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User's Manual for AC-20-53A Protection of Airplane Fuel Systems Against Fuel Vapor Ignition Due to Lightning

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SAE-AE4L Lightning Subcommittee

October 1984

User's Manual

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15. Supplementary Notes

This manual is designed to supplement the information found in AC 20-53A and is to be used for information purposes only, and is not to be used as a regulatory document.

16. Abstract

This manual provides users of AC 20-53A, "Protection of Aircraft Fuel Systems Against Fuel Vapor Ignition Due to Lightning," with information on the subject of fuel system lightning protection and methods of compliance of aircraft design with the Federal Aviation Regulations 23.954 and 25.954.

The manual is the result of a 3-year effort requested by the FAA Technical Center of the SAE-AE4L committee which is comprised of experts in the field of lightning research and protection of aircraft and systems from the adverse effects associated with atmospheric electricity. The committee is comprised of experts from the National Aeronautics and Space Administration, Department of Defense, Federal Aviation Administration, industry, and independent testing laboratories.

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EXECUTIVE SUMMARY

This manual is designed to supplement the information found in AC 20-53A and provides additional guidance information.

The user's manual culminates the results of a 3-year effort of the SAE-AE4L subcommittee. This committee is comprised of experts in the field of lightning research and protection of aircraft structures and avionic systems from the adverse effects associated with atmospheric electrical hazards (lightning and static electricity). The committee is comprised of experts from the National Aeronautics and Space Administration, Department of Defense, Federal Aviation Administration, industry, and independent testing laboratories. The document will provide the users of AC 20-53A, "Protection of Aircraft Fuel Systems Against Fuel Vapor Ignition Due to Lightning," with information on fuel systems lightning protection and methods of compliance of aircraft design for Federal Aviation Regulations 23.954 and 25.954.

Elements of aircraft fuel systems are typically spread throughout the aircraft and occupy much of its volume. These elements consist of the fuel tanks, transfer plumbing, electronic controls, instrumentation, and fuel venting systems. Extreme care must be exercised in the design, installation, and maintenance of all of these elements to ensure that adequate protection is obtained.

The protection of the fuel systems from lightning and static electricity should be accomplished by at least one of the following approaches:

- Eliminating sources of ignition.

- Ensuring that tank allowable pressure levels are not exceeded if ignition does occur, and/or ensure that the atmosphere within the fuel tank will not support combustion.

The user's manual delineates the following areas of concern:

Aircraft Fuel System Lightning Interaction which includes the combustion process, sources of ignition and minimum ignition currents.

Approaches to Compliance includes a detailed step-by-step procedure to ensure that the acceptable means of compliance in AC 20-53A are met. This section also includes a detailed description of aircraft-lightning strike zones, lightning environment, and recommended simulated test procedures.

Protection Considerations include procedures and methodologies to determine both hot-spot and melt-through thresholds for various materials, bonding and grounding procedures, and electrical considerations for skin joints and interfaces in tubing.

Although this manual is as complete as possible, only experienced engineers and scientists should undertake the task of implementation of lightning protection of aircraft against atmospheric electrical hazards (lightning and static electricity).

1.0 PURPOSE.

This report is intended to provide users of Advisory Circular (AC) 20-53A with information on the subject of fuel system lightning protection and methods of compliance of aircraft design with Federal Aviation Regulations (FAR) 23.954 and 25.954.

2.0 BACKGROUND.

Airplanes flying in and around thunderstorms are often subjected to direct lightning strikes as well as to nearby lightning strikes which may produce corona and streamer formation on the aircraft.

Elements of the fuel system are typically spread throughout much of an aircraft and occupy much of its volume. They include the fuel tanks themselves, as well as associated vent and transfer plumbing, and electronic controls and instrumentation. Careful attention must be paid to all of these elements if adequate protection is to be obtained.

For the purposes of design and of lightning protection, it is assumed that the properties of the fuel used by civil aircraft, both piston and turbine engine powered, are such that a combustible mixture is present in the fuel tank at all times. Therefore, the combination of the flammable fuel/air ratio and an ignition source at the time of a lightning strike could produce a hazardous condition for the vehicle. To prevent this condition from occurring, a review and elimination of the possible ignition sources within the fuel tank/fuel system should be conducted.

Assuming that flammable mixtures may exist in any part of the fuel system, some items and areas susceptible to fuel ignition include, but are not limited to, vent outlets, metal fittings inside fuel tanks, fuel filler caps and access doors, drain plugs, tank skins, fuel transfer lines inside and outside of the tanks, electrical bonding jumpers between components in a tank, mechanical fasteners inside of tanks, and electrical and electronic fuel system components and wiring.

Protection of fuel systems from lightning should be accomplished by at least one of the following approaches:

a. Eliminating sources of ignition.

b. Ensuring that tank allowable pressure levels are not exceeded if ignition does occur, and/or ensuring that the atmosphere within the tank will not support combustion.

The preferred approach most often followed is to prevent any direct or indirect source of ignition of the fuel by lightning. Accomplishment of this approach is quite challenging because thousands of amperes of current are conducted through the airframe when the aircraft is struck by lightning, and that most conducting elements, including structures and fuel tank plumbing, in and on the aircraft are involved to some degree in this conduction process. A spark of $\sim 2 \times 10^{-4}$ joule may be all the energy that need be released inside a fuel tank to initiate a fire or explosion.

The excellent lightning safety record of civil aircraft is attributed to the high electrical conductivity of the aluminum alloys used in aircraft fuel tank construction and to designs which suppress interior sparking at very severe lightning current levels.

However, composite materials, such as the carbon fiber composites (CFC), when associated with fuel systems present difficulties in providing equivalent protection because of their lower electrical conductivity. Also, new construction techniques such as adhesive bonding may have limited conductivity for lightning current flow. Also, indirect effects, such as lightning-induced voltages in fuel system electrical wiring and other conducting elements may be more severe within composite structures than within conventional aluminum airframes.

3.0 SCOPE.

Information contained in this document includes discussions of aircraft fuel system lightning interactions, approaches that have been used to show compliance, the impact of materials and construction, lightning test waveforms and techniques, and methods for analysis of lightning-induced transients.

The document incorporates improvements in the state-of-the-art with respect to lightning effects and verification methods that have taken place since the previous version of AC 20-53 were published. It was written to provide assistance to users of AC 20-53A. The lightning environment defined in this document is in agreement with SAE Committee AE4L report, "Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware," dated June 20, 1978 (AE4L-78-1) (Appendix A).

4.0 AIRCRAFT FUEL SYSTEM LIGHTNING INTERACTION.

Lightning can be a hazard to aircraft fuel systems if they are not properly designed. The protection of a properly designed system may be negated if it is not correctly constructed and maintained.

The effects of lightning on aircraft can range from severe obvious damage (such as tearing and bending of aircraft skins resulting from high magnetic forces, shock waves and blast effects caused by the high current, and melting of metal skins caused by the lower level longer duration currents of some lightning strikes) to seemingly insignificant sparking at fasteners or joints. However, if the sparking occurs in a fuel vapor space, ignition of the fuel vapor may result, with unacceptable explosion damage.

All or a portion of the lightning current may be conducted through fuel tanks or fuel system components. It is important to determine the current flow paths through the aircraft for the many possible lightning attach points so that current entry into the fuel system can be safely accounted for by appropriate protective measures.

Metals, low electrical conductivity composite materials (e.g., carbon fiber reinforced composites) and electrical insulating materials (e.g., fiber glass or aramid reinforced composites) all behave differently when subjected to lightning. Yet each of these materials may be used in similar aircraft applications (e.g., wing skins or fuel tanks). The metals offer a high degree of electrical shielding and some magnetic shielding, whereas the electrical insulating materials (dielectrics) offer almost no electrical or magnetic shielding. As a result of the latter properties, lightning does not have to come in direct contact with fuel systems to constitute a hazard. Lightning can induce arcing, sparking, or corona in fuel areas which may result in fuel ignition. This arcing, sparking, or corona can occur in areas widely separated from any lightning strike attachment point due to conduction of extremely high currents (associated with lightning) through the aircraft structure or fuel system components.

The damage to totally nonconducting materials such as the fiber glass and aramid (e.g., Kevlar™) reinforced composites can be considerably more severe, as the discharge can more easily penetrate into the interior and cause direct fuel vapor ignition.

Lightning strikes can result in sparking and arcing within fuel systems unless they are to be spark free. Flammable vapors can be ignited in metal and semiconducting fuel tanks by arcing and in dielectric fuel tanks by magnetic and electric field penetration which can cause sparking, arcing, streamer, or corona discharge. Assuming that flammable mixtures may exist in any part of the fuel system, some items and areas susceptible to fuel ignition include but are not limited to the following: Vent outlets, metal fittings inside fuel tanks, fuel filler caps and access doors, drain plugs, tank skins, fuel transfer lines inside and outside of tanks, electrical bonding jumpers between components in a tank, mechanical fasteners inside of tanks, and electrical and electronic fuel system components and wiring.

4.1 COMBUSTION PROCESSES.

4.1.1 Fuel Flammability.

The flammability of the vapor space in a fuel tank varies according to the concentration of evaporated fuel in the available air. Reducing the fuel-to-air ratio may produce a vapor/air mixture too lean to burn. Conversely, a vapor space mixture may exist that could be too rich to be flammable. In between these extremes, there is a range of mixtures that will burn when provided an ignition source. A typical equilibrium flammability envelope is shown in figure 1.

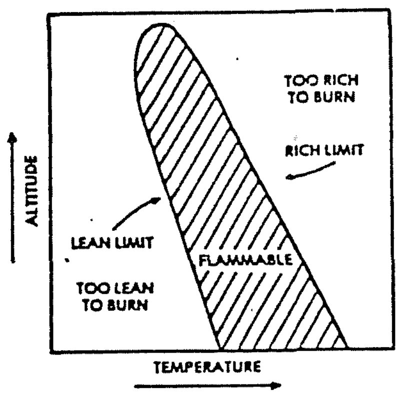


FIGURE 1. TYPICAL FLAMMABILITY ENVELOPE OF AN AIRCRAFT FUEL

However, there are a wide variety of factors that effect the resultant fuel/air ratio in the vapor space of a fuel tank. The variety of temperatures, pressures and motions that exist in flight can result in a wide variation of mixtures in the vapor space.

Another example is the variation in initial oxygen content in the fuel, again providing an additional factor in the resultant tank fuel/air ratio. Aeration of a fuel or spray from a pump or pressurized fuel line can also result in extending the lower temperature flammability below the lean limit.

Considering the possible variables, the properties of the fuel used by civil aircraft, both piston and turbine engine powered, are such that a combustible mixture is generally assumed to be present in the fuel tank at any time.

Therefore, the combination of the flammable fuel/air ratio and an ignition source at the time of a lightning strike, could produce a hazardous condition for the vehicle. To prevent this condition from occuring, a review and elimination of the possible ignition sources within the fuel tank/fuel system should be conducted.

4.1.2 Sources of Ignition.

Laboratory studies involving simulated lightning strikes to fuel tanks or portions of an airframe containing fuel tanks have demonstrated several possible ignition mechanisms. Examples of ignition sources are as follows:

1. Direct contact of the lightning arc with the fuel-air mixture, as at a vent outlet.

2. Hot spot formation or complete melt-through of a metallic tank skin by lightning arc attachment.

3. Heated filaments and point contacts resulting from lightning current passage through structures or components.

4. Electrical sparking between two pieces of metal conducting lightning current, such as poorly bonded sections of a fuel line or vent tube.

5. Sparking from an access door or filler cap (which has been struck) to its adapter assembly.

6. Sparking among elements of a capacitive-type fuel quantity probe, caused by lightning-induced voltages in the electrical wires leading to such a probe.

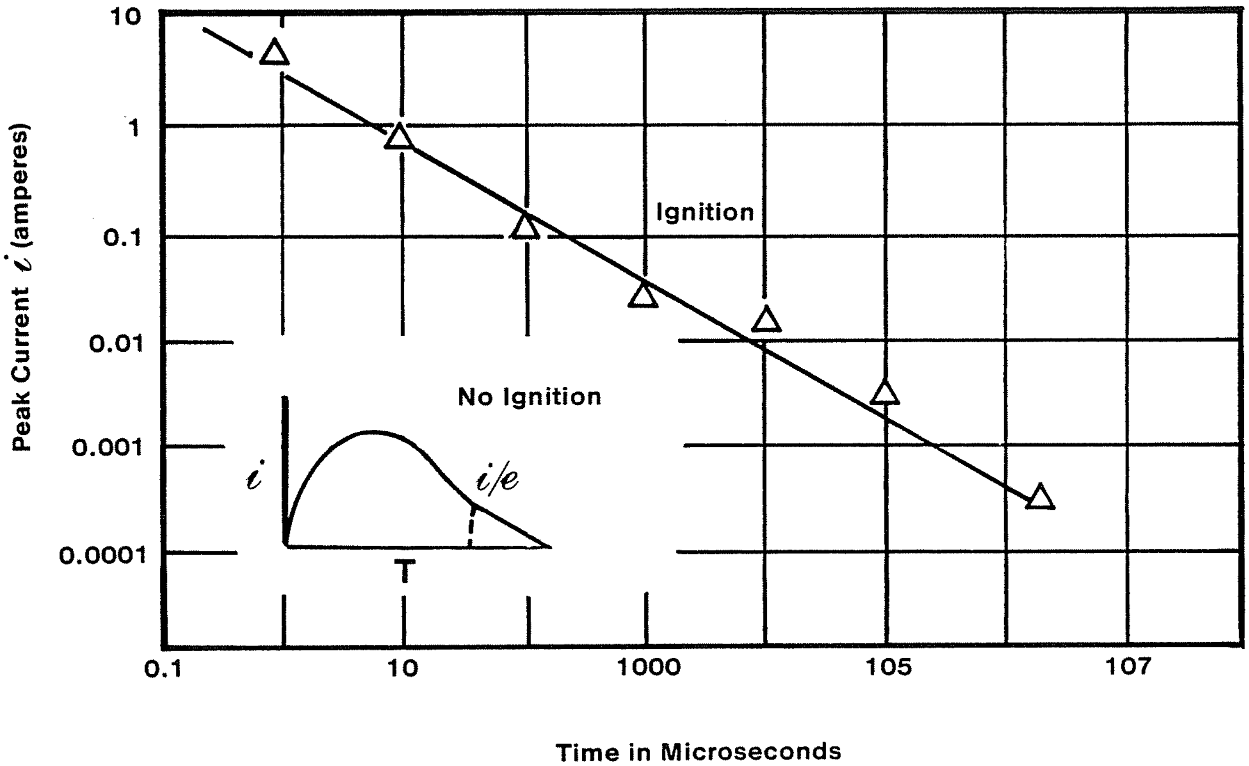
7. Sparking between two conducting elements at different potentials as might exist between an aluminum vent line and adjacent carbon fiber composite structure.

8. Corona and streamering from fuel tank components within nonmetallic tanks.

4.1.2.1 Minimum Ignition Current.

In the process of fuel vapor ignition by electric sparks, a very concentrated source of energy is released in the unburned fuel vapor over a very short period of time. The vapor in the immediate vicinity of the discharge is raised well above the ignition temperature and an extremely steep temperature gradient is formed. As the flame zone grows, the temperature gradient becomes flatter as the excess heat deposited by the spark is added to the heat of combustion being conducted out through the surface of the combustion wave. If sufficient heat and energy have been deposited by the spark, the minimum combustion flame size will have been reached and ignition will occur.

The concept of a minimum ignition energy is of importance in lightning protection as it suggests that the critical factor is in the total heat input into the spark. Sparking in fuel tanks is often determined experimentally in terms of the current and time magnitudes. An example of a curve of minimum ignition peak current as a function of time is shown in figure 2.

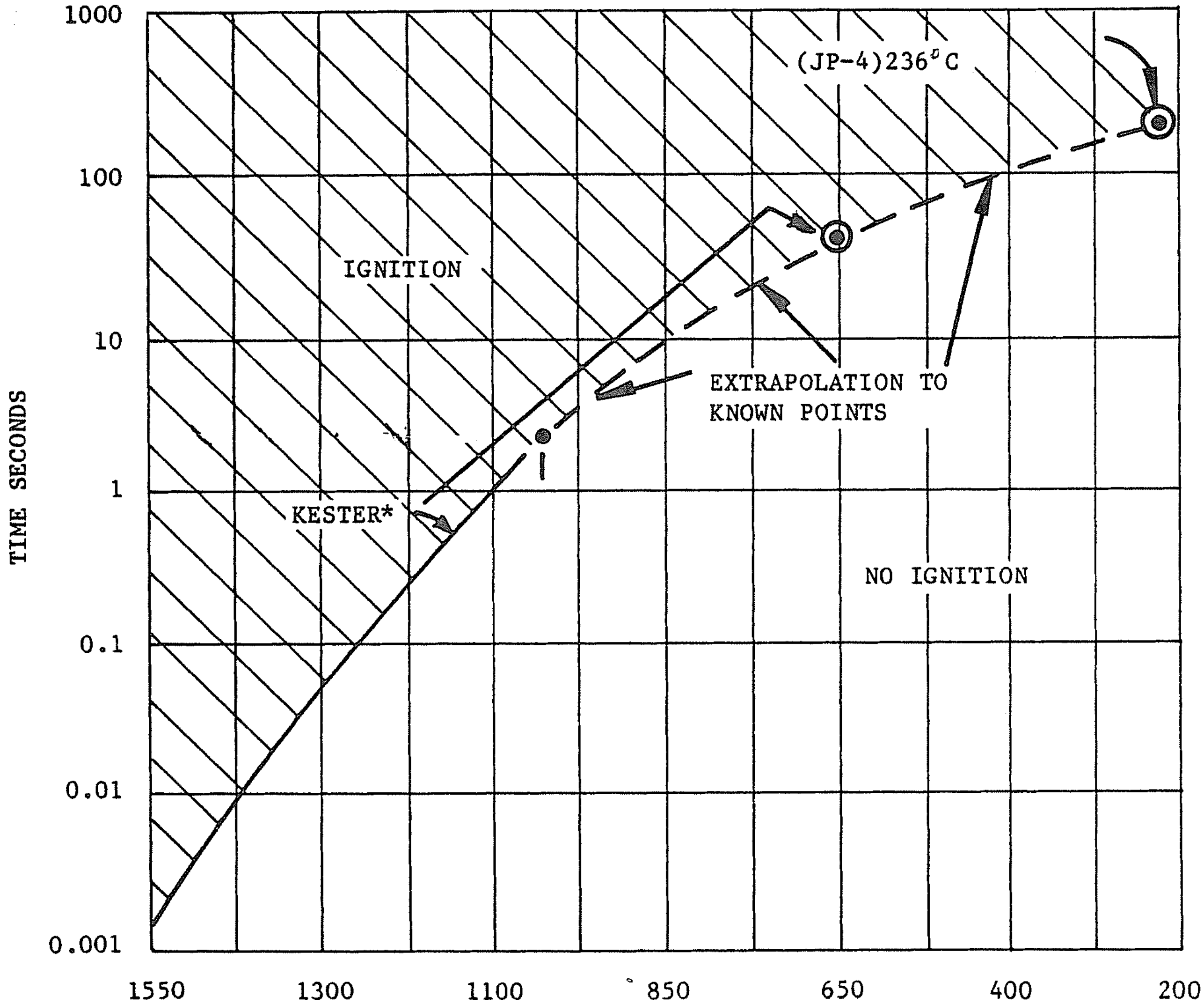


Note: This data is provided as an example only and should not be relied upon for proof of design.

FIGURE 2. PLOT OF MINIMUM CURRENT VS TIME DURATION OF EXPONENTIALLY DECAYING PULSE FROM CAPACITOR SOURCE FOR IGNITION OF STOICHIOMETRIC MIXTURE OF AVIATION GASOLINE UNDER LABORATORY CONDITIONS

4.1.2.2 Ignition From Hot Spots.

Ignition can also occur as a result of contact of fuel vapor with hot spots formed by lightning strikes contacting metal or composite fuel tank surfaces, even if the surface is not punctured or melted completely through. In this case, if the inside surface of the tank skin becomes sufficiently hot and remains so for a sufficient period of time (and is in contact with a flammable vapor), "hot spot ignition" may occur. The time required to ignite a flammable fuel-air vapor in contact with a titanium metal surface at various temperatures is shown in figure 3. The data shown is for example only. Specific materials should be evaluated by test.



Temperature - degrees Celsius

(Data shown is for Titanium Surfaces)

Note: This data is provided as an example only and should not be relied upon for proof of design.

FIGURE 3. TIME-TEMPERATURE FOR IGNITION OF HYDROCARBON FUEL VAPOR SURFACE

5.0 APPROACHES TO COMPLIANCE.

In general, the steps below outline an effective method to show compliance.

1. Determine the Lightning Strike Zones - Determine the aircraft surfaces, or zones, where lightning strike attachment is likely to occur, and the portions of the airframe through which currents may flow between these attachment points. The strike zone locations are defined in paragraph 5.1.2. Guidance for location of the strike zones on a particular aircraft is provided in paragraph 5.1.3.

2. Establish the Lightning Environment - Establish the component(s) of the total lightning flash to be expected in each lightning strike zone. They are the voltages and currents that should be considered, and are defined in paragraph 5.2.

3. Identify Possible Ignition Sources - Identify systems and/or components that might be ignition sources to fuel vapor. Ignition hazards may include structures as well as fuel system mechanical and electrical/electronic components. Refer to paragraph 4.1.2.

Note: In order to provide concurrence on the certification compliance, the above three sequential steps should be accomplished, reviewed with the appropriate FAA personnel, and agreement reached prior to test initiation to prevent certification delays.

4. Establish Protection Criteria - Establish lightning protection pass-fail criteria for those items to be evaluated.

5. Verify Protection Adequacy - Verify the adequacy of the protection design by similarity with previously proven installation designs, simulated lightning tests or acceptable analysis. Developmental test data may be used for certification when properly documented and coordinated with the certification agency.

Note: Except for standard design/installation items which have a history of acceptability, any new material, design, or unique installation should follow the additional guidelines provided herein to insure certification compliance can be accomplished.

As appropriate:

a. Generate a certification plan which describes the analytical procedures and/or the qualification procedures to be utilized to demonstrate protection effectiveness. This plan should describe the production or test article(s) to be utilized, test drawing(s) as required, the method of installation that simulates the production installation, the lightning zone(s) applicable, the lightning simulation method(s), test voltage or current waveforms to be used, spark detection methods, and appropriate schedules and location(s) of proposed test(s).

b. Obtain FAA concurrence that the certification plan is adequate.

c. Obtain FAA detail part conformity of the test articles and installation conformity of applicable portions of the test setup.

d. Schedule FAA witnessing of the test.

e. Submit a final test report describing all results and obtain FAA approval thereof.

The following paragraphs provide information on each of the above steps.

5.1 DETERMINATION OF LIGHTNING STRIKE ZONES AND THE LIGHTNING ENVIRONMENT.

It is well known that lightning strikes do not reach all surfaces of an aircraft, and that the intensity and duration of currents entering those surfaces that may be struck vary according to location. To account for these variations, lightning strike zones have been defined. Once the locations of these zones have been established for a particular aircraft, the lightning environment and need for protection can be determined. The mechanism of lightning strike attachment zone definitions, and some guidelines for location of lightning strike zones on a particular aircraft are given in the following paragraphs.

5.1.1 Aircraft Lightning Strike Phenomena.

5.1.1.1 Natural Lightning Strike Electrical Characteristics.

Lightning flashes are of two fundamentally different forms, cloud-to-ground flashes and inter/intracloud flashes. Because of the difficulty of intercepting and measuring inter/intracloud flashes, the great bulk of the statistical data on the characteristics of lightning refer to cloud-to-ground flashes. Aerospace vehicles intercept both inter/intracloud and cloud-to-ground lightning flashes. There is evidence that the inter/intracloud flashes, figure 4, lack the high peak currents of cloud-to-ground flashes. Therefore, the use of cloud-to-ground lightning strike characteristics as design criteria for lightning protection seems conservative.

There can be discharges from either a positive or a negative charge center in the cloud. A negative discharge is characterized by a return stroke, possibly one or more restrikes, and continuing currents as shown in figure 5(A). A positive discharge which occurs a smaller percentage of the time is shown in figure 5(B). It is characterized by lower peak current, higher average current, and longer duration in a single stroke and must be recognized because of its greater energy content. This possibility is accounted for in the action integral associated with current component A, and the charge associated with component B. The following discussion describes the more frequent negative flashes.

5.1.1.1.1 Prestrike Phase.

The lightning flash is typically originated by a step leader which develops from the cloud toward the ground or toward another charge center. As a lightning step leader approaches an extremity of the vehicle, high electrical fields are produced at the surface of the vehicle. These electric fields give rise to other electrical streamers which propagate away from the vehicle until one of them contacts the approaching lightning step leader as shown in figure 4. Propagation of the step leader will continue from other vehicle extremities until one of the branches of the step leader reaches the ground or another charge center. The average velocity of propagation of the step leader is about one meter per microsecond (μs) and the average charge in the whole step leader channel is about 5 coulombs.

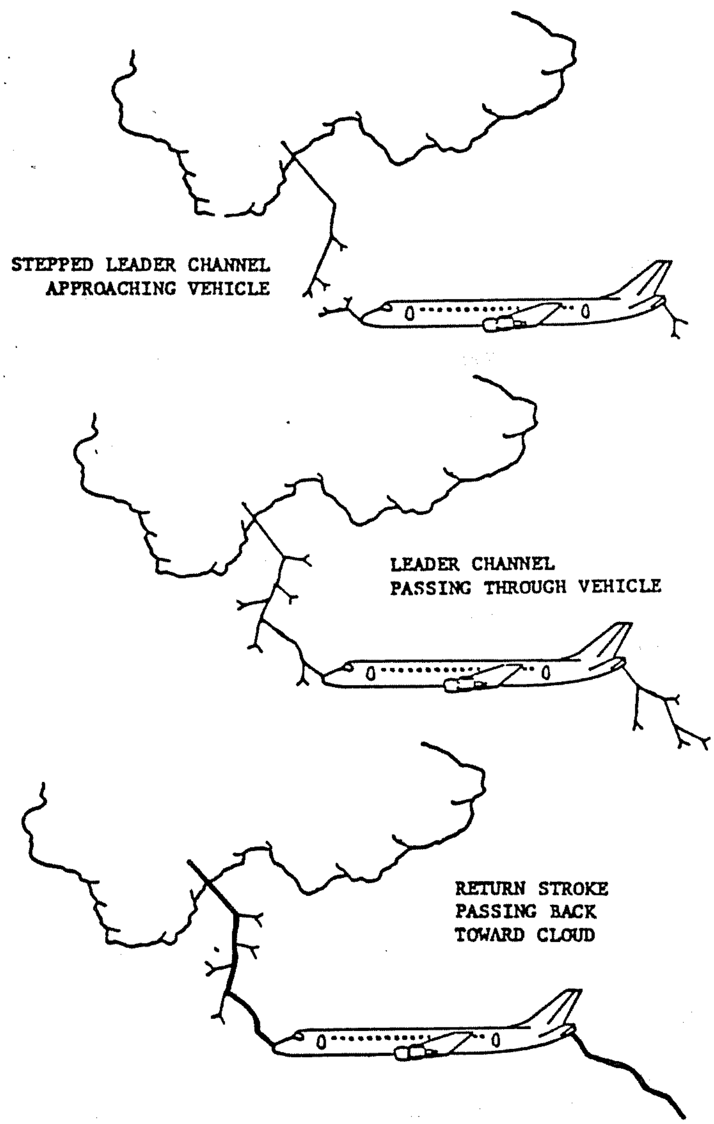
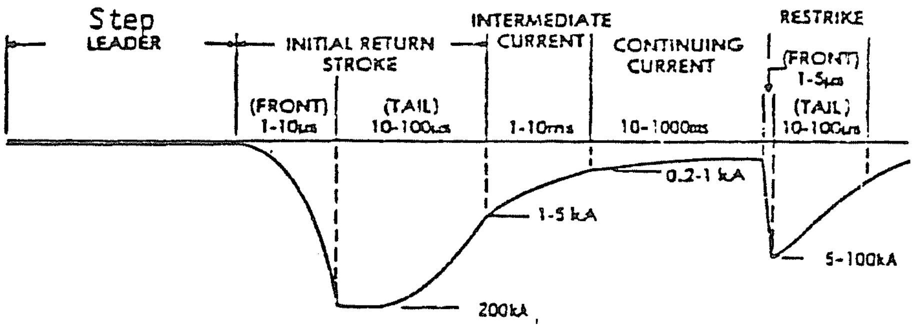
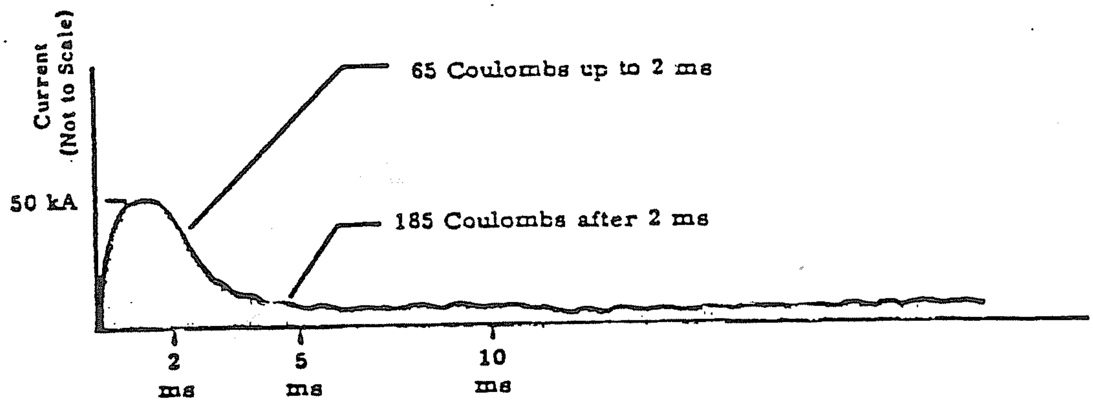


Figure 4 - Lightning Flash Striking an Aircraft.



(A) Generalized waveshape of current in negative cloud-to-ground lightning.



(Time not to scale)

(B) Moderate positive lightning flash current waveform.

FIGURE 5. LIGHTNING FLASH CURRENT WAVEFORMS

5.1.1.1.2 High Peak Current Phase.

The high peak current associated with lightning occurs after the step leader reaches the ground and forms what is called the initial return stroke of the lightning flash. This return stroke occurs when the charge in the leader channel is suddenly able to flow into the low impedance ground and neutralize the charge attracted into the region prior to the step leader's contact with the ground. Typically, the high peak current phase is called the return stroke and is in the range of 10 to 30kA (amperes x 10^3). Higher currents are possible though less probable. A peak current of 200kA represents a very severe stroke, one that is exceeded only about 0.5 percent of the time for flashes to earth. While 200kA may be considered a practical maximum value of lightning current, in rare cases, higher peak currents can occur. The current in the return stroke has a fast rate of change, typically about 10 to 20kA per μs and exceeding, in rare cases, 100kA per microsecond. Typically the current decays to half its peak amplitude in 20 to 40 μs. No correlation has been shown to exist between peak current and rate of rise.

5.1.1.1.3 Continuing Current.

The total electrical charge transported by the lightning return stroke is relatively small (a few coulombs). The majority of the charge is transported immediately after the first return stroke. This is an intermediate phase where a few thousand amperes flow for only a few milliseconds, followed by a continuing current phase (200 to 400 amperes) which varies from 100 milliseconds to a second. The maximum charges transfered in the intermediate and continued phases are 10 and 200 coulombs, respectively.

5.1.1.1.4 Restrike Phase.

In a typical lightning flash there will be several high current strokes following the first return stroke. These occur at intervals of several tens of milliseconds as different charge pockets in the cloud are tapped and their charge fed into the lightning channel. Typically, the peak amplitude of the restrikes is about one half that of the initial high current peak, but the rate of current rise is often greater than that of the first return stroke. The continuing current often link these various successive return strokes, or restrikes.

5.1.1.1.5 Initial Attachment.

The lightning flash is a high current discharge between charge centers in clouds, or between cloud and ground. Initially, the lightning flash produces at least two attachment points on the aircraft, between which the lightning channel current will flow. Typically, these initial attachment points are at the extremities of the aircraft. These include the nose, wing tips, elevator and stabilizer tips, protruding antennas, and engine nacelles or propeller blades.

5.1.1.1.6 Swept Stroke Phenomenon.

The lightning channel is somewhat stationary in air while it is transferring electrical charge. When an aircraft is involved, the aircraft becomes part of the channel. However, due to the speed of the aircraft and the period of time that the lightning channel exists, the aircraft can move relative to the lightning channel. When a forward extremity, such as a nose or wing mounted engine pod is an initial attachment point, the movement of the aircraft through the lightning channel causes the channel to sweep back over the surface, as illustrated in figure 6, producing subsequent attachment points. This is known as the swept stroke phenomenon. As the sweeping action occurs, the characteristics of the surface can cause the lightning channel to reattach and dwell at various surface locations for different periods of time, resulting in a series of discrete attachment points along the sweeping path.

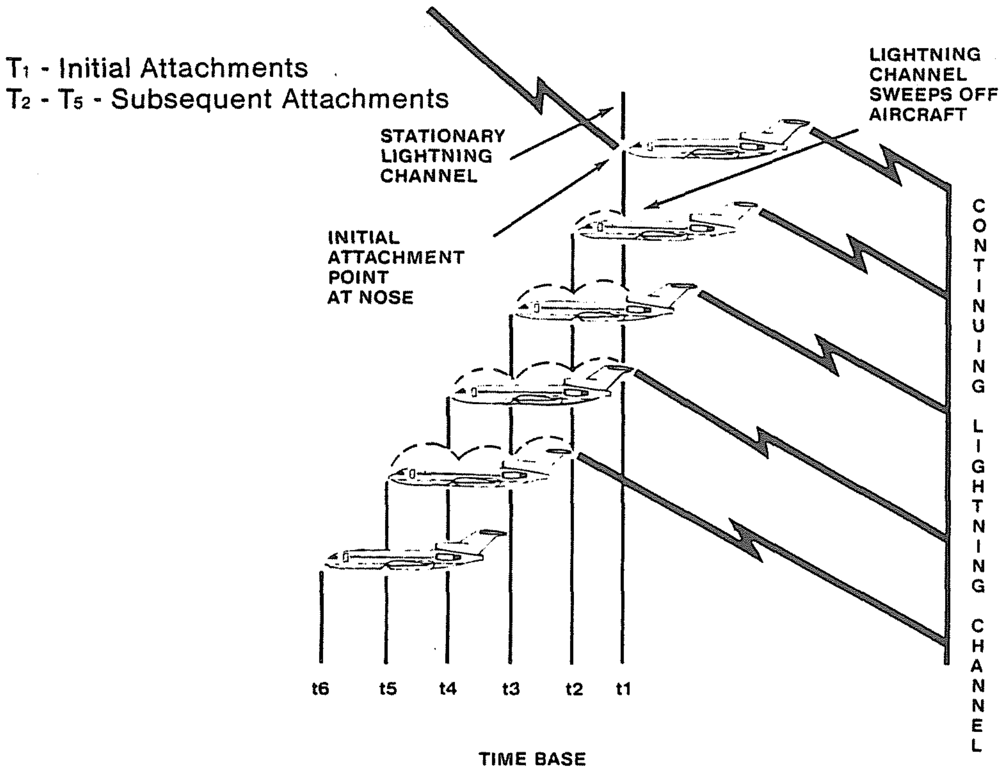


FIGURE 6. SWEPT-STROKE PHENOMENON (LIGHTNING CHANNEL POSITION SHOWN RELATIVE TO AIRCRAFT)

The amount of damage produced at any point on the aircraft by a swept-stroke depends upon the type of material, the dwell time at that point, and the lightning currents which flow during the attachment. High peak current restrikes with intermediate current components and continuing currents may be experienced. Restrikes typically produce reattachment of the arc at a new point.

When the lightning channel has been swept back to one of the trailing edges, it may remain attached at the point for the remaining duration of the lightning event. An initial attachment point at a trailing edge, of course, would not be subjected to any swept stroke action, and therefore, this attachment point will be subjected to all components of the lightning event.

The significance of the swept stroke phenomena is that portions of the vehicle that would not be targets for the initial attachment points of a lightning flash may also be involved in the lightning strike process as the lightning channel is swept backwards, although the channel may not remain attached at any single point for very long. On the other hand, strikes that reach trailing edges must be expected to remain attached there (hang-on) for the balance of their natural duration.

5.1.2 Lightning Strike Zone Definitions.

To account for each of the possibilities described in the foregoing paragraphs, the following zones have been defined.

Zone 1

Zone 1A: Initial attachment point with low possibility of lightning arc channel hang-on.

Zone 1B: Initial attachment point with high possibility of lightning arc channel hang-on.

Zone 2

Zone 2A: A swept stroke zone with low possibility of lightning arc channel hang-on.

Zone 2B: A swept stroke zone with high possibility of lightning arc channel hang-on.

Zone 3

Zone 3: All of the vehicle areas other than those covered by zone 1 and 2 regions. In zone 3, there is a low possibility of any attachment of the direct lightning channel. Zone 3 areas may carry substantial amounts of electric current, but only by direct conduction between some pair of direct or swept stroke attachment points.

The zone definitions are in basic agreement with the definitions of earlier versions of advisory circular 20-53, except that the former zones 1 and 2 have been subdivided to account for low and high possibilities of the lightning arc channel hang-on (figures 7 and 8). The locations of these zones on any aircraft are dependent on the aircraft's geometry and operational factors, and often vary from one aircraft to another.

5.1.3 Location of Lightning Strike Zones.

With these definitions in mind, the locations of each zone on a particular aircraft may be determined as follows:

a. Extremities such as the nose, wing and empennage tips, tail cone, wing mounted nacelles and other significant projections should be considered as within a direct strike zone because they are probable initial leader attachment points. Those that are forward extremities or leading edges should be considered in zone 1A, and extremities that are trailing edges should be in zone 1B. Most of the time, the first return stroke will arrive shortly after the leader has attached to the aircraft, so zone 1A is limited to the immediate vicinity (18 inches or approximately 0.5 m) aft of the forward extremity. However, in rare cases the return stroke may arrive somewhat later, thereby exposing surfaces further aft to this environment. This possibility should be considered if the probability of a flight safety hazard due to a zone 1A strike to an unprotected surface is high. Where questions arise regarding the identification of initial attachment locations or where the airframe geometry is unlike conventional designs for which previous experience is available, scale model attachment point tests may be in order.

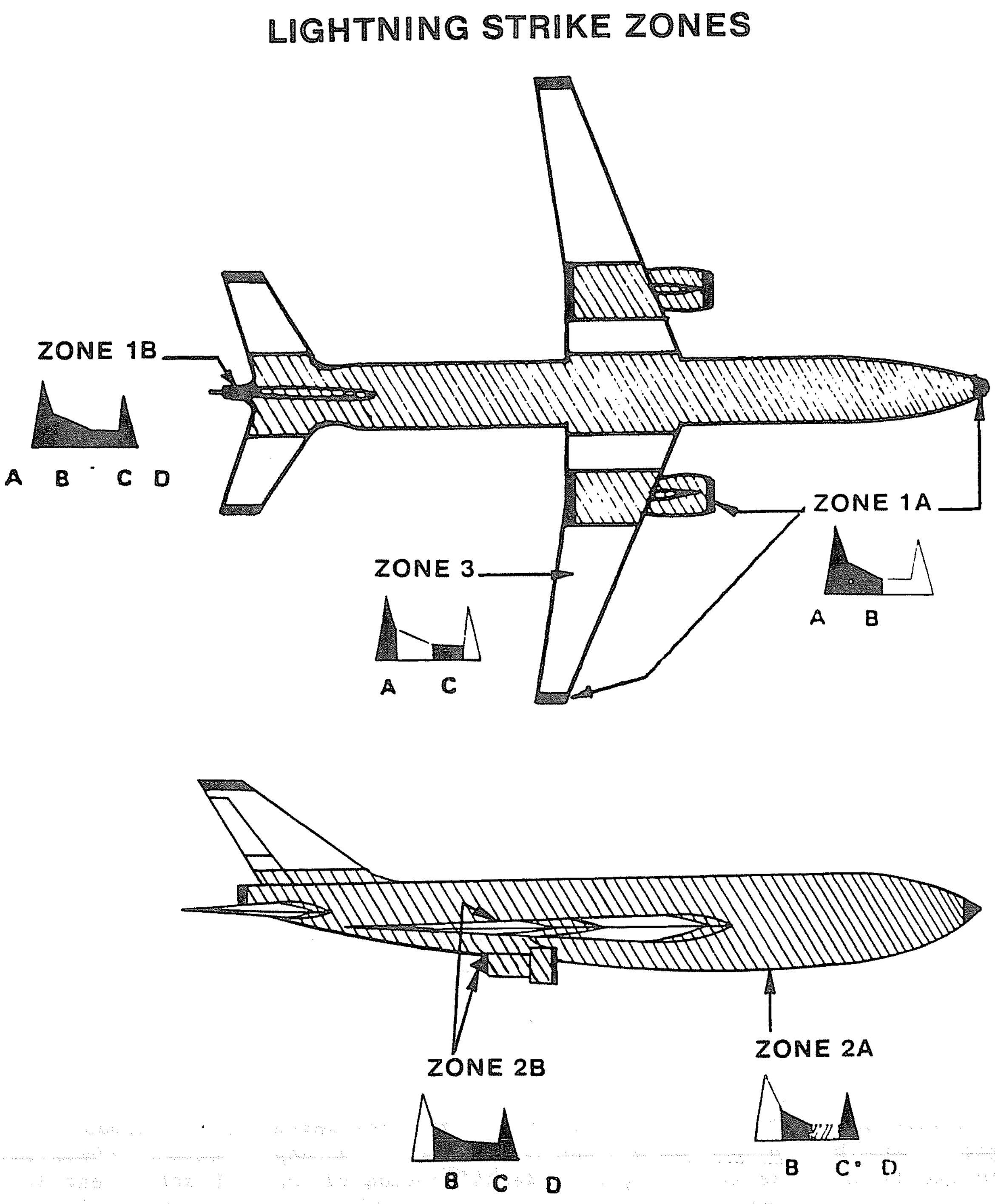


FIGURE 7. LIGHTNING STRIKE ZONES (TYPICAL)
(See Sections 5.1.2 and 5.1.3)

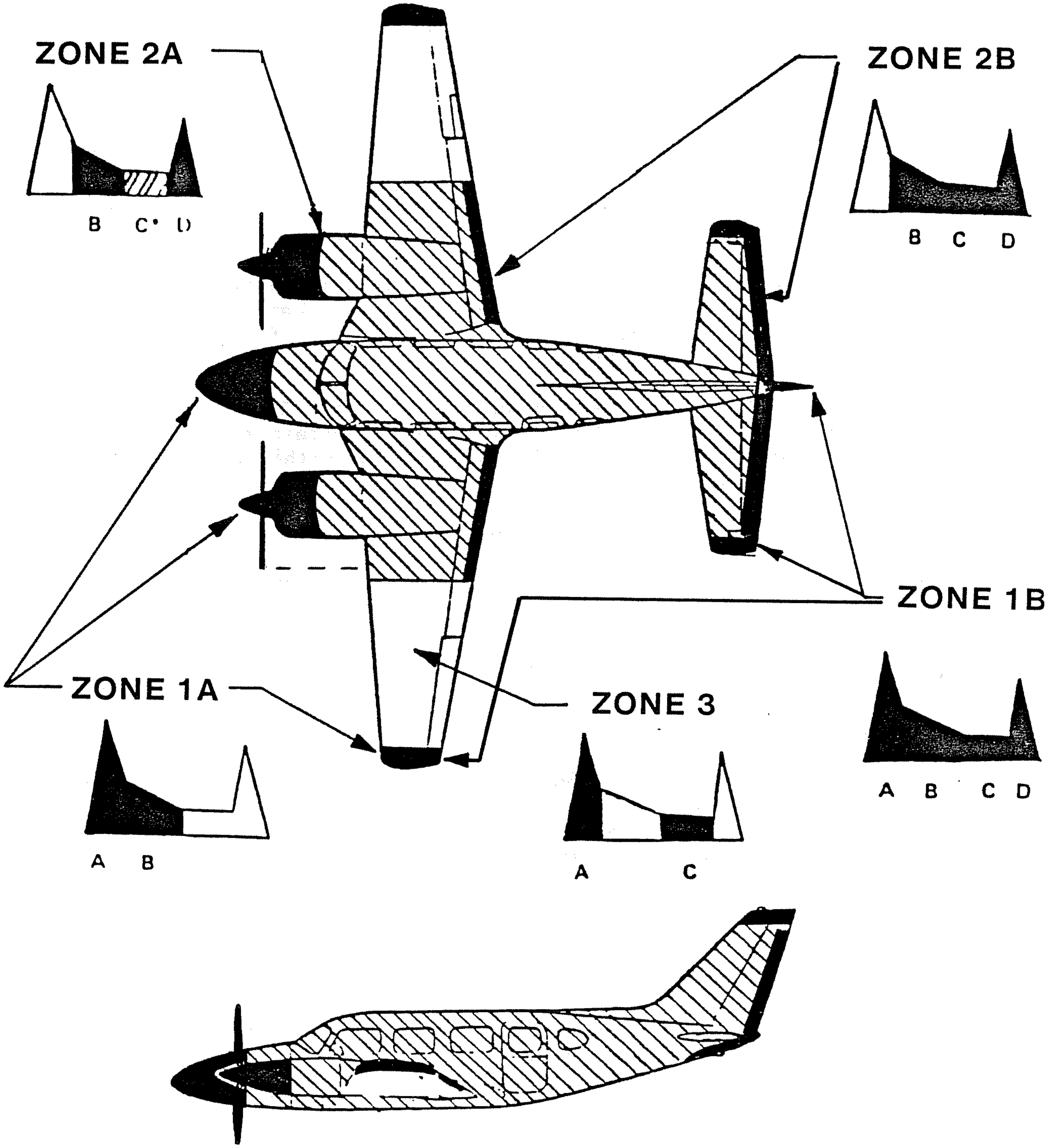


FIGURE 8. LIGHTNING STRIKE ZONES (TYPICAL)
(See Sections 5.1.2 and 5.1.3)

b. Surfaces directly aft of zone 1A should be considered as within zone 2A. Generally, zone 2A will extend the full length of the surface aft of zone 1A, such as the fuselage, nacelles, and portions of the wing surfaces.

c. Trailing edges of surfaces aft of zone 2A should be considered zone 2B, or zone 1B if initial attachment to them can occur. If the trailing edge of a surface is totally nonconductive, then zone 2B (or 1B) should be projected forward to the nearest conductive surface.

d. Surfaces approximately 18 in. (0.5 m) to either side of initial or swept attachment points established by steps (a) and (b) should also be considered as within the same zone, to account for small lateral movements of the sweeping channel and local scatter among attachment points. For example, the tip of a wing would normally be within zone 1A (except for its trailing edge, which would usually be in zone 1B). To account for lateral motion of the channel and scatter, the top and bottom surfaces of the wing, 18 in. (0.5 m) inboard of the tip, should also be considered as within the same zones.

e. Surfaces of the vehicle for which there is a low possibility of direct contact with the lightning arc channel that are not within any of the above zones, but which lie between them, should be considered as within zone 3. Zone 3 areas may carry substantial amounts of electrical energy.

5.2 ESTABLISHMENT OF THE LIGHTNING ENVIRONMENT.

For verification purposes, the natural lightning environment (which comprises a wide statistical range of current levels, duration, and number of strokes) is represented by current test components A through E, and voltage test components A, B, and D. When testing or analysis is required, the waveforms defined below should be used. Applications of waveforms and lightning zones are detailed in table 1.

a. Current Waveforms - Test

There are four current components (A, B, C, and D) that are applied to determine direct effects. Current waveform E is used to determine indirect effects. Components A, B, C, and D each simulate a different characteristic of the current in a natural lightning flash and are shown in figure 9. They are applied individually or as a composite of two or more components together in one test. The tests in which these waveforms are applied are presented in table 1.

(1) Component A - Initial High Peak Current - Component A has a peak amplitude of 200kA ($\pm$10 percent) and an action integral ($\int i^2 \, dt$) of $2 \times 10^6 A^2 s$ ($\pm$20 percent) with a total time duration not exceeding 500 μs. This component may be unidirectional or oscillatory. For analysis purposes, a double exponential current waveform should be used. This waveform, represents a return stroke of 200,000 amperes peak at a peak rate of rise of $1 \times 10^{11} A/s$. This waveform is defined mathematically by the double exponential expression shown in the following equation.

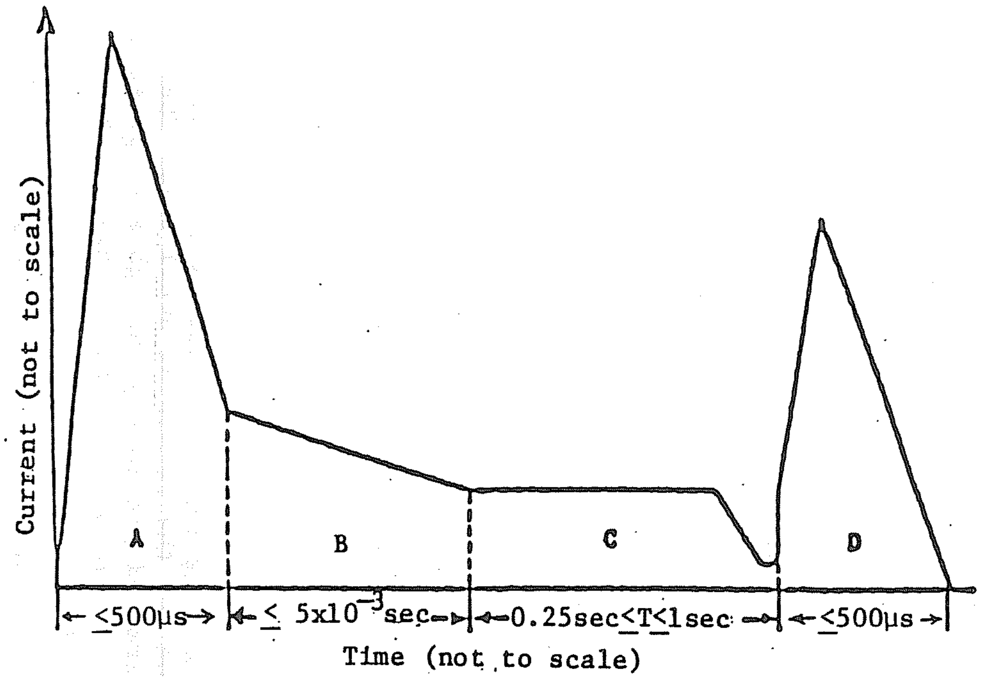
TABLE 1. APPLICATION OF WAVEFORMS FOR LIGHTNING TESTS

Test	Zone	Voltage A	Voltage B	Voltage D	Waveforms Current Components A	B	C	D	E
Full Size Hardware Attachment Point	1A,1B	X		X[1]					
Direct Effects Structural	1A				X	X			
	1B				X	X	X	X	
	2A					X[2]	X[2]	X	
	2B					X	X	X	
	3				X		X		
Direct Effects Combustible Vapor Ignition	1A				X	X			
	1B				X	X	X	X	
	2A					X[2]	X[2]	X	
	2B					X	X	X	
	3				X		X		
Direct Effects Corona and Streamers			X						
Indirect Effects Related to Spark Generation Within Fuel Vapor Areas									X[3]

NOTE 1: Voltage waveform "D" may be applied to identify lower probability strike points.

NOTE 2: Use an average current of 2kA ± 10 percent for a period equal to the dwell time up to a maximum of 5ms. If the dwell time is more than 5ms, apply an average current of 400A for the remaining dwell time. The dwell time shall have been determined previously through a swept stroke attachment test or by analysis. If such determination has not been made, the dwell time shall be taken to be 50ms.

NOTE 3: Indirect effects should also be measured with current components A,B, C, or D as appropriate.



COMPONENT A (Initial Stroke)
Peak Amplitude = 200kA ± 10%
Action Integral = 2 x $10^6 A^2$ s ± 20%
Time Duration = ≤ 500μs

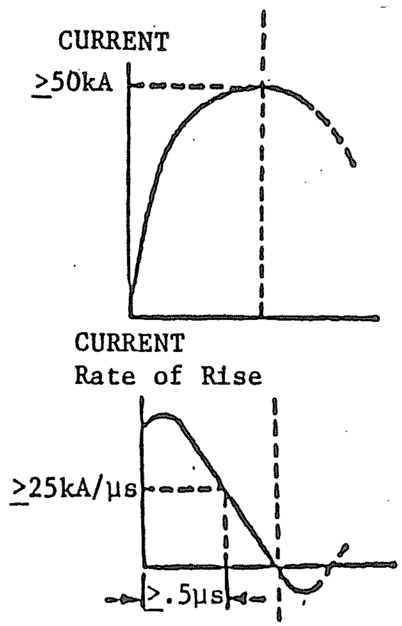
COMPONENT B (Intermediate Current)
Maximum Charge Transfer = 10 Coulombs
Average Amplitude = 2kA ± 10%

COMPONENT C (Continuing Current)
Charge Transfer = 200 Coulombs ± 20%
Amplitude = 200-800A

COMPONENT D (Restrike)
Peak Amplitude = 100kA ± 10%
Action Integral = 0.25 x $10^6 A^2$ s ± 20%
Time Duration = ≤ 500μs

(a) Current Waveform

Definition of rate of rise requirement of waveform E



Peak Amplitude = ≥ 50kA
Rate of Rise = ≥ 25kA/μs
for at least 0.5μs

(b) Component Waveform

FIGURE 9. CURRENT WAVEFORMS

$$i(t) = I_o(\varepsilon^{-\alpha t} - \varepsilon^{-\beta t})$$

where

$$I_o = 233{,}000\ (A)$$

$$\alpha = 11{,}000\ (s^{-1})$$

$$\beta = 460{,}000\ (s^{-1})$$

$$t = \text{time}(s)$$

(2) Component B - Intermediate Current - Component B has an average amplitude of 2kA ($\pm$10 percent) flowing for a maximum duration of 5ms. This component should be unidirectional; e.g., rectangular, exponential or linearly decaying. For analysis, a double exponential current waveform should be used. This waveform is described mathematically by the double exponential expression shown below:

$$i(t) = I_o(\varepsilon^{-\alpha t} - \varepsilon^{-\beta t})$$

where:

$$I_o = 11{,}300\ (A)$$

$$\alpha = 700\ (s^{-1})$$

$$\beta = 2000\ (s^{-1})$$

$$t = \text{time}\ (s)$$

If the dwell time is more than 5ms, apply an average current of 400A for the remaining dwell time. The dwell time shall have been determined previously through a swept-stroke attachment test or by analysis. If such determination has not been made, the dwell time shall be taken to be 50ms.

(3) Component C - Continuing Current - Component C transfers a charge of 200 coulombs ($\pm$20 percent in a time of between 0.25 and 1 second). This implies current amplitudes of between 200 and 800 amperes. The waveform shall be unidirectional; e.g., rectanglular, exponential, or linearly decaying. For analysis purposes, a square waveform of 200A for a period of 1 second should be utilized.

(4) Component D - Restrike Current - Component D has a peak amplitude of 100kA ($\pm$10 percent) and an action integral of $0.25 \times 10^6 A^2 s$ ($\pm$20 percent). This component may be either unidirectional or oscillatory with a total time duration not exceeding 500 μs. For analysis purpose a double exponential waveform should be used. This waveform represents a restrike of 100,000 amperes peak at a peak rate-of-rise of 0.5x11A/s. The waveform is defined mathematically by the double exponential expression shown in the following equation.

$$i(t) = I_o'(\varepsilon^{-\alpha t} - \varepsilon^{-\beta t})$$

$$I_o = 130{,}000 \text{ (A)}$$

$$\alpha = 27{,}500 \text{ (s}^{-1}\text{)}$$

$$\beta = 415{,}000 \text{ (s}^{-1}\text{)}$$

$$t = \text{time (s)}$$

(5) Current Waveform E - Fast Rate-of-Rise Stroke Test for Full-Size Hardware - Current waveform E has a rate-of-rise of at least 25kA/μs for at least 0.5μs, as shown in figure 9. Current waveform E has a minimum amplitude of 50kA. Alternatively, components A or D may be applied with a 25kA/μs rate-of-rise for at least 0.5μs and the direct and indirect effects evaluation conducted simultaneously.

. Indirect effects measured as a result of this waveform must be extrapolated as follows. Induced voltages dependent upon resistive or diffusion flux should be extrapolated linearly to a peak current of 200 kA.

Induced voltages dependent upon aperture coupling should be extrapolated linearly to a peak rate-of-rise of 100 kA/μs.

b. Voltage Waveforms - Test - There are three voltage waveforms, "A," "B," and "D," which represent the electric fields associated with a lightning strike. Voltage waveforms "A" and "D" are used to test for possible dielectric puncture and other potential attachment points. Voltage waveform "B" is used to test for streamers. The test in which these waveforms are applied are presented in table 1.

(1) Voltage Waveform A - Basic Lightning Waveform - Waveform A has an average rate-of-rise of 1×10^6 volts per microsecond (± 50 percent) until its increase is interrupted by 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 the lightning voltage generator), is not specified. Voltage waveform A is shown in figure 10.

(2) Voltage Waveform B - Full Wave - Waveform B rises to crest in 1.2 (± 20 percent) microseconds. Time-to-crest and decay time refer to the open circuit voltage of the 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 10.

(3) Voltage Waveform D - Slow Front - The slow fronted waveform has a rise time between 20 and 250 μs to allow time for streamers from the test object to develop. It should give a higher strike rate in tests to the low probability regions that might have been excepted in flight. This waveform is shown in figure 11.

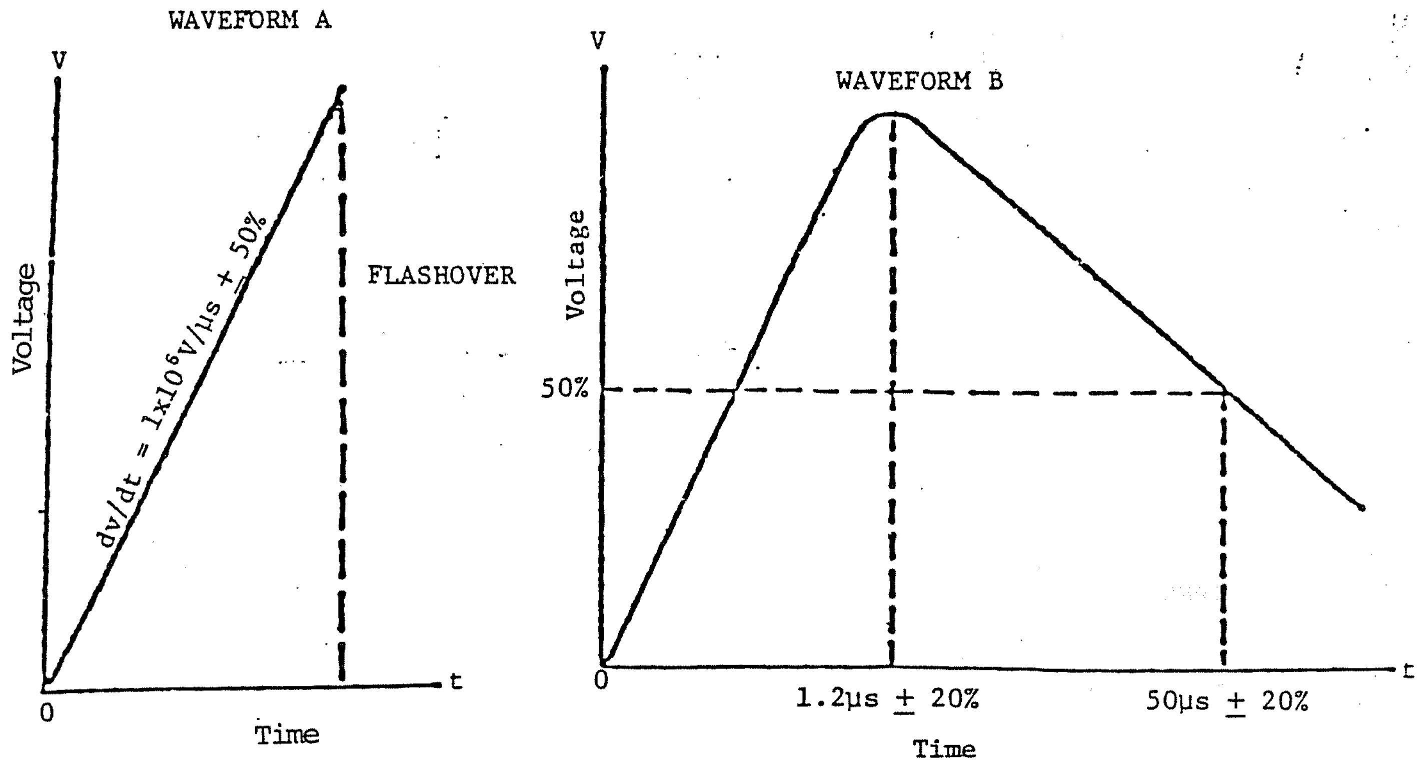


FIGURE 10. VOLTAGE WAVEFORMS A AND B

NOTE: Voltage Waveform "B" Full Wave - Wave "B" rises to crest in 1.2 (± 20 percent) µs. Time to crest and decay time (refer to open circuit voltage) of the lightning voltage generator, and assume that the waveform is not limited by puncture or flashover of the object under test.

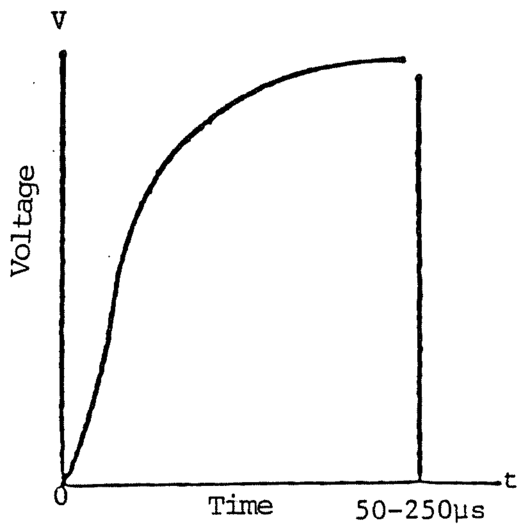


FIGURE 11. VOLTAGE WAVEFORM D

c. Current Waveforms - Analysis - For analysis of direct effects, the waveforms defined in paragraph 8a above will be used. For analysis of indirect effects, the waveform to be used represents a return stroke of 200,000 amperes peak at a rate of rise of $1x10^{11}$A/s. The waveform is defined mathematically by the double exponential expression shown below.

$$i(t) = I_o(\varepsilon^{-\alpha t} - \varepsilon^{-\beta t})$$

where:

I_o = 223,000 A

α = 11,000

β = 460,000

t = time (s)

5.3 IDENTIFICATION OF POSSIBLE IGNITION SOURCES.

In this step, the fuel system structures, components, and subsystems that may possibly constitute a source of ignition or other hazard to flight safety during a lightning strike should be identified. Examples include:

Access doors
Filler caps
Dip sticks
Sump drains
Fuel probe mounting doors
Skin joints and structural interfaces
Fuel tank plumbing hardware (i.e., couplings and fittings)
Vent outlets
Jettison outlets
Temperature compensators
Electrical apparatus (i.e., quantity probes, pumps, electrical feed-through connectors, low level indicators).
Bond lines between composite structural components which are structurally bonded together.

In addition to the sources noted, voltages and currents induced by lightning in fuel system electrical wiring or plumbing may create electrical sparks or arcs at components within the fuel tanks.

5.4 VERIFICATION METHODS.

Verification methods may encompass the range from (1) comparison with previous design; (2) analysis; (3) developmental tests under controlled conditions; (4) "qualification testing."

5.4.1 Comparison With Previous Design.

In some cases, lightning protection can be inferred if the design is the same or very similar to a design which has been shown to be "safe" with respect to lightning. However, sometimes what may appear to be small changes in design may result in a design going from "safe" to "unsafe." It is therefore desirable to conduct tests on the modified design to verify its integrity.

5.4.2 Analysis.

The aircraft designer generally uses analysis to predict the operation of a new aircraft, and analysis could possibly be used to determine if a new fuel system is free of ignition hazards related to lightning. However, due to the complexity of today's aircraft and the transient nature of lightning, it is extremely difficult to predict the exact lightning current flow paths and the behavior of the fuel system. For this reason, it is generally better to use comparison to a similar design or to actually conduct "qualification testing."

5.4.3 Comparison with Development Tests.

Wherever appropriate and practicable, government and industry personnel should specify or use the lightning test techniques, waveform characteristics, and procedures of appendix A during all phases of the lightning protection development. Test results and test article configuration should be well documented. By so doing, it is frequently possible to assemble test data from the development phase which is of adequate validity and applicability to be used for qualification. For some large complex systems, it may not be possible or economically feasible to conduct lightning qualification tests on a production configuration. For these cases, the final qualification verification must be synthesized from the verification of the subsystems or equipment. For more complex programs, utilizing the above approach, will result in substantial program savings in cost, schedule, and time. (These savings can be significant even in low complexity programs).

New designs should generally be tested at qualification levels to verify that they are satifactory. Sometimes during a development program several different designs are tested to determine the best design for a particular application. If during these preliminary tests certain shortcomings become evident, it may be possible to show by comparison to development tests and analysis of a modified design that modified production configurations do not suffer the same shortcomings revealed during the development tests.

5.4.4 Qualification/Certification Testing.

Qualification/certification testing means that the system and/or its parts are representative of production items and are tested at full threat level.

The threat level is determined by the location of the fuel system on the aircraft (see paragraph 5.1.3). Verification that a fuel system is safe from the deleterious effects of lightning requires that a system and/or its components be: (1) Subjected to the appropriate simulated lightning strike(s); and (2) instrumented and tested in a manner so that an unsafe condition can be identified.

5.4.4.1 Lightning Environment and Test Setup.

The lightning test voltage or current levels and waveshapes are dictated by the strike zones in which the fuel system/components are located on the aircraft (refer to table 1). The test components should be production hardware (or equivalent) and set up and connected to the lightning generator(s) so that the current transfer into and out of the test sample is similar to that which would be experienced by these components if they were installed in the aircraft.

If testing is used, characteristics of the in-flight environment such as altitude, temperature, pressure, aircraft motion and aerodynamic forces should be evaluated and accounted for, if appropriate.

5.4.4.2 Tests Utilizing Fuel-Air Mixtures.

One technique used to verify the "safe" fuel system is to use ignitable mixtures of fuel-air in the test object during the time when it is struck by the simulated lightning discharge. Optimum fuel-air mixtures; i.e., those that require a minimum energy for ignition, are used, and tests are required to demonstrate that the proper ignitable mixture was present in the fuel system at the time when the lightning tests were conducted.

5.4.4.3 Tests Utilizing Photographic and Temperature Sensing Apparatus.

Another technique used to verify the "safe" fuel system relies on photographic, infrared, and/or temperature measurement to infer ignition of a flammable mixture without using fuel for the test. If the suspected problem is hot spot ignition, then a camera equipped with infrared film, an image converter, temperature sensitive paints, or thermocouples may be used. If the suspected problem is the result of arcing or sparking, then photographic or image converter techniques should be used. Mirrors and auxiliary lenses and other optical systems should be used with care. The particular photographic system selected should be capable of detecting a 0.2 millijoule spark produced by a capacitor discharge. Additional information on use of photographic methods for detection of sparks may be found in appendix A, paragraph 4.1.3.

5.4.4.4 Pass-Fail Criteria.

Any indication of sparking or hot spots, or actual fuel ignition constitutes a failure. If fuel-air mixtures are used for testing, then ignition of the fuel could constitute failure. However, if flame suppressants such as reticulated foam are used, and if the flame was suppressed without damage to the system, then the system would have passed and could be classified as "safe."

If photographic and similar techniques are used to detect hot spots and sparks, etc., then any hot spot above the ignition temperature or arcing and sparking would be considered unacceptable.

6.0 PROTECTION CONSIDERATIONS.

The following paragraphs present basic guidelines and areas of concern with respect to lightning protection. It is recognized that protection design is a constantly changing technology and that many other approaches may be possible.

With the establishment of methods to predict the lightning current amplitude and charge, as well as dwell time, sufficient information is available to utilize the charts of figures 12 or 13 to determine the skin thicknesses which will or will not be melted through.

NOTE: It is not a recommended practice to extend the fuel system into a zone 1A or 1B area. If it is deemed necessary to utilize the zone 1 area for the fuel system, special design considerations must be incorporated to assure satisfactory lightning protection. This protection criteria must address potential areas of concern such as binding radius, etc.

6.1 DETERMINATION OF ALUMIMUM SKIN THICKNESS REQUIREMENTS.

For example, let us assume that a bare solid aluminum skin is planned for an integral tank in zone 2A, and that it is desired to determine how thick this skin should be to prevent melt-through. Further, let us say that this aircraft will fly at velocities as low as 58 m/s (130 mph). From table 2, the expected dwell time for this unpainted skin would be 2 ms. From figure 14, an average of 2kA would flow into the dwell point during this period, delivering 4 C of charge. According to figure 12, these parameters intersect at a point about half-way between the coulomb ignition threshold curves for 0.051cm (0.020 in.) and 0.102cm (0.040 in.) aluminum skins, indicating that 0.102cm is the thinnest skin that should be considered.

TABLE 2. LIGHTNING DWELL TIMES ON TYPICAL AIRCRAFT SURFACES IN ZONE 2A

Surface Type	Aircraft Velocities		
	15.5 m/s (35 mph)	58 m/s (130 mph)	103 m/s (230 mph)
Aluminum and titanium unpainted	[1] 1 to 4 ms	[2] 2.0 ms	[2] 1.0 ms
Aluminum anodized		[4] 4.8 ms	[2] 2.6 ms
Aluminum painted		[3] up to 20 ms	up to 10 ms

Note 1 - See Reference 1
Note 2 - See Reference 2
Note 3 - See Reference 3
Note 4 - See Reference 4

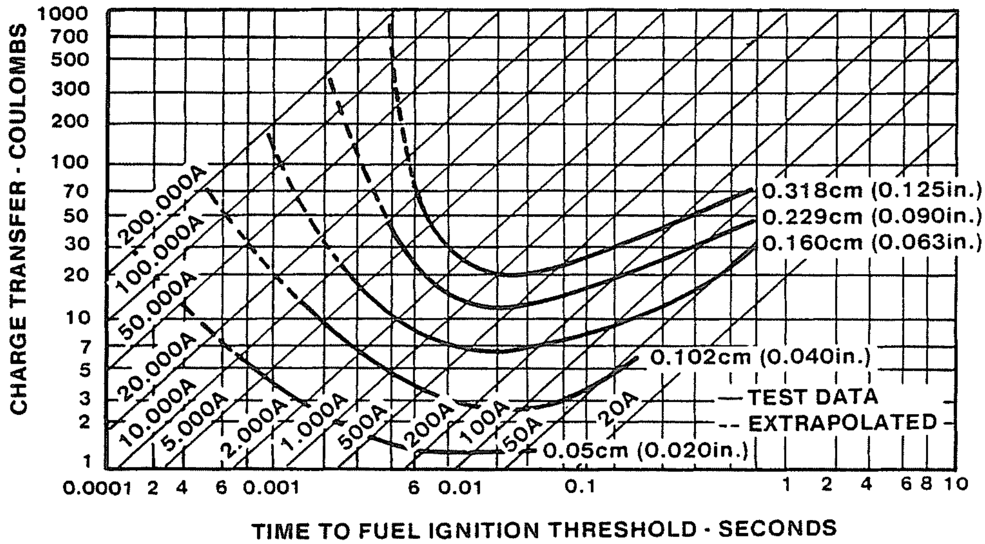


FIGURE 12. MELT-THROUGH AND IGNITION THRESHOLD FOR ALUMINUM SKINS

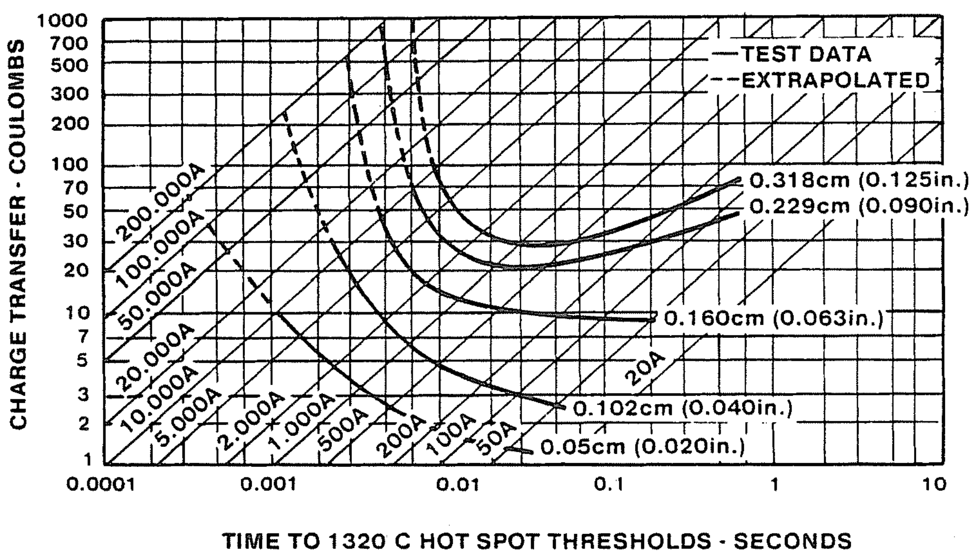


FIGURE 13. HOT-SPOT AND IGNITION THRESHOLDS FOR TITANIUM SKINS

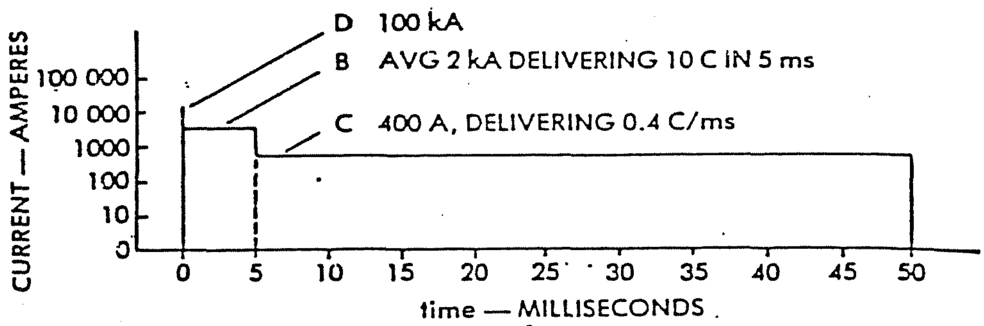


FIGURE 14. CURRENT AND CHARGE EXPECTED AT A ZONE 2A DWELL POINT

- Delivers 10C in first 5ms at any dwell point
- Delivers 0.4C/ms thereafter
- Delivers 400A for all 50ms if dwell time not known (Drawn with straight lines for explanation purposes only)

Different dwell points, different coatings, and different thicknesses will cause correspondingly different dwell times. Consider, for example, the longest dwell time, 20ms, reported in table 2 for a painted surface. During this period, the current of figure 14 would deliver 16 C. These parameters intersect at a point just above the 0.229cm (0.090 in.) curve in figure 12 indicating that even the 0.203cm (0.080 in.) thickness may be insufficient to prevent ignition where certain paints are used. In-flight experience has shown that 0.080 inch aluminum skins without thick paints can tolerate zone 2A currents without melt-through.

Therefore, if paints or other surface treatments must be used, it is advisable to perform swept-stroke tests to establish the actual dwell time, or to perform melt-through tests to determine the actual melt-through (or hot spot) threshold.

6.2 DETERMINATION OF TITANIUM SKIN THICKNESS REQUIREMENTS.

By using the chart of figure 13, it is possible to determine titanium skin thicknesses in a manner similar to that for determining aluminum skin thicknesses. The ignition threshold for titanium occurs when the backside (fuel side) of the skin reaches 1320° C, a temperature sufficient to ignite a fuelair vapor. (Reference 4)

6.3 DETERMINATION OF PARTIALLY-CONDUCTIVE COMPOSITE MATERIAL SKIN THICKNESS REQUIREMENTS.

No charts of the type in figures 12 and 13 have as yet been generated for other metals or conductive composite materials, and the vulnerability of these should be evaluated by test.

Lightning effects within fuel systems are a problem generic to both metallic and composite fuel tanks. The problem in a composite structure is complicated by the reduced electrical conductivity and the complex mechanical properties of the material and the joints.

6.4 INTEGRAL FUEL TANKS WITH ELECTRICALLY NONCONDUCTIVE SKINS.

In some cases, nonconducting materials such as fiberglass-reinforced plastics (FRP) are used instead of metals for integral fuel tank skins. In these cases, the lightning channel will either:

Puncture the skin and attach to an electrically conductive object inside the skin (tank), path (a) on figure 15; or

Divert around the nonmetallic skin and attach to an adjacent metallic skin or other object, path (b).

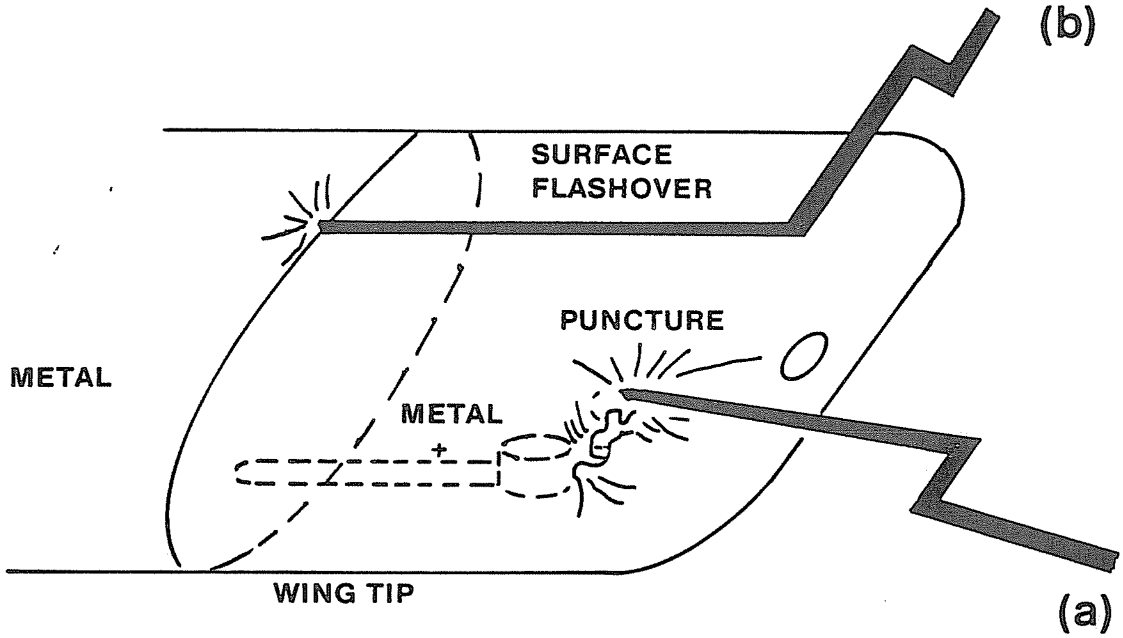


FIGURE 15. POSSIBLE LIGHTNING ATTACHMENT TO NONCONDUCTING SKINS

If the channel reaches the skin but remains on the outside surface, path (b), it is not likely that the skin will burn through or that its inside surface will become hot enough to ignite fuel. The reason for this is that the current is not electrically conducted by the skin, and the hot arc channel does not lie close enough or long enough against the skin to burn through it. In fact, its effects are usually limited to burning of external paints, if present, or to slight singeing of the nonmetallic skin. However, an approaching leader induces streamers from conductive elements of the aircraft including objects located beneath nonconducting skins. If the electric field producing the streamers is strong enough, the skin may suffer dielectric breakdown (puncture) and allow the streamer to reach the approaching leader. This is most likely to occur when there is no external conductive object nearby from which another streamer can propagate and reach the leader first. Obviously, if a puncture occurs through an integral fuel tank wall, fuel is placed in direct contact with the lightning arc channel and ignition is possible; therefore, normal practice has been not to have fuel extend into the zone 1A wing tip area.

Puncture of skins can be prevented, or at least greatly minimized by placement of conductive diverters on the outside surface of the tank as shown in figure 16. These diverters should be placed close enough to each other or to other conductors to prevent an internal streamer from puncturing the skin. In theory, this means that the diverters should be close enough to greatly reduce the internal electric field and prevent internal streamer formation, since such streamers will intensify the field as they propagate outward. Prevention of internal streamers by diverters is called electrostatic shielding, and successful accomplishment of this function is necessary to prevent skin punctures and, equally important, to prevent internal streamers from forming and becoming a source of ignition.

Because streamers form most readily from sharp conducting edges and corners, the number of metallic parts inside a nonconducting fuel tank should be minimized and those that remain should be located as far from nonconducting skins as possible and designed with smooth, rounded edges instead of sharp points. These concepts are illustrated in figure 16. Also, metallic parts should be located with as great a spacing from nonconducting skins as possible.

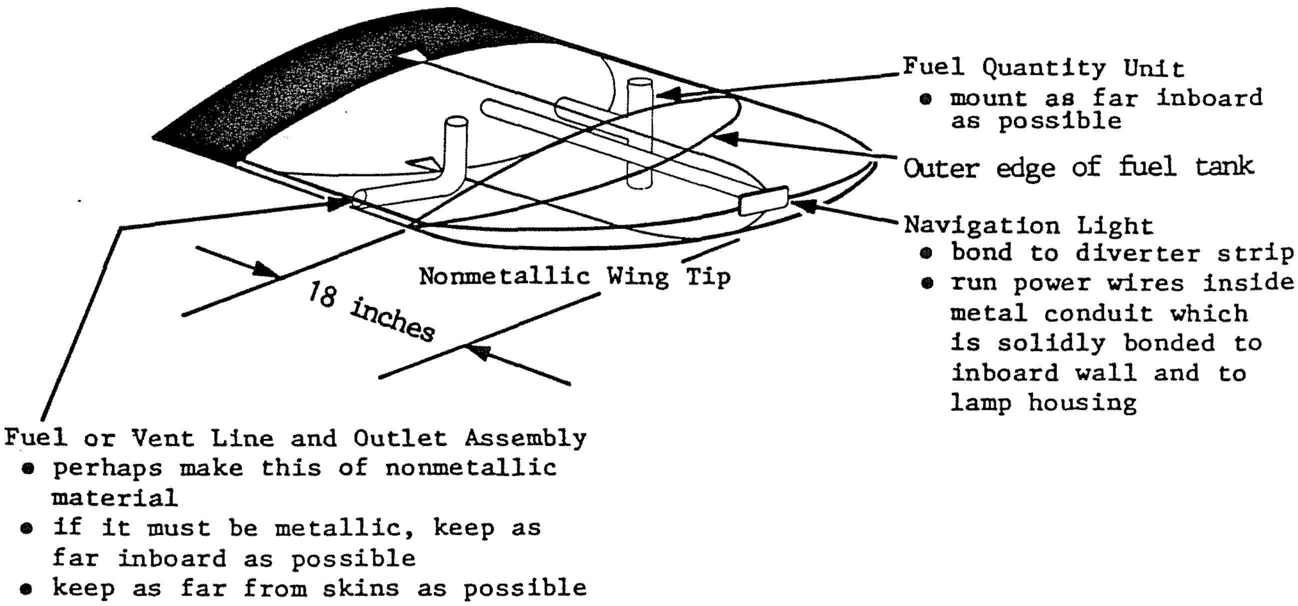


FIGURE 16. LOCATION OF METALLIC PARTS WITHIN NONCONDUCTING FUEL TANKS

If a diverter protection system such as that shown in figure 16 is used, it will often be most effective if not painted. Painting of the fiberglass skin itself, of course, is to be encouraged, as the added insulation provided by the paint will further reduce the probability of skin puncture.

If a diverter arrangement is not practical for some reason, a conductive coating may be applied to the tank instead. Such a coating may be a metal foil or a paint heavily doped with metal or carbon particles. The major disadvantage of these coatings is that a relatively large portion of the coating may be melted or burned away when the flash attaches to it. A coating may have to be prohibitively thick (one approaching the thickness of conventional metallic skins themselves) to avoid these results.

On the other hand, a conductive coating has the important advantage of providing an overall electrostatic shield that will virtually eliminate internal electric fields and streamering. Thus, if metallic objects must be located inside the tank in such a manner that streamers are of concern, it may be advisable to consider a conductive coating over the entire nonconducting skin. This precaution is particularly appropriate if occasional burnoff of part of the coating is acceptable from a maintenance standpoint.

Precipitation-static must be considered carefully in applying conducting coatings to plastic surfaces. If the external conductive coatings are not well bonded to the airframe, severe precipitation-static interferences with substantial RF interference can result.

Coatings rely on one of two techniques: High and low electrical conductivity to protect the dielectric material.

High conductivity coatings having a low electrical resistance in which the current is conducted directly in the coating. The current density is very high at the strike attachment point but it diminishes rapidly as the current spreads from the lightning attachment point. This will probably result in a minimum of electromagnetic coupling to systems (wiring, metallic tubing, metal brackets, etc.) behind or in the vicinity of the strike.

Low conductivity coatings such as carbon or metal filled paints, in which the lightning current is not conducted by the material but rather the conditions, are established so that the lightning arc can more easily flash across the surface than puncture the dielectric material. Since the lightning current probably does not spread out but remains as a single conducting plasma path, the electromagnetic coupling would be similar to that obtained by a wire carrying a similar current.

Some metal filled paints are nonconductive and do not offer electrostatic shielding. As a result, the approaching lightning channels can induce streamers from conductors mounted behind the coating. Typical coating and diverter systems are listed below:

TABLE 3. COATINGS AND DIVERTER SYSTEMS

TECHNIQUE	TYPE
Coatings	Thin metal foil
	Wire meshes (braided or woven)
	Sprayed metal coatings
	Metal-filled paint -highly conductive
	Metal-filled paint -not conductive
	Carbon filled paint -high conductivity
	Carbon-filled paint -low conductivity
	Aluminum-coated fiber glass cloth
Diverters	Heavy conductive metal strips
	Expendable thin conductive metal strips
	Button diverter
	Metal particles on dielectric strip

Users of any of the techniques listed in table 3 should be aware that improper designs can create additional problems such as structural damage or systems interface, and should carefully evaluate proposed designs and verify adequacy by test.

6.5 COMPONENTS, JOINTS, AND INTERFACES.

Electrical wires and plumbing within fuel tanks pose another problem due to negligible electromagnetic shielding properties of these materials.

In the past, much attention has been given to keeping lightning currents out of the interior of the aircraft by providing conductive and tightly bonded skins. Since most lightning currents, due to their short duration, will not have sufficient time to diffuse completely to interior structural elements such as spars and ribs, some current will flow in other internal conductors such as fuel and vent lines.

Since so little energy is needed for an igniting spark, the behavior of these internal currents is of great importance to fuel system safety. Of course, when the lightning currents which do flow in the skin encounter discontinuities at access doors, filler caps, and the like, a possibility of sparking exists if electrical bonding is inadequate; therefore, the behavior of lightning currents remaining in the skins is important.

Figure 17 shows the possible lightning current paths in a typical fuel tank and calls attention to these areas of greatest concern. These areas are discussed in the following subparagraphs.

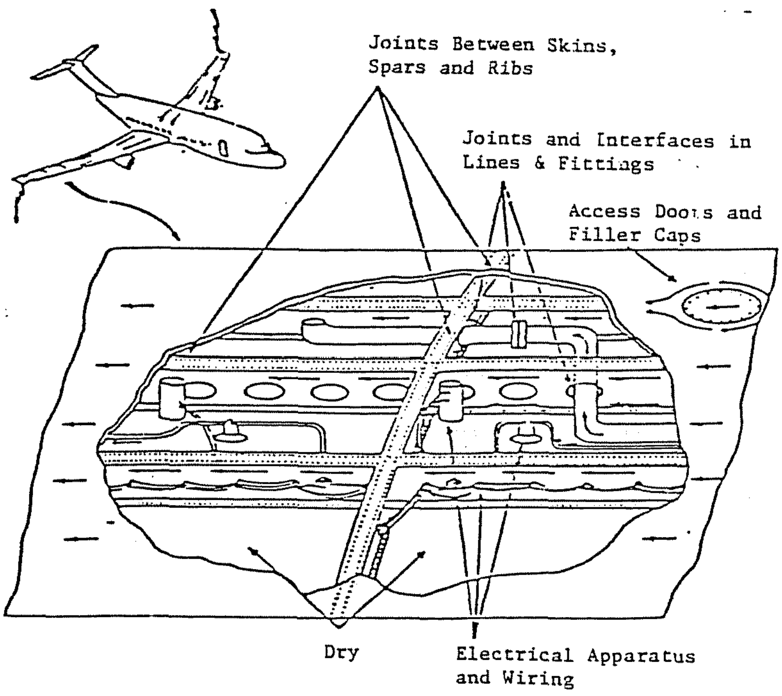


FIGURE 17. LIGHTNING CURRENT PATHS IN A FUEL TANK

6.5.1 Filler Caps.

The need to provide a liquid-tight seal around fuel tank filler caps has led to use of various gaskets and seals between the cap and its mating surface in the tank. Most of these have little or no electrical conductivity, leaving the metallic screws or other fasteners as the only conducting paths into the cover. If these fasteners are inadequate or if they present too much inductance, lightning currents may build sufficient voltage along such paths to spark across the nonconducting seals, creating shorter paths. Some of these sparks may occur at the inside surfaces of the joints and be a source of fuel ignition.

Research has been accomplished to evaluate this possibility and it has been demonstrated that direct strikes to filler caps can cause profuse spark showers, inside the tank, of ample energy to ignite fuel. Such a situation is illustrated in figure 18.

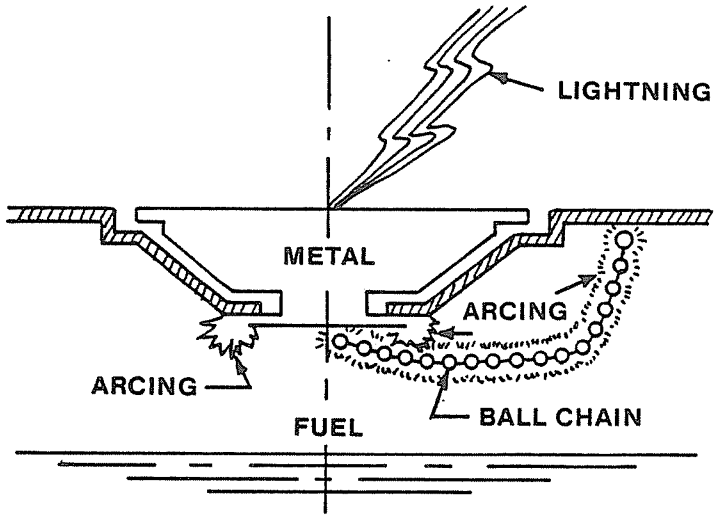


FIGURE 18. SOURCES OF IGNITION AT AN UNPROTECTED FUEL FILLER CAP

Lightning protected filler caps have been designed to prevent internal sparking. Figure 19 illustrates this type of cap. It incorporates a plastic insert that precludes any sparking at interior faying surfaces and replaces the previous ball chain with a nonconducting plastic strap. Lightning protected fuel tank filler caps are commercially available and are being used in many aircraft where filler caps must be located in direct or swept-lightning strike zones. Even though lightning protected fuel filler caps are used, attention must also be given to assuring that the cap adapter-to-tank skin interface is free of ignition sources.

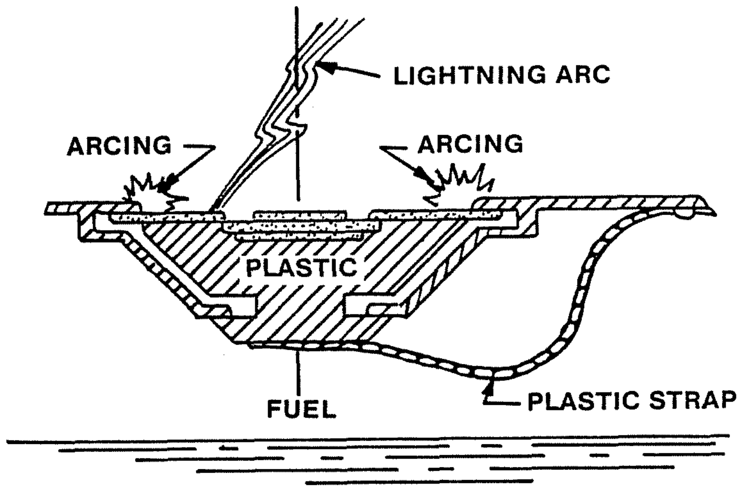


FIGURE 19. LIGHTNING-PROTECTED FUEL FILLER CAP

NOTE: It is most important to assure that filler cap mounting adapters and fasteners will not spark internally to the adjacent skin during a lightning strike to the cap, adaptor or fastner.

6.5.2 Fuel Probes.

Extreme care must be taken to ensure that adequate gaps are maintained between the active electrodes of the probe and airframe. It is particularly important that sufficient insulation be provided between active electrodes and the airframe because the highest induced voltages appears between all of the incoming wires and airframe. This is shown in figure 20.

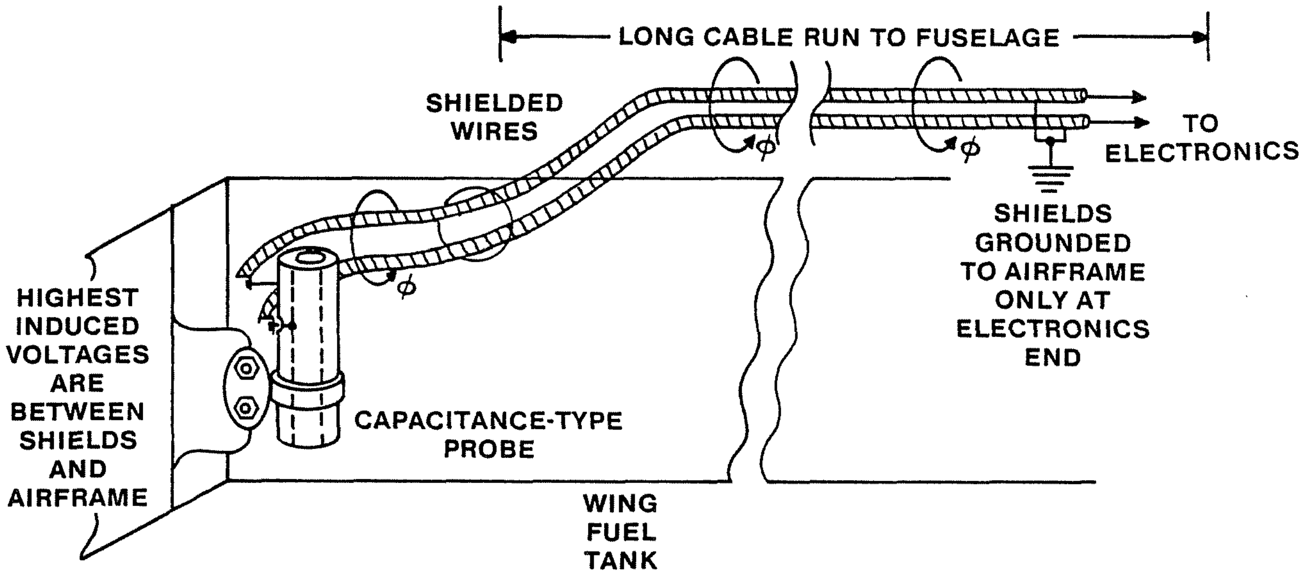


FIGURE 20. TYPICAL FUEL PROBE WIRING

Electrical devices, such as fuel probes, have been intentionally designed to withstand comparatively high voltages without sparking. However, structural designs or material changes may alter this situation and permit excessive induced voltages to appear in the fuel tank electircal circuit.

When determining the breakdown voltages of fuel quantity probes, test voltages must be applied to all of the electrode combinations which may exist, (this is not required to be accomplished simultaneously). In most probes both the "high" and "low" electrodes are insulated from "ground" (airframe) as shown in figure 21, but the mounting bracket brings the probe into proximity of the airframe. Therefore, test voltages should be applied across each of the basic electrode combinations as shown in figure 21 (taken from reference 5).

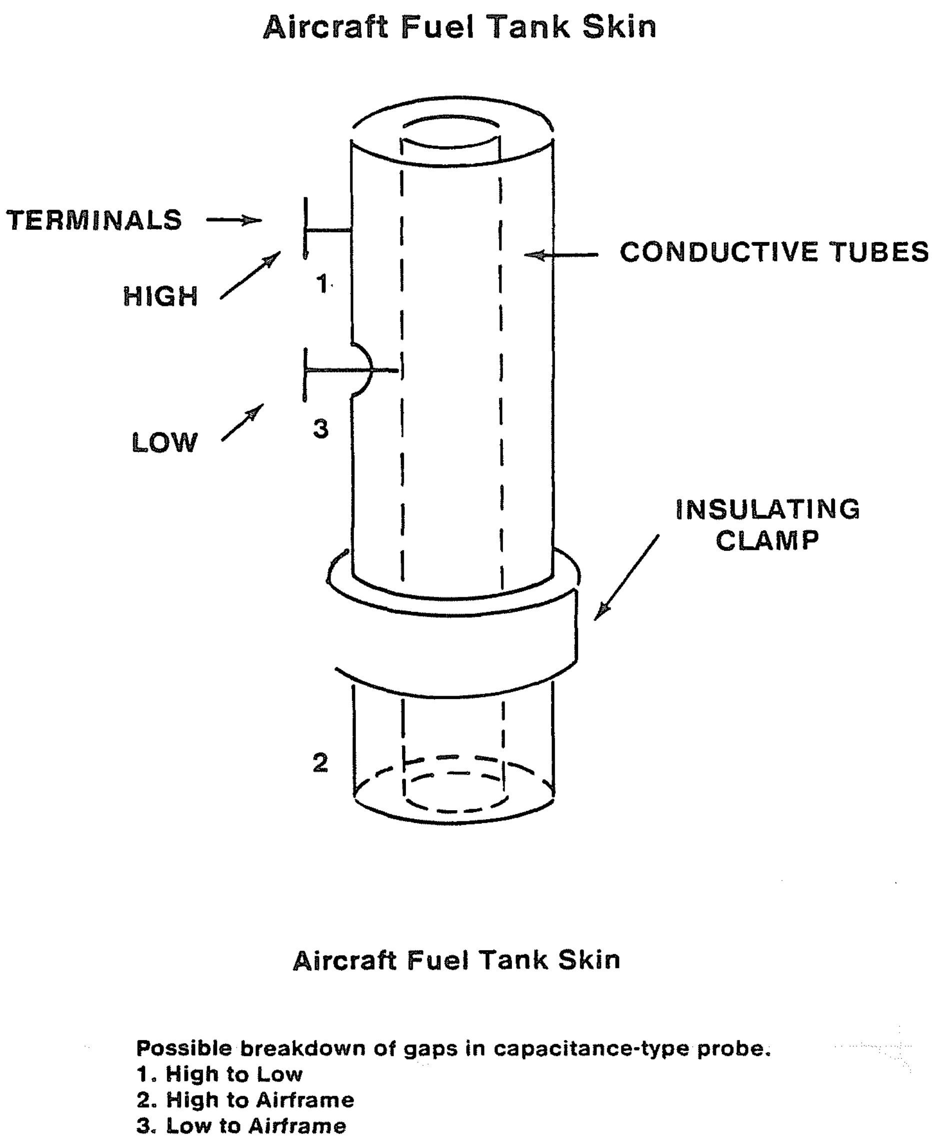


FIGURE 21. TYPICAL IMPULSE SPARKOVER VOLTAGES FOR A CAPACITANCE-TYPE PROBE

6.5.3 Joints in Skins.

Sparking is sometimes a result of current densities through small paths across the joints in which the current density exceeds the fusing current (e.g., currents that melt or vaporize material) density. Small burrs of aluminum with insufficient cross sectional area to carry the localized current are vaporized or melted and exploded into small spark showers. These can be generated across joints with even low joint impedances, as illustrated in figure 22. Thus, the edge treatment of wing planks and splice plates, for example, is critical in preventing sparking inside fuel tanks.

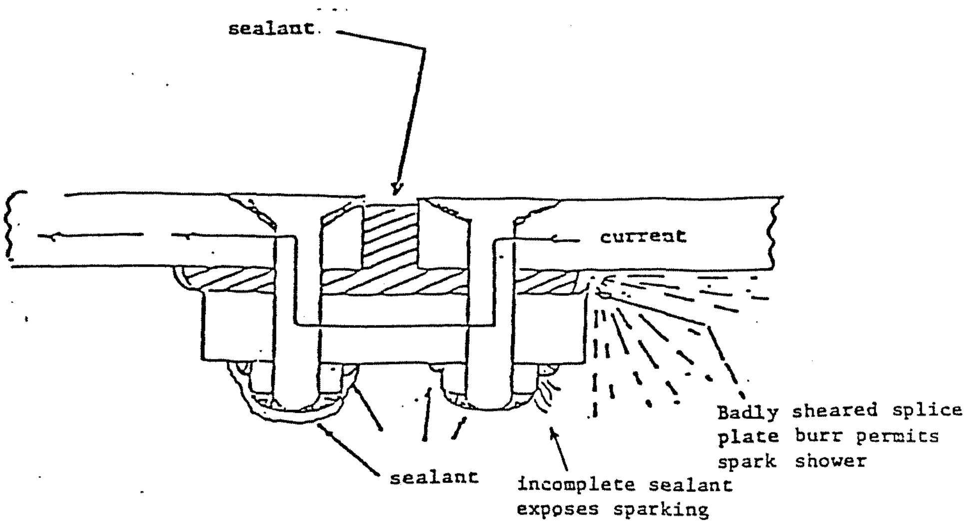


FIGURE 22. POSSIBLE SPARKING AT STRUCTURAL JOINT

There is no hard-and-fast rule for the number of fasteners per meter of joint (density) which are necessary to avoid sparking. Any sparking usually occurs at the interfaces between the fastener and surrounding metal, and the occurrence of such sparking depends on other physical characteristics, such as skin metal thickness, surface coatings, and fastener tightness. Tests in which simulated lightning currents are conducted through the joint should always be made on samples of joints involving new materials or designs following production manufacturing techniques.

Graphite/epoxy composite material can have a severe corrosion problem due to galvanic action between graphite and other aircraft material, mainly aluminum. Direct (uncoated) aluminum-to-graphite compostie joints should be avoided.

6.5.4 Joints and Interfaces in Pipes and Coupling.

When lightning currents are flowing through the structure, small amounts of current may be diverted through metallic fuel lines, vent pipes, other plumbing inside a fuel tank, and hydraulic lines. For nonmetallic tanks, these currents may be significant. This current may cause sparking at pipe joints and couplings where there is intermittent or poor electrical conductivity. Some pipe couplings, for example, are designed to permit relative motion between the mating ends of a pipe so as to relieve mechanical stresses caused by wing flexure and vibration. These actions may wear away this insulation, providing unintentional and intermittent conductive paths. This should, therefore, be given particular attention in the design of aircraft fuel systems.

7.0 DEFINITIONS.

The following definitions apply to this document.

1. Action Integral - The action integral concept is difficult to visualize, but is a critical factor in the production 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 resistance of the system. For example, the instantaneous power dissipated in a resistor is by Ohm's Law, $i^2(t)r$, and is expressed in watts. For the total energy expended, the power must be integrated over time to get the total watt-seconds (or kilowatt hours). The watt-second is equivalent to the joule, which is the common unit of electrical energy used in high-voltage practice. Without a knowledge of r, we cannot specify the energy deposited. But by specifying the integral of $i^2(t)$ over the time interval involved, a useful quantity is defined for application to any resistance value of interest. In the case of lightning, therefore, this quantity is defined as the action integral and is specified as $\int i^2(t)\,dt$ over the time the current flows.

2. Arcs - An electrical discharge between conductors in contact.

3. Attachment Point - A point of contact of the lightning flash with the aircraft surface.

4. Average Rate-of-Rise of Voltage - The average rate-of-rise, dv/dt, of a waveform is defined as the slope of a straight line drawn between the points where the amplitude is 30 percent and 90 percent of its peak value.

5. Charge Transfer - The charge transfer is defined as the integral of the time-varying current over its entire duration.

6. Corona - A luminous discharge that occurs as a result of an electrical potential difference between the aircraft and the surrounding atmosphere.

7. Decay Time of a Voltage Waveform - The decay time of a waveform is defined as the time interval between the intersect with the abcissa of a line drawn through the points where the voltage is 30 percent and 90 percent of its peak value during its rise, and the instant when the voltage has decayed to 50 percent of its peak value.

8. Direct Effects - Physical damage effects caused by lightning attachment directly to hardware or components, such as arcing, sparking, or fuel tank skin puncture.

9. Direct Stroke Attachment - Contact of the main channel of a lightning flash with the aircraft.

10. Dwell Time - The period of time that the lightning arc channel remains attached to a single point.

11. Entry Point - A lightning attachment point where charge enters the aircraft.

12. Exit Point - A lightning attachment point where charge exits the aircraft.

13. Incendiary Arcs/Sparks - Arcs, sparks, or spark showers capable of igniting flammable vapors.

14. Indirect Effects - The results of electromagnetic coupling from lightning (such as induced sparking in fuel quantity probe wiring).

15. Leader - The stepped leader is initiated by a preliminary breakdown within the cloud. The preliminary breakdown sets the stage for negative charge to be channeled towards the ground in a series of short luminous steps.

16. Lightning Flash - The total lightning event in which charge is transferred from one charge center to another. It may occur within a cloud, between clouds, or between a cloud and ground. It can consist of one or more lightning strokes.

17. Lightning Strike - Any attachment of the lightning flash to the aircraft.

18. Lightning Stroke (Return Stroke) - A lightning current surge, return stroke, that occurs when the lightning leader makes contact with the ground or another charge center.

19. Spark Showers - Luminous particles resulting from electric arcs or sparks, often associated with high current.

20. Streamering - The branch-like ionized paths that occur in the presence of a direct stroke or under conditions when lightning strokes are imminent.

21. Swept Stroke - A series of successive attachments due to sweeping of the flash across the surface of the airplane by the motion of the airplane.

22. Time-to-Crest of a Voltage Waveform - The time-to-crest of a waveform is defined as 1.67 times the time interval between the instants when the amplitude is 30 percent and 90 percent of its peak value.

23. Time Duration of a Current Waveform - The time duration of a current waveform is defined as the time from initiation of current flow until the amplitude (peak amplitude in the case of a damped sinusoid) has reduced to 5 percent of its initial peak value.

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Appendix A

LIGHTNING TEST WAVEFORMS AND TECHNIQUES FOR AEROSPACE VEHICLES AND HARDWARE

Report of

SAE Committee AE4L

June 20, 1978

Users of this document should ascertain that they are in possesion of the latest version.

This version supersedes SAE Special Task F Report "Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware" dated May 5, 1976.

LIGHTNING TEST WAVEFORMS AND TECHNIQUES
FOR AEROSPACE VEHICLES AND HARDWARE

TABLE OF CONTENTS

Section

1.0 INTRODUCTION

This document presents test waveforms and techniques for simulated lightning testing of aerospace vehicles and hardware. The waveforms presented are based on the best available knowledge of the natural lightning environment coupled with a practical consideration of state-of-the-art laboratory techniques. This document does not include design criteria nor does it specify which items should or should not be tested.

Tests and associated procedures described herein are divided into two general categories:

- o Qualification tests
- o Engineering tests

Acceptable levels of damage and/or pass-fail criteria for the qualification tests must be provided by the cognizant regulatory authority for each particular case.

The engineering tests provide important data that may be necessary to achieve a qualifiable design.

The term Aerospace Vehicle covers a wide variety of systems, including fixed wing aircraft, helicopters, missiles, and spacecraft. In addition, natural lightning is a complex and variable phenomenon and its interaction with different types of vehicles may be manifested in many different ways. It is therefore difficult to address every possible situation in detail. However, the test waveforms described herein represent the significant aspects of the natural environment and are therefore independent of vehicle type or configuration. The recommended test techniques have also been kept general to cover as many test situations as possible. Some unique situations may not fit into the general guidelines; in such instances, application of the waveform components must be tailored to the specific situation.

The test waveforms and techniques described herein for qualification tests simulate the effects of a severe lightning strike to an aerospace vehicle. Where it has been shown that test conditions can affect results of the test, a specific approach is recommended as a guideline to new laboratories and for consistency of results between laboratories.

It is not intended that every waveform and test described herein be applied to every system requiring lightning verification tests. The document is written so that specific aspects of the environment can be called out for each specific program as dictated by the vehicle design, performance, and mission constraints.

2.0 LIGHTNING STRIKE PHENOMENA

2.1 Natural Lightning Strike Electrical Characteristics

Lightning flashes are of two fundamentally different forms, cloud-to-ground flashes and inter/intracloud flashes. Because of the difficulty of intercepting and measuring inter/intracloud flashes the great bulk of the statistical data on the characteristics of lightning refer to cloud-to-ground flashes. Aerospace vehicles intercept both inter/intracloud and cloud-to-ground lightning flashes as shown in Figure 2-1. There is evidence that the inter/intracloud flashes lack the high peak currents of cloud-to-ground flashes. Therefore, the use of cloud-to-ground lightning strike characteristics as design criteria for lightning protection seems conservative.

There can be discharges from either a positive or a negative charge center in the cloud. A negative discharge is characterized by several intermittent strokes and continuing currents as shown in Figure 2-2(A). A positive discharge, which occurs only a small but significant percentage of the time, is shown in Figure 2-2(B). It is characterized by both higher average current and longer duration in a single stroke and must be recognized because of its greater energy content. The following discussion describes the more common negative flashes.

2.1.1 Prestrike Phase

The lightning flash is typically originated by a step leader which develops from the cloud toward the ground or towards another charge center. As a lightning step leader approaches an extremity of the vehicle, high electrical fields are produced at the surface of the vehicle. These electric fields give rise to other electrical streamers which propagate away from the vehicle until one of them contacts the approaching lightning step leader as shown on Figure 2-1. Propagation of the step leader will continue from other vehicle extremities until one of the branches of the step leader reaches the ground or another charge center. The average velocity of propagation of the step leader is about one meter per microsecond and the average charge in the whole step leader channel is about 5 coulombs.

2.1.2 High Peak Current Phase

The high peak current associated with lightning occurs after the step leader reaches the ground and forms what is called the return stroke of the lightning flash. This return stroke occurs when the charge in the leader channel is suddenly able to flow into the low impedance ground and neutralize the charge attracted into the region prior to the step leader's contact with the ground. Typically, the high peak current phase is called the return stroke and is in the range of 10 to 30 kA (amperes x 10^3). Higher currents are possible though less probable. A peak current of 200 kA represents a very severe stroke, one that is exceeded only about 0.5 percent of the time. While 200 kA may be considered a practical maximum value of lightning current, it should be emphasized that in rare cases a larger current can occur. Reliable measurements are few, but there is circumstantial evidence that peak currents can exceed 400 kA. The current in the return stroke has a fast rate of change, typically about 10 to 20 kA per micro-

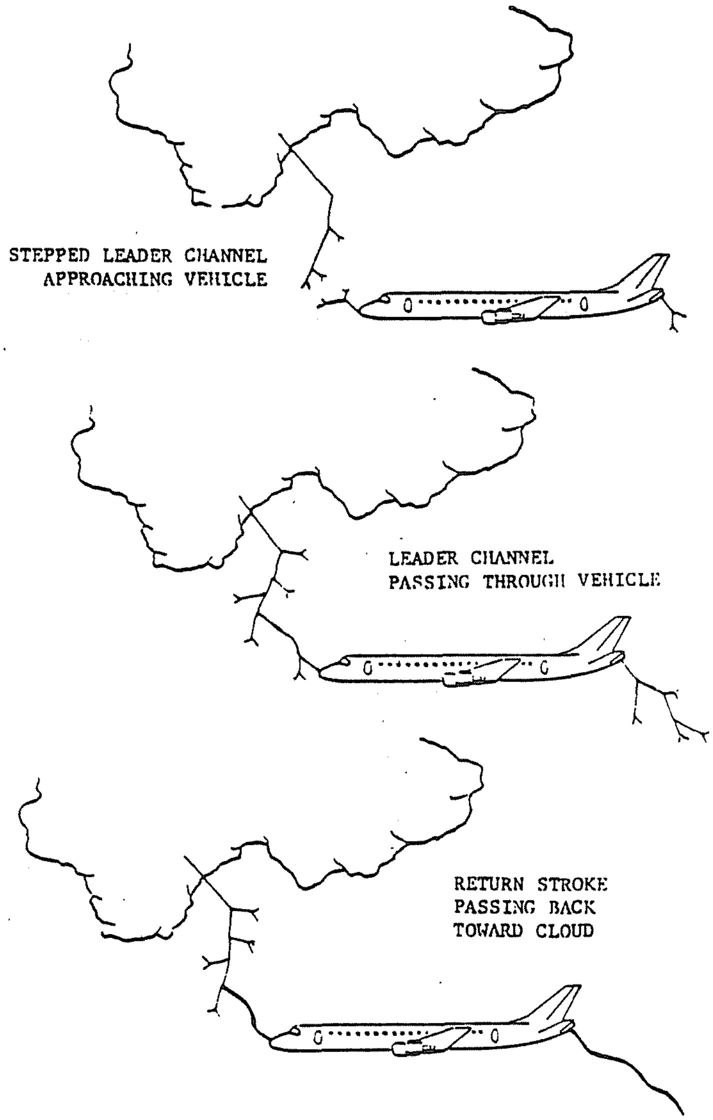
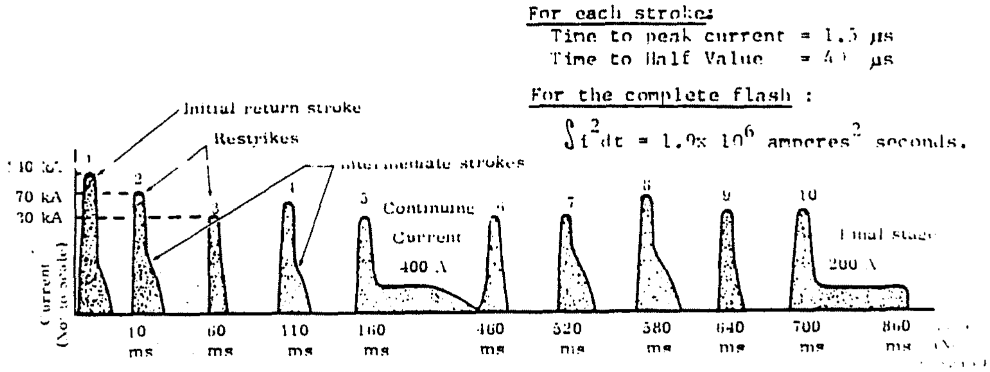


Fig. 2-1 Lightning flash striking an aircraft.

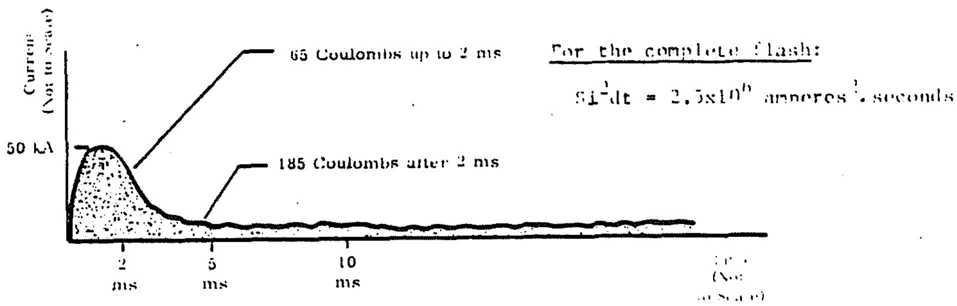
second and exceeding, in rare cases, 100 kA per microsecond. Typically the current decays to half its peak amplitude in 20 to 40 µsec. No correlation has been shown to exist between peak current and rate of rise.

2.1.3 Continuing Current

The total charge transported by the lightning return stroke is relatively small, a few coulombs. Most of the charge is transported in two phases of the lightning flash following the first return stroke. These are an intermediate phase in which currents of a few thousand amperes flow for times of a few milliseconds and a continuing current phase in which currents of the order of 200-400 amperes flow for times varying from about a tenth of a second to one second. The maximum charge transferred in the intermediate phase is about 10 coulombs and the maximum charge transported during the total continuing current phase is about 200 coulombs.



(A) Severe negative lightning flash current waveform.



(B) Moderate positive lightning flash current waveform.

Figure 2-2 Lightning flash current waveforms.

2.1.4 Restrike Phase

In a typical lightning flash there will be several high current strokes following the first return stroke. These occur at intervals of several tens of milliseconds as different charge pockets in the cloud are tapped and their charge fed into the lightning channel. Typically the peak amplitude of the restrikes is about one half that of the initial high current peak, but the rate of current rise is often greater than that of the first return stroke. The continuing current often links these various successive return strokes, or restrikes.

2.2 Aerospace Vehicle Lightning Strike Phenomena

2.2.1 Initial Attachment

Initially the lightning flash will enter and exit the aircraft at two or more attachment points. There will always be at least one entrance point and one exit point. It is not possible for the vehicle to store the electrical energy of the lightning flash in the capacitive field of the vehicle and so avoid an exit point. Typically these initial attachment points are at the extremities of the vehicle. These include the nose, wing tips, elevator and stabilizer tips, protruding antennas, and engine pods or propeller blades. Lightning can also attach to the leading edge of swept wings and some control surfaces.

2.2.2 Swept Stroke Phenomenon

The lightning channel is somewhat stationary in space while it is transferring electrical charge. When a vehicle is involved it becomes part of the channel. However, due to the speed of the vehicle and the length of time that the lightning channel exists, the vehicle can move relative to the lightning channel. When a forward extremity, such as a nose or wing mounted engine pods are involved, the surface moves through the lightning channel. Thus the lightning channel appears to sweep back over the surface as illustrated in Figure 2-3. This is known as the swept stroke phenomenon. As the sweeping action occurs, the type of surface can cause the lightning channel attach point to dwell at various surface locations for different periods of time, resulting in a skipping action which produces a series of discrete attachment points along the sweeping path.

The amount of damage produced at any point on the aircraft by a swept-stroke depends upon the type of material, the arc dwell time at that point, and the lightning currents which flow during the attachment. Both high peak current restrikes with intermediate current components and continuing currents may be experienced. Restrikes typically produce reattachment of the arc at a new point.

When the lightning arc has been swept back to one of the trailing edges it may remain attached at that point for the remaining duration of the lightning flash. An initial exit point, if it occurs at a trailing edge, of course, would not be subjected to any swept stroke action.

The significance of the swept stroke phenomenon is that portions of the vehicle that would not be targets for the initial entry and exit point of a lightning flash may also be involved in the lightning flash process as the flash is swept backwards across the vehicle.

2.2.3 Lightning Attachment Zones

Aircraft surfaces can then be divided into three zones, with each zone having different lightning attachment and/or transfer characteristics. These are defined as follows:

Zone 1: Surfaces of the vehicle for which there is a high probability of initial lightning flash attachment (entry or exit).

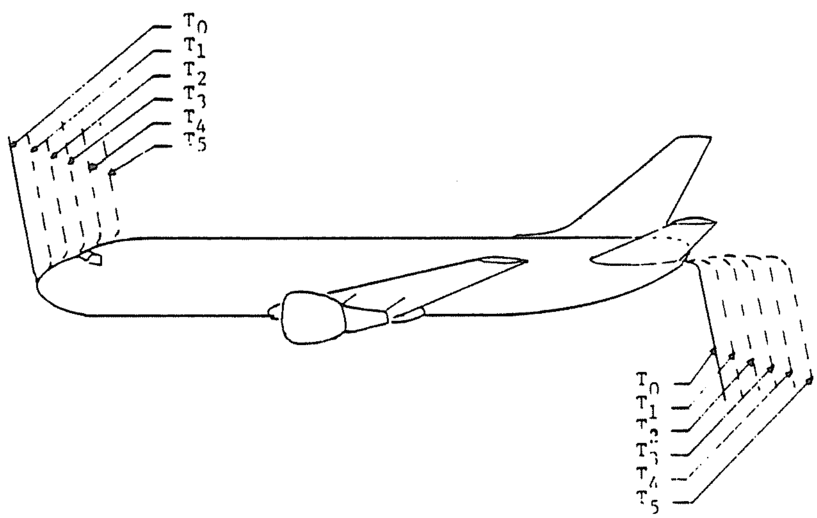


Figure 2-3 Swept stroke phenomenon.

Zone 2: Surfaces of the vehicle across which there is a high probability of a lightning flash being swept by the airflow from a Zone 1 point of initial flash attachment.

Zone 3: Zone 3 includes all of the vehicle areas other than those covered by Zone 1 and Zone 2 regions. In Zone 3 there is a low probability of any attachment of the direct lightning flash arc. Zone 3 areas may carry substantial amounts of electrical current but only by direct conduction between some pair of direct or swept stroke attachment points.

Zones 1 and 2 may be further divided into A and B regions depending on the probability that the flash will hang on for any protracted period of time. An A type region is one in which there is low probability that the arc will remain attached and a B type region is one in which there is a high probability that the arc will remain attached. Some examples of zones are as follows:

Zone 1A: Initial attachment point with low probability of flash hang-on, such as a leading edge.

Zone 1B: Initial attachment point with high probability of flash hang-on, such as a trailing edge.

Zone 2A: A swept stroke zone with low probability of flash hang-on, such as a wing mid-span.

Zone 2B: A swept stroke zone with high probability of flash hang-on, such as a wing inboard trailing edge.

2.3 Aerospace Vehicle Lightning Effects Phenomena

The lightning effects to which aerospace vehicles are exposed and the effects which should be reproduced through laboratory testing with simulated lightning waveforms can be divided into DIRECT EFFECTS and INDIRECT EFFECTS. The direct effects of lightning are the burning, eroding, blasting, and structural deformation caused by lightning arc attachment, as well as the high-pressure shock waves and magnetic forces produced by the associated high currents. The indirect effects are predominatly those resulting from the interaction of the electromagnetic fields accompanying lightning with electical apparatus in the aircraft. Hazardous indirect effects could in principle be produced by a lightning flash that did not directly contact the aircraft and hence was not capable of producing the direct effects of burning and blasting. However, it is currently believed that most indirect effects of importance will be associated with a direct lightning flash. In some cases both direct and indirect effects may occur to the same component of the aircraft. An example would be a lightning flash to an antenna which physically damages the antenna and also sends damaging voltages into the transmitter or receiver connected to that antenna. In this document the physical damage to the antenna will be discussed as a direct effect and the voltages or currents coupled from the antenna into the communications equipment will be treated as an indirect effect.

2.3.1 Direct Effects

The nature of the particular direct effects associated with any lightning flash depends upon the structural component involved and the particular phase of the lightning current transfer discussed earlier.

2.3.1.1 Burning and Eroding

The continuing current phase of a lightning stroke can cause severe burning and eroding damage to vehicle structures. The most severe damage occurs when the lightning channel dwells or hangs on at one point on the vehicle for the entire period of the lightning flash, such as in Zone 1B. This can result in holes of up to a few centimeters in diameter on the aircraft skin.

2.3.1.2 Vaporization Pressure

The high peak current phase of the lightning flash transfers a large amount of energy in a short period of time, a few tens of microseconds. This energy transfer can result in a fast thermal vaporization of material. If this occurs in a confined area such as a radome, a high pressure may be created which may be of sufficient magnitude to cause structural damage. The vaporization of metal and other materials and the heating of the air inside the radome, create the high internal pressure that leads to structural failure. In some instantces intire radomes have been blown from the aircraft.

2.3.1.3 Magnetic Force

During the high peak current phase of the lightning flash the flow of current through sharp bends or corners of the aircraft structure can cause extensive magnetic flux interaction. In certain cases, the resultant magnetic forces can twist, rip, distort, and tear structures away from rivets, screws, and other fasteners. These magnetic forces are proportional to the square of the magnetic field intensity and thus are proportional to the square of the lightning current. The damage produced is related both to the magnetic force and to the response time of the system.

2.3.1.4 Fire and Explosion

Fuel vapors and other combustibles may be ignited in several ways by a lightning flash. During the prestrike phase high electrical stresses around the vehicle produce streamers from the aircraft extremities. The design and location of fuel vents determine their susceptibility to streamer conditions. If streamers occur from a fuel vent in which flammable fuel-air mixtures are present, ignition may occur. If this ignition is not arrested, flames can propagate into the fuel tank area and cause a major fuel explosion.

The flow of lightning current through vehicle structures can cause sparking at poorly bonded structure interfaces or joints. If such sparking occurs where combustibles such as fuel vapors are located, ignition may occur.

Lightning attaching to an integral tank skin may puncture, burn holes in the tank, or heat the inside surface sufficiently to ignite any flammable vapors present.

2.3.1.5 Acoustic Shock

The air channel through which the lightning flash propagates is nearly instantaneously heated to a very high temperature. When the resulting shock wave impinges upon a surface it may produce a destructive overpressure and cause mechanical damage.

2.3.2 Indirect Effects

Damage or upset of electrical equipment by currents or voltages is defined as an indirect effect. In this document such damage or upset is defined as an indirect effect even though such currents or voltages may arise as a result of a direct lightning flash attachment to a piece of external electrical hardware. An example would be a wing-tip navigation light. If lightning shatters the protective glass covering or burns through the metallic housing and contacts the filament of the bulb, current can be injected into the electrical wires running from the bulb to the power supply bus. This current may burn or vaporize the wires. The associated voltage surge may cause breakdown of insulation or damage to other electrical equipment.

Even if the lightning flash does not contact wiring directly, it will set up changing electromagnetic fields around the vehicle. The metallic structure of the vehicle does not provide a perfect Faraday cage electromagnetic shield and therefore some electromagnetic fields can enter the vehicle, either by diffusion through metallic skins or direct penetration through apertures such as skin joints and windows or other nonmetallic sections. If the fields are changing with respect to time and link electrical circuits inside the vehicle, they will induce transient voltages and currents into these circuits. These voltages may be hazardous to avionic and electrical equipment, as well as a source of fuel ignition.

Voltages and currents may also be produced by the flow of lightning current through the resistance of the aircraft structure.

2.3.3 Effects on Personnel

One of the most troublesome effects on personnel is flash blindness. This often occurs to flight crew member(s) who may be looking out of the vehicle in the direction of the lightning flash. The resulting flash blindness may persist for periods of 30 seconds or more, rendering the crew member temporarily unable to use his eyes for flight or instrument-reading purposes.

Personnel inside vehicles may also be subjected to hazardous effects from lightning strikes. Serious electrical shock may be caused by currents and voltages, conducted via control cables or wiring leading to the cockpit from control surfaces or other hardware struck by lightning. Shock can also be induced by the intense thunderstorm electromagnetic fields.

The shock varies from mild to serious; sufficient to cause numbness of hands or feet and some disorientation or confusion. This can be quite hazardous in high-performance aircraft, particularly under the thunderstorm conditions during which lightning strikes generally occur.

Tests to evaluate these personnel effects are not included in this document.

3.0 STANDARD LIGHTNING PARAMETER SIMULATION

3.1 Purpose

Complete natural lightning flashes cannot be duplicated in the laboratory. Most of the voltage and current characteristics of lightning, however, can be duplicated separately by laboratory generators. These characteristics are of two broad categories: The VOLTAGES produced during the lightning flash and the CURRENTS that flow in the completed lightning channel. With a few exceptions, it is not necessary to simulate high-voltage and high-current characteristics together.

The high-voltage characteristics of lightning determine attachment points, breakdown paths, and streamer effects, whereas the current characteristics determine direct and indirect effects.

In most cases, lightning voltages are simulated by high-impedance voltage generators operating into high-impedance loads, while lightning currents are simulated by low-impedance current generators operating into low-impedance loads.

The waveforms described in this section are idealized. Definitions relating to actual waveshapes are covered in ANSI and IEEE Standard Techniques for Dielectric Tests. ANSI C68.1 (1968) and IEEE No. 4. These specifications are equivalent and are in turn equivalent to High Voltage Test Techniques, IEC 60-2 (1973). The definitions in these documents should be used to determine the front time, duration and rate of rise of actual waveforms.

Severe lightning flash voltage and current waveforms, as described in Paragraph 3.2 have been developed for purposes of qualification testing: waveforms in Paragraph 3.3 are for R&D or screening test purposes and are designated engineering tests.

3.2 Waveform Descriptions for Qualification Tests

3.2.1 Voltage Waveforms

The basic voltage waveform to which vehicles are subjected is one that rises until breakdown occurs either by puncture of solid insulation or flashover through the air or across an insulating surface. The path that the flashover takes, either puncture or surface flashover, depends on the rate of rise of the voltage as shown in Figure 3-1.

During some types of testing it is 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 occur on a vehicle as a lightning flash approaches.

Although the exact voltage waveform produced by natural lightning is not known, flight service data and conservative test philosophy justify the definition of fast rising voltage waveforms for the tests just described. Voltage testing for qualification purposes thus calls for two different standard voltage waveforms. These are shown in Figure 3-2 and are described in the following sections. The qualification tests in which these waveforms are applied are presented in the test matrix of Table 1. The objectives of each test, the test setup, measurement and data requirements are described in Section 4.0.

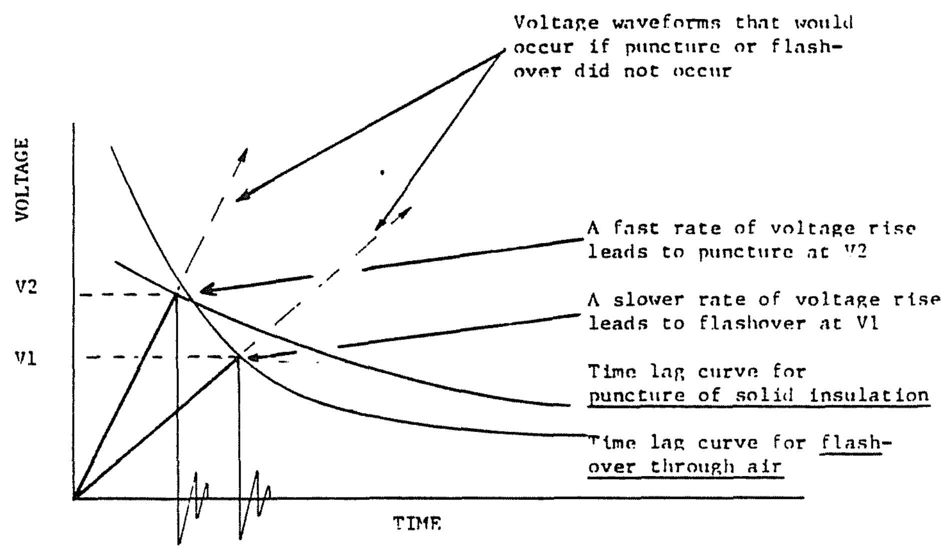


Figure 3-1 Influence of rate of rise on flashover path

3.2.1.1 Voltage Waveform A - Basic Lightning Waveform

This waveform rises at a rate of 1000 kV per microsecond (±50%) until its increase is interrupted by 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 the lightning voltage generator) is not specified. Voltage waveform A is shown in Figure 3-2.

3.2.1.2 Voltage Waveform B - Full Wave

Waveform B is a 1.2 x 50 microsecond waveform which is the electrical industry standard for impulse dielectric tests. It rises to crest in 1.2 (±20%) microseconds and decays to half of crest amplitude in 50 (±20%) microseconds. Time to crest and decay time refer to the open circuit voltage of the lightning voltage generator, and assume that the waveform is not limited by puncture or flashover of the object under test. This waveform is shown on Figure 3-2.

3.2.2 Current Waveforms

It is difficult to reproduce a severe lightning flash by laboratory simulation because of inherent facility limitations. Accordingly, for determining the effects of lightning currents and for laboratory qualification testing of vehicle hardware, an idealized representation of the components of a severe lightning flash incorporating the important aspects of both positive and negative flashes has been defined and is shown on Figure 3-3.

For qualification testing, there are four components, A, B, C, and D, used for determination of direct effects and test waveform E used for determination of indirect effects. Components A, B, C, and D each simulate a different characteristic of the current in a natural lightning flash and are shown on Figure 3-3. They are applied individually or as a composite of two or more components together in one test. There are very few cases in which all four components must be applied in one test on the same test object. Rise time or rate of change of current has little effect on physical damage, and accordingly has not been specified in these components. Current waveform E, also shown on Figure 3-3, is intended to determine indirect effects. When evaluating indirect effects, rate of change of current is important and is specified.

The tests in which these waveforms are applied are presented in Table 1. The objectives of each test along with setup, measurement, and data requirements are described in Section 4.0.

3.2.2.1 Component A - Initial High Peak Current

This component simulates the first return stroke and is characterized by a peak amplitude of 200 kA (±10%) and an action integral ($\int i^2 dt$) of 2 x 10^6 amp^2-seconds (±20%) with a total time duration not exceeding 500 microseconds.

The actual waveshape of this component is purposely left undefined, because in laboratory simulation the waveshape is strongly influenced by the type of surge generator used and the characteristics of the device under test. Natural lightning currents are unidirectional, but for laboratory simulation this component may be either unidirectional or oscillatory.

3.2.2.2 Component B - Intermediate Current

This component simulates the intermediate phase of a lightning flash in which currents of several thousand amperes flow for times on the order of several milliseconds. It is characterized by a current surge with an average current of 2 kA (±10%) flowing for a maximum duration of 5 milliseconds and a maximum charge transfer of 10 coulombs. The waveform should be unidirectional, e.g. rectangular, exponential or linearly decaying.

3.2.2.3 Component C - Continuing Current

Component C simulates the continuing current that flows during the lightning flash and transfers most of the electrical charge. This component must transfer a charge of 200 coulombs (±20%) in a time of between 0.25 and 1 second. This implies current amplitudes of between 200 and 800 amperes. The waveform should be unidirectional, e.g. rectangular, exponential or linearly decaying.

3.2.2.4 Component D - Restrike Current

Component D simulates a subsequent high peak current. It is characterized by a peak amplitude of 100 kA (±10%) and an action integral of 0.25 x 10^6 ampere^2-second (±20%).

3.2.2.5 Current Waveform E - Fast Rate of Rise Stroke Test for Full-Size Hardware

Current waveform E simulates a full-scale fast rate of rise stroke for testing vehicle hardware which at full scale would be 200 kA at 100 kA/µs. The peak amplitude of the derivative of this waveform must be at least 25 kA per microsecond for at least 0.5 microsecond, as shown in Figure 3-3. Current waveform E has a minimum amplitude of 50 kA. An amplitude of 50 kA is used to enable testing of typical aircraft components with conventional laboratory lightning current generators. The action integral, fall time, and the rate of fall are not specified. If desired and feasible, components A or D may be applied with a 25 kA per microsecond rate of rise for at least 0.5 microsecond and the direct and indirect effects evaluation conducted simultaneously.

3.3 Waveform Descriptions for Engineering Tests

3.3.1 Purpose

Lightning voltage and current waveforms described in the following paragraphs have been developed for engineering design and analysis.

The tests in which these waveforms are applied are presented in Table 2. The objectives of each test, along with setup, measurement and data requirements are described in Section 4.0.

3.3.2 Voltage Waveforms

During tests on model vehicles to determine possible attachment points the length of gap used between the electrode simulating the approaching leader and the vehicle depends upon the model scale factor. During such tests it is desirable to allow the streamers from the model sufficient time to develop. Accordingly, for model tests it is necessary to standardize the time at which breakdown occurs, even though the rate of rise of voltage is different for different tests.

It has been determined in laboratory testing that the results of attachment point testing are influenced by the voltage waveform. Fast rising waveforms (on the order of a few microseconds) produce a relatively few number of attach points, usually to the apparent high field regions on the model and all such attach points are classified as Zone 1. Fast rising waveforms have been used for practically all aircraft model attach points tests in the U.S. Slow front waveforms (on the order of hundreds of microseconds) produce a greater spread of attach points, possibly including attachments to low field regions. Therefore the test data must be analyzed by appropriate statistical methods in defining Zone 1 regions.

Two high voltage waveforms are described in the following paragraphs and shown on Figure 3-4. The first is a fast waveform which is to be used for what will be termed "fast front model tests." The second waveform is a slow rising waveform which will be employed for "slow front model tests."

3.3.2.1 Voltage Waveform C - Fast Front Model Tests

This is a chopped voltage waveform in which flashover of the gap between the model under test and the test electrodes occurs at 2 microseconds (±50%). The amplitude of the voltage at time of flashover and the rate of rise of voltage prior to breakdown are not specified. The waveform is shown on Figure 3.4.

3.3.2.2 Voltage Waveform D - Slow Front Model Tests

The slow fronted waveform has a rise time between 50 and 250 microseconds so as to allow time for streamers from the model to develop. It should give a higher strike rate to the low probability regions than otherwise might have been expected.

3.3.3 Current Waveforms

Current waveform components F and G, shown on Figure 3-5, are intended to determine indirect effects on very large hardware and full size vehicles. These waveforms are specified at reduced amplitudes to overcome inherent full vehicle test circuit limitations and also to allow testing at non-destructive levels to be made on operational vehicles at non-destructive levels. Scaling will depend on the nature of the coupling process as detailed in the following paragraphs.

3.3.3.1 Test Waveform F - Reduced Amplitude Unidirectional Waveform

Component F simulates, at a low current level, both the rise time and decay time of the return stroke current peak of the lightning flash. It has a rise time of 2 microseconds (±20%), a decay time to half amplitude of 50 microseconds (±20%) and a minimum amplitude of 250 amperes. Indirect effects measurements made with this component must be extrapolated to the full lightning current amplitude of 200 kA.

3.3.3.2 Test Waveforms G_1 and G_2 - Damped Oscillatory Waveforms

Fast rate of rise current waveforms and higher amplitude waveforms may often be usefully employed for indirect effects testing. For indirect effects dependent upon resistive or diffusion flux effects (i.e. not aperture coupling) a low frequency oscillatory current - waveform G_1, in which the period (1/f) is long compared with the diffusion time, should be used. This requires a frequency, f, of 2.5 kilohertz or lower (i.e. the duration of each half-cycle is equal to or greater than 200 μs). Where resistive or diffusion effects are measured, the scaling should be in terms of the peak current, with full scale being 200 kA.

For indirect effects dependent upon aperture coupling the high frequency current, waveform G_2 should be used. The maximum frequency of waveform G_2 should be no higher than approximately 300 KHz or 1/10 of the lowest natural resonant frequency of the aircraft/return circuit, whichever is lower. Where aperture-coupled effects are measured the scaling should be in terms of rate-of-rise (di/dt), with full scale being 100 kA/μs.

When testing composite structures with waveform G_2, resistive and diffusion flux induced voltages may occur as well as aperture coupled voltages, and results should be scaled both to 200 kA and to 100 kA/μs.

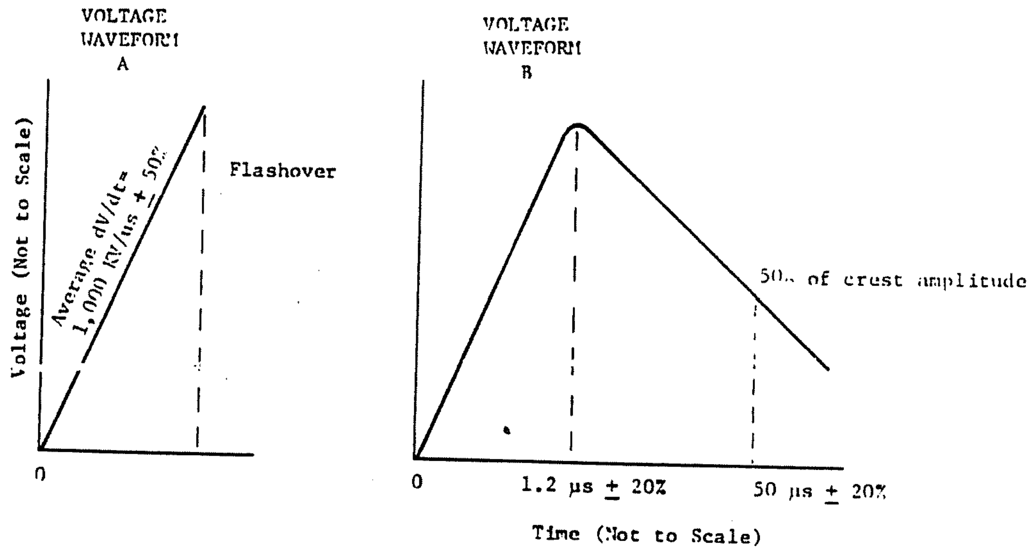


Figure 3-2 Idealized High-voltage test waveforms for qualification testing.

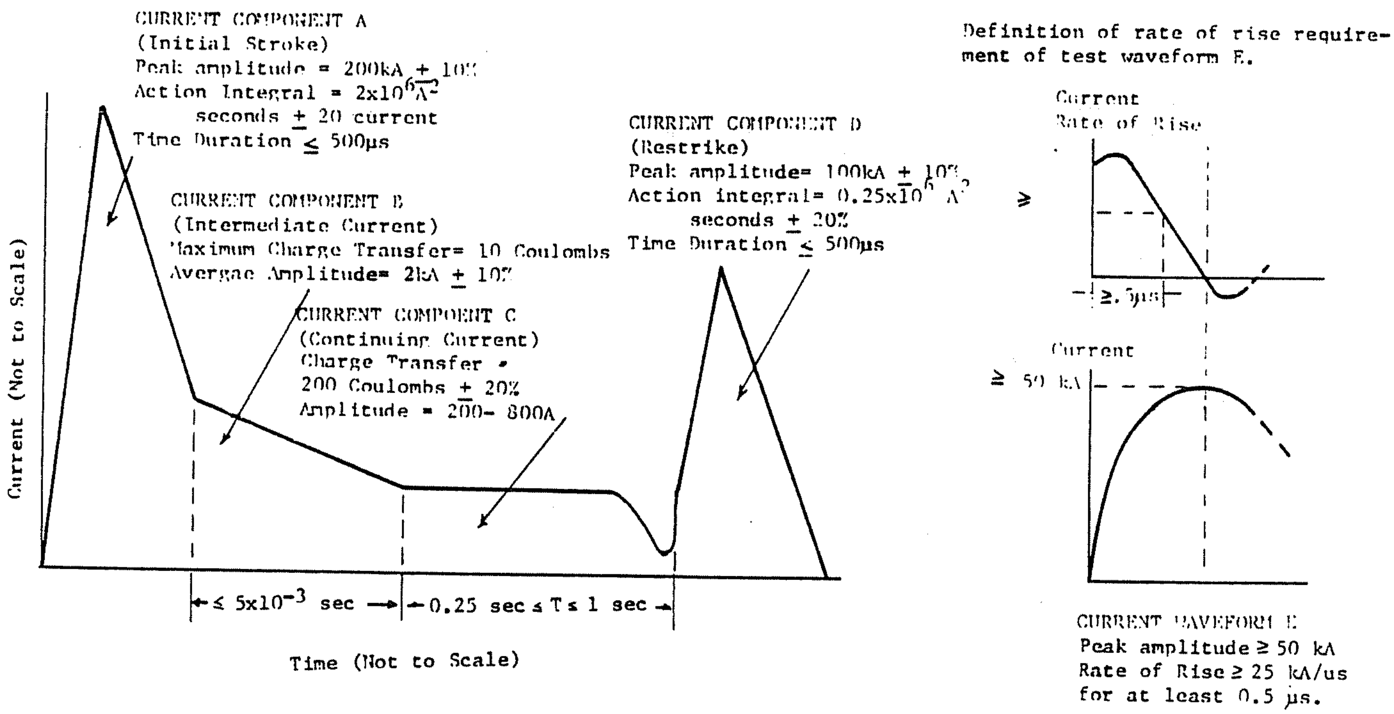


Figure 3-3 Idealized current test waveform components for qualification testing.

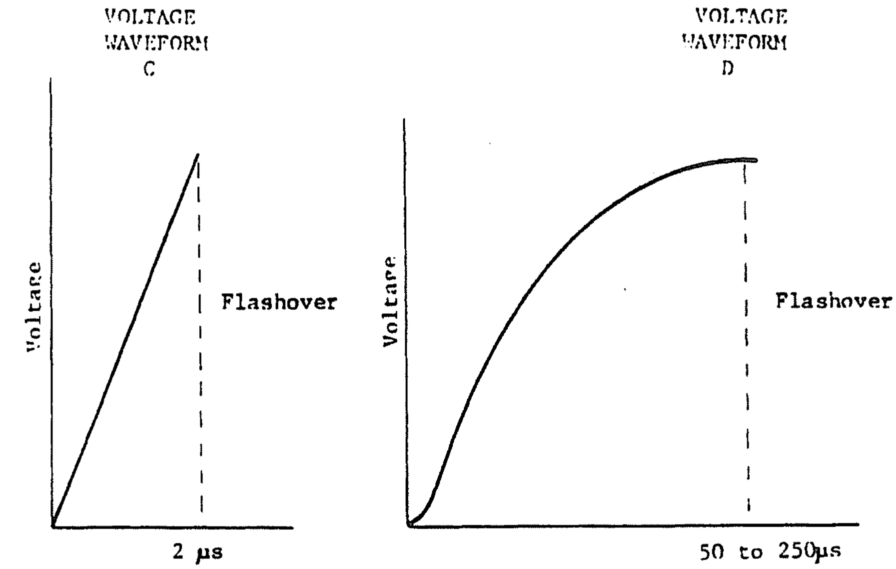


Figure 3-4 Idealized high voltage waveforms for engineering tests.

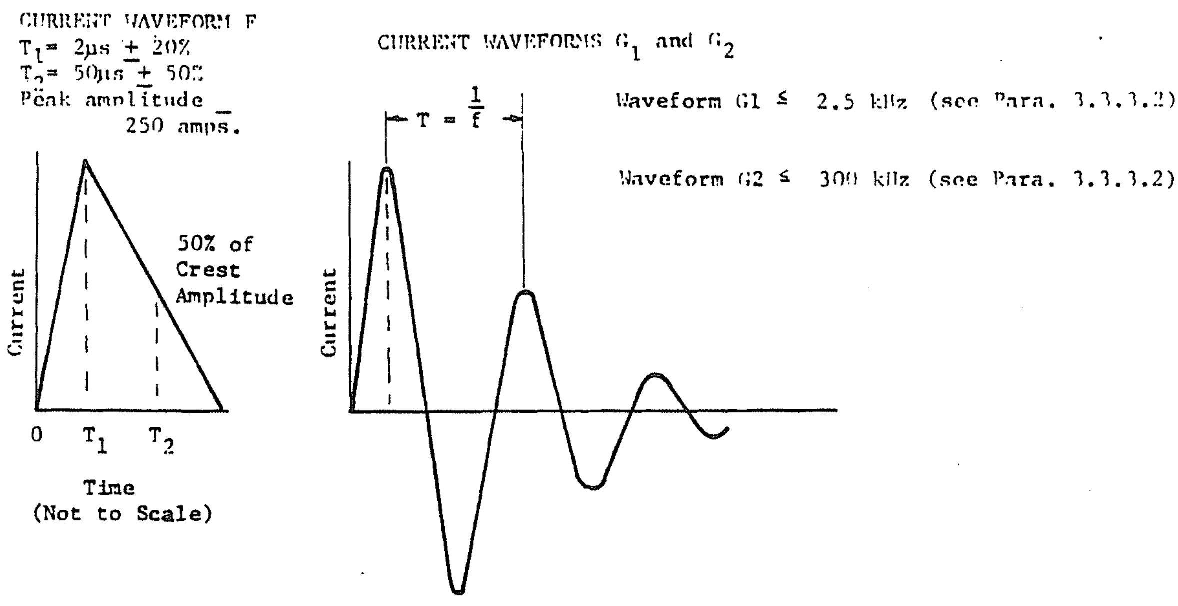


Figure 3-5 Idealized current waveforms for engineering tests. (Note: Peak amplitudes are not the same.)

Table 1

Application of Waveforms for Qualification Tests

Test	Zone	Voltage Waveforms A	B	D	Current Waveforms/Components A	B	C	D	E	Test Technique Para. No.
Full size hardware attachment point	1A,B	X		X						4.1.1
Direct effects - structural	1A				X	X				4.1.2, 4.1.2.2.1
"	1B				X	X	X	X		4.1.2, 4.1.2.2.2
"	2A					X	X	X		4.1.2, 4.1.2.2.3
"	2B					X	X	X		4.1.2, 4.1.2.2.4
"	3				X		X			4.1.2, 4.1.2.2.5
Direct effects - combustible vapor ignition	Same current components as for structural tests									4.1.3
Direct effects - streamers			X							4.1.4
Indirect effects - external electrical hardware									X[3]	4.1.5

Note 1. Use average current of 2 kA ± 10% for a dwell time less than 5 milliseconds measured in Test 4.2.2 up to a maximum of 5 milliseconds

Note 2. Use average current of 400 amp for dwell time in excess of [illegible] msec as determined by engineering tests.

Note 3. Indirect effects shoud also be measured with current components A, B, C, D as appropriate to the test zone

Note 4. The appropriate fraction of component "C" expected for the location and surface finish.

Table 2

Application of Waveforms for Engineering Tests

Test	Zone	Voltage Waveforms C	D	Current Waveforms/Components C	E	F	G_1	G_2	Test Technique Para. No.
Model aircraft lightning attachment point test									
Fast front		X							4.2.1
Slow front			X						4.2.1
Full size hardware attachment test	2A			X	X				4.2.2
Indirect effects - complete						X or	X +	X	4.2.3

4.0 TEST TECHNIQUES

The simulated lightning waveforms and components to be used for qualification testing are presented in Table 1. This table gives the current components that will flow through an aircraft structure or specimen in each zone. In some cases, however, not all of the current components specified in the table will contribute significantly to the failure mechanism. Therefore, in principle, the non-contributing component(s) can be omitted from the test. If components are to be omitted from a test for this reason, the proposed test plan should be agreed upon with the cognizant regulatory authority.

Table 2 presents waveforms suggested for engineering tests. The objective of each qualification or engineering test, setup and measurement details and data requirements are described in the following paragraphs.

4.1 Qualification Tests

4.1.1 Full Size Hardware Attachment Point Tests - Zone 1

4.1.1.1 Objective

This attachment point test will be conducted on full size structures that include dielectric surfaces to determine the detailed attachment points on the external surface, and if the surface is nonmetallic, the path taken by the lightning arc in reaching a metallic structure.

4.1.1.2 Waveforms

Test voltage waveform A should be applied between the electrode and the grounded test object. In the case of test objects having particularly vulnerable or flight-critical components it may be advisable to repeat the tests using waveform D as a confirmatory test.

4.1.1.3 Test Setup

The test object should be a full-scale production line hardware component or a representative prototype, since minor changes from design samples or prototypes may change the lightning test results. All conducting objects within or on nonmetallic hardware that are normally connected to the vehicle when installed in the aircraft should be electrically connected to ground (the return side of the lightning generator). Surrounding external metallic vehicle structure should be simulated and attached to the test object to make the entire test object look as much like the actual vehicle region under test as possible.

The test electrode to which test voltage is applied should be positioned so that its tip is 1 meter away from the nearest surface of the test object. Dimensions of the test electrode are not critical. Generally, model tests or field experience will have indicated that lightning flashes can approach the object under test from several different directions. If so, the tests should be repeated with the high voltage electrode oriented to create strokes to the object from these different directions.

If the test object is so small that a 1-meter gap permits strokes to miss the test object, or if a 1-meter gap is inappropriate for other reasons, shorter or longer gaps may be used. Multiple flashovers should be applied from each electrode position. Tests may be commenced with either positive or negative polarity. If test electrode positions are found from which the simulated lightning flashovers do not contact the test piece, or do not puncture it if it is nonmetallic, the tests from these same electrode positions should be repeated using the opposite polarity.

4.1.1.4 Measurements and Data Requirements

Measurements that should be taken during these tests include the following:

a. Test Voltage and Amplitude Waveform. The voltage applied to the gap should be measured. Photographs of the voltage waveform should be taken to establish that waveform A is in fact being applied. Voltage measurements should be made of each test voltage waveform applied since breakdown paths, and hence the test voltage, may change. Particular attention should be given to assuring that the gap flashes over on the wavefront. If a flashover occurs on the wave tail, the test should be repeated with the generator set to provide a higher voltage or the test electrode positioned closer to the test object so as to produce flashover on the wavefront.

b. Attachment Points and/or Breakdown Paths. The voltage generators used for these tests are high impedance devices. The test current may be much less than natural lightning currents. Consequently, they will produce much less damage to the test object than a natural lightning flash, even though the breakdown will follow the path a full-scale lightning stroke current would follow. Occasionally a diligent search will be required to find the attachment point on metals or the breakdown path through nonmetallic surfaces. These attachment points or breakdown paths should be looked for after each test and marked, when found, with masking tape or crayon markings to prevent confusion with further test results.

4.1.2 Direct Effects - Structural

4.1.2.1 Objective

These tests determine the direct effects which lightning currents may produce in structures.

4.1.2.2 Waveforms

Simulated lightning current waveform components should be applied, depending on the vehicle zone of the test object, as follows:

4.1.2.2.1 Zone 1A

Waveform components A and B should be applied.

4.1.2.2.2 Zone 1B

Waveform components A, B, C, and D should be applied in that order, but not necessarily as one continuous discharge.

4.1.2.2.3 Zone 2A

Although Zone 2A is a swept stroke zone, static tests can be conducted once the attachment points and dwell times have been determined. Current components D, B, and C should be applied in that order as appropriate to the following discussion.

High peak current restrikes typically produce re-attachment of the arc at a new point. Therefore, current component D is applied first. The dwell time for components B and C in Zone 2A may be determined from swept stroke tests as described in Paragraph 4.2.2 or, alternatively, a worst case dwell time of 50 milliseconds may be assumed without conducting swept stroke tests. The timing mechanism of the generator producing component B should be set to allow current to flow into the test object (at any single point) for the maximum dwell time at that point as determined from the dwell point tests. If the measured dwell time is greater than 5 milliseconds or if a 50 millisecond dwell time has been assumed, the component B current should be reduced to 400 amperes (component C) for the dwell time in excess of 5 milliseconds. If the measured dwell time is less than 5 milliseconds, component B should be applied for the length of time measured, down to a minimum of 1 millisecond.

4.1.2.2.4 Zone 2B

Current components B, C and D should be applied in that order.

4.1.2.2.5 Zone 3

Current components A and C should be applied in that order to test objects in Zone 3. The test currents should be conducted into and out of the test object in a manner similar to the way lightning currents would be conducted through the aircraft.

4.1.2.3 Test Setup

4.1.2.3.1 Test Electrode and Gap

The test currents are delivered from a test electrode positioned adjacent to the test object. The test object is connected to the return side of the generator(s) so that test current can flow through the object in a realistic manner.

CAUTION: There may be interactions between the arc and current carrying conductors. Care must be taken to assure that these interactions do not influence the test results.

The electrode material should be a good electrical conductor with ability to resist the erosion produced by the test currents involved. Yellow brass, steel, tungsten and carbon are suitable electrode materials. The shape of the electrode is usually a rounded rod firmly affixed to the generator output terminal and spaced at a fixed distance above the surface of the test object.

The polarity of components A and D can be either positive or negative. The polarity of the generators used to produce components B and C should be set so that the electrode is negative with respect to the test object, because greater damage is generally produced when the test object is at positive polarity with respect to the test electrode.

4.1.2.4 Measurements and Data Requirements

Measurements for these tests include test current amplitude(s) and waveform(s). Initial stroke, restrike and intermediate current components may be measured with noninductive resistive shunts, current transformers, or Rogowski coils. Continuing currents may be measured with resistive shunts. The output of each of these devices should be measured and recorded.

NOTE: Indirect effects measurements are frequently required for external electrical hardware, as specified in Paragraph 4.1.6. If desired, some of these measurements can be made during the direct effects tests.

Since the condition of the test object or other parts of the test circuit may affect the test current(s) applied, measurements of these parameters should be made during each test applied, and the details of the test setup recorded for each test.

4.1.3 Direct Effects - Combustible Vapor Ignition Via Skin or Component Puncture, Hot Spots or Arcing

4.1.3.1 Objective

The objective of these tests is to ascertain the possibility of combustible vapor ignition as a result of skin or component puncture, hot spot formation, or arcing in or near fuel systems or other regions where combustible vapors may exist.

CAUTION: These tests simulate the possible direct effects which may cause ignition. Ignition of combustible vapors may also be caused by lightning indirect effects such as induced voltages in fuel probe wiring, etc.

If a blunt electrode is used with a very small gap, the gas pressure and shock wave effects in the confined area may cause more physical damage than would otherwise be produced. The electrode should be rounded to allow relief of the pressure formed by the discharge.

For multiple component tests, the test electrode should be placed as far from the test object surface as the driving voltage of the intermediate component B or continuing current component C will allow. A gap spacing of at least 50 mm is desirable but a lesser gap of at least 10 mm is required which will result in more conservative data. When components B or C are preceded by the high peak current component A, the high driving voltage of this generator initiates the arc and subsequent components B and/or C follow the established arc even though driven by a much lower voltage.

4.1.3.2 Waveforms

The same test current waveforms should be applied as are specified for structural damage tests in Paragraph 4.1.2.2.

4.1.3.3 Test Setup

Test setup requirements are the same as those described in Paragraph 4.1.2.3 for structural damage tests, with the following additional considerations:

If a complete fuel tank is not available or impractical for test, a sample of the tank skin or other specimen representative of the actual structural configuration (including joints, fasteners and substructures, attachment hardware, as well as internal fuel tank fixtures) should be installed on a light-tight opening or chamber. Photography is the preferred technique for detecting sparking. If photography can be employed, the chamber should be fitted with an array of mirrors to make any sparks visible to the camera. However, for regions where possible sparking activity cannot be made visible to the camera, ignition tests may be used by placing an ignitable fuel-air mixture inside the tank. This can be a mixture of propane and air (e.g., for propane: a 1.2 stoichiometric mixture) or vaporized samples of the appropriate fuel mixed with air. Verification of the combustibility of the mixture should be obtained by ignition with a spark or corona ignition source introduced into the test chamber immediately after each lightning test in which no ignition occurred. If the combustible mixture was not ignitable by this artificial source, the lightning test must be considered invalid and repeated with a new mixture until either the lightning test or artificial ignition source ignites the fuel.

4.1.3.4 Measurements and Data Requirements

The same test current measurements should be made as are specified for structural damage tests in Paragraph 4.1.2.4.

The presence of an ignition source should be determined by photography of possible sparking. For this purpose a camera is placed in the test chamber and the shutter left open during the test. Experience indicates that ASA 3000 speed film exposed at f4.7 is satisfactory. All light to the chamber interior must be excluded. Any light indications on the film due to internal sparking after test should be taken as an indication of sparking sufficient to ignite a combustible mixture.

CAUTION: This method of determining the possibility of sparking should be utilized only if certainty exists that all locations where sparking might exist are visible to the camera.

More specialized instrumentation may be added if additional information such as skin surface temperatures, pressure rises, or flame front propagation velocities are desired.

4.1.4 Direct Effects - Streamers

4.1.4.1 Objective

Electrical streamers initiated by a high voltage field represent a possible ignition source for combustible vapors. The objective of this test is to determine if such streamers may be produced in regions where such vapors exist.

4.1.4.2 Waveforms

Test voltage waveform B should be applied for this test. The crest voltage should be sufficient to produce streamering, but not sufficient to cause flashover in the high-voltage gap. Generally, this will require that the average electric field gradient between the electrodes be at least 5 kV/cm.

4.1.4.3 Test Setup

The test object should be mounted in a fixture representative of the surrounding region of the airframe and be subjected to the high-voltage waveform. The voltage may be applied either by (1) grounding the test object and arranging the high-voltage test electrode sufficiently close to the test object to create the required field at the test voltage level applied or (2) connecting the test object to the high-voltage output of the generator and arranging the test object in proximity to a ground plane or other ground electrode that is connected to the ground or low side of the generator. In either case the low voltage side of the generator should be grounded. Either arrangement can provide the necessary electric field at the test object aperture. The test object should be at positive polarity with respect to ground, since this polarity usually provides the most profuse streamering.

4.1.4.4 Measurements and Data Requirements

Measurements should include test voltage waveform and amplitude, and degree and location of streamering. The presence of streamering at locations where combustible vapors are known to exist is considered an ignition source. The presence of streamering can best be determined with photography of the test object while in a darkened area. If the presence of streamers is questionable, the test should be run with a combustible mixture actually present in the test object to determine if ignition occurs, but care should be taken to ensure that the test arrangement simulates relevant operational (i.e., in-flight) characteristics.

4.1.5 Direct Effects - External Electrical Hardware

4.1.5.1 Objective

The object of this test is to determine the amount of physical damage which may be experienced by externally mounted electrical components, such as pitot tubes, antennas, navigation lights, etc. when directly struck by lightning.

4.1.5.2 Waveforms, Test Setup, and Measurements and Data Requirements

Same as for structures test as described in Paragraph 4.1.2.

4.1.6 Indirect Effects - External Electrical Hardware

4.1.6.1 Objective

The objective of this test is to determine the magnitude of indirect effects that occur when lightning strikes externally mounted electrical hardware, such as antennas, electrically heated pitot tubes, or navigation lights. For such hardware the indirect effects include conducted currents and surge voltages, and induced voltages. These currents and voltages may then be conducted via electrical circuits to other systems in the vehicle. Therefore, during the direct effects tests of electrical hardware mounted within Zones 1 or 2, measurements should be made of the voltage appearing at all electrical circuit terminals of the component. In addition, a fast rate of rise test should be conducted for evaluation of magnetically induced effects.

4.1.6.2 Waveforms

Current components A through D used for evaluation of direct effects are also used for evaluation of indirect effects, particularly those relating to the diffusion or flow of current through resistance. The specific waveforms to be used are the same as those specified in Paragraph 4.1.2. In addition, the fast rate of change current waveform E should be applied for evaluation of magnetically induced effects.

Indirect effects measured as a result of this waveform must be extrapolated as follows. Induced voltages dependent upon resistive or diffusion flux should be extrapolated linearly ~~to a peak current~~ of 200 kA.

Induced voltages dependent upon aperture coupling should be extrapolated linearly to a peak rate-of-rise of 100 kA/μs.

4.1.6.3 Test Setup

The test object should be mounted on a shielded test chamber so that access to its electrical connector(s) can be obtained in an area relatively free from extraneous electromagnetic fields. This is necessary to prevent electromagnetic interference originating in the lightning test circuit from interfering with measurement of voltages induced in the test object itself. The test object should be fastened to the test chamber in a manner similar to the way it is mounted on the aircraft, since normal bonding impedances may contribute to the voltages induced in circuits. If the shielded enclosure is large enough, the measurement/recording equipment may be contained within it. If not, a suitable shielded instrument cable may be used to transfer the induced voltage signal from the shielded enclosure to the equipment. In this case, the equipment should be located so as not to experience interference.

The test electrode should be positioned so as to inject simulated lightning current into the test object at the probable attachment point(s) expected from natural lightning. For tests run concurrently with direct effects tests on the same test object, this should be an arc-entry (flashover from test electrode to test object); but for tests made only to determine the indirect effects, hard-wired connections can be made between the generator output and test object. This is appropriate especially if it is desired to minimize physical damage to the test object. The test object should be grounded via the shielded enclosure so that simulated lightning current flows from the test object to the shielded enclosure in a manner representative of the actual installation.

4.1.6.4 Measurements and Data Requirements

Measurements should include test current amplitude(s) and waveform(s) as specified for the direct effects tests utilizing the same waveforms in Paragraph 4.1.2. In addition, measurements should be made of conducted and induced voltages at the terminals of electrical circuits in the test object.

Measurement of the voltages appearing at the electrical terminals of the test object should be made with a suitable recording instrument having a bandwidth of at least 30 megahertz.

In some cases it is appropriate to make measurements of the voltage between two terminals, as well as of the voltage between either terminal and ground. Since the amount of induced voltage originating in the test object which can enter systems such as a power bus or an antenna coupler depends partly on the impedances of these items, these impedances should be simulated and connected across the electrical terminals of the test object where the induced voltage is being measured.

The resistance, inductance and capacitance of the load impedance should be included. A typical test and measurement circuit is shown in Figure 4.1.

CAUTION: Interference-free operation of the voltage measurement system should be verified.

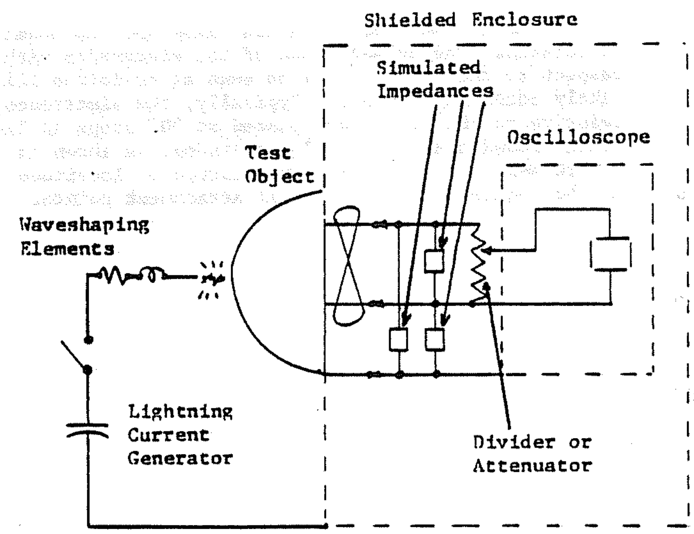


Figure 4-1 Essential elements of electrical hardware indirect effects, test and measurement circuit.

4.2 Engineering Tests

4.2.1 Model Aircraft Lightning Attachment Point Test

4.2.1.1 Objective

The objective of the model test is to determine the places on the vehicle where direct lightning strikes are likely to attach.

4.2.1.2 Waveforms

If it is desired to determine the places on the aircraft where lightning strikes are most probable, then voltage waveform C may be utilized. If it is desired, in addition, to identify other surfaces where strikes may also occur on rare occasion, voltage waveform D may be utilized. The longer rise-time of waveform D allows development of streamers and attachment points in regions of lower field intensity (in addition to those of high intensity at surfaces of high strike probability.

4.2.1.3 Test Setup

Tests on small-scale models are helpful for determining attachment zones. In some cases, tests on models must be supplemented by other means to determine exact attachment zones or points. This is particularly true of aircraft involving large amounts of nonmetallic structural materials.

An accurate model of the vehicle exterior from 1/30 to 1/10 full scale should be constructed. The various possible vehicle configurations should also be modeled. Conducting surfaces on the aircraft should be represented by conductive surfaces on the model, and vice versa.

The model is then positioned on insulators between the electrodes of a rod-rod gap or the electrode and a ground plane of a rod-plane gap. The length of the upper gap should be at least 1.5 times the longest dimension of the model. The direction of approach becomes less controllable at much higher ratios and the stroke may even miss the model. The lower gap, may be as much as 2.5 times the longest dimension of the model and should be at least equal to the model dimension.

Commonly the electrodes are fixed and the model is rotated. The orientations of the electrodes with respect to the model should be such as to define all likely attachment points. Typically, the electrodes, relative to the model, are placed at 30° steps in latitude around the 0° and 90° longitudes, as shown in Figure 4-2. Smaller steps in latitude or longitude may be required to identify all attachment points.

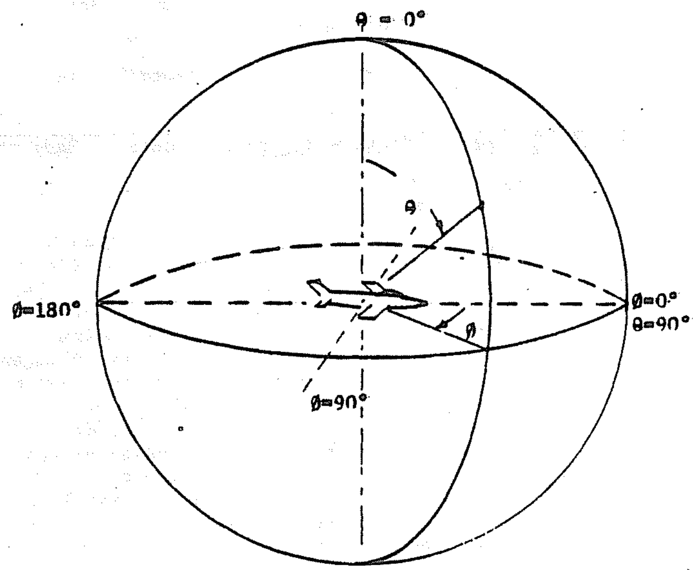


Figure 4-2 Aircraft coordinate system.

If rotation of the model significantly changes the gap lengths, it may be necessary to reposition the electrode. Typically three to ten shots are taken with the aircraft in each orientation to simulate lightning flashes approaching from different directions. Photographs, preferably with two cameras at right angles to each other, should be taken of each shot in order to determine the attachment points. The upper electrode should be positive with respect to ground and/or the lower electrode.

4.2.2 Full-Size Hardware Attachment Point Test - Zone 2

4.2.2.1 Objective

The mechanism of arc attachment in Zone 2 regions is fundamentally different from that in Zone 1. The basic mechanism of attachment is shown on Figure 4-3. The arc first attaches to point 1 and then, viewing the test object as stationary, is swept back along the surface to point 2. When the heel of the arc is above point 2 the voltage drop at the arc-metal interface is sufficiently high to cause flashover of the air gap and puncture of the surface finish at point 2 causing it to re-attach there.

The arc will again be blown back along the surface until the voltage along the arc channel and arc-metal interface is sufficient to cause flashover and attachment to another point. The voltage at which each new attachment will occur depends strongly upon the surface finish of the object under test. The voltage available to cause puncture depends upon the current flowing in the arc and the degree of ionization in its channel. There is an inductive voltage rise along the arc as rapidly changing currents flow through it. There will also be a resistive voltage rise produced by the flow of current. The inductive voltage rise as well as the resistive rise can be quite significant when a lightning restrike occurs at some point in the flash.

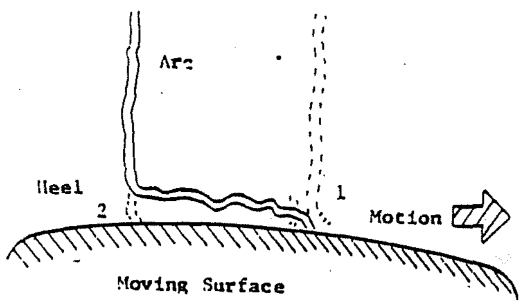


Figure 4-3 Basic mechanism of swept stroke attachment.

In addition, if the flash is discontinuous for a brief period a very high voltage is available prior to flow of the next current component. Because the channel remains hot and may contain residual ionized particles, this voltage stress is greatest along it and subsequent current components are likely to flow along the same channel. Such a voltage may well be higher than voltages created by currents flowing in the channel and may cause re-attachment to metallic surfaces or puncture of nonmetallic surfaces or dielectric coatings.

The time during which an arc may remain attached to any single point (dwell time) is a function of the lightning flash and surface characteristics which govern reattachment to the next point. The dwell time is also a function of aircraft speed.

Swept stroke attachment point and dwell time phenomena are therefore of interest for two main reasons. First, if there is an intervening nonmetallic surface along the path over which the arc may be swept, the swept stroke phenomena may determine whether the nonmetallic surface will be punctured or whether the arc will pass harmlessly across it to the next metallic surface.

Second, the dwell time of an arc on a metallic surface is a factor in determining if sufficient heating may occur at a dwell point to burn a hole or form a hot spot capable of igniting combustible mixtures or causing other damage. Thus, over a fuel tank it is particularly important that the arc move freely, in order that the metal skin of the tank not be heated or burned to a point that fuel vapors are ignited.

The objectives of attachment studies in Zone 2 are then:

<u>For metallic surfaces</u>
(including conventional painted or treated surfaces):
To determine possible attachment points and associated dwell times.

<u>For nonmetallic surfaces</u>
(including metallic surfaces with high dielectric strength coatings):
To determine if punctures may occur.

4.2.2.2 <u>Waveforms</u>

4.2.2.2.1 <u>Metallic Surfaces</u>

To determine arc dwell times on metallic surfaces, including conventional painted or treated surfaces, it is necessary to simulate the continuing current component of the lightning flash. Thus the simulated continuing current should be in accordance with current component C.

The current generator driving voltage must be sufficient to maintain an arc length that moves freely along the surface of the test object. The test electrode should be far enough above the surface so as not to influence the arc attachment to the test surface. If the technique of Figure 4-3 is used, the electrode should be a rod parallel to the air stream and approximately parallel to the test object.

A restrike may be added to the continuing current after initiation to determine whether a restrike with its associated high current amplitude would cause re-attachment to points other than those to which the continuing current arc would re-attach. If a restrike is used it is most appropriate that it be the fast rate of change of current waveform shown as current waveform E on Figure 3-3.

4.2.2.2.2 <u>Nonmetallic Surfaces</u>

To determine whether it is possible for dielectric punctures or reattachments to occur on nonmetallic surfaces or coating materials, including metallic surfaces with high dielectric strength coatings, it is necessary to simulate the high-voltage characteristics of the arc. High voltages are caused by (1) current restrikes in an ionized channel, or (2) voltage buildup along a deionized channel. These characteristics are simulated by a test in which a restrike is applied along a channel previously established by a continuing current. The restrike must be initiated by a voltage rate of rise of 1000 kV/μs or faster and must discharge a high rate of rise current stroke in accordance with current waveform E. This restrike must not be applied until the continuing current has decayed to near zero (a nearly deionized state) as shown in Figure 4-4.

Several tests should be applied with the continuing current duration and restrikes applied according to different times, T, in order to produce worst-case exposures of the surface and underlying elements to voltage stress.

The amplitude of the continuing current is not critical and may be lower or higher than that of current component C. Other aspects of this test are as described in Paragraph 4.2.2.2.1.

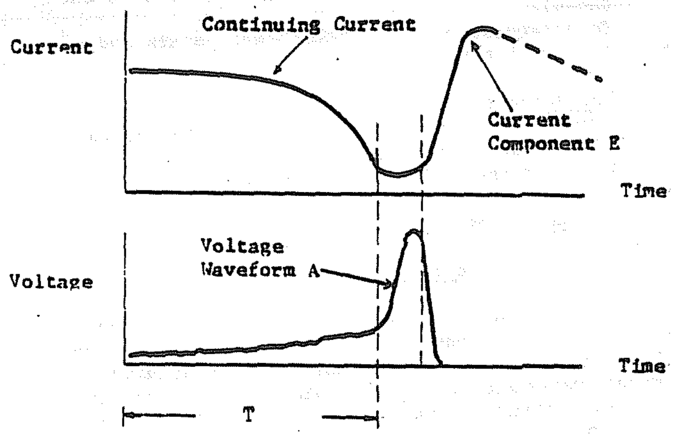


Figure 4-4 Swept stroke waveforms for tests of nonmetallic surfaces.

4.2.2.3 Test Setup

Two basic methods have been used to simulate the swept stroke mechanism. One of these involves use of a wind stream to move the arc relative to a stationary test surface as shown in Figure 4-5. The other method involves movement of the test surface relative to a stationary arc as shown in Figure 4-6. Other methods may also be satisfactory if they adequately represent the in-flight interaction between the arc and the aircraft surface. Relative velocity should include but not be limited to the minimum in-flight velocity of the vehical, which is when the dwell time condition is most critical.

The test electrode should be far enough above the surface so as not to influence the arc attachment to the test surface. If the technique of Figure 4-5 is used, the electrode should be a rod parallel to the air stream and approximately parallel to the test object.

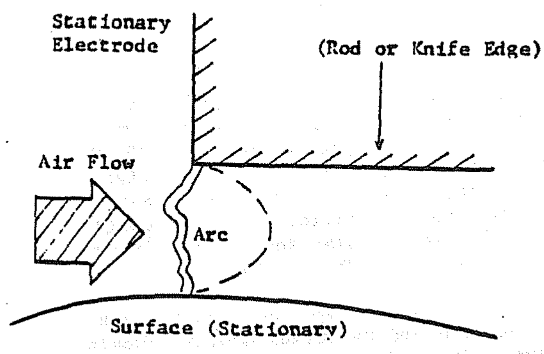


Figure 4-5 Arc moved relative to stationary test surface.

4.2.2.4 Measurements and Data Requirements

The most important measurements are those giving the attachment points, arc dwell times, breakdown paths followed, and the separation between attachment points. These are most easily determined from high speed motion picture photographs of the arc. Measurements should be made of the air flow or test object velocity and the amplitude and waveform of the current passing through the test object.

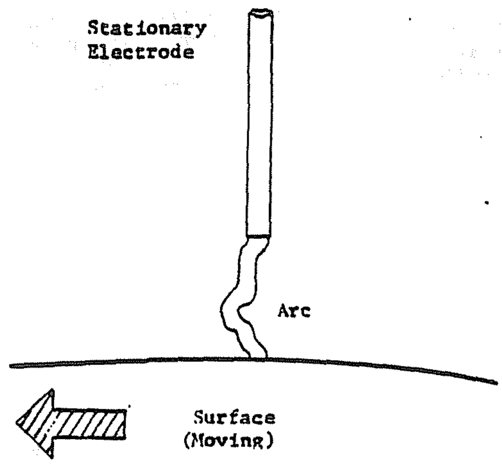


Figure 4-6 Test surface moved relative to stationary arc.

4.2.3 Indirect Effects - Complete Vehicle

4.2.3.1 Objective

The objective of this test is to measure induced voltages and currents in electrical wiring within a complete vehicle. Complete vehicle tests are intended primarily to identify circuits which may be susceptible to lightning induced effects.

4.2.3.2 Waveforms

Two techniques, utilizing different waveforms, may be utilized to perform this test. One involves application of a scaled down unidirectional waveform representative of a natural lightning stroke.

The second technique involves performance of the test with two or more damped oscillatory current waveforms, one of which (component G_2) provides the fast rate of rise characteristic of a natural lightning stroke wavefront, and the other (component G_1) provides a long duration period characteristic of natural lightning stroke duration. Induced voltages should be measured in the aircraft circuits when exposed to both waveforms and the highest induced voltages taken as the test results.

Each test is carried out by passing test currents through to the complete vehicle and measuring the induced voltages and currents. Checks are also made of aircraft systems and equipment operations where possible.

4.2.3.2.1 Unidirectional Test Waveform

Waveform F should be applied.

4.2.3.2.2 Oscillatory Waveforms

Waveforms G_1 and G_2 should be applied.

4.2.3.3 Test Setup

The test current should be applied between several representative pairs of attachment points such as nose-to-tail or wing tip-to-wing tip. Typical test setups are shown in Figure 4-7.

Attachment pairs are normally selected so as to direct current through the parts of the vehicle where circuits of interest are located.

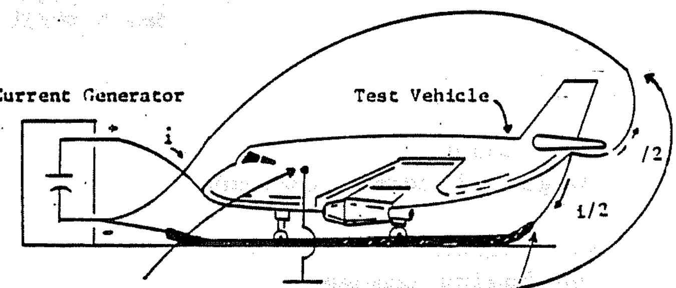
Multiple return conductors should be used to minimize test circuit inductance and proximity effects. Typical test setups are shown in Figure 4-7.

4.2.3.4 Measurements and Data Requirements

The test current amplitude, waveform, and resulting induced voltages and currents in the aircraft electrical and avionics systems should be measured.

CAUTION: Interference-free operation of the voltage measurement system should be verified.

Voltages measured during the complete vehicle tests should be extrapolated to full threat levels in the same manner as described in Para. 4.1.6.2 for indirect effects measurements in external electrical hardware. Situations such as arcing paths or nonlinear impedances exist which may result in nonlinear relationships between induced voltages and applied current. Careful study of the vehicle under test, however, can usually identify such situations. When testing fueled vehicles, care should be taken to prevent sparks across filler caps, as even low amplitude currents can cause sparking across poor bonds or joints. In doubtful situations, fuel tanks should be rendered nonflammable by nitrogen inerting.



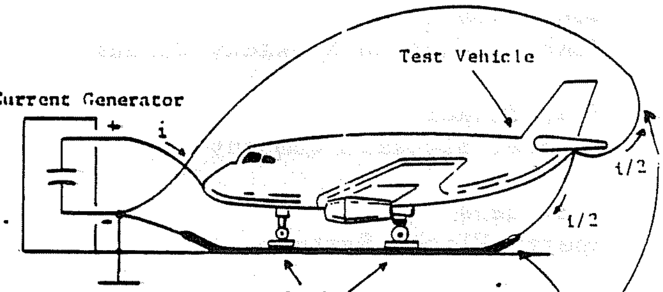


Figure 4-7. Typical setups for complete vehicle tests.

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