SAE Aerospace
An SAE International Group

AEROSPACE RECOMMENDED PRACTICE

ARP5412 REV. B

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Superseding ARP5412A

(R) Aircraft Lightning Environment and Related Test Waveforms

RATIONALE

This revision was published to update the certification lightning environment as required to reflect the current state of knowledge and address issues as identified by the aerospace community. This involved the update of lightning parameter information and the modification of the standard waveforms.

Due to the extensive re-work and re-organization of this revision the standard 'change bar' indications for the changes are not shown; therefore, an 'R' has been placed before the document title.

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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 other weather phenomenon, is probabilistic in nature. Levels and waveforms vary considerably from one flash to the next. Within this document, standardized voltage and current waveforms have been derived to represent the lightning environment external to an aircraft. These standardized waveforms are used to assess the effects of lightning on aircraft. The standardized external current waveforms have in turn been used to derive standardized transient voltage and current test waveforms that can be expected to appear on cable bundles and at equipment interfaces within an aircraft. When deriving these latter internal induced test waveforms, considerations such as testability and important waveform characteristics that can demonstrate lightning design effectiveness, have been taken into account.

The parameters of the standardized waveforms, both external and derived internal induced 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. These standardized waveforms are thus referred to as idealized standard lightning environment waveforms, idealized standard waveforms, or just idealized waveforms within this document. The waveforms associated with the external environment are termed, the idealized standard external lightning environment. The waveforms associated with the internal induced environment are termed the idealized standard induced transient waveforms.

In every case more severe versions of each of the individual characteristics of the idealized standard external lightning environment waveforms have been recorded in natural lightning flashes. The more severe individual characteristics of the idealized standard external lightning environment waveforms have never been recorded together within a single lightning flash. Therefore the parameters combined in the idealized standard lightning environment waveforms provided in this document represent a very severe environment.

The 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), and applicable FAA and EASA 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). The relationship between the environment, zoning, and testing, along with the associated document number, is depicted in Figure 1.

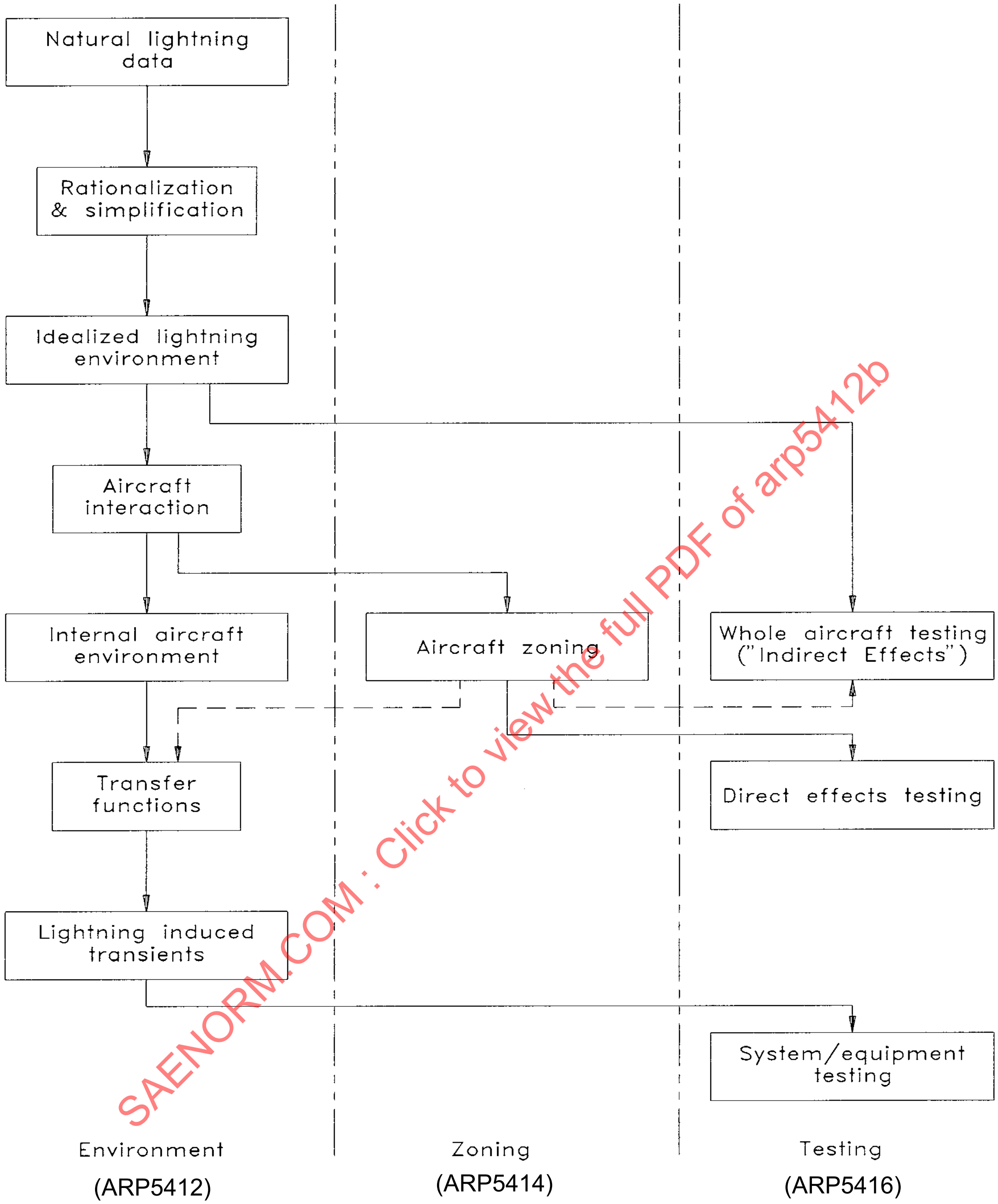


FIGURE 1 - RELATIONSHIP BETWEEN AIRCRAFT ENVIRONMENT, ZONING AND TESTING

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

ARP5414 Aircraft Lightning Zoning

ARP5415 User's Manual for Certification of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning

ARP5416 Aircraft Lightning Test Methods

2.1.2 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

RTCA DO-160G Environmental Conditions and Test Procedures for Airborne Equipment

2.2 Related Federal Aviation Administration Information

2.2.1 Federal Aviation Regulations (FAR)

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

Federal Aviation Regulations 14 CFR Parts 23.867, 23.954, 23.1306, 23.1309(a)(1), 25.581, 25.954, 25.981, 25.1316, 27.610, 27.954, 27.1316, 29.610, 29.954, 29.1316 and 33.28(d)

2.2.2 FAA Advisory Circulars

The following Advisory Circulars (AC) may provide additional information. Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

AC 23.1309-1D System Safety Analysis and Assessment for Part 23 Airplanes, dated January 16, 2009

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

AC 27-1B Certification of Normal Category Rotorcraft, Change 3, dated September 30, 2008

AC 29-2C Certification of Transport Category Rotorcraft, Change 3, dated September 30, 2008

AC 21-16G RTCA Document DO-160 versions D, E, F, and G, "Environmental Conditions and Test Procedures for Airborne Equipment, dated June 22, 2011

AC 20-136B Aircraft Electrical and Electronic System Lightning Protection, dated September 7, 2011

AC 20-155 SAE Documents to Support Aircraft Lightning Protection Certification, dated April 28, 2006

AC 20-53B Protection of Airplane Fuel Systems Against Fuel Vapor Ignition Due to Lightning, dated June 5, 2006

2.3 Related European Aviation Safety Agency Information

2.3.1 European Aviation Safety Agency Certification Specifications

Available from European Aviation safety Agency, Otto Platz 1, Koln Deutz, Postfach 101253, D-50452 Cologne, Germany, Tel: +49-221-8999-000, http://easa.europa.eu/.

Certification Specifications 23.867, 23.954, 23.1309(e), 23.1316, 25.581, 25.899, 25.954, 23.1309(a)(1), 27.610, 27.954, 27.1309(d), 27.1316, 29.610, 29.954, 29.1309(h), 29.1316, and E.170

2.3.2 European Aviation Safety Agency Acceptable Means of Compliance

Available from European Aviation safety Agency, Otto Platz 1, Koln Deutz, Postfach 101253, D-50452 Cologne, Germany, Tel: +49-221-8999-000, http://easa.europa.eu/.

AMC 25.581 Lightning Protection

ACJ 25.899 Electrical Bonding and Protection Against Lightning and Static Electricity

AMC 20-1 Certification of Aircraft Propulsion Systems Equipped with Electronic Controls

AMC to CS-E 170 Engine Systems and Component Verification

2.4 Other References

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

2.4.2 “The Lightning Discharge”, Uman, M. A., Academic Press, London, 1987; revised edition, Dover, New York, 2001.

2.4.3 Lightning - Physics and Effects”, Rakov, V. A. and Uman, M. A., Cambridge University Press, 2003.

2.4.4 “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, pp. 575-580.

2.4.5 “New Results for Quantification of Lightning/Aircraft Electrodynamics,” Pitts, F. L., Perala, R. A., and Dee, L., Electromagnetics Vol. 7, 1987.

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

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

2.5 Definitions/Abbreviations/Acronyms

2.5.1 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).

ACTUAL TRANSIENT LEVEL: The level of transient voltage and/or current which appears at the equipment interfaces as a result of the external lightning environment.

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 x 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 TRANSIENT DESIGN LEVEL: The peak amplitude of transients to which the equipment is qualified

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.

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.

INTERMEDIATE CURRENT: A low-level current of a few kiloamperes, following a return stroke, that persists for several milliseconds.

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). 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.

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 a time dependent function. Given the time dependent function, i(t), the peak rate-of-rise may be expressed as:

$$\text{Peak rate-of-rise} = \text{maximum of } di(t)/dt$$

RECOIL STREAMER: Miniature return strokes associated with intercloud or intracloud lightning thought to be a consequence of the leader encountering a pocket of opposite charge.

SHIELD: A conductor which is grounded to an equipment case or aircraft structure at both ends and is routed in parallel with and bound within a cable bundle. It usually is a wire braid around some of the wires or cables in the cable bundle or may be a metallic conduit, channel or wire grounded at both ends within the cable bundle. The effect of the shield is to provide a low resistance path between equipment so connected.

STEPPED LEADER: The intermittent low luminosity, low current precursor of a lightning return stroke, accompanied by an intense electric field, and usually associated with a negative first return stroke.

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.

SUBSEQUENT STROKE: 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.

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.

TRANSIENT CONTROL LEVEL: The maximum allowable level of transients appearing at the equipment interfaces as a result of the defined external lightning environment

UPSET: See system functional upset.

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.

2.5.2 Abbreviations

A^2s action integral (ampere squared seconds)

A amperes

A/s amperes per second

C charge transfer (coulombs or ampere - seconds)

ft feet

kA kiloamperes

kV kilovolts

kV/m kilovolts per meter

m/s meters per second

μs microseconds

ms milliseconds

ns nanoseconds

s seconds

t time

2.5.3 Acronyms

AC Advisory Circular

AMJ Advisory Material Joint

ATL Actual Transient Level

CFC Carbon Fiber Composite

DLTW Downward Lightning Measured on Towers

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

RTLT Rocket Triggered Lightning

TCL Transient Control Level

ULTW Upward Lightning Measured on Towers

3. BACKGROUND

This standard defines the idealized standard lightning environment waveforms appropriate for aircraft lightning protection. It gives a brief discussion of the mechanisms for transforming the external lightning 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 lightning 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 2.4.1), who extensively studied thunderstorms in South Africa.

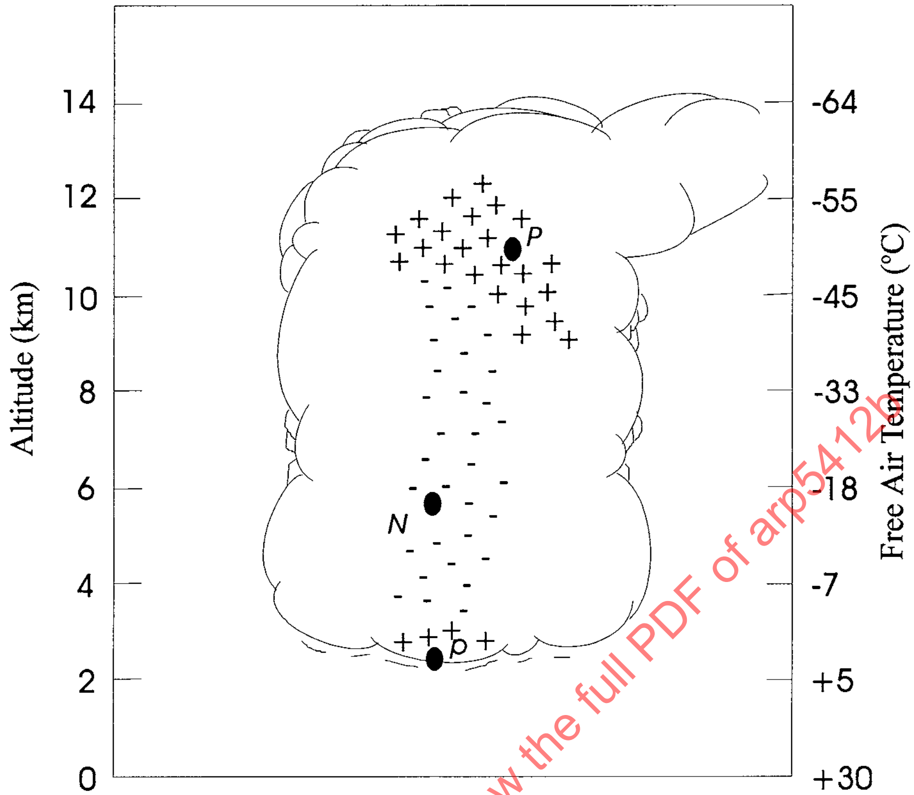


FIGURE 2 - GENERALIZED DIAGRAM SHOWING DISTRIBUTION OF ELECTRICAL CHARGE IN TYPICAL CUMULONIMBUS CLOUD

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

a. Flashes from cloud-to-ground and from ground-to-cloud of either polarity.

b. Flashes between regions of opposite polarity in different clouds (intercloud discharges).

c. Flashes between regions of opposite polarity within a cloud (intracloud discharges).

Over 50% of all flashes are intracloud flashes.

4.2 Cloud-to-Ground Flashes

4.2.1 The Discharge Process

A negative flash lowers negative charge to earth while a positive flash lowers positive 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 (first return strokes and subsequent return 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 20 to 100 μs.

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 2×10^5 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 $(1\text{-}2) \times 10^8$ 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 other 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 $(1\text{-}2) \times 10^7$ m/s.

Return stroke modeling indicates that there is a decrease in the value of the return stroke current as altitude increases (Reference 2.4.2 and Reference 2.4.3). 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 observed is up to 26. 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 μs, with a decay time (to half the peak amplitude) of 40 μs. Subsequent strokes in the flash tend to have a higher rate-of-rise with lower peak amplitudes than the initial stroke and 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 subsequent stroke can occur the continuing current must cease, as illustrated after stroke 5 in Figure 3A.

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. Positive flashes usually consist of one stroke only. Positive strokes have slower rise times with higher peak current and charge transfer than negative strokes. The duration of a positive stroke is longer than a single stroke of a negative flash but usually shorter than a complete negative flash. The positive stroke may be followed by a continuous current.

An example of the current in a positive flash is shown in Figure 3B. Typically the rise time of a positive flash is 20 μs 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.

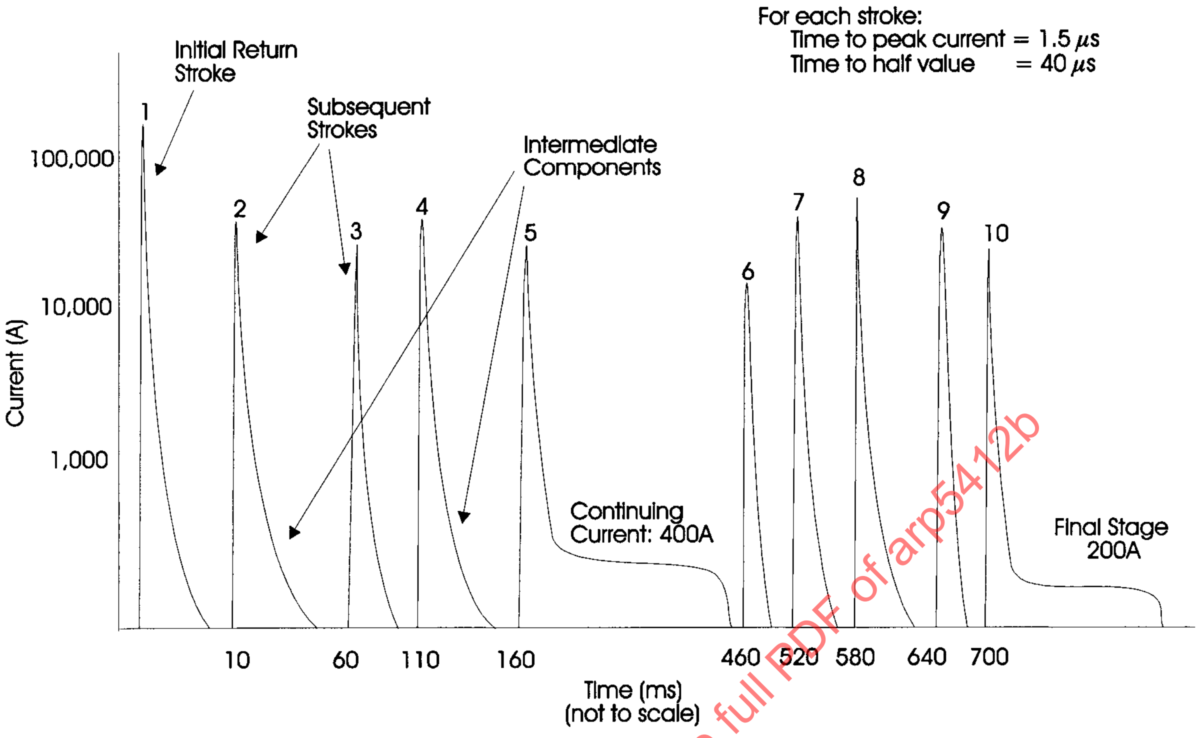


FIGURE 3A - MODEL OF A SEVERE NEGATIVE LIGHTNING FLASH CURRENT WAVEFORM

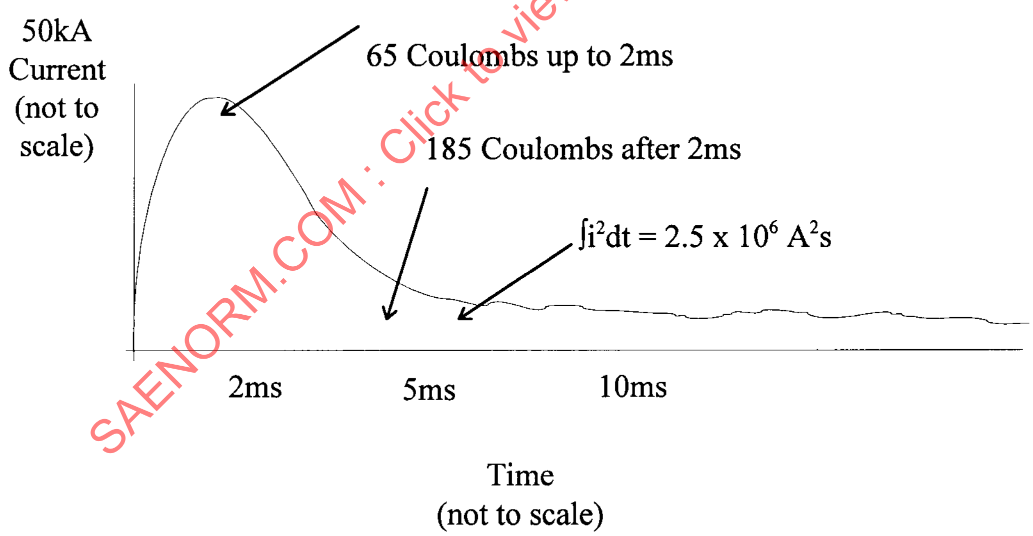


FIGURE 3B - MODEL OF A MODERATE POSITIVE LIGHTNING FLASH CURRENT WAVEFORM

4.3 Intercloud and Intracloud 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 USA 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 μs) 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 intracloud flashes. Similar pulses due to charge redistribution in a cloud have been observed between return stokes in flashes to ground.

For intracloud discharges, recoil streamers of up to 60 kA peak current have been recorded, but are more typically 20 to 30 kA (Reference 2.4.4). A typical intracloud 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 measured on instrumented towers or by artificially (rocket) triggered lightning experiments. The relevant parameter values for negative flashes are presented in Table 1 and for positive flashes in Table 2. Measured lightning data from which the parameter values were derived are provided in Appendix A. The tables include statistical values for the lightning currents and all related parameters of interest for the definition of the idealized standard external lightning 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.

Less data are available with respect to intercloud and intracloud 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-groud flashes which transport 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/μs.

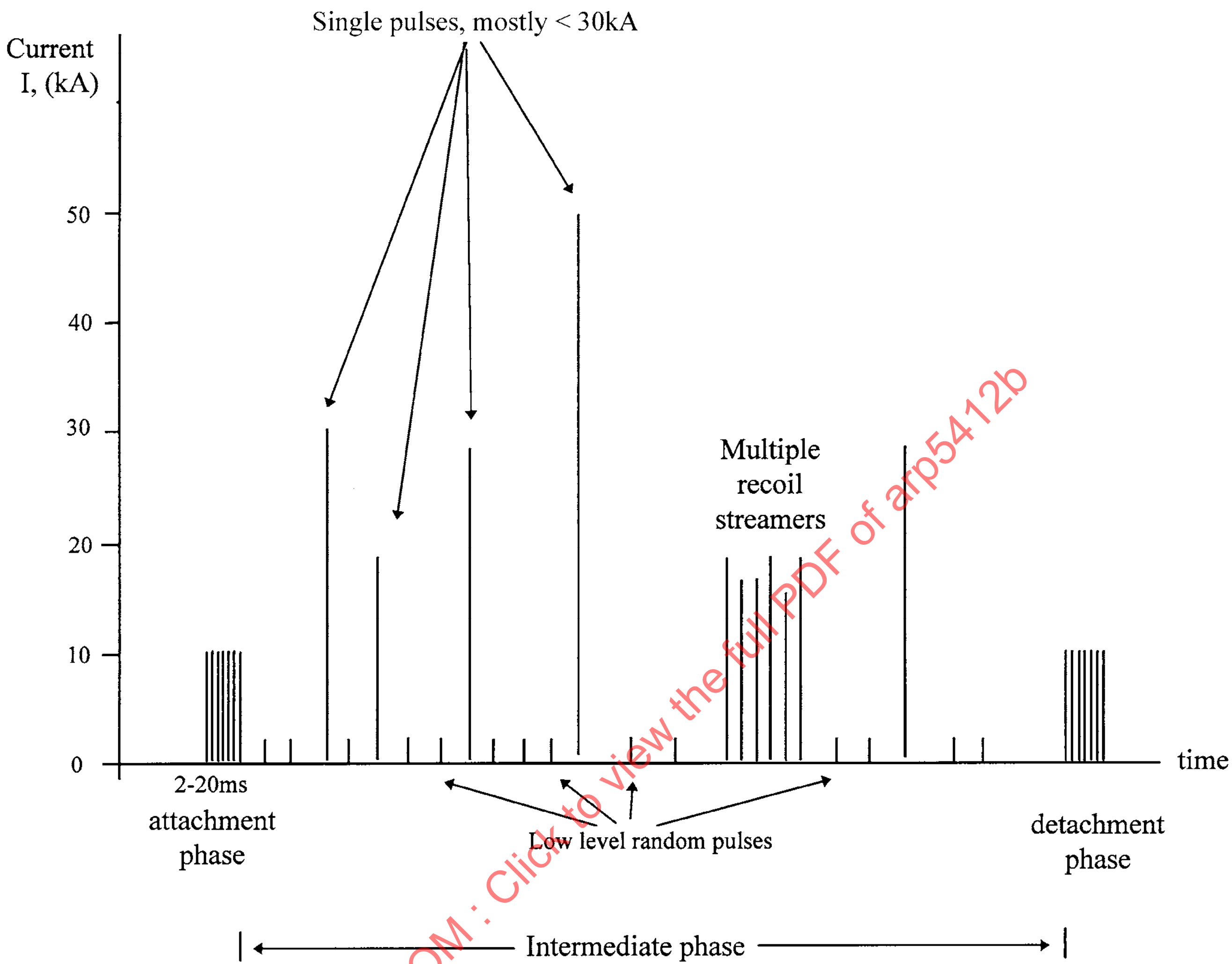


FIGURE 4 - TYPICAL INTRACLOUD LIGHTNING FLASH TO AN AIRCRAFT

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	12	47	180
Flash duration	ms	37	240	910
Charge in flash	C	1.4	16	98
Negative First Stroke:				
Peak current	kA	14	30	80
Peak rate-of-rise	kA/µs	5.5	12	32
Front duration[1]	µs	1.8	5.5	18
Stroke duration[2]	µs	30	75	200
Total charge[3]	C	1.1	5.2	24
Impulse charge	C	1.1	4.5	20
Action integral	A^2s	6×10^3	5.5×10^4	5.5×10^5
Negative Subsequent Strokes:				
Peak Current	kA	4.6	11	30
Peak rate-of-rise	kA/µs	20	37	200
Front duration[1]	µs	0.20	0.90	3.2
Stroke duration[2]	µs	8.3	31	110
Total charge[3]	C	0.30	1.6	12
Impulse charge	C	0.23	0.73	3.6
Action integral	A^2s	4.8×10^2	3.1×10^3	3.5×10^4
Continuing Current[4]:				
Amplitude	A	48	140	427
Duration	s	0.077	0.16	0.344
Charge	C	8	26	85

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.

[1] 2 kA to Peak
[2] 2 kA to half peak (50%) value on tail
[3] Includes continuing current
[4] The values for 5% and 95% are interpolated from data in Reference A1; Cianos & Pierce (Aug. 1972)

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[3]	C	20	80	350
Positive Stroke:				
Peak current	kA	4.6	35	250
Peak rate-of-rise	kA/µs	0.2	2.4	32
Front duration[1]	µs	3.5	22	200
Stroke Duration[2]	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.

[1] 2 kA to Peak
[2] 2 kA to half peak (50%) value on tail
[3] Includes continuing current

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 an 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, etc.). 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 likely 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, 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: intercloud, intracloud and cloud-to-ground.

As noted, most intracloud 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 lightning 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 2.4.5, 2.4.6, and 2.4.7) 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.

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. This movement of the attachment point is not continuous, except possibly on smooth unpainted metal surfaces, 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 approximately 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 lead 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:

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

where:

H = Field strength in amperes per meter

I = Lightning current in amperes

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

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 can be divided into different lightning strike zones. Zone definitions and methods of locating them on particular aircraft are given in ARP5414. 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

6. IDEALIZED STANDARD EXTERNAL LIGHTNING ENVIRONMENT

6.1 General

The lightning 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 are intended to be composite waveforms whose effects upon aircraft are those expected from natural lightning.

The idealized standard external 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 direct effects evaluations, peak current amplitude, action integral, and time duration are of primary importance. 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 related parameters to be applied for aircraft structures and equipment lightning protection design and verification purposes.

6.2 Idealized Standard External Voltage Waveforms

The idealized standard external voltage waveforms represent 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.

Laboratory testing shows the results of attachment point testing of aircraft models are influenced by the voltage waveform. Fast rising waveforms (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.

Since there is a wide range of possible electric field waveforms produced by natural lightning, four voltage waveforms have been established. 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.

The first voltage waveform, Voltage Waveform A, represents a fast rate-of-rise electric field and is discussed in 6.2.1. The second waveform, Voltage Waveform B, is a full voltage waveform to be used wherever an impulsive field that does not reach breakdown is required (i.e., streamer testing). This waveform is described in 6.2.2. The third waveform, Voltage Waveform C, is employed for fast front model tests and is described in 6.2.3. The fourth waveform, Voltage Waveform D, represents a slow rate-of-rise electric field and is discussed in 6.2.4. Voltage Waveform D can also be used for slow front model tests.

6.2.1 Voltage Waveform A

This waveform rises at a rate of 1000 kV/μs (±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.

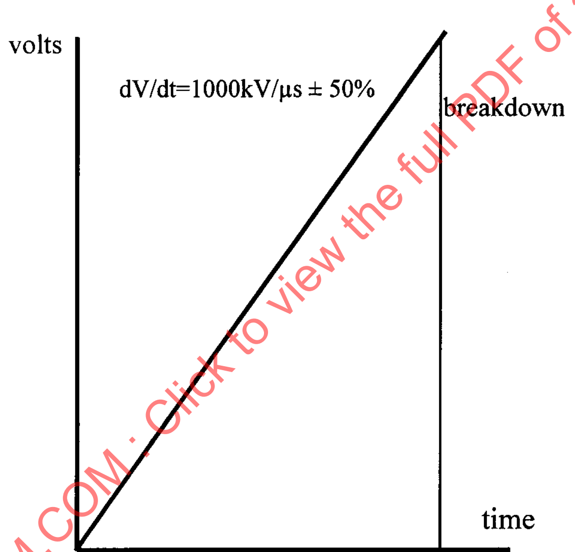


FIGURE 5 - VOLTAGE WAVEFORM A

6.2.2 Voltage Waveform B

Voltage Waveform B is a 1.2 μs x 50 μs waveform which is the electrical industry standard for impulse dielectric tests. It rises to crest in 1.2 μs (±20%) and decays to half of crest amplitude in 50 μs (±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.

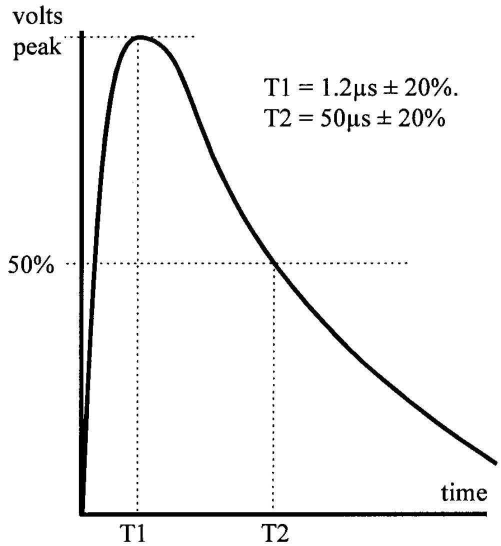


FIGURE 6 - VOLTAGE WAVEFORM B

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 μs (±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.

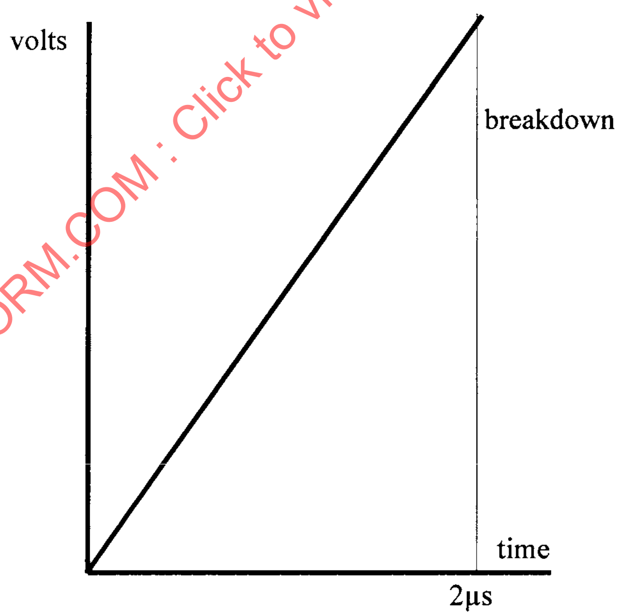


FIGURE 7 - VOLTAGE WAVEFORM C

6.2.4 Voltage Waveform D

The slow fronted Voltage Waveform D has a rise time between 50 and 250 μs 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.

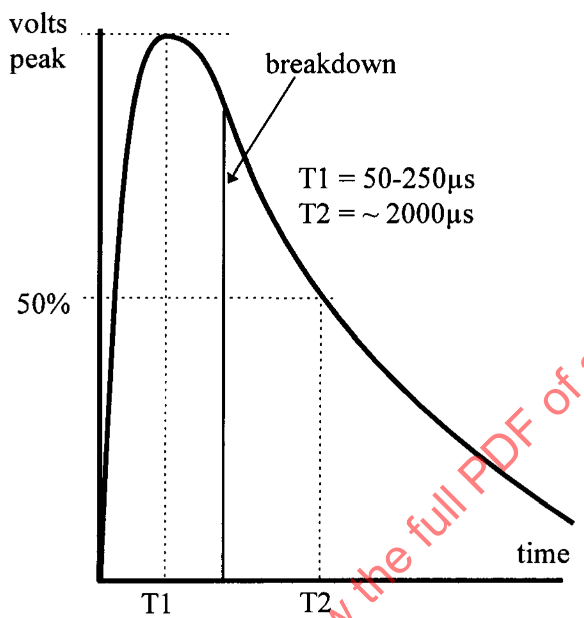


FIGURE 8 - VOLTAGE WAVEFORM D

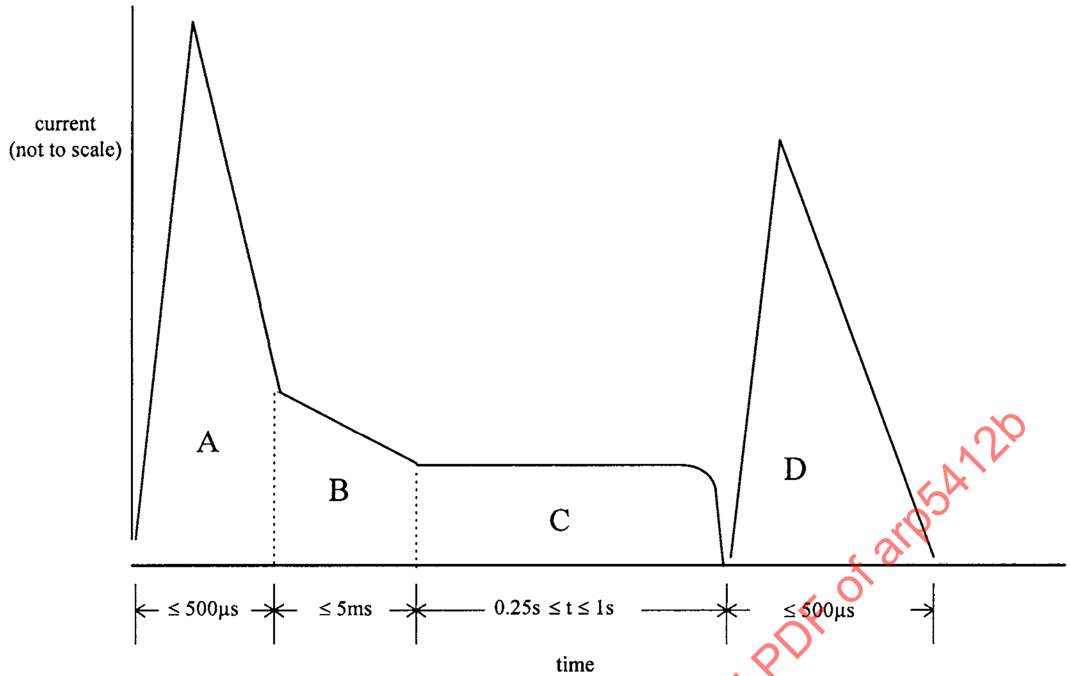
6.3 Idealized Standard External Current Components

The idealized standard external lightning environment is comprised of current Components A, A_H, B, C, C*, D, and H, and the Multiple Stroke (MS) Waveform Set and Multiple Burst (MB) Waveform Set. 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, 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.

In some documents Component A, Component A_H, Component B, Component C, Component C*, Component D, and Component H, are referred to as, current waveform A, current waveform A_H, current waveform B, current waveform C, current waveform C*, current waveform D, and current waveform H, respectively.

The current components are defined in the following sections.



COMPONENT A (First Return Stroke)

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

COMPONENT B (Intermediate Current)

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

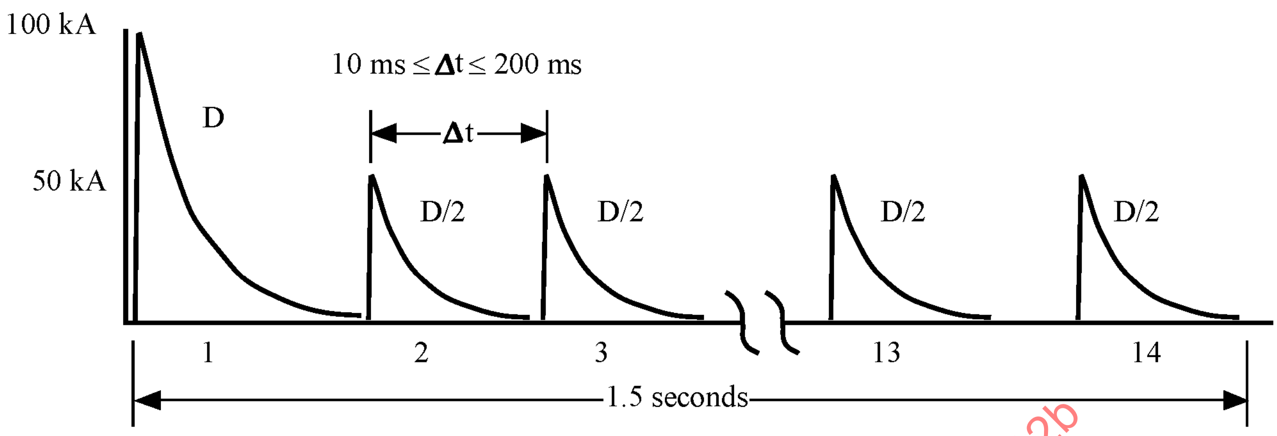
COMPONENT C (Continuing Current)

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	:	$0.25 \times 10^6 A^2s$ (± 20%) (in 500μs)
Time Duration	:	≤ 500μs

FIGURE 9 - CURRENT COMPONENTS A THROUGH D FOR DIRECT EFFECTS TESTING



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

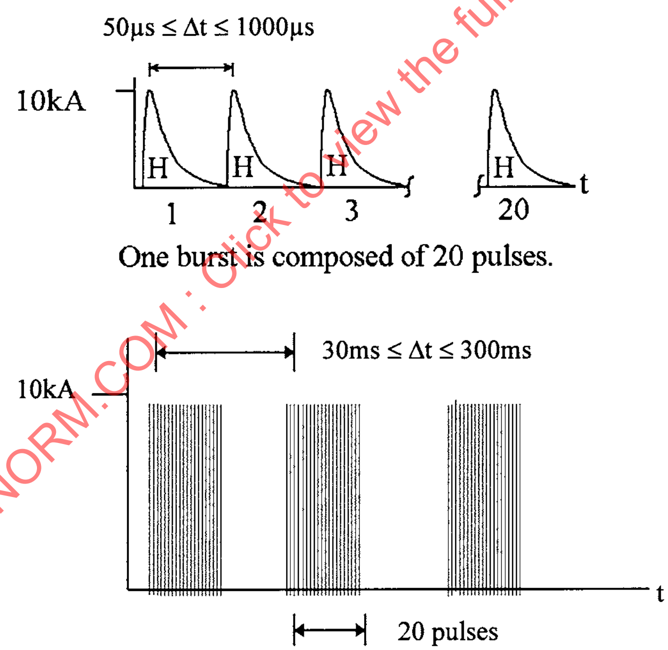


FIGURE 11 - MULTIPLE BURST WAVEFORM SET

6.3.1 Current Component A - First Return Stroke

Current Component A combines the severe parameters of the negative first return stroke, negative subsequent strokes, and the positive return stroke. The environment represented by such a pulse occurs most frequently to aircraft flying at lower altitudes.

The lightning parameters selected for representation by Component A are:

- Peak current
- Peak rate-of-rise
- Action integral

The values associated with these parameters, for a negative first return stroke, and the negative subsequent stroke, were listed in Table 1 of this document. The corresponding values for a positive return stroke were provided in Table 2. The peak current of 200 kA for Component A and the corresponding action integral were selected to lie between the 5% exceedance value of the negative first return stroke and the 5% exceedance value of the positive return stroke. Since positive lightning makes up approximately 10% of all lightning flashes, the committee determined the selected peak current and action integral for Component A to be greater than the respective 5% exceedance values when all lightning, both positive and negative, are considered. The peak rate-of-rise of Component A is defined to lie between that of the 5% exceedance value of the negative first return stroke and that of the negative subsequent stroke. The 5% exceedance value for peak rate of rise of the subsequent stroke was not used for Component A because it is already incorporated into Component H.

The exponential waveform shown in Figure 12A should be used for analysis and indirect effects aircraft testing. This waveform is defined mathematically by the exponential expression given below.

$$I(t) = I_0(e^{-\alpha t} - e^{-\beta t})(1 - e^{-\gamma t})^2 \quad \text{(Eq. 2)}$$

where:

I_0 = 218 810 A

α = 11 354 s^{-1}

β = 647 265 s^{-1}

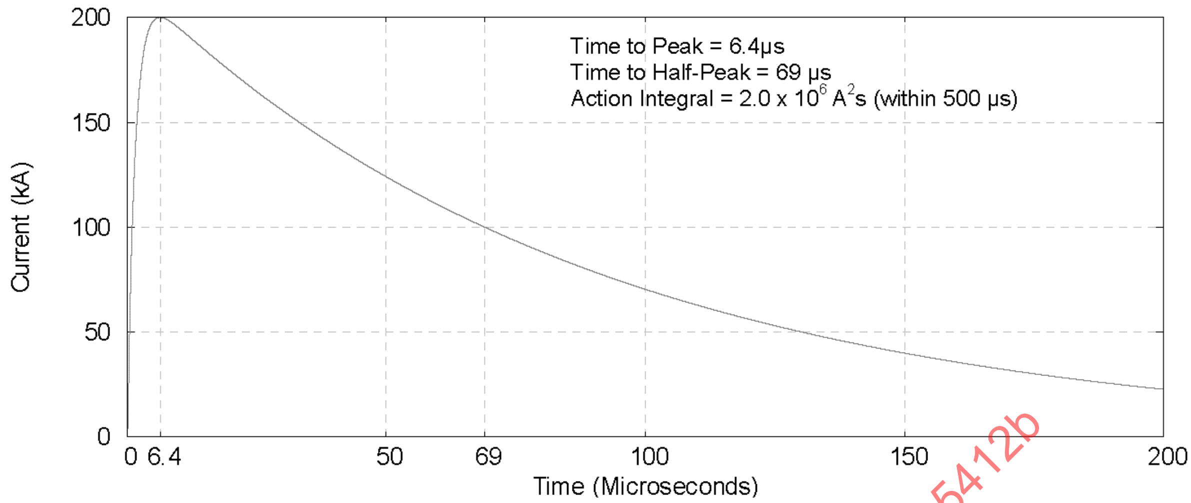
γ = 5 423 540 s^{-1}

t = time (s)

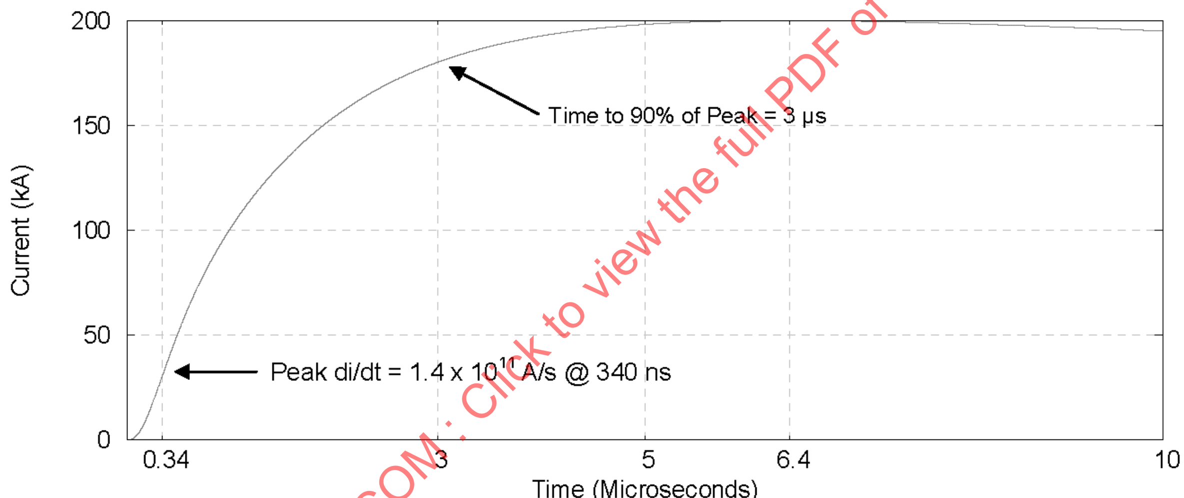
An expanded view of the waveform front end, up to 10 μs, is shown in Figure 12B.

The frequency content (amplitude only) of current Component A is plotted in Figure 12C. The frequency content is defined mathematically by the expression given below.

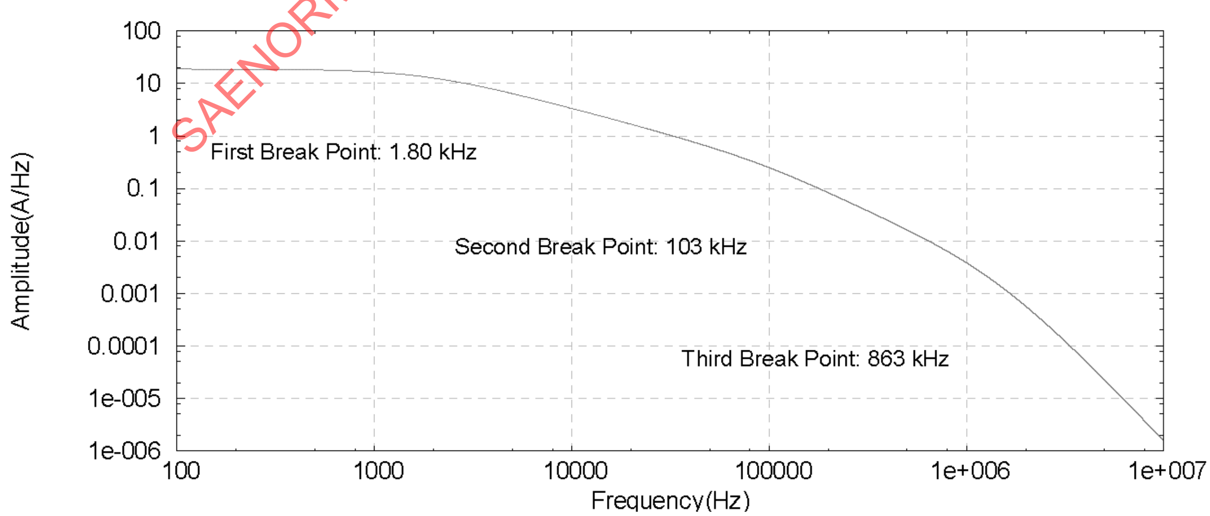
$$I(\omega) = I_0\left(\frac{1}{\alpha + j\omega} - \frac{1}{\beta + j\omega}\right) - 2I_0\left(\frac{1}{(\alpha+\gamma) + j\omega} - \frac{1}{(\beta+\gamma) + j\omega}\right) + I_0\left(\frac{1}{(\alpha+2\gamma) + j\omega} - \frac{1}{(\beta+2\gamma) + j\omega}\right) \quad \text{(Eq. 3)}$$



(A) TIME DOMAIN WAVEFORM TO 200 MICROSECONDS



(B) TIME DOMAIN WAVEFORM TO 10 MICROSECONDS



(C) FREQUENCY CONTENT (AMPLITUDE SPECTRUM)

FIGURE 12 - CURRENT COMPONENT A FOR ANALYSIS AND INDIRECT EFFECTS TEST PURPOSES

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 (±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 x 10^6 A^2s (±20%), and the total time to 1% of peak value shall not exceed 500 μs.

The action integral, $\int i^2dt$, 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^2R, 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). The action integral can be applied to any resistance value to identify the total energy deposited.

For indirect effects pulse tests on aircraft, Component A can be simulated by a unipolar waveform with characteristics of those presented in the Figures 12A, 12B, and 12C. The waveform should achieve 90% of the peak within 3 μs and reach the peak within 6.9 μs (±20%). The time to half value should be 69 μs (±30%).

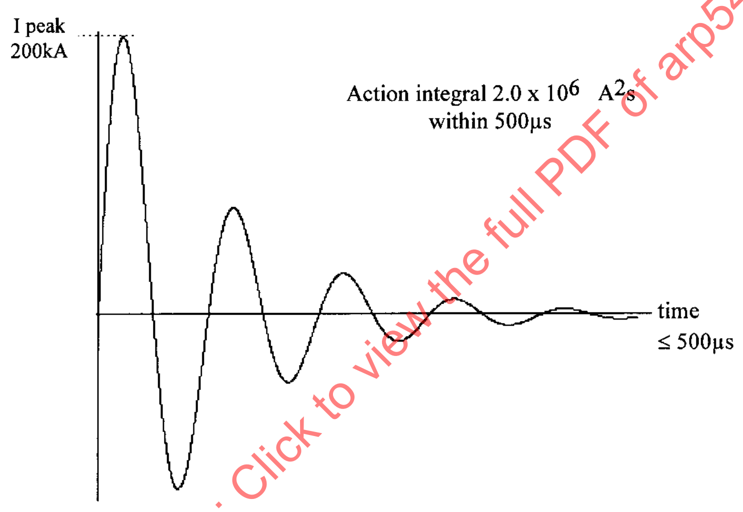


FIGURE 13A - DAMPED SINUSOIDAL CURRENT

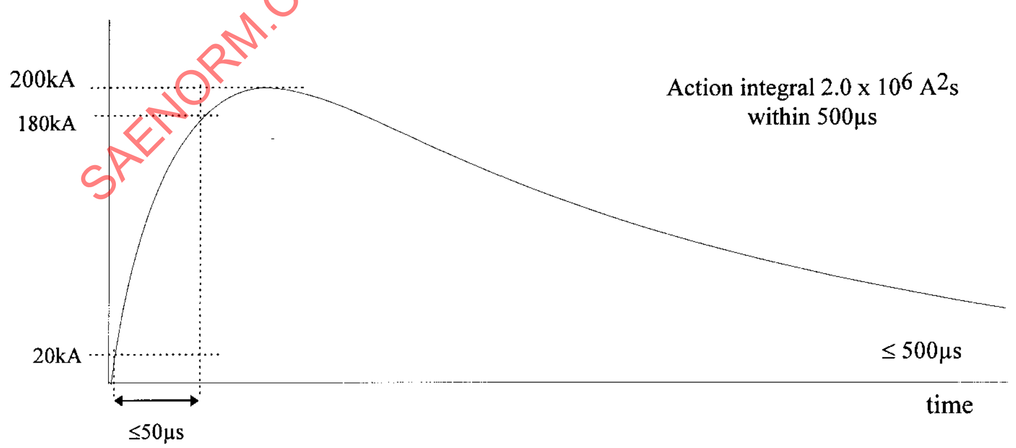


FIGURE 13B - UNIPOLAR CURRENT

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. However, if the initial leader attachment is to a leading edge, the first return stroke may occur further aft on the aircraft (i.e., in Zone 1C). This zone was setup to account for a stroke larger than a subsequent stroke, but smaller than a first return strike due to the sweeping action of the leader attachment. Current Component A_H is a waveform applicable in the transition Zone 1C and represents the peak current of the first return stroke at higher altitudes.

The exponential waveform shown in Figure 14A should be used for analysis and indirect effects aircraft testing. This waveform is defined mathematically by the exponential expression given below.

$$I(t) = I_0(e^{-\alpha t} - e^{-\beta t})(1 - e^{-\gamma t})^2 \quad \text{(Eq. 4)}$$

where:

I_0 = 164 903 A

α = 16 065 s^{-1}

β = 858 888 s^{-1}

γ = 7 253 750 s^{-1}

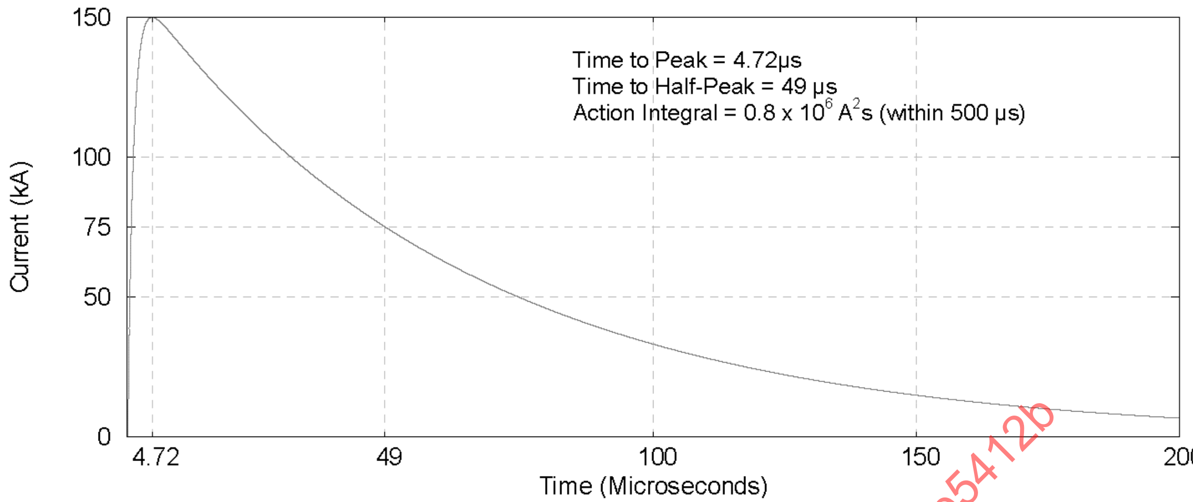
t = time (s)

An expanded view of the waveform front end, up to 10 μs, is shown in Figure 14B.

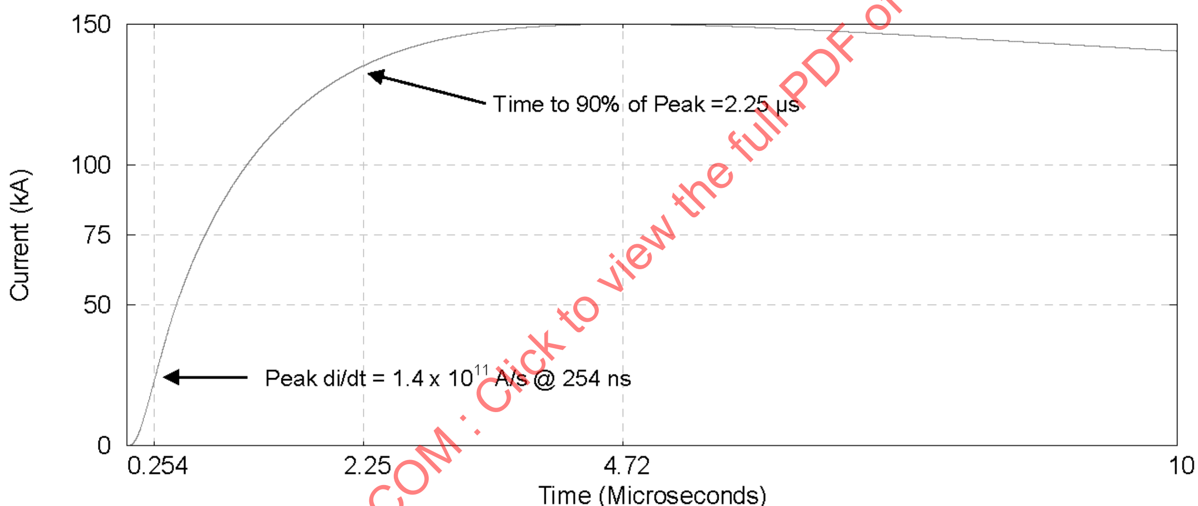
The frequency content (amplitude only) of current Component A_H is plotted in Figure 14C. The frequency content is defined mathematically by the expression given below.

$$I(\omega) = I_0\left(\frac{1}{\alpha + j\omega} - \frac{1}{\beta + j\omega}\right) - 2I_0\left(\frac{1}{(\alpha+\gamma) + j\omega} - \frac{1}{(\beta+\gamma) + j\omega}\right) + I_0\left(\frac{1}{(\alpha+2\gamma) + j\omega} - \frac{1}{(\beta+2\gamma) + j\omega}\right) \quad \text{(Eq. 5)}$$

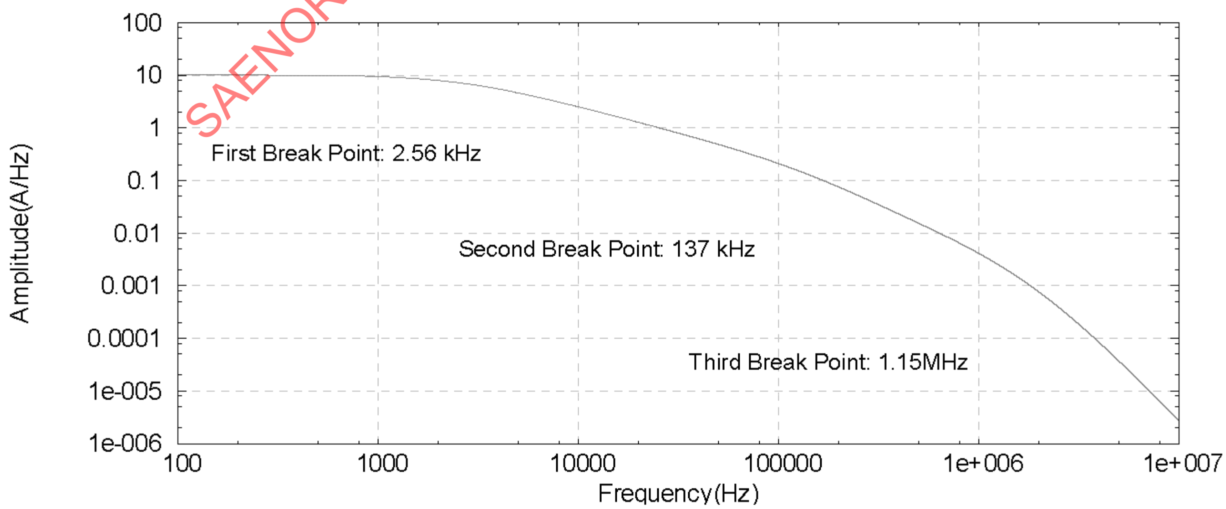
For direct effects testing, Component A_H can be simulated by an oscillatory or unidirectional waveform as shown in Figures 15A and 15B. The current must have an amplitude of 150 kA (±10%) with a rise time of up to 37.5 μs (the time between 10% and 90% peak amplitude). The action integral has to be 0.8 x 10^6 A^2s (±20%), and the total time for the current to decay to 1% of peak value shall not exceed 500 μs.



(A) TIME DOMAIN WAVEFORM TO 200 MICROSECONDS



(B) TIME DOMAIN WAVEFORM TO 10 MICROSECONDS



(C) FREQUENCY CONTENT (AMPLITUDE SPECTRUM)

FIGURE 14 - CURRENT COMPONENT A_H FOR ANALYSIS AND INDIRECT EFFECTS TEST PURPOSES

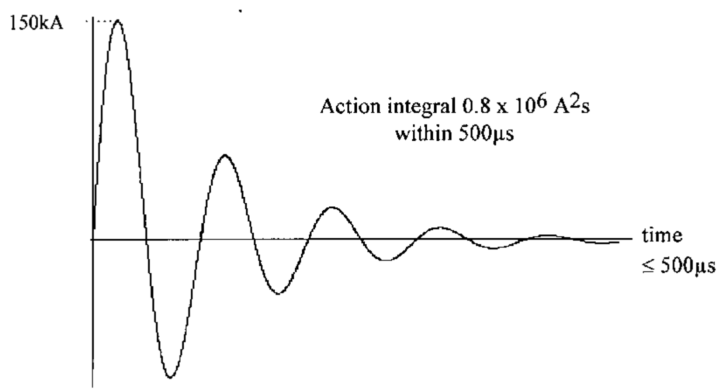


FIGURE 15A - EXAMPLE OF CURRENT COMPONENT A_H FOR DIRECT EFFECTS, DAMPED SINUSOIDAL CURRENT

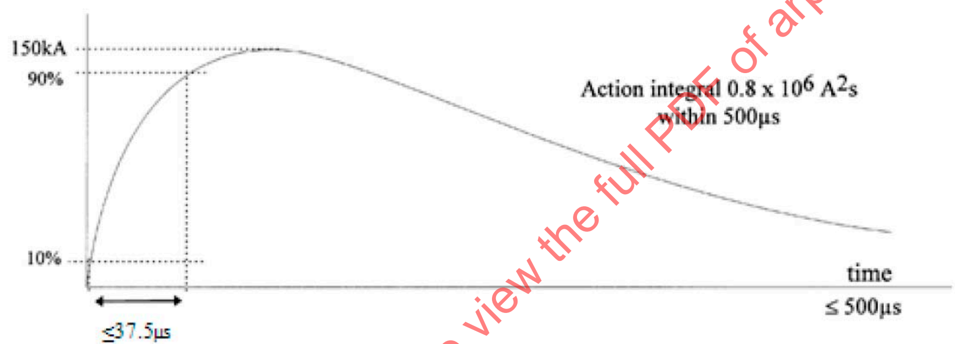


FIGURE 15B - EXAMPLE FOR CURRENT COMPONENT A_H FOR DIRECT EFFECTS, UNIPOLAR CURRENT

6.3.3 Current Component B - Intermediate Current

Component B represents the intermediate current that is often observed following a negative return stroke (Figure 3A). The intermediate current is described in Reference A1. The intermediate current in this reference has an average current of 4 kA and an average charge transfer of 4 coulombs. The charge transfer for Component B was set at 10.5 coulombs to duplicate damage seen on aircraft in service. This waveform results in lightning puncture of thin wing skins used in integral fuel tanks which has been observed on in-service aircraft.

For analysis purposes, the exponential current waveform presented in Figure 16A should be used. This waveform is defined mathematically by the exponential expression given below.

$$I(t) = I_0(e^{-\alpha t} - e^{-\beta t})(1 - e^{-\gamma t})^2 \quad \text{(Eq. 6)}$$

where:

I_0 = 11 300 A

α = 700 s^{-1}

β = 2000 s^{-1}

γ = 22 000.0 s^{-1}

t = time (s)

An expanded view of the waveform front end, up to 1 ms, is shown in Figure 16B.

The frequency content (amplitude only) of current Component B is plotted in Figure 16C. The frequency content is defined mathematically by the expression given below.

$$I(\omega) = I_0\left(\frac{1}{\alpha + j\omega} - \frac{1}{\beta + j\omega}\right) - 2I_0\left(\frac{1}{(\alpha+\gamma) + j\omega} - \frac{1}{(\beta+\gamma) + j\omega}\right) + I_0\left(\frac{1}{(\alpha+2\gamma) + j\omega} - \frac{1}{(\beta+2\gamma) + j\omega}\right) \quad \text{(Eq. 7)}$$

For direct effects testing, this component should be unidirectional, e.g., rectangular, exponential, or linearly decaying as shown in Figures 17A and 17B. The average amplitude must be 2 kA (±20%) flowing for a duration of 5 ms (±10%) with a charge transfer of 10 coulombs (±10%).

6.3.4 Current Component C - Continuing Current

This current component represents the long duration lightning currents that follow some subsequent strokes of the negative cloud-to-ground lightning strikes and the return stroke of the positive cloud-to-ground lightning flash. The charge transfer of 200 coulombs lies between the 5% exceedance value of the negative lightning flash and the 5% exceedance value of the positive lightning flash. Since positive lightning makes up approximately 10% of all lightning flashes, the committee determined the selected charge transfer for Component C to be greater than the 5% exceedance value when all lightning, both positive and negative, are considered. The duration was set at the 5% exceedance value for positive lightning. The current amplitude was set to produce the intended charge transfer.

For analysis purposes, a square waveform of 400 A for a period of 0.5 s should be utilized (Figure 18A).

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 (±20%). This waveform should be unidirectional; e.g., rectangular, exponential or linearly decaying. Some examples are presented in the Figures 18B and 18C.

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 19.

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.

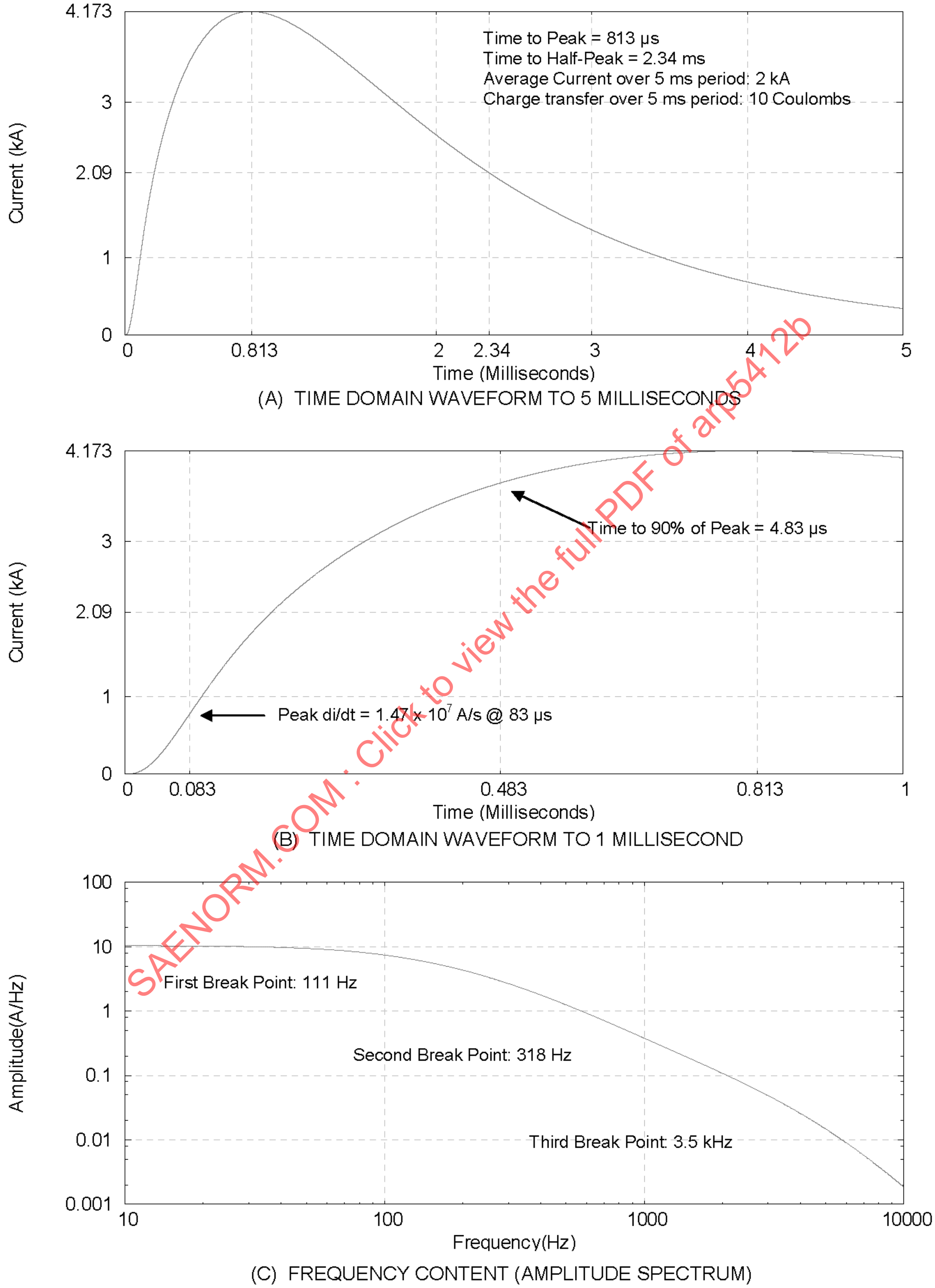


FIGURE 16 - CURRENT COMPONENT B FOR ANALYSIS AND INDIRECT EFFECTS TEST PURPOSES

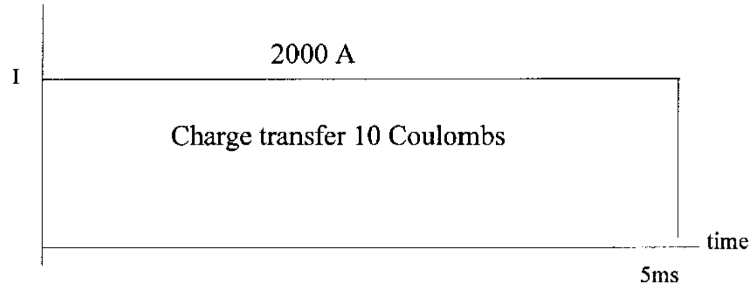


FIGURE 17A - EXAMPLE OF CURRENT COMPONENT B FOR DIRECT EFFECTS TESTING

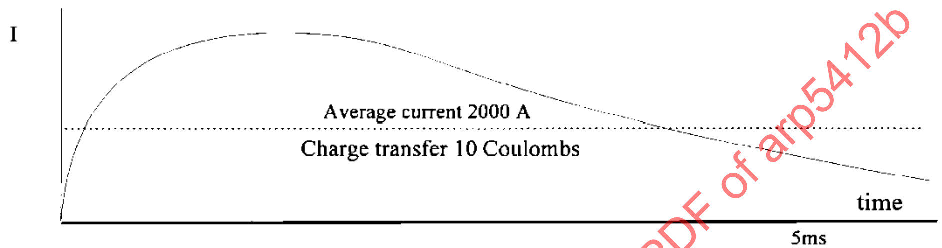


FIGURE 17B - EXAMPLE OF CURRENT COMPONENT B FOR DIRECT EFFECTS TESTING

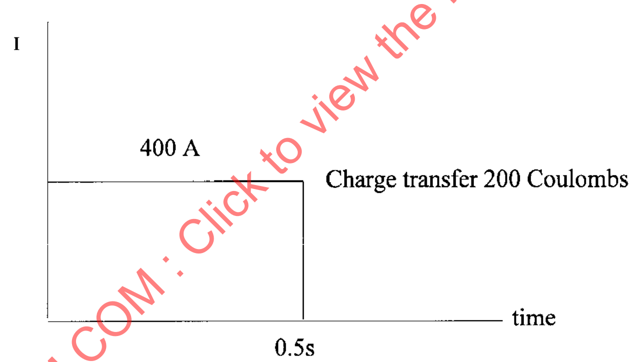


FIGURE 18A - CURRENT COMPONENT C FOR ANALYSIS PURPOSE

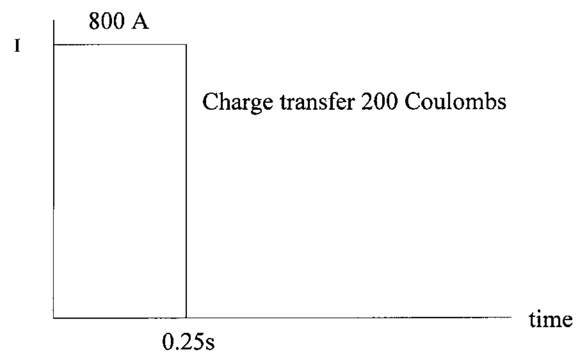


FIGURE 18B - EXAMPLE OF CURRENT COMPONENT C FOR DIRECT EFFECTS TESTING

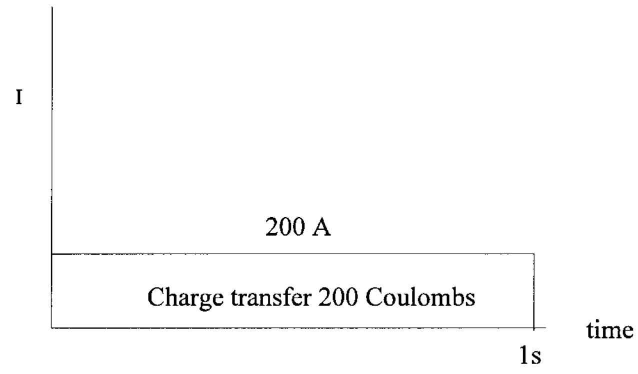


FIGURE 18C - EXAMPLE OF CURRENT COMPONENT C FOR DIRECT EFFECTS TESTING

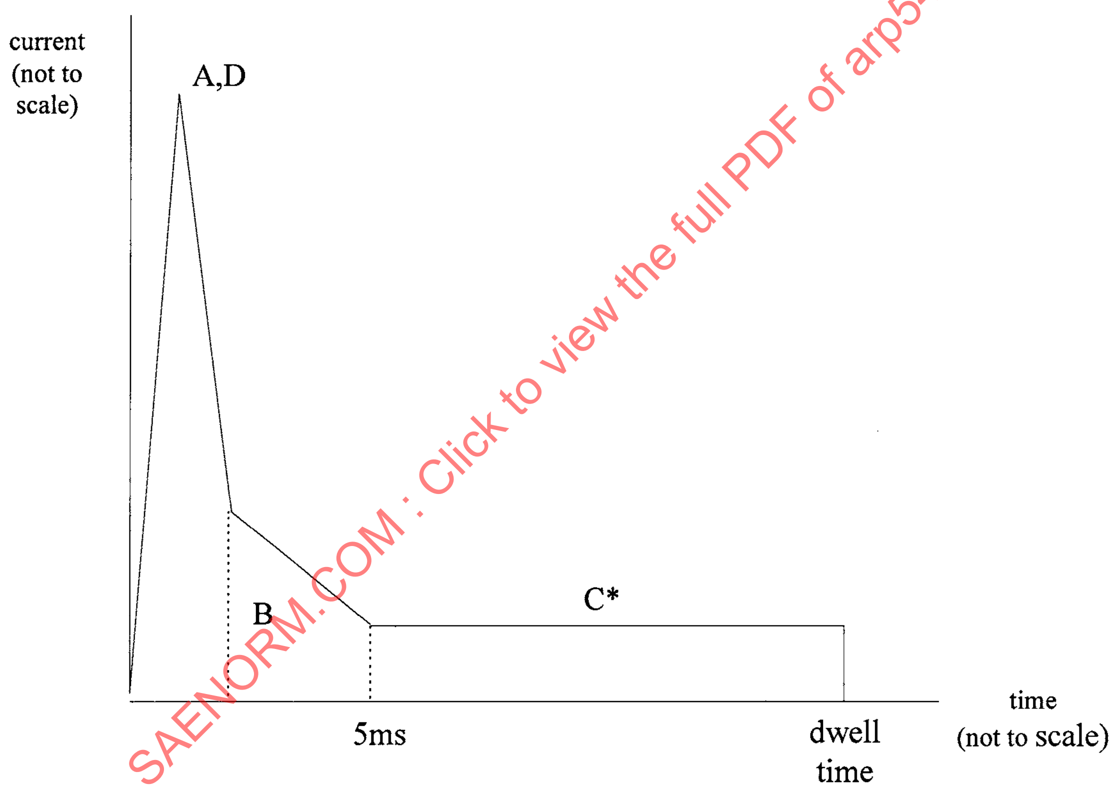


FIGURE 19 - APPLICATION OF CURRENT COMPONENT C*

6.3.6 Current Component D - Subsequent Stroke Current

Current Component D has two applications. For indirect effects investigations, Component D represents the initial stroke in the Multiple Stroke Waveform Set (see Figure 10). For direct effects assessments, Component D represents a subsequent return stroke (see Figure 9). Component D was devised to represent some of the more severe parameters of negative subsequent strokes. The parameters selected for representation were:

- Peak current
- Peak rate-of-rise

The values associated with these parameters for negative subsequent return strokes were listed in Table 1 of this document. A negative subsequent stroke is approximately half the value of a negative first return stroke. Since the value of Component A was selected to be 200 kA, the value of component D was selected to be 100 kA. The value of 140 kA/µs was selected, instead of the 5% exceedance value of 200 kA/µs, to allow for the greater time duration associated with the peak derivative, as defined for Component D. The 5% exceedance value of 200 kA/µs is incorporated into Component H.

The exponential waveform shown in Figure 20A should be used for analysis and indirect effects aircraft testing. This waveform is defined mathematically by the exponential expression given below.

$$I(t) = I_0(e^{-\alpha t} - e^{-\beta t})(1 - e^{-\gamma t})^2 \quad \text{(Eq. 8)}$$

where:

I_0 = 109 405 A

α = 22 708 s^{-1}

β = 1 294 530 s^{-1}

γ = 10 847 100 s^{-1}

t = time (s)

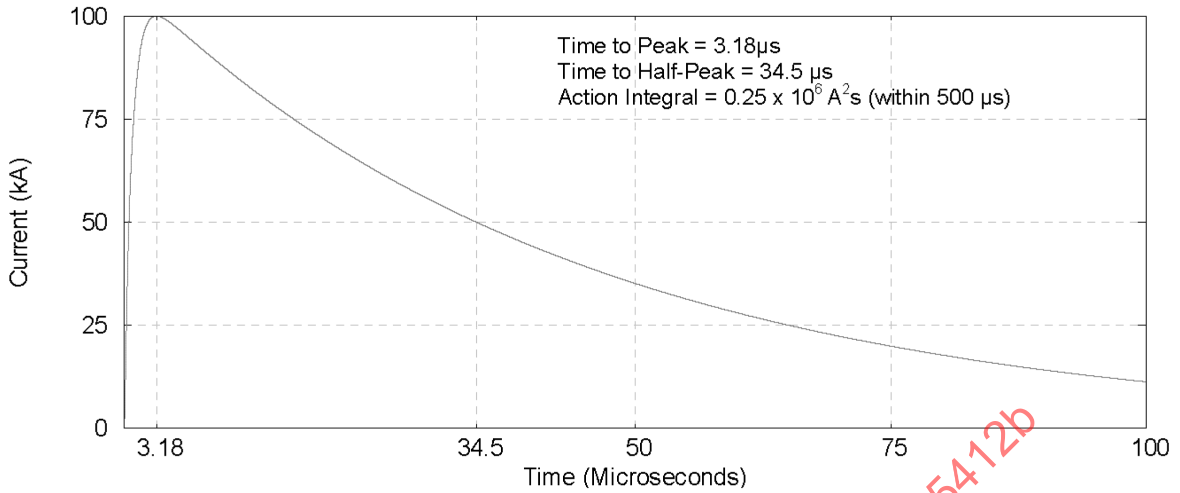
An expanded view of the waveform front end, up to 5 µs, is shown in Figure 20B.

The frequency content (amplitude only) of current Component D is plotted in Figure 20C. The frequency content is defined mathematically by the expression given below.

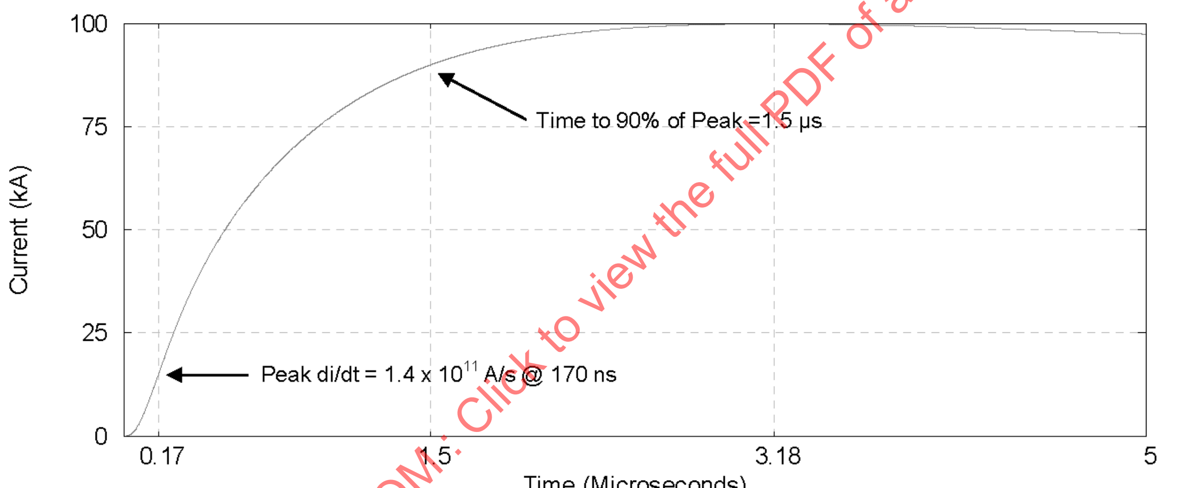
$$I(\omega) = I_0\left(\frac{1}{\alpha + j\omega} - \frac{1}{\beta + j\omega}\right) - 2I_0\left(\frac{1}{(\alpha+\gamma) + j\omega} - \frac{1}{(\beta+\gamma) + j\omega}\right) + I_0\left(\frac{1}{(\alpha+2\gamma) + j\omega} - \frac{1}{(\beta+2\gamma) + j\omega}\right) \quad \text{(Eq. 9)}$$

For direct effects testing, Component D can be simulated by either oscillatory or unidirectional waveforms (Figures 21A and 21B) with a total time duration to 1% peak value of 500 µs. The amplitude shall be 100 kA (±10%), the rise time shall not exceed 25 µs (time between 10% and 90% of the amplitude). The action integral is 0.25 x 10^6 A^2s (±20%).

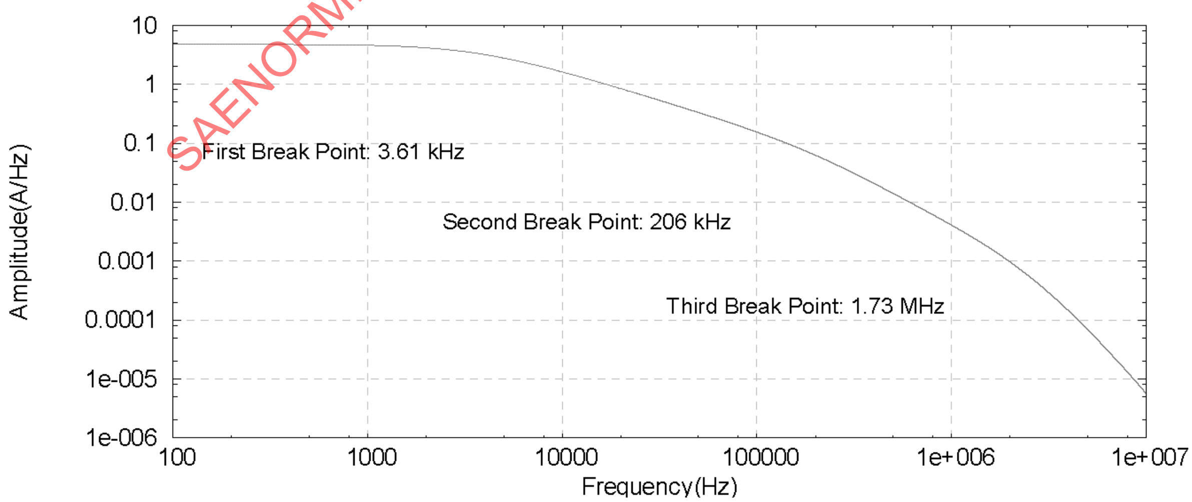
For indirect effects pulse tests on aircraft, Component D can be simulated by a unipolar waveform with characteristics of those presented in the Figures 20A, 20B, and 20C. The waveform should achieve 90% of the peak within 1.5 µs and reach the peak within 3.18 µs (±20%). The time to half value should be 34.5 µs (±30%).



(A) TIME DOMAIN WAVEFORM TO 100 MICROSECONDS



(B) TIME DOMAIN WAVEFORM TO 5 MICROSECONDS



(C) FREQUENCY CONTENT (AMPLITUDE SPECTRUM)

FIGURE 20 - CURRENT COMPONENT D FOR ANALYSIS AND INDIRECT EFFECTS TEST PURPOSES

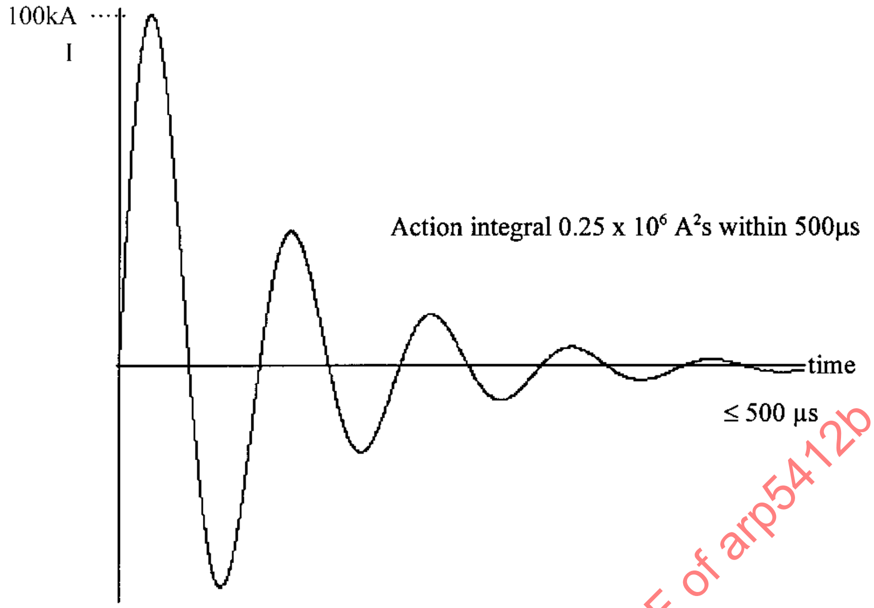


FIGURE 21A - DAMPED SINUSOIDAL CURRENT

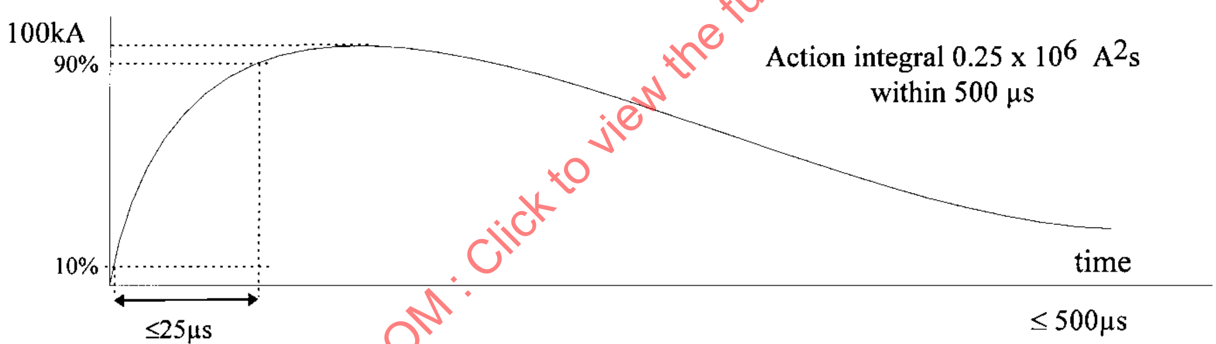


FIGURE 21B - UNIPOLAR PULSE

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 intracloud event as illustrated in Figure 4.

The Multiple Stroke Waveform Set was devised to simulate the effects of multiple induced transients as a result of the multiple strokes within a natural negative lightning flash. Cianos and Pierce (see Reference A1) reported the maximum number of return strokes per flash to be 26, although their distribution of the number of return strokes per flash shows a maximum of 14. Earlier SAE committee reports set the number of return strokes at 24 (SAE AE-4L Committee Report AE4L-87-3). During preparation of this ARP, review of available data on the number of return strokes per flash determined that a maximum number of return strokes per flash was 14. The 50% and 5% exceedance values associated with a negative lightning flash are shown in Table 1.

The 5% exceedance value for the number of strokes is 12. To define a slightly more severe environment, the value of 14 was selected. The average time between strokes for the Multiple Stroke environment was set at approximately 115 ms. This value lies between the 50% and 5% exceedance values in Table 1. The combination of 14 return strokes with an average time of 115 ms results in a flash duration of 1.5 s. The peak current values of 100 kA for the first return stroke and 50 kA for the 13 following subsequent strokes provide a more severe environment than the respective 5% exceedance values of Table 1.

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 at the derived levels.

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

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.

6.3.8 Multiple Burst Waveform Set

The Multiple Burst Waveform Set was derived from lightning current data observed on airborne research programs, particularly during the NASA F-106 airborne lightning research. Multiple pulses, generally containing higher derivatives than those observed in natural cloud-to-ground lightning, have been found to occur in groups at the initiation of a lightning strike to an aircraft and randomly throughout the lightning flash duration. 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. These multiple pulses are extremely random in peak current, rate-of-rise, and timing. The multiple pulses were observed during lightning flashes with low to moderate return stroke current. The lightning committee determined that the multiple pulse characteristics should be applied separately from the high-amplitude return stroke current waveforms, so the Multiple Burst Waveform Set was defined to incorporate the multiple pulses. The Multiple Burst Waveform Set is believed to represent a severe environment for an aircraft and its avionics systems. 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 Burst combination of induced transients applied to the system/equipment at the derived levels.

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 Multiple Burst Waveform Set is used only for indirect effects evaluation.

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 μs and the maximum is 1000 μs. The three 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.

Component H is presented in Figure 22A. Component H can be defined mathematically by the exponential expression shown below.

$$I(t) = I_0(e^{-\alpha t} - e^{-\beta t})(1 - e^{-\gamma t})^2 \quad \text{(Eq. 10)}$$

where:

I_0 = 10 572 A

α = 187 191 s^{-1}

β = 19 105 100 s^{-1}

γ = 153 306 000 s^{-1}

t = time (s)

An expanded view of the waveform front end, up to 500 ns, is shown in Figure 22B.

The frequency content (amplitude only) of current Component H is plotted in Figure 22C. The frequency content is defined mathematically by the expression given below.

$$I(\omega) = I_0\left(\frac{1}{\alpha + j\omega} - \frac{1}{\beta + j\omega}\right) - 2I_0\left(\frac{1}{(\alpha+\gamma) + j\omega} - \frac{1}{(\beta+\gamma) + j\omega}\right) + I_0\left(\frac{1}{(\alpha+2\gamma) + j\omega} - \frac{1}{(\beta+2\gamma) + j\omega}\right) \quad \text{(Eq. 11)}$$

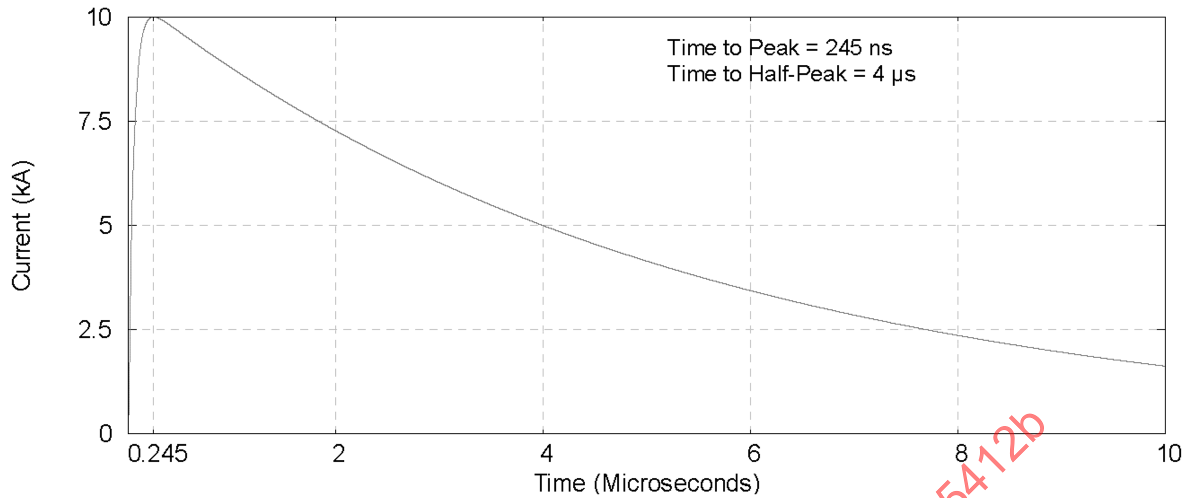
The primary purpose of the Multiple Burst Waveform Set is to evaluate system functional upset of systems that may be susceptible to effects of multiple induced transients. It is not necessary that this waveform set be applied at the defined levels in a test. Instead, the internal environment, due to 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.

6.3.9 Altitude Considerations

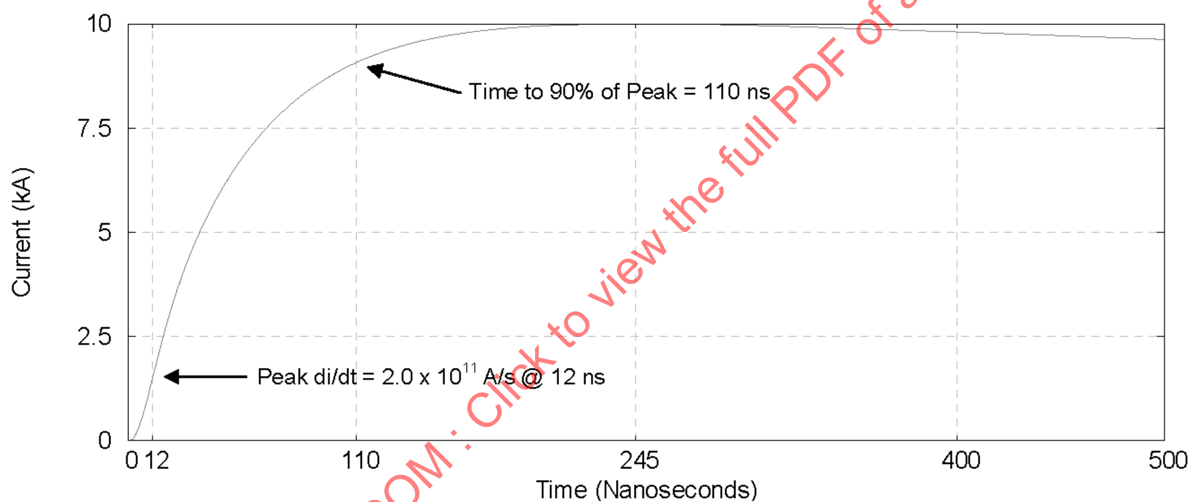
As noted in (5.2), it is accepted that lightning parameters seen by an aircraft at altitude are different than the parameters measured at the ground during cloud-to-ground events. In fact, numerous lightning channel models have been developed which show a decrease in peak amplitude seen at increasing altitude. It is also generally accepted that intracloud and aircraft triggered lightning also result in lower amplitude currents than those measured at the ground. This effect has been accounted for in defining the aircraft zone extension distance by the transition of Zone 1A to 1C to 2A in ARP5414 as a function of altitude, each zone with progressively lower peak amplitudes representing the current expected from a first return stroke.

For equipment located in unpressurized areas of aircraft, increasing altitude results in reduced voltages where breakdown of air could occur, when air represents all or part of the insulation for a given design. Given that current peak amplitudes are reduced at increasing altitudes and to avoid unnecessary conservatism in design for such cases, it is considered acceptable to evaluate air gap breakdowns based on the following criteria:

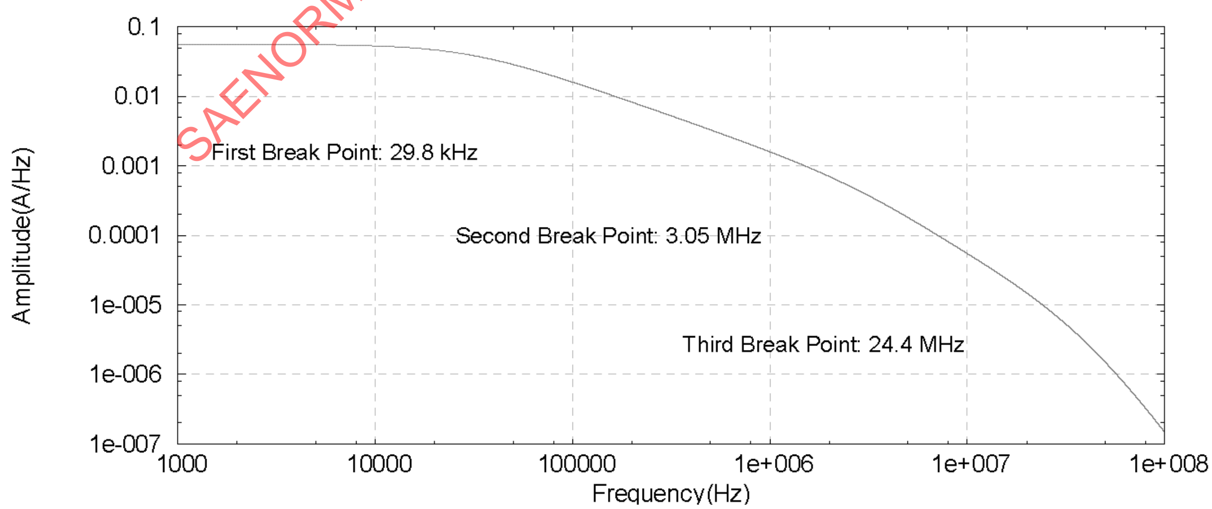
- 5000 ft and below - standard threat for each lightning zone
- 5000 to 10 000 ft - Zone 1A areas can assume a current Component A_H first stroke
- 10 000 to 20 000 ft - All Zone 1 and Zone 2 areas can assume a current Component D first stroke
- Above 20 000 ft - Utilize current Component D for the first stroke and design for the voltage breakdown conditions at 20 000 ft



(A) TIME DOMAIN WAVEFORM TO 10 MICROSECONDS



(B) TIME DOMAIN WAVEFORM TO 500 NANOSECONDS



(C) FREQUENCY CONTENT (AMPLITUDE SPECTRUM)

FIGURE 22 - CURRENT COMPONENT H FOR ANALYSIS AND INDIRECT EFFECTS TEST PURPOSES

The latter design criteria (above 20 000 ft) is selected for two reasons – first, well in excess of 90% of reported lightning strikes to commercial aircraft are below this altitude and second, higher altitude lightning will likely be intracloud events which are significantly lower in amplitude, so utilizing this design criteria is considered conservative relative to the environment yet sufficient to bound higher altitude but lower amplitude strikes. For example, a design based on current Component D at 20 000 ft adequately protects for the conditions of a 40 kA peak current (which would be a very severe intracloud event) at 40 000 ft.

There may be other potential design conditions that are altitude dependent, such as aircraft functions whose criticality may change in different phases of flight. For these cases, the standard lightning threat for each lightning zone should remain the basis for those designs.

6.4 Application of the Idealized Standard External Lightning 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 (Conducted)	-	A, B, C, D, H
3 (Direct attachment for new or novel designs- refer to 6.4.1)	A	A/5, B, C*
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 current Component A making current Component D 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 with magnitudes as defined by the MS Waveform Set.

The uses of these waveforms are described in detail in ARP5416, ED-14/DO-160, and ARP5415.

6.4.1 Direct Attachment Lightning Environment for Zone 3 External Surfaces

To define criteria associated with direct lightning attachment in Zone 3 areas for new or novel designs (to meet the intent of ARP5414/ED91), the following is the certification threat level:

One-fifth current Component A (i.e., A/5) followed by Component B, and Component C or C* depending upon the likelihood of lightning channel hang-on.

This results in a peak stroke current of 40 kA and an action integral of 8 x 10^4 A^2s. Use of Components B and C/C* is consistent with their usage for the other lightning zones where flash hang on is expected or not. This represents conservative criteria for aircraft lightning strike conditions where initial lightning attachment or sweeping is possible, but unlikely.

In cases where these Zone 3 surfaces are non-conductive an assessment of initial lightning attachment and/or a swept channel lightning attachment using Voltage Waveform A should be applied to determine whether lightning attachments to interior conductors are actually possible.

7. IDEALIZED STANDARD INDUCED TRANSIENT WAVEFORMS

7.1 General

The idealized transient waveforms presented in this section are intended for design and verification of adequate lightning indirect effects protection of systems and equipment by analysis and/or test.

The external lightning environment will interact with an aircraft to induce voltage and current transients in conductors such as wiring inside the aircraft.

The high amplitudes and rates of change of Components A, D, and H (6.3.1, 6.3.6, and 6.3.8, respectively) produce the major induced transients in aircraft wiring. Components B and C do not induce significant transients.

There are several mechanisms by which the external environment induces transients. These can be broadly divided into aperture coupling and resistive coupling. Most actual induced transients are complex waveforms that result from combinations of both coupling mechanisms. For design and verification purposes it has proved most practical to separate them and define a set of simpler waveforms described below. Typical Transient Control Level (TCLs) or Equipment Transient Design Level (ETDLs) associated with these waveforms are provided in 7.6.

7.2 Aperture Coupling

Magnetic fields penetrating through apertures will induce currents and voltages on wires and shields. Currents induced on wires and shields terminated to structures through low impedances at each end can have waveshapes that are proportional to the lightning current Component A. Waveform 1 in Figure 23 represents these current waveforms. Voltages induced on wires can have waveshapes that are proportional to the derivative of the lightning current Component A in wires forming a loop circuit. Waveform 2 in Figure 24 represents these voltage waveforms.

Electric and/or magnetic fields penetrating through apertures will drive or excite resonances on cables producing oscillatory currents and voltages which have the form of damped sinusoids (Waveform 3, Figure 25). The frequency will be dependent on the structure length, and/or cable length and terminating components. Frequencies often range between 1 and 10 MHz; other frequencies outside this range have also sometimes been observed.

7.3 Structural IR Voltage and Diffusion Coupling

These mechanisms will produce voltages in loops existing between cables and the structure, which are the sum of the structural IR voltage between the end points of the cables and the voltage resulting from fields diffused through the structural materials. These voltages may have the shape of the external environment Component A for resistive structures or slower double exponential like waveshapes for highly conductive structures. However, in this latter case, the voltage levels become very much smaller and of little consequence. Hence the most common transient voltage waveshape (Waveform 4, Figure 26) is that of the lightning stroke current waveshape Component A. This type of voltage waveform will also appear on conductors within shields due to the product of shield current and shield transfer impedance.

The current in low resistance cables connected to structures at both ends involves a redistribution mechanism resulting from the relatively high inductance of the cable with respect to the structure. Inside an airframe made of a good conductor, such as aluminum, the current will be long but of insignificant amplitude. For cables inside a more resistive structure of Carbon Fiber Composite (CFC) for instance, the current can have a lengthened double exponential like waveform and significant amplitude. The waveshape can vary widely and two forms are defined to cover varying circumstances, these having rise and fall times, respectively, of 40 and 120 μs (Waveform 5A, Figure 27) and 50 and 500 μs (Waveform 5B, Figure 28).

Current flowing on the conductive structure at a frequency characteristic of the length of the structure may induce voltages and currents, with the damped sinusoidal shape, directly into cable bundles (Waveform 3, Figure 25). The frequencies will normally be in the range 1 to 10 MHz.

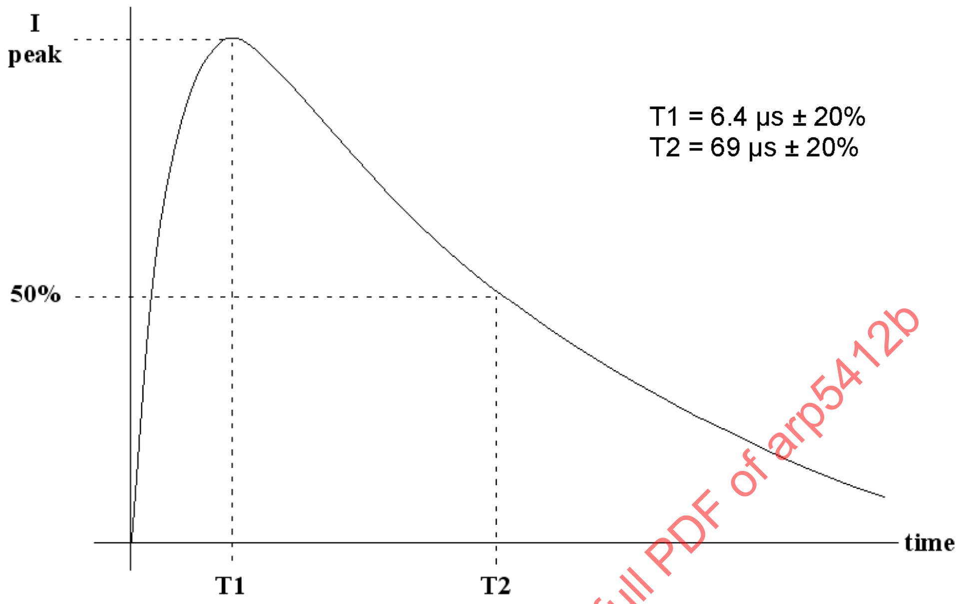


FIGURE 23 - EXPONENTIAL CURRENT WAVEFORM 1

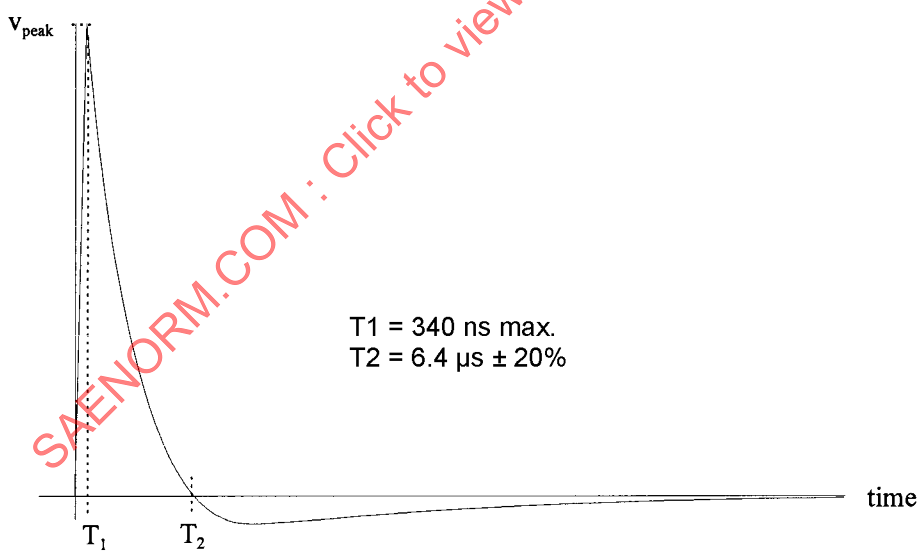


FIGURE 24 - EXPONENTIAL DERIVATIVE VOLTAGE WAVEFORM 2

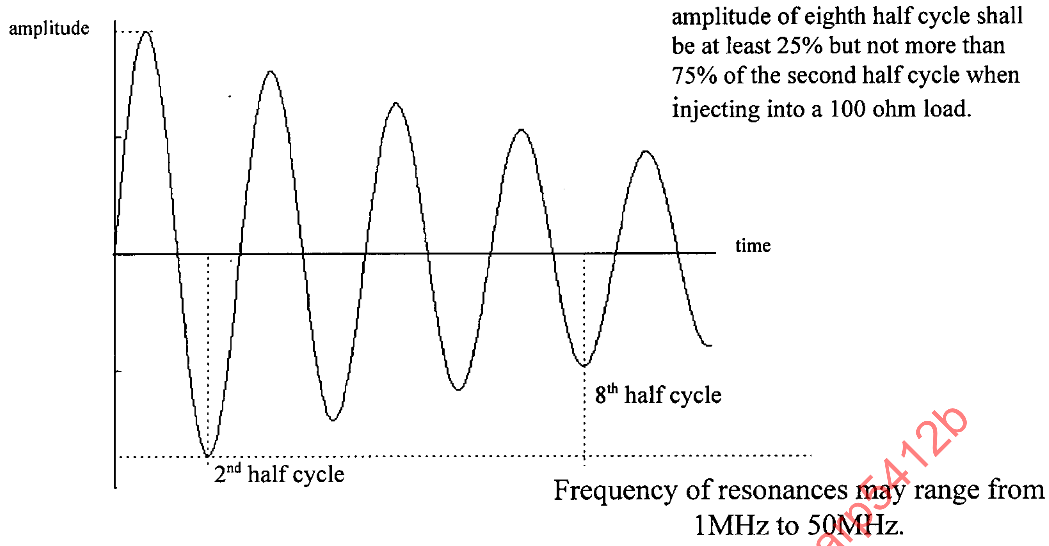


FIGURE 25 - DAMPED SINUSOIDAL VOLTAGE/CURRENT WAVEFORM 3

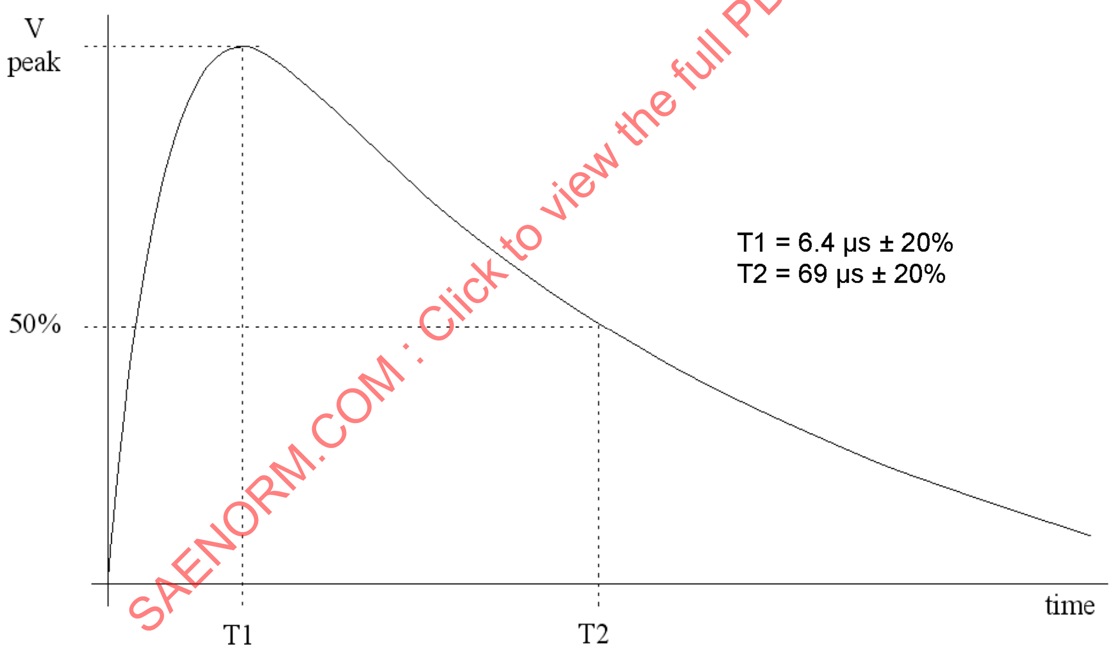


FIGURE 26 - EXPONENTIAL VOLTAGE WAVEFORM 4

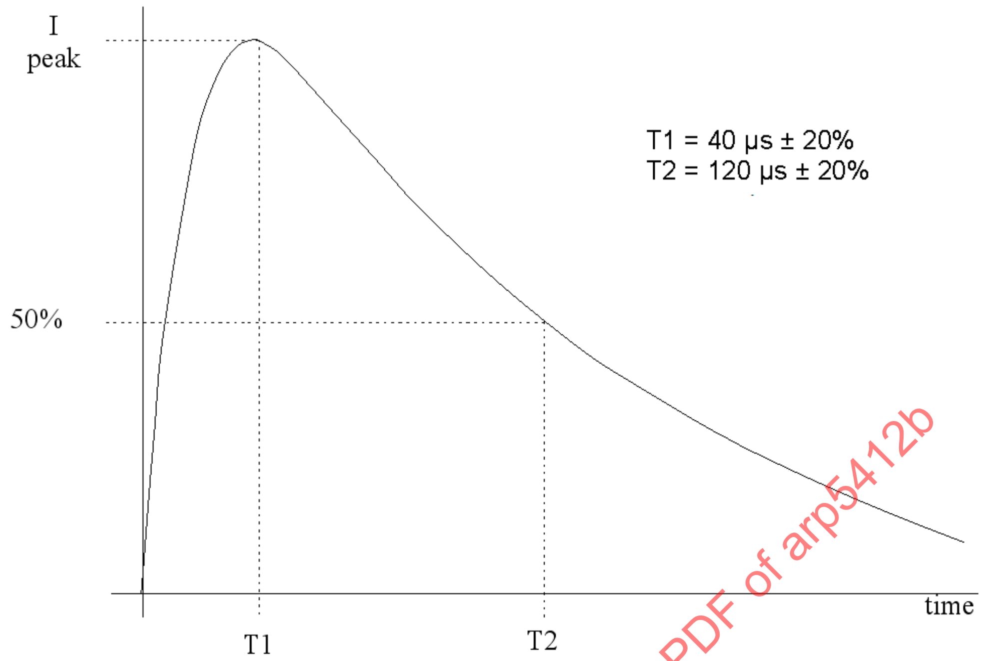


FIGURE 27 - EXPONENTIAL CURRENT WAVEFORM 5A

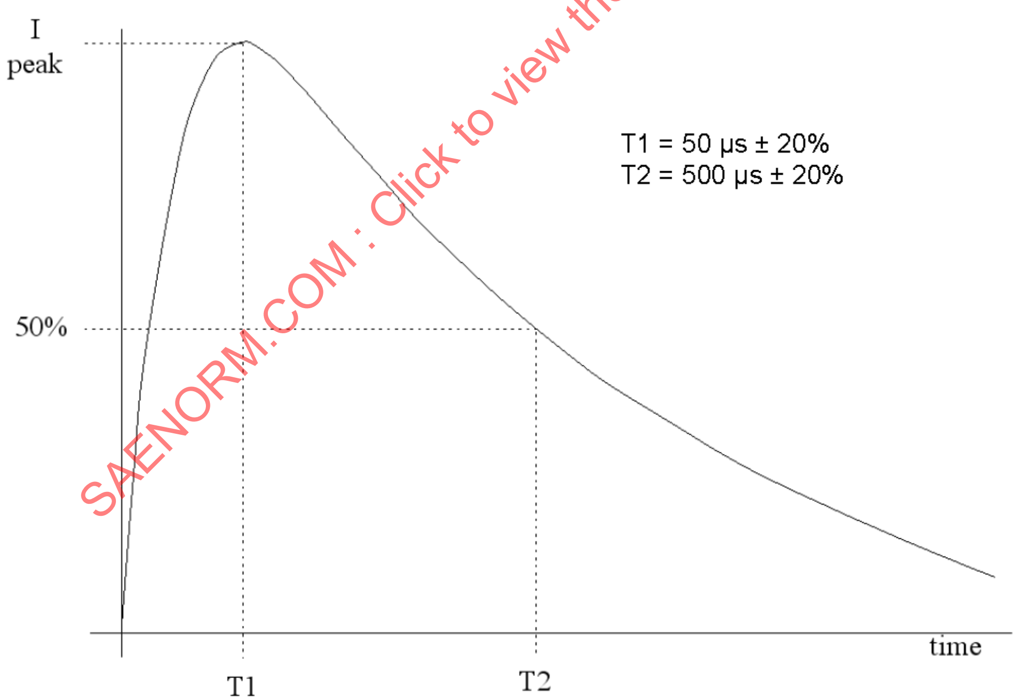


FIGURE 28 - EXPONENTIAL CURRENT WAVEFORM 5B

7.4 Multiple Stroke

The Multiple Stroke transients include a first transient which corresponds to the first negative return stroke (Component D) followed by 13 transients which correspond to subsequent negative return strokes.

All of the transient waveform responses arising from the mechanisms described in (7.2) and (7.3) above may occur in the Multiple Stroke mode. However, not all of the transient waveforms will occur in particular system installations and it is therefore not necessary to conduct Multiple Stroke tests with all of the transient waveforms. Guidance for selection of applicable transient waveforms can be found in ARP5416, ED-14/DO-160, AC20-136, and ARP5415. The responses to D and D/2 can be represented as a fraction of the response to Component A for the various waveforms as shown in Table 4. Typical transient amplitudes are provided in (7.6), Tables 5 and 6.

TABLE 4 - RESPONSE TO D AND D/2 AS A FRACTION IN RESPONSE TO A

Transient Responses	Waveform 1	Waveform 2	Waveform 3	Waveform 4	Waveform 5
Response to D	1/2	1	1	1/2	2/5
Response to D/2	1/4	1/2	1/2	1/4	1/5

7.5 Multiple Burst

Transient responses arising from Component H of the Multiple Burst Waveform Set will also occur in the Multiple Burst sequence. The predominant waveform responses are voltage Waveform 3_H in a frequency range between 1 and 10 MHz or a current waveform (Waveform 6_H) (see Figure 29) which has the same shape as the external environment Component H. In this latter case, for test purposes, the Component H rise time can be effectively produced with a current Waveform 3_H at a frequency of 5 MHz or higher. Equipment and system test levels for voltage Waveform 3_H typically have an amplitude of 60% of the Waveform 3 voltage response to Component A. Current Waveform 3_H typically has an amplitude of 1/20th of the Waveform 3 current response to Component A. Equipment and systems test levels for Waveform 6_H would typically have a maximum level of 1/20th of the Component A Waveform 1 response.

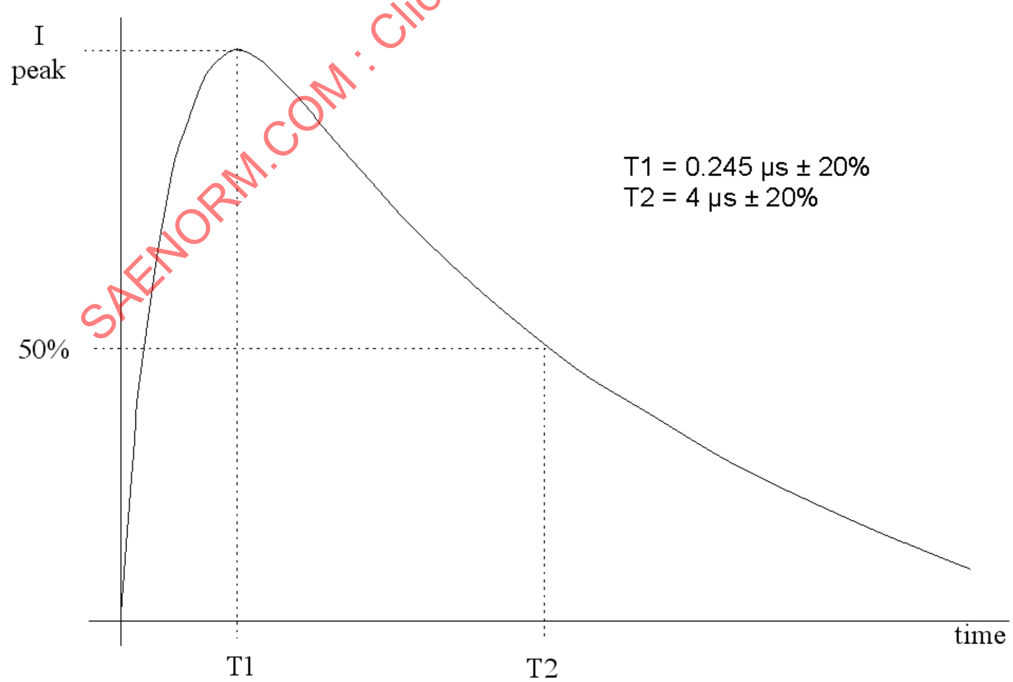


FIGURE 29 - EXPONENTIAL CURRENT WAVEFORM 6_H

7.6 Typical Transient Amplitudes

The amplitudes of induced voltages in individual conductors and cable bundles encountered in a wide variety of aircraft installations have ranged from less than 50 to 3200 V. The amplitudes of typical induced currents have ranged from less than 20 to 1600 A in individual conductors and from less than 20 to 5000 A in typical cable bundles.

This broad range has been subdivided into five narrower ranges that correspond roughly to aircraft electromagnetic regions that have been or can be achieved through design measures. Since the various transient waveforms arise from different coupling mechanisms, it follows that regions in an airframe designed to meet a particular level for one waveform will not necessarily meet the same level for the other transient waveforms.

Descriptions of 5 voltage and current amplitude levels and the aircraft areas with which they can be associated are provided in ED-14/DO-160. These levels are shown in Table 5 for individual conductors and Table 6 for cable bundle single and Multiple Stroke amplitudes, and Table 7 for cable Multiple Burst amplitudes.

TABLE 5 - INDIVIDUAL CONDUCTOR TCL, ETDL OR TEST LEVELS DUE TO CURRENT COMPONENT A

Level	Waveform 3 V/I	Waveform 4 V/I	Waveform 5 V/I
1	100/4	50/10	50/50
2	250/10	125/25	125/125
3	600/24	300/60	300/300
4	1500/60	750/150	750/750
5	3200/128	1600/320	1600/1600

TABLE 6 - CABLE BUNDLE TCL, ETDL OR TEST LEVELS DUE TO CURRENT COMPONENT A

Level	Waveform 1 V/I	Waveform 2 V/I	Waveform 3 V/I	Waveform 4 V/I	Waveform 5 V/I
1	50/100	50/100	100/20	50/100	50/150
2	125/250	125/250	250/50	125/250	125/400
3	300/600	300/600	600/120	300/600	300/1000
4	750/1500	750/1500	1500/300	750/1500	750/2000
5	1600/3200	1600/3200	3200/640	1600/3200	1600/5000

TABLE 7 - CABLE BUNDLE TCL, ETDL OR MB TEST LEVELS DUE TO CURRENT COMPONENT H

Level	Waveform 3_H V/I	Waveform 6_H I
1	60/1	5
2	150/2.5	12.5
3	360/6	30
4	900/15	75
5	1920/32	160

8. SUMMARY OF WAVEFORMS/WAVEFORM SETS

A summary of the idealized standard external lightning current component waveform information for analysis purposes is provided in tables in this section. The idealized current components refer to Component A, Component A_H, Component B, Component C, Component D, Component D/2, and Component H. The exponential mathematical expression for all components, except Component C, is provided below.

$$I(t) = I_0(e^{-\alpha t} - e^{-\beta t})(1 - e^{-\gamma t})^2 \quad \text{(Eq. 12)}$$

The parameter values associated with this mathematical expression, for each of the current components, are provided in Table 8. The idealized lightning current component waveform norm values are provided in Table 9.

TABLE 8 - IDEALIZED LIGHTNING CURRENT COMPONENT MATHEMATICAL EXPRESSION PARAMETER VALUES

Parameter	Lightning Current Component						
	A	A_H	B	C	D	D/2[(1)]	H[(2)]
I_0 (A)	218 810	164 903	11 300	400	109 405	54 703	10 572
α (s^{-1})	11 354	16 605	700	N/A	22 708	22 708	187 191
Β (s^{-1})	647 265	858 888	2000	N/A	1 294 530	1 294 530	19 105 100
γ (s^{-1})	5 423 540	7 253 750	22 000	N/A	10 847 100	10 847 100	153 306 000

(1) Applicable for the Multiple Stroke
(2) Applicable for the Multiple Burst

TABLE 9 - IDEALIZED LIGHTNING CURRENT COMPONENT WAVEFORM NORM VALUES

Waveform Norm	Lightning Current Component						
	A	A_H	B	C	D	D/2[(1)]	H[(2)]
Peak Current (kA)	200	150	4.2	400	100	50	10
Peak Rate-of-Rise (kA/µs)	140	140	0.0147	N/A	140	70	200
Time to Peak (µs)	6.4	4.72	813	N/A	3.18	3.18	0.245
Time to Half-Value (µs)	69	49	2340	N/A	34.5	34.5	4
Charge (C)	18.9	10.1	10.5	200	4.8	2.4	0.056
Action Integral (A^2s)	2.0×10^6	0.8×10^6	2.85×10^4	N/A	2.5×10^5	0.625×10^5	2.90×10^2

(1) Applicable for the Multiple Stroke
(2) Applicable for the Multiple Burst

A summary of the characteristics of the idealized standard induced transient waveforms and the parameters necessary for their mathematical descriptions is presented in Table 10.

TABLE 10 - SUMMARY OF INDUCED TRANSIENT WAVEFORM PARAMETERS

Parameter	Waveform							
	1	2	3	4	5A	5B	3_H	6_H
	V/I	V/I	V/I	V/I	V/I	V/I	V/I	I
Pin Tests								
Level 1 V_0/I_0	N/A	N/A	100/4	50/10	50/50	50/50	N/A	N/A
Level 2 V_0/I_0	N/A	N/A	250/10	125/25	125/125	125/125	N/A	N/A
Level 3 V_0/I_0	N/A	N/A	600/24	300/60	300/300	300/300	N/A	N/A
Level 4 V_0/I_0	N/A	N/A	1500/60	750/150	750/750	750/750	N/A	N/A
Level 5 V_0/I_0	N/A	N/A	3200/128	1600/320	1600/1600	1600/1600	N/A	N/A
Cable Tests								
Level 1 V_0/I_0	50/100	50/100	100/20	50/100	50/150	50/150	60/1	5
Level 2 V_0/I_0	125/250	125/250	250/50	125/250	125/400	125/400	150/2.5	12.5
Level 3 V_0/I_0	300/600	300/600	600/120	300/600	300/1000	300/1000	360/6	30
Level 4 V_0/I_0	750/1500	750/1500	1500/300	750/1500	750/2000	750/2000	900/15	75
Level 5 V_0/I_0	1600/3200	1600/3200	3200/640	1600/3200	1600/5000	1600/5000	1920/32	160
Mathematical Expression Parameters (Note 1)								
Waveform Type	Quad Exponential (Note 2)	Derivative (Note 3)	Damped sinusoid (Note 4)	Quad Exponential (Note 2)	Quad Exponential (Note 2)	Quad Exponential (Note 2)	Damped sinusoid (Note 4)	Quad Exponential (Note 2)
Peak Multiplier K_0 (Note 5)	1.094	1.00	1.059	1.094	2.334	1.104	1.059	1.057
α (s^{-1})	11 354	11 354	0.231*f (Note 6)	11 354	12 632	1585	0.231*f (Note 6)	187 191
β (s^{-1})	647 265	647 265	N/A	647 265	43 605	80 022	N/A	19 105 100
γ (s^{-1})	5 423 540	5 423 540	N/A	5 423 540	454 813	648 845	N/A	153 306 000
ω (radians/sec)	N/A	N/A	$2\pi f$ (Note 6)	N/A	N/A	N/A	$2\pi f$ (Note 6)	N/A

NOTE 1: These mathematical expressions are for analysis purposes and are not meant to be verified for the test waveforms
NOTE 2: Quad exponential expression: $F(t) = F_0(e^{-\alpha t} - e^{-\beta t})(1-e^{-\gamma t})^2$
NOTE 3: Derivative of the quad exponential: $F(t) = F_0(\beta e^{-\beta t} - \alpha e^{-\alpha t})(1-e^{-\gamma t})^2 + F_0(e^{-\alpha t} - e^{-\beta t})(1-e^{-\gamma t})(2\gamma e^{-\gamma t})$
NOTE 4: Damped sinusoid of the form: $F(t) = F_0 \sin(\omega t)\, e^{-\alpha t}$
NOTE 5: $F_0=K_0V_0$ or $F_0=K_0I_0$
NOTE 6: f is the frequency in hertz