

Aircraft Lightning Environment and Related Test Waveforms

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1. SCOPE:

The environment and test waveforms defined in this SAE Aerospace Recommended Practice (ARP) account for the best lightning data and analysis currently available. The quantified environment and levels herein represent the minimum currently required by certifying authorities, consistent with the approach applied in related lightning documents.

Lightning, like any natural phenomenon, is probabilistic in nature. Levels and waveforms vary considerably from one flash to the next. These standardized voltage and current waveforms have been derived to represent the lightning environment, and are used to assess the direct effects of lightning on aircraft. The standardized external current waveforms have in turn been used to derive standardized transient voltage and current waveforms which can be expected to appear on the cable bundles and at equipment interfaces.

In addition, test waveforms based on current industry best practice are included to supplement these waveforms that are derived directly from the lightning environment. Considerations such as testability and important waveform characteristics that can demonstrate lightning design effectiveness are taken into account.

The parameters of the standardized waveforms, both external and derived transients, represent severe versions of each of the characteristics of natural lightning flashes and include all parameters of interest with respect to lightning protection for aircraft. However, it should be noted that in every case more severe versions of each of the characteristics of the standardized waveforms have been recorded in natural lightning flashes as well as additional parameters such as electric field effects in non-conductive structures.

The test waveforms provided in this ARP are considered to be adequate for the demonstration of compliance for the protection of an aircraft and its systems against the lightning environment and should be applied in accordance with the aircraft lightning strike zones (see ARP5414) and test methods (see ARP5416 (DRAFT)), and applicable FAA and JAA advisory and interpretive material.

1.1 Purpose:

This ARP is one of the set of three documents covering the whole spectrum of aircraft interaction with lightning. The purpose of this ARP is to provide the characteristics of lightning that are encountered by aircraft as well as transients appearing at the interfaces of equipment associated with electrical/electronic systems as a result of that interaction. These characteristics are referred to as the aircraft lightning environment. The two other documents provide information on aircraft lightning zoning (see ARP5414) and aircraft lightning testing (see ARP5416 (DRAFT)). The relationship between the three documents is shown in Figure 1.

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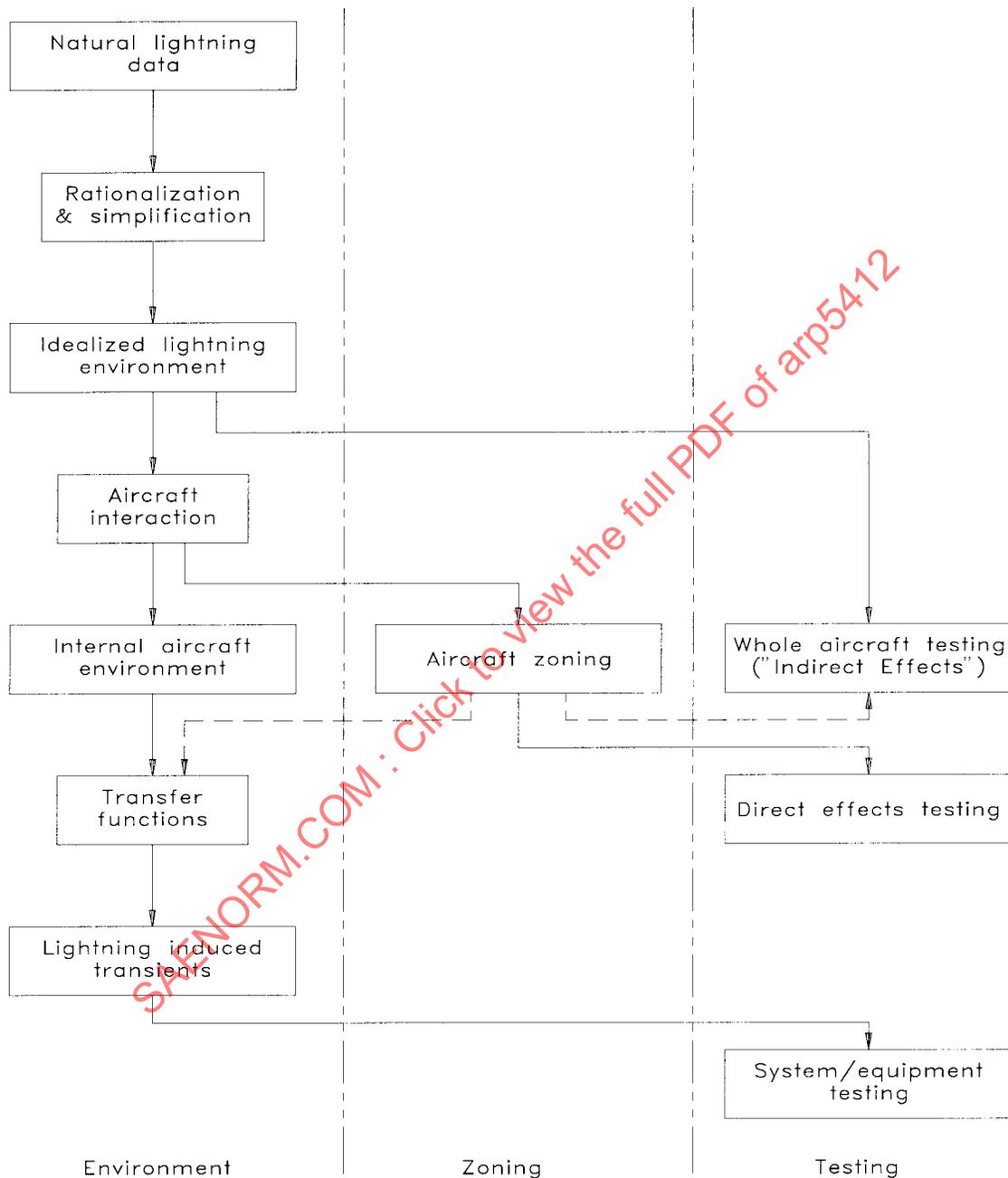


FIGURE 1 - Relationship Between Aircraft Environment, Zoning and Testing

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2. REFERENCES:

2.1 SAE Publications:

Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

ARP5413, Certification of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning

ARP5414, Aircraft Lightning Zoning

ARP5415 (DRAFT), User's Manual for Certification of Aircraft Electrical/Electronic Systems Against the Indirect Effects of Lightning

ARP5416 (DRAFT), Aircraft Lightning Test Methods

2.2 RTCA Publications:

EUROCAE ED-14D/RTCA DO-160D, "Environmental Conditions and Test Procedures for Airborne Equipment" Section 22: "Lightning Induced Transient Susceptibility"

EUROCAE ED-14D/RTCA DO-160D, "Environmental Conditions and Test Procedures for Airborne Equipment" Section 23: "Lightning Direct Effects"

2.3 AC/AMJ Publications:

AC/AMJ 20-53B, "Protection of Airplane Fuel Systems Against Fuel Vapor Ignition Due to Lightning"

2.4 Related FAR and JAR Information:

2.4.1 Federal Aviation Regulations (FAR):

Federal Aviation Regulations 14 CFR Parts 23.867, 23.954, 23.1309(e), 23.1316, 25.581, 25.954, 25.1316, 27.610, 27.954, 27.1309(d), 27.1316, 29.610, 29.954, 29.1309(h), 29.1316 and 33.28(d)

2.4.2 FAA Advisory Circulars: The following Advisory Circulars (AC) may provide additional information.

AC 23.1309-1C, System and Equipment Installations in Part 23 Airplanes, dated March 12, 1999

AC 25.1309-1A, System Design and Analysis, dated June 21, 1988

AC 27-1A, Certification of Normal Category Rotorcraft, dated August 8, 1985, including to Change 4 dated September 30, 1997

AC 29-2B, Certification of Transport Category Rotorcraft, dated September 16, 1987, including to Change 3 dated July 30, 1997

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2.4.2 (Continued):

AC 21-16D, Radio Technical Commission for Aeronautics Document DO-160D, dated March, 1998

AC 20-136, Certification of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning

2.4.3 Joint Airworthiness Requirements (JAR):

Joint Airworthiness Requirements Parts 23.867, 23.954, 23.1309(e), 23.1316, 25.581, 25X899, 25.954, 25.1316, 27.610, 27.954, 27.1309(d), 27.1316, 29.610, 29.954, 29.1309(h), 29.1316, 33.28(d) and JAR E.50

2.4.4 JAA Advisory and Interpretive Material:

ACJ 25X899, Electrical Bonding and Protection Against Lightning and Static Electricity (Interpretive Material and Acceptable Means of Compliance)

ACJ 29.610, Lightning and Static Electricity Protection (Interpretive Material and Acceptable Means of Compliance)

AMJ 20X-1, Certification of Aircraft Propulsion Systems Equipped with Electronic Controls

2.5 Other References:

2.5.1 "The Distribution of Electricity in Thunderclouds", Malan, D. J. and Schonland, B. F. J.: Proc. Roy. Soc. London, A 209 (1951)

2.5.2 "Lightning", Uman, M. A., McGraw Hill Book Company, London 1988

2.5.3 "Aircraft Triggered Lightning: Process Following Strike Ignition that Affect Aircraft", Mazur, V. and Moreau J.-P., Journal of Aircraft, Volume 29, Nr. 4, July/August 1992, pages 575-580

2.5.4 "New Results for Quantification of Lightning/Aircraft Electrodynamics", F. L. Pitts, R. A. Perala, L. Dee, Electromagnetics Vol.7, 1987

2.5.5 "Analysis of Correlated Electromagnetic Fields and Current Pulses During Airborne Lightning Attachments", J. S. Reaser, A. V. Serrano, L. C. Walko, and H. D. Burket, Electromagnetics, Vol. 7, 1987

2.5.6 "Analysis of the First Milliseconds of Aircraft Lightning Attachments", Moreau J.-P., Alliot J. C., 11th International Aerospace and Ground Conference on Lightning and Static Electricity, Dayton, OH, 1986

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2.6 Definitions/Abbreviations/Acronyms:

2.6.1 Definitions:

ACTION INTEGRAL: The integral of the square of the time varying current over its time duration. It is usually expressed in units of ampere squared seconds (A^2s).

APERTURE: An electromagnetically transparent opening.

APERTURE COUPLING: The process of inducing voltages or currents in avionics wiring or systems by electric or magnetic fields passing through apertures.

ATTACHMENT POINT: A point of contact of the lightning flash with the aircraft.

BREAKDOWN: The production of a conductive ionized channel in a dielectric medium resulting in the collapse of a high electric field.

CABLE BUNDLE: A group of wires and/or cables bound or routed together that connect two pieces of equipment.

CHARGE TRANSFER: The time integral of the current over its entire duration, in units of coulombs ($A \times s$).

CONTINUING CURRENT: A low level long duration lightning current that occurs between or after the high current strokes.

DART LEADER: A leader which occurs before subsequent strokes without stepping but with a continuous progression of the leader tip.

DIFFUSION: The process by which electric current flow spreads through the thickness of a conductive material which results in a slower increase in current density on interior surfaces as compared with exterior surfaces.

DIRECT EFFECTS: Any physical effects to the aircraft and/or equipment due to the direct attachment of the lightning channel and/or conduction of lightning current. This includes dielectric puncture, blasting, bending, melting, burning and vaporization of aircraft or equipment surfaces and structures. It also includes directly injected voltages and currents in associated wiring, plumbing, and other conductive components.

DWELL TIME: The time that the lightning channel remains attached to a single spot on the aircraft.

EQUIPMENT INTERFACE: A location on an equipment boundary where connection is made to the other components of the system of which it is part. It may be an individual wire connection to an electrical/electronic item, or wire bundles that interconnect equipment. It is at the equipment interface that the equipment transient design level (ETDL) and transient control level (TCL) are defined and where the actual transient level (ATL) should be identified.

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2.6.1 (Continued):

EXTERNAL ENVIRONMENT: Characterization of the natural lightning environment for design and certification purposes.

FIRST RETURN STROKE: The high current surge that occurs when the leader completes the connection between the two charge centers. The current surge has a high peak current, high rate of change of current with respect to time (di/dt) and a high action integral.

FLASHOVER: This term is used when the arc produced by a gap breakdown passes over or close to a dielectric surface without puncture.

INDIRECT EFFECTS: Electrical transients induced by lightning in aircraft conductive components such as electric circuits.

INDUCED VOLTAGES: A voltage produced in a circuit by changing magnetic or electric fields or structural IR voltages.

INTERFACE TRANSIENTS: Induced voltages and currents appearing in cable bundles or in individual conductors, and which appear at equipment interfaces.

INTERNAL ENVIRONMENT: The fields and structural IR voltages inside the aircraft produced by the external environment.

K CHANGES: Electric (E) field changes and current pulses seen inside the cloud during cloud to ground flashes and often associated with current pulses.

LEADER: The low luminosity, low current precursor of a lightning return stroke, accompanied by an intense electric field.

LIGHTNING CHANNEL: The ionized path through the air along which the lightning current pulse passes.

LIGHTNING FLASH: The total lightning event. It may occur within a cloud, between clouds or between a cloud and ground. It can consist of one or more return strokes, plus intermediate or continuing currents.

LIGHTNING STRIKE: Any attachment of the lightning flash to the aircraft.

LIGHTNING STRIKE ZONES: Aircraft surface areas and structures classified according to the possibility of lightning attachment, dwell time and current conduction. See ARP5414.

MULTIPLE BURST: Randomly spaced groups of short duration, low amplitude current pulses, with each pulse characterized by rapidly changing currents (i.e., high di/dt 's). These pulses may result from lightning leader progression or branching. The pulses appear to be most intense at the time of initial leader attachment to the aircraft.

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2.6.1 (Continued):

MULTIPLE STRIKE: Two or more lightning strikes during a single flight.

MULTIPLE STROKE: Two or more lightning return strokes occurring during a single lightning flash.

PEAK RATE OF RISE: The maximum value of the derivative with respect to time of $i(t)$ and may be expressed as follows:

Peak rate of rise = maximum of $di(t)/dt$

RECOIL STREAMER: Equivalent to restrike during a cloud to cloud or intra cloud discharge and associated with isolated current pulses.

RESTRIKE: A subsequent high current surge attachment, which has a lower peak current, a lower action integral, but a higher di/dt than the first return stroke. This normally follows the same path as the first return stroke, but may reattach to a new location further aft on the aircraft.

SHIELD: An overall conductive covering around wires in the cable bundle. The covering is usually a wire braid with at least 85% coverage, or a metallic conduit with 100% coverage that is terminated to the equipment case at both ends. The effect of the shield is to provide an electromagnetic enclosure and a low impedance path between connected equipment.

SLOW COMPONENTS: The intermediate current and the continuing current collectively.

STEPPED LEADER: See Leader.

STRUCTURAL IR VOLTAGE: The portion of the induced voltage resulting from the product of the distributed current (I) and the resistance R of the aircraft skin or structure.

SWEPT CHANNEL: The lightning channel relative to the aircraft, which results in a series of successive attachments due to sweeping of the flash across the aircraft by the motion of the aircraft.

SWEPT LEADER: A lightning leader that has moved its position relative to an aircraft, subsequent to initial leader attachment, and prior to the first return stroke arrival, by virtue of aircraft movement during leader propagation.

SYSTEM FUNCTIONAL UPSET: An impairment of system operation, either permanent or momentary (e.g., a change of digital or analog state) which may or may not require manual reset.

UPSET: See system functional upset.

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2.6.1 (Continued):

V_{90} : This is normally the voltage to which an HV impulse generator must be erected in order that 90% of all discharges will result in gap breakdown.

ZONING: The process (or the end result of the process) of determining the location on an aircraft to which the components of the external environment are applied.

2.6.2 Abbreviations:

A^2s	action integral (ampere squared seconds)
A	amperes
A/s	amperes per second
C	charge transfer (coulombs or ampere - seconds)
kA	kiloamperes
kV	kilovolts
kV/m	kilovolts per meter
m/s	meters per second
μs	microseconds
ms	milliseconds
s	seconds
t	time

2.6.3 Acronyms:

AC	Advisory Circular
AMJ	Advisory Material Joint
ATL	Actual Transient Level
CFC	Carbon Fiber Composite
ETDL	Equipment Transient Design Level
FWHM	Full Width Half Maximum: The time interval between 50% amplitudes of a pulse
HC	High current
HV	High voltage
LRU	Line replaceable unit: An element of a system which may be removed and replaced by a line maintenance crew while the aircraft is in operational status
MB	Multiple Burst
MS	Multiple Stroke
N/A	Not Applicable
TCL	Transient Control Level

3. BACKGROUND:

The environment information and the test waveforms have been removed from AC/AMJ 20-136 and AC/AMJ 20-53, and included in this Standard. This Standard also explains the idealized external waveforms and gives a brief discussion of the mechanisms for transforming the external environment into an internal environment and the resulting transients on cable bundles and at equipment interfaces.

4. NATURAL LIGHTNING DESCRIPTION:

4.1 General:

Lightning flashes usually originate from charge centers in a cloud, particularly the cumulonimbus cloud, although they can occur in other atmospheric conditions. The charges in clouds are produced by complex processes of freezing and melting, and by collisions and splintering resulting from movements of raindrops and ice crystals. Typically, most positive charges accumulate at the top of the cumulonimbus clouds, leaving the lower regions negative, although there may be a small positive region near the base. The result is the typical structure of Figure 2 depicted by Malan (Reference 2.5.1), who extensively studied thunderstorms in South Africa.

During their process of development thunder clouds extend vertically over more than 3 km. The strong electric fields can initiate discharges, called lightning flashes, which may be of three types, namely:

- a. Flashes between regions of opposite polarity within a cloud (inter cloud discharges),
- b. Flashes between regions of opposite polarity in different clouds (inter cloud charges), and,
- c. Flashes from clouds to ground and from ground to clouds of either polarity. Ground to cloud flashes, however, become only relevant to taller objects (e.g., towers and mountains).

Over 50% of all flashes are intra cloud flashes.

4.2 Cloud to Ground Flashes:

- 4.2.1 The Discharge Process: A positive flash lowers positive charge to earth while a negative flash lowers negative charge.

It is common for a negative flash to discharge several charge centers in succession, with the result that the flash contains several distinct pulses of current, and these are usually referred to as strokes.

The process that culminates in a lightning flash begins with the formation of an ionized column called a leader which travels out from a region where the electric field is so high that it initiates progressive breakdown; this critical field is thought to be about 900 kV/m for water droplets or 500 kV/m for ice crystals. For a negative discharge to earth the column advances in zigzag steps (hence the name stepped leader) each about 50 m long and separated by pauses of 40 to 100 ms.

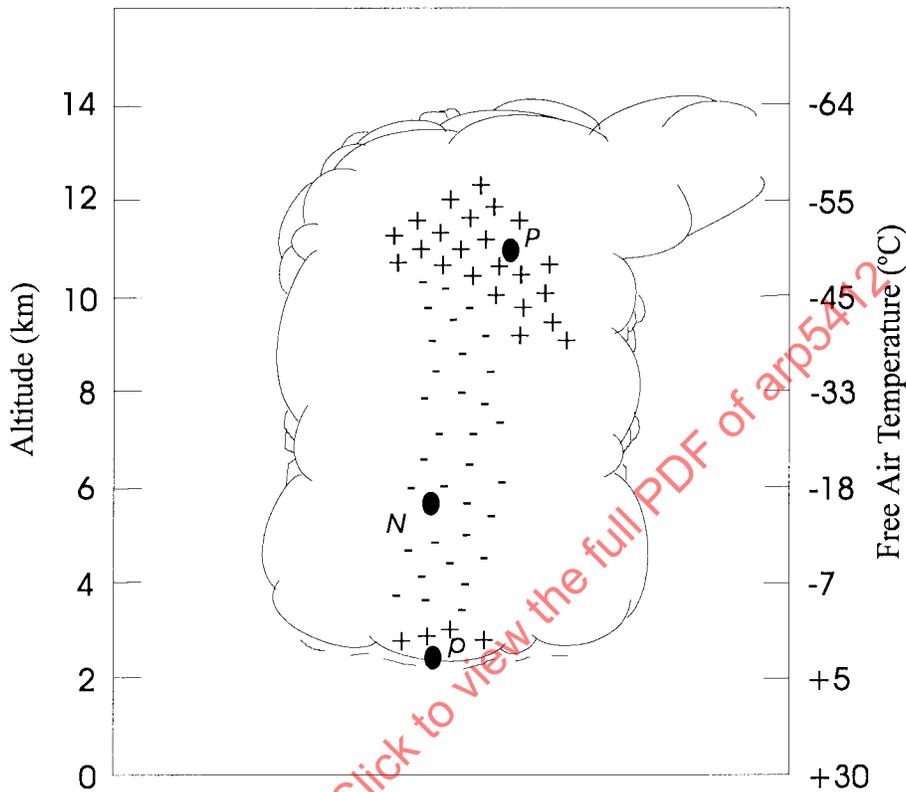


FIGURE 2 Generalized Diagram Showing Distribution of Electrical Charge in Typical Cumulonimbus Cloud

4.2.1 (Continued):

The diameter of the stepped leader is between 1 and 10 m although the current, which is low (about 100 A), is probably concentrated in a small highly ionized core, about 1 cm diameter. The average velocity of propagation is 1.5×10^5 m/s. The leader may form branches on its downward path to the ground. When a branch is near to the ground, it causes high fields to form at projections such as trees and buildings and these then send up leaders, one of which will make contact with the tip of the downward propagating leader. This has the effect of closing a switch and the position in the channel where it occurs is known as the switching point. When that occurs, a return stroke is initiated which retraces and discharges the leader channel at a velocity of about 5×10^7 m/s. This initial return stroke is characterized by a current pulse of high amplitude accompanied by high luminosity. After the first return stroke, further strokes may occur as higher areas of the negative charge regions are discharged; the dart leaders for these usually traverse the same path as the first but in one continuous sweep at a velocity of 2×10^6 m/s.

Return stroke modeling indicates that there is a decrease in the value of the return stroke current as altitude increases (Reference 2.5.2). This is typical of a negative flash to open ground, but over mountains and tall buildings the leader may be of the upward moving type, originating from a high point such as a mountain peak. When such a leader reaches the charge pocket in the cloud, a return stroke is initiated and subsequent events follow the same pattern as for initiation by a downward moving leader. Thus the "switching" point is near the ground for downward leaders but near the charge pocket in the cloud for upward leaders. This can make a significant difference to the waveform and amplitude of the current experienced by an airborne vehicle that forms part of the lightning path.

4.2.2 The Negative Flash to Ground: An example of the return stroke current in a severe negative flash is sketched in Figure 3A. The number of strokes in a negative flash is usually between 1 and 11, the mean value being 3; the maximum number is up to 24. The total duration is between about 20 ms and 1 s, with a mean value of 0.2 s. The time interval between the strokes is typically about 60 ms. There is some correlation among these parameters, the flashes with the most strokes tending also to be the longest duration. The rise time of the first stroke is about $2 \mu\text{s}$, with a decay time (to half the peak amplitude) of $40 \mu\text{s}$. Subsequent strokes in the flash tend to have a higher rate-of-rise although lower peak amplitudes than the initial stroke and they can, therefore, be significant for inducing voltages in wiring, where the inductively coupled voltages are proportional to the rate of change of the lightning current.

Near the end of some of the strokes in a negative flash, there is often a lower level current of a few kA persisting for several milliseconds, known as an "intermediate current component," as shown in Figure 3A. After some strokes a "continuing current" of 100 to 400 A flows with a duration of 100 to 800 ms, so that there is substantial charge transfer in this phase. It is particularly common for there to be a continuing current after the last stroke.

It is generally thought that before a restrike can occur the continuing current must cease, as illustrated after stroke 5 in Figure 3A.

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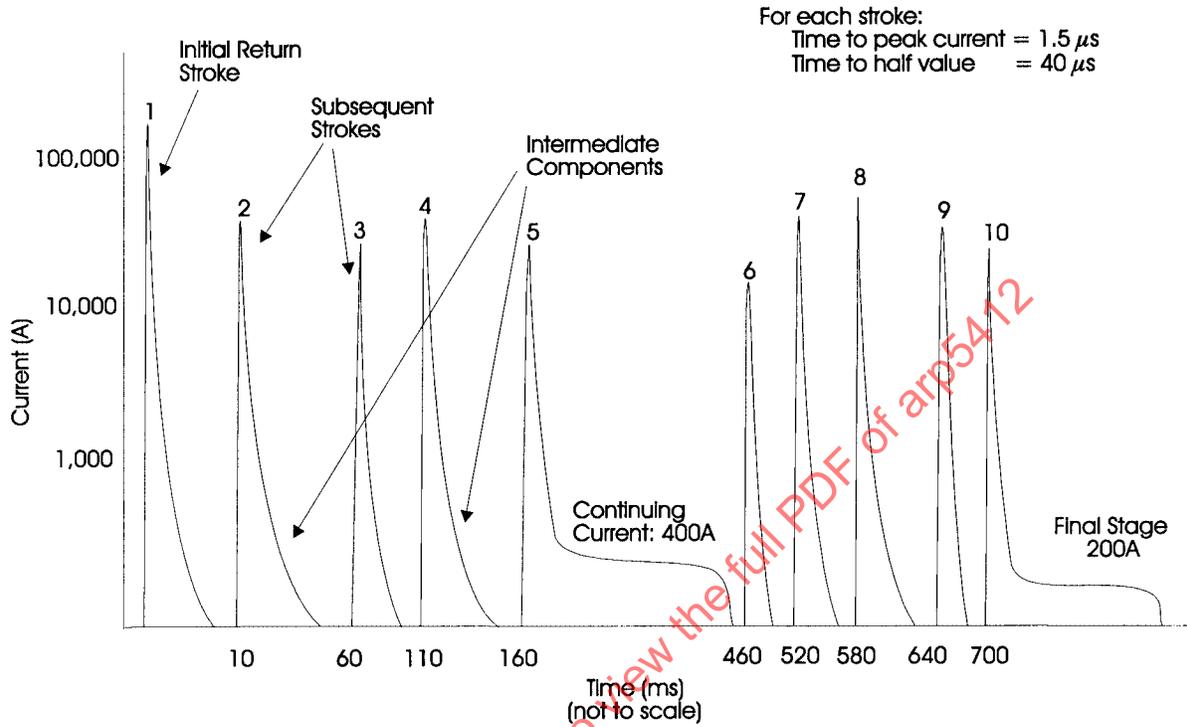


FIGURE 3A - Model of a Severe Negative Lightning Flash Current Waveform

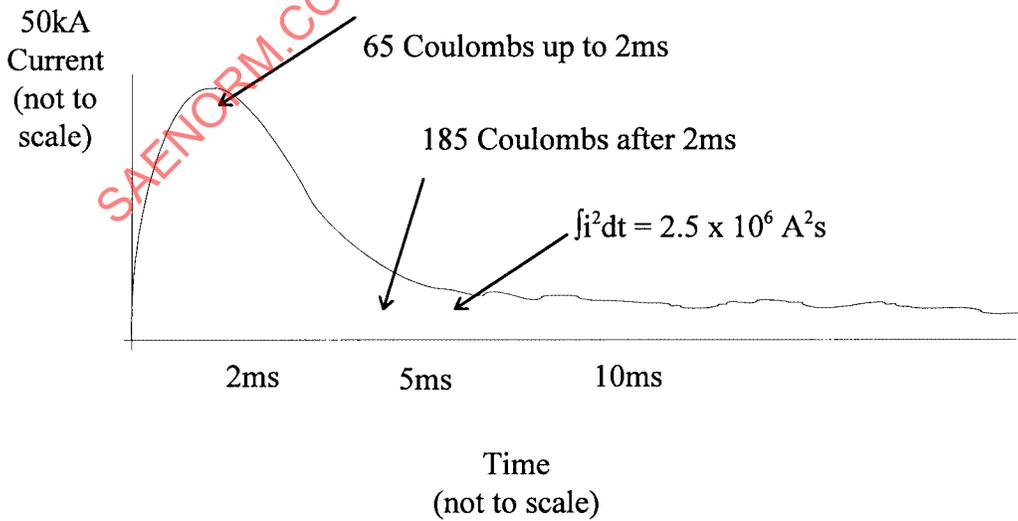


FIGURE 3B - Model of a Moderate Positive Lightning Flash Current Waveform

FIGURE 3

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4.2.3 The Positive Flash to Ground: Positive flashes to ground generally occur less frequently than negative flashes, however in certain geographic locations there may be more positive flashes to ground. Present standards have assumed an average of around 10% positive flashes to ground. Positive flashes are usually initiated by upward moving leaders and more commonly occur over mountains than over flat terrain. Normally they consist of one stroke only. They have slower rise times than negative flashes, with high peak current and charge transfer; the duration is longer than a single stroke of a negative flash but usually shorter than a complete negative flash. The stroke may be followed by a continuous current.

An example of the current in a positive flash is shown in Figure 3B; it is a moderately severe example although not the "super flash" which occurs occasionally. Typically the rise time of a positive flash is 20 μ s and the total duration 0.1 s. Although positive flashes are far less globally frequent than negative, they have to be taken into consideration in the selection of design and test parameters.

4.3 Inter and Intra Cloud Flashes:

The preceding discussion relates to flashes of either polarity to ground since most available knowledge relates to flashes of that type. Instrumented aircraft have been employed in U.S.A. and France to record the characteristics of cloud flashes. Generally speaking, the conclusion is that cloud flashes are less severe than flashes to the ground, certainly with respect to peak current, charge transfer and action integral. However, the airborne measurements show some evidence that over a portion of some pulse wavefronts the rate-of-rise for a short time (less than 0.4 μ s) may be higher than the figure related to cloud to ground flashes. Short pulses of low amplitude but high rate-of-rise have been observed during intra cloud flashes. Similar pulses due to charge redistribution in a cloud have been observed between return strokes in flashes to ground.

For intra cloud discharges, recoil streamers of up to 60 kA peak current have been recorded, but are more typically 20 to 30 kA (Reference 2.5.3). A typical intra cloud lightning flash is presented in Figure 4. The pulses occurring during the initial attachment phase might also occur in negative cloud to ground flashes.

4.4 Flash Parameters

Most of the available statistical data are from cloud to ground and ground to cloud lightning flashes. The relevant data are presented in Tables 1 and 2 divided into negative and positive flashes. The tables include statistical data for the lightning currents and all related parameters of interest for the definition of the external environment. For a given flash or stroke parameter, the tables show that as the magnitude increases, the percentage of occurrence decreases. The extreme parameters do not occur together in one flash.

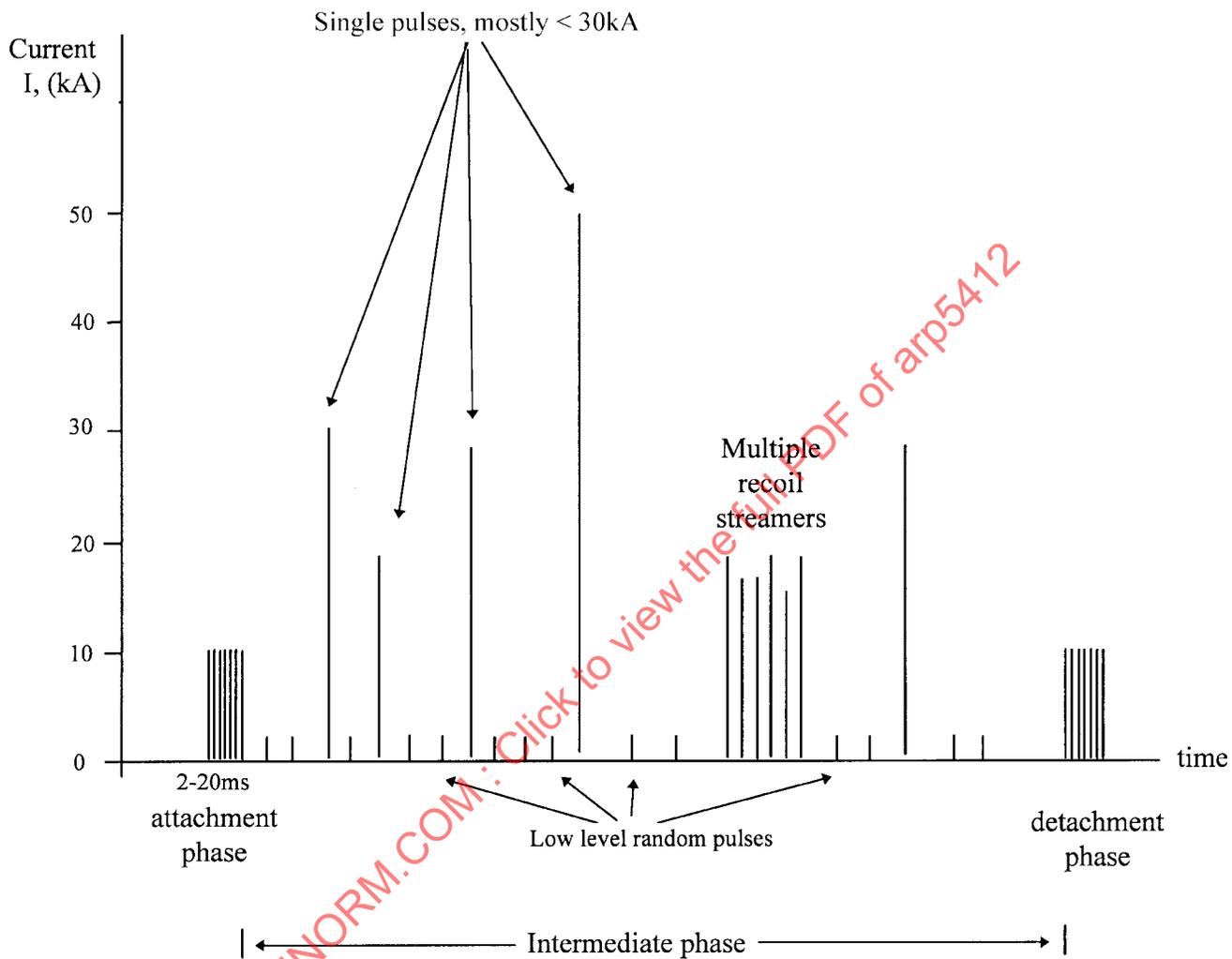


FIGURE 4 - Typical Intra Cloud Lightning Flash to an Aircraft

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TABLE 1 - Parameters for Negative Lightning Flashes Measured at Ground

Parameters	Unit	Lightning Parameters 95%	Lightning Parameters 50%	Lightning Parameters 5%
Negative Flashes:				
Number of strokes		1 - 2	3 - 4	12
Time intervals between strokes	ms	8	35	140
Flash duration	s	0.03-0.04	0.2	1
Charge in flash	C	1.3	7.5	40
Negative First Stroke:				
Peak current	kA	14	30	80
Peak rate-of-rise	A/s	5.5×10^9	1.2×10^{10}	3.2×10^{10}
Time to peak	μ s	1.8	5.5	18
Time to half value	μ s	30	75	200
Impulse charge	C	1.1	5.2	24
Action integral	A ² s	6×10^3	5.5×10^4	5.5×10^5
Negative Subsequent Strokes:				
Peak Current	kA	4.6	12	30
Peak rate-of-rise	A/s	1.2×10^{10}	4×10^{10}	1.2×10^{11}
Time to peak	μ s	0.22	1.1	4.5
Time to half value	μ s	6.5	32	140
Impulse charge	C	0.2	1.4	11
Action integral	A ² s	5.5×10^2	6×10^3	5.2×10^4
Continuing Current:				
Amplitude	A	98%	50%	2%
Duration	s	33	140	520
Charge	C	0.058	0.16	0.40
		7	26	110

NOTE 1: The above lightning parameters 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.

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TABLE 2 - Parameters for Positive Lightning Flashes Measured at Ground

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	μ s	3.5	22	200
Time to half value	μ s	25	230	2000
Impulse charge	C	2	16	150
Action integral	A ² s	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.

4.4 (Continued):

Less data are available with respect to inter and intra cloud lightning flashes (4.3). The available data indicate that the cloud to ground and ground to cloud flashes represent the most severe lightning threat to the aircraft with the only exception being the high rate of rise pulse wavefronts measured during the initial and the final attachment phases to the Instrumented aircraft referred to in 4.3. Similar pulses with fast rates of change have also been reported in cloud to earth flashes which convey negative charge to the earth.

In addition to the lightning currents, electric fields exist before and during a lightning strike event. Initially, these fields result in breakdown of the air to form the attachment and may also cause breakdown of dielectric materials on an aircraft. The magnitudes of these fields are dependent upon air breakdown thresholds and range between 400 and 3000 kV/m, with rates of rise of up to 1000 kV/m/ μ s.

5. LIGHTNING INTERACTIONS WITH AIRCRAFT:

A lightning strike to an aircraft will either be triggered (i.e., initiated) by the presence of the aircraft in a strong electric field and will originate at the aircraft, or will occur as a result of encounter with a naturally occurring leader which originated elsewhere.

5.1 Strike Occurrence:

The probability of a lightning strike to an aircraft depends on various parameters, e.g. the local climate, flight profile, type of aircraft. From a significant sample of reported strikes to large transport aircraft operating in scheduled airline service, the average probability of a lightning strike has been estimated to be approximately one strike in every 10,000 flight hours. A separate study of transport aircraft experience within a region known to be prone to lightning estimated the average probability of a lightning strike to be approximately one strike in every 1000 flight hours. Therefore, the average probability of a lightning strike to a given aircraft will be likely to fall somewhere between one strike per 1000 and 20,000 flight hours.

These data are based on reported strikes, which get noticed because of bright light, (especially at night), loud noises, or associated physical damage effects or interference or damage to cockpit avionics. Other strikes to aircraft undoubtedly occur but go unnoticed or are not reported.

5.2 Aircraft Intercepted Lightning:

An intercepted flash can occur when a lightning leader advances sufficiently close to the aircraft to be diverted to it. This latter interaction can occur for all types of discharges: inter, intra and cloud to ground.

As noted, most intra cloud flashes are probably less severe than cloud to ground flashes. If we consider only ground flashes, however, it is likely that the parameters at the altitude of an aircraft in flight will be different from those measured at stations on the ground. This is because the lightning channel acts as a lossy transmission line and the return stroke current experiences changes in both shape and amplitude as it develops from the switching point towards the vehicle.

5.3 Aircraft Triggered Lightning:

Aircraft may also trigger the flashes that they interact with in regions where there are strong electric fields. These flashes would not have occurred in the absence of the aircraft. Many storm cloud penetrations made during in-flight measurement programs (References 2.5.4, 2.5.5, and 2.5.6) produced lightning strikes which were probably triggered by the aircraft.

It is thought that most triggered lightning flashes have a lower amplitude than most cloud to ground flashes. The latter will, however, continue to be the basis of protection design.

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5.4 Swept Channel Process:

If a fast moving vehicle such as an aircraft experiences a direct strike, then throughout the flash, the point(s) of arc attachment is likely to be swept backwards along the vehicle, since the lightning channel tends to remain stationary relative to the surrounding air. Except possibly on smooth unpainted surfaces, this movement of the attachment point is not continuous but progresses in a series of discrete irregular steps. The dwell time at any particular step is not likely to exceed 50 ms, being chiefly dependent on the nature of the surface and the velocity of the vehicle. The movement of the points of arc attachment is known as the "Swept Channel" phenomenon. For an airspeed of 300 knots an aircraft moves through its own length of (say) 15 m in 100 ms, which is well within the average duration of a lightning flash. When the lightning channel has swept back to a trailing edge, it can progress no further and may remain there, or "hang on," for the remainder of the flash. When the entry and exit portions of the lightning channel have swept aft to trailing edges, the channel may rejoin behind the aircraft and the aircraft is no longer in the lightning current path.

The sweeping action of the channel can have several consequences. For example, inboard areas of an aircraft wing such as those behind an inboard engine will be subjected to the Swept Channel phenomenon because they are in the path of a sweeping channel. On the other hand, the effects of the flash are spread out over a considerable number of points so that except for an attachment point at a trailing edge, no single point receives the full energy of the flash. The proportion of the flash experienced by any particular point depends on its location on the vehicle surface and this has led to the concept of dividing the surface into lightning strike zones depending on the probability of initial attachment, sweeping and hang-on.

5.5 Nearby Lightning:

Nearby flashes might cause some indirect effects. These effects, due predominantly to magnetic field coupling, are in general significantly smaller than those caused by direct lightning strikes to the aircraft.

The magnetic fields (H-fields), which can be expected from a nearby lightning strike, can be estimated by the following expression:

$$H = \frac{I}{2\pi r} \quad (\text{Eq. 1})$$

where:

H = Field strength in amperes per meter

I = Lightning current in amperes

r = Distance between the lightning channel and the aircraft in meters

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5.6 Lightning Strike Zones:

Due to the lightning attachment process, not all locations on an aircraft are exposed to the same lightning environment components. To optimize lightning protection, the aircraft will, therefore, be divided into different lightning strike zones. These zones will then be protected against their applicable components of the lightning environment.

In general an aircraft can be divided into the following zones:

- Zone 1A: First Return Stroke Zone
- Zone 1B: First Return Stroke Zone with Long Hang-On
- Zone 1C: Transition Zone for First Return Stroke
- Zone 2A: Swept Stroke Zone
- Zone 2B: Swept Stroke Zone with Long Hang-On
- Zone 3: Current Conduction Zone

Zone definitions and methods of locating them on particular aircraft are given in ARP5414.

6. IDEALIZED STANDARD LIGHTNING ENVIRONMENT:

6.1 General:

The environment waveforms presented in this chapter represent idealized environments which are to be applied to the aircraft for purposes of analysis and testing. The waveforms are not intended to replicate a specific lightning event, but they are intended to be composite waveforms whose effects upon aircraft are those expected from natural lightning.

The standard lightning environment is comprised of individual voltage waveforms and current waveform components which represent the important characteristics of the natural lightning flashes.

In the waveform descriptions that follow, parameters of particular importance to the effects (direct or indirect) to be considered, are included whereas other parameters are omitted. For example, for direct effects evaluations, peak current amplitude, action integral and time duration are of primary importance, whereas for indirect effects evaluations, rates of current rise and decay as well as peak amplitude are important.

Not all surfaces of an aircraft need to be designed to survive the same lightning threat. The applicable design parameters and test waveforms for each zone are presented in 6.4.

This section presents waveforms and their related parameters to be applied for aircraft structures and equipment lightning protection design and verification purposes.

6.2 Idealized Voltage Waveforms:

The idealized voltage waveform represents that portion of the electric field important for assessment of lightning attachment to aircraft structures.

The basic voltage waveform to which vehicles are subjected for analysis or test is one that represents an electric field which increases until breakdown occurs either by puncture of solid insulation such as the fiberglass skin of a radome, or flashover through the air or across an insulating surface. The path that the flashover takes, either puncture or surface flashover, depends in part on the waveshape of the electric fields.

It is sometimes necessary to determine the critical voltage amplitude at which breakdown occurs. This critical voltage level depends upon both the rate-of-rise of voltage and the rate of voltage decay. Two examples are: (1) determining the strength of the insulation used on electrical wiring; and, (2) determining the points from which electrical streamers appear on a vehicle as a lightning flash approaches.

Since there is a wide range of possible electric field waveforms produced by natural lightning, two voltage waveforms have been established, representing fast and slow rates of field rise. These are Waveform A described in 6.2.1 and Waveform D presented in 6.2.4.

Two other high voltage waveforms designated B and C are described in 6.2.2 and 6.2.3 respectively. The first is a full voltage waveform to be used wherever an impulsive field that does not reach breakdown is required, i.e. streamer testing. The second waveform is employed for fast front model tests. Waveform D can also be used for slow front model tests.

It has been determined in laboratory testing that the results of attachment point testing of aircraft models are influenced by the voltage waveform. Fast rising waveforms (rise in the order of a few microseconds) produce a relatively small number of attachment points, usually to the apparent high field regions on the model and may produce a greater likelihood of puncture of dielectric skins. Slow front waveforms (in the order of hundreds of microseconds) produce a greater spread of attachment points, possibly including attachments to lower field regions.

The voltage waveforms presented in this ARP are intended for evaluation of possible lightning attachment locations and/or dielectric breakdown paths through non-conducting surfaces or structures.

- 6.2.1 Voltage Waveform A: This waveform rises at a rate of $1000\text{kV}/\mu\text{s}$ ($\pm 50\%$) until its increase is interrupted by voltage breakdown of the intervening air gap, resulting in the puncture of, or flashover across, the object under test. At that time the voltage collapses to zero. The rate of voltage collapse or the decay time of the voltage if breakdown does not occur (open circuit voltage of a lightning voltage generator) is not specified. The voltage Waveform A is shown in Figure 5.

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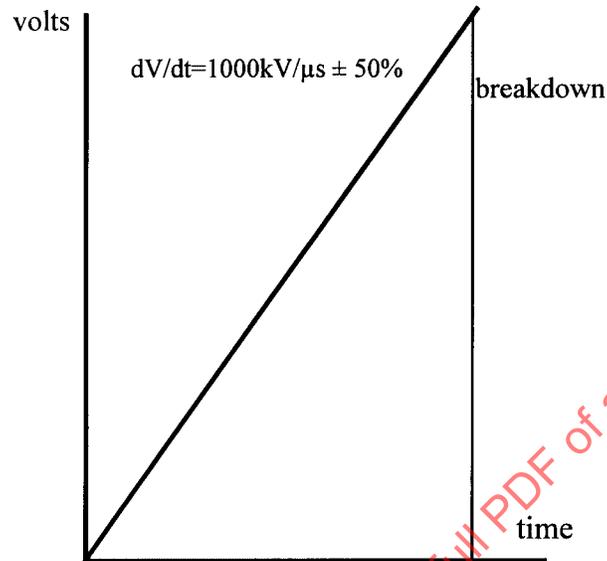


FIGURE 5 - Voltage Waveform A

- 6.2.2 Voltage Waveform B: Waveform B is a $1.2 \mu s \times 50 \mu s$ waveform which is the electrical industry standard for impulse dielectric tests. It rises to crest in $1.2 \mu s (\pm 20\%)$ and decays to half of crest amplitude in $50 \mu s (\pm 20\%)$. Time to crest and decay time refer to the open circuit voltage of a lightning voltage generator, and assume that the waveform is not limited by puncture or flashover of the object under test. This waveform is shown in Figure 6.
- 6.2.3 Voltage Waveform C: This is a chopped voltage waveform in which breakdown of the gap between an object under test and the test electrodes occurs at $2 \mu s (\pm 50\%)$. The amplitude of the voltage at time of breakdown and the rate-of-rise of voltage prior to breakdown are not specified. The waveform is shown in Figure 7.
- 6.2.4 Voltage Waveform D: The slow fronted waveform has a rise time between 50 and $250 \mu s$ so as to allow time for streamers from an object to develop. It should give a higher strike rate to the low probability regions than otherwise might have been expected. This waveform is shown in Figure 8.

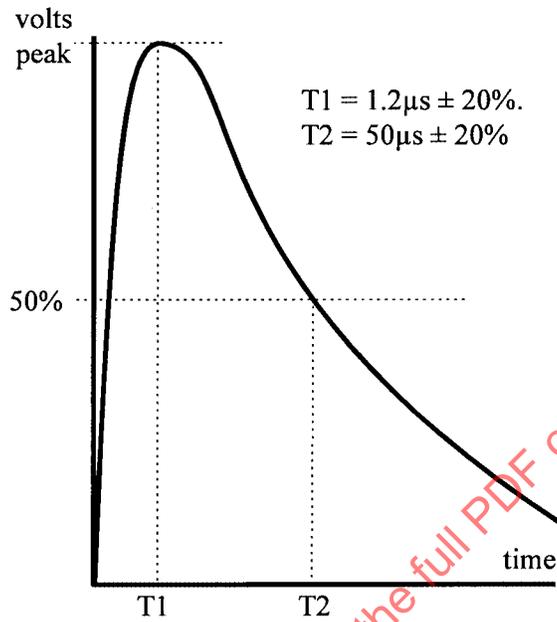


FIGURE 6 - Voltage Waveform B

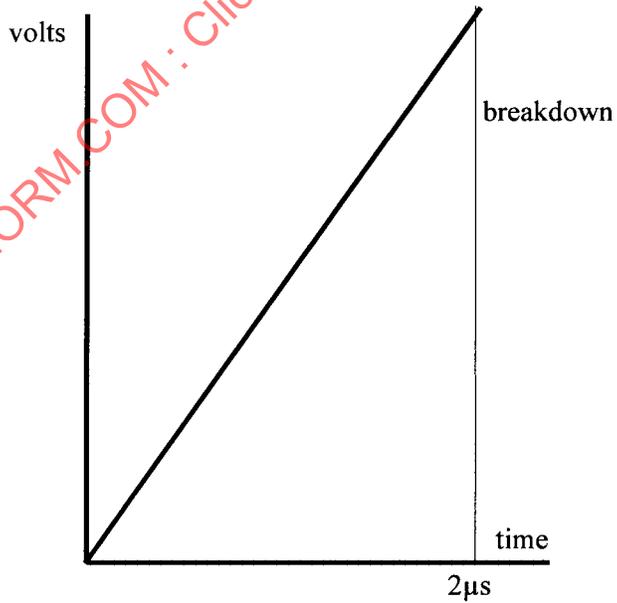


FIGURE 7 - Voltage Waveform C

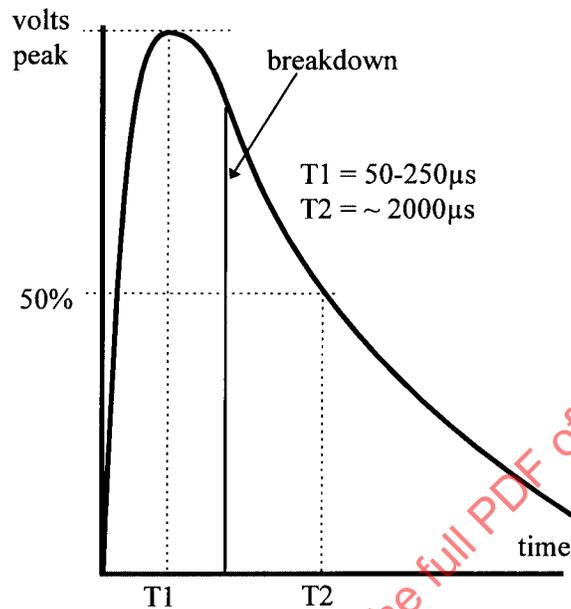


FIGURE 8 - Voltage Waveform D

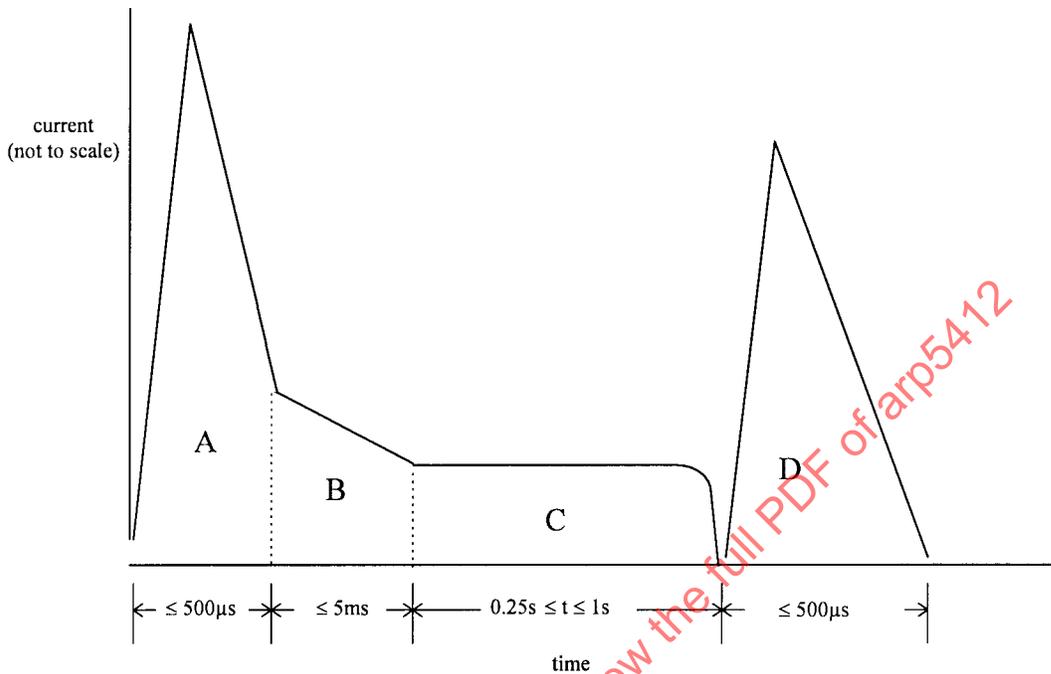
6.3 External Idealized Current Components:

The external lightning environment is comprised of current components A, A_h, B, C, D, and H, and the Multiple Stroke (MS) and Multiple Burst (MB) Waveform sets. The MS is comprised of components D and D/2, and the MB is comprised of component H pulse sequences.

Current components A, B, C, and D comprise the lightning flash current waveform for evaluating direct effects and are shown in Figure 9. Current components A and D, and Waveform sets MS and MB are applicable for evaluating indirect effects. The latter two are shown in Figures 10 and 11.

The current components are defined in the following sections.

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COMPONENT A (First Return Stroke)

Peak Amplitude	:	200kA (± 10%)
Action Integral	:	$2 \times 10^6 \text{A}^2\text{s}$ (± 20%) (in 500μs)
Time Duration	:	≤ 500μs

COMPONENT B (Intermediate Current)

Max. Charge Transfer	:	10 Coulombs (± 10%)
Average Amplitude	:	2kA (± 20%)
Time Duration	:	≤ 5ms

COMPONENT C (Continuing Current)

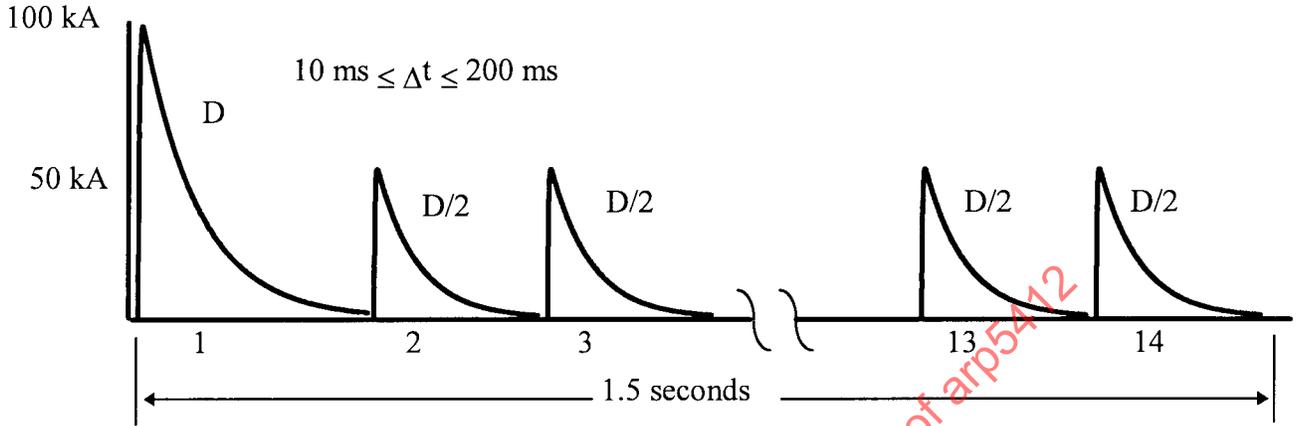
Amplitude	:	200 - 800A
Charge Transfer	:	200 Coulombs (± 20%)
Time Duration	:	0.25 to 1 s

COMPONENT D (Subsequent Return Stroke)

Peak Amplitude	:	100kA (± 10%)
Action Integral	:	$0.25 \times 10^6 \text{A}^2\text{s}$ (± 20%) (in 500μs)
Time Duration	:	≤ 500μs

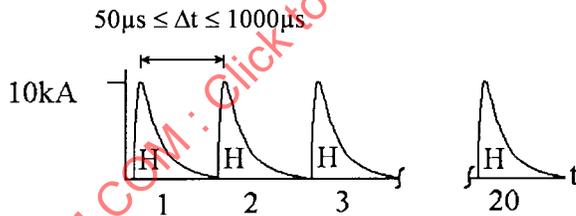
FIGURE 9 - Current Components A Through D for Direct Effects Testing

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One current component D followed by thirteen current component D/2s distributed over a period of up to 1.5 seconds.

FIGURE 10 - Multiple Stroke Waveform Set



One burst is composed of 20 pulses.

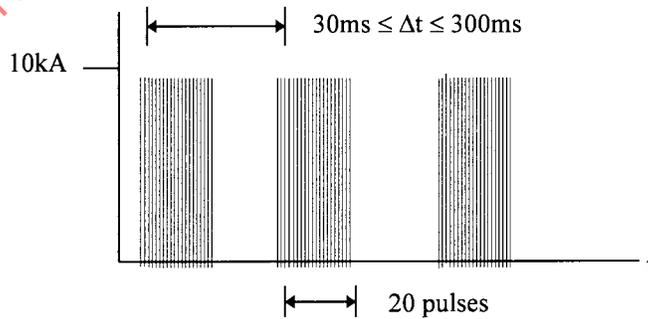


FIGURE 11 - Multiple Burst Waveform Set

6.3.1 Current Component A - First Return Stroke: This waveform combines the severe parameters of both the negative and the positive first return strokes. It occurs most frequently to aircraft flying at lower altitudes.

For analysis purposes and indirect effect considerations the double exponential waveform shown in Figure 12A shall be applied.

This waveform is defined mathematically by the double exponential expression shown below:

$$i(t) = I_0(e^{-\alpha t} - e^{-\beta t}) \quad (\text{Eq. 2})$$

where:

$$\begin{aligned} I_0 &= 218,810 \text{ A} \\ \alpha &= 11,354 \text{ s}^{-1} \\ \beta &= 647,265 \text{ s}^{-1} \\ t &\text{ is time (s)} \end{aligned}$$

The frequency content of current component A is given in Figure 12B.

For direct effects testing purposes component A can be simulated by an oscillatory or unidirectional waveform like those presented in the Figures 13A and 13B. The current must have an amplitude of 200 kA ($\pm 10\%$) with a rise time of up to 50 μs (the time between 10 and 90% of peak amplitude). The action integral has to be $2 \times 10^6 \text{ A}^2\text{s}$ ($\pm 20\%$), and the total time to 1% of peak value shall not exceed 500 μs .

The action integral, $\int i^2 dt$, is a critical factor in the extent of damage. It relates to the energy deposited or absorbed in a system. However, the actual energy deposited cannot be defined without a knowledge of the total resistance of the system. For example, the instantaneous power dissipated in a resistor is $i^2 R$, and is expressed in Watts. For the total energy expended, the power must be integrated over time to get the total Watt-seconds (or Joules). Action integral can be applied to any resistance value to identify the total energy deposited.

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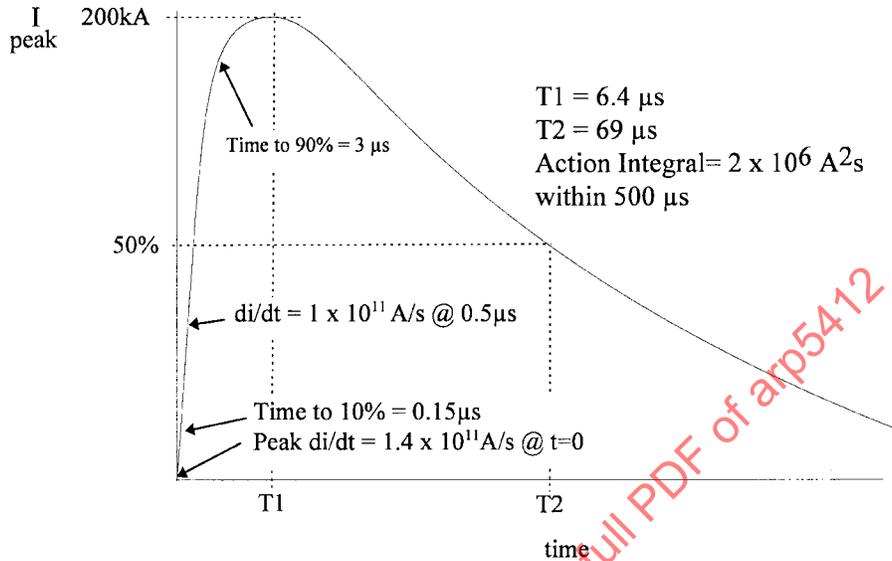


FIGURE 12A - Current Component A for Analysis and Indirect Effects Test Purposes

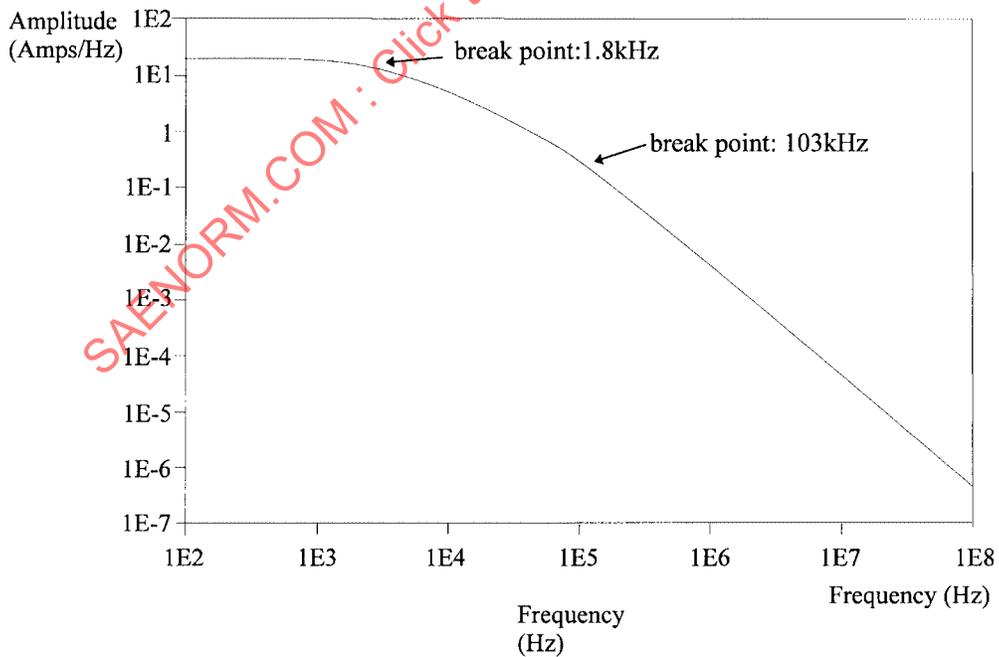


FIGURE 12B - Frequency Content (Amplitude Spectrum) of Component A

FIGURE 12

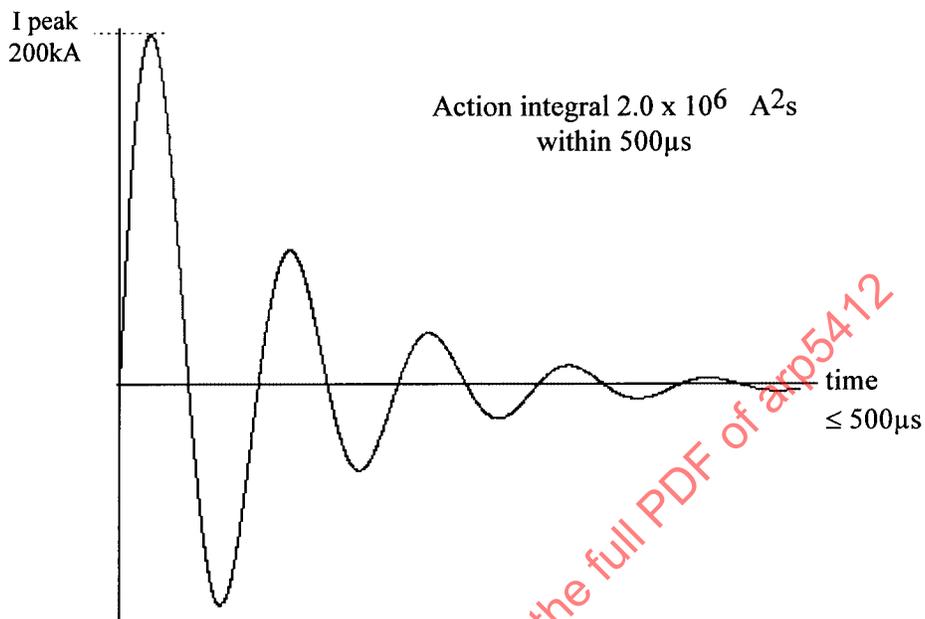


FIGURE 13A - Damped Sinusoidal Current

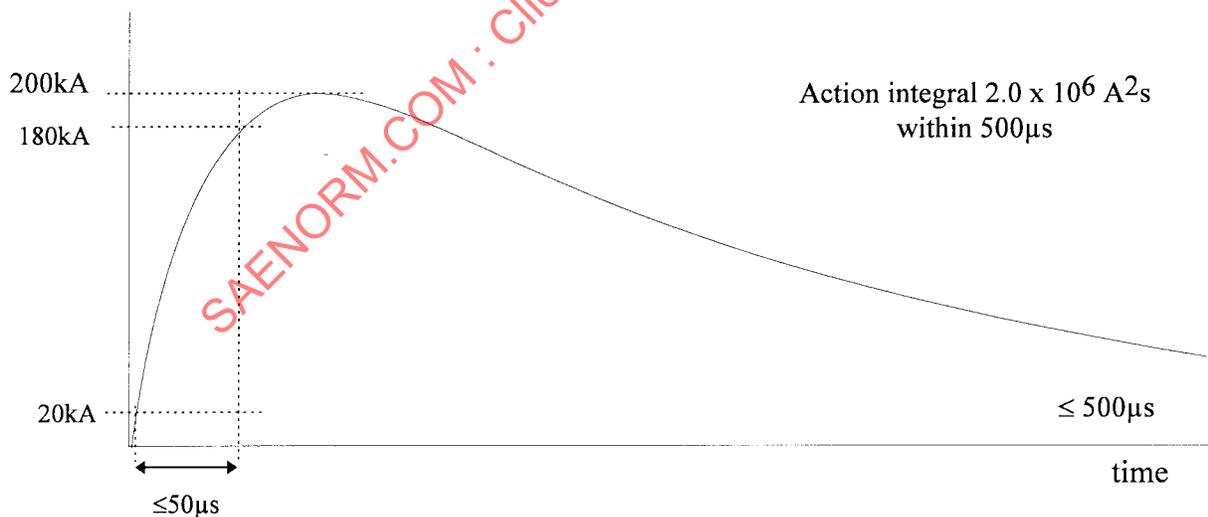


FIGURE 13B - Unipolar Current

FIGURE 13

6.3.2 Current Component A_h - Transition Zone First Return Stroke: The amplitude and waveform of the first return strokes, which might hit an aircraft, depend on the flight altitude. In general, lower amplitudes and action integrals can be expected at higher altitudes.

For analysis purposes a double exponential as shown in Figure 14A shall be applied. This waveform is applicable in the transition Zone 1C and represents the estimated shape of the first return stroke (Component A) at higher altitudes.

This waveform is defined mathematically by the following double exponential function:

$$i(t) = I_0(e^{-\alpha t} - e^{-\beta t}) \quad (\text{Eq. 3})$$

where:

$$\begin{aligned} I_0 &= 164,903 \text{ A} \\ \alpha &= 16,065 \text{ s}^{-1} \\ \beta &= 858,888 \text{ s}^{-1} \\ t &\text{ is time (s)} \end{aligned}$$

For direct effects testing, component A_h can be simulated by an oscillatory or unidirectional waveform as shown in Figures 14B and 14C. The current must have an amplitude of 150 kA ($\pm 10\%$) with a rise time of up to 37.5 μs (the time between 10 and 90% peak amplitude). The action integral has to be $2 \times 10^6 \text{ A}^2\text{s}$ ($\pm 20\%$), and the total time for the current to decay to 1% of peak value shall not exceed 500 μs .

6.3.3 Current Component B - Intermediate Current: This component represents mainly the intermediate currents following some of the negative initial return strokes and/or restrikes (see Figure 3A).

For analysis purposes a double exponential current waveform could be used as presented in Figure 15A. This waveform is described mathematically by the following expression:

$$i(t) = I_0(e^{-\alpha t} - e^{-\beta t}) \quad (\text{Eq. 4})$$

where:

$$\begin{aligned} I_0 &= 11,300 \text{ A} \\ \alpha &= 700 \text{ s}^{-1} \\ \beta &= 2,000 \text{ s}^{-1} \\ t &\text{ is time (s)} \end{aligned}$$

For direct effects testing, this component should be unidirectional, e.g. rectangular, exponential, or linearly decaying as shown in Figures 15B and 15C. The average amplitude must be 2 kA ($\pm 20\%$) flowing for a duration of 5 μs ($\pm 10\%$) with a charge transfer of 10 coulombs ($\pm 10\%$).

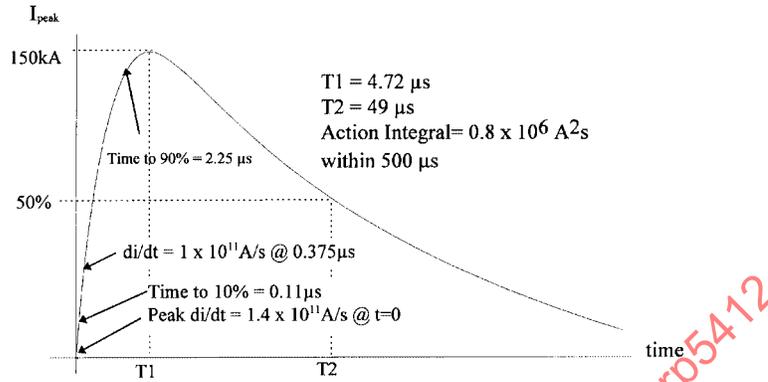


FIGURE 14A - Current Component A_h for Analysis Purposes

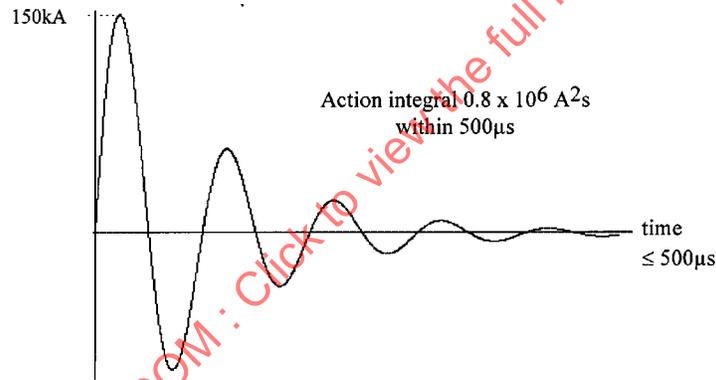


FIGURE 14B - Example of Current Component A_h for Direct Effects, Damped Sinusoidal Current

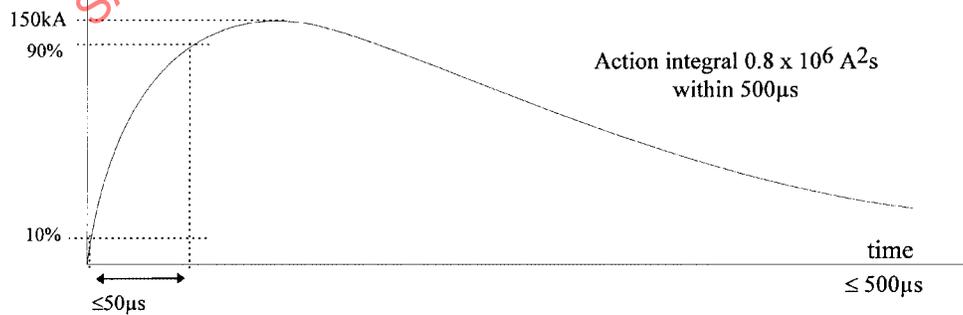


FIGURE 14C - Example for Current Component A_h for Direct Effects, Unipolar Current

FIGURE 14

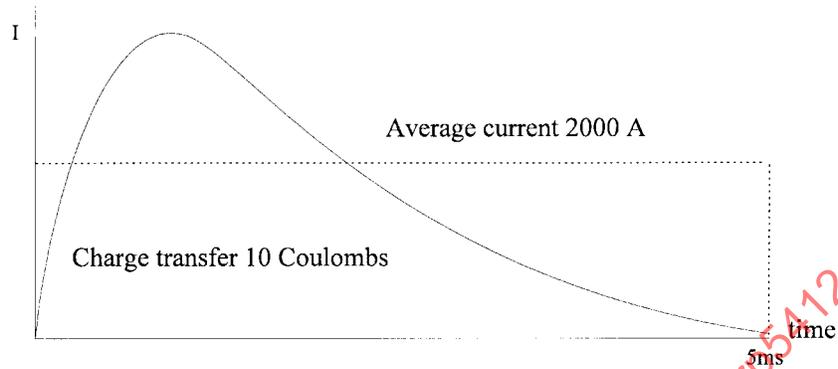


FIGURE 15A - Current Component B for Testing and Analysis Purposes

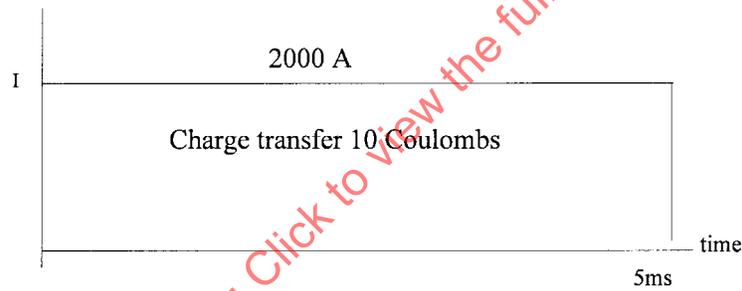


FIGURE 15B - Example of Current Component B for Direct Effects Testing

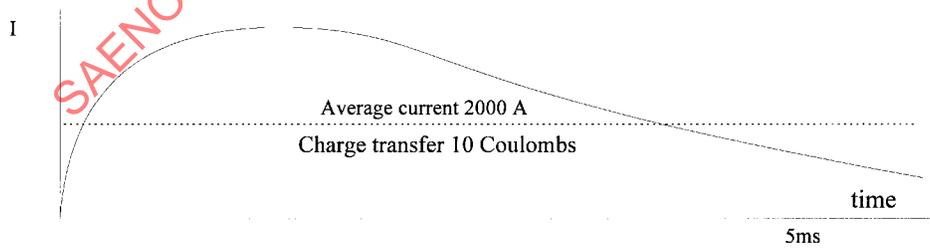


FIGURE 15C - Example of Current Component B for Direct Effects Testing

FIGURE 15

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6.3.4 Current Component C - Continuing Current: This current component represents the lightning environment that might be caused by the long duration currents which may follow some restrikes of the negative cloud to ground lightning strikes and also the return stroke of the positive cloud to ground lightning flashes.

For analysis purposes, a square waveform of 400 A for a period of 0.5 s should be utilized (Figure 16A).

For direct effects testing, the Component C should have a current amplitude between 200 and 800 A, a time duration between 0.25 and 1.0 s and transfer charge of 200 coulombs ($\pm 20\%$). This waveform should be unidirectional; e.g. rectangular, exponential or linearly decaying. Some examples are presented in the Figures 16B and 16C.

6.3.5 Component C* - Modified Component C: This component represents the portion of component C which flows into an attachment point in Zone 1A or 2A if the dwell time at that point exceeds 5 ms. Component C* is primarily used for evaluating melt through of metal skins. Component C* is a current averaging not less than 400 A for a period equal to the dwell time minus the 5 ms duration of the component B. An example of component C* for test applications is shown in Figure 17.

The combination of components A or D, B, and C* therefore represent the dwell time, which may range from 1 to 50 ms. For aircraft surfaces finished with conventional primers and paints dwell times of 20 ms will normally be sufficient. Other surfaces may experience shorter or longer dwell times. For example, dwell times of 1 to 5 ms are typical of lightning attachments to unpainted metal surfaces when only components A or D, and B would be applied. Dwell times on surfaces covered with especially thick or high dielectric strength coatings may range from 20 to 50 ms.

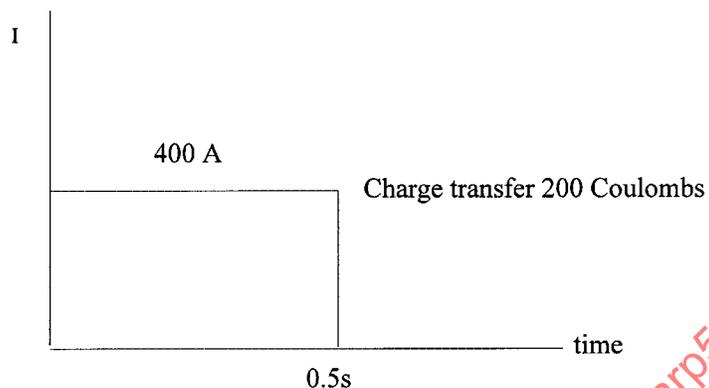


FIGURE 16A - Current Component C for Analysis Purpose

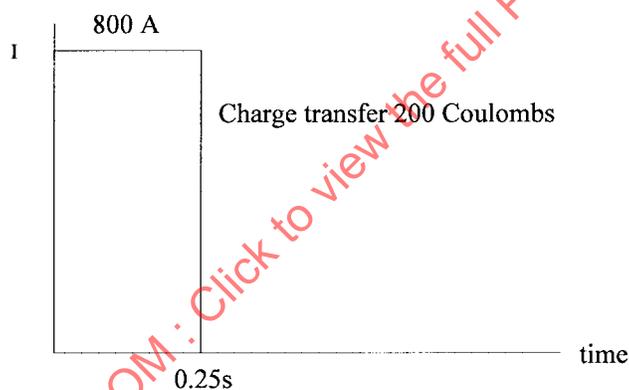


FIGURE 16B - Example of Current Component C for Direct Effects Testing

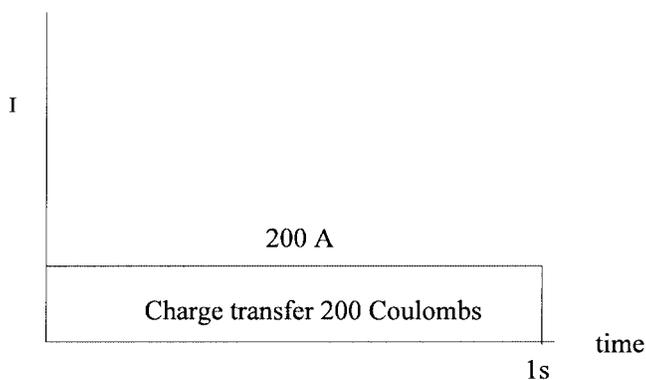


FIGURE 16C - Example of Current Component C for Direct Effects Testing

FIGURE 16

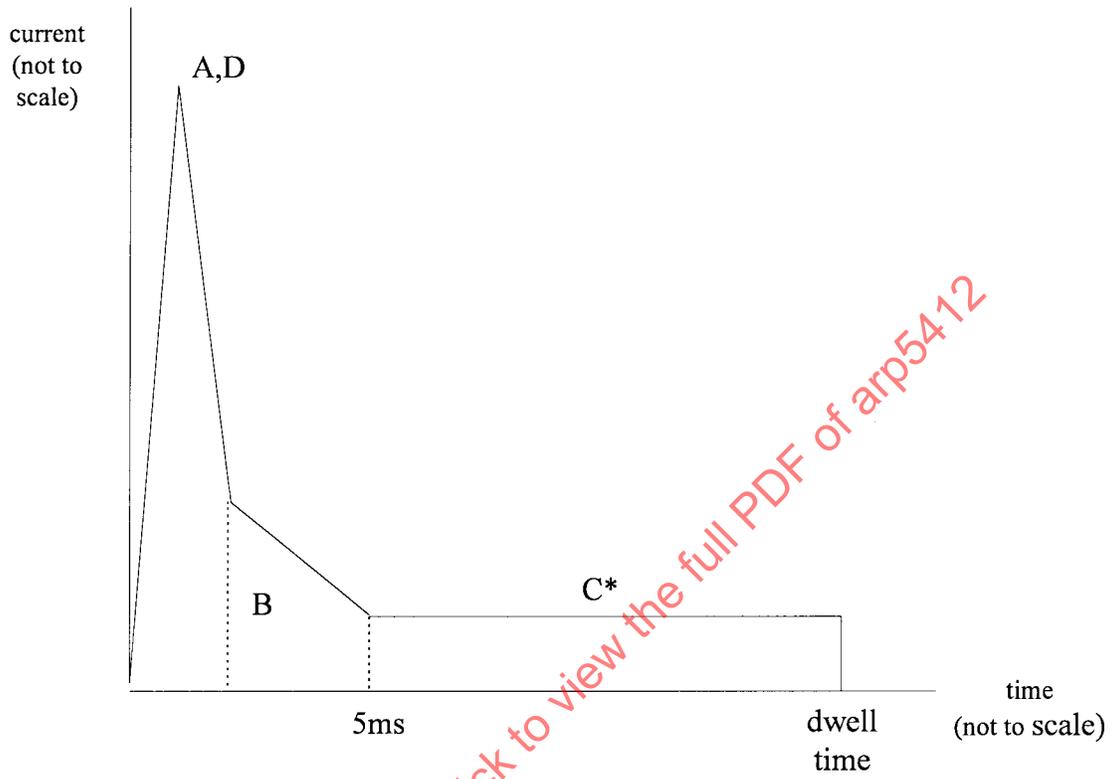


FIGURE 17 - Application of Current Component C*

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6.3.6 Current Component D - Subsequent Stroke Current: Current Component D has two applications.

For direct effects assessments current Component D represents a subsequent stroke. (Figure 9).

For direct effects testing, Component D can be simulated by either oscillatory or unidirectional waveforms (Figures 18A and 18B) with a total time duration to 1% peak value of 500 μ s. The amplitude shall be 100 kA ($\pm 10\%$), the rise time shall not exceed 25 μ s (time between 10 and 90% of the amplitude). The action integral is 2×10^6 A²s ($\pm 20\%$).

For indirect effects investigations and analysis purposes, the double exponential current waveform presented in Figure 19A should be used. This waveform represents the initial stroke in the Multiple Stroke waveform set (Figure 10).

The waveform is defined mathematically by the double exponential expression shown below:

$$i(t) = I_0(e^{-\alpha t} - e^{-\beta t}) \quad (\text{Eq. 5})$$

where:

$$\begin{aligned} I_0 &= 109,405 \text{ A} \\ \alpha &= 22,708 \text{ s}^{-1} \\ \beta &= 1,294,530 \text{ s}^{-1} \\ t &\text{ is time (s).} \end{aligned}$$

The frequency content of component D is given on Figure 19B.

6.3.7 Multiple Stroke Waveform Set: In many cases up to 14 randomly spaced strokes have been observed in negative cloud-to-ground flashes. Also several pulses of approximately 30 kA can occur in a random sequence in an intra cloud event as illustrated in Figure 4.

The synthesized Multiple Stroke Waveform set is defined as a current component D followed by 13 components D/2 as shown in Figure 10. The components D/2 are distributed randomly over a period of up to 1.5 s according to the following constraints:

- the minimum time between components is 10 ms
- the maximum time between components is 200 ms

The D/2 Waveform parameters are identical to the current component D parameters with the exception that $I_0 = 54,703$ A.

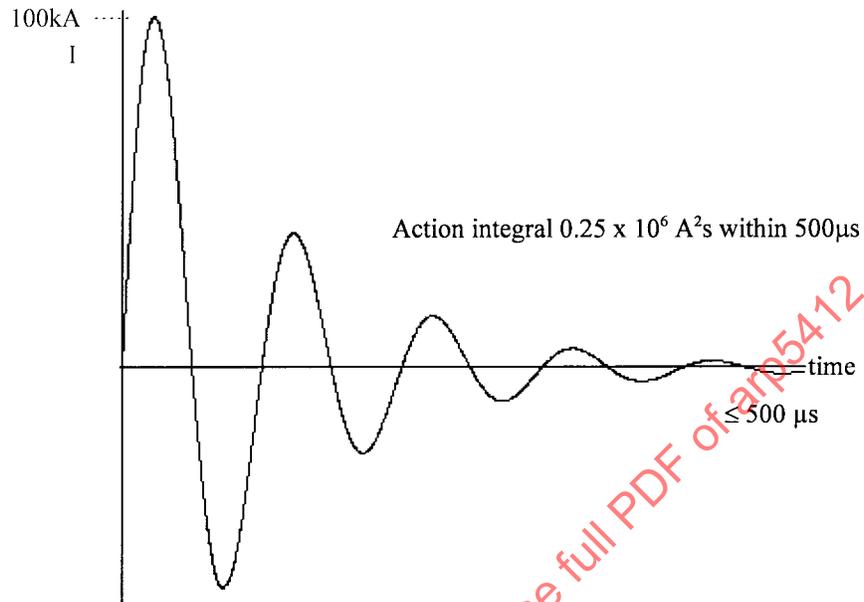


FIGURE 18A - Damped Sinusoidal Current

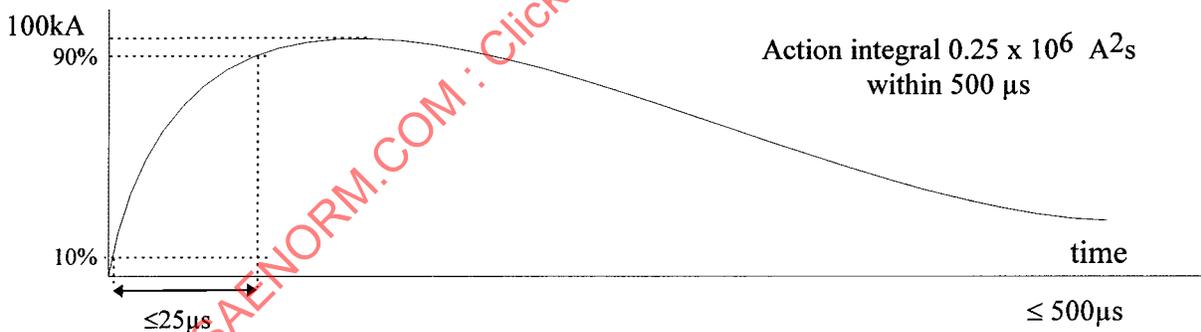


FIGURE 18B - Unipolar Pulse

FIGURE 18

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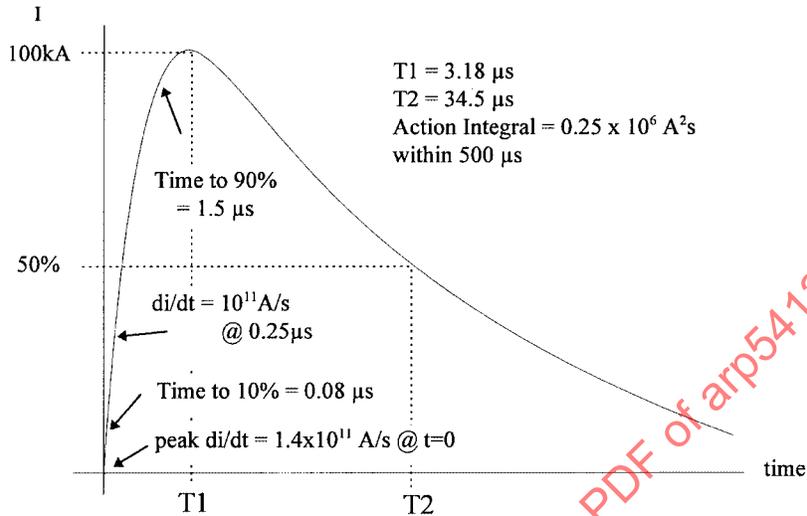


FIGURE 19A - Current Component D for Analysis Purpose and Indirect Effects Test Purposes

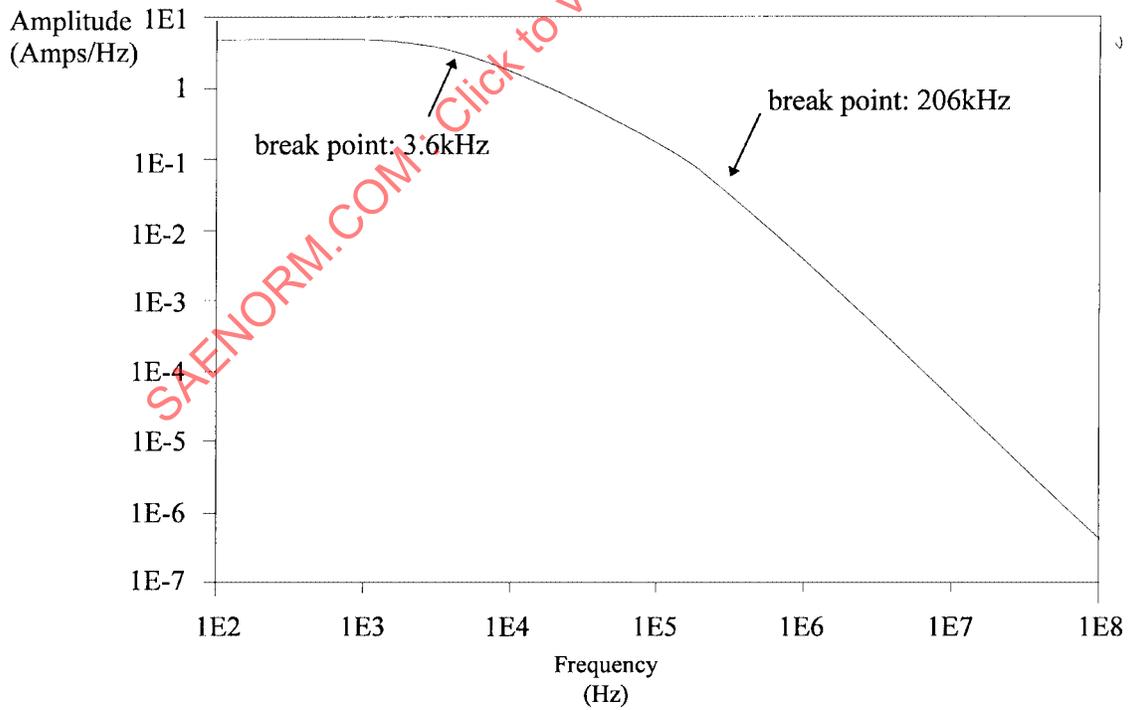


FIGURE 19B - Frequency Content (Amplitude Spectrum) of Component D

FIGURE 19

6.3.7 (Continued):

The primary purpose of the Multiple Stroke Waveform set is to evaluate system functional upset of systems that may be susceptible to effects of multiple induced transients. It is not necessary that this Waveform set be applied at the defined levels in a test. Instead, the internal environment due to a single component may be determined by analysis or test and the Multiple Stroke combination of induced transients applied to the system/equipment.

The Multiple Stroke Waveform set is used only for indirect effects evaluation.

6.3.8 Multiple Burst Waveform Set: The Multiple Burst Waveform set is comprised of component H waveforms. Component H represents a high rate-of-rise current pulse whose amplitude and time duration are much less than those of a return stroke. Such pulses have been found to occur in groups at the initiation of a lightning strike to an aircraft and randomly throughout the lightning flash duration, together with the other current components (Figure 4). While not likely to cause physical damage to the aircraft, the random and repetitive nature of these pulses may cause interference or upset to certain systems. The recommended waveform set comprises repetitive component H waveforms in three bursts of 20 pulses each as shown in Figure 11. The minimum time between induced Component H pulses within a burst is 50 μ s and the maximum is 1000 μ s.

The 3 bursts are distributed according to the following constraints:

- the minimum time between bursts is 30 ms
- the maximum time between bursts is 300 ms

If the maximum times between individual pulses and bursts were assumed, the Multiple Burst Waveform set would occupy 0.62 s.

Waveform H can be mathematically described by using the following formula:

$$i = I_0(e^{-\alpha t} - e^{-\beta t}) \quad (\text{Eq. 6})$$

where:

$$\begin{aligned} I_0 &= 10,572 \text{ A} \\ \alpha &= 187,191 \text{ s}^{-1} \\ \beta &= 19,105,100 \text{ s}^{-1} \\ t &\text{ is time (s)} \end{aligned}$$

Component H is presented in Figure 20A.

The frequency content of component H is given on Figure 20B.

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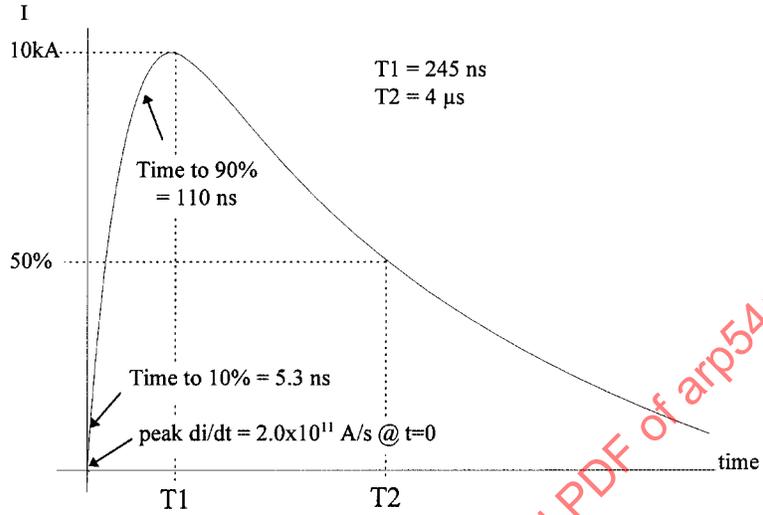


FIGURE 20A - Current Component H for Analysis Purposes and Indirect Effects Test Purposes

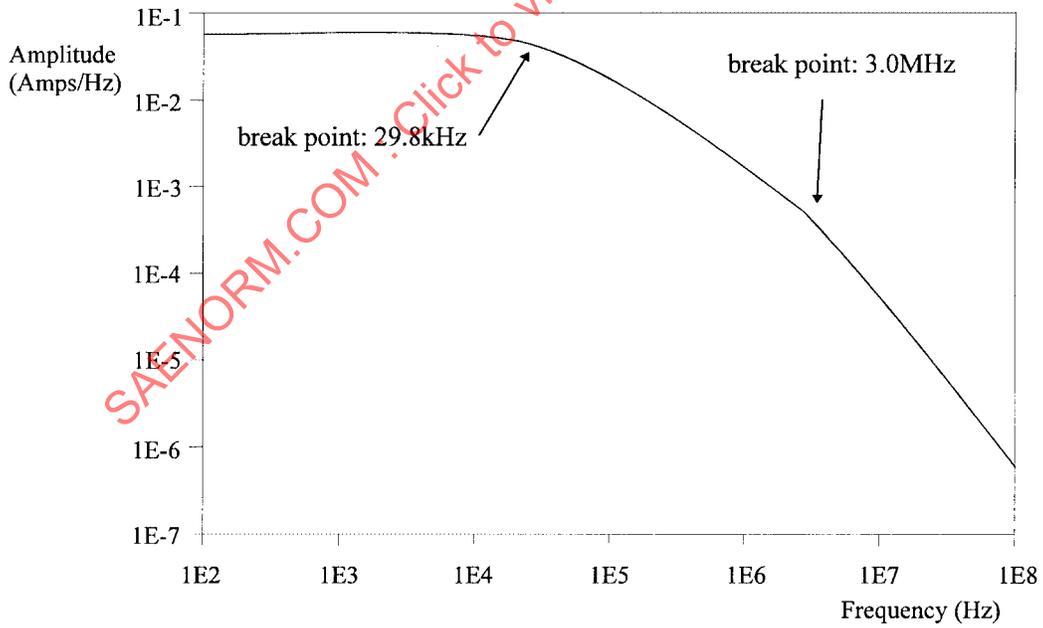


FIGURE 20B - Frequency Content (Amplitude Spectrum) of Current Component H

FIGURE 20

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6.3.8 (Continued):

The primary purpose of the Multiple Burst Waveform set is to evaluate system functional upset of systems that may be susceptible to effects of multiple induced transients. It is not necessary that this waveform set be applied at the defined levels in a test. Instead, the internal environment due to a single component H Waveform may be determined by analysis or test and the Multiple Burst combination of induced transients applied to the system/equipment.

The Multiple Burst Waveform set is used only for indirect effects evaluation.

6.4 Application of the Idealized External Environment Waveforms/Components to Aircraft Testing:

The application of the lightning environment waveforms and components to specific zones as described in ARP5414 is shown in Table 3.

TABLE 3 - Application of Lightning Environment to Aircraft Zones

Aircraft Zone	Voltage Waveforms(s)	Current Component(s)
1A	A, B, D	A, B, C*, H
1B	A, B, D	A, B, C, D, H
1C	A	A _h , B, C*, D, H
2A	A	D, B, C*, H
2B	A	D, B, C, H
3		A, B, C, D, H
Lightning Strike Model Tests	C	

Subsets of these waveforms are to be used for direct and indirect effect evaluation. Waveforms appropriate for direct effects include voltage Waveforms A, B, C, D, and current Components A, A_h, B, C, C*, and D.

Waveforms appropriate for indirect effects evaluation include current components A, D, and H which are individual components of the single stroke, MS and MB Waveform sets.

Since most of an airframe is located within Zone 3, the single stroke, MS and MB Waveform sets are nearly always applicable. However, there may be special cases in Zone 2 where the aircraft system or subsystem and its wiring are isolated from the effects of the initial A current component and current component D is more applicable for single stroke evaluation. In addition there may be situations where a system (i.e., equipment and associated wiring) is located solely within one area of the aircraft (e.g., a nose equipment bay), this system may not be exposed to all of the strokes of the magnitude as those defined by the MS waveform set.

The uses of these waveforms are described in detail in ARP5416 (DRAFT), ED-14D/DO-160D, ARP5415 (DRAFT).