A PROPOSED ADDITION TO THE LIGHTNING ENVIRONMENT STANDARDS APPLICABLE TO AIRCRAFT TO ACCOUNT FOR EFFECTS OF POSITIVE LIGHTNING STROKES OF LONG DURATION AND MODERATE INTENSITY

J. Anderson Plumer
Lightning Technologies, Inc.
10 Downing Industrial Parkway
Pittsfield, Massachusetts 01201
U.S.A.
japlumer@aol.com

ABSTRACT

Lightning strike incidents to commercial and military aircraft and helicopters have produced damage unlike what is usually inflicted by laboratory tests conducted in accordance with the aircraft lightning environment defined in present aircraft lightning environment standards including SAE ARP5412 and EUROCAE ED 81 and US Military Standard 464A (and predecessor standards dating back to 1970). These standards define a first stroke current of 200 kA peak amplitude and overall time duration of 500 μs followed by intermediate and continuing currents whose amplitudes do not exceed 4 kA. There is no recognition of the possibility of lightning stroke currents of higher amplitude than 200 KA or, more likely, of lower than 200 kA amplitude, but of longer time duration than 500 μs. The physical damage effects that have prompted this review appear to have resulted from lightning stroke currents that have long durations and moderate to severe amplitudes, but not the fast rates of rise (di/dt) usually associated with lightning stroke currents especially those that lower negative charge to earth. A proposal is made to add to the present aircraft lightning standards a current component that represents a long duration stroke current of moderate amplitude. It is suggested that this proposal be taken up by the committees responsible for updating aircraft lightning standards: SAE AE2 and EUROCAE WG31. This proposal might be extended to incorporate a higher amplitude version of this current component to account also for some effects that can only be attributable to strokes of very high action integrals, but such an extension is not discussed in this paper.

ACRONYMS AND SYMBOLS

SAE	Society of Automotive Engineers Inc.
CG	cloud to earth lightning flash
+CG	positive cloud to earth lightning flash
EUROCAE:	European Organization for Civil Aircraft Equipment
NLDN	National Lightning Detection Network (US)
LPC+CG	large peak current positive cloud to ground lightning flash
A	current (amperes)
α	double exponential waveform coefficient, (s^{-1})
A·s	charge (ampere-seconds, also coulombs)
A/s	rate of change of current (amperes/sec)
A²s	action integral (ampere-squared seconds)
β	double exponential waveform coefficient, (s^{-1})
C	capacitance (farads, or microfarads)
C	charge (ampere-seconds, or coulombs)
cm	distance (centimeters)
D	distance (m, cm)
EMC	electromagnetic compatibility
F	force (newtons/m)
H	inductance (henries)
I	current (amperes)

J	energy (joules)
kA	current (10^3 amperes)
L	inductance (henries, microhenries)
m	distance (meters)
ms	milliseconds
P	pressure (newtons)
Q	charge (ampere-seconds or coulombs)
R	resistance (ohms)
S^{-1}	1/time (s)
US	United States of America
µF	capacitance (10^{-6} farads)
µH	inductance, (10^{-6} henries)
t	time (seconds)
µ	permeability of free space ($4\pi \times 10^{-6}$ henries/m)
µs	time (microseconds)
V	voltage (volts)

PRESENT AIRCRAFT LIGHTNING STANDARDS

The lightning current components applicable to aircraft lightning protection design and certification are published in SAE and EUROCAE [i,ii] include synthesized current waveforms representing several aspects of the cloud to earth lightning flash currents as listed in Table 1.

Table 1. Standard Lightning Currents for Aircraft

Lightning Current	Standard Component	I_{pk} (kA)	Q (A·s)	Time
First Stroke	A	200	15	500 µs
Intermediate Current	B	4	10	5 ms
Continuing Current	C	0.4	200	0.5 s
Subsequent Stroke	D	100	2.5	250 µs

These standard waveforms have evolved through early US and European standards originating in the 1960's to include the current components listed above and more fully defined in [i,ii]. The present standards were last agreed upon among aircraft lightning specialists in the US and Europe in the mid 1980s. The origins of these standard current components come from several databases containing measurements of cloud-to-earth lightning flash currents [iii,iv]. Examples of negative stroke currents contained in one of the databases are shown in Figure 1.

Unlike electromagnetic compatibility (EMC) environments that prescribe a continuous frequency and corresponding amplitude environment, the lightning environment has been confined to a group of time domain pulses with no information between the specific characteristics of these pulses which represent stroke, intermediate, and continuing currents.

Statistics show that negative first stroke amplitudes rarely exceed 100 kA and have decay time durations within the 500 µs decay times (to ~5%) assumed for standard first stroke. The 200 kA peak amplitude assigned to the 500 ms stroke, called Component A, was chosen to reflect positive polarity strokes though statistics [i,ii] indicate that 5% of positive strokes reach peaks of up to 250 kA.

POSITIVE LIGHTNING STROKES

The time durations of positive lightning strokes are widely believed to extend to several ms, so that larger amounts of charge are transferred by the positive stroke currents. A recent summary of positive lightning flash characteristics, compiled by the US and European lightning standards committees, is found in [i,ii] and reproduced here as Table 2.
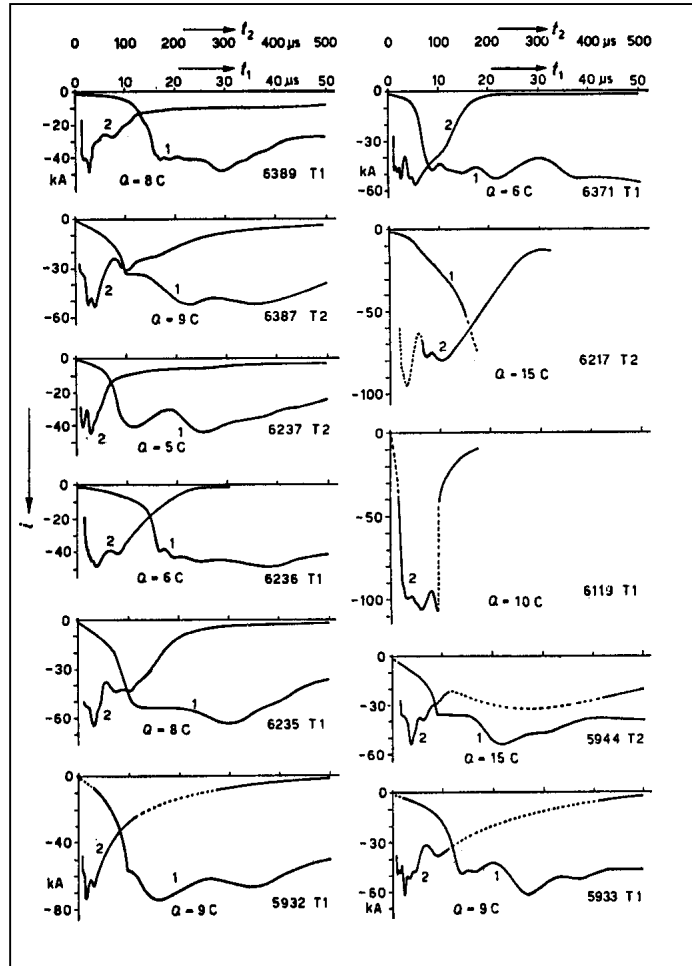
Figure 1. Current oscillograms from initial strokes of negative cloud-to-earth flashes [v]

Table 2. Statistics of positive lightning flash currents [i,ii]

Parameters	Unit	Lightning Parameters 95%	Lightning Parameters 50%	Lightning Parameters 5%
Positive Flashes:				
Flash duration	ms	14	85	500
Total charge	C	20	80	350
Positive Stroke:				
Peak current	kA	4.6	35	250
Peak rate-of-rise	A/s	2×10^8	2.4×10^9	3.2×10^{10}
Time to peak	µs	3.5	22	200
Time to half value	µs	25	230	2000
Impulse charge	C	2	16	150
Action integral	A^2s	2.5×10^4	6.5×10^5	1.5×10^7

NOTE 1: The above lightning parameters listed above do not necessarily occur together in one flash.
NOTE 2: The percentage figures represent percentiles, that is, the percentage of events having a greater amplitude than those given.

It will be noted that the decay times to 50% at the 5% (exceeding) severity level is about 2 ms which is over 20 times the decay time assigned to the first stroke component in the present aircraft standard.

The impulse charge (transferred by the stroke alone) of 150 A·s (coulombs) is also much greater than delivered by Component A. Oscillographic records of positive lightning strokes to earth are rare; the most important data being that published on 26 positive stroke currents by Berger and Vogelsanger [v,vi], examples of which are shown in Figure 3. Rakov, in his review of positive lightning stroke characteristics

[vii], has noted that a reliable distribution of positive lightning stroke peak currents is not available, and that positive stroke currents from leaders that originate in the cloud (like most negative leaders) are of much shorter duration (100s of µs) than are stroke currents resulting from leaders originating from tall objects on the ground. The latter often result in multiple upward leaders, each neutralizing positive charge in a different region within the cloud above. It is questionable, then, whether an aircraft struck by such a flash would experience all of the stroke current, since some would likely be transferred by leaders not attaching to the aircraft. Such a flash is illustrated in Figure 2. But, there is no assurance that an airplane would not be a conduit for all upward leaders and stroke currents which may branch upward from an aircraft that first encountered only one upward leader.
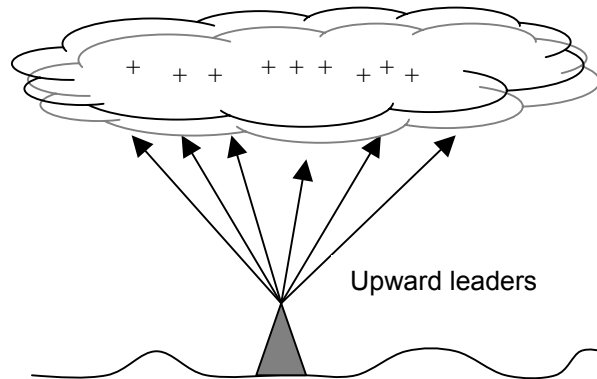

Figure 2. Upward branching flash to positive charge in cloud
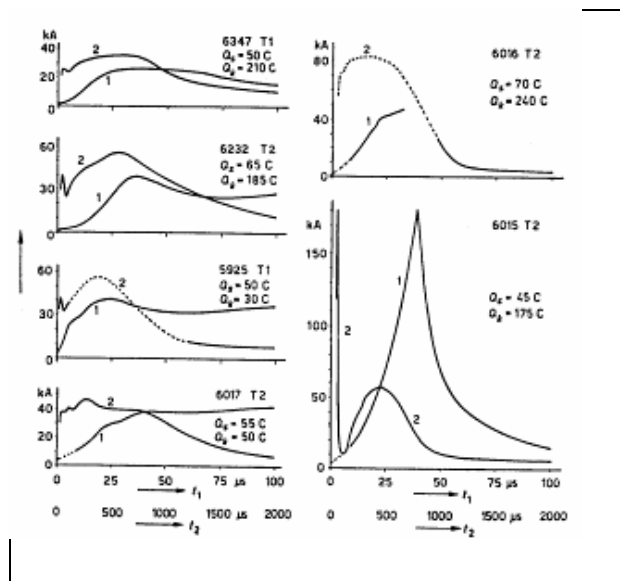

Figure 3. Examples of positive stroke currents [v]

AIRCRAFT EXPERIENCE

Several in-flight lightning strike incidents have shown physical damage that is indicative of moderate to severe stroke currents with time durations to several milliseconds or even 10s of milliseconds. The physical damage appears to have resulted from unusually strong magnetic forces among conductors including bond straps, forces that have been strong as well as persistent, and these incidents have also left evidence of large charge transfers well in excess of those assigned to the presently defined intermediate and continuing currents Components B and C*.

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One of the incidents is described briefly here, together with an assessment of what the nature of the lightning current may have been. The basic scenario, which has been repeated in several recent incidents involves the effects of severe lightning currents in bond straps across parallel paths not intended for lightning currents as shown simply in Figure 4.
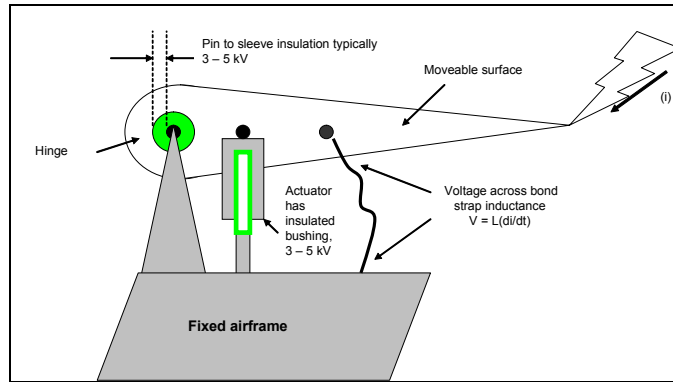
**Figure 4. Basic scenario: Bond straps across hinges and actuators**

A mid-sized aircraft was approaching an airport when it received a lightning strike that ***initially entered*** one of the horizontal stabilizer tips and ***initially exited*** from the lower surface of the nose.

The ***final entry*** location was the aft end of the fuselage, and the ***final exit*** location was also at the same horizontal stabilizer tip. This is a very typical lightning strike scenario, particularly when the aircraft has encountered a cloud-to-earth flash as can happen when the altitude was between 12,000-14,000 ft. The airspeed was reported to be 280 knots when the lightning strike occurred. Significantly, the pilots did not report a loud noise associated with this strike.

The horizontal stabilizer was attached to the aircraft by a mechanical hinge and a hydraulic trim actuator. Two parallel braided copper bond straps provided paths for lightning currents to flow between stabilizer and fixed airframe.

This aircraft is ~30 m long and the lightning seems to have been mostly done by the time of the last visible lightning attachment point which was on the tail of the fuselage. At 280 knots, this would imply a typical flash time duration of ~300 ms. The US National Lightning Detection Network (NLDN) reported a cloud-to-earth flash of positive polarity at about the same time and place as the aircraft was struck.

A hypothetical positive lightning flash that may have caused the observed damage is shown in Figure 5. It includes one long duration stroke current followed by continuing current. Its peak stroke current is 30 kA and total charge transfer is 220 coulombs (A·s). Its total time duration is ~300 ms.
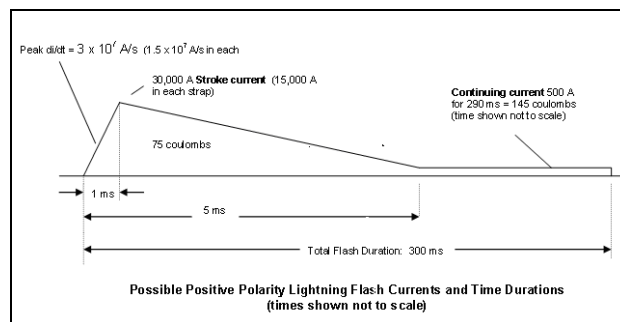
Figure 5. Hypothetical positive lightning current waveform

The stroke current of Figure 5 has an average rate of rise of 3 x 10^7 A/s. It may be presumed that the peak di/dt for such as stroke would be about one order of magnitude greater or 3 x 10^8 A/s (not unreasonable when compared with the ranges in Table 1), thus 1.5 x 10^8 A/s in each of the two parallel bond straps. If the inductance of each bond strap is assumed to be 0.25 µH (a typical value for a short bond strap), the voltage in the loop between each bond strap and the nearest structural element (i.e. an hydraulic actuator piston) would be 37.5 volts which is not enough to cause sparkover of the bushing insulation surrounding the hydraulic actuator piston. Sparkover voltages of insulation such as this are typically in the 3,000-5,000 volt range (not adjusted for reduced pressures at flight altitudes). Inspection of the aircraft after landing showed no evidence of sparkover of a hydraulic actuator bushing or of the lubricating sleeves surrounding the hinge pins, either of which would have provided additional paths for lightning currents to transfer from the moveable surface to the aircraft fixed structure. Visual inspection of the aircraft after landing indicated more than 200 coulombs worth of erosion effects on the fuselage belly where the flash currents entered the airplane, and a similar amount of erosion at the static wick base on the horizontal stabilizer tip where the flash currents exited from the aircraft. The terms "entry" and "exit" have nothing to do with the physical effects of lightning attachment. The effects of charge entering or exiting a location on the same type of structural surface are nearly the same.

Significant effects: Two bond straps, which provide paths for lightning currents between the horizontal tail surfaces and the vertical fin, were broken or pulled away from their lugs, but they had not been melted or vaporized. These bond straps bypass hydraulic actuators that have non-conducting cylinder bushings. As noted above, there was no evidence of surface flashover across the bushing insulation which would have happened had there been the usual fast rate of rise (di/dt) of negative stroke starting to flow in the bond strap inductances.

Instead, it is evident that all this stroke current flowed in the failed bond straps or in the electric arcs that followed the broken straps.

Mechanical forces on the bond straps: During lightning current flow in the two parallel bond straps, each approximately 15 cm long and approximately 15 cm apart, there would have been electromotive forces pulling on these straps in the vertical and horizontal directions. These forces attract the current carrying conductors together if the currents are in the same direction as in the two bond straps. Currents in opposite directions produce repelling forces.

Some forces in both directions would have existed on these straps, and would have canceled at the straps as illustrated in Figure 5, but the strongest forces would have been attraction between the two that were parallel to each other. The expression for these forces is:

$$dP/dL = (2\mu I_1 I_2)/D \ \ (Newtons/m)$$

Where I_1 and I_2 are the currents in the two bond straps (assumed to be 15,000 A in this example) and D is the distance between the straps (m), assumed to be 0.15 m in this example. µ is the permeability of free space (4π x 10^{-7} H/m). P is pressure (Newtons) and L is the unit of conductor length (m).
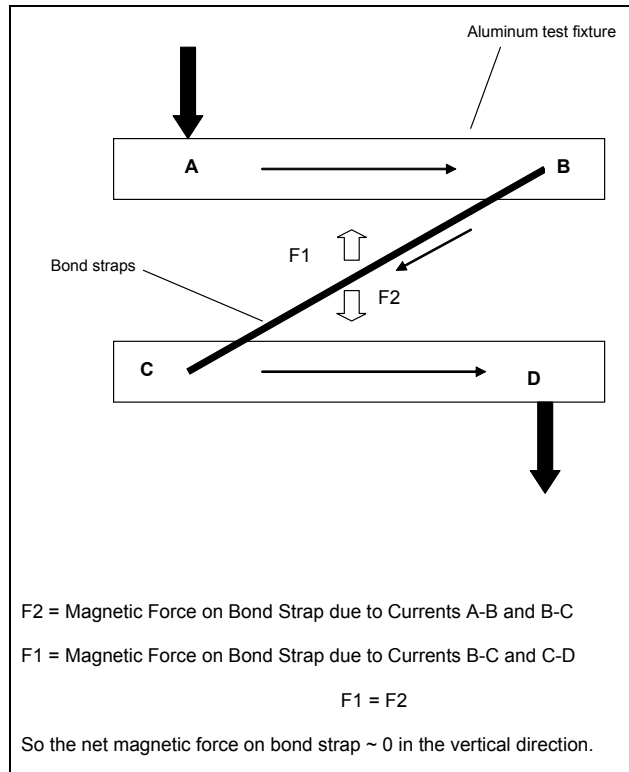
Figure 5. Magnetic forces on a bond strap in the vertical direction (test fixture shown)

Nevertheless, strong forces existed in the horizontal direction to pull the straps out of their connection lugs. The origin of these forces is evident in the top view of the same bond strap installation as shown in Figure 6.
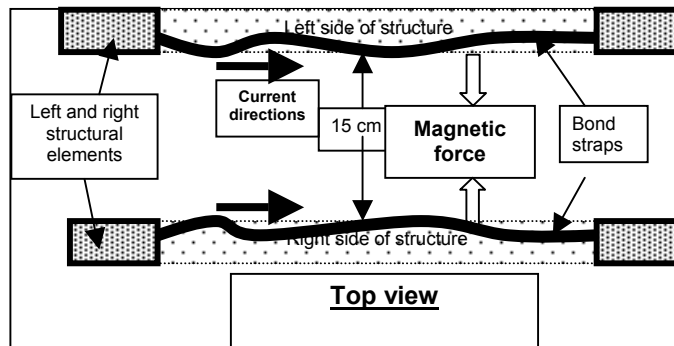
Figure 6. Top view of bond strap arrangement of Figure 4

The resulting magnetic forces under the hypothetical conditions described above are ~128 lbs. acting on each parallel strap in the direction of the other strap. The magnetic force amplitude is due to the peak current, but not the rate of change of current. However, the effect of this force on the bond strap (and associated crimped-on lugs, brackets, rivets) would certainly be influenced by the time duration of this force which, in the hypothesized lightning flash described in Figure 5, is considerably longer (5 ms) than the time duration assigned to the present standard lightning stroke (Component A, ~0.5 ms).

Other flight lightning strike incidents have caused similar effects including excessive melting and deformations of metals, breaking of bond straps, and burning of materials which are not characteristic of effects of the standard lightning environment (Components A, B, C and D). An example is shown in Figure 7.

**Figure 7. Example of severe stroke damage to small airplane wing tip
(same damage occurred to opposite wing tip)**

There have not usually been indirect effects associated with the same lightning strike incidents indicating that the rates of rise (di/dt) of the lightning stroke currents have not been unusually high.

There is some recorded evidence that the lightning strikes that have caused this unusual damage have been "positive" cloud-to-earth lightning strikes that, in fact, raise negative charge from the earth to the cloud.

**PROPOSAL TO ADDRESS LONG DURATION STROKE CURRENT EFFECTS**

An addition, such as the combined long duration stroke and continuing current of Figure 5, could be added to the family of standard lightning current components as shown in Figure 8. Such an environment, if applicable when the bond strap installation described above was designed, might have prompted a design modification that would have prevented the damage that occurred during this strike. There are numerous combinations of stroke current amplitude and time duration that would explain the effects observed following the strike incidents described above.

There is some recorded evidence that the lightning strikes that have caused this unusual damage have been "positive" cloud-to-earth lightning strikes that, in fact, raise negative charge from the earth to the cloud.
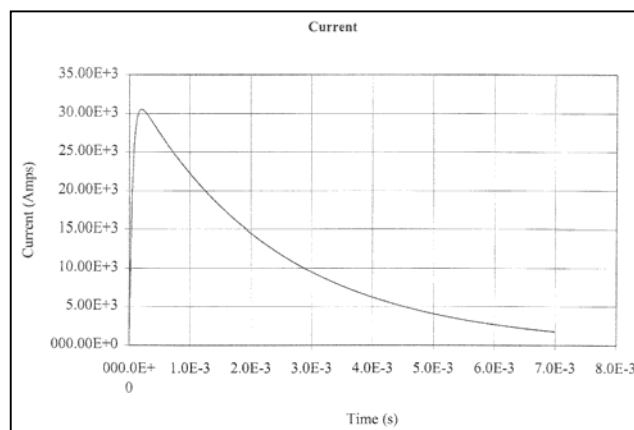
a. Stroke current waveform

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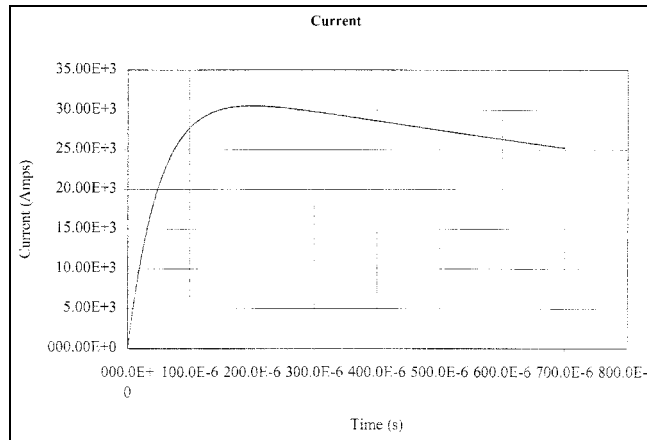
b. Stroke current wavefront

Figure 8. Proposed positive stroke current addition to the aircraft lightning standard
(To account for effects not produced by present standard currents)

The double exponential parameters of the proposed waveform of Figure 8 are as follows:

$$I_0 = 33945 \text{ A}$$
$$\alpha = 425.7289 \text{ s}^{-1}$$
$$\beta = 19574.27 \text{ s}^{-1}$$

The rise time to crest is 200 μs and the decay time to ½ peak amplitude is about 2 ms. The total charge transfer (to 7 ms) is 74 coulombs. The action integral (specific energy) is 1.26×10^6 A^2s (also J/ohm). The rise and decay time parameters are (coincidentally) the same as those shown for the 5% severity (95% are less severe) column for positive strokes in Table 2. They are, coincidentally, also similar to the positive polarity lightning stroke current oscillogram that was presented to the SAE and EUROCAE lightning committees by observers in Japan [viii] and shown in Figure 9. It will also be noted that the double exponential waveshape parameters for standard Component B ($\alpha = 700$ s^{-1}, $\beta = 2000$ s^{-1}) are similar to those proposed above, except that the Component B waveform rises to crest in approximately 1 ms, somewhat long for a stroke current.

The amplitude of 30 kA will produce magnetic forces among bond straps, etc. sufficient to pull such straps out of lugs and terminals as shown earlier. It is noteworthy that the bond strap braids themselves have not been vaporized during the reported strike incidents. A copper strap of equivalent cross section of an American Wire Guide (AWG) No. 8 conductor will experience a temperature rise of ~110ºC and the temperature of an AWG No. 10 conductor will increase by 380º C due to a stroke current with action integral of 1.26×10^6 A^2s. This is not sufficient to melt or vaporize these copper conductors, but it may weaken terminal lugs and allow the magnetic forces to pull the straps free.
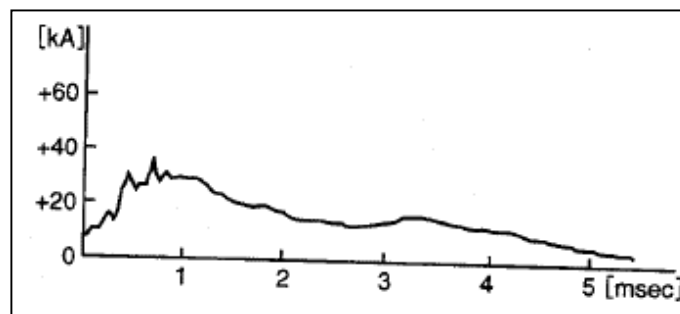
Figure 9. Natural lightning stroke current of long duration [viii]

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The rate of rise (di/dt) of the proposed waveform is 6.5 x 10^8 A/s at T = O+. This produces 650 volts across an inductance of 1 μH and only 163 V across the bond strap inductance of 0.25 μH which was assumed in the assessment of the bond strap damage described earlier in this paper. This peak di/dt is between the 50% and 5% values of peak di/dt in Table 2. There is no intent to assign a high value of di/dt to this new waveform, since high di/dt values are already assigned to Components A, D and H in the existing standard. Conversely, it is intended to assign a di/dt that will not produce sparkovers of traditional aircraft hardware insulation, such as control surface hinges, actuators and other small gaps among conducting structures, while representing typical positive stroke currents of moderate intensity. The peak di/dt associated with the waveform of Figure 8 appears to meet this intent.

The decay time of 2 ms to 50% and about 5 ms to 10% (the approximate amplitude of standard Component B) appears representative of +CG strokes, as indicated by Berger's oscillograms of Figure 3, and the physical evidence of substantial current spread along significant percentages of the aircraft length in some of the strike incidents giving rise to this proposal.

The impulse charge of 75 coulombs (A·s) is also within the range of 50% and 5% severities listed in Table 2 and observed on aircraft that appear to have encountered +CG stroke currents. Total charge transfers of 80 and 350 coulombs for the 50% and 5% severities, respectively, include the charge transferred by the continuing currents that usually follow the stroke currents in the same channel. For design and test purposes, the proposed waveform of Figure 8 would be followed by an appropriate amount of continuing current, probably Component C, so that the total charge transferred would be ~275 coulombs.

Applications of the proposed waveform: The primary purpose of the proposed waveform is for design of protection against effects of the lightning environment not represented by the present standards.

Laboratory tests with the proposed waveform to evaluate or verify designs, using common capacitor discharge circuits, will not be possible with most impulse generators presently available for aircraft lightning testing. It is easy to make high amplitude currents of short duration and low amplitude currents of long duration (i.e. the standard Components A and C), but more difficult to make intermediate combinations. The waveform of Figure 8 was computed from a 1,200 μF capacitor bank charged to 65 kV and discharged through a 2-ohm resistance and 100 μH inductance. The energy stored in the 1200 μF capacitor bank is 2.5 megajoules.

Other combinations of R, L and C can produce similar waveshapes, but the 75 coulomb impulse charge necessitates that the product of C and V be 75. Since it is impractical to operate most banks of paralleled capacitors above 100 kV, a large amount of capacitance will be needed. Inductive energy storage might be an option, where 30 kA current is first established in a C-L circuit and then commuted to an L-R circuit. The energy stored in rotating machinery may also be used to make this waveform, i.e. being similar to that driving short circuit currents produced for tests of switchgear in power industry laboratories.

Assessments of the ways the proposed current divides and redistributes among aircraft structural elements and internal conductors, such as fuel tubes and flight control cables, can, of course, be done by tests at lower amplitudes with results extrapolated to establish full threat levels throughout an airframe. Once the distributions are known, it will be easier to test coupon specimens at proportionately lower, more practical currents. The proposed waveform fits within the description of Component B which is routinely produced in most aircraft test laboratories.

Finally, most of the physical effects, such as temperature rises and magnetic force effects of the proposed current waveform on aircraft structural materials and other conductors, like bond straps, can be computed. The possibilities of arcing at structural interfaces and tube couplings cannot be evaluated by computation, but these can be usually evaluated by tests at the component level.

One unique current component, like the other current components in the standard lightning environment, may not be what is needed to deal with the effects of the lightning current environments that have been causing effects such as the dual bond strap failure noted above.   It is possible that ranges of amplitudes

and time durations of stroke currents should be given in the standards as design parameters, though this complicates the job of the designer.

Positive CG flash statistics: There have not been many oscillographic measurements of +CG stroke currents. A review of statistics of positive cloud to earth (+CG) lightning stroke parameters, deduced from far field signatures of CG flashes by the US National Lightning Detection Network (NLDN), shows that about 10% of all CG flashes in the US are +CG flashes and the mean amplitude of the stroke currents in these flashes is between 25 kA and 40 kA, depending on location and time of year.

For example, cloud-to-ground lightning data have been analyzed by Orville and Huffines [ix] for the years 1995–97 for the contiguous United States for total flashes, the percentages of +CG flashes, peak currents for negative and positive flashes. The authors examined a total of 75.8 million flashes. The highest flash densities were found in Louisiana and Florida, typically exceeding 11 flashes km^{-2}. Positive flash densities reported in [ix] exceeded 1.1 flashes km^{-2} in these states, and parts of Tennessee, Mississippi and Kentucky.

The monthly percentage of +CG lightning reported in [ix] ranged from 6.5% (July 1995) to 24.5% (January 1996). The annual percentage of positive lightning was 9.3% (1995), 10.2% (1996), and 10.1% (1997). Areas of +CG occurrence greater than 25% existed from the Canadian border to as far south as Kansas, and along the West Coast, and in Maine.

The median positive peak currents were highest in February (25 kA) and decreased to a minimum in July (15 kA). Median positive peak currents exceeded 40 kA in the upper Midwest, but were less than 10 kA in Louisiana and Florida. Thus the proposed waveform of Figure 8 is apparently near the median for +CG strokes where the range of amplitudes has been the highest in the US.

Lyons, Uliasz and Nelson [x] studied the same data source for statistics of +CG flashes in the summer months that exceed 75 kA. They termed these "LPC+CG" flashes and found that 13% of all CG flashes exceeding 75 kA were LPC+CG and that almost 70% of these occurred in the central US (30-50ºN, 88-110ºW). They also found that the percentage of all flashes that were positive approached 30% in the central US and 4.5% for the remainder of the country.

Statistics of +CG stroke current amplitudes in other parts of the world were not obtained for reference in this paper. There is evidence, from several aircraft lightning strike incidents, that high intensity +CG strokes have occurred in northern Europe and in Japan. The damage from some of these in-flight strike incidents indicated action integrals well in excess of the 1.26×10^6 A^2s associated with the proposed stroke waveform. Thus, at the proposed 30 kA, the waveform does not account for the high action integral effects.

Table 2 indicates that 5% of all +CG stroke currents have action integrals exceeding 15×10^6 A^2s. This value could be reached if the amplitude of the proposed stroke current is increased to ~100 kA.

Thus, the incidence of positive lightning strokes of moderate intensity would seem significant enough to prompt consideration of this part of the lightning environment in the standards applicable to aircraft.

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