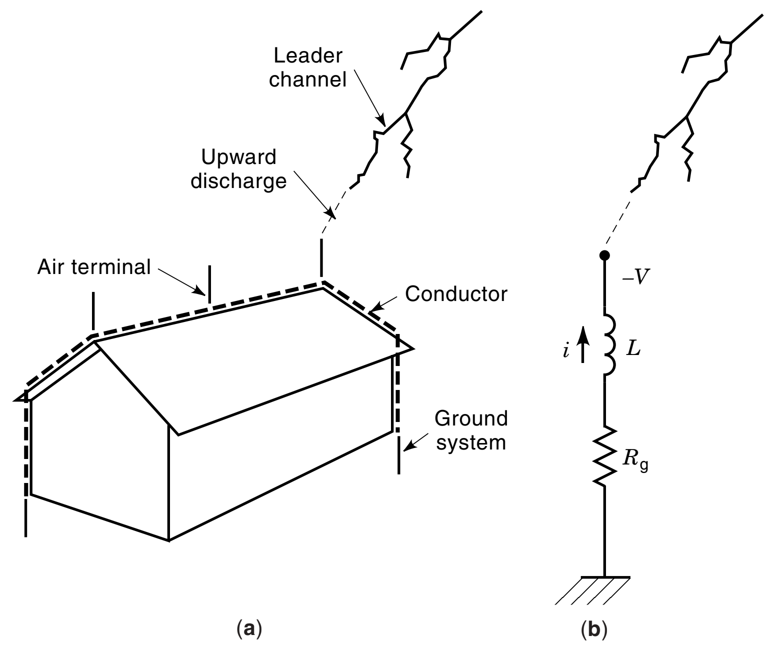

Figure 3. (a) Sketch of a standard lightning-protection system that is appropriate for small structures, and (b) its equivalent electric circuit at low frequencies. (Adapted from Ref. 19.)

the point of attachment to the structure. The air terminals do not attract significantly more strikes to the structure than the structure would receive in their absence. The function of the down conductors and grounding system is to divert the lightning current around the outside of the structure and into the ground as harmlessly as possible. The space that is "protected" by a vertical rod or overhead wire is often described in terms of a zone of protection (see Fig. 4), but, of course, this is not absolute. Tall towers (> 30 m) are limited in the space that they protect [see Fig. 4(c)]. Further details about lightning rods and their installation are available in the *Lightning Protection Code* [NFPA (14)].

The grounding system or earth-termination network provides a sink where the lightning current can be discharged harmlessly into the earth. To minimize side-flashes, the ground impedance should be kept as low as possible, and the geometry should be arranged so as to minimize surface breakdown. Many technical articles and books have been written about grounding electric-power systems and associated equipment [e.g., Sunde (15)]. Much of this information also applies to a lightning-protection system, although the rapidly changing and large lightning current sometimes poses special problems.

Protection of the contents of a structure should include limiting any transient currents and voltages that are produced by the strike and that typically propagate into the structure as traveling waves on any electric power, telephone, or other wires that are connected to the outside environment. The detailed design and installation of the current- and voltage-limiting devices and the associated grounding circuits will depend on the nature of the system that is to be protected and the signals that are to be controlled. For further details, see the discussion in Standler (16) and the references therein.

Figure 5 illustrates the concept of *topological shielding* that provides optimum lightning protection for most structures and their contents (17,18). The technique consists of isolating and then nesting several layers of imperfect or partial shields inside each other, and then "grounding" the outside surface of each inner shield to the inside surface of the next outer shield [see Fig. 5(c)]. All wires that penetrate a shield are equipped with transient protectors that are shunted successively to the outside surface of each shield layer; therefore, the hazardous voltage and power levels are reduced at each successive inner shield.

For further discussions of lightning protection, the reader can consult Golde (12), Krider (19), Uman (20,21), and the references given in these reviews.

TEST STANDARDS

Various test methods and standards have been developed to enable engineers to evaluate the effectiveness of protective measures or to verify the adequacy of protection designs. Often, the specifications for testing are divided into "direct" and "indirect" effects. As noted earlier, the direct effects are those due to the lightning current and include damage to metal and insulator surfaces and possible ignition of flammable vapors. Indirect effects include the transient currents and voltages induced on internal circuits by flashes that strike on or near the structure.

There are separate standards for the many different types of lightning arresters, transformers, and circuit breakers used in 50 Hz and 60 Hz power systems. There are also separate standards for line-powered and mounted telecommunication equipment and for the gas tubes and carbon block arresters that are mounted at the telephone service entrances to structures. Some of the better-known standards for simulating the indirect effects of lightning are IEEE/ANSI C62.41-1991, C62.11-1997, and C62.64-1996. A listing of IEEE Standards is available from IEEE Customer Service, P.O. Box 1331, Piscataway, NJ 08855-1331 (see also http://standards.ieee.org/).

For testing equipment that operates on power systems, an open-circuit voltage waveform of 1.2/50 μs (1.2 μs rise and 50 μs decay) with appropriate amplitudes is often used as the test waveform. Unfortunately, the actual voltage and current

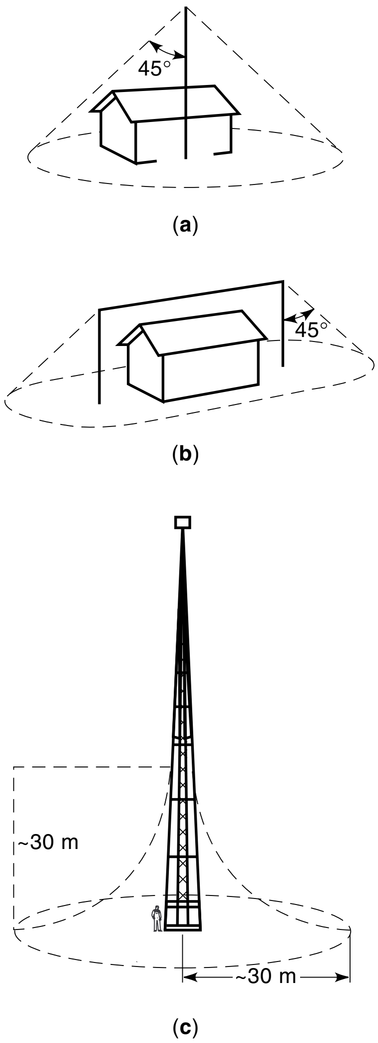

Figure 4. The volumes enclosed by the dashed lines are the probable "zones of protection" provided by (a) a vertical mast not exceeding a height of 15 m, (b) an overhead ground wire above a small structure, and (c) a tower taller than about 30 m. (Adapted from Ref. 19.)

waveforms produced by both direct and nearby lightning strikes can have much faster rise times and longer durations than this test waveform. The electrical industry's standard voltage waveform for dielectric tests and the aerospace industry's standard for fuel ignition tests is also the 1.2/50 μs wave. Gas tube telephone protectors are tested to the following three requirements: a 10/1000 μs current wave for currents from 50 to 500 A, an 8/20 μs current wave for 5 kA to 20 kA, and linear voltage ramps of 100, 500, 5000, 10,000 V/μs up to sparkover (IEEE STD 465.1). Additionally, various government agencies and jurisdictional authorities have drafted lightning protection requirements for specific types or classes of systems or equipment. Unfortunately, many of these standards address only one or two characteristics of lightning (such as the voltage surge arriving at the terminals of a protective device) and do not recognize the need for system-wide protection. Also, many of these standards were written prior to the widespread use of low-voltage electronics, so the specified protection levels are not low enough to provide adequate protection. As a result, damage to ground-based electronic installations from direct or nearby lightning strikes is a common occurrence. A need clearly exists for more comprehensive design standards and guidelines for the systems and devices used in lightning protection.

Possibly because of the potential for catastrophic damage, the requirements and standards used to protect aircraft from

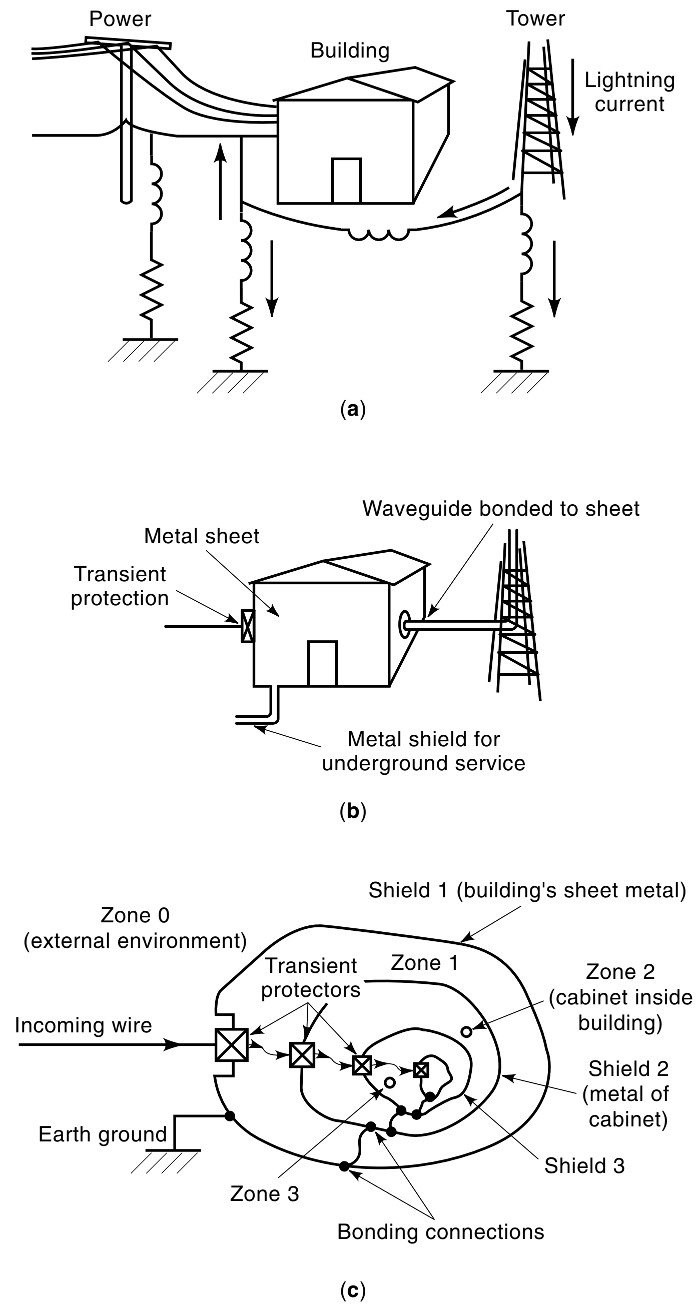

Figure 5. Diagram illustrating the principles of topological shielding: (a) Building to be protected is served by overhead power lines and a communications tower. (b) External view of building after topological shielding. (c) Schematic of the topological shielding. The transient surge to be controlled enters on the incoming wire. Higher zone numbers represent better levels of protection. (Adapted from Ref. 20.)

lightning have kept better pace both with advances in airframe and avionics system design and with improvements in understanding of lightning physics than have the requirements for most ground-based systems. Information on lightning test standards for aircraft is given in Clifford et al. (22), Fisher et al. (23), and Plumer (24). The Federal Aviation Administration (FAA) and the Department of Defense (DOD) have jurisdiction over lightning protection of all aircraft operating in the United States, and equivalent organizations in other countries have similar responsibilities. The design and test standards for aircraft and aerospace vehicles have been developed primarily by the Society of Automotive Engineers (SAE) Committee AE4L on lightning protection (25,26). This committee has been functioning since 1970, and its criteria have been published and incorporated at regular intervals in related DOD and FAA standards and advisory circulars.

In testing to determine the immunity of a system to a direct lightning strike, the conservative approach is to use the parameters of a relatively severe discharge—that is, the current thought to exist at the base of a CG flash. Airborne vehicles will likely encounter smaller currents associated either with the upper portion of return strokes or with various components of intracloud discharges. The current specified in one lightning test standard, MIL-STD-1757A (Lightning Qualifications Test Techniques for Aerospace Vehicles and Hardware, Military Standard MIL-STD-1757A, 20 July 1983), is illustrated in Fig. 6. This waveform simulates a first return stroke and one subsequent stroke with a continuing current in between. The peak currents of 200 kA for the first stroke and 100 kA for the subsequent stroke, as well as the charge transfer of over 200 C and the first stroke action integral of 2×10^6 A^2s, each occur at the 1% level or less in negative flashes to ground (see Table 1). For the less common positive cloud-to-ground flashes, which nearly always comprise one stroke plus a continuing current, the first stroke peak current, action integral, and charge transfer exceed the MIL-STD-1757A values in each category only about 10% of the

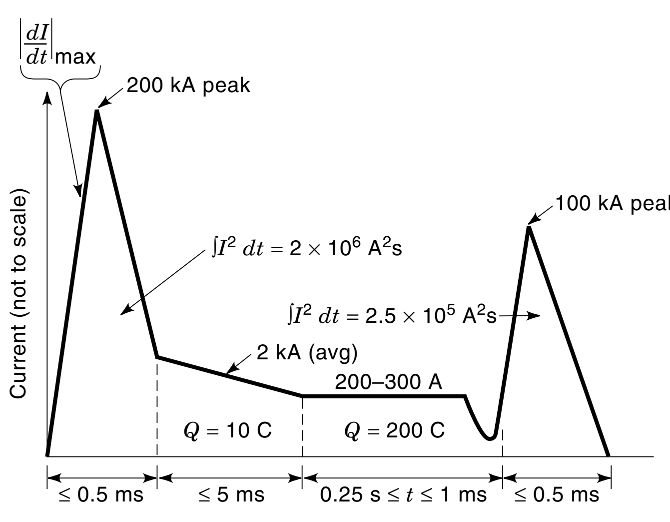

Figure 6. Test current waveform specified in MIL-STD-1757A. The maximum current rate-of-rise, dI/dt_{max}, has been inferred from DOD-5TD-1795, a standard intended to take account of induced effects. (Adapted from Ref. 21.)

time (4). The maximum rate-of-rise of the stroke current given in Fig. 6 has been inferred from DOD-STD-1795 [Lightning Protection of Aerospace Vehicles and Hardware, Department of Defense Standard DOD-STD-1795 (USAF), 30 May 1986].

Recently, a new current component, the so-called multiple burst component or component H, has been added to the test waveforms of Refs. 25 and 27. According to Ref. 27, the multiple burst environment described below is also adopted as part of the following standards:

1. SAE Committee Report, SAE AE4L-83-3, Rev. C, Certification of Aircraft Electrical/Electronic Systems Against the Indirect Effects of Lightning.
2. DOT/FAA/CT-89/22, Aircraft Lightning Protection Handbook.
3. US MIL-STD-1795A, Lightning Protection of Aerospace Vehicles and Hardware.
4. NASA STS 07636, Rev. A, Space Shuttle Lightning Criteria.

The H component contains three pulse bursts, each with 20 pulses separated by 50 μs to 1000 μs. The individual bursts are separated by 30 ms to 300 ms over a period of up to 2 s. Pulses within a burst, characterized in terms of current, are defined to have peak of 10 kA, a relatively low value compared to other components of the standard lightning environment (200 kA for the first return-stroke peak and 100 kA for the subsequent return-stroke peak), a rise time of 240 ns, and a decay time to half-peak value of 4 μs.

Rakov et al. (28) have recently criticized the H component, as given above, in view of the ground-based measurements of electric and magnetic field pulse bursts by Krider et al. (29), Villanueva et al. (30), and Rakov et al. (28) and the airborne current measurements of Thomas and Carney (31), Mazur (32), and Mazur and Moreau (33), and other information. Clearly, more experimental measurements of the microsecond-scale current pulses in an aircraft lightning environment and in the lightning electromagnetic radiation are needed for an adequate definition of the H component in the lightning standard.

In conclusion, we would like to point out that many of the physical properties of lightning are still not well understood, especially those parameters that dominate in electromagnetic coupling problems. The submicrosecond onset of the return-stroke current, for example, and the associated maximum dI/dt and its duration have been inferred from measurements of the broadband electromagnetic radiation from lightning and one or two experiments on rocket-triggered discharges. Whether these results are valid at the point of attachment in natural CG flashes or for strikes to towers or tall structures is still not known (see discussions in Refs. 7 and 8). The parameters of positive CG flashes, especially those occurring during winter storms, are poorly understood even though this type of lightning is unusually deleterious to electric power systems in Japan. Finally, we note the still mysterious sources of narrow positive (and negative) bipolar waveforms (34) that produce copious HF and VHF radiation and are probably the sources of trans-ionospheric pulse pairs detected on satellites (35). Such impulses are not simulated by any of the present lightning test standards.

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