A Critical Assessment of the U.S. Code for Lightning Protection of Boats

Ewen M. Thomson, *Member, IEEE*

Abstract—**The lightning protection code for boats is published by various authorities in the United States, but common features appear in each rendition: 1) down conductor conductance equivalent to #8 gauge copper wire; 2) a one-square-foot ground plate area; 3) an effective "cone of protection" with 90° apex angle. Data obtained from sailboats that have been struck by lightning indicate that some of these points are deficient, and others need more careful interpretation. These data are presented, and the reasons for the deficiencies in the code are discussed. Theory shows that #8 gauge copper heats up to close to its melting point when subject to a lightning action integral of 5×10^6 A^2s, which is the largest recorded by Berger at Mt. San Salvatore, Switzerland [37]. In fresh water, a lightning current of 30 kA flowing out of a 1-ft^2 ground plane gives rise to potential differences of up to 44 MV between the rigging and the water that can, and apparently do, give rise to destructive side flashes. Lower voltages arise if the ground resistance is lowered as a result of dynamic grounding, but these are still hazardously high. The concept of the cone of protection is closely related to the striking distance to the mast of a boat and, hence, to the probability of a strike to the boat. Estimates of the effective attractive area based on strikes to sailboats in Aboco, Bahamas, in a two-day period indicate that this area is about an order of magnitude larger than that predicted by the 90° cone of protection.**

I. INTRODUCTION

PROTECTING boats from lightning poses some distinctive problems. A typical recreational sailboat comprises many risk factors and features that make reliable protection extremely challenging—small size, proximity of low-voltage electronic systems, presence of people, and, in the case of fresh water, a poorly conducting ground medium. Scientific data concerning the frequency of lightning strikes to recreational boats is nonexistent. On the basis of repair records of lightning-induced damage to marine electronics, the frequency of damage in southwest Florida is about 100 boats out of a total of perhaps 3000, that is, about 3% of all moored sailboats per year [38]. Calculations presented later in this paper are consistent with this figure. There has been significant recent interest in lightning protection of structures [1], distribution lines [2], and telecommunication systems [3]. In contrast, little concerning lightning protection of boats has appeared in scientific literature since the nineteenth century. Bernstein and Reynolds [4], list several papers concerning lightning protection of boats that were published from 1761 to 1850, e.g., [5], [6]. The lack of recent scientific papers is in stark contrast with the high frequency of appearance of articles concerning lightning protection of boats published in the popular press, e.g., [7]-[9]. Further irony is evident when we consider that the main topic covered by Bernstein and Reynolds [4] was Harris' difficulty in convincing the authorities of the value of lightning protection. More than a century later, it is disturbing that 1) boat manufacturers are not obliged to install lightning protection during or after manufacture and frequently do not; 2) manufacturers of marine electronics similarly are not obliged to include transient suppressors to limit damage from lightning-induced overvoltages and typically do not; 3) despite the barrage from the popular press, many boats remain unprotected.

Although specifications for effective lightning protection of boats are defined by many agencies including the American Boat and Yacht Council [10], the Coast Guard [11], the Florida Sea Grant [12], and the National Fire Protection Association [13], each rendition has common features. According to all of these agencies, a boat should have a continuous electrical path that is equivalent to at least #8 gauge copper wire leading from the highest conductor to a conducting ground plane of at least a 1-ft^2 area below the boat. When so constructed, the system is designed to protect an area on the boat within a conical region—the "cone of protection"—whose apex is at the top of the highest conductor and subtends a half-apical angle of 45° from the vertical. We show here how the three major aspects of this code are inaccurate: 1) #8 gauge copper is marginally adequate to dissipate the heat generated by a high-energy lightning current; 2) a 1-ft^2 ground plane results in too large a ground resistance to prevent side flashes in fresh water; 3) the attractive area for lightning strikes to boats may be an order of magnitude larger than that due to a 90° cone.

II. DATA

Data were obtained from sailors whose boats had been struck by lightning. Each sailor completed a standard survey form giving details of the boat description, water conditions, weather observations, electronics damage, hull damage, injuries, and the lightning protection system. The analysis presented here is based on 71 surveys from sailboats that met the following criteria: 1) the boat hull was constructed of fiberglass, 2) the mast was aluminum, and 3) there was clear evidence of lightning attachment to the top of the mast, usually in the form of damage to a masthead antenna. In-

---

Manuscript received July 12, 1989; revised October 29, 1990. This work was supported by the Florida Sea Grant College Program with support from the National Oceanic and Atmospheric Administration, Office of Sea Grant, U. S. Department of Commerce, Grant R/MI-10.

The author is with the Department of Electrical Engineering, University of Florida, Gainesville, FL 32611.

IEEE Log Number 9142856.

0018-9375/91/0500-0132$01.00 ©1991 IEEE

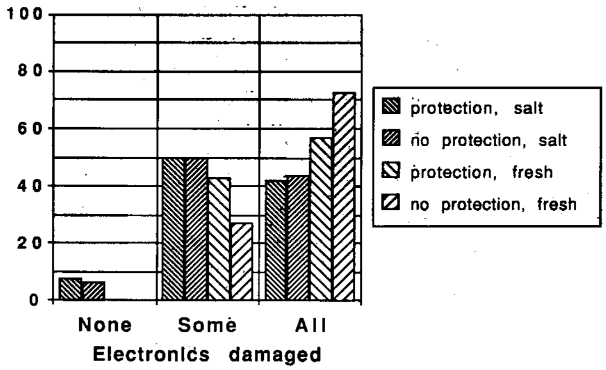


Fig. 1. Frequency distribution for proportion of boats with electronics systems that had none, some, or all of their electronics systems damaged as a result of a direct lightning strike.

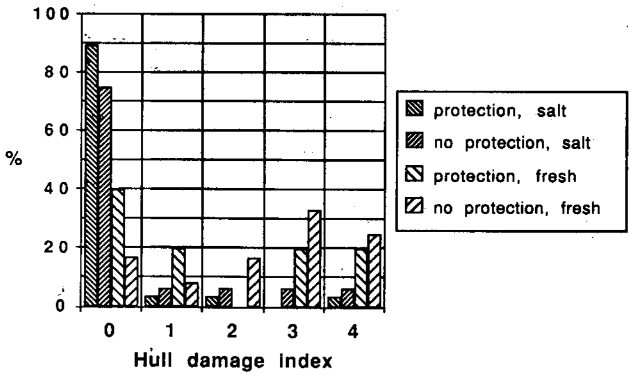


Fig. 2. Frequency distribution for the proportion of boats that incurred hull damage, on a 0 to 4 scale, as a result of a direct lightning strike. The index values are defined in the text.

cluded in the database were boats that had been struck multiple times. One boat was struck on three separate occasions, and two boats were struck twice each.

III. Results

The data were divided into four categories depending on whether the boats were in salt or fresh water and whether they did or did not have lightning protection systems when struck. A boat was considered to have a protection system if a connection existed between the base of the mast or shrouds to either a metallic keel or a ground plate below the hull. Damage to electronics was classified in three categories depending on whether all, some, or no electronics systems were made inoperative as a result of the strike. Typical marine electronics systems are VHF radios, Loran and Satellite navigation systems, weather radar, stereo, knotmeter, wind velocity indicator, and 12-V generator. Four boats in the survey did not have any electronics and were excluded from this analysis. Damage to the boat hull was classified on a 0 to 4 severity index scale according to the following criteria: 0—no discernible burns or fractures, 1—small non-leaking cracks or burns, 2—small holes (typically described as "pin holes" of a millimeter or less diameter) that did not pose a threat of serious leaks, 3—large (several millimeter diameter) holes above the waterline, and 4—large holes (several millimeter diameter) below the waterline. Indices 2 to 4 represented flashover through the hull. Boats with hull damage in category 4 were in sinking condition.

Bar graphs showing the frequency of occurrence of the three degrees of electronics damage are given in Fig. 1. The frequency of occurrence is given as the percentage of all boats in each category falling in the particular damage class. The number of boats in each category are as follows: 26 with protection in salt water, 16 with no protection in salt water, 14 with protection in fresh water, and 11 with no protection in fresh water. Several features in Fig. 1 are worth noting. A particularly disturbing feature is the high proportion of boats —64 out of the total of 67 (96%)—that sustained at least some damage to electronics. There was a slight difference between protected boats—19 out of 40 (48%)—and unprotected boats—15 out of 27 (56%)—reporting damage to all electronics systems. Apparently, the present state of lightning protection is particularly ineffective for marine electronics. Boats in fresh water sustained slightly more electronics damage than boats in salt water—16 out of 25 (64%) versus 18 out of 42 (43%), respectively, with damage to all systems.

Fig. 2 gives bar graphs showing the frequency of occurrence of the five classes of hull damage. The number of boats in each category are as follows: 28 with protection in salt water, 16 with no protection in salt water, 15 with protection in fresh water, and 12 with no protection in fresh water. A major difference between boat strikes in fresh and salt water was apparent in the severity of hull damage. Hull damage of index 2 or higher indicates through-hull flashover, that is, a failure of the lightning protection system. Although only 5 out of 44 (11%) boats in salt water reported hull damage of index 2 or higher, 15 out of 27 (56%) boats in fresh water experienced similar damage. Boats with protection systems fared somewhat better than unprotected boats. In salt water, only 2 out of 28 (7%) with protection systems suffered hull damage severity of index 2 or higher, whereas 3 of 16 (19%) without protection systems suffered similar damage. In fresh water, 6 of 15 boats (40%) with protection systems suffered severity 2 or higher hull damage, whereas 9 of 12 (75%) without protection systems suffered damage of this severity.

IV. Discussion

A. Electronics Damage

The above results display a high incidence of electronics damage that is only marginally better for boats with protection systems. Further, the broad extent of the damage includes electronics that do not have masthead transducers, indicating that phenomena other than the direct flow of lightning current through the system may be important. One such mechanism is induced overvoltages in the boat's dc supply via magnetic coupling from a lightning current flowing in a nearby downconductor. Assume that the lightning current of I amperes flows up a long straight conductor aligned with the z axis. Then, the magnetic flux density at a distance ρ meters from the current is e.g., [14]

$$\vec{B}(\rho) = \frac{\mu_0 I}{2\pi\rho}\vec{a}_\phi \ \mathrm{Wb.m^{-2}} \qquad (1)$$

where $\bar{a}_\phi$ is the unit vector in the ϕ direction. Hence, the emf induced around a wiring loop is

$$\epsilon = \frac{\mu_0}{2\pi} \iint_S \frac{dI/dt}{\rho} \, d\rho \, dz \ \mathrm{V} \tag{2}$$

where S is any surface bounded by the loop. For a sailboat, a typical maximum value of ρ is 2 m, corresponding, for example, to a navigation station placed 2 m away from the mast. Indeed, since sailboats are typically 4 m or less in width, it is practically impossible to route wires past the mast at distances greater than 2 m. Thus, for $dI/dt = 100$ kA/μs [15], the induced emf is about 10 kV/m^2 of equivalent loop area. When we consider that manufacturers of marine electronics are not required to install transient protection and that an overvoltage of a few volts on a 12-V supply is sufficient to harm sensitive integrated circuits, it is not surprising that electronics damage is so pervasive. A partial solution to this problem is to connect a transient suppressor across the 12-V input to each item of electronics equipment, e.g., see [16], and to use twisted-pair wiring throughout the boat. However, this still does not prevent magnetically coupled overvoltages from being induced in printed circuit boards that may have dimensions of the order of 100 cm^2 and therefore be subjected to induced transient voltages of about 100 V.

B. Hull Damage

When lightning strikes an object on the ground, the peak current depends only on the charge present on the stepped leader tip [17]. Hence, lightning behaves as a low impedance Norton current generator with a current waveshape that rises to a peak of typically 30 kA [18]. The electric fields developed in the vicinity of the current flow from a boat ground plate into the water depend on the current density field, which is a function of the geometry of the hull/ground-plate/water system. These electric fields give rise to potential differences between the ground plate, including all conductors attached to it, and the water surrounding the boat. If sufficiently large, these potential differences result in side flashes that may pass through and hole the hull or cause personal injury. Since the current risetime is of the order of 100 ns or longer [15], corresponding to a frequency spectrum below a few megahertz and wavelengths longer than 100 m, the potential field associated with this current flow can be approximated as electrostatic over the length of a typical sailboat (about 10m).

As the lightning current flows through the ground plate into the water, it raises the ground plate and lightning protection system to a potential that depends on the total resistance between the plate and a distant surface at zero potential. The 1-ft^2 area specified in the protection code is supposed to provide a sufficiently small resistance to limit the potential to a harmless value. Saraoja [19] gives formulae for the resistance of various ground electrode configurations. A reasonable approximation for a boat with a single ground plate is a horizontal circular electrode at the water surface. For this geometry, Saraoja quotes a resistance of

$$R = 1/2\sigma D \tag{3}$$

where σ is the water conductivity (10^{-3} $(\Omega.\mathrm{m})^{-1}$ for fresh water with no dissolved minerals), and D is the plate diameter (34 cm for an area of 1 ft^2, that is, for a boat that meets the present lightning protection code). For these values, the resistance is 1.45 kΩ, meaning that in the absence of mitigating phenomena (see below), the peak ground plate potential is 44 MV for a lightning current of 30 kA. Since the current flow is approximately radial, the potential falls off at about the inverse of distance, and the potential in the water is close to zero at distance greater than a few plate radii, that is, more than about 1m away. A potential gradient of 500 kV/m is sufficient for electrical breakdown for lightning impulses [20], [21]. Since potential differences of the order of 44 MV exist over distances of about 1m, potential gradients far in excess of the breakdown value are inevitable. Thus, a side flash is highly likely between the ground plate, or any above-water electrical fittings attached to it, and the water.

A lower resistance is possible for different ground plate geometries. For example, if the ground plate consists of a long narrow strip of length L *m* and width d *m* placed along the centerline of the boat, the resistance according to Saraoja [19] is

$$R = \frac{\ln(2L/1.36d)}{\pi L \sigma} \ \Omega. \tag{4}$$

For a strip 10 m long and 1 ft^2 in area ($d = 9.3$ mm), the resistance is 234 Ω, and the plate potential is 7 MV for the above lightning current in fresh water. Although this is a six times improvement over the circular ground plate, it is still hazardously high.

Note that both of these ground plate geometries produce much lower potentials in salt water with a conductivity of 4 $(\Omega \cdot \mathrm{m})^{-1}$. For the circular electrode, the resistance is 0.36 Ω, and the potential is 11 kV; for the strip electrode, the resistance is 0.06 Ω, and the potential 1.8 kV. Neither of these potentials indicate a serious side flash problem. These findings—that sideflashes are inevitable in fresh water and unlikely in salt water—are consistent with the above survey results that show a much higher incidence of serious hull damage in fresh water than in salt water.

In fact, since the voltages developed for fresh water are about two orders of magnitude larger than those required for breakdown, it is surprising that 60% of protected boats in fresh water experienced no through-hull electrical breakdown. In this regard, the mitigating factor may be the dynamic ground resistance that arises when breakdown occurs in the water as the lightning current flows out of the ground plate. This is smaller than the static ground resistance as the effective ground plate area is increased significantly [22]. Petropoulos [22] described how, for a radial current flow, the electric field exceeds breakdown for radii less than

$$r_0 = \sqrt{\frac{I}{2\pi\sigma E_b}} \tag{5}$$

where I is the current, σ the ground conductivity, and E_b the breakdown electric field. Hence, the effective ground plate area is that of a hemisphere of radius r_o. Petropoulos

[22] notes that a 5-cm-radius sphere in "town water" did not produce streamers when subjected to an impulse voltage of 50 kV so that E_b in this case was in excess of 10^6 V/m. For fresh water with $\sigma = 10^{-3}\ (\Omega \cdot \mathrm{m})^{-1}$, $I = 30$ kA, and $E_b = 1 \times 10^6$ V/m, we get $r_o = 2.2$ m. For a single ground plate, the effective area with dynamic grounding is thus 30 m^2 and is independent of the actual area of the plate. The effective resistance [22]

$$R = 1/2\pi\sigma r_o \tag{6}$$

is 72 Ω, and the maximum voltage is 2.2 MV, which is a factor of about 20 smaller than that developed for a circular plate of 1-ft^2 area. It is, however, still larger than the 500 kV/m needed to form a spark over a distance of 1 m.

Further, the assumed value of 1×10^6 V/m for the breakdown electric field is a lower limit for a spherical electrode, as was explained above. A larger breakdown electric field will result in a smaller r_o and higher maximum voltage than that calculated above. For example, a breakdown field of 3 E_b gives a resistance that is $\sqrt{3}$ times that of calculated above. The actual form factor of the ground plate is also important. In order to get the lowest breakdown voltage in a dynamic ground, it is desirable to initiate streamers from the ground surface. Petropoulos [22] found that a 5-cm-radius spherical electrode equipped with seven 4-cm-long points started producing small sparks at an impulse crest voltage of 28 kV, whereas the 5-cm sphere without points did not produce sparks even at 50 kV. Thus, a ground surface with sharp corners or points will initiate streamers at a lower voltage and result in a lowering of ground resistance due to the dynamic ground effect at a lower current than will a smooth surface.

In order to find the dynamic ground resistance for a long narrow conductor placed along the centerline of the boat, it is necessary to assume an appropriate discharge model. Rather than current flowing as a uniform current density from the conductor, arcing patterns on the lead keels of sailboats frequently indicate that the mode of discharge is from a small number of discrete points that are spaced at regular intervals. Assume that a current I_o is divided equally amongst N points on the centerline conductor with two points being at either end and the rest equally spaced at a spacing of $2r_o$, where r_o is the breakdown radius corresponding to the current flowing from each point I_o/N. If R_o is the breakdown radius for a single ground plane, and L is the length of the long conductor, then

$$L = (N-1)2r_o \tag{7}$$

and from (5) $r_o \sqrt{I_o/N/2\pi\sigma E_b}$

$$= R_o/\sqrt{N}. \tag{8}$$

Eliminating N from (7) and (8) gives the quadratic

$$r_o^2 + \frac{L}{2} r_o - R_o^2 = 0. \tag{9}$$

This has the solution

$$r_o = -\frac{L}{4} + \frac{1}{2}\sqrt{\frac{L^2}{4} + 4R_o^2}. \tag{10}$$

For $R_o = 2.2$ m, as for the single ground plate described above, we find $r_o = 0.83$ m and $N = 7$. Hence, the effective dynamic resistance per exit point is (from (6)) 191 Ω, and the total resistance is 27 Ω, compared with 234 Ω for the nondynamic resistance ((4)) and 72 Ω for a single ground plate ((6)). The maximum voltage for a 30-kA current is 810 kV, which is about one ninth the nondynamic maximum voltage and one third that for a single ground plate with dynamic grounding. Although this is still high enough to initiate sideflashes to the water, by placing a conductor along the centerline, we establish an equipotential that inhibits sideflash formation from any conductors directly above the centerline. This includes both the forestay and the backstay, which are conductors that are highly susceptible to initiating sideflashes if only a single ground plate is used.

Although the dynamic ground effect results in a lowering of ground resistances after discharge paths have been established in the water, higher resistance and voltage values than those predicted above are likely as a result of propagation delays in the discharges in the water. This effect produces delays in the onset of the resistance decrease. Petropoulos [22] estimated the speed of propagation from the Bellaschi *et al.* [23] data to be about 10^5 m/s for various types of soil. The corresponding delay is 20 μs for a 2-m discharge in the water, such as from the single ground plate considered above. Liew and Darveniza [24] dealth with this propagation delay by means of an ionization time constant for the current that they found to be about 2 μs. Both Bellaschi and Liew used current waveshapes with risetimes of several microseconds; therefore, their results may differ from those to be expected from currents in subsequent return strokes with risetimes that are often as short as 0.2 μs [25] or even 0.1 μs [15]. Although no quantitative predictions are possible, all the above findings indicate that the onset of the reduction in ground resistance resulting from breakdown in the water is delayed by several microseconds, which is a delay that is similar to the current risetime in first strokes but several times longer than the current risetime in subsequent strokes. Berger *et al.* [26] found a mean current risetime of 5.5 μs for first strokes and 1.1 μs for subsequent strokes in lightning that lowered negative charge. The effect for subsequent strokes is mitigated somewhat because they tend to have lower peak currents: about one half of the peak currents of first strokes (mean of 12 versus 30 kA [26]). However, this is not sufficient to compensate for the factor of 2–20 difference between the risetime and the onset delay for subsequent strokes. Thus, the voltages calculated above for dynamic grounds should be regarded as very conservative lower limits.

C. The Attractive Area for Direct Strikes

The so-called "cone of protection" has its roots in early observations of lightning strikes to buildings. Specifically, lightning would frequently strike the corner of a building rather than a lightning rod at the highest point in the middle of the roof, which would be the intended target. For effective protection, a ratio is 1 : 1 is needed for the height of the lightning rod above the edge of the roof to the distance from rod to edge [27], hence, the cone of protection with height equal to the radius of its base, which is that with a 90° apex angle. Lightning that would, in the absence of the lightning rod, strike within the region bounded by the conical surface is supposed to strike the cone apex. The mechanism for this attachment is that the top of the lightning rod launches an upward-going discharge to meet the downward-going lightning-stepped leader before other objects within the cone of protection [25]. Some statistical variation is to be expected [28]. Muller-Hillebrand [29] found that lightning struck tall chimneys in proportion to the square of their height rather than linearly, as the "cone" concept implies. No research appears to have been done on the validity of the cone concept for boat protection.

We define the attractive area as the effective area from which a sailboat mast attracts a lightning attachment, that is, the expected number of lightning attachments is $N \cdot A$ flashes for a boat with an effective area A in a region where the gound flash density in the time interval of interest is N flashes per unit area. If we assume that each lightning attaches to only one boat mast, which is an assumption that may not be valid as discussed below, the attractive area and zone of protection are identical. In this case, we can estimate the apex angle of the "cone of protection" using data supplied to the author. In two days in mid July 1987, it was reported [39] that a total of nine boats were struck in Aboco, Bahamas, within an area roughly 20 miles by 1.5 miles containing from 150 to 250 boats. Assume that all boats had a mast height of 15 m, which is typical of cruising yachts. In order to underestimate the attractive area, also assume that the ground flash density within the two days was $N = 10$ km^{-2}, which is ten times the density for a single storm in Tampa [30], and that there were 250 boats. Convective storms typically have a lifetime of about 30 min to 1 hr, and the downdrafts associated with the dissipating stage tend to inhibit further convection in the same area. However, the downdraft front can give rise to uplift and, hence, further development on the leading edge of the storm [31]. If the storm-steering wind advected these new cells over the area of interest, several storms could traverse the same area in a single day. Five per day would be an extreme upper limit. Thus, $N = 10$ km^{-2} is possible if this unusual set of meteorological conditions prevailed. If the effective area for the average boat is A_{eff}, then the total effective area is $250 \cdot A_{\text{eff}}$, and the expected number of strikes is $250 \cdot N \cdot A_{\text{eff}}$. Equating this to the observed number of strikes (nine) and assuming that the attractive area is the base of a cone of protection with apex angle α, we can estimate a lower limit for α from

$$9 = 10 \times 10^{-6} \cdot 250 \cdot \pi \cdot 15^2 \cdot \tan^2(\alpha/2) \qquad (11)$$

Hence $\alpha = 132°$. The attractive area per boat $\pi \cdot 15^2 \cdot \tan^2(\alpha/2)$ is thus 3.6×10^3 m^2, which is five times larger than the area of the base of a cone with a 90° apex angle 7.0×10^2 m^2. We can assess the statistical likelihood of the significance of this difference (a factor of five) in the following way. Since the probability of each lightning striking a boat is small ($= 6 \times 10^{-5}$) but the number of strikes (nine) is moderate, we can model the parent distribution as Poisson with a mean of 9 and standard deviation (= [mean]1/2) of 3. The range of α corresponding to the number of strikes within 1 standard deviation of the mean is 123 to 138°, which is a span that does not include the 90° apex angle quoted in the code. In fact, an apex angle of 90° corresponds to 1.8 strikes, or 2.4 standard deviations from the mean. This represents a significant difference at the 2% level of confidence, even though we have drastically overestimated the ground flash density. If the Bahamian storms followed similar life cycles to convective summer storms in Tampa, it is more likely that only two, rather than ten, active storms formed over this area in the two-day period, as was explained above. In the absence of the fortuitous steering winds needed for ten storms, a more likely value for N would be 2 km^{-2}, corresponding to one thunderstorm cell per day. If we use this more likely ground flash density, α becomes 158° and the ratio of the attractive area per boat to the area of the base of a 90° cone becomes 25 instead of five.

A corollary to the above calculation is the expected frequency of occurrence of lightning strikes (or effects) on boats as a function of the ground flash density, which is a parameter that is now widely measured [32]. Assuming that a lower limit to the attractive area is the area of the base of a 132° cone, as is found above, and that a typical mast height is 15 m, the frequency of occurrence of lightning strikes per boat per year as a function of the yearly ground flash density N_y km^{-2} yr^{-1}, is

$$f = N_y \times 10^{-6} \cdot \pi \cdot 15^2 \cdot \tan^2(132/2). \qquad (12)$$

For example, in Tampa, FL, where the ground strike density per year is about 10 km^{-2} yr^{-1} [33], f is about 4% or one boat in every 30/yr. Note that the 132° cone was determined from a ground flash density that may have been five times too large (10 km^{-2}/yr rather than 2 km^{-2}/yr). Using the more reasonable density of 2 km^{-2}/yr, the corresponding f is 18% or about 1 boat in every 5/yr. A frequency of occurrence of between four and 18 strikes per 100 boats per year represents a considerable hazard.

The assumption that each lightning affects only one boat may not be valid in crowded anchorages since upward-going streamers can be triggered from several points on the ground in response to a single stepped leader [34], and the current in an upward streamer may be sufficient to cause electronics damage suggestive of a direct strike. Further, induced effects from nearby lightnings may be responsible for damage to electronics that could similarly be interpreted as being from a direct strike. However, the concept of "attractive area" developed above is important even if it is not limited to direct strikes since it gives a quantitative measure of the probability of lightning-caused damage, whether from direct strikes, upward streamers, or induced effects.

D. Downconductor Damage

The lightning protection code requires at least a #8 gauge copper downconductor connecting mast to ground plate. This corresponds to a cross-sectional area of 8.3 mm^2, which is considerably smaller than the 29 mm^2 specified for downconductor cross-sectional area for buildings [13] in the NFPA code. The history of protection of houses has been documented by Muller-Hillebrand [35]. Concerning downconductors, Muller-Hillebrand concluded from a study in Poland that 10 mm^2 iron wire, which is equivalent to 4 mm^2 copper, was about 95% effective in preventing fires in rural houses in Poland. He also states that the minimum cross section based on current loading is in many cases 6 mm^2 of copper and notes that the 35 mm^2 in the Swedish code is based only on mechanical reasons. The relevant plots are given in Fig. 3, which is based on data presented by Golde [36]. It shows the temperature rise of copper conductors of various gauges versus the action integral from a lightning stroke, taking into account the skin effect. The maximum action integral ever measured directly for strokes that lower negative charge was 5×10^6 A^2s [37]. Fig. 3 shows that, coincidentally, this action integral dissipated in a #8 gauge copper conductor raises its temperature to about its melting point (1083°C), leaving no margin for safety. Muller-Hillebrand [35] describes a case where an 8.4-mm^2 copper downconductor on a church in Bavaria was destroyed by lightning. He estimates that the heating corresponded to an action integral of 7×10^6 A^2s, which is consistent with Fig. 3 for #8 wire. The experience of one sailor demonstrates the marginal adequacy of a #8 gauge copper downconductor. His boat, protected with a single #8 gauge copper downconductor, was struck twice within a month. After the first strike, he observed "no obvious signs of damage." In contrast, as a result of the second strike, "the copper grounding wire has fused open circuit at both the mast and at the keel bolt." During the second strike, the protection system failed completely because "the teak bulkhead shattered scattering teak shrapnel around the boat," posing an obvious hazard had anyone been on board. It is possible that the first strike had somehow increased the resistance of the downconductor connections. However, a reliable protection system should be capable of withstanding multiple strikes.

Protection requirements for a boat are more stringent than those for most buildings since a failure such as that described above are more likely to result in personal injury in a boat. A failure rate of 5% may be acceptable for economic reasons on rural buildings in Poland [35] but is clearly unacceptable on a boat in midocean. Although there is, as yet, no scientific data, the incidence of lightning strikes to cruising sailboats appears high. Rofhenhaus, in a private communication, indicates that "out of scores of cruisers, very few have *not* been struck by lightning." Safety margins much higher than that offered by #8 gauge copper are needed. According to Fig. 3, #4 gauge copper heats up to about 100°C, which is a factor of 10 below the melting point for an action integral of 5×10^6 A^2s. If we arbitrarily assign a safety margin of a factor of 10 as being desirable, then all connections should have equivalent conductance to #4 gauge copper.

V. CONCLUSIONS

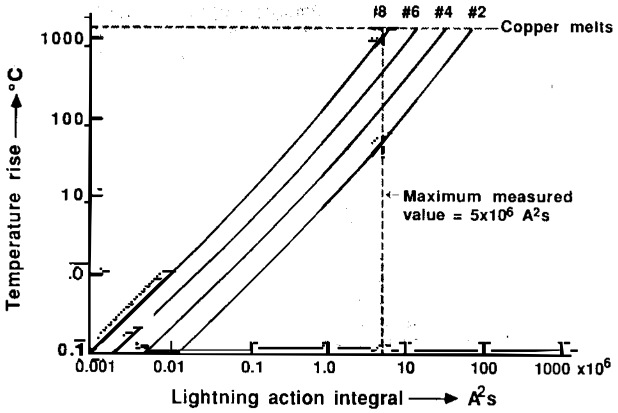


Fig. 3. Temperature rise in copper downconductors of #8, #6, #4, and #2 gauge versus lightning action integral.

The U.S. code for lightning protection of boats is seriously inadequate. Downconductor conductance should be specified as that of #4 gauge copper rather than the #8 gauge presently quoted in order to minimize the risk of overheating and melting. The 1-ft^2 ground plate is shown to be hopelessly inadequate to prevent side flashes in fresh water. The magnitude of the potential gradients involved is 2 orders of magnitude larger than the breakdown value if we ignore the effect of breakdown in the water and points to no simple solution to this problem. In salt water, a 1-ft^2 ground plate is adequate. The concept of a cone of protection with a 90° apex angle is not applicable to the attractive effect of sailboat masts because it underestimates the probability of strike occurrence by an order of magnitude.

ACKNOWLEDGMENT

The author is grateful to the many sailors who provided the data that made this work possible and especially to those who are quoted in the text. Useful discussions were held with N. Lasseter, W. Cerny, K. Fickett, and M. Uman. Comments made by C. J. Olszewski resulted in a significant improvement in the manuscript.

REFERENCES

[1] R. H. Golde, *Lightning Protection*. London: Arnold, 1973.

[2] S. Rusck, "Protection of distribution lines," in R. H. Golde, Ed., *Lightning, Vol.* 2, *Lightning Protection*. New York: Academic, 1977, pp. 747-771.

[3] C. F. Boyce, "Protection of telecommunication systems," in R. H. Golde, Ed., *Lightning, Vol.* 2, *Lightning Protection*. New York: Academic, 1977, pp. 793-829.

[4] T. Bernstein and T. S. Reynolds, "Protecting the Royal Navy from lightning—William Snow Harris and his struggle with the British Admiralty for fixed lightning conductors," *IEEE Trans. Education*, vol. E-21, no. 1, pp. 7-14, 1978.

[5] W. Watson, "Some suggestions concerning the preventing the mischiefs which happen to ships and their masts by lightning," *Royal Soc. Philosoph. Trans.*, vol. 52, pp. 629-635, p. 1761.

[6] W. S. Harris, "On the protection of ships from lightning," *Nautical Mag.*, vol. 3, pp. 151-156, 225-233, 353-358, 402-407, 477-484, 739-744, 781-787, 1834.

[7] P. G. Gill, "Lightning at sea," *Saltwater Sportsman* (Florida ed.), pp. 19-22, Nov. 1989.

[8] K. Burkhardt, "Protect your boat from lightning," *Sail*, vol. 18, no. 10, pp. 49-52, 1987.

[9] S. Weller, "Can you really protect your boat from lightning?," *Practical Sailor*, vol. 14, no. 14, pp. 8-14, 1988.

[10] American Boat and Yacht Council, "Recommended practices and standards covering lighting protection," Project E-4, ABYC E-4-85, 1985.

[11] U.S. Coast Guard, "Lightning: Cone of protection," MICHU-SG-79-114, Mich. Sea Grant, 1979.

[12] W. J. Becker, "Boating—Lightning protection," SGEB-7, Flor. Sea Grant, 1985.

[13] National Fire Protection Assoc., *Lightning Protection Code 1980*, NFPA, 1980.

[14] H. P. Neff, *Basic Electromagnetic Fields*. New York: Harper and Row, 1987.

[15] C. D. Weidman and E. P. Krider, "Submicrosecond risetimes in lightning return stroke fields," *Geophys. Res. Lett.*, vol. 7, pp. 955-958, 1980; Correction, *J. Geophys. Res.*, vol. 87, 7351, 1982.

[16] E. P. Krider, "Lightning damage and lightning protection," in E. Kessler., Ed., *Thunderstorms: A Social, Scientific and Technological Documentary. Vol. 1. The Thunderstorm in Human Affairs.* Norman, OK: University of Oklahoma Press, 1983, pp. 111-124.

[17] R. H. Golde, "The British code of practice on the protection of structures against lightning," *Elek. Tech. Zeit.*, vol. 92, pp. 516-520, 1971.

[18] Y. T. Lin, M. A. Uman, and R. B. Standler, "Lightning return stroke models," *J. Geophys. Res.*, vol. 85, pp. 1571-1583, 1980.

[19] E. K. Saraoja, "Lightning earths," in R. H. Golde, Ed., *Lightning, Vol. 2, Lightning Protection*. New York: Academic, 1977, pp. 577-598.

[20] R. H. Golde, "The attractive effect of a lightning conductor," *J. Inst. Elec. Eng.*, vol. 9, pp. 212-213, 1963.

[21] L. Thione, "The dielectric strength of large air insulation," in K. Ragaller, Ed., *Surges in High Voltage Networks*. New York: Plenum, 1980, pp. 165-206.

[22] G. M. Petropoulos, "The high voltage characteristics of earth resistances," *JIEEE*, vol. 95, pp. 59-70, 1948.

[23] P. L. Bellaschi, R. E. Armington, and A. E. Snowden, "Impulse and 60-cycle characteristics of driven grounds, Pt. II," *Trans. Amer. Inst. Elec. Eng.*, vol. 61, pp. 349-363, 1942.

[24] A. C. Liew and M. Darveniza, "Dynamic model of impulse characteristics of concentrated earths," *Proc. Inst. Elec. Eng.*, vol. 121, pp. 123-135, 1974.

[25] A. J. Eriksson, "Lightning and tall structures," *Trans. South Afr. Inst. Electr. Eng.*, vol. 69, pp. 2-16, 1987.

[26] K. Berger, R. B. Anderson, and H. Kroninger, "Parameters of lightning flashes," *Electra*, vol. 80, pp. 23-37, 1975.

[27] R. H. Golde, "The lightning conductor," in R. H. Golde Ed., *Lightning, Vol. 2, Lightning Protection*. New York: Academic, 1977, pp. 545-576.

[28] ——, "The lightning conductor," *J. Franklin Inst.*, vol. 283, pp. 451-477, 1967,

[29] D. Muller-Hillebrand, "On the frequency of lightning flashes to high objects on the Gulf of Bohemia," *Tellus*, vol. 12, pp. 444-449, 1960.

[30] D. W. Peckham, M. A. Uman, and C. E. Wilcox, Jr., "Lightning phenomenology in the Tampa Bay area," *J. Geophys. Res.*, vol. 89, pp. 11,789-11,805, 1984.

[31] H. R. Byers and R. R. Braham, "Thunderstorm structure and dynamics," in H. R. Byers, Ed., *Thunderstorm Electricity*. Chicago: University of Chicago Press, 1953,

[32] R. E. Orville, R. B. Pyle, and R. W. Henderson, "The East Coast lightning detection network," *IEEE Trans. Power Systems*, vol. PRWS-1, pp. 243-246, 1986.

[33] M. Darveniza and M. A. Uman, "Research into lightning protection of distribution lines II—Results from Florida field work 1978 and 1979," *IEEE Trans Power App. Syst.*, vol. PAS-103, pp. 673-682, 1984.

[34] K. B. McEachron and W. A. Morris, "The lightning stroke: Mechanism of discharge," *Gen. Elect. Rev.*, vol. 39, pp. 487-496, 1936.

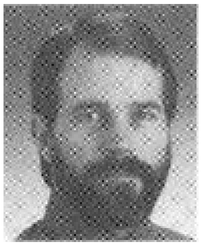
[35] D. Muller-Hillebrand, "The protection of houses by lightning conductors—An historical review," *J. Franklin Inst.*, vol. 274, pp. 34-54, 1962.

[36] R. H. Golde, "Protection of structures against lightning," *Proc. IEE Contr. Sci.*, vol. 115, pp. 1523-1529, 1968.

[37] K. Berger, "Novel observations on lightning discharges: Results of research on Mount San Salvatore," *J. Franklin Inst.*, vol. 283, pp. 478-525, 1967.

[38] W. Cerny, Private communication.

[39] W. Blood, Private communication.



Ewen Thomson (M'88) received the B.Sc. and M.Sc. degrees from the University of Auckland, New Zealand, in 1971 and 1973 respectively, and the Ph.D. degree from the University of Queensland, Australia, in 1985.

In 1974, he joined the Department of Physics, University of Papua New Guinea, and moved to the Department of Electrical Engineering at the University of South Florida in 1981. He is now an Associate Professor at the University of Florida. His research activities include experimental and theoretical work concerning electromagnetic effects of lightning.