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Lightning Protection Guidelines for Aerospace Vehicles

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PREFACE

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ABBREVIATIONS AND ACRONYMS

A	ampere
ATP	authority to proceed
C	coulomb
CDR	critical design review
DCR	design certification review
DOD	Department of Defense
ECP	engineering change proposal
EED	electroexplosive device
EME	electromagnetic effects
EOM	end of mission
EMP	electromagnetic pulse
ETDL	equipment transient design level
FAA	Federal Aviation Administration
FRR	flight readiness review
GSE	ground support equipment
I_{SC}	short circuit current
LCIL	lightning critical items list
LRU	line replaceable unit
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NSTS	National Space Transportation System
PDR	preliminary design review
PRCB	Program Requirements Control Board
PRR	preliminary requirements review
RFP	request for proposal
s	second
SAE	Society of Automotive Engineers
SIR	system integration review
TCL	transient control level
TPS	thermal protection system
US	United States
V_{OC}	open circuit voltage

LIST OF DEFINITIONS

Action integral—A critical factor in the production of lightning damage related to the energy deposited or absorbed in a system. The actual energy deposited cannot be defined without knowledge of the resistance of the system.

Arc attachment—The point of contact of the lightning flash with the vehicle so that current can flow onto the vehicle from this point.

Cable—Any quantity of electrical wires grouped together to form a single bundle.

Cable shield—Any metallic covering on a single (coaxial) or multiple conductor cable. The shield form may be tinned or untinned copper braid, wrapped aluminum or copper foil tape, or rigid metal conduit.

Cable tray—Refers to standard supporting members for signal and power cable groups.

Charge transfer—The integral of the current over its entire duration, $I(t)dt$ (coulombs).

Direct effects—Any physical damage to an element's structure due to the direct attachment of the lightning channel or the flow of current through the vehicle's structures, either when the vehicle is on the ground or in flight. This includes thermal and shock wave effects on the exterior skins, coatings, or other exposed components such as windshields, nozzles, umbilical, fuel and oxidizer lines, edges, control surfaces, and engines. Damage to electrical or avionics systems or individual equipment due to direct attachment of the lightning flash to an exposed part of such a system is also termed a direct effect.

Final entry point—The spot where the lightning flash channel last "enters" the vehicle (usually a trailing edge).

Indirect effects—Voltage and/or current transients produced in vehicle electrical wiring due to lightning currents in the elements that can upset and/or damage components within electrical/electronic systems. These transients occur due to one or more coupling mechanisms; i.e., changing magnetic or electric fields and structural voltage rises due to lightning currents in structural resistance. Thus, voltage induced in a sensor wire harness by changing magnetic fields accompanying lightning currents in the vehicle is termed an indirect effect. Voltages appearing in umbilical conductors due to lightning currents in umbilical cable shields are also called indirect effects.

Induced currents—Currents, known as capacitively coupled currents, appearing in electrical circuits due to changing electrical fields. Also currents in complete or closed circuits driven by induced voltages in these circuits.

Induced voltages—Voltages, known as magnetically coupled voltages, appearing in electrical circuits due to changing magnetic fields passing through circuits.

Initial entry point—The spot where the lightning flash channel first "enters" the vehicle (usually an extremity).

Initial exit point—The spot where the lightning flash channel first "exits" the vehicle (usually a trailing edge).

Internal environment—Includes the structural current and voltage changes with associated distribution and the aperture-coupled and diffused electromagnetic fields.

Lightning attachment points—Any spot where the lightning flash attaches to the vehicle.

Lightning flash—The total lightning event in which charge is transferred from one charge center to another within a cloud, between clouds, or between a cloud and ground. The event can consist of one or more strokes plus intermediate or continuing currents. Typically, the duration of a flash is 2 seconds or less.

Lightning strike—Any attachment of the lightning flash to a vehicle or ground facility.

Lightning stroke (return stroke)—A lightning current surge that occurs when the lightning leader makes contact with the ground or other region of opposite charge.

Multiple burst—A randomly spaced series of bursts of short-duration, low-amplitude current pulses and an arc pulse or pulses characterized by rapidly changing currents. These bursts may result from lightning leader progression or branching and may be accompanied by or superimposed upon a stroke or continuing current. The multiple bursts appear to be most intense at time of initial leader attachment to a vehicle.

Multiple stroke—Two or more lightning return strokes occurring during a single lightning flash.

Subsystem—A major functional element of a system, usually consisting of several components essential to the operational completeness of the subsystem. Subsystem examples include frame, propulsion, guidance, navigation, and communication. The vehicle is referred to as the overall system.

Swept "flash" (or "strike") points—Spots where the flash channel reattaches between the initial and final points, usually associated with the entry part of the flash channel.

Powerful electrical storm near NASA Kennedy Space Center launch complex 39A prior to launch of STS–8, August 30, 1983 (NASA photograph).

TECHNICAL MEMORANDUM

LIGHTNING PROTECTION GUIDELINES FOR AEROSPACE VEHICLES

1. INTRODUCTION

1.1 Historical Perspective

Atmospheric electricity must be considered in the design, transportation, and operation of aerospace vehicles. Inadequately protected aerospace vehicles can be upset, damaged, or destroyed by a direct lightning stroke to the vehicle or launch support equipment before or after launch.[1–3] Damage can also result from current induced in the vehicle from changing electric fields produced by a nearby lightning stroke. The effect of the atmosphere as an insulator and conductor of high-voltage electricity at various atmospheric pressures must also be considered. Improperly designed high-voltage systems aboard the vehicle can arc or break down at low atmospheric pressure.

The first airplane lightning protection test standards were published in the mid-1950's by the United States (US) Federal Aviation Administration (FAA) and the US Department of Defense (DOD).[4,5] MIL–B–5087B deals exclusively with the electrical bonding of aircraft components. Bonding refers to a low-resistance electrical connection between components that is sufficient to withstand lightning currents. It was gen-erally believed that the damaging effects of lightning were limited to the exterior of the aircraft or to structures directly exposed to a lightning strike and sufficient protection would be provided if these components were adequately bonded to the main airframe.[6] The FAA Advisory Circular 25–3 deals exclusively with the protection of aircraft fuel systems.[4]

In the 1960's two spectacular incidents indicated clearly that other lightning-related effects led to catastrophic accidents. On December 8, 1963, a lightning strike ignited fuel in the reserve tank of a Boeing 707 commercial airliner. The left wing of the aircraft was destroyed and 81 people on board were killed. In 1969, Apollo 12 was launched into clouds that had been producing lightning. The Saturn V rocket artificially triggered two discharges. The lightning strikes produced major system upsets but only minor permanent damage; the vehicle and crew survived and completed their mission.[1] These accidents motivated the FAA and the DOD to request that the Society of Automotive Engineers (SAE) Committee on Electromagnetic Compatibility (SAE–AE4) formulate improved lightning protection design and test standards. The SAE report quickly became the standard for the US civil aviation industry.[7] A revised report followed in 1978.[8] This report, given a blue cover, became known as the "blue book" and was adopted for both civil and military aircraft by the US and foreign certification agencies. The SAE-defined lightning environment was formally incorporated into military and civil protection specifications in MIL–STD–1757, revision MIL–STD–1757A, and FAA Advisory Circular 20–53A.[9–11]

A panel convened in the early 1970's to formulate lightning protection standards for the National Aeronautics and Space Administration (NASA) Space Shuttle program. The result was "Shuttle Lightning Protection Criteria Document," *NSTS–07636*.[12] The lightning environment defined in this document predated and differed somewhat from the SAE 1978 report, but key aspects of the current test waveforms are practically the same.

Several recent trends in the design of aerospace vehicles result in an increased vulnerability to the indirect effects of lightning. These developments include the use in the skin and structure of the vehicle of nonmetallic, lightweight composite materials that do not shield the interior of the aircraft as efficiently as a metal body and an increased reliance on digital flight control electronics as opposed to analog and mechanical systems. If composite material is not fabricated with a metallic screen, significant structural damage could occur from spurious signals induced or coupled into the interior of the vehicle where they may damage or upset electronic processing equipment.[13] A recent example of hazards associated with indirect lightning effects is provided by the Atlas/Centaur accident in March 1987.[3] Investigation of that incident determined that the vehicle was struck by a triggered cloud-to-ground flash. The lightning current caused a transient signal to be coupled into the Centaur digital computer unit where data in a single memory location were changed. The computer subsequently issued an erroneous yaw command that resulted in large dynamic stresses on the vehicle and caused vehicle breakup.

Indirect lightning hazards have required additional measures in protection design philosophy. To better evaluate lightning hazards, new research programs were undertaken in the 1980's by the NASA, U.S. Air Force, FAA, and French Government. Experimental results from these studies were incorporated into the most recent aerospace vehicle lightning standards and guidelines.[14–17]

1.2 Requirements and Responsibilities

Aerospace vehicles, flight hardware, ground support equipment (GSE), and all facilities where potentially hazardous tests or operations are performed should be designed to withstand the lightning environment, as defined in section 2.2, without creating unsafe flight conditions or hazards to crew and ground personnel. The vehicle should withstand this environment during vehicle prelaunch processing and flight to an altitude of 60 000 ft.

Specifically, critical structures, equipment, systems, interconnecting wiring, and cabling should be analyzed for susceptibility to lightning-induced failures. Critical items identified as susceptible to the effects of lightning should be designed to withstand the lightning environment without jeopardizing the mechanical strength or function of the equipment or systems.

To ensure adequate lightning protection for a specific project, the following functions should be performed by the Lightning Protection Engineer assigned to the project:

1. Prepare, modify, and review lightning protection specifications and electromagnetic effects (EME) control plans.
2. Prepare and/or review lightning protection test plans and test reports.
3. Participate in planning and performing lightning tests.
4. Perform and/or review damage and upset analyses.
5. Perform analyses and develop computer codes for test data scaling, circuit modeling, and bond strap modeling.
6. Support project office activities; i.e.;
   a. Participate in reviews: engineering change proposals (ECP's), waivers/deviations, etc.
   b. Participate in level II reviews; system integration reviews (SIR's) and Program Requirements Control Board (PRCB).
7. Verify completeness and accuracy of requirements.
8. Prepare and/or review lightning critical items list (LCIL).
9. Prepare and/or review transient control levels (TCL's).
10. Prepare and/or review equipment transient design levels (ETDL's).

A typical flow for lightning protection tasks is illustrated in figure 1. The Lightning Protection Engineer is responsible for accomplishing all tasks, including those performed by project and/or lightning specialty contractors.

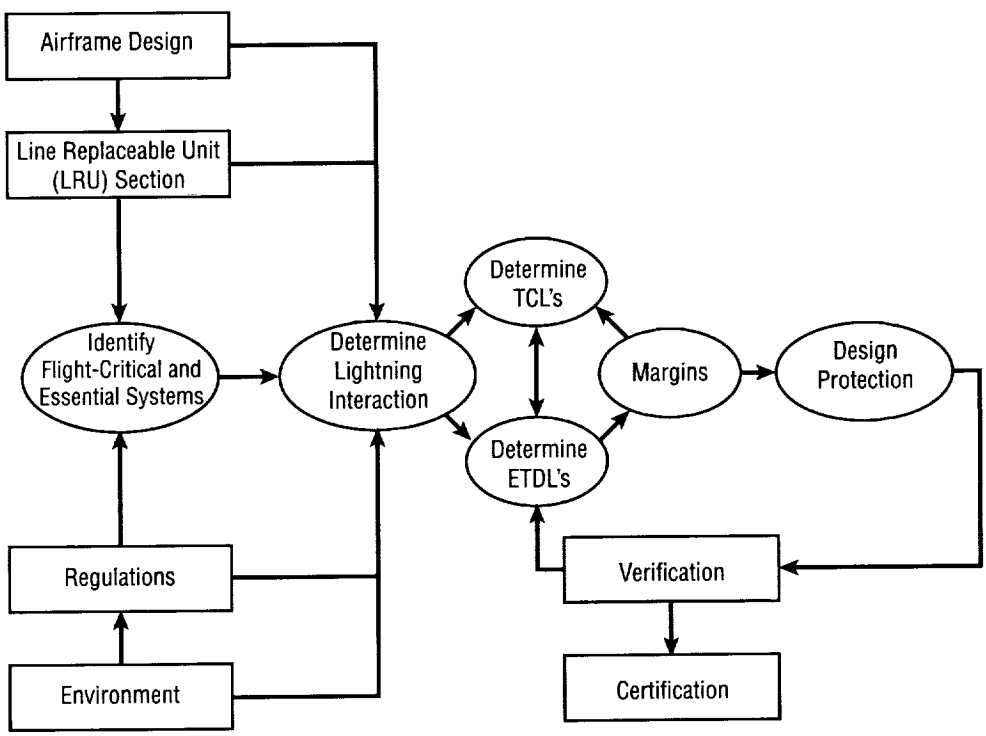


Figure 1. Lightning protection approach.

Generally, the Lightning Protection Engineer begins by developing and understanding requirements relative to the aerospace vehicle's mission. Questions concerning the vehicle addressed by the engineer includes: (1) Is the vehicle intended as an "all-weather" vehicle, (2) what form of lightning protection will be provided at the launch site, (3) is lightning protection needed during shipping/storage and/or at test sites, and (4) what are the lightning protection problem areas inherent in the vehicle design? With this information, lightning protection design requirements and lightning strike models of the vehicle are developed.

Lightning strike points are located and classified by analysis or tests. The lightning protection design is then addressed for protection from direct and indirect effects of lightning. The internal and external effects of a lightning strike are determined, analyzed, and compared with an LCIL, TCL, and ETDL to determine if the lightning protection design achieves adequate safety margins. If the lightning protection design is deficient, there are two courses of action: (1) Redesign and correct the hardware or (2) rely on launch site protection and avoidance of weather conducive to natural or triggered lightning.

1.3 Program Support

Technical support for lightning protection design must be fully coordinated with the Project Office, chief engineer, design engineers, and appropriate contractors. Coordination is important during all phases of a program. It is particularly important to establish an effective coordination procedure to allocate the necessary manpower, facilities, and tests early in the life of a program.

1.3.1 Program Phases

NASA programs consist of the following distinct phases:

Phase A—preliminary analysis
Phase B—definition and preliminary design
Phase C—design
Phase D—development/operation.

General program level information on each program phase is found in the NASA Marshall Space Flight Center (MSFC) *Systems Engineering Handbook.*[17] An example of tasks and deliverables specific to lightning protection during each phase is outlined in figure 2.

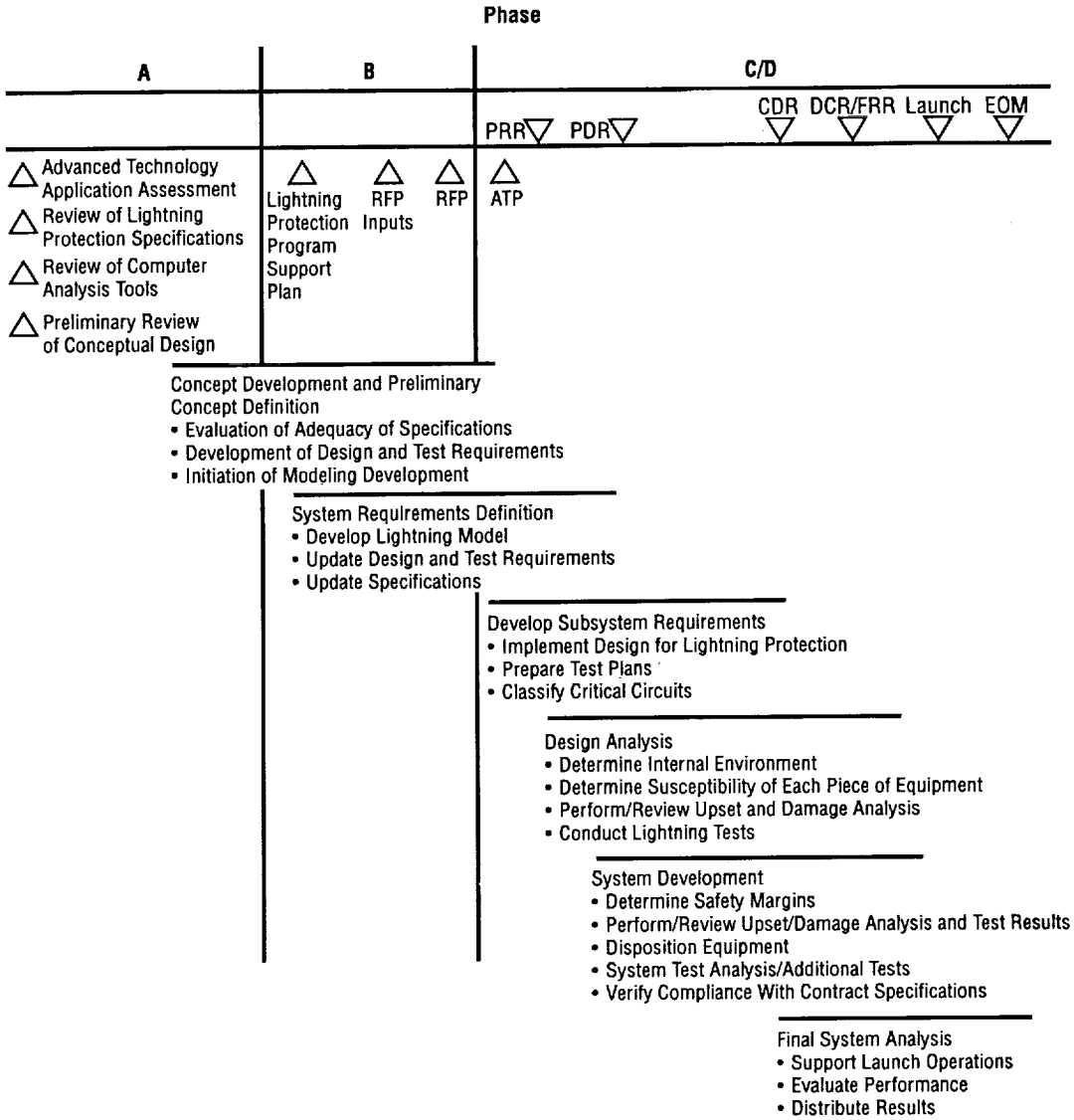


Figure 2. Lightning protection program support plan.

1.3.2 Phase A—Preliminary Analysis

The first step in phase A is to determine if a lightning protection system is required, and if so, to identify the basic requirements. Once a basic set of requirements is outlined, an analysis is performed to determine if current technology meets the requirements or if advanced technology is needed. Assessment of the need for lightning protection during phase A is an iterative process. In addition to safety, cost and weight should be primary consideration factors in the selection of any lightning protection system concept.

1.3.3 Phase B—Definition and Preliminary Design

During phase B, mission and vehicle preliminary designs are incorporated into the lightning protection requirements. Special studies may be required, such as determination as to whether the vehicle structure and covering (thermal protective system (TPS)) can withstand the direct effects of a lightning strike. An initial estimate of internal and external effects of a lightning strike is made. Preliminary consideration is given to the development of a lightning protection specification, a control plan, an LCIL, and assessments of TCL's and ETDL's. Lightning protection requirements during this phase are usually generic since the vehicle and equipment are still in the preliminary design. Figure 3 illustrates the flow process through phases A and B.

1.3.4 Phases C/D—Design and Development/Operations

During the design development phase, lightning strike models and lightning protection requirements are developed or updated. As a program progresses, the baseline design for protection from direct and indirect lightning effects is determined, test requirements are prepared, and tests are conducted. As hardware becomes available, tests are conducted to verify the modeling analyses and proposed lightning protection design.

Vehicle and payload configurations are modeled to locate the most likely entry/exit strike points and to compute the division of lightning current on the structure. This information determines the direct effects of lightning (burning and blasting) and indirect effects (induced cable coupling and circuit upset or damage). An upset and damage analysis and other special analyses are performed on each lightning critical item to established susceptibility levels. Safety margins are determined by comparing susceptibility levels with threat levels. Discrepancies are resolved by modifying the lightning protection design or the equipment.

When neither modification to the lightning protection design nor modification to equipment provides adequate safety margins, the solution must either be reliance on the launch site and facility lightning protection system or operations restriction when weather conductive to lightning activity is forecast.

The deliverables produced should constitute a sound system engineering approach to lightning protection for the project. Many of the steps described may be performed by various organizations or contractors. However, the overall responsibility to ensure that these deliverables are accurately produced is the project's Lightning Protection Engineer.

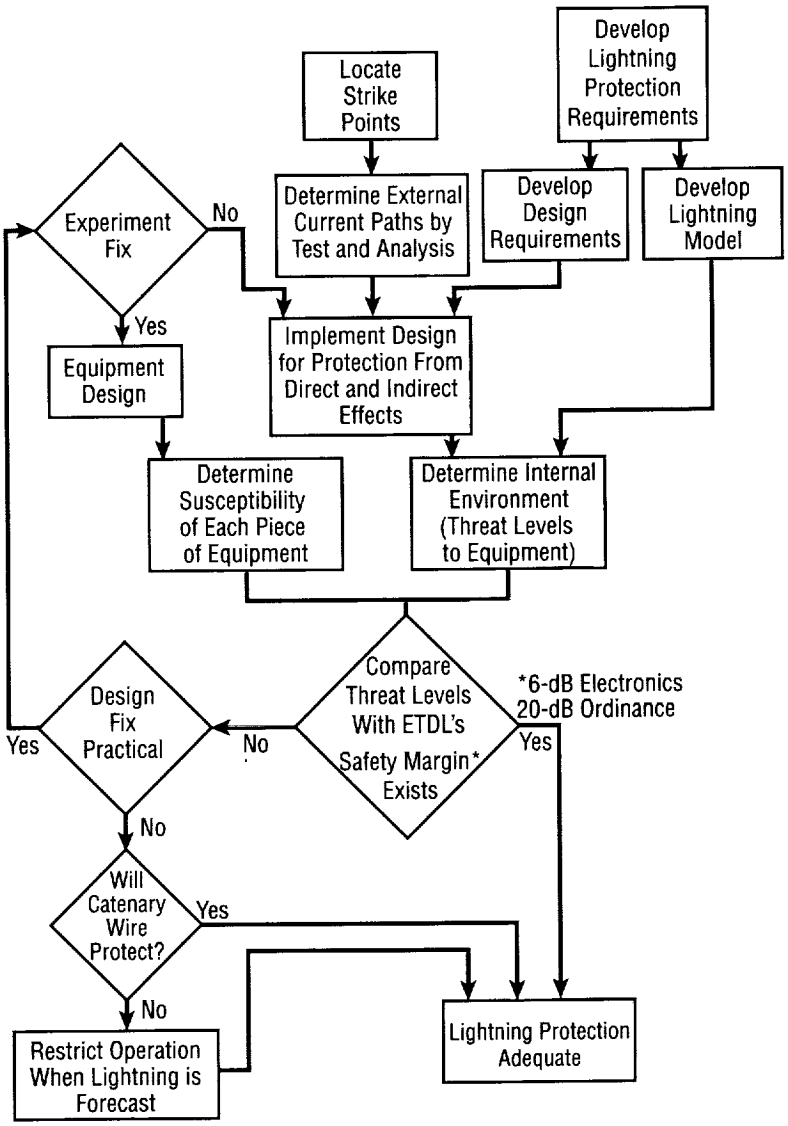


Figure 3. Lightning protection process.

2. LIGHTNING—COMPLEX ELECTRICITY

2.1 Overview

Lightning is a secondary effect of electrification within a thunderstorm cloud system. It is a giant electrical spark that can have a peak current flow >200 000 A during a period of a few microseconds.

Thunder results from the sudden heating of the air to ≈20 000 K by the flow of current along a narrow channel. This flow of current can be from cloud to ground as several individual strokes separated by a tenth of a second, or it can be from cloud to cloud in strokes that are not readily visible from the ground but which diffusely illuminate the cloud. It can also be from cloud through an aircraft or aerospace vehicle operating in the vicinity. About 1 800 thunderstorms are active over the Earth's surface at any given time. Lightning strikes the Earth ≈100 times per second.

On a cloudless day, the potential electrical gradient in the atmosphere near the surface of the Earth is relatively low (<300 V/m); but when clouds develop, the potential gradient near the surface of the Earth increases. If the clouds become large enough to have water droplets of sufficient size to produce rain, the atmosphere potential gradient may be sufficient to result in a lightning discharge with measured gradients >10 000 V/m at the surface.

A variety of charge separation processes occurs at the microphysical and cloud-size scales.[18] These processes vary in importance, depending on the developmental stage of convective clouds. However, it has been suggested that both induction and interface charging are the primary electrification mechanisms in convective clouds.[19] Inductive charging involves bouncing collisions between particles in the external field. The amount of charge transferred between the polarized drops at the moment of collision depends on the time of contact, contact angle (no charge transferred at grazing collisions), charge realization time, and net charge on the particles. Interface charging involves the transfer of charge due to contact or freezing potentials during the collisions between riming precipitation particles and ice crystals. The size and magnitude of the charge transfer depend on the temperature, liquid water content, and ice crystal size and impact velocity.

Gradients may be considerably higher at altitudes than those just above the surface. The Earth-ionospheric system can be considered as a large capacitor with the Earth's surface as the negatively charged plate, the ionosphere as the positively charged plate, and the atmosphere as the dielectric.

When a cloud develops into the cumulonimbus state, lightning discharges result. For a discharge to occur, the potential gradient at a location reaches a value equal to the critical breakdown value of air at that location. Laboratory data indicate this value is as high as 1M V/m at standard sea level atmospheric pressure. Electrical fields measured at the surface of the Earth are much lower than 1M V/m during lightning discharges. There are several reasons why:

1. Most clouds have centers of both polarities that tend to neutralize values measured at the surface.

2. Each charge in the atmosphere and its image within the Earth resemble an electrical dipole, and the intensity of the electrical field decreases with the cube of the distance from the dipole.

3. The atmospheric electric field measured over land at the surface is limited by discharge currents arising from grounded points, such as grass, trees, and other structures, which ionize the air around the points, thus producing screen space charges.

When lightning strikes a protected or unprotected object, such as an aerospace vehicle on a launch pad, the current flows through a path to the true Earth ground. The voltage drop along this path may be great enough over a short distance to be dangerous to people and equipment. Cattle and humans have been electrocuted from the current flow through the ground and the voltage potential between their feet while standing under a tree struck by lightning.

A static charge may accumulate on an object such as an aerospace vehicle from its motion through an atmosphere containing raindrops, ice particles, or dust. A stationary object, if not grounded, can also accumulate a charge from windborne particles (often as nuclei too small to be visible), or rain, or snow particles striking the object. This charge can build up until the local electric field at the point of sharpest curvature exceeds the breakdown field and, thus, triggers a lightning discharge. The quantity of maximum charge depends on the size and shape of the object (especially if sharp points are on the structure).

If a charge builds up on a structure that is not grounded, any discharges that occur could ignite explosive gases or fuels, interfere with radio communications or telemetry, or cause severe shocks to people. Static electrical charges occur more frequently during periods of low humidity and can be expected at any geographical area.

2.2 Lightning Environment

The waveforms defined in this section are idealized representations of severe lightning flashes and constitute the lightning environment that the aerospace vehicle must withstand when it is exposed on the ground to lightning and during each phase of atmospheric flight (see fig. 4 for a lightning display). This environment represents both naturally occurring and triggered lightning strikes.

The waveforms constitute an industrywide standard for lightning protection design as the fundamental basis for analyses and, where practical, for verification tests. It is recognized that testing laboratories may not be capable of generating these idealized waveforms. The issue of waveforms suitable for tests is addressed further in section 4. Results from test waveforms that deviate from the idealized waveforms should, therefore, be capable of being related to the waveforms discussed in this report.

Figure 4. A New Mexico lightning display.

The currents in a lightning flash are conveniently separated into three categories:

1. Return stroke surges with peak currents up to 200 000 A or more and duration on the order of tens of microseconds.

2. Intermediate currents up to 10 000 A or more and duration on the order of milliseconds.

3. Continuing currents up to 1 000 A and duration on the order of hundreds of milliseconds.

Intermediate and continuing currents are primarily responsible for damage such as hole burning, while return stroke currents mainly produce explosive and indirect effects.

Currents are also associated with subsequent return strokes. Phases of the return strokes are characterized by rapid rates of change. These categories, represented by idealized waveforms designated A, B, C, D, and H, are described in the following paragraphs. In mathematical definitions, the various constants are given to multidigit precision, intended only for mathematical consistency. It is not implied that the physical characteristics of lightning are known to such accuracy or that analyses and tests need to reflect such extreme accuracy and precision.

Five current component waveforms which represent a severe lightning strike event are specified in the SAE 1997 Report AE4L–97–4, the industry standard for transport aircraft.[15] AE4L–97–4 test specifications were also incorporated into a recent revision of the NASA "Lightning Protection Criteria Document."[14] AE4L–97–4 current waveforms are illustrated in figures 5 through 8.

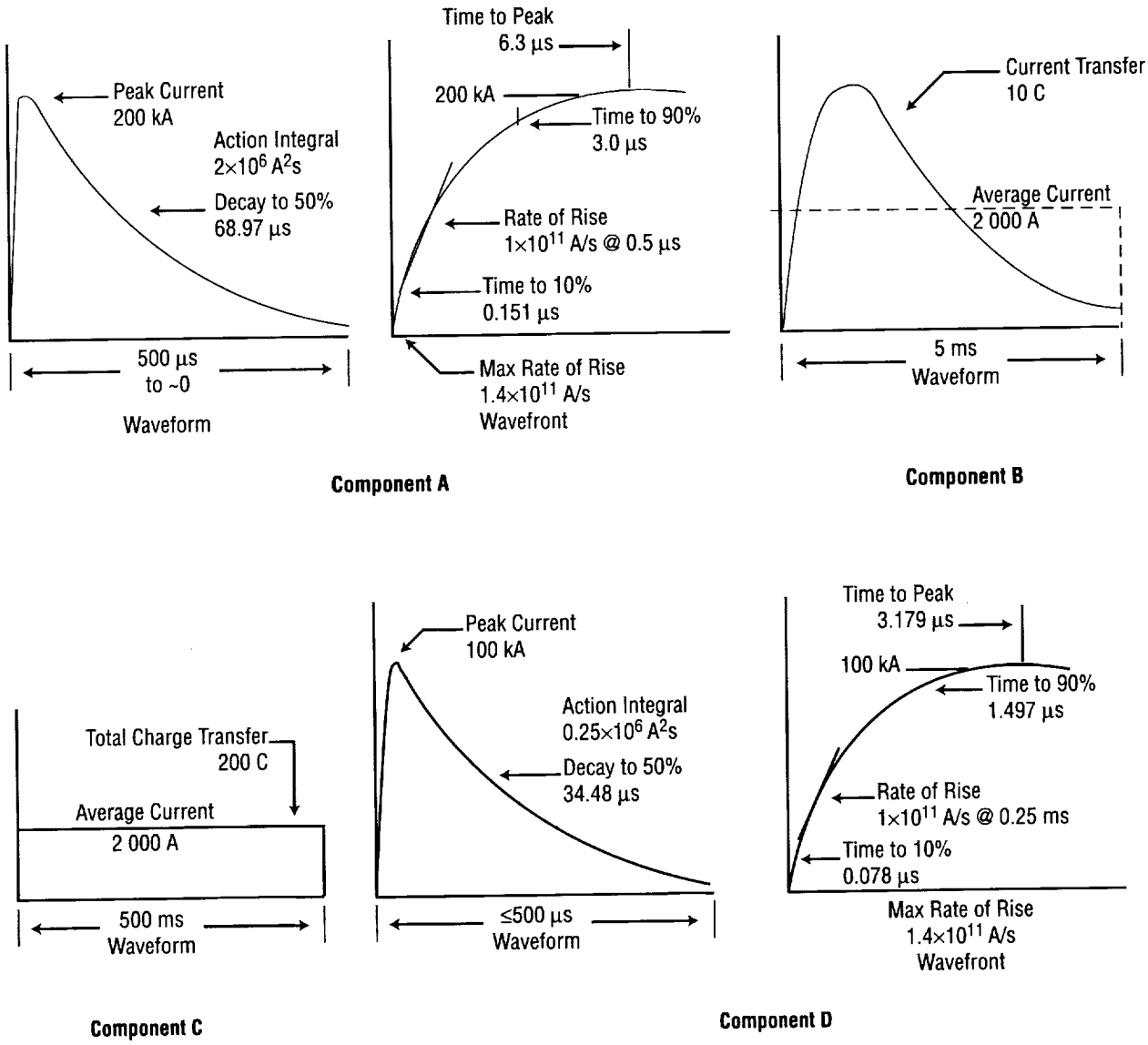
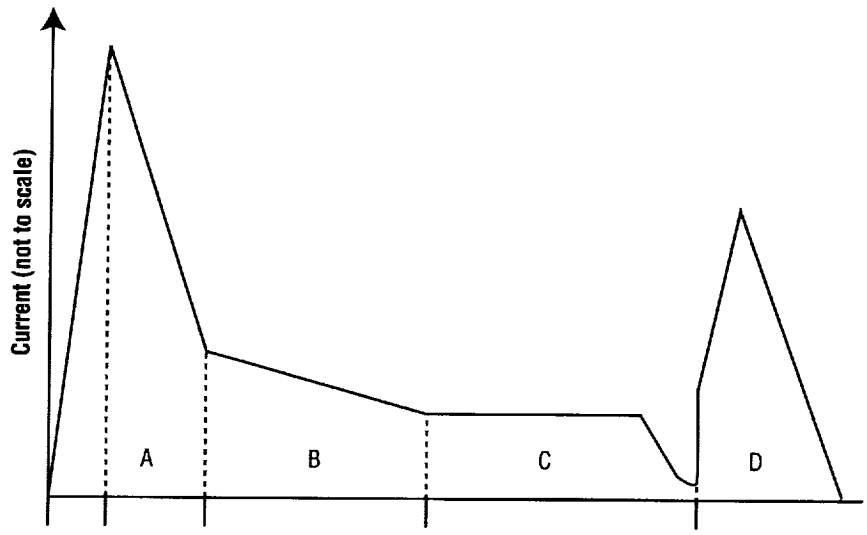


Figure 5. Current test waveforms for severe direct lightning strikes.



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

Component C (Continuing Current)
Charge Transfer = 200 C±20%
Amplitude = 200 to 800 A
Time Duration 0.25<T≤1 s

Component B (Intermediate Current)
Maximum Charge Transfer = 10 C
Average Amplitude = 2 kA±10%
Duration ≤5 ms

Component D (Restrike)
Peak Amplitude = 100 kA±10%
Action Integral = 0.25×10^6 A^2s±10%
Duration ≤5 μs

Figure 6. Current waveform composed of the four components A, B, C, and D.

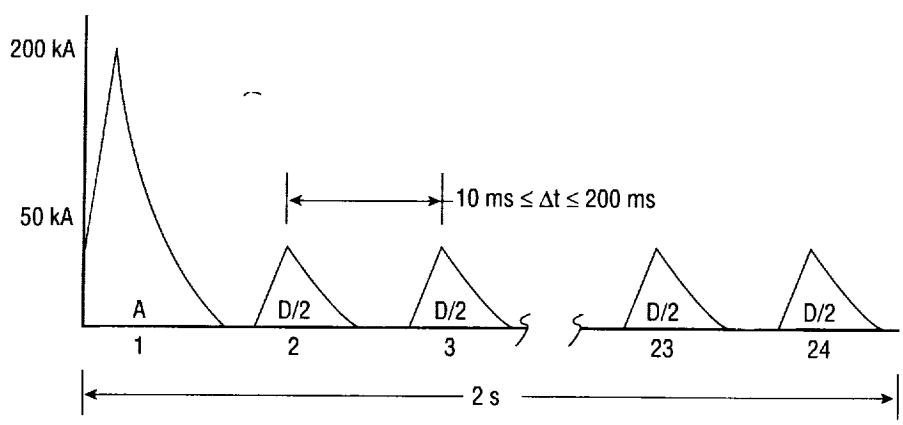


Figure 7. Multiple-stroke lightning current test waveform consisting of a first stroke (component A) followed by 23 subsequent strokes (attenuated D components).

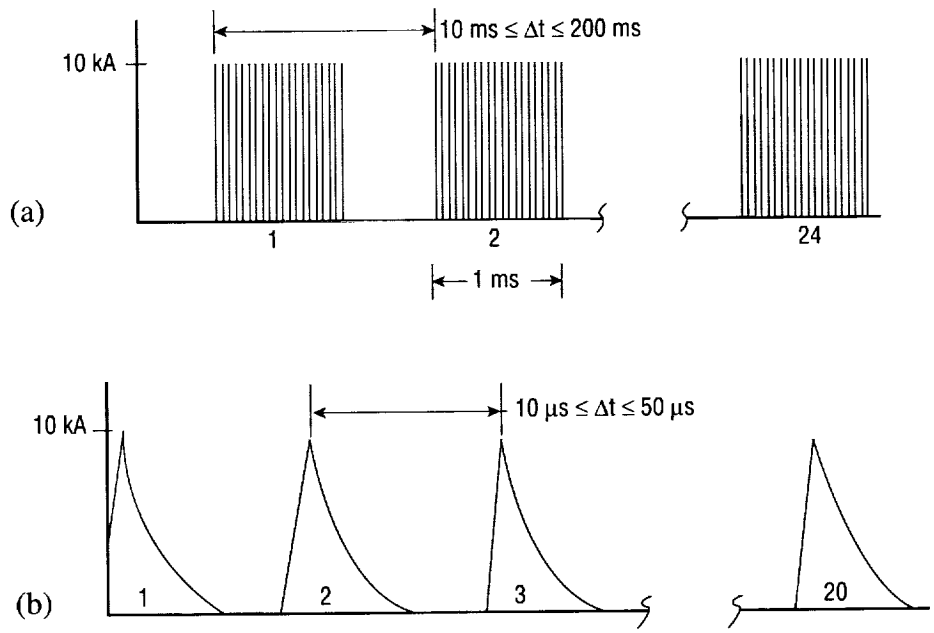


Figure 8. Current test waveform composed of 24 bursts (a) randomly spaced within a 2-second period. (Each burst (b) consist of 20 pulses randomly spaced within a 1-millisecond period.)

2.2.1 Compound A

This waveform represents a first return stroke with a peak current of 200 000 A and is defined mathematically by:

$$I(t) = I_O\,(e^{-at} - e^{-bt}) \tag{1}$$

where

I_O = 218 810 A
a = 11 345 s^{-1}
b = 647 265 s^{-1}
t = time (s).

This waveform component has a very large peak current, peak current derivative, and action integral.

2.2.2 Component B

This component represents an intermediate current following the first return stroke. Component B has an average amplitude of 2 000 A and transfers 10 C of charge. This component is described by a double exponential of the form shown in equation (1) where I_O = 11 300 A, a = 700 s^{-1}, b = 2 000 s^{-1}, and t = time (s).

2.2.3 Component C

This waveform represents a continuing current. Component C is a square waveform with a current amplitude between 200 and 800 A and a duration of 1.0 to 0.25 s, chosen to give a total charge transfer of 200 C. The primary purpose of this waveform is charge transfer.

2.2.4 Component D

Component D represents a subsequent stroke with a peak current of 100 000 A. This component is described by a double exponential of the form shown in equation (1) with I_O = 109 405 A, a = 22 708 s^{-1}, and b = 1 294 530 s^{-1}.

2.2.5 Component H

Component H is a short-duration, high rate of rise current pulse with a peak current amplitude of 10 000 A. This test waveform incorporates important characteristic lightning discharges recorded during trigger strikes to instrumented aircraft in flight. This waveform is also defined by a double exponential where I_O = 10 752 A, a = 187 191 s^{-1}, and b = 19 105 s^{-1}. Component H has a peak current derivative of 2×10^{11} A/s.

Figure 6 depicts and characterizes the key aspects of a current waveform consisting of the sum of components A, B, C, and D. The test values, a peak current of 200 000 A, a charge transfer of 200 C, and an action integral of 2×10^6 A^2 s, occur at the 1-percent level or less in negative ground discharges (at least 99 percent of the lightning strikes will be lesser in magnitude). Approximately 10 percent of positive ground discharges, however, while generally more infrequent, are expected to exceed these tests values. The peak current derivative test value, 1.4×10^{11} A/s, probably does not represent a severe level test.

Ten percent of the return strokes triggered in Florida during 1987 and 1988 had current derivatives which exceeded 215 000 A/μs.[20] A maximum peak *di/dt* value of 411 000 A/μs has been measured in Florida. A stroke current of ≈60 000 A, with *di/dt* value of 380 000 A/μs was recorded during measurements conducted with the NASA F–106 aircraft.

A typical flash consists of a first return stroke followed by several subsequent strokes. For protection against direct effects, it is adequate to consider only one return stroke (component A or D). For a proper evaluation of indirect effects, such as coupling into the interior of an aerospace vehicle, it is necessary to consider the multiple-stroke nature of an actual flash. For this purpose, a multiple stroke consisting of a component A current pulse followed by 23 randomly spaced subsequent strokes of 50 000 A peak amplitude (component D divided by 2), all occurring within 2 s, has been defined. The multistroke test waveform is illustrated in figure 7.

Rapid sequences of pulses with low-peak current amplitude, but large current derivative values, were observed during the lightning strike measurements made with instrumented aircraft. While a single current pulse, like component H, is not likely to cause physical damage, a burst of randomly distributed pulses may cause interference or upset in some systems. A test standard, consisting of component H current pulses occurring repetitively in a 2-second period in 24 randomly spaced groups of 20 pulses each, has been defined. This multiple burst waveform is illustrated in figure 8.

The idealized waveforms described above are appropriate for design analyses. The cost of constructing a simulator capable of delivering these test waveforms to actual vehicles may be prohibitive. In that case, actual testing may involve the use of different waveforms. It must be possible, however, to extrapolate or scale the test results made with the alternate waveforms to the severe hazard level described above.

3. LIGHTNING PROTECTION REQUIREMENTS

Several lightning current parameters are important in assessing the potential for lightning damage; i.e., peak current (*I*), the peak current derivative (*di/dt*), the charge transfer (Q—the integral of current over time), and the action integral (the integral of the square of the current over time, $\int i^2\, di$.

For objects having primarily a resistive impedance, the peak voltage that develops across the object will depend on the peak current. A large voltage that develops at one end or across an object may lead to discharges through the air and around the object (creating a short circuit) from the object to ground.

For objects and systems consisting primarily of an inductive impedance, such as cabling in electronics systems or electrical connections on printed circuit cards, the peak voltage is proportional to the time derivative of the current. For example, if a current with a peak *di/dt* of 1 000 A/μs (one hundredth of a typical lightning peak *di/dt* value) is injected into a straight length of wire with an inductance of 1 μH/m, a voltage of 1 000 V will develop across 1 m of the wire. It is easy to imagine the damage this produces in solid state electronic systems that are sensitive to transient voltages in the tens-of-volts range.

The heating or burn through of metal sheets such as airplane wings or metal roofs is, to a crude approximation, proportional to the charge transferred during a lightning strike. Generally, large charge transfers occur during the long-duration, low-current amplitude portions of lightning discharges such as the continuing current phase, rather than during the short-duration, high-current amplitude return stroke processes.

The heating of electrically conducting materials and the explosion of nonconducting objects are, to a first approximation, determined by the value of the action integral since the quantity $\int i^2\, R di$ is the Joule heating (*R* is the resistive impedance). Generally, electrical heating vaporizes internal material and the resulting increase in pressure causes a fracture or explosion to occur.[21]

3.1 Flight Hardware

A determination should be made as to which systems and components on or within each element of the aerospace vehicle are lightning critical. Protection should be incorporated into each of these items.[22]

3.1.1 Direct Effects

Protection should be provided against the direct effects of lightning to surfaces, structures, components, and joints exposed to direct arc attachment and current conduction. Protective measures include the following:

1. Electrical cables should not be exposed to the direct effects of lightning. When unavoidable, exposed cables should be covered by conductive enclosures of proper mechanical strength and thickness with appropriate electrical continuity.

2. Vehicle structural interfaces between elements of the aerospace vehicle should be capable of conducting the applicable portion of the lightning current without detrimental effects on the structure and electrical, pyrotechnic, or propellant subsystems.

3. Suitable, nondetrimental conductive current paths (lightning bonds) should be provided between structures, components, joints, and extremities to conduct, attenuate, or redirect the applicable portion of the lightning currents and voltages. Attainment of a specific electrical resistance should not, solely, be taken as evidence that structures, components, and joints can safely carry lightning currents. Section 4 discusses the criteria for lightning bonds.

4. Lines, containers/tanks, drains, and vents should be designed to ensure that the ignition point of the materials (flammable fluids, gases, and solids) contained by or transferred through them should not be reached due to any effects of a lightning flash.

3.1.2 Indirect Effects

Protection from the indirect effects of lightning should be provided to ensure that all lightning critical systems, equipment, components, and propellants tolerate the lightning-induced voltages and currents appearing at their interfaces. Protective measures include the following:

1. The internal environment, which arises as a result of direct strike to the vehicle, should be determined. Induced voltages and currents resulting from the internal environment must also be determined. Methods for determining the internal environment and induced voltages and currents are provided in section 4.

2. All cables and/or wires should have an overall shield for lightning protection, unless protection is provided by other means. The overall shield, as a minimum, should be grounded to bulkhead metallic structure or equipment grounding terminals at each end. Intermediate grounding should be used where the overall shield penetrates or touches metal. Overall cable shields should have a minimum optical coverage of 85 percent. Termination of overall shields should be made along a 360-degree periphery of the bulkhead feedthrough connector shell. The feedthrough connector should be grounded in a 360-degree manner to the surface upon which it is mounted. Terminating and grounding overall shields at such surfaces with pigtails or single pins are not acceptable design. All wiring interfaces should be protected in order to eliminate or minimize effects due to lightning-induced voltages and/or currents.

3. Apertures, which allow detrimental lightning-generated electromagnetic fields to penetrate the vehicle structure, should have metallic screens to prevent these fields from inducing hazardous indirect effects.

3.2 Ground Support Equipment and Facilities

3.2.1 Direct Effects

Protection should be provided against direct effects of lightning on equipment and/or facilities exposed to direct arc attachment and current conduction.[22] Electrical continuity to Earth as the ground should be maintained between launch vehicle and integrating support facilities during all phases of ground operations.

Suitable, nondetrimental current paths (lightning bonds) should be provided between equipment and/or facilities to conduct, attenuate, or redirect the applicable portion of lightning currents and voltages. Attainment of a specific electrical resistance shall not, solely, be considered evidence that structures, components, and joints can safely carry lightning currents. The criteria for lightning bonds are discussed in section 4.

3.2.2 Indirect Effects

Protection from the indirect effects of lightning should be provided to ensure that all equipment and/or facilities tolerate the induced voltages and currents at their interfaces.

3.2.3 Vehicle-to-Facilities Interfaces

All metallic penetrations of the vehicle skin should be electrically bonded to the vehicle skin. If bonding is accomplished with a jumper, this jumper should be as short as possible.

Wiring interfaces should be designed to prevent voltage or current resulting from the direct or indirect effects of lightning from damaging or interfering with equipment. Ground hardware electrical lines should interface with the vehicle as close to the base of the vehicle as practical to minimize the indirect effects of lightning.

3.3 Pyrotechnics

3.3.1 Protection of Materials and Devices

A specific current path around pyrotechnic materials and devices should be designed so that effects of the lightning environment do not cause either the inability to fire or inadvertent firings.[22]

3.3.2 Protection of Electrical Systems

Pyrotechnic electrical firing circuits, power sources, and controlling logic should be designed so that no failures will result from the direct and indirect effects of lightning currents.

All enclosures that contain pyrotechnic devices or components should be electrically bonded to the vehicle structure. An overall shield should be provided for each electroexplosive device (EED) firing circuit cable. Separate twisted pair wires should be provided within each cable. Shields should be continuous without breaks or splices, with exception of through pins in pressure bulkhead electrical connectors. Shields should be terminated at connectors using 360-degree coverage. The shield design should provide a minimum optical coverage of 85 percent.

4. BASIC STEPS IN DESIGNING TO WITHSTAND LIGHTNING

Lightning protection is incorporated in the aerospace vehicle most effectively and economically if designed by the steps listed below.[22] These steps provide a methodology that has been proven to work on prior aerospace vehicle projects.

4.1 Lightning Critical Systems

Identify the systems and/or components which may be affected by lightning and whose proper operation is critical or essential to the vehicle. These items make up the LCIL. The LCIL hardware is analyzed to ensure that each item can withstand the lightning environment. In some areas, it is obvious that a system is either susceptible or not affected. Identify the level of voltage and current each system and item should be designed to accommodate. In areas where questions remain after appropriate analysis, the system or subsystem must be tested.

Identify systems and components vulnerable to interference or damage by lightning from either direct effects (physical damage) or indirect effects (electromagnetic coupling). To some extent, lightning strikes affect nearly the entire vehicle and the systems located within. In many cases, the effects are minor and of no consequence to flight safety. However, in order to be certain, each system or subsystem susceptible to lightning or potentially vulnerable to its effects should be reviewed during the lightning protection process.

4.2 Lightning Strike Zones

Location of lightning strike zones on an aerospace vehicle depends on geometry, structural material, and operational factors such as flight altitude and velocity.

Characteristics of currents entering the aerospace vehicle may vary according to location on the vehicle. To account for these variations, lightning strike zones are defined as follows:

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

Zone 1B—Initial attachment point with high possibility of lightning channel hang-on. (All components of a long-duration continuing current are realized in this zone.)

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

Zone 2B—A swept stroke zone with high possibility of lightning channel hang-on. (No initial stroke, but a long-duration continuing current is realized in this zone.)

Zone 3—Those portions of the airframe that lie within or between the other zones which may carry substantial amounts of electrical current by conduction between areas of direct or swept stroke attachment points. Zone 3 includes those surfaces where attachment of the lightning channel is a very low possibility.

4.3 Direct Effects Protection

Provide protection against the direct effects of lightning to surfaces, structure, components, and joints exposed to direct arc attachment and conduction. Electrical cables should not be exposed to direct effects of lightning. When exposure is unavoidable, cover cables with a conductive enclosure of proper mechanical strength and thickness to protect against the lightning environment.

4.3.1 External Lightning Environment

Identify the components of the total lightning flash current expected in each lightning strike zone. These are currents against which the vehicle must be protected. Lightning flashes are subdivided into components and important characteristics are described. Hardware is analyzed for direct and indirect susceptibility to each lightning flash component described in section 2.2.

In evaluating direct effects, the most significant parameters are peak current, action integral, charge transfer, and duration. Tests to evaluate direct effects on structural components must be performed at full threat. It is feasible to generate full threat currents with the required combination of these parameters.

The full threat model lightning flash for direct effects test is defined in reference 14. It has four components corresponding to the four components of the model lightning flash defined for purposes of analysis. Each component (A, B, C, and D) simulates a different characteristic of the current in a natural lightning flash. The waveforms are shown in figure 4. The waveform selected for a particular test or analysis depends on the classification of vehicle strike zones and whether direct or indirect effects are to be evaluated.

4.4 Indirect Effects Protection

The protection design is determined by demonstrating that (1) the maximum induced transients appearing at the equipment/harness interfaces are less than the established TCL and (2) the equipment can tolerate the ETDL at input terminals. Appropriate margins must be maintained. Verification is accomplished by test, analysis, or similarity to other systems and/or equipment or combinations of these methods.

4.4.1 Internal Environment

The internal environment is the environment created as a result of a direct strike to the vehicle and is associated with the vehicle's internal E and H fields.

Electromagnetic fields appear in the interior of any element of the vehicle by aperture coupling or diffusion. Voltages and currents induced by these fields constitute the internal environment.

The magnitude of these internal fields, determined by shielding effectiveness of the vehicle, may damage electrical/electronic equipment. The fields and structural potentials (current × resistance (*IR*)) produce voltages and currents on interconnecting wiring at equipment enclosures and, thus, compromise system operation.

4.4.2 Induced Voltage/Current Levels

For each lightning critical system, the induced voltage and current appearing at electrical/electronic equipment interfaces are determined. In most cases, these are defined in terms of the open circuit voltage (V_{oc}) and short circuit current (I_{sc}) developed at the wiring/equipment interfaces. The V_{oc} and I_{sc} are related by the source impedances of interconnecting wiring. Different levels may be determined for different circuit functions or operating voltages. These levels are determined by analysis or test and are defined on pp. 467 and 481 of *Lightning Protection of Aircraft*.[23]

4.4.3 Transient Control Levels/Equipment Transient Design Levels

Establishing system TCL's and ETDL's is the best method of specifying indirect effects protection requirements. The TCL's are the actual environment (i.e., pin injection voltage) that the equipment experiences during a lightning strike. This environment is the result of the internal lightning-induced environment after application of system-level equipment shielding and transient suppression (i.e., filters or Transzorbs) effects.

The ETDL is the environment (i.e., pin injection voltage) that the equipment should be designed to withstand. For equipment to survive a lightning encounter, the ETDL must be greater than the TCL. The difference between ETDL and TCL is the design margin. A positive design margin indicates successful hardening of the system.

The relationship between transient control and equipment transient design and susceptibility levels is illustrated in figure 9. The TCL and ETDL are established by the system integrator who assesses the impact of shielding cables versus hardening equipment to establish the most efficient levels.

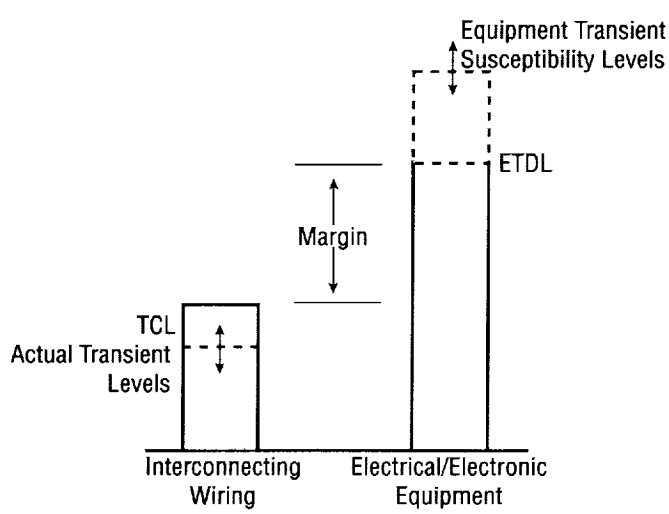


Figure 9. Relationship between transient levels.

4.5 Lightning Protection Measures

Twelve lightning protection design measures should be considered for each system and/or component needing protection. Use of these design measures helps carry the lightning current on the outside of the vehicle and minimizes apertures and joints where fields can enter, thus keeping equipment and cables away from higher fields. The design measures are as follows:

- Electrical bonding/structural bonding
- Electromagnetic shielding
- Surge suppression
- Adequate skin thickness
- Dielectric coatings
- Flame arresters
- Flame-sprayed coatings
- Wire mesh
- Location
- Sealants
- Metal foils

4.6 Successful Lightning Protection Design and Certification

Numerous considerations are important throughout the design and certification process for an aerospace vehicle.

4.6.1 Begin the Process Very Early in the Design Stage

The basic fabricated materials of an aerospace vehicle contribute significantly to the effects of lightning strikes and to the interactions that lightning currents and associated electromagnetic fields have with onboard systems. Composite materials are often vulnerable to lightning damage and require protection. Current protection methods often become an integral part of skins and structures. Decisions on what protection approach to take should be made early and coordinated with other structural requirements. Frequently, developing design details takes time, so the overall approach needs to be established very early to avoid expensive retrofit.

4.6.2 Locate Lightning Strike Zones Early in the Design Phase

Lightning strike zone locations depend on vehicle geometry and the expected operational envelope. Since these zones define specific lightning environments, it is imperative that zones are located and understood as early as possible to avoid later controversies and misunderstandings.

4.6.3 Test During Development Phases

In the past it was often possible to successfully complete a lightning protection design and perform a verification test on the finished article. Due to the complex electrical and mechanical nature of many current vehicle designs, there is a very high risk of failure in this approach. Instead, it is prudent to perform lightning current transfer tests (for example) on candidate structural joints and other ele-ments, as well as critical components of other systems, at an early date. Such tests are usually referred to as "developmental tests" or "engineering tests" and are performed on small structural coupons or individual pieces of a complete system. They provide data for design selection and minimize the risk of failure during a complete systems test later in the program.

Because some structures and systems cannot be lightning tested as a whole due to size or complexity, developmental testing must be relied on to support design verification and certification. In such cases, verification must usually be shown by analysis. Analysis shows how developmental test results are combined to demonstrate design adequacy and/or compliance with specifications. For this to be done, developmental test specimens, procedures, and results should be carefully documented when conducted.

4.7 Electromagnetic Effects Control Plan

Some combination of analysis, similarity with previous designs, developmental testing, and qualification testing is required to ensure adequate lightning protection for the vehicle. To ensure that all flight-critical elements of the design are verified and to avoid costly and unnecessary testing, an EME control plan should be prepared. This is particularly important for new and "untried" advanced launch vehicle designs which usually involve high authority electrical/electronic systems. The control plan need not be a lengthy document describing detailed test or analysis procedures. It should present in brief and concise terms descriptions of the roles of developmental testing, analysis, qualification testing, etc.

4.8 Pass-Fail Criterion

Lightning currents of the magnitude defined in present test standards nearly always inflict some damage to the element's structure. Sometimes this damage results only in superficial discoloration of a part. In other cases it may result in pinching or deformation of aluminum parts or puncture and delamination of composites. Often these effects do not comprise a hazard to flight safety, but it must be demonstrated that this is the case. Unfortunately, the nature of the damage cannot always be predicted in advance of a lightning test, so the "pass-fail" requirement is established after the test is completed. This may involve aerodynamic and structural analyses of the damaged parts before a decision is made.

5. PROTECTION DESIGN VERIFICATION

Verify adequacy of the lightning protection designs by similarity with previously proven installation designs, simulated lightning tests, or acceptable analysis. When analysis is utilized, appropriate margins to account for uncertainties in the analytical techniques may be required. Use developmental test data for certification when properly documented and coordinated with the Lightning Protection Engineer. This section discusses specific analyses and test details to verify protection adequacy.[22]

5.1 Analysis Techniques

External direct effects and internal E and H fields that appear inside the vehicle skins are associated with a strike to the aerospace vehicle system. The magnitude of the internal fields is determined by the shielding effectiveness of the vehicle and the properties of the lightning strike. These internal fields may cause damage to the electrical/electronic equipment or introduce signals which may upset operation of the equipment. To adequately perform verification of the equipment, an understanding of the external and internal environments and interactions is required.

5.1.1 Direct Effects Analysis Verification Techniques

Direct effects are physical damage at the points of attachment, at the point of exit, and any interstructural current-carrying effects.

5.1.2 Electrical Bonding

Providing an aerospace vehicle a suitable, nondetrimental path for lightning-produced currents and voltages is an important part of lightning protection. To provide this protection, each interface must be considered separately. An interface is any place two pieces, parts, or components join together. This includes interfaces from the manufacturing process and from adding bond straps to existing structure.

Each interface must be designed for the vehicle, recognizing that the lightning event is dominated by time-varying currents. This is the reason lightning current paths are governed much more by inductance rather than resistance. The voltage rise due to inductance is a function of the rate of change. Even on paths in which the amplitude is reduced by current division, the inductive voltage rise can be severe. For example, if the current rate of rise is 1×10^{11} A/s and the inductance is 1 μH/m, 100 000 V appear across each meter of the path. Experience shows that achieving a direct current resistance of 2.5 mΩ has little significance to adequate lightning protection.

The criteria to assess the adequacy of lightning protection (bonding) at each interface is more than the direct current resistance of the interface. Detrimental arcing and sparking at an interface are more functions of area current density and strength of dielectric insulation than direct current resistance.

Additional assessment criteria include the following:

1. Specific descriptions of materials contacting the interface (corrosion can degrade the bond over time).

2. Specific descriptions of the surface contact area and surface treatments.

3. Specification of the compression of joints and fasteners (pounds per square inch or foot-pounds of torque).

4. Specification of path dimension sufficient to determine inductance as well as direct current resistance.

5. Specification of the lightning strike zone or zones within which each interface falls.

Use of a resistance measurement alone does not verify a good lightning bonding. But resistance measurements can be used for manufacturing and quality control.

5.1.3 Indirect Effects Analysis Techniques

The upset or damage generated by lightning-induced voltages and currents are indirect effects.

Internal electric and magnetic field environments must be estimated. The highest E fields exist just prior to and during the attachment process of the lightning strike. The voltage between the charge center and the vehicle must reach the point at which the air gap breaks down (typically fields of 500 000 V/m). Until breakdown occurs and the leader is complete from the cloud to Earth (or the opposite charge center), the current levels are low and magnetic fields are low. Once the leader is complete, the return current begins creating significant magnetic fields.

Electric fields are in the lightning strike, but levels are generally quite low (10 to 100 V/m). Magnetic fields associated with the lightning strike are most intense at the outside surface of the vehicle. Internal magnetic fields depend on the shielding afforded by the vehicle structure and the geometry of the vehicle between attachment points. Magnetic fields on the outside of the vehicle skin enter the interior by leakage through apertures and diffusion through the skin itself. Holes in the conductive structure, windows, and seams or joints are the apertures through which the magnetic flux can leak into the interior of the vehicle. Internal magnetic fields are highest near these apertures.

Internal-induced voltage and current environment must also be estimated. Before flight hardware exists, analysis is the only tool available to provide estimates of the induced voltages and currents that can enter/exit the wiring. Estimates are required of magnetic field levels in different regions of the systems. These estimates are based on the magnetic field intensities at the surface next to the apertures, which are then extrapolated internally. These field levels are the representative conservative levels associated with a severe strike attaching near the region of interest. If use of these field levels results in protection requirements that severely impact design, cost, and weight, further analysis or test to refine the threat must be made.

To calculate the open circuit common mode voltage of a wire,

$$V_{oc} = \mu_o \, AdH/dt \tag{2}$$

where

A = loop area in square meters
$\mu_o = 4\times10^{-7}$ H/m (permeability of free space)
H = magnetic field in A/m
t = time (s).

It must be emphasized that the voltage calculated is between the wire and the structure. Since the differential voltage is the result of variations in terminations, it is not possible to accurately predict the value from the circuit parameters. In practice, the differential voltage is less than the common mode by a factor of 10 to 100. The wire or cable short-circuit current is calculated from the open circuit voltage, and the cable self-inductance is estimated as follows:

$$I_{sc} = 1/L \, V_{oc} \, dt \tag{3}$$

where

L = self-inductance of the cable in H/m
V_{oc} = open circuit voltage
t = time (s).

Cable inductance is estimated:

$$L = 2\times10^{-7} \, ln \, (h/d) \tag{4}$$

where

d = conductor diameter
h = height above structure.

Note: The induced voltage, V_{oc}, which drives the current is proportional to the cable height, but the cable inductance which resists the current is proportional to the logarithm of height.

In some cases, the circuits of concern are superimposed on the AC and DC bus voltages, V_{bus}. Since the power buses are quite extensive, they experience inducted voltages of their own.

In addition to the magnetic-coupled voltage, structural voltages, V_s also appear. For the worst case, it must be assumed that the power bus voltage is added to the signal line-induced voltage. In those cases, the total induced voltage is

$$V_t = V_{bus} + V_s + V_{oc} \tag{5}$$

where

V_t = total voltage
V_{bus} = power bus voltage
V_s = structure voltages
V_{oc} = open circuit voltage.

If a circuit routes through several sensors or several pieces of equipment, the voltage from each section must be added.

Two major areas, upset and transient damage (failure) analysis, must be addressed when verifying lightning protection for complex digital systems that utilize solid state electronic devices.

Upset must be assessed with statistical methodologies. Upset usually occurs when voltage and current levels are below device failure levels. Upset may affect input data lines, devices, or any combination of these. Because the effects of upset occur randomly with time, upset is a stochastic phenomenon. Redundancy is no protection against upset due to lightning. Lightning can affect all redundant systems identically and simultaneously.

Transient damage (failure) analysis relates to the maximum power levels, which may appear at the input/output solid state devices. This analysis provides the maximum levels of voltage and current a given interface can withstand. If it is shown that actual transient levels are equal to or exceed these levels, then steps must be taken to reduce these levels to acceptable values.

Lightning strike to a vehicle causes open circuit voltage and short circuit current to be induced on wire cables. These voltages and currents could couple into electrical equipment and cause a critical logic upset. If the upset generates erroneous input/output states, it could produce a risk of vehicle loss.

Two independent methods determine if an electronic element could enter a critical logic upset. The first method seeks equipment containing memory devices capable of changing state within 100 μs. The second determines if the equipment has the authority to influence the system and, if upset, produce a risk to the system.

The first upset analysis technique uses an "assumed upset" method of identifying the LCIL elements that respond in <100 μs and maintain this changed state. These memory elements, due to their fast response time, are referred to as low inertia memories. It is then assumed that each low inertia memory is upset and the effect of an upset upon the system is determined.

Give careful consideration to the ability of the equipment to recover or reset before it contributes significantly to data or logic pollution. If a recovery method exists for upset equipment, what is the maximum elapsed time for the recovery? Does recovery rely on external (automatic or procedural) inputs or self-recovery? Do override controls exist? Are there cues, talkbacks, or warnings during recovery? Can recovery be assured before the upset causes risk to the vehicle?

Under this analysis technique, flight-critical, active-on-ascent equipment has low inertia memories, which could cause risk to vehicle mission success or have no significant acceptable recovery or reset method, both of which are considered mission critical.

The second upset analysis technique involves determining if the equipment has independent authority to control its output. If a sensor's input data are used to make the decision whether or not an event actually occurred, this decision must be made using multiple samples of the sensor to say the system is immune to logic upset of the subject sensor.

Declare the vehicle immune to the logic upset of a multiple mode whole value sensor if the following conditions are true:

1. The correct sensor mode can be reestablished following the logic upset event before the sensor's performance or the system's performance is impacted because of a lack of critical sensor data.

2. If the sensor mode can be reestablished in time, the sensor data processing must be performed in the same manner described for a single-mode, whole-value readout sensor.

Using these two analysis techniques, each piece of equipment is analyzed and declared critical or not critical to upset.

Perform a transient and failure analysis to determine the lightning transient survivability of electrical components and equipment. Theoretical and experimental work by D.C. Wunsch and R.R. Bell has shown that the power level required to damage a semiconductor junction is proportional to minus one-half power of the pulse width of the applied power for pulse widths between 0.1 and 100 μs[22]

$$P_F = Kt^{-1/2} \tag{6}$$

where

P_F = failure power
K = proportionality constant
t = time of pulse width.

The proportionality constant was named the "Wunsch" or "damage" constant. Lightning-induced voltage pulse widths, in general, fall within a range of 0.1 to 100 μs. Thus, the Wunsch damage equation is used directly to predict whether avionics semiconductors will survive lightning voltages. Damage levels are calculated to within ±1 to 2 orders of magnitude. Through the use of derating techniques, a damage constant is calculated to ensure that 95 percent of the components actually have a higher damage constant.

Damage constants were determined for over 18 000 components and stored in an Air Force computer program "SUPERSAP." The program is available from the MSFC Electromagnetics and Aerospace Environments Branch for vehicle analyses purposes. The internal circuits must be identified by external pin and connector numbers for each lightning-critical black box or component. Using standard electromagnetic pulse (EMP) analysis techniques, the damage levels, failure voltage, and failure current are established for each connector pin,

$$V_F = V_{BD}/I_F R_B \tag{7}$$

where

V_F = failure voltage
I_F = failure current
R_B = reverse bulk resistance
V_{BD} = reverse breakdown voltage

and

$$I_F = (R_B - V_{BD})/P_F \tag{8}$$

where

P_F = failure power.

In the analysis, all damage constants are derated by a factor of 0.1, unless other data indicate that the damage constant is below the lower 95-percentile failure level. A pulse width of 5 microsecond is used for damage analysis of circuits with the following exceptions: (1) Those circuits that use the vehicle structure for power return should be analyzed with a 25-microsecond pulse width and (2) those circuits that cross the elements interfaces, including those to the launch facility, or those interface circuits where lightning currents flow directly on the cable shields are analyzed with a 50-microsecond pulse width.

5.2 Test Techniques

As a design requirement, the lightning environment was defined in section 2.2. Artificial generation of composite waveform in laboratories is not always technically or economically feasible. For test purposes, waveforms differing from those specified for design may be used. The parameters important to the direct and indirect effects being evaluated must be included either in the test waveforms or in the interpretation of test results. This section provides descriptions of test waveforms acceptable for tests to verify lightning protection against direct and indirect effects.

5.2.1 Direct Effects Test Techniques

Lightning tests attempt to duplicate the effects of lightning, not to duplicate lightning itself. This point is important because limitations of test equipment make it necessary to evaluate high-voltage effects separately from high-current effects.

Test machinery is not available to duplicate the energy levels of lightning; i.e., to produce currents of the magnitude involved in the lightning event while simultaneously duplicating the high voltages of a developing lightning leader. High voltage and high current can readily be developed but not simultaneously by the same machines.

Perform direct effects verification in accordance with NSTS–07636.[14] The voltage and current waveforms applicable for each lightning component are listed below.

The most significant parameters for evaluation of direct effects are peak current, action integral, charge transfer, and duration. Tests to evaluate direct effects on vehicle and structural components must be performed at the full threat current. It is feasible to generate full threat currents with the required combinations of those parameters. While rate of rise and rise time of current are important for evaluation of indirect effects, they are less important for direct effects. Components A, B, C, and D (fig. 5) each simulate a different characteristic of the current in a natural lightning flash. During a test, components may be applied individually or as a composite of two or more.

Important characteristics of the current waveforms are the following:

Component A—first return stroke. This has a peak current of 200 000 A (±10 percent) and an action integral of 2×10^6 (A^2s) (±20 percent) with a total time duration not exceeding 500 μs. This component may be unidirectional or oscillatory and the rate of rise time is intentionally not specified.

Component B—intermediate current. This has an average amplitude of 2 000 A (±10 percent) flowing for a maximum duration of 5 ms and transferring a maximum of 10 C. The waveform should be unidirectional, but may be rectangular, exponential, or linearly decaying. Most commonly, tests are made with a double exponential waveshape.

Component C—continuing current. This transfers a charge of 200 C (±20 percent) in a time between 0.25 and 1.0 s. The waveform may be either rectangular, exponential, or linearly decaying. Most commonly, tests are made with rectangular currents of between 200 and 800 A.

Component D—subsequent stroke current. This has a peak amplitude of 100 000 A (±10 percent) and an action integral of 0.25×10^6 (A^2s) (±20 percent) with a total duration not exceeding 500 μs. This component may be unidirectional or oscillatory and the rate of rise time is intentionally not specified.

Upset or damage generated to electronic equipment by a lightning-induced electromagnetic pulse is called indirect effects. The vehicle's interactions with the electromagnetic pulse generate voltages and currents throughout the system. This testing can be divided into two sections: (1) Complete vehicle test and (2) electronic (box level) equipment tests.

A lightning-induced voltage (indirect effects) complete vehicle test comprises injecting a reduced magnitude lightning current pulse into the vehicle at various points and measuring the induced voltages and currents on the vehicle wiring harness. This requires a pulse current generator, waveshaping impedances, return circuit system, and measurement equipment to monitor the applied threat and the system response.

Test electrical/electronic equipment to ensure that induced transients do not cause damage to the equipment that results in loss of critical function or in a response (upset) that creates a hazard. Two types of testing verify damage and upset. Upset and transient damage (failure) analysis are two major topics to be addressed when verifying lightning protection for complex digital systems utilizing solid state electronic devices. Upset tests are typically conducted by coupling transients into an operating system and monitoring critical system functions. Because upset of digital systems is fundamentally a statistical process or event, a transient single pulse test is not adequate. Use of multiple transients represented by multiple stroke and/or multiple burst test waveforms is theoretically more correct than using a single transient. Damage tests are typically applied to equipment inputs (powered but not functioning) at the connector pins to determine if input circuits are damaged.

Voltage waveforms are used for verification testing. These waveforms represent the electric fields associated with a lightning strike. Voltage waveforms A and D are used to test for possible dielectric puncture and potential attachment for a lightning flash. Voltage waveform B is used to test for streamers. These voltage waveforms are intentionally similar to those used in high voltage laboratories for evaluating effects of lightning on electrical power systems. The objective setup, measurement, and data requirements for each test are described in NSTS–07636.[14]

Important characteristics of the voltage waveforms (fig. 10) are as follows:

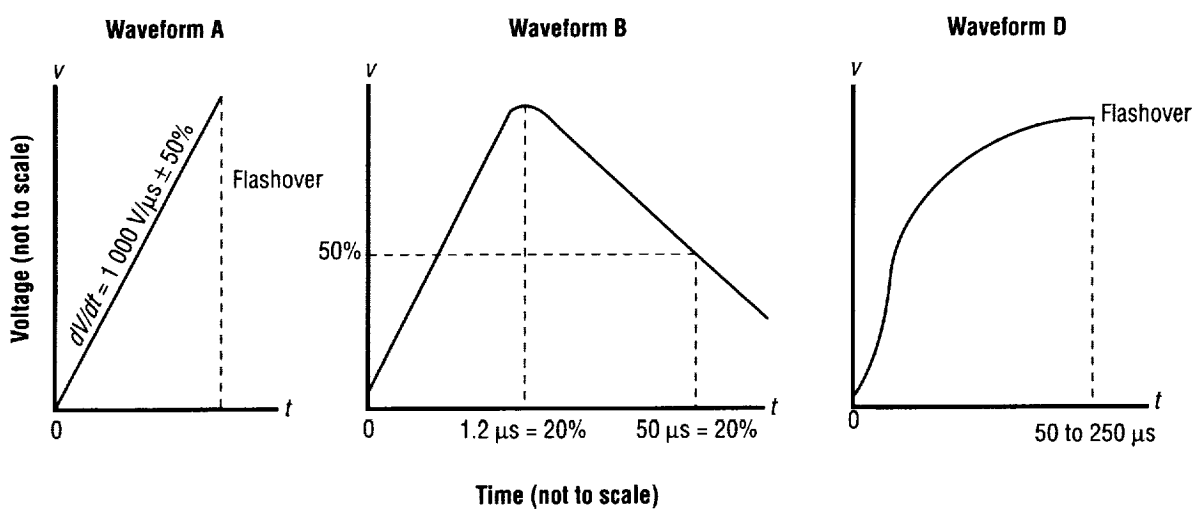


Figure 10. Voltage attachment test waveforms.

Voltage waveform A—basic lightning waveforms. This has a virtual rate of rise of 1M V/μs (±50 percent) until the increase of voltage is interrupted by puncture of, or flashover across, the object under test. At that time the voltage collapses to zero. The rate of voltage collapses or the decay time of the voltage if breakdown does not occur (open circuit voltage of the lightning voltage) is not specified.

Voltage waveform B—full wave. This has a virtual front time of 1.2 μs (±20 percent) and a decay to half value of 50 μs. The waveform is the open circuit voltage of the generator or that which is produced if it is not limited by puncture or flashover of the object under test.

Voltage waveform D—slow front. This waveform has a front time of between 50 and 250 μs and is generally used to allow more time for streamers to develop regions from the test object than would waveform A. Normally it should give a higher strike rate to the low probability regions than would waveform A.

6. CONCLUSIONS

Lightning protection assessment and design are critical functions in the development and design of an aerospace vehicle. The project's Lightning Protection Engineer must be involved in the preliminary design phase and remain an integral member of the design and development team throughout construction of the vehicle and all verification testing. The guidelines in this document provide an overview of the criteria necessary for an adequate lightning protection design.

Questions concerning lightning protection assessment and design for an aerospace vehicle should be directed to ED44/Lowell Primm, Group Lead, Environments Group, 256–544–9145.

REFERENCES

1. "Analysis of Apollo 12 Lightning Incident," NASA Document No. MSC–01540, prepared jointly by Marshall Space Flight Center, Kennedy Space Center, and Manned Spacecraft Center, National Aeronautics and Space Administration, February 1970.

2. Brook, M.; Holmes, C.R.; and Moore, C.B.: "Lightning and Rockets—Some Implications of the Apollo 12 Lightning Event," *Naval Research Reviews*, Vol. 23, No. 4, pp. 1–17, April 1970.

3. Christian, H.J.; Mazur, V.; Fisher, V.D.; Ruhnke, L.H.; Crouch, K.; and Perala, R.A.: "The Atlas/ Centaur Lightning Strike Incident," *J. Geophys. Res.*, Vol. 94, pp. 13,169–13,177, 1989.

4. Federal Aviation Administration: "Protection of Aircraft Fuels Systems Against Lightning," U.S. FAA Advisory Circular 25–3, Washington, DC, November 10, 1965.

5. "Bonding, Electrical, and Lightning Protection for Aerospace Systems," *MIL–B–5087B*, Department of Defense, October 15, 1964.

6. Plumer, J.A.; and Robb, J.D.: "The Direct Effects of Lightning on Aircraft," *IEEE Trans. on Electromag. Com., EMC–24*, pp. 158–172, 1982.

7. "Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware," Report of SAE Committee AE–4, Special Task F, Society of Automotive Engineers, May 5, 1976.

8. "Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware," Report of SAE Committee AE–4L, Society of Automotive Engineers, June 20, 1978.

9. "Lightning Qualification Test Techniques for Aerospace Vehicles and Hardware," *MIL–STD–1757*, Department of Defense, June 17, 1980.

10. "Lightning Qualification Test Techniques for Aerospace Vehicles and Hardware," *MIL–STD–1757A*, Department of Defense, June 20, 1983.

11. "Protection of Airplane Fuel Systems Against Fuel Vapor Ignition Due to Lightning," U.S. FAA Advisory Circular 20–53A, Federal Aviation Administration, Washington, DC, April 12, 1985.

12. "Lightning Protection Criteria Document," *NSTS–07636*, NASA Johnson Space Center, 1973.

13. Perala, R.A.; Rudolph, T.; and Eriksen, F.: "Electromagnetic Interaction of Lightning With Aircraft," *IEEE Trans. on Electromag. Comp., EMC–24*, pp. 173–203, 1982.

14. "Lightning Protection Criteria Document," *NSTS–07636*, Rev. E, NASA Johnson Space Center, March 19, 1988.

15. "Protection of Aircraft Electrical/Electronic Systems Against the Indirect Effects of Lightning," Report of SAE Committee AE4L, Society of Automotive Engineers, Recommended Draft Advisory Circular, February 4, 1987.

16. "Lightning Protection of Aerospace Vehicles and Hardware," *DOD–STS–1795*, Department of Defense, May 30, 1986.

17. *Systems Engineering Handbook*, 2nd Edition, Vols. 1 and 2, MSFC–HDBK–1912A, MSFC, July 1994.

18. Beard, K.V.K.; and Ochs, H.T.: "Cloud Electrification," *Rev. Geophys. Space Phys.*, Vol. 21, pp. 984–992, 1983.

19. Leteinturier, C.; Weidman, C.; and Hameslin, J.: "Current and Electric Field Derivatives in Triggered Lightning Return Strokes," *J. of Geo. Res.*, Vol. 95, pp. 818–828, 1990.

20. Johnson, D.L., Editor: *"Terrestrial Environment (Climate) Criteria Guidelines for Use in Aerospace Vehicle Development, 1993 Revision," NASA Technical Memorandum 4511*, 1993.

21. "Lightning Protection Engineering Processes Document," Systems Analysis & Integration Laboratory, *MSFC–DOD–2259*, MSFC, September 1993.

22. "EMP Susceptibility of Semiconductor Components," *Report D244–13042–1*, Department of Defense, September 1974.

23. Fisher, F.A.; Plumer, J.A.; and Perala, R.A.: *Lightning Protection of Aircraft*, Lightning Technologies, Inc., Pittsville, MA, 1990.

BIBLIOGRAPHY

Krider, E.P.: "75 Years of Research on the Physics of a Lightning Discharge," Historical Essays on Meteorology 1919–1995, J.R. Fleming (ed.), American Meteorological Society, Boston, MA, 1996.

Ruhnke, L.H.; and Latham, J., (eds.): *Proceedings in Atmospheric Electricity*, A Deepak Publishing, Hampton, VA, 1983.

Uman, M.A.: *Lightning*, McGraw-Hill, New York, NY, 1969.

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13. ABSTRACT *(Maximum 200 words)*

This technical memorandum provides lightning protection engineering guidelines and technical procedures used by the George C. Marshall Space Flight Center (MSFC) Electromagnetics and Aerospace Environments Branch for aerospace vehicles. The overviews illustrate the technical support available to project managers, chief engineers, and design engineers to ensure that aerospace vehicles managed by MSFC are adequately protected from direct and indirect effects of lightning. Generic descriptions of the lightning environment and vehicle protection technical processes are presented. More specific aerospace vehicle requirements for lightning protection design, performance, and interface characteristics are available upon request to the MSFC Electromagnetics and Aerospace Environments Branch, mail code EL23.

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