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AEROSPACE RECOMMENDED PRACTICE

SAE ARP5415

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

FOREWORD

Whenever a reference document appears in this Recommended Practice, it carries the minimum revision level of the reference document acceptable to meet the intended requirements. Later versions of the reference document are also acceptable but earlier versions are not acceptable. In all cases, other documents shown to be equivalent to the reference document are also acceptable.

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1. SCOPE:

This user's manual provides additional information and references relevant to identifying: (1) acceptance criteria for the indirect effects of lightning compliance approaches, (2) verification (analysis and test) methods including those associated with multiple stroke and multiple burst and (3) recommended design options to optimize needed system immunity to lightning indirect effects. Equipment hazards addressed include those due to the indirect effects on equipment mounted on the aircraft exterior and equipment located within the aircraft interior as well as all associated interconnecting wiring. This document has specific application toward those topics and subsystems addressed in ARP5413 but also provides additional guidelines in the application of those tests identified in DO-160/ED-14, Section 22.

1.1 Purpose:

This user's manual expands on the topics introduced in ARP5413, Certification of Aircraft Electrical/ Electronic Systems for the Indirect Effects of Lightning. Guidelines are provided which explain the approaches to compliance with the US Federal Aviation Regulations (FAR) and the European Joint Airworthiness Regulations (JAR). Discussions are applicable to all categories of airplanes and rotorcraft. This material as well as the Aerospace Recommended Practices (ARPs) it supports are not intended to provide mandatory approaches to compliance. In many cases, the path to compliance may use one or more of several methods. Applicants for Federal Aviation Administration (FAA) or Joint Aviation Authority (JAA) approval may elect to demonstrate compliance through alternative methods found acceptable by the FAA/JAA.

2. REFERENCES:

2.1 US Federal Aviation Regulations (FAR) and European Joint Airworthiness Requirements (JAR):

2.1.1 FAR: The following documents can be obtained from the US Department of Transportation; Subsequent Distribution Office; Ardmore East Business Center; 3341 Q 75th Avenue; Landover, MD 20785.

US Code of Federal Regulations 14 CFR Parts 23.867, 23.954, 23.1309(e), 23.1529, 25.581, 25.901, 25.954, 25.1309, 25.1316, 25.1529, 27.610, 27.954, 27.1309(d), 27.1529, 29.610, 29.954, 29.1309(h), 29.1529, 33.4 and 33.28(d).

2.1.2 JAR: The following documents may be obtained from the Civil Aviation Authority (CAA), Printing and Publication Services, Greville House, 37 Grafton Road, Cheltenham, Glostershire GL50 2BN, England.

Joint Airworthiness Requirements, Sections 23.867, 23.954, 23.1309(e), 23.1529, 25.581, 25.901, 25.954, 25.1309, 25.1316, 25.1529, 27.610, 27.954, 27.1309(d), 27.1529, 29.610, 29.954, 29.1309(h), 29.1529, 33.4, and 33.28(d).

2.2 FAA Advisory Circulars:

The following documents can be obtained from the US Department of Transportation; Subsequent Distribution Office; Ardmore East Business Center; 3341 Q 75th Avenue; Landover, MD 20785.

AC 20-53A "Protection of Aircraft Fuel Systems Against Fuel Vapor Ignition Due to Lightning". AC 20-53A contains zoning definitions and procedures that are used for direct effects protection and is used as a guide to describe zoning as it applies to indirect effects.

AC 23.1309-1C "System Design and Analysis", dated March 12, 1999. AC 23.1309-1C describes acceptable design practices for showing compliance with the requirements of amendment 41 to FAR 23.1309.

AC 25.1309-1A "System Design and Analysis", dated June 21, 1988. AC 25.1309-1A describes various acceptable means for showing compliance with the requirements of FAR 25.1309, Equipment, Systems and Installations.

AC 27-1A "Certification of Normal Category Rotorcraft", dated July 30, 1997. AC 27-1A covers policy on methods of compliance with Part 27 of the FARs, which contains airworthiness standards for normal category rotorcraft.

AC 29-2B "Certification of Transport Category Rotorcraft", dated July 30, 1997. AC 29-2B provides information on methods of compliance with Part 29 of the FARs, including methods of compliance in the areas of basic design, ground tests and flight tests.

DOT/FAA/CT-89/22 "Aircraft Lightning Protection Handbook", dated September 1989. DOT/FAA/CT-89/22 contains information on the natural phenomenon of lightning, the interaction between the aircraft and the electrically charged atmosphere, the mechanism of the lightning strike and the interaction with the airframe, wiring and fuel system. This document also covers details for protection design.

2.3 Related Reading Material:

This section of the document specifies the minimum revision level of the reference document acceptable to meet the intended requirements. Later versions of the reference document are also acceptable but earlier versions are not acceptable. In all cases, other documents shown to be equivalent to the referenced document are also acceptable. For convenience, revision levels are not noted in the remainder of the document unless the intent only applies to a specific version of the referenced document.

2.3.1 Military Documents: The following standards and handbooks are available from the Standardization Documents Order Desk, 700 Robbins Avenue, Building 4D, Philadelphia, PA 19111-5094.

MIL-HDBK-217F "Military Handbook, Reliability Prediction of Electronic Equipment", dated 2 December 1991. This handbook provides methods and data to calculate a predicted failure rate for electronic components considering component type, reliability level and environment.

MIL-STD-461E "Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment", dated 20 August 1999. MIL-STD-461E contains equipment level electromagnetic interference requirements and test methodology similar to those in DO-160. The particular requirements in this standard that are related to indirect lightning effects are CS115 and CS116. CS115 is an impulse excitation bulk cable injection requirement while CS116 is a damped sine wave bulk cable injection requirement.

MIL-STD-464 "Electromagnetic Environmental Effects Requirements for Systems", dated 18 March 1997. MIL-STD-464 establishes electromagnetic environmental effects (E^3) interface and performance requirements and verification criteria for systems. This document includes definitions of the lightning environment to be used for both indirect and direct effects. This document replaces MIL-STD-1818A (4 October 1993), MIL-E-6051D (7 September 1967), MIL-B-5087B (15 October 1964) and MIL-STD-1385B (6 August 1986).

MIL-STD-882D "Standard Practice for System Safety", dated 10 February 2000. This standard outlines the requirements for safety systems including definitions of organizations and compliance and verification methods.

D180-27423-49 "Atmospheric Electricity Hazards Protection, Part IV, Design Guide for Air Vehicles", dated February 1987. This report was produced by the Boeing Military Airplane Company for the Air Force Wright Aeronautical Laboratories.

2.3.2 SAE Publications: The following documents can be obtained from Society of Automotive Engineers (SAE), 400 Commonwealth Drive, Warrendale, PA 15096-0001.

NOTE: ARP4761 states that ARP926 and ARP1834 are superseded by ARP4761 for civil aircraft safety assessment.

ARP4754 "Certification Considerations for Highly Integrated or Complex Aircraft Systems", issued November, 1996.

ARP4761 "Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment", issued December, 1996.

ARP5412 "Aircraft Lightning Environment and Related Test Waveforms", issued November, 1999.

ARP5413 "Certification of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning", issued November, 1999.

ARP5414 "Aircraft Lightning Zoning", issued December, 1999.

ARP5416 "Aircraft Lightning Test Methods" – (Draft), not yet published.

2.3.3 RTCA, Inc. Documents: The following documents can be obtained from RTCA, Inc., 1140 Connecticut Avenue, NW, Suite 1020, Washington, DC 20036-4001.

RTCA/DO-160D "Environmental Conditions and Test Procedures for Airborne Equipment", Section 22 "Lightning Induced Transient Susceptibility", dated July 29, 1997. Section 22 provides basic test setups, levels, waveforms and procedures for the evaluation of equipment to the indirect effects lightning.

RTCA/DO-178B "Software Considerations in Airborne Systems and Equipment Certification", dated December 1, 1992. This document is a standard for the design, development and certification of software for airborne systems.

2.3.4 EUROCAE Documents: The following documents can be obtained EUROCAE, 17, rue Hamelin, 75116 Paris, Attn. Mr. Francis Grimal.

EUROCAE ED-14 "Environmental Conditions and Test Procedures for Airborne Equipment", Section 22 "Lightning Induced Transient Susceptibility", dated July 29, 1997. Section 22 provides basic test setups, levels, waveforms and procedures for the evaluation of equipment to the indirect effects lightning.

EUROCAE ED-84 "Aircraft Lightning Environment and Related Test Waveforms Standard", dated September, 1997.

2.4 Definitions, Abbreviations and Acronyms:

2.4.1 Definitions: The following are definitions of terms as they are utilized in this document.

ACTUAL TRANSIENT LEVEL (ATL): The level of transient voltage and/or current which appears at the equipment interfaces as a result of the external environment. This level may be less than or equal to the transient control level but should not be greater.

APERTURE: An electromagnetically transparent opening.

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

COMPONENT DAMAGE: That condition where the electrical characteristics of a circuit component are permanently altered so that it no longer performs to its specifications.

CONTINUED SAFE FLIGHT AND LANDING: This phrase means that the aircraft is capable of safely aborting or continuing a takeoff or continuing controlled flight and landing, possibly using emergency procedures but without requiring exceptional pilot skill or strength. Some aircraft damage may occur as a result of the failure condition or upon landing. For airplanes, the safe landing must be accomplished at a suitable airport. For rotorcraft, this means maintaining the ability of the rotorcraft to cope with adverse operating conditions and to land safely at a suitable site. See the AC/AMJ XX.1309.

CONTROL FUNCTION: A function that has some automated influence on a system (i.e., engine control system, flight control system) and whose failure would prevent the continued safe flight and landing of the aircraft.

DIRECT EFFECTS: Any physical damage to the aircraft and/or electrical/electronic systems due to the direct attachment of the lightning channel. This includes tearing, bending, burning, vaporization, or blasting of aircraft surfaces/structures and damage to electrical/electronic systems.

DISPLAY SYSTEMS: Those Flight, Navigation and Power Plant Instruments required by FAR XX.1303 and XX.1305.

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

EQUIPMENT TRANSIENT DESIGN LEVEL (ETDL): The peak amplitude of transients to which the equipment is qualified.

EQUIPMENT TRANSIENT SUSCEPTIBILITY LEVEL (ETSL): The transient peak amplitude which will result in damage or upset to the system components.

2.4.1 (Continued):

EXTERNAL ENVIRONMENT: Characterization of the natural lightning environment for design and certification purposes as defined in the Standard, Aircraft Lightning Environment and Related Test Waveform Standard.

INDIRECT EFFECTS: Electrical transients induced by lightning in aircraft electric circuits.

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

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

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

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

LIGHTNING STROKE (RETURN STROKE): A lightning current surge that occurs when the lightning leader makes contact with the ground or another charge center.

MARGIN: The difference between the equipment transient design level and the transient control level.

MULTIPLE BURST: A randomly spaced series of bursts of short duration, low amplitude current pulses, with each pulse characterized by rapidly changing currents (i.e., high di/dt's). These bursts may result from lightning leader progression or branching, and are associated with the cloud-to-cloud and intra-cloud flashes. The multiple bursts appear to be most intense at the time of initial leader attachment to the aircraft. See Standard, Aircraft Lightning Environment and Related Test Waveform Standard.

MULTIPLE STROKE: Two or more lightning return strokes occurring during a single lightning flash. See Standard, Aircraft Lightning Environment and Related Test Waveform Standard.

RETURN STROKE: (see Lightning Stroke)

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

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

2.4.1 (Continued):

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

TRANSIENT CONTROL LEVEL (TCL): The transient control level is the maximum allowable level of transients appearing at the equipment interfaces as a result of the defined external environment.

Upset: (See System Functional Upset)

2.4.2 Abbreviations:

A	Amperes
AC	Alternating Current
C	Capacitance
cm	Centimeters
dB	Decibel
DC	Direct Current
f or F	Frequency
I	Current
K	Constant
kA	Kilo Amperes
kHz	Kilo Hertz
L	Inductance
mA	Milli Amperes
MHz	Mega Hertz
µH	Micro Henry
µs	Micro Seconds
mm	Millimeters
nH	Nano Henry
P	Power
ps	Pico Seconds
Q	Resonance characteristics
R	Resistance
V	Voltage
W	Watts
Z	Impedance

2.4.3 Acronyms:

AC	Advisory Circular
AFWL	Air Force Weapon Laboratory
ARINC	Aeronautical Radio Incorporated
ARP	Aerospace Recommended Practice
ATL	Actual Transient Level
ATS	Air Turbine Starter
AWG	American Wire Gauge
BITE	Build In Test Equipment
CFC	Carbon Fiber Composite
CMOS	Complementary Metal Oxide Semiconductor
CMR	Common Mode Rejection
CW	Continuous Wave
DAL	Development Assurance Level
DAU	Digital Acquisition Unit
DOT	Department Of Transportation
EDAC	Error Detection And Correction
EFIS	Electronic Flight Instrument System
EICAS	Engine Indication and Crew Alerting System
EME	Electromagnetic Environment
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
ETDL	Equipment Transient Design Level
ETSL	Equipment Transient Susceptibility Level
EUROCAE	EURopean Organization for Civil Aviation Equipment
EUT	Equipment Under Test
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Engine Control
FAR	Federal Aviation Regulation
FBW	Fly-By-Wire
FCC	Failure Condition Classification
FHA	Functional Hazard Assessment
FWD	Forward
GUI	Graphical User Interface
HIRF	High Intensity Radiated Fields
HP Bleed	High Pressure Bleed
IFR	Instrument Flight Rules
IR	I * R (structural current times resistance)
JAA	Joint Airworthiness Authority
JAR	Joint Airworthiness Requirements
LLPT	Low Level Pulse Test
LLSC	Low Level Swept Coupling
LP Bleed	Low Pressure Bleed
LRU	Line Replaceable Unit
LTA	Lightning Transient Analysis

2.4.3 (Continued):

LVDT	Linear Variable Differential Transformer
MB	Multiple Burst
MIL-HDBK	Military Handbook
MIL-STD	Military Standard
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MOV	Metal Oxide Varistor
MS	Multiple Stroke
MTBF	Mean Time Between Failures
MTBUR	Mean Time Between Unscheduled Removals
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NTIS	National Technical Information Service
OAS	Overall Shield
PAT	Production Acceptance Test
PMA	Parts Manufacturing Approval
PRF	Pulse Repetition Frequency
RF	Radio Frequency
RTCA	Radio Technical Committee on Aeronautics
SAE	Society of Automotive Engineers
SCEPTRE	System for Circuit Evaluation and Prediction of Transient Radiation Effects, is a general purpose circuit analysis program, which provides all three major analyses, AC, DC, and transient analysis, on either linear or nonlinear networks.
SPD	Surge Protection Device
SPICE	Simulation Program with Integrated Circuit Emphasis [circuit analyzer software]
STC	Supplemental Type Certificate
TC	Type Certificate
TCL	Transient Control Level
TDFD	Three Dimensional Finite Difference
TPD	Terminal Protection Device
TR	Technical Report
TSO	Technical Standard Order
USAF	United States Air Force
VFR	Visual Flight Rules
WG	Working Group

3. BACKGROUND/EXPERIENCE:

The trend toward increased reliance on electrical/electronic systems for flight and engine control functions, navigation and instrumentation requires that effective protection against lightning-induced transients be designed and incorporated into these systems. Reliance upon redundancy as a sole means of protection against lightning indirect effects is generally not adequate because the electromagnetic field and structural IR voltages can interact concurrently with all electrical wiring aboard an aircraft.

3.1 Aircraft Lightning Interactions:

Commercial aircraft experience lightning strikes. The various lightning environment components encountered during an aircraft interaction with lightning are discussed in ARP5412.

In-flight lightning research programs such as the USAF/FAA CV-580, the NASA F-106 and the French C-160 have shown that many aircraft lightning events can be triggered by the aircraft itself. These events occur when the aircraft flies into an atmospheric electric field and this field is locally enhanced at aircraft extremities. The aircraft may also acquire a net charge from triboelectrification or other processes. This net charge enhances the local field at aircraft extremities. When this local field exceeds air breakdown levels over a sufficiently large region, arcs form and propagate (usually in two directions) away from the aircraft toward the charge centers, which created the ambient electric field. These initial arcs are usually of small amplitude (a few hundred amperes or a few kiloamperes), but they can eventually form the path for the much larger currents associated with an actual lightning strike, which neutralizes the relatively large amounts of charge in the charge centers. These currents have been measured to be as large as several tens of kiloamperes at flight altitudes. Physical damage left by other strikes to in-flight aircraft are indicative of much higher amplitude strikes, based on comparisons with damage caused by laboratory strikes of known magnitude.

Lightning related damage is believed to be most severe when the aircraft encounters a main cloud-to-ground lightning channel. Less severe damage occurs when the aircraft is struck by a branch of a leader system, or by an intra-cloud flash, though apparently the intra-cloud flashes have also produced significant damage on occasion.

In either type of event described above, the lightning attachment process always begins with streamers and junction leaders originating at the aircraft. For the cloud-to-ground case, the junction leaders may connect to an approaching or nearby lightning leader. This phase of the lightning event is commonly called the attachment phase and is generally associated with relatively small current amplitudes and large electric fields. The large currents and magnetic fields are usually associated with the return strokes in cloud-to-ground flashes and the recoil streamers for intra-cloud lightning events.

3.2 Lightning Indirect Effects:

On some occasions, damage or interference to one or more on-board electronic components is reported. In one study[1], this occurred in approximately 10% of the reported strike incidents, with the most frequent occurrence being temporary interference, with recovery of the affected item following the strike incident. Failures have ranged from damage to antennas, radios and engine instruments to burnout of components such as Electromagnetic Interference (EMI) filter capacitors and relay suppression diodes. In a few cases, power distribution circuit breakers have "tripped" indicating spark-over of insulation at terminal boards, connectors, relays and circuit boards due to lightning-induced transients. In most cases, these spark-overs are across air gaps, which recover when the transient has passed and circuit breakers have been reset. Electric power has been lost temporarily, however and this has caused related upsets in other systems.

1. McDowall, Rosemarie L., Plumer, J. Anderson, and Glynn, Michael S., "Lightning Data Acquisition," Addendum to the 15th International Aerospace and Ground Conference on Lightning and Static Electricity, Atlantic City, New Jersey, October 1992.

3.2 (Continued):

Indirect effects can cause upset of or damage to electrical/electronic systems performing functions that can affect continued safe operation of the aircraft. Such events have been very rare, and flight critical systems aboard modern airplanes, which include Full Authority Digital Engine Controls (FADEC), Electronic Flight Instrument Systems (EFIS) and Fly-By-Wire (FBW) flight controls have demonstrated the effectiveness of the protection design and certification methods described in this document.

These systems have been installed and certified in composite as well as conventional aluminum airframes and protection designs have been verified by combinations of test and analysis. The occurrence of damage or upset to other electronic components, not protected or verified by the same methods, is a reminder that the potential exists for upset or damage if adequate protective measures are not employed.

3.3 Prior Criteria:

Airframe manufacturing companies have established lightning-induced electrical transient protection requirements for on-board electronic equipment. Similar requirements have been incorporated in industry-wide commercial specifications such as DO-160/ED-14, in military specifications and standards, and in the NASA space shuttle lightning criteria. Equipment manufacturers frequently have been required to verify ability of equipment to tolerate these transients. Until recently, these transient requirements have not included the effects of the multiple burst or multiple stroke environments and the specified levels have not been related directly to Actual Transient Levels (ATLs) in the interconnecting wiring. In addition, the established requirements were compatible with installations within conventional metal airplane installations and equipment/systems have performed satisfactorily in these installations.

The employment of electrical/electronic systems to perform functions that can affect continued safe operation of the aircraft has increased the need to assure that equipment can safely tolerate the lightning environment within the specific aircraft for which they are intended. This begins with establishment of the ATLs expected within system interconnected wiring and is followed by designation of specific transient descriptions and levels which are to be withstood by system equipment. Verification of damage and upset tolerances is then accomplished by analyses, tests, or similarity with previously certified designs. Acceptable steps in this process are described in ARP5413 and methods and examples for accomplishing them are described in this User's Manual and ARP5416 (Draft).

3.4 External and Internal Lightning Environment Criteria:

The transient waveforms and levels presented in Section 8 of ARP5412 are based on actual transients measured in circuits of tested aircraft. The levels associated with these waveforms are also shown in Tables 22.2 and 22.3 of Section 22 in DO-160/ED-14. A large amount of such data exists in the technical literature and was utilized to establish the transient waveforms and the amplitude levels. The lower levels (1, 2) are representative of transients observed in well-protected short wire bundles installed in metal airframes. The higher levels are more typical of longer wire bundles installed in less well shielded regions within metal or composite airframes. Other transients considerably different than those tabulated have also been observed. Those applicants intending to choose from among these waveforms and levels are cautioned to be certain that other transients will not actually occur in their installations.

The lightning environment specified in ARP5412 is intended to represent the characteristics of a severe, but not the most severe, lightning flash. The peak amplitude and peak rate-of-rise of the first return stroke are believed to be exceeded in approximately one percent of recorded natural lightning flashes. However such extremes in both parameters do not occur at the same time. Illustrative of this are the limited statistical basis that exists for establishing the severity of other characteristics of the lightning environment, such as charge transfer, stroke current time duration, action integral and numbers of strokes in a flash. Physical damage effects produced by lightning strike currents exceeding the intensities of those included in the external environment have been evidenced on aircraft struck in flight, yet not all of the defined parameters have appeared to be exceeded at once. Peak current amplitude and action integral may be exceeded, but rate of rise (di/dt) does not appear to be exceeded at the same time. In fact, recorded flashes to earth that have high action integrals usually do not have high rates of change.

The test waveforms provided in ARP5412 are considered to be adequate for the demonstration of compliance for the protection of an aircraft and its systems against the lightning environment and should be applied in accordance with the aircraft lightning strike zones in ARP5414 and test methods in ARP5416 (Draft), and applicable FAA and JAA advisories and other interpretive material.

3.5 Increased Attention to Indirect Effects Protection:

The trend toward miniaturization of electronics means that unprotected circuit boards and components are inherently more vulnerable to damage or upset from electrical transients than earlier electronics comprised of discrete semiconductor devices or electromechanical devices. Transient voltage and current waveforms that exceed logic levels may cause burnout or upset. Transients of amplitudes that exceed the logic levels may be induced by lightning on interconnecting wiring. This means that protective measures may be needed (see 3.6 and 4.4) to control transients to tolerable levels.

3.5 (Continued):

Additionally, the trend toward digital architecture has placed emphasis on large quantities of computed data. This data tends to be volatile and thereby vulnerable to loss as a result of circuit upsets produced by lightning induced transients. This may, in principle, occur even when no permanent damage results to the processing circuit elements. The transient pulses resulting from the multiple stroke and burst environments can be sufficient to cause data errors and erroneous commands.

3.6 Protection Design:

The approach is to optimize the use of installation design techniques, equipment immunity and protective devices. Equipment immunity is ideally achieved through circuit/software designs that provide sufficient inherent immunity so that reliance on dedicated circuit protection devices can be minimized. Dedicated protection devices are usually undesirable because they require periodic surveillance, can reduce system Mean Time Between Failures (MTBF) and degrade installation performance. Design protection guidance can be found in Appendix C.

4. APPROACHES TO COMPLIANCE:

The approach to compliance involves seven elements of an interactive process for certification of aircraft electrical/electronic systems with respect to the indirect effects of lightning. These seven elements are:

a. Review safety assessment (4.1)
b. Determine the lightning strike zones to direct effects (4.2)
c. Establish the external lightning environment for the zone (4.3)
d. Establish the effects of the internal environment (4.4)
e. Establish transient control levels and equipment transient design levels (4.5)
f. Verify compliance (4.6)
g. Corrective measures (4.7)

The particular order of activities addressed and the iterative application of the elements appropriate for a particular situation is left to the applicant and strict adherence to the particular ordering of the elements in the list is not intended.

4.1 Review Safety Assessment:

The aircraft safety assessment is one of the fundamental activities of an overall certification process. Depending upon failure effects, lightning protection requirements may apply to systems and equipment that are installed in an aircraft under the provisions of a new or amended Type Certificate (TC). They may also apply to systems and equipment installed under the provisions of a Supplemental Type Certificate (STC). A general path for demonstration of regulatory compliance for indirect effects of lightning is shown in the flow charts of Figures 2 through 4 in Section 7 of ARP5413. Lightning protection requirements for electrical and electronic systems are contained in FAR/JAR Parts 23.1309 (e), 25.1316, 27.1309 (d) and 29.1309 (h) (see Appendix A). Compliance with Technical Standard Order (TSO) guidelines or Parts Manufacturing Approval (PMA) as defined in FAR/JAR Part 21 does not ensure certification of the system on an aircraft via a TC, STC.

The Functional Hazard Assessment (FHA) is an integral part of the aircraft safety assessment.

An aircraft FHA is conducted to identify all failures and classify them in functional and operational terms. An assessment of functional upset involves making pass/fail judgments as they relate to safe operation of the aircraft. Such pass/fail criteria fundamentally rely upon the results of the FHA, a key step of the aircraft safety assessment process. This is a system design and validation issue requiring the application of systems engineering disciplines and systems engineering participation. The aircraft safety analysis is important in the demonstration of regulatory compliance for the various types of aircraft systems. The failure condition classification of a function will determine the development assurance level of a system. Reference documents are as follows: ARP4754, ARP4761, AC 23.1309-1C, AC 25.1309-1A, AC 27-1A and AC 29-2B. This analysis should be assessed to determine the impact of lightning induced effects on each piece of installed equipment as it pertains to the specific installation and aircraft safe operation. Similarity to an existing system installation may be used to show compliance to the applicable lightning regulations and special conditions (as appropriate). Early coordination with the appropriate aviation certification authorities is recommended to ensure a timely certification process. (For details on ETSL damage and upset effects, please see Section 5).

The development assurance level of a system on an aircraft is determined by the function(s) performed by the system and the impact of a failure of the function(s) on the operational safety of the aircraft. The failure condition classification of a function has the following characteristics:

a. Unique for each aircraft design,

b. Applicable to overall aircraft installation configuration, not to the individual electrical/electronic equipment, and

c. Cumulative, i.e., the criticality of a group of functions can be higher than the criticality of an individual function within the group.

4.1 (Continued):

When completed, the FHA provides:

a. A list of the functions and their failure condition classifications, and

b. Information for the identification of development assurance levels associated with the systems providing such functions.

Failure condition classifications are derived from the FHA and represent the top-level pass/fail performance criteria for an aircraft function. These criteria provide the information from which system and equipment performance pass/fail criteria can be derived. The system and equipment pass/fail criteria can be used subsequently during compliance/qualification activities.

Table 1 shows a cross reference between AC 23.1309-1C, 25.1309-1A and the nomenclature used in ARP5413, derived from ARP4754.

TABLE 1 - Nomenclature Cross Reference

FAILURE CONDITION CLASSIFICATION (AC 23.1309-1C, AC 25.1309-1A and ARP4754)	**SYSTEM DEVELOPMENT ASSURANCE LEVEL** (ARP4754)
No Effect	Level E
Minor	Level D
Major	Level C
Severe Major/Hazardous	Level B
Catastrophic	Level A

The definitions for each failure condition classification and development assurance level are provided in Section 4.a of ARP5413. It should be noted that the Failure Condition Classification is related to the function performed by the electrical/electronic system under consideration. However, the System Development Assurance Level is related to the electrical/electronic system.

The terms Level A, etc., come from ARP4754 and designate particular system development assurance levels to be assigned to system implementations of those functions whose failure impact safety. System development assurance levels refer to processes used during system development (design, implementation, verification/certification, production, etc.). It was deemed necessary to focus on the development processes for systems based upon 'highly-integrated' or 'complex' (whose safety cannot be shown solely by test and whose logic is difficult to comprehend without the aid of analytical tools) elements (primarily digital electronic elements).

4.1 (Continued):

Development assurance activities support system development processes. Systems and items are assigned "development assurance levels" based on failure condition classifications associated with aircraft-level functions implemented in the systems and items. The rigor and discipline needed in performing the activities supporting development processes will vary corresponding to the assigned development assurance level.

ARP5413 comes into play during the verification and compliance demonstration phases of the system development process. It provides the appropriate discipline and rigor associated with the appropriate system development assurance level categorization.

With respect to the indirect effects of lightning, Level A systems are placed in one of two subcategories, Control or Display. Level A Control systems perform functions with failure condition classification(s) considered to be catastrophic and perform the function in such a manner that the flight crew is not in the loop and an alternate means of flying the aircraft is not available to the flight crew. Level A Display systems perform functions with failure condition classification(s) considered to be catastrophic and perform the function in such a manner that the flight crew is in the loop and has an alternate means of flying the aircraft. In the case of Display systems, while the failure condition is considered to be catastrophic, given quick action and the right choices by the flight crew, the effect of the failure may be lessened. This is not considered to be true for Level A Control systems.

Classification of functions and subsequently the system(s) performing each function resulting from the FHA usually follows predictable guidelines. Electrical/electronic systems that provide functions such as FBW flight controls and FADEC are usually examples of Level A Control systems. Attitude, altitude and airspeed sensing and display are usually examples of Level A Display systems. As aircraft size and complexity increase, other systems such as Engine Indication and Crew Alerting Systems (EICAS), i.e., thrust rating, could also fall into the Level A Display classification. Level B and C systems generally include navigation, and displays providing heading, position and enroute data and communication. Emergency and/or warning systems, not identified as Level A, will generally be classified as Level B or C.

When analyzing a function failure condition classification, consideration of the unique aspects of the indirect effects of lightning should be included. The lightning environment may induce failures in ways not encountered under other operating conditions. Normally, system redundancy reduces the probability of function failure; however, a lightning flash may affect redundant systems simultaneously. Therefore, lightning is considered a possible common mode threat and thus a source of common cause threat and thus a source of common mode failure in redundant system architectures. As a result, protection on all redundant elements may be required. An example is the function of attitude display. While redundant attitude displays may allow loss of one or more displays under certain failure conditions and still maintain the attitude display function, a lightning strike may affect multiple displays simultaneously.

4.1 (Continued):

Redundancy and partitioning may not be sufficient for like systems performing identical functions to survive a lightning event, and as such, may not be given credit in a certification. Once transient protection has been added to the systems of interest, then, in practice, partitioning can help ensure that like systems do not see the same transient levels during a lightning event. Installations utilizing wire bundle and Line Replaceable Unit (LRU) separation for like systems take advantage of the low probability of a symmetrical lightning event. Examples of partitioning are wire bundle routing on opposite sides of the fuselage and LRU installations in different equipment bays.

Although a failure by itself may not be catastrophic or major, it may be a contributing factor when combinations of failures are considered. For example, a latent or undetected failure could contribute to a major or catastrophic failure condition when combined with one or more specific failures or events. For example, the loss of all communication systems and all navigation systems may be classified as a higher failure condition classification than the loss of only the communication system or only the navigation system. Therefore, combinations of failures must be considered.

4.2 Determine the Lightning Strike Zones for the Aircraft:

Methods for identifying the lightning strike zones on an aircraft can be found in ARP5414.

Identification of the locations where lightning attaches to aircraft is important for indirect effects evaluation. This is primarily because the surface current densities and electromagnetic fields are largest near the lightning attachment points. It is therefore important to identify those lightning attachment points which may require special attention. Some examples include:

- Attachment to an aircraft nacelle containing a FADEC or similarly critical equipment.
- Attachment near the cockpit windows, thereby creating large electromagnetic fields in the cockpit region.
- Attachment to carbon fiber or other poorly conducting surfaces, thus providing especially large fields directly underneath the lightning attachment point.
- Attachment to wheel struts during landing or take off, thereby creating large fields in the wheel well as well as providing for large excitation of wire bundles along the wheel struts.

It is therefore important to identify not only the more traditional lightning attachment points (e.g., wing tips, nose, tail), but to also identify those points which may have special significance for certain critical systems. In addition, identification of the lightning strike zones helps in assessing the exposure of electrical/ electronic equipment and interconnecting wiring. Equipment mounted on the exterior of the aircraft may encounter direct lightning attachment and can provide a path for a portion of the full lightning current to enter the aircraft. For equipment mounted on the aircraft exterior, identification of zones will probably indicate the need for careful equipment design and installation and the possible need for additional protection of interconnected equipment. The lightning attachment zones indicate the starting point, distribution, and associated magnitudes of the excitation currents on the aircraft exterior. These currents produce the internal lightning environment encountered by the equipment mounted in the aircraft. Thus, the lightning strike zone is a region of points on the aircraft exterior any one of which may, for that zone, have the full concentration of the external environment.

4.2.1 Relationship of Lightning Strike Zones to Direct Effects: Equipment mounted external to the fuselage, wings, or tail of the aircraft are exposed to the possibility of a direct lightning strike. Examples of such equipment are antennas, sensors and probes. Section 23 of DO-160/ED-14 provides environmental TSO testing of such equipment. Antennas, sensors and probes mounted behind a dielectric material integral to the aircraft skin may need to be protected from both direct and indirect effects.

Once zoning of the aircraft is completed, the relevant threat to the externally mounted equipment is then identified. This threat (zone) correlates directly with the test categories of Section 23 in DO-160/ED-14, which establish the test requirements for each piece of equipment. However, variations in installation location from aircraft to aircraft and aircraft type to aircraft type must be considered and the worst case zoning classification for each piece of equipment should be used to establish the test category in Section 23 of DO-160/ED-14.

4.2.2 Relationship of Lightning Strike Zones to Indirect Effects: Equipment mounted inside the fuselage, wing, or tail of the aircraft is generally considered to be in Zone 3 of the aircraft. Zone 3 areas conduct current components of the lightning flash as well as multiple stroke and multiple burst waveform sets. Zone 3 currents are generally shared among all conductive aircraft components and low impedance wire bundles. There are cases such as some fuselage-mounted engines, which can be classified as being located in a Zone 2 region. Such a classification would replace exposure to the high amplitude current Component A by the re-strike current Component D. In these cases, the indirect threat is lower.

The identification of the lightning strike zones on the aircraft can be used in the determination of the probable lightning attachment points and the current paths between them. Identification of these areas will help in assessing the exposure of electrical/electronic equipment and the interconnecting wiring to the conducted and radiated electromagnetic environment encountered inside the aircraft. Generally, it should be noted that the threat is determined by interconnecting wiring routes and Zone 3 exposure level usually is most important. However, equipment and interconnecting wiring which are located in areas near probable attachment points may experience much higher current densities and may require careful equipment design and installation and the possible need for additional protection of interconnected equipment. If it is impossible to provide additional protection to the installation or equipment itself, then the location of lightning attachment points can be used to identify areas where the equipment cannot be located.

4.3 Establish the External Lightning Environment for the Zone:

Once the aircraft lightning strike zoning has been determined it is necessary to establish the external lightning environment applicable for indirect effects assessment of the installed electrical/electronic systems. The accepted detailed definition of this environment is contained in ARP5412 and consists of the current components (A, A_h, B, C, D and H) which comprise the lightning flash. Those components which are important (for system assessments) to indirect effects are current Components A, D and H since they will produce the largest transients in system wiring because of their large current magnitudes and/or rates of rise.

4.3 (Continued):

The lightning current flows through the aircraft between attachment points. For any given system there may be several attachment points which cause current to flow in a manner to couple to that system. The external environment applicable to a given system consists of those current components, which are to be applied at the aircraft exterior where coupling to systems can occur. The lightning/aircraft attachment configuration (entry and exit points for lightning current) i.e., zoning information is used to determine which components of the external environment are to be applied to the system under evaluation.

Table 2 identifies the external environment associated with each zone. Time domain and associated frequency domain plots of current Component Waveforms A, D and H are described in Section 6 of ARP5412.

TABLE 2 - Zonal Application of the External Environment for Determination of Indirect Effects

Current Conduction Zone	Current Components and Waveform Sets			
	A	D	Multiple Stroke (D, D/2)	Multiple Burst (H)
Within Zones 2A and 2B only		X	X	X
Within Zone 3	X	X	X	X

TCLs and ETDLs assigned to systems installed exclusively within structures between only Zones 2A and/or 2B may be based on the current Component D external environment instead of the current Component A environment; however equipment interfaces connecting to equipment in other regions must be certified to withstand the current Component A based environment. This means that ATLs, TCLs and ETDLs assigned to wiring that is located solely within a section of the airframe whose external surfaces are in lightning strike Zones 2A and/or 2B only can be based upon transients induced by current Component D instead of by current Component A. This, in turn, means that magnetically induced voltages in unshielded circuit loops are the same amplitude(s) as those induced by current Component A, but voltages due to structural IR voltages, as occur in circuits within carbon fiber reinforced composite structures, will be 50% of those induced by current Component A. Also all induced currents, whether due to magnetic field or structural IR voltages, will be 50% of those that would be induced by the current Component A lightning environment.

The most common example of this situation (current Component D instead A) applies to fuselage mounted engine electronic control system circuits that are installed entirely within an engine nacelle located in Zones 2A with trailing edges in Zone 2B. Any equipment interfaces that connect from the engine (in this example) to equipment in the rest of the airframe (i.e., the instrument panel) are in Zone 3 and must tolerate ETDLs derived from the Zone 3 lightning environment.

4.4 Establish the Effects of the Internal Environment:

The design and verification process for lightning protection of aircraft electrical/electronic systems must include establishing the effects of the internal aircraft environment due to lightning. The external lightning environment will generate an internal environment of electromagnetic fields and structural currents and voltages. The internal environment will in turn induce voltage and current transients which appear at the interfaces of installed equipment. Ultimately, it must be shown that these voltage and current transients do not adversely affect the safe operation of electrical and electronic systems. The concerns for such systems are component damage and functional upset that can be the result of lightning-induced interface voltages and currents. Electrical and electronic system immunity to the effects of these interface voltages and currents is ideally achieved through installation, system architecture (fault tolerance, data bus protocols, input/output software, etc.) and equipment (circuit and software) designs that provide inherent immunity so that reliance on dedicated protection devices can be eliminated or minimized (see Appendix C). Dedicated protection devices may have latent failures that negate their protection and periodic maintenance may need to be performed to assure continued protection. In addition, these devices may also degrade circuit performance (example: add capacitive loading to digital buses).

Before system and equipment effects and system immunity can be assessed, the voltage and current transient amplitude and waveform characteristics must be determined. These voltage and current transient amplitude and waveform characteristics are the result of complex electromagnetic processes. The approach for establishing these characteristics may include test, analysis, comparison with similar aircraft data, or a combination of these. Whatever the approach, it must be based on methods that can be validated and can provide the appropriate data for ultimately verifying adequate lightning protection margins. Also, the methods must account fully for the aircraft structure, materials, apertures and arrangement of subsystems within the aircraft.

The voltage and current transient amplitude and waveform characteristics are used to select the aircraft transient control levels (TCL). In some cases the aircraft voltage and current transient data determined in this process can also establish the aircraft actual transient levels (ATL) used to verify compliance. However, often the expected voltage and current transient amplitude and waveform characteristics are estimated before detailed system, wiring, and aircraft designs are completed. Therefore, the estimates are used to select the TCL. Then the ATL is determined during the compliance verification tests or analysis.

4.4.1 Relationship between External and Internal Environment: Many years of in-flight and ground-based data have led to an aircraft lightning certification environment definition. This definition takes into account the phenomenology of lightning and aircraft interaction and the characteristics associated with aircraft lightning strikes by severe cloud-to-ground and intracloud lightning flashes. Detailed information on the external lightning environment and typical induced voltages and currents in aircraft wiring is given in ARP5412 and includes multiple stroke and multiple burst waveform sets. The multiple stroke and burst currents are relevant to systems located between Zone 1A and/or 1B lightning attachment points. Systems located between other lightning zones may be subjected to a reduced number of strokes of the multiple stroke environment. This also means that the Zone 3 environment within structures, such as some fuselage mounted engine nacelles, whose surfaces are in Zones 2A or 2B only may not experience the induced effects of Current Component A. Such systems would experience the effects of current Component D. Since most aircraft systems are installed in airframe sections that do indeed lie between Zone 1A or 1B attachment zones, or within an associated Zone 3, this usually exposes all system installations to current Component A and the total multiple stroke and multiple burst waveform sets.

The key features for lightning induced transients are the large di/dt and current associated with current Components A and D. Current Component H, although only 10 kA, has a very large di/dt associated with it and must be considered, typically for upset effects.

The external environment described in 4.3 is defined as the external lightning current components, which are associated with their appropriate zones. The interaction with these zones results in electromagnetic fields on both the exterior and interior of the aircraft during the application of the lightning current components. For further discussions on the relationship between the external and internal environments see Appendix B.

When determining internal environments it is frequently convenient to define the current and charge densities on the aircraft surface as the surface environment and the electromagnetic fields and structural currents within the aircraft interior as the internal environment. This separation of the interaction process is an approximation, which is valid when the surface environment is not significantly affected by the internal environment, so that the surface and internal environments are significantly decoupled. This is the case for all metal or mostly metal aircraft with small apertures and includes most commercial aircraft. In these cases it is clear that changes to the aircraft internal structures and wire bundle layouts will not significantly affect the surface current and charge density on the metal exterior. As a result, the interaction process can be accomplished in two steps.

For aircraft whose interaction with lightning can be approximated by breaking it up into two independent processes it is logical first to establish the external surface environment. This can be done experimentally or by analysis. With either method, external lightning environments are applied to their appropriate zones and the surface electromagnetic fields at the aperture locations are recorded. This needs to be done for the entire set of external lightning environments, in order to ensure that the worst case is obtained.

4.4.1 (Continued):

The first step is to calculate the surface currents and charge densities with all of the apertures short-circuited. A second step would then be to use these surface currents and charge densities to define equivalent sources at the apertures and obtain the internal environment from these sources, without any feedback mechanism from the interior environment to the external environment.

The word "aperture" is a general term. It not only involves openings in the skin such as glass windows, but it also includes seams, joints and composite panels, if these are significant contributors to the internal environment. For the latter types of apertures, the normal surface electric fields (charge density) do not couple significantly and only the surface magnetic fields (surface current densities) are important.

However, there are two significant classes of aircraft for which de-coupling the surface and internal environments is not a valid approximation.

The first class includes those aircraft, which are largely open structures, such as certain helicopters. Although the basic structure may be metal, large portions of the skin may be glass, fiberglass, Kevlar, or other nonconducting material. In this case the distinction between interior and exterior electromagnetic environments becomes less pronounced and one must therefore determine the entire environment (electromagnetic fields and wire bundle responses) simultaneously.

The second aircraft class for which the decoupled approximation is not valid includes aircraft, which have large amounts of carbon fiber composite (CFC) structure, especially if the CFC structure is not protected by any metallization. Typically, the CFC structure surrounds metal substructure, hydraulic tubes, etc. By the process of redistribution, the current will initially flow on the exterior and gradually transfer to metal components. This process simultaneously involves both the external and internal features of the aircraft and cannot be separated into two distinct processes.

4.4.2 Induced Transient Mechanisms: Complex voltage and current transient waveforms occur in aircraft wiring due to lightning strikes. However, such complex composite waveforms can be generally represented by a combination of any of six standardized transfer waveforms. Each of these waveforms is the result of particular transfer mechanisms.

Waveforms 1, 2, 4 and 5 of ARP5412 may occur in aircraft wiring as responses to the external environment Current Component A waveform. Waveforms 1 and 4 are proportional to the Current Component A double exponential waveform, and Waveforms 5A and 5B are lengthened double-exponential waveforms. Waveform 2 is proportional to the derivative of Current Component A. These waveforms will be significant in circuits using airframe return and also for circuits installed within non-metallic aircraft structures.

4.4.2 (Continued):

Waveforms 1, 2, 4 and 5 can be referred to as particular, fundamental, or forced responses to input excitation Current Component A and are the responses expected in a circuit that is electrically short. A circuit becomes electrically short when the duration of an excitation pulse is very long when compared to the transit time of an electrical wave traveling down the wiring connecting the termination points of the circuit. Appendix B shows that the internal Waveforms 1, 2, 4 and 5 can be derived from the external Current Component A. However, there are other types of current waveforms in the structure and the effect of these should also be considered.

Waveform 3 will also occur as a response to Current Component A. The rapid changes in airframe charge occurring during the lightning attachment process produce a traveling wave in the aircraft, resulting in oscillations of airframe current. These traveling wave effects will influence derivative parameters di/dt (where i is the airframe current) and dB/dt, which determine the magnitudes of induced voltages and currents in wiring installations.

The oscillatory nature of these airframe traveling wave currents is responsible for Waveform 3. Whether or not an oscillating waveform is significant depends on the Q of the existing waveform if it is a forced response or the Q of the wire bundle and airframe return loop if it is a natural response. Both the currents flowing on the conductive structure of the aircraft and the transients induced on wiring and wire bundles may show oscillatory components. The parameters of the oscillatory portion of the transient are related to the electrical length of the aircraft and/or wire bundle and to the waveform of the excitation source.

When the aircraft is exposed to a lightning transient, wire bundles may be excited into electrical resonance and an initial oscillatory response may occur. The oscillations will damp out, in general, within 10 to 20 cycles. As wire bundle and/or aircraft lengths approach an electrically long condition, this oscillatory response becomes more dominant in the total response. A circuit becomes electrically long when the duration of an excitation pulse is very short when compared to the electrical wave transit time. For an electrically long circuit, the Waveform 3 traveling wave response dominates.

The oscillatory response is sometimes referred to as the homogeneous or natural response. It can also be a forced response. Except for some exceptional cases, the oscillatory response is always present, to some extent, in the total response. As discussed previously, the other components in the total response are also referred to as forced responses. Thus, since the pulse duration for current Waveform A is such that electrical circuit lengths associated with most aircraft and aircraft wiring lengths are not clearly electrically long, the total response to Current Component A could be a Waveform 3 combined with Waveform 1, 2, 4 or 5. Examples associated with qualitative discussion in Appendix B provide some insight into the variety of waveforms that have been observed in measurements of transients induced on aircraft wiring.

The coupling mechanism between external and internal environments, which drives the forced internal wire bundle response, is the same regardless of the external current waveform shape. Forced responses will be significant in equipment circuits that use airframe for their return and/or those installed within aircraft structures whose electrical resistance is of the order of tens of milliohms.

4.4.2 (Continued):

The total response could be a complex combination of the natural and forced responses with their associated waveforms and levels. The waveform sets of DO-160/ED-14, Section 22 together represent the total complex waveform for a particular installation. As has been reviewed from several perspectives, the waveforms identified in these sets are the result of various coupling mechanisms and are the solutions to the algebraic, ordinary differential and partial differential equations that quantitatively represent these mechanisms (see Appendix B). These waveform sets are divided into two broad aircraft construction classes with their associated installations:

1. Metallic aircraft; aircraft whose airframes are comprised of metal framework and composite skin panels; and aircraft whose airframes are comprised of CFC and whose major surface areas have been protected with meshes or foils.

2. Aircraft whose airframes are comprised of CFC or airframe sections whose structural electrical resistance is of the order of tens of milliohms. In aircraft of this type of construction, wiring could be exposed to high structural voltages and redistributed lightning currents.

Although any of the waveforms could produce component damage or functional upset, Waveforms 2, 3 (damped sinusoid) and 6 are usually considered important for functional upset and the longer time duration 1, 4 and 5 waveforms are usually considered important for component damage.

Generally, the lightning transients are defined by common mode voltage and current. That is, the voltage and the associated current are measured relative to aircraft structure.

For the case where currents are driven by voltage Waveforms 2, 3 or 4, the current in the loop would be:

$$I_L = \frac{V_L}{Z_L} \quad \text{(Eq. 1)}$$

where:

I_L = Current in the loop in amperes, which could be applied to an interface circuit
V_L = Voltage in volts, being driven around the loop
Z_L = Impedance in ohms, around the loop

4.4.2 (Continued):

For the case where Waveform 3 is the result of inducing a traveling wave, the current transferred to an interface circuit would be bounded by (see Appendix B, Section B.1.3):

$$I_T = \frac{V_T}{Z_o} \qquad \text{(Eq. 2)}$$

where:

I_T = Current in amperes, transferred to an interface circuit
V_T = Traveling wave voltage, in volts
Z_o = Transmission line characteristic impedance, in ohms

Traveling wave current amplitudes are determined by the characteristic impedances of the interconnecting circuits (i.e., the individual wires with respect to airframe references), and not by remote equipment load impedances. Typical characteristic impedances range between 25 and 100 Ω. Thus it is not appropriate to add impedances (resistances) higher than this to pin injection test circuits during applications of Waveform 3 transients, due to traveling waves, to further limit the amplitudes of the Waveform 3 currents. This is why Note 6 of Table 22-2 of DO-160/ED-14 limits such additional impedances to 75 Ω, for a total of 100 Ω in series with the Waveform 3 transient generator. Additional discussion of the Waveform 3 responses of aircraft wiring may be found in Appendix B of this document.

For most cases, the traveling wave is not the prominent source of Waveform 3 in aircraft wiring. The aircraft structure's response to lightning may also be a damped sinusoidal current. This current in the structure produces fields which couple to wiring and the wiring response is, in turn, Waveform 3. In this case, the current available from Waveform 3, which in turn could be imposed on an interface circuit, would be the common mode voltage induced around the circuit loop divided by the total impedance around the loop or, as an upper limit, the current given in Table 9 of ARP5412.

Traveling wave responses could be significant when:

a. Wire bundles are excited by significant magnetic fields of current Component H.

b. Relatively long wire bundles are routed through regions where exposure to relatively high field intensities is possible, e.g., a wire bundle run along the wing leading edge.

c. Shorter wire bundles are routed through regions where exposure to very intense fields is possible, e.g., wire bundle spanning a gap between the horizontal stabilizer and fuselage.

Such traveling wave responses need to be identified and the interface circuits being exposed to them need to be qualified appropriately. In this case, the Waveform 3 period is a function of the wire length of a “complete” aircraft circuit. Therefore, as illustrated in Appendix B, the shorter the wire, the shorter the period (duration) for the Waveform 3 transient. Also, the shorter the wire, the smaller the amount of energy it could collect and manifest as a traveling wave.

4.4.2 (Continued):

Waveforms D and D/2 are constituents of the multiple stroke environment. The multiple burst environment is a series of Waveform H pulses. As with current Waveform A, the response to Waveform D would be a combination of Waveform 3 and forced response that would have waveforms similar to 1, 2, 4 or 5.

The pulse duration of the Current Component H associated with the multiple burst external environment is short enough that the electrical circuit length associated with aircraft and most wiring lengths will approach the electrically long case. Waveform 3 will therefore be the dominant response to Current Component H. For the special case where the natural response is relatively flat over the frequency range, the current associated with a short circuit loop configuration would follow the excitation waveform (see Appendix B). In this case the response to Current Component H will be a waveform proportional to Current Component H, which is represented by Waveform 6.

4.4.3 Determining Induced Transients: The lightning induced transients expected at electrical or electronic system interfaces must be determined during the system and aircraft design process. The expected induced transient amplitude and waveforms are used to select an appropriate transient control level (TCL) for the aircraft, and the appropriate equipment transient design level (ETDL) for the electrical and electronic systems. The expected induced transient levels and waveforms may be determined by aircraft tests, detailed analysis, estimates based on basic calculations, or data from similar aircraft and installations.

When lightning tests are performed on the actual aircraft and installation, or analysis is based on the final aircraft and system installation design, then the induced transient levels can be considered the actual transient levels (ATL) for the installation. However, for new or significantly modified aircraft or systems, there may be no existing test data to determine the expected induced transients. After the aircraft is designed and built, the ATLs are determined during verification tests, analysis, or similarity assessments described in 4.6.

4.4.3.1 Survey: The first step in determining the expected induced transients is a survey of the aircraft. The survey should be initiated early in the program to identify the potential lightning effects and to categorize these effects based on a safety assessment review and the lightning zone(s) within which the equipment is located. The information collected during this initial survey should include those areas used for equipment location and wire bundle runs and include apertures in the structure.

The lightning zones determine the current path(s) through the aircraft and aid in locating the particular path(s) which represent(s) the most severe threat to the system under investigation. For most applications, the airframe is located in Zone 3 as well as one or more of the other zones (i.e., Zone 1A, 2A, or 2B). The protection assessment shall be based upon the external lightning environment assigned to the surface zones at the extremities of the airframe within which the wiring is installed. For example, wiring in the leading and trailing edges of a wing whose primary structure is in Zone 3 will experience the induced effects of Zone 3 currents (i.e., current component A and Waveform H. However wiring that is located solely within a fuselage engine nacelle whose exterior surfaces are entirely within Zones 2A and 2B, or 3, have only to withstand the effects of the current Component D (and also Waveform H) external environments.

4.4.3.1 (Continued):

The potential results of lighting indirect effects such as current distributions due to skin panels, or transient pulses coupling to wiring will be a major part of the survey. One must also consider the direct effects of lightning such as puncture and internal arcs, which could result in changes to the expected induced transients.

Additional information on analytical techniques and computer modeling is available in Appendix B.

4.4.3.2 Initial Estimates: Using the results of the survey, the overall external airframe currents and fields can be calculated. Analysis techniques range from simple calculations to complex three-dimensional analytical models solved using computer programs. The three-dimensional computer modeling techniques generally give adequate detail for assessing the external fields and currents, but more detailed analysis may be required to determine the internal voltages and currents. For example, specific analysis is often required in areas where the airframe shape is complex, or if metal and poorly conducting composite structure and skins are used in the same area of the airframe. In these cases, two dimensional field and current mapping analysis may be used.

After the external fields and currents are determined, an initial estimate of the induced currents and voltages can be calculated. This initial estimate will help to determine the level of additional testing and analysis required to identify the desired lightning protection for certification compliance. Since this method uses the external magnetic field for the calculation the resulting estimate represents an upper bound for possible induced voltages and currents. Five basic equations can be used for this initial estimate.

The magnetic field close to the surface of the structure is equal to the current density, J_s, on the structure and is determined by:

$$H = J_s \approx \frac{I}{w} \approx \frac{I}{C_{eff}} \quad \text{(Eq. 3)}$$

where:

H = Magnetic field, in amperes/meters
I = Peak current, in amperes
w = Width of the surface on which the current is flowing, in meters
C_{eff} = Effective circumference if the structure is a cylinder, in meters

4.4.3.2 (Continued):

The open circuit drive voltage on a wire bundle is determined by:

$$V = \frac{d\phi}{dt}\bigg|_{t=0} = \mu A\frac{dH}{dt} \approx \mu A\frac{H}{\tau} \quad \text{(Eq. 4)}$$

where:

V = Peak voltage, in volts
ϕ = Magnetic flux, in Webers
μ = Permativity of free space, which is 1.257 x 10^{-6} Henry/meter
A = Projected area of the loop perpendicular to the direction of the current flow (length, l (in meters), of wire bundle times height, h (in meters), above structure), in meters^2
τ = Current rise time to 1/e (for the lightning Current Component A waveform this is 1.39 μs)
e = Natural logarithm

The short circuit current on the wire bundle or shield is:

$$i = \frac{1}{L}(v\ dt) \approx \frac{Vt}{L} \quad \text{(Eq. 5)}$$

where:

i = Short circuit current, in Amperes
L = Self-inductance of the wire bundle (typically 0.5 μH per meter times the length of bundle)
t = Time, in seconds
V = Volts

Substituting for V from (4), then for H from (3) yields:

$$i \approx \frac{\mu AH}{L} \approx \frac{\mu AI}{LC_{eff}} \quad \text{(Eq. 6)}$$

The voltage on a shielded core wire where the shield has a 360° connection to the backshell (assuming a solid shield with no apertures) is:

$$v \approx iR \quad \text{(Eq. 7)}$$

where:

R = Resistance of the shield in ohms (typically 0.01 Ω per meter times the length of the bundle) plus the connector resistance, if applicable

4.4.3.2 (Continued):

The model can be further refined for special cases.

If the shield is terminated in pigtails then an additional voltage should be included as:

$$V_p = L\frac{di}{dt} \quad \text{(Eq. 8)}$$

where:

L = Total inductance of all pigtails (typically 1 nH per millimeter times the total length of pigtails)

$\frac{di}{dt}$ = Peak current rate of rise (1.39×10^{11} amperes/second for the lightning Current Component A waveform)

Detailed analysis methods to determine the expected induced transients seen at the equipment interfaces can range from simple initial estimates to the use of complex computer modeling. A simple method is nearly always used for a quick look at the problems that may be encountered. More elaborate analysis methods may be used later to optimize the design.

Expected lightning induced transients may be obtained by conducting tests on representative aircraft structures and wire installations. These tests may be conducted by using low level methods to the aircraft structures, measuring the resultant responses on the wiring or at equipment interfaces and applying the appropriate scaling factors or transformations. ARP5416 (Draft) and DOT/FAA/CT-89/22 contain details of these approaches.

Nonlinear processes may be present (e.g., arcing between adjacent conductors, arcing across joints and apertures) during an aircraft lightning interaction. Nonlinearity, if present, would be a principal problem associated with the extrapolation process. In general, nonlinear effects tend to reduce resulting equipment interface transients but enhancement is also possible. Nonlinear effects may not be experienced during low level testing but should be anticipated and accounted for in the process of compliance verification (see 4.6.2).

It is important to note that the specific nature of lightning induced currents/voltages at equipment interfaces can vary widely from one location of the aircraft to another. The voltages and currents induced at the interfaces depend, in the first order, on (1) the structural attributes of the aircraft, (2) the way the lightning attachment to the vehicle takes place and (3) the wire routing.

In many cases, the actual induced transient levels are defined in terms of open circuit voltage (V_{OC}) and the short circuit current (I_{SC}) appearing at wiring/equipment interfaces. The voltage and current will be related by the equivalent source impedance (i.e., loop impedances of interconnecting wiring and equipment) and there may be different levels determined for different circuits. Measurements made on a large transport aircraft, on wires expected to have high-induced levels, showed a spread of transient amplitudes to be as high as a factor of 20.

4.5 Establish Transient Control Levels and Equipment Transient Design Levels:

Transient control levels (TCLs) and equipment transient design levels (ETDLs) should be established during the initial development phases of aircraft electrical and electronic systems as targets to insure effective lightning protection designs. When such aircraft systems are developed and certified, TCLs and ETDLs become qualification levels. The TCL would be the qualification level for the aircraft installation and the ETDL the equipment qualification level. To establish TCLs and ETDLs, it is necessary to understand their relationship with actual transient levels (ATLs) and equipment transient susceptibility levels (ETSLs). Ultimately, whether these systems are for a new aircraft design or are a modification of an existing aircraft design, the system integrator seeking aircraft certification must demonstrate TCL and ETDL compatibility. Verification of compliance is covered in 4.6.

4.5.1 Actual Transient Level (ATL): The actual transient levels (ATLs) are current and voltage waveforms and levels that are induced on aircraft wires by the internal environment and appear at associated equipment interfaces. Thus, ATLs are primarily dependent upon the system installation and wiring design rather than the equipment design. For systems that are being certified, the ATLs are determined by tests, analysis, or similarity assessment of aircraft and system installation features.

4.5.2 Transient Control Level (TCL): With different lightning strike attachment points and current components, wire bundles in different areas of the aircraft and even wires within the same wire bundle will experience different transient waveforms and levels. It is convenient to identify a standardized set of transient waveforms and levels for each individual system, equipment, or equipment set of pins. Each standardized waveform and level is called a transient control level (TCL). TCLs are the maximum allowable level of transient current and voltage appearing at the equipment interface for a given characteristic waveform. In other words, the TCL is the control value above which transients will not be observed at an interface (system, equipment, or equipment set of pins). In general, TCLs should be higher than ATLs. In some cases a TCL may be equal to its corresponding ATL, but a general design objective should be that ATLs be lower than the TCL.

The TCL is dependent on the installation of the equipment and wiring in the aircraft. Design considerations which directly affect the TCL are:

a. location of the equipment within the aircraft (zones);
b. shielding provided by the airframe; and
c. location, length and type of interconnecting cables.

In many aircraft certification projects, the ATLs are determined by test or analysis on the production aircraft just prior to certification. However, the TCLs must be selected early in the design process to allow appropriate lightning protection to be designed for the aircraft and systems. Therefore, the TCLs are often selected by simple analysis, similarity to previous aircraft installations, engineering tests, or engineering judgement.

4.5.3 Equipment Transient Design Level (ETDL): The ETDL is a level and waveform which the equipment will withstand without damage or functional upset. The ETDL is a design target to which equipment will eventually be qualified. It may be selected by the equipment manufacturer or it may be specified by the system integrator (aircraft manufacturer, aircraft modification company, etc.). A particular system may have multiple ETDLs to incorporate the different waveforms and corresponding amplitudes that the system may be exposed to during a lightning strike. The ETDL is ultimately based on the TCL to which the component will be exposed.

ETDL requirements are found in Section 22 of DO-160/ED-14, or in aircraft manufacturers' procurement specifications. DO-160/ED-14 is used by avionics suppliers in the process for obtaining an FAA/JAA TSO approval. Based upon a generic aircraft internal lightning environment approach, Section 22 provides ETDLs in terms of a variety of levels with associated waveforms. An aircraft manufacturer's procurement specification would provide requirements for equipment specific to their aircraft. These requirements would include a definition of the ETDL based upon the internal lightning environment specific to the aircraft. Requirements governing the design and verification of equipment providing Level A control functions will probably be through an aircraft manufacturer's procurement process and not the TSO process.

For equipment designed to meet the requirements of an aircraft manufacturer's procurement specification, some tailoring of waveform sets may be possible. For instance, if the specific aircraft construction were primarily metal and the system was centralized in a compact and integrated architecture, then Waveform 4 may not be an issue. In this case, Waveform 4 could be eliminated from the waveform set. On the other hand, for a system with a widely distributed architecture, several ETDLs with the complete waveform set may be required. Finally, for equipment intended for a wide variety of aircraft installations and qualified under the TSO process the complete waveform set will probably be required and a relatively conservative set of ETDLs may be required.

4.5.4 Equipment Transient Susceptibility Level (ETSL): The ETSL is the amplitude of voltage or current which, when applied to equipment, will result in damage or upset such that the equipment can no longer perform its intended function. The ETSL must be greater than the appropriate ETDL.

Designing to a target ETSL for component damage is a relatively deterministic process. However, determining the ETSL for system functional upset is more complex. For example, determining the ETSL for a complex fault tolerant digital data processing architecture will require stochastic or probability system design efforts (see 5.2).

In contrast to the ETDL, the ETSL is the minimum transient peak current or voltage amplitude and waveform that will cause damage to and/or functional upset of the equipment.

4.5.5 TCL and ETDL Selection: Since TCLs establish levels to which equipment interfaces may be exposed, they also establish the levels which equipment interfaces must tolerate. For a particular installation, the accuracy with which TCLs have been determined will also determine the magnitude of the margin applied to the TCL. The result of applying this margin gives the ETDL. For further discussion on margins (see Section 6).

It is important that TCLs and ETDLs have common specification bases such as open circuit voltage and short circuit current. The process flow for determining the levels is shown in Figure 1, and as can be seen, the ETDL can be determined by either the aircraft manufacturer or the equipment manufacturer and quite often will be a coordinated between the two.

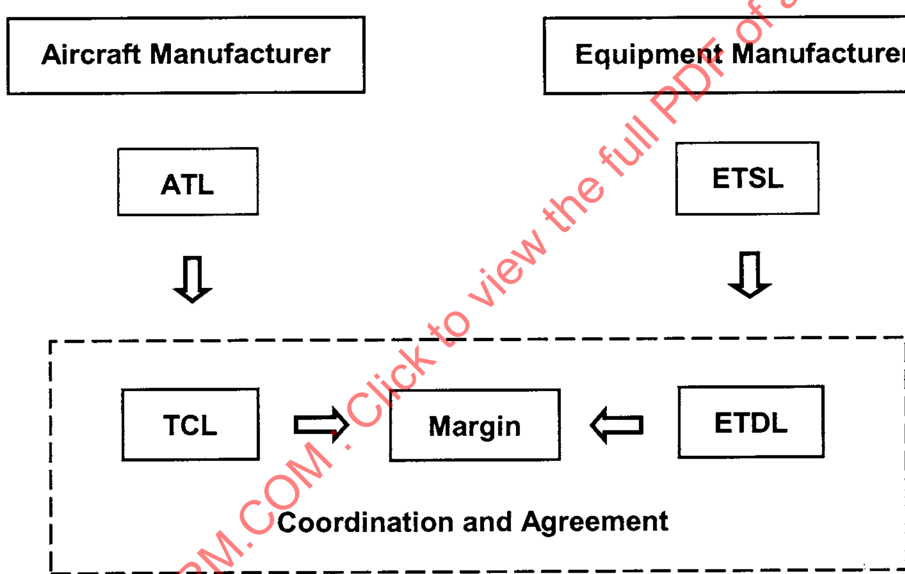


FIGURE 1 - TCL and ETDL Selection Process

It is critical that the ETDLs be defined as “system shields on” or “system shields off”. If the aircraft manufacturer specifies a core wire voltage ETDL (i.e., the voltage induced on a core wire) and the equipment vendor tests the LRU to the ETDL with the shields on, then the LRU will not have been adequately tested. In addition, if the aircraft manufacturer specifies the ETDL as a shield current, and the equipment vendor applies the current to the core wire, then the LRU will have been over tested.

The voltages and currents shown in ARP5412 and DO-160/ED-14, Section 22, Tables 22-2 and 22-3 provide standardized levels which can form the basis for the TCL and ETDL targets. The Section 22 levels are for equipment qualification, thus, they represent ETDLs.

4.5.5 (Continued):

Descriptions given in ARP5413, Section 7.2(c)(2) for the levels shown in Tables 22-2 and 22-3 of DO-160/ED-14 are for guidance only. The anticipated exposure of interconnecting wiring, not equipment location, determines these levels. Design objectives should be the result of tradeoffs which optimize the inherent protection afforded by an installation and capabilities associated with the equipment design and qualification. Levels, with their associated voltage and current values, can then be used to establish design objectives. The levels in ARP5412 and Section 22 tables cannot be used as a substitute for the basic assessment effort necessary to identify margins and associated system immunity to lightning indirect effects.

Two typical certification situations, (a) an existing airframe having a new system installed, and (b) a new airframe using off-the-shelf equipment. In the first case the airframe manufacturer may have existing ATL data based on previous certification test or analysis. Then the airframe manufacturer can establish the TCL and ETDL appropriately.

In the second case the equipment manufacturer has either previously certified the equipment in another installation, or has identified the likely installations for good market penetration of his product. Based on these the equipment manufacturer will select a set of ETDLs. Then, when this equipment is selected for installation and certification on a particular aircraft, the system integrator must select TCLs that provide appropriate margin for these ETDLs.

The whole process of establishing ETDLs is often iterative, resulting from coordination between the airframe manufacturer, who can increase installation protection to reduce the ATL and TCL, and the equipment manufacturer, who can increase equipment immunity/protection to increase the ETSL and hence the ETDL. The choice of ETDLs and TCLs will directly influence the need for, and cost of, protection required to achieve certification. The TCLs may be chosen to reduce the number of different levels required for system qualification tests, while not exposing the majority of equipment circuits to excessive transient levels.

4.5.5.1 ETDL Selection: The ETDLs applicable to the system establish the transient levels which the system must withstand without damage and in many cases without upset.

Level A, B, and C systems must withstand these pre-determined transients without damage. Pin-injection tests, single stroke wire bundle induction, or ground injection tests may be used to determine an equipment or system damage tolerance level. In the latter case, a single stroke or a multiple stroke test with the initial transient derived from current Component A may be used to determine damage tolerance.

4.5.5.1 (Continued):

For Level A, and potentially B and C systems, it is necessary to establish ETDLs for both damage tolerance and functional upset. As indicated in the prior paragraph, damage tolerance can be addressed by pin-injected, single stroke, or appropriately defined multiple stroke tests. Multiple stroke and multiple burst tests, however, must both be conducted to determine system upset tolerance, and these tests are applied as cable bundle tests. An applicant should, therefore, establish ETDLs for damage tolerance verification (i.e., individual pin or conductor levels), and separate ETDLs for upset tolerance verification (i.e., wire bundle levels, applied in the multiple stroke and burst modes). Alternately, the applicant may elect to modify the multiple stroke to include the initial stroke derived from current Component A and, therefore, define a single set of ETDLs for both damage and upset tolerance. This might be done, for example, for a system being certified at the system level, as a whole, in which case individual pin or conductor levels might not have to be designated, and the individual components would not be tested individually. This approach has a disadvantage in that substituted equipment may have to be certified in a complete system test, instead of on a TSO basis. Power inputs to components within such a system may have to be tested individually, and not as part of system interconnecting wire bundles.

Verification of compliance with pin ETDL requirements usually means the application of a pin-injection test. In this test, transients are applied to pins individually. This means that the equipment may not be interconnected with other equipment on the test bench. A pin specification and pin-injection test are not capable of evaluating the synergistic effects that may occur due to the simultaneous application of transients on all interface circuits and at all connectors within the system. Hence the need for wire bundle ETDLs applicable to a fully interconnected and operating system.

This second ETDL set is often a wire bundle current specification that defines the waveform and amplitude of the total current expected to be induced in the wire bundles, which interconnect the various components of the system. For this purpose, a wire bundle current waveform, such as Waveform 1 or 5 (as shown in ARP5413) is often selected together with a peak amplitude. For example, amplitudes of wire bundle currents induced on intra-engine wire bundles of a FADEC system might range in the thousands of amperes, whereas the amplitudes of wire bundle currents circulating in wire bundles installed within an aluminum fuselage might be less than 100 A.

Wire bundle current specifications are most appropriate for wire bundles in which the bundle of wires is enclosed within an overall shield or in which most of the circuits are enclosed within individual shields and these shields are grounded to equipment cases at each end. In this case, of course, the lightning magnetic fields induce voltages and currents in the wire bundle that forms the loop between the wire bundle shields and the airframe. In some cases, wire bundles may not simply extend between two pieces of equipment but may branch and extend from one piece of equipment, such as a computer, to several remote items such as actuators and sensors. In these cases, care must be given to selection of realistic current levels. For example, the wire bundle current at the computer end of such a wire bundle would be the sum of the wire bundle currents entering each of the accessories, which are fed, from branches of this same wire bundle.

4.5.5.1 (Continued):

The wire bundle current specification is viewed as a system specification, both from a component-damage and system-upset perspective. Wire bundle shields, connectors, equipment cases and components within the equipment must, of course, withstand the effects of the specified currents flowing on the wire bundle shields. Currents on shields will, of course, produce transient voltages in conductors and at equipment interfaces within those shields. These transients will be lower in amplitude than they would be were the shields ungrounded or not present. Nonetheless, these transients still exist and in some cases may reach damaging levels. Also, induced transients which do not meet damaging levels still may be capable of upsetting digital-processing circuits, especially since there may be more than one transient produced by an individual lightning flash. The wire bundle current specification, therefore, enables realistic transients to be induced simultaneously in all wire bundles and conductors within a system (see 4.6.1.1.2 and 4.6.1.2 for wire bundle testing). If for verification purposes this ETDL is applied in a multiple-stroke or multiple-burst mode, it is indeed possible to evaluate system upset possibilities and/or verify that the system will not upset when exposed to the specified ETDL.

For interconnecting wire bundles, which are fully shielded, it is usually appropriate to specify a wire bundle current as the wire bundle ETDL and test level (I_t) as from among the standardized levels in DO-160/ED-14 Section 22 since the shields will prevent the cable – airframe loop voltage from appearing in the shielded circuits. The ETDL test current level selected should be based upon aircraft test data or analysis.

For some shielded circuits (as defined in DO-160/ED-14 Section 22, that also contain some unshielded conductors, the inductances of the shield – airframe loops may prevent intended shield currents I_t from being reached before unrealistically high loop voltages are reached. In this situation any unshielded conductors in the cable bundle may experience these excessive loop voltages. To prevent applications of unrealistically high loop voltages to the unshielded conductors the I_t levels in Section 22 are accompanied by limits on the loop voltages, called V_l. Test plans for systems employing shielded wire bundles that contain some unshielded conductors should include the intended shield current test levels (I_t) as well as accompanying loop voltage limits (V_l). When system verification tests are being conducted with test current levels as well as loop voltage limits specified, loop voltage as well as the wire bundle (i.e., shield) current should be measured. If prior to reaching the specified test current amplitude the voltage limit is reached, no attempt should be made to increase the wire bundle current further and the test is considered completed. It is considered that the system has been exposed to the desired environment. The current and voltage levels reached should, of course be compared with available test or analysis data to be sure that adequate margin(s) exist between test levels and the ATLs or TCLs assigned to the tested cables.

4.5.5.1 (Continued):

There are some situations, such as the fully shielded bundle described earlier, where the shield current must be reached in tests regardless of what the loop voltage is. These are wire bundles that are known to experience higher than normal loop voltages, are sometimes overbraided, or are installed in electrically exposed regions as determined by aircraft tests or analyses. These often include engine and flight control system wire bundles. In these situations the voltage limit guidelines of DO-160/ED-14 Section 22, Table 22-3 may not be adequate, and the test current must be increased to the intended test level regardless of the loop voltage that is necessary to reach the test current level on the test bench. Flight and engine control circuits that extend into high magnetic field regions in the aircraft are often in this category. The test and limit levels presented in DO-160/ED-14 Section 22 are based primarily upon measurements of induced transients in wiring installed within conventional metal airplanes.

Conversely, ETDLs and verification test plans for systems employing unshielded cables (also as defined in DO-160/ED-14 Section 22) should designate the loop voltage, V_t, as the test level and a current limit, I_l, is assigned. In this situation both the loop voltage and wire bundle current must be measured and if the current exceeds the limit level, no further attempt is made to reach the test voltage level, and the system is again assumed to have been exposed to the intended transient levels. Comparisons with available aircraft test and or analysis data should be made to assure that adequate margins exist.

4.5.5.2 Selection of ETDL - Equipment Manufacturer's Perspective: The ETDL defines the equipment requirement or minimum hardening level. The ETDL may represent the TCL plus an appropriate margin. Alternatively, with an absence of airframe-specific data, the ETDL may merely be selected from Tables 22-2 and 22-3 of DO-160/ED-14.

The ETDL selection process may be initiated by the equipment manufacturer. In this case, the ETDL selection process should consider the equipment function and target aircraft application(s). That is, ETDLs representative of Level 4 or 5 may be appropriate for a flight control system intended for installation in composite airframes, whereas Level 2 or 3 may be appropriate when the host aircraft is all-aluminum and wiring from aircraft extremities is appropriately shielded.

The ETDL selection process should also consider the expected coupling mechanism(s) and associated waveform(s) described in ARP5412. For instance, a system with shields terminated in pigtails might generally utilize Level 3 of Waveform 4. However, Level 4 might be appropriate for Waveform 3 (damped sinusoids) due to the inductive impedance associated with pigtails. As a second example, consider a system with loads electrically isolated from the airframe. With no low impedance circuit loops through the aircraft structure, Waveform 5 would not develop and, therefore, an ETDL for Waveform 5 would not be necessary.

4.5.5.2 (Continued):

In any case, ETDL selection should be based on the best available technical data and should not be based arbitrarily on the assumption that the greater the hardening level the better the equipment. As the ETDL increases, inherent circuit hardening techniques become impractical. At this point, TPDs may be utilized to achieve the ETDL. Such widespread application of TPDs can produce low impedance circuit loops to aircraft structure. (Example: TPDs at both the receiving and transmitting ends of an ARINC 429 data bus.) Such low impedance loops allow the development of high-energy Waveform 5 transients. With proper choice of an ETDL, inherent circuit hardening techniques, which increase loop impedance, would have inhibited the development of Waveform 5 transients.

Selecting too high an ETDL may force widespread application of TPDs, allowing the development of Waveform 5 transients. In many cases, a second design iteration may be needed (possibly doubling up TPDs, etc.) to ensure that the originally deployed protection devices are capable of withstanding or dissipating the power in the longer duration Waveform 5. In addition, equipment which does not utilize TPDs reduce maintenance. That is, the use of TPDs may necessitate periodic test to ensure the integrity of the protection devices themselves.

4.5.5.3 Selection of ETDL - Aircraft Perspective: The ETDL for each equipment or each equipment interface can be established by adding an appropriate margin to the TCL for that particular wire run. For uniformity in test specifications, ETDL waveforms and amplitudes should be chosen from a standardized table such as Table 22-2 of DO-160/ED-14 for pin tests or Table 22-3 of DO-160/ED-14 for wire bundle tests.

For simplification, an ETDL could be chosen to cover most equipment with wiring located in well-protected areas with another ETDL specification for equipment with wiring in exposed areas. A high ETDL may be chosen to minimize the degree of structural shielding and wire shielding required in the aircraft. Reducing the ETDLs may reduce equipment costs and testing cost, while increasing the ETDLs may not increase safety. Very high ETDLs may force the use of terminal protection devices (TPDs) which would change circuit impedance and make the system more vulnerable to a different aspect of the transients. For instance, a high impedance balanced circuit is relatively immune to the ground potential or IR drop. If high ETDL is requested, which then requires use of TPDs, the vulnerability of the circuit to the IR drop is increased due to the low impedance of the terminal device. The selection of a higher ETDL may be applicable to areas where the exposure is extreme such as wiring along a landing gear strut.

4.5.5.4 TCL Selection: The TCL waveform specification may be determined by generalizing the waveforms obtained for the ATLs to match one or more of the representative test waveforms shown in Figures 21 through 26, taken from ARP5412 (Waveforms 1 through 5). The TCL specification may then be determined by picking a level that is equal to or above the level of the ATLs.

4.5.5.4 (Continued):

More than one TCL may be needed for a particular aircraft's electrical and avionics systems due to the variations of wire routing and equipment locations. The TCL specification is also dependent upon any shielding that may be applied to the wires.

It is not necessary (nor is it intended) to include each of the standard transient waveforms in the TCL and ETDL specifications. However, the waveforms must represent the expected coupling mechanism(s) and the level(s) selected must account for the highest voltage and current levels anticipated in the circuits to which the TCL/ETDLs are applied. If the wiring in a particular system has both shielded and unshielded conductors, then more than one waveform may be appropriate. For instance, wiring driven by a magnetic field from Current Component A will induce open circuit voltages similar to Waveform 2 and short circuit currents similar to Waveform 1 in unshielded circuits. The voltages and currents appearing in shielded conductors may instead resemble voltage Waveform 4 and current Waveform 5A.

In Table 22-1 and in Paragraph 22.3.1 of DO-160/ED-14, six different waveform sets, each containing two or three of the standard waveforms, have been defined to allow for certification of equipment and systems intended for installation in varied aircraft applications. ETDLs assigned to a system intended for installation in only one aircraft type might not need to include as many of the transient waveforms.

Figure 2 illustrates how waveform sets and test conditions might be selected from Table 22-1 of DO-160/ED-14, Section 22. The waveform sets are developed in Figure 2 by starting at the place where the waveform set label appears in the figure and accumulating any specific waveforms that are in the path from that point downward.

Selection of the waveform set and test conditions appropriate for a particular system is based on the characteristics of the intended airframe into which it will be installed and whether or not the interconnecting wiring is to be shielded. If the system is intended for a conventional metal airframe, waveform set A and either C or E are appropriate. If the wiring is to be unshielded, set C is appropriate, but if the wiring is to have shields, set E is appropriate for the wire bundles. If the system is intended for airframes with resistive structures, such as those fabricated of carbon fiber reinforced composites, waveform sets B, D and F are appropriate. The difference between these two groups of waveform sets is that current Component 5 may be induced in system shields and ground planes, resulting also in voltages of a similar waveshape appearing also in certain conductors. This is why current Component 5 appears in sets B, D and F.

With a structure of relatively low resistance, such as an aluminum alloy airframe, the predominant induced voltages are Waveforms 2, and 3 (if the coupling is via magnetic fields) and also Waveform 4 if the coupling is due to structural voltage rises. In the former case the associated current is Waveform 1, and in the latter it is Waveform 5, but the amplitude of the Waveform 5 currents in a conventional metal airframe are nearly always less than the Waveform 1 currents, so Waveform 5 is omitted. Hence for systems intended for an aircraft with a low resistance structure, waveform sets A, C or E can be chosen.

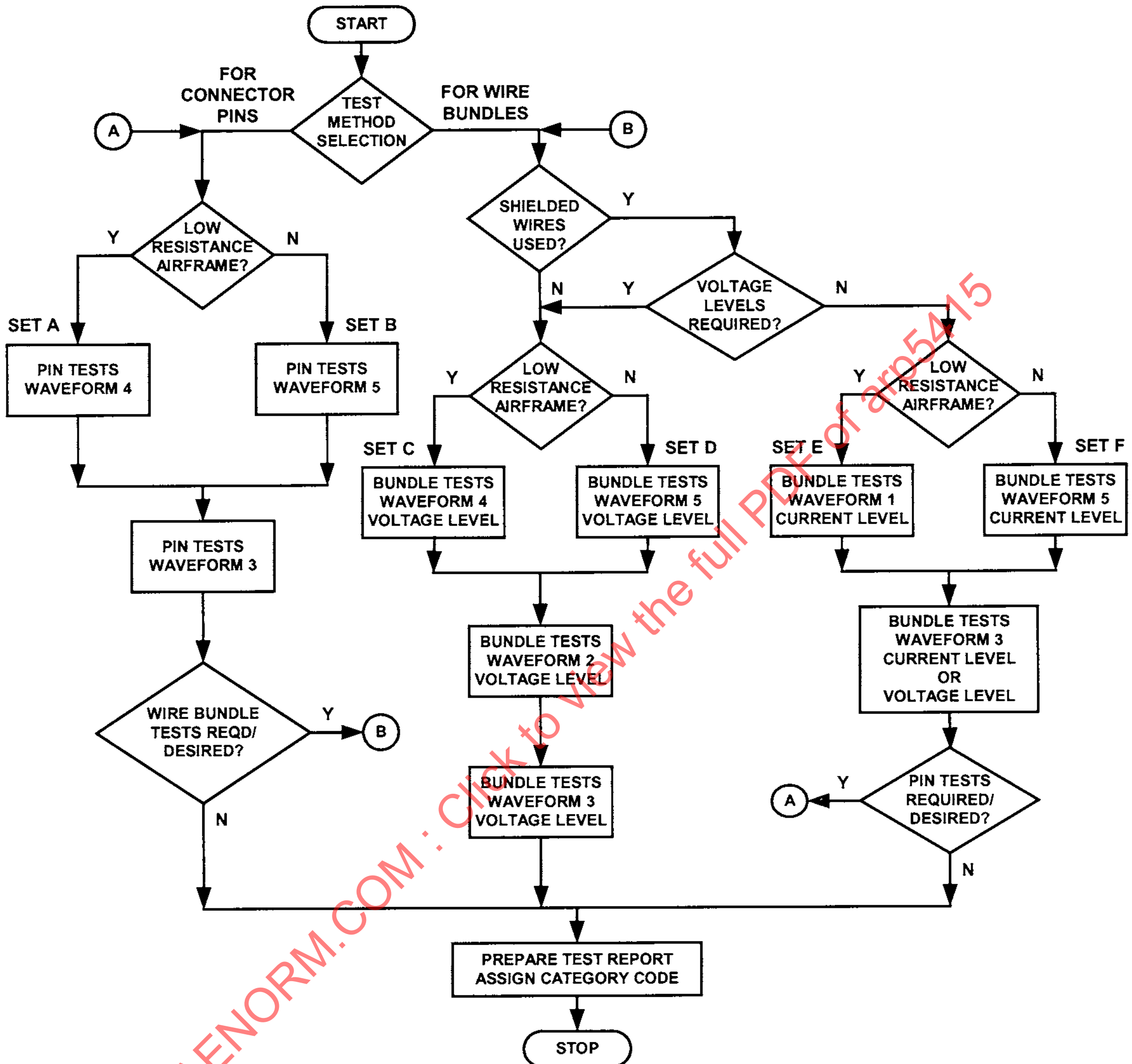


FIGURE 2 - Waveform Set Selection Flow

4.5.6 Waveform Set Selection: When wire bundle testing (also known as cable bundle testing) is selected, it becomes necessary to decide whether the test levels should be established in terms of voltages or currents. Table 22-2 of DO-160/ED-14 gives separate levels for the open circuit voltages and short circuit currents which comprise each level. The test generator has to be capable of providing the voltage across high impedance loads, and the current through low impedance loads (i.e., short circuits). It will apply some combination of intermediate voltage and current levels across finite load impedances. Table 22-3, for wire bundle tests, establishes test and limit levels. If the test level for a specific waveform is a voltage, the limit level will be a current, and vice versa. If the decision in the top diamond of Figure 2 had been to employ wire bundle tests, Waveform 3 should be applied.

4.5.6 (Continued):

Following the chosen path on the flow diagram leads to the question, "Low resistance structure?" If the wire bundle is routed through an aluminum structure, then Waveforms 1, 2 and 4 should be considered. If the structure material is CFC, then Waveforms 2, 4 and 5 are applicable. One of these waveforms could be eliminated from a waveform set if it can be shown that such waveform does not in fact appear significantly in the circuit(s) being considered. In many cases both pin and wire bundle testing is selected, for verification of equipment damage and system functional upset tolerances, respectively.

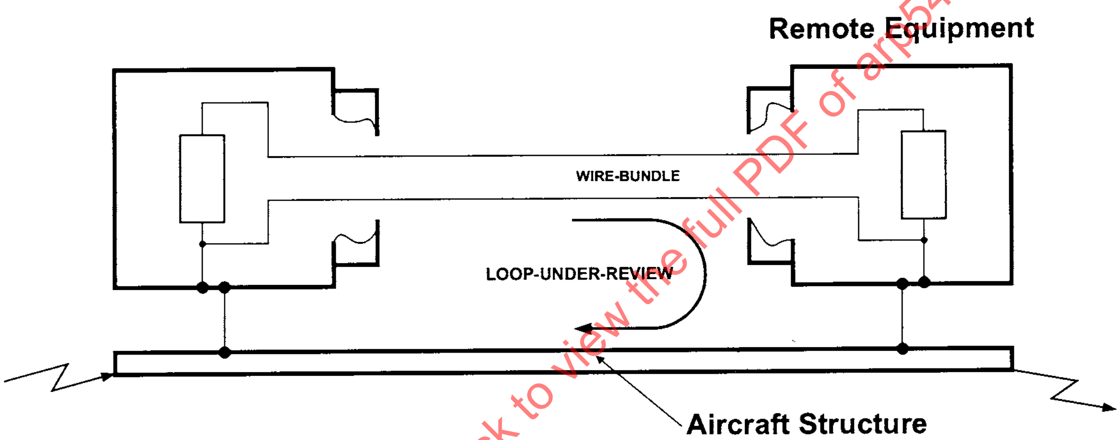


FIGURE 3 - Simple System Exposed to Lightning Induced Effects

Inside the remote equipment, a connection is shown between the circuit and the equipment case and thence to the airframe. If that connection did not exist, the electrical elements within that equipment will be "floating" and very little current can flow in the wire-bundle/structure path. Consequently, any pin injection or wire bundle test will result in the test (i.e., open circuit) voltage level being reached, and the ability of the remote end circuit element-to-case insulation to withstand this voltage (plus the margin) must be verified, usually by a pin injection test. In this situation, the test voltage waveform selected would be Waveform 2, 3 or 4, depending on the expected coupling mechanism and response of the wire bundle.

If the wire bundle is shielded and the shield is connected to the equipment at each end, then the shield-airframe loop will have a lower impedance than the unshielded configuration described above and a higher current (i.e., the short circuit current) will flow in the wire/airframe loop, if the remote end equipment is connected to the airframe. Test current Waveforms 1 or 5 are then appropriate. In this latter case, current in the wire shield will induce an open circuit voltage and a short circuit current in the shielded conductors, in accordance with the shield transfer function. If damage tolerance verification tests are to be conducted on the equipment, the test levels should be based on these conductor transient levels (plus the margin). Note that, if the remote end equipment could be electrically insulated from the airframe, little or no current would flow in the shield and the conductor transients would be negligible.

4.5.6 (Continued):

The relationship between the peak current, I_p, of Waveform 1 and the peak voltage, V_p, of Waveform 2 in a circuit loop between an unshielded wire and the airframe that is exposed to changing magnetic fields is determined primarily by the inductance of this circuit loop. A simple relationship that can be used to relate short circuit current to open circuit (loop) voltage is:

$$I_p = 1.4\frac{V_p}{L} \qquad \text{(Eq. 9)}$$

where:

I_p = Peak short circuit current, in amperes
V_p = Peak loop voltage, in volts
L = Inductance of the loop, in μH

Similarly, for a test using current Waveform 5, the output voltage waveform of the transient generator would be a waveform similar to Waveform 4. Because Waveform 5 is much slower than Waveform 1, the simple relationship between voltage and current no longer holds, as it is possible that the resistive voltage developed in the wire bundle under test is comparable to the inductive voltage. For Waveform 1, the resistive component is usually quite small. Because of the resistive effects, the simple relationship given above cannot be used in comparing Waveform 4 with Waveform 5.

Whether the test is made to a current level or to a monitored voltage limit depends on how the equipment is to be qualified. For example, if test data are available in terms of measured wire bundle currents (in shielded wire bundles) from the aircraft test, then equipment or system tests with the same length and impedance wire bundle can be made using either Waveform 1 or 5 transients driven to an appropriate level, regardless of the monitored voltage value.

If the wire bundle is not shielded, then changing magnetic flux between the wire(s) and the airframe will induce voltage Waveform 2 in this loop.

Some aircraft provide shielding in the form of conduits. These can be described as conductive tubing, bonded to structure at both ends and should be regarded as structural components through which the wire bundles are routed. If such conduits are used, then they will carry most of the current in a transient, even in situations where the wire bundle itself is shielded. So, if the wire bundle is unshielded, but routed through a conduit, then the appropriate test would involve voltage Waveform 4 or current Waveform 5. If the wire bundle is shielded by an integral shield, then current Waveform 1 or current Waveform 5 could be selected.

4.5.7 Other TCL and ETDL Selection Considerations: TCLs and ETDLs are best defined in terms of the waveforms and amplitudes of induced voltage and current transients that appear at the connector pins of interfaces between equipment and interconnecting conductors. In most cases, lightning strikes will induce the maximum level of transients between interconnecting wires and the airframe ground. Therefore, the maximum induced transients will normally occur between the connector pins and case ground. Since the equipment is grounded to the airframe, it is usually preferable to define the ETDLs as the levels of transients that must be withstood by the equipment between incoming connector pins and case ground.

This is often referred to as a pin specification. Of course, in any complex system there will be many wires and pins interfacing with each piece of equipment. These wires will extend to varied locations within the aircraft and will experience induced transients of varying amplitudes and waveforms. In addition, these circuits may themselves operate at different or varied system voltage levels. For example, some incoming wires bring 115 VAC or 28 VDC aircraft power to the equipment. Others, however, only transmit very small signal voltages whose amplitudes do not exceed 1 5 V. Thus, it often makes sense to establish more than one transient design level for a single piece of equipment, with the individual levels being related to either the function of the incoming circuit and connector pin or the routing of that circuit through the aircraft.

Thus, for example, for a typical flight control computer, one transient design level could be established for incoming 115 VAC power circuits, a second level established for incoming 28 VDC aircraft power circuits and a third ETDL established for incoming or outgoing signal and control circuits.

Frequently, each of these functions passes through the same multi-pin connector. In this example, a single connector can have pins, which must withstand differing ETDLs. But in all cases, the ETDLs would be defined by a waveform, a peak voltage and a peak current.

The voltage referred to above is the maximum voltage, which would be expected to appear at the open-circuit terminals of the interfacing wire with no load. This is referred to as the open-circuit voltage. The current specification is the maximum current expected to be induced in the same interconnecting circuit(s) when that circuit is shorted to ground at the equipment. Of course, in most cases, the load within the equipment is a finite impedance, so that neither the open-circuit voltage nor the short-circuit current will appear at the equipment in an actual lightning strike event. But if the transient design level specification is described in this manner, then the proper amplitude of transient will appear at the equipment when the equipment is tested with a test set that can also produce either the open-circuit voltage or the short-circuit current, provided the loop impedance is relatively high or the loop impedance is relatively low, respectively.

4.5.8 TCL and ETDL Parametric Discussion: As has been discussed in ARP5412 and in this User's Manual, there is a broad range in the amplitude of induced voltages and currents encountered in a wide variety of aircraft installations. Five levels, designated Levels 1 through 5, have been selected from within this range, to provide standardized criteria for design and testing purposes. Levels 1 through 5 encompass the majority of transients that may exist in typical aircraft circuits, but transient voltage and/or current amplitudes lower or higher than levels 1 and 5 may exist in some circuits.

In general, the amplitudes given in Tables 5 and 6 of ARP5412 for current Waveform 1 and voltage Waveform 2 are governed by a relationship, which is simply: $V = d\Phi/dt$, where the magnetic flux is due to significant coupling of magnetic fields from Current Component A. The voltage and current amplitudes for Waveforms 3, 4 and 5 (induced by Current Component A) are or can be the result of more complex mechanisms (see Appendix B for further explanation). Since Waveform 4 arises from the possible voltage rise from Current Component A flowing in the airframe, the amplitude of this waveform is strongly influenced by the electrical characteristics of the materials used in the structure and lengths of installation wire bundles. For instance, it would be expected that much lower Waveform 4 amplitudes could occur in aircraft whose structure is composed primarily of metal than that which could occur in an aircraft whose structure is composed of a material, such as carbon fiber reinforced composites, that has significantly lower conductivity. In ARP5412 the Current Component A induced voltage and current amplitudes of Table 5 are for individual conductors and those in Table 6 are for wire bundles. Table 7 provides Current Component H, associated with multiple burst, induced voltages and currents. ARP5412, Table 4 provides induced responses to Current Components D and D/2, associated with a multiple stroke, in terms of a fraction of the response to Current Component A.

Establishment of these five ranges (see Tables 5, 6 and 7 of ARP5412 and Tables 22-2 and 22-3 of DO-160/ED-14) for voltage and current amplitudes has facilitated the practical integration of equipment into aircraft electrical/electronic systems and thus, these amplitudes could be regarded by a system integrator as an integration parameter. Depending upon the perspective, this integration parameter can play a variety of roles, including TCLs for interconnecting wiring and ETDLs for equipment. ETDLs are set higher than TCLs to establish an appropriate safety margin to account for uncertainties in the compliance demonstration process.

It should be appreciated that normally a TCL is specified in terms of V_{OC} and I_{SC}, while ETDL may be specified in those same terms (V_{OC}, I_{SC}) or some other voltage and current parameter. For example, when DO-160/ED-14, Section 22 is used to qualify a piece of equipment, the parameters for wire bundle testing are in terms of test (V_T, I_T) and limit (V_L, I_L) voltages and currents. Such parameters (V_T, I_T and V_L, I_L) may be considered either an ETDL or an equipment qualification level, which may or may not match the TCL of a specific aircraft. Whatever the perspective (V_{OC}, I_{SC} or V_T, I_T and V_L, I_L), this parameter effectively defines the energy (current or voltage amplitude and waveform) that must be delivered by the generator used to simulate the lightning induced transient.

However, as has been observed when DO-160/ED-14, Section 22 is used, equipment interface wire bundles are qualified using a V_T, I_T and V_L, I_L approach which could expose equipment to energies on the order of twice that using the V_{OC}, I_{SC} approach.

4.5.9 Multiple Pulse Waveform Sets: Two waveform sets involving more than a single transient have been defined, representing the multiple stroke aspects of cloud to earth lightning flashes and the multiple bursts of lightning leader currents that flow through an aircraft during an aircraft initiated, intracloud strike. These are known as the Multiple Stroke and Multiple Burst environments and are described in ARP5412. Such characteristics of a strike need to be considered from the point of view of functional upset of systems. System functional upset test methods employing the multiple stroke and burst environments are described in ARP5416 (Draft).

Aircraft systems are exposed to the induced effects of the multiple stroke and burst environments because multiple current pulses pass through the airframe during a lightning strike. Therefore whenever an ETDL is defined, it should consider the multiple-transient aspects of the lightning environment.

For the multiple stroke (MS) waveform set, the first pulse of the series is based on the ETDL for current Component D. Whereas current Component D represents a subsequent stroke in the cloud to earth environment defined in ARP5412 for evaluation of lightning direct effects, it also happens to represent a typical severe first return stroke in a cloud to earth flash which lowers negative charge to the earth. Positive polarity flashes (i.e., which raise negative charges from earth to cloud) contain only one stroke. The subsequent 13 pulses in the MS are based on the response to current Components D/2, which represent typical subsequent strokes in the cloud to earth flash. Thus systems and equipment components must be designed and verified to withstand the first ETDL transient associated with current Component D and the subsequent 13 transients associated with current Component D/2.

The ETDL for equipment damage tolerance purposes must be based on current Component A of the external lightning environment. Tables 4 and 6 of ARP5412 provide guidance to relate the ETDL and test voltage and current waveform amplitudes associated with current Components A, D, and D/2.

The second waveform set is the multiple burst waveform set. The ETDL for the multiple burst waveform set is based on the response to Current Component H. Damaging effects of multiple-burst transients are usually negligible and need not be considered in selection of circuit elements or circuit protection devices. However, the multiple-burst transients are important from an upset standpoint. ARP5412 Section 7.5 provides information on typical transient responses to the Current Component H for determining multiple burst ETDL.

4.6 Verify Compliance:

The verification process must show that the system is capable of tolerating the ETDLs assigned to the various parts of the system, in accordance with the acceptance criteria assigned to the system as a consequence of the FHA.

4.6 (Continued):

This means in particular that the system equipment must be shown able to tolerate ETDLs assigned to any individual equipment and other elements (i.e., terminal strips, relays), and also to tolerate ETDLs assigned to the system as a whole, in accordance with applicable acceptance criteria. These ETDLs may be assigned as individual equipment connector pin levels, or connector cable bundle levels, for damage tolerance purposes, together with system interconnecting cable bundle levels, for system functional upset purposes, as described more fully in 4.6.1.

In the simplest terms, the system and equipment should be shown able to tolerate ETDLs, and actual lightning induced transients (ATLs) induced in system interconnecting wiring (and any other wiring that interfaces with the system) should be shown not to exceed the TCLs assigned to the system wiring.

The verification process may be accomplished by showing similarities to previously certified equipment and/or installations, aircraft and/or equipment tests, and/or analyses, or a combination of these methods. The specific methods that are proposed should be described in general terms in the Certification Plan that is recommended in ARP5413, and this plan should be submitted to the certifying authorities for review and approval.

System and subsystem suppliers to whom certification responsibilities have been delegated should prepare certification plans for their systems and, generally, should submit these plans through the airframe manufacturers to the certifying authorities. An exception is when a system supplier has applied for a Supplementary Type Certificate (STC) for installation of a new system on an existing aircraft. In this case the STC applicant must usually submit the certification plan directly to the certifying authorities.

The following subsections outline suitable verification processes that have been acceptable in providing evidence of compliance with lightning protection requirements. Details of aircraft tests to verify that ATLs do not exceed TCLs and system functional upset tests can be found in ARP5416 (Draft). Details of equipment damage tolerance test procedures can be found in DO-160/ED-14 Section 22.

Test and/or analysis plans must be prepared to describe the individual equipment and/or systems tests that are proposed and described generally in the certification plan. These also must be reviewed and approved by the certifying authorities. Test and analyses plans can be reviewed and recommended for approval by FAA Designated Engineering Representatives (DERs) if agreed in advance by the authorities.

Once the tests and/or analyses have been completed details of these must be documented in test/ analyses reports. Tests should be witnessed by certifying authority personnel and/or DERs, and test reports need to be approved as to compliance with the approved test plans by the authorities or DERs.

4.6 (Continued):

Figures 2, 3 and 4 of ARP5413 are flow charts that illustrate acceptable routes for showing compliance with the indirect effects requirements. Section 7 of ARP5413 provides guidance for each of the steps illustrated in the flow charts and this information is further clarified by the examples in Section 7 of this document.

4.6.1 Equipment and System Tests:

4.6.1.1 Equipment Damage Tolerance Verification: Two basic methods are available for verifying the ability of individual pieces of equipment to tolerate the ETDLs assigned to that equipment. These include Pin Injection and Wire Bundle tests (also known as Cable Bundle tests), as described in DO160/ED-14, Section 22.

4.6.1.1.1 Pin Injection Tests: Pin Injection Tests are applied to individual equipment connector pins, usually between pin and case ground. The purpose of the Pin Injection test is to verify that equipment components can withstand the ETDL in which the specified Equipment Transient Design Level (ETDL) transient voltage (specified as an open circuit voltage, V_{OC}, in the interfacing circuit, together with a short circuit current, ISC, in the same circuit) without damage. The process of establishing ETDLs for damage tolerance, and also for system functional upset evaluations is described in 4.5. Since lightning-induced effects nearly always appear conductor (pin) -to-airframe ground, the pin injection tests are usually applied between individual pins and case ground. The test generator must be capable of applying a transient up to the maximum voltage (V_{OC}) or the maximum current (I_{SC}) that could appear at the equipment interface. An impedance (usually 5 or 25 Ω) is included in the test generator to represent typical wire impedances and provide the appropriate relationship between V_{OC} and I_{OC}. This relationship is embodied in the V_{OC} and I_{SC} levels in Table 22-2 of DO-160/ED-14. The actual voltage (or current) that appears at a pin depends on the pin-to-case impedance.

To provide the margin described in ARP5413 and in Figure 1 of this document, the V_{OC} and I_{SC} transient amplitudes are set higher than the actual transient levels (ATLs) measured in individual interconnecting circuit conductors during full vehicle tests.

The pin injection test method has the advantage that it provides definite information on the tolerance levels of individual pin interface circuit elements. However it has the disadvantage that since the tests are usually applied to one pin at a time, they can not usually be relied upon to evaluate effects that may occur as a result of transients arriving at all pins of an equipment connector at once, or between pins.

In addition, pin injection test requirements, may necessitate the addition of terminal protection devices, typically not necessary when transients are introduced by more natural means such as cable induction or ground injection.

The pin injection test method is described in Section 22.5.1 of DO-160/ED-14. Waveform sets A or B should be used. Additional considerations with respect to pin injection tests are found in the following paragraphs.

4.6.1.1.1 (Continued):

Sometimes additional series impedance is added to represent remote equipment loads, when these are known and can be relied upon to be present in the aircraft installation, as shown in Figure 4.

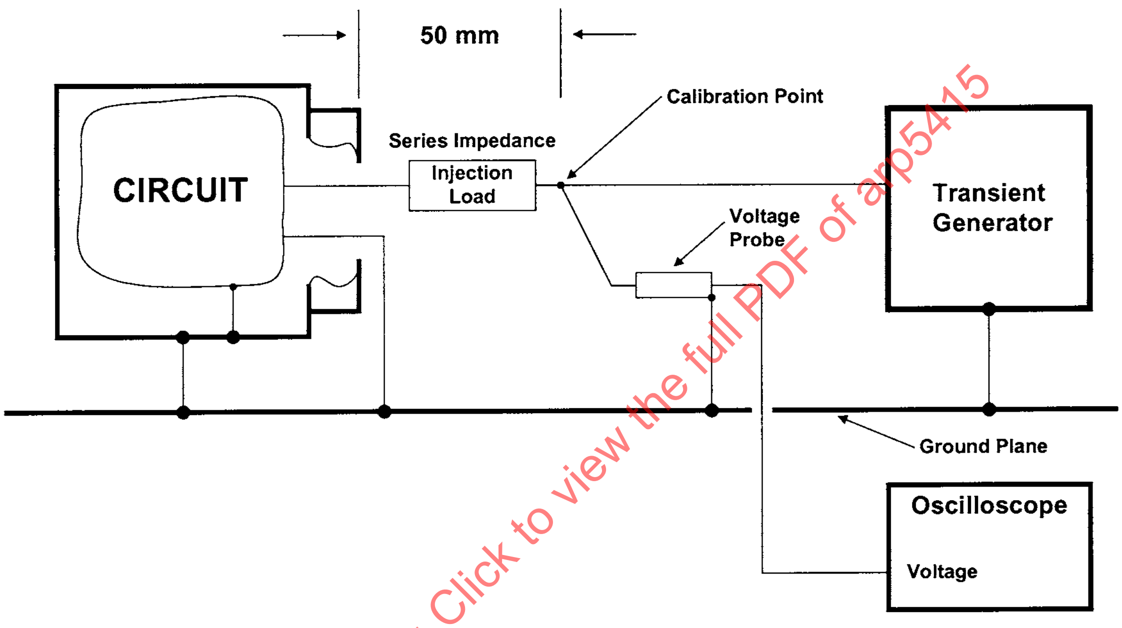


FIGURE 4 - Typical Pin Injection Test Setup

Care should be taken to select the appropriate series impedance to simulate the remote equipment line-to-case impedance. Hence, when the remote equipment circuit elements are isolated from case, as shown in Figure 5, and have a dielectric withstand voltage in excess of the ETDL assigned to that equipment the series impedance may be equal to the remote equipment line-to-case impedance (i.e., be a capacitance of several hundred pico-farads) if the ETDL voltage waveform is due to a structural or cable shield transfer function (i.e., Waveform 3, 4 or 5A). However, if the primary coupling mode is due to changing magnetic fields which induce a fast rising voltage in the circuit (i.e., traveling Waveform 3), the series resistance that is inserted into the test circuit should be no more than 75 Ω, so as to provide a relationship between voltage and current that is similar to the circuit characteristic impedance – typically 100 Ω.

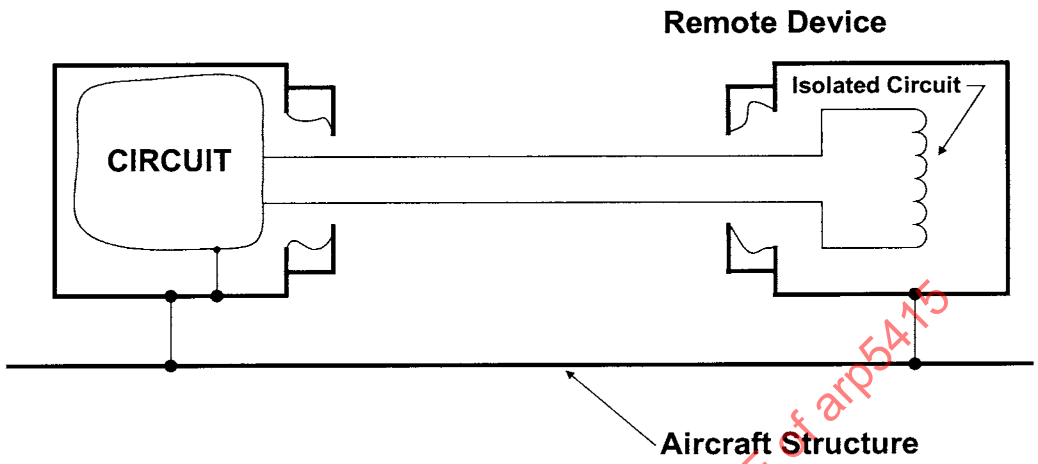


FIGURE 5 - Equipment Pins With Remote Isolated Circuit

4.6.1.1.1 (Continued):

Remote equipment containing EMI filters may insert much larger capacitances line-to-case, which must be represented instead of the stray capacitance across circuit insulation. In cases as shown in Figure 6, where the remote equipment has circuits referenced to case or to local aircraft structure via a finite impedance, the series impedance added to the circuit must not exceed this EMI filter impedance to case ground. In fact, it may be appropriate to use the EMI filter capacitor itself, or an equivalent.

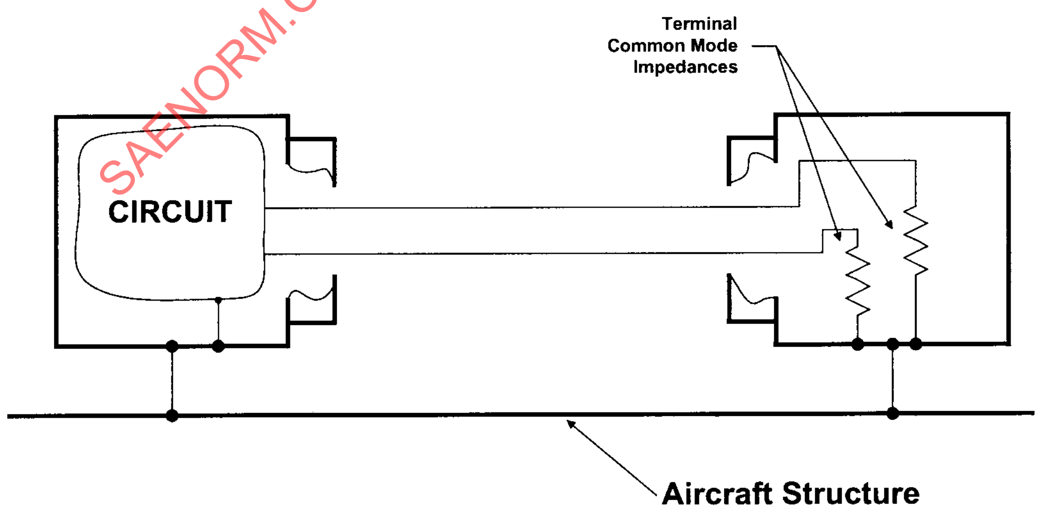


FIGURE 6 - Equipment Pins With Remote Circuits Referenced to Case/Aircraft Structure

4.6.1.1.1 (Continued):

Remote equipment that utilize transient voltage suppressors such as metal oxide varistors or diodes from line to case, as illustrated in Figure 7, or to a signal/power return which is referenced locally to aircraft structure should be considered as presenting a short circuit during a lightning-induced transient event, so no series impedance should be added to the test circuit for connector pins which interface with protective devices in remote equipment.

NOTE: The 5 and 25-Ω relationships between V_{OC} and I_{SC} in most of the pin test levels of Table 22-2 of DO-160/ED-14, Section 22,are intended to represent typical wire to airframe loop impedances (such as wire resistance and loop inductance) to the unipolar and oscillatory voltages, respectively. Thus any additional series impedance that is inserted into a pin test circuit must represent remote equipment impedances only.

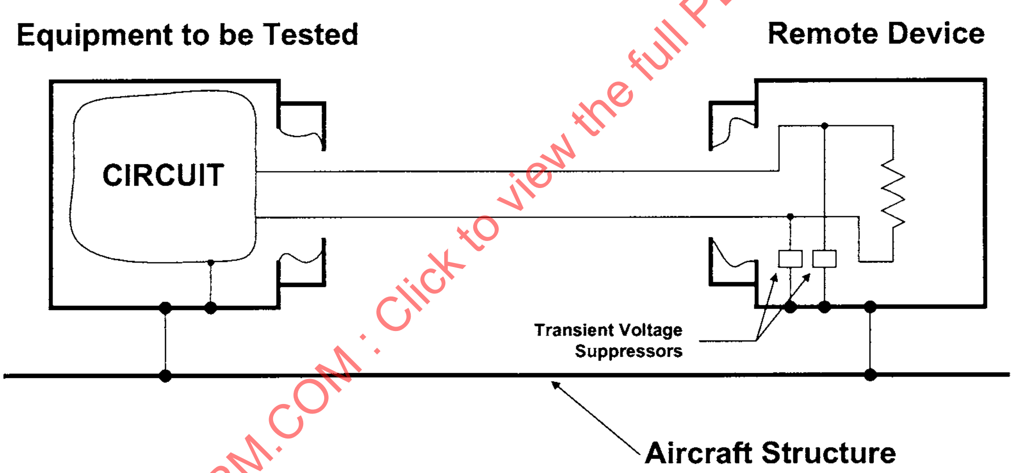


FIGURE 7 - Equipment Pins With Remote Transient Voltage Suppressors

In most cases the ETDL will have been established (or verified) by full vehicle tests or analyses in which the individual conductor V_{OC} has been measured with circuit remote end grounded locally to equipment case or the airframe and the I_{SC} has been measured with both ends grounded. This method gives the total loop voltage (V_{OC}) and the maximum induced current (I_{SC}). When performing pin injection tests, the addition of a series impedance to represent the remote equipment load impedance, as described in the foregoing paragraphs and illustrated in Figure 4, is appropriate.

4.6.1.1.1 (Continued):

However if the assigned ETDL has been determined (or verified) based upon full vehicle measurements of conductor voltages with remote ends connected to their interfacing equipment, then it is not appropriate to include the remote end impedances in the pin injection test circuits, since the effect of the remote equipment impedances will have already been accounted for in establishing/verifying the ETDL. Addition of a remote end impedance to the test circuit in this latter case would be taking credit for the remote equipment twice; once during the full vehicle testing (or analysis), and once during the equipment damage tolerance verification.

In some cases the series resistance should be the characteristic impedance of the aircraft wire (i.e., treating the wiring as a transmission line above the aircraft structure ground plane) and not the resistance to aircraft structure of the remote LRU. As reviewed in 4.4.2, the Waveform 3 response produced in aircraft wiring can be the result of traveling waves that have been induced in the aircraft structure which, in turn, drive the aircraft wiring or are induced directly into such wiring as a traveling wave. At any rate, Waveform 3 will almost always be present, to some extent, in the total response.

A dielectric withstand voltage or high potential (hi-pot) test may be used in lieu of the pin injection test to verify ability of electrically simple devices such as actuators, linear variable differential transformers (LVDTs), and speed sensors to tolerate the assigned ETDL voltage. These simple electrical devices must be passive with no electrical circuit elements, including EMI filters and transient voltage suppressors, connected between incoming circuit elements and case ground. In these situations the test voltage is applied between the circuit pins and case. This test is applicable when the interface signal and return wires are routed together to the source and the line-to-line induced voltage is insignificant. For configurations where the component interfaces with the aircraft power, the ETDL test voltage must be added to the DC or peak AC voltage (i.e., 180 V peak) to establish the hi-pot test voltage level. This test voltage may be conducted from each pin to case or from all pins, simultaneously, to case.

4.6.1.1.2 Wire Bundle Tests for Damage Tolerance Verification Purposes: While Wire (or Cable) Bundle Tests are normally used for upset determinations, they can also be used to evaluate equipment damage tolerance if an aircraft wire bundle specimen that is appropriately representative of the aircraft installation design is available, and if the remote ends of the conductors in this wire bundle are terminated in the impedances also appropriately representative of the aircraft installation (these must include the line-to-ground impedances of any protective devices when in the conductive state). If wire bundle tests are to be used for verifying equipment damage tolerance, then a wire bundle ETDL that is assigned to the interconnecting wire bundle should be applied, and the implication is that the same voltages and/or currents (plus a margin) that exist in the aircraft conductors will exist in the test wire bundle conductors.

4.6.1.1.2 (Continued):

Wire bundle voltages are driven by a generator that produces the selected ETDL voltage and current waveforms and levels as defined in Table 6 of ARP5412 and/or Table 22-3 of DO-160/ED-14 Section 22. The specific voltage/current applied to each equipment connector pin will not be known. Therefore, in many cases the tolerance levels of individual electronic components such as resistors, diodes, transistors, and filter capacitors within a piece of equipment will not be known. Thus, to obtain the tolerance levels of individual components to damage, the specific voltage/current at connector pins would have to be measured.

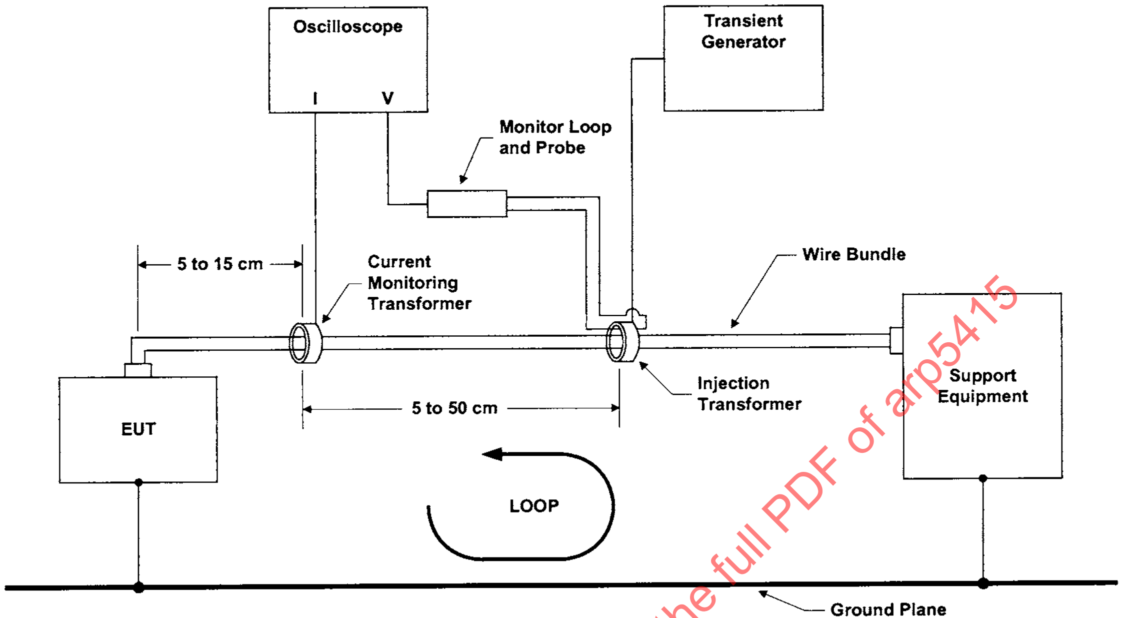
The wire bundle test method has the advantage of applying transients, of some magnitude, to all pins of a connector simultaneously and may more realistically represent the lightning stimulus in the installation. It has the disadvantage that it may not establish individual component tolerance levels.

The wire bundle tests can be applied using either the cable induction or ground injection method as described in Section 22.5.2 of DO-160/ED-14 and illustrated in Figures 8 and 9. Test waveforms should be selected from waveform sets C, D, E or F appropriate for the particular system installation. However it should be recognized that, when using DO-160/ED-14 Section 22 methodology for wire bundle testing, the pulse generator power is adjusted until either the test level (V_T or I_T) or limit level (V_L or I_L) is reached, as opposed to, the V_{OC}, I_{SC} methodology used for pin injection tests.

The test setup should reflect important installation features (shielding, interface equipment isolation from structure, etc.), which affect responses of the system to injected ETDL transients.

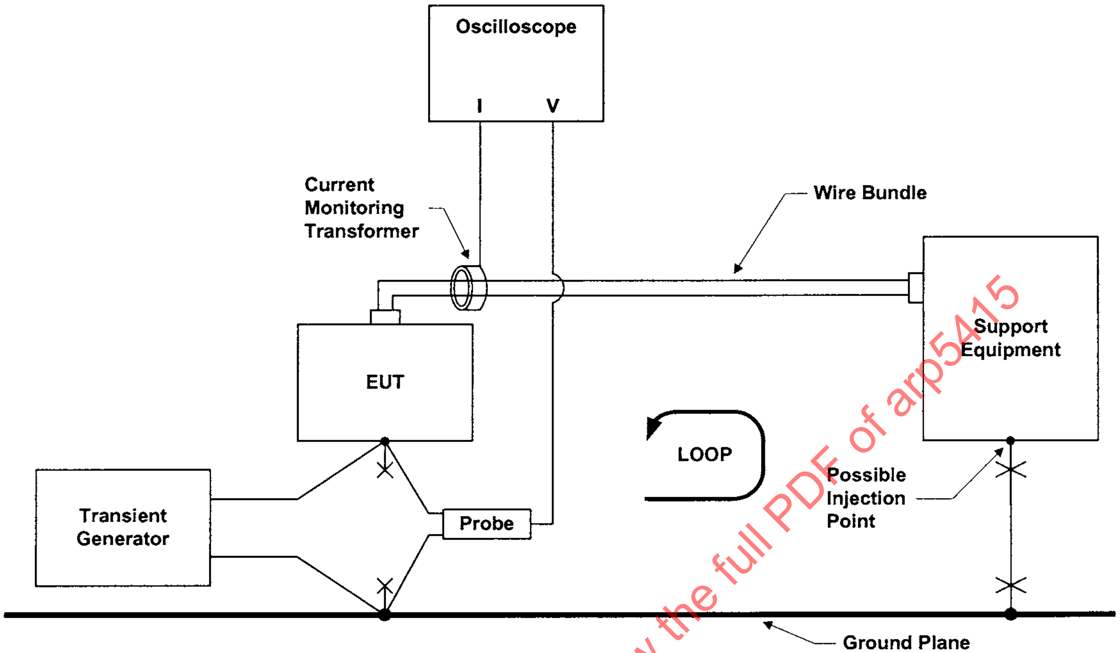
It should be noted that, Tables 5 and 6 in ARP5412 and Tables 22-2 and 22-3 in DO-160/ED-14, Section 22, the voltage magnitudes associated with each level for wire bundle (cable bundle) tests in Table 22-3 are the same as those indicated for the pin injection tests in Table 22-2 and it is the amplitude of the associated currents that differ for the wire bundle tests as compared with the pin injection test levels. The wire bundle current levels are higher because they reflect multiple conductors, rather than a single conductor. The tabulated currents are typical, but not necessarily reflective of what would appear in an individual wire bundle. Full vehicle lightning induced voltage test data from the aircraft to be certified can be used to establish more accurate voltage and current levels. The tabulated current levels are based upon data from many aircraft tests that have been complemented by analyses using worst case assumptions of magnetic field exposures of interconnecting wire harnesses.

It should be recognized that for systems such as electronic engine and flight controls which extend outside the fuselage and into high magnetic field or structural IR regions, the magnitudes of current on wire bundle shields (or of voltages experienced by unshielded circuits) could be much higher than those listed in Tables 22-2 and 22-3 of DO-160/ED-14, Section 22, or Tables 5-2 and 5-3 of ED-84 and Tables 5 and 6 of ARP5412.



NOTE: A series current-monitoring resistor may be used instead of the current-monitoring transformer.

FIGURE 8 - Typical Wire Bundle Induction Test Setup



NOTE: A series current-monitoring resistor may be used instead of the current-monitoring transformer.

FIGURE 9 - Typical Ground Injection Test Setup

4.6.1.2 Wire Bundle Tests for System Functional Upset Verification: Tests are normally performed by inducing transients sequentially on each interconnecting wire bundle of a complete, functioning system to verify tolerance against system functional upset. The system functions are monitored during the tests to see if any of the combinations of multiple stroke or burst transients results have any affect on system functions, and whether such effects are acceptable or not. For equipment that has redundant interfaces that need to be excited concurrently for proper evaluation of common mode effects, simultaneous injection on more than one interface should be accomplished.

4.6.1.2 (Continued):

The basic test arrangement for the system and/or representative loads functional upset tests is as described in Figures 8 and 9, except that all equipment and wire bundles in the system are included in the test setup. For testing of redundant interfaces, it may be necessary to employ multiple injection cores when the wire bundle induction method is employed. The ground injection technique is an alternative. In some cases, the ETDL is applied to the main or "trunk" wire bundle, with currents in other branches not being specified. In other situations different ETDLs are assigned to each wire bundle in a system. Controlling each wire bundle ETDL(s) to the correct level is important. It may be necessary to employ multiple injection points or add impedances to individual equipment grounds to the test bench to control individual currents to desired levels. Except for wire bundle lengths, the intention of test configurations for wire bundle testing is to provide an appropriately accurate electromagnetic simulation of the system installation. Wire bundle tests have the advantage of applying transients, of some magnitude, to all wires in a wire bundle (see 4.6.1.1.2) simultaneously.

4.6.2 Aircraft Tests: Aircraft tests, also known as full vehicle tests, are conducted to determine the ATLs in individual conductors and wire bundles that can be used to verify or define TCLs assigned to individual conductors and wire bundles in accordance with the certification process described in ARP5413. The TCLs are compared with equipment ETDLs to verify that an adequate margin exists. If the margin between the two is insufficient, protection of interconnecting wiring may be improved by increasing harness shielding or adding protection within the equipment. Some shielding modifications may be made to selected circuits in the aircraft and verified during the test. Any such modifications and test results would be documented together with the rest of the test results.

In situations where the TCLs and ETDLs have not yet been established, the ATLs measured in aircraft tests may be used as the basis for establishing TCLs and ETDLs for interconnecting wiring and equipment. For equipment without established ETDLs, the full aircraft test and extrapolation analysis results will provide TCLs for use in ETDL determination.

Two basic approaches for performing aircraft (full vehicle) tests are available. One involves injection of current pulses identical in waveform to the external lightning current waveforms defined in ARP5412. The second involves circulating continuous sinusoid currents through the aircraft, at frequencies and amplitudes similar to the constituent frequencies and amplitudes of a Fourier series that represents the defined lightning currents. This is known as the “swept continuous waveform (CW)” method. Voltages and currents induced by the test currents in interconnecting wiring are measured, usually with voltage and current probes optically coupled to recording instruments outside of the aircraft.

4.6.2 (Continued):

Both of these approaches generally apply current amplitudes less than full threat, so that measured transients must be extrapolated to establish the ATLs corresponding with the full threat lightning environment. Coupling theory and prior experimental work have confirmed the generally linear relationship between amplitudes of current in an airframe and voltages/currents induced in electrical wiring within. The necessary extrapolation factors range from 20 - 200:1 for the pulse injection technique and between 200,000 and 1,000,000:1 for the Swept CW method. Comparisons between the two approaches have shown that the swept CW method yields somewhat more pessimistic results (i.e., predicts higher ATLs) than does the pulse method because the very low CW current amplitudes can not take full advantage of conductive paths through airframe structural elements and interfaces.

Further details of both aircraft test methods are contained in ARP5416 (Draft). The major elements of verifying or establishing the internal environment of the aircraft should follow the guidelines listed below:

a. Determine the lightning strike zone for the aircraft - Zones are the means by which the external environment is applied to the aircraft. The locations of these zones on any aircraft are dependent on the aircraft's geometry, materials and operational factors, often vary from one aircraft to another; therefore, a determination must be made for each aircraft configuration. Guidance for location of the strike zones on particular aircraft is provided in ARP5414).

b. Establish the external lightning environment for zones - Current flow paths through the airframe and around apertures are derived from aircraft lightning zones. Zones 1 and 2 define where lightning is likely to attach and, as a result, the entrance and exit points for current flow through the vehicle. The entrance and exit points selected for the aircraft test should represent the worst case for the equipment location. For example, the worst case entrance and exit points for an on-engine mounted electronic engine control may be the engine inlet to opposite wingtip.

c. Establish the effects of the internal environment - The internal lightning environment, which is produced by the external environment, is a result of current flow through the airframe and the penetration of electromagnetic fields. The fields and structural voltages are the internal lightning environment that causes the voltages and currents on interconnecting wiring which, in turn, appear at equipment interfaces.

It is possible to establish the actual transient levels from interface voltages and currents from data taken on a different aircraft if the aircraft are similar in construction, size and wire routing. These transient levels can be used to establish or verify TCLs and ETDLs for systems being certified on a new aircraft.

With wiring routed through all regions of the aircraft, it is possible to use carefully selected wires in the test aircraft to represent similar paths for other wire bundles within the aircraft.

4.6.2.1 Swept Frequency Testing: The swept frequency (or swept CW) test method is very useful for determining voltages and currents on aircraft wires, wire bundles, or shields. The method is illustrated in Figure 10. A low level swept frequency current of about one ampere is conducted through the aircraft under test, between pairs of entry and exit points defined from the aircraft zoning assessment. The low level current should be swept from about 100 Hz to about 30 MHz, in order to cover the range of constituent frequencies in the Fourier series that represents, where there is significant lightning energy, as well as the high frequency components, where there may be significant aircraft and wiring resonances.

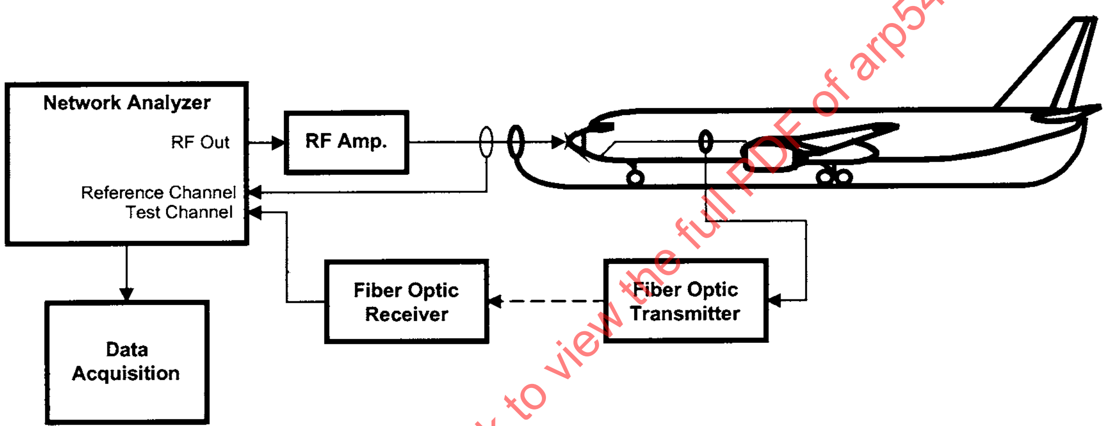


FIGURE 10 - Swept Frequency Test Setup

Typically, a vector (phase-amplitude) network analyzer is used to measure the ratio of the response voltage or current to the current injected onto the aircraft. The ratio of the response to the injected current as a function of frequency becomes the transfer function for that test point. This transfer function can then be used to calculate time domain transient responses for any lightning current waveform (see ARP5412).

The time domain transient response is calculated from the swept frequency transfer function using inverse Fourier transform methods according to:

$$R(t) = \Im^{-1}(H(\omega)*I(\omega)) \quad \text{(Eq. 10)}$$

4.6.2.1 (Continued):

where:

$H(\omega)$ = Measured transfer function
$R(t)$ = Desired time domain voltage or current response
$I(\omega)$ = Spectrum of the appropriate lightning Current Component (A, D, D/2, H, etc.). The spectrums for the Current Components A, D, and H can be found in ARP5412, Figure 12B, 19B and 20 respectively
$\Im^{-1}$ = Inverse Fourier transform and ω is the angular frequency (2 times π times frequency).

NOTE: The above equation requires knowledge of both the phase and amplitude of $H(\omega)$.

A vector network analyzer should be used for these swept frequency tests because it measures both phase and amplitude of the response, whereas a spectrum analyzer or scalar network analyzer only measures the amplitude. The entire process can be automated with personal computers so that the measurements can be recorded and the transient response calculated using standard laboratory software and data analysis programs.

A full aircraft swept frequency test requires that the aircraft and return conductors approximately form a parallel or coaxial transmission line. Then the swept current is driven at the selected lightning attachment points and the aircraft is connected to the return wires at the selected lightning exit points. Typically, the drive and exit points are selected to cause test currents to flow through parts of the airframe which contain the wiring being measured, while representing possible lighting entry and exit locations.

A current probe, such as a calibrated current transformer or current viewing resistor, is used to measure the injected swept frequency current at the drive point. The conductor open circuit voltages, short circuit currents and wire bundle currents are measured with calibrated probes. Individual conductor measurements should be taken with the remote end of the wire grounded to the structure (giving the total voltage induced in the loop), wire bundle measurements are usually made with the cable plugged into the equipment at each end so that any shields or grounded wires in the bundle can conduct induced currents. Typically, wide bandwidth analog fiber optic links are used between the voltage or current probe and the network analyzer, to minimize response contamination from unintentional coupling to measurement wire bundles.

An important step during swept frequency tests is to characterize the frequency-dependent instrumentation response of the probes, amplifiers, coaxial cables and the network analyzer. This instrumentation response can easily be removed from the measured responses, to eliminate the effect of this response. The corrected transfer function is multiplied with any of the threat spectrums, i.e., A, D/2 or H and inverse Fourier transformed to obtain the resulting time domain ATL of the circuit of interest. The ATL must be equal to or less than the TCL established for each threat. An example of this process is given in Appendix B.

4.6.2.1 (Continued):

There are several key considerations for swept frequency tests. The instrumentation, including the network analyzer, probes, wire bundles and fiber optic links, must have adequate operating bandwidth for these measurements. The operating frequency range typically ranges from a low frequency on the order of 100 to 1000 Hz and a high frequency on the order of 30 MHz. The instrumentation must also have adequate sensitivity to produce an acceptable noise floor for the desired responses.

Nonlinearity in the aircraft response should be considered. The swept frequency current at approximately one ampere will be used to measure a response to a transient current of 10,000, 100,000 or 200,000 A, an extrapolation of up to a factor of 2 times 10^5. This is the largest extrapolation factor of the three methods described in this section. However, tests performed to compare the results of swept frequency tests and pulse injection tests, which are typically conducted with much higher currents, have shown that the swept frequency currents tend to predict higher induced transients than do the tests with higher amplitude currents. This is probably because airframe structural joints become more conductive when loaded with higher amplitude currents. This is acceptable as long as the equipment can tolerate the higher levels. In certain cases, high amplitude currents, such as those of moderate to severe intensity lightning strikes may cause arcing between aircraft parts. This arcing may change lightning current paths in the airframe and in certain cases result in higher transients induced in the wiring than if the arcing did not occur. The low level test currents may not produce such effects, so when using low level test currents (either swept CW or pulse), the applicant should consider these factors in preparing the airplane for test. Jumpers may be employed to create current paths across insulated parts if it is expected that a full threat lightning current would jump across this insulation. References[2] and[3] suggest the results from this method were within ±3 dB compared to the results of pulse testing with higher amplitude currents.

One method to address the nonlinearity is by insuring good electrical bonding between aircraft parts, which is particularly effective on aluminum aircraft. On aircraft without effective electrical bonding or with extensive use of composite structures, structural voltages should be measured. If the extrapolated structural voltages exceed approximately 3000 V, additional bonding may need to be considered or temporary bonding jumpers may be added where arcing is anticipated to simulate the arcing conditions during the low level current tests.

4.6.2.2 Low Current Pulse Tests: Low current pulse tests, also known as Lightning Transient Analysis (LTA) tests, may be used to measure wire and wire bundle voltages and currents. In this method, the aircraft is subjected to low amplitude current pulses with waveshapes representative of Current Component A and H. Current Component A test amplitudes are typically within the range of 500 to 5000 A. Current Component H test currents of several hundred amperes are typically applied.

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2. D. B. Walen and M. M. Simpson, "Atmospheric Electricity Hazards Protection Part II. Assessment, Tests, and Analysis - F-14A," US Air Force report AFWAL-TR-87-3025 Part II, June 1987.
3. D. B. Walen and M. J. Katzer, "Atmospheric Electricity Hazards Protection Part IV. Assessment, Tests, and Analysis - ACAP Helicopter," US Air Force report AFWAL-TR-87-3025 Part IV, June 1987.

4.6.2.2 (Continued):

The test currents should have the same double exponential waveform parameters as defined in ARP5412 for current Component A and H. In this way, induced effects due to current rate of change and to peak amplitude or time duration will have the same relationships as if they were induced by the defined full threat currents, and a single extrapolation factor may be used for all induced effects. The multiple stroke and multiple burst environments are not applied in the full tests. Responses to current Components D and D/2 are usually derived from the responses to current Component A.

The pulse generator attachment point and the current exit point attached to the current return should be selected based on entry and exit points defined from the aircraft zoning assessment. The current return should be configured to approximate a parallel or coaxial transmission line with the aircraft. This is necessary to provide a low inductance path for the current pulse generator. Conductor open circuit voltages, short circuit currents and wire bundle currents, are typically measured with calibrated probes. The remote ends of measured conductors should be disconnected from the equipment and grounded locally to have all of the induced voltage appear at the current probes. In most cases, a linear extrapolation is used to estimate the levels that would be induced by full-threat Current Component A and H currents. Figure 11 shows a typical low current pulse test setup.

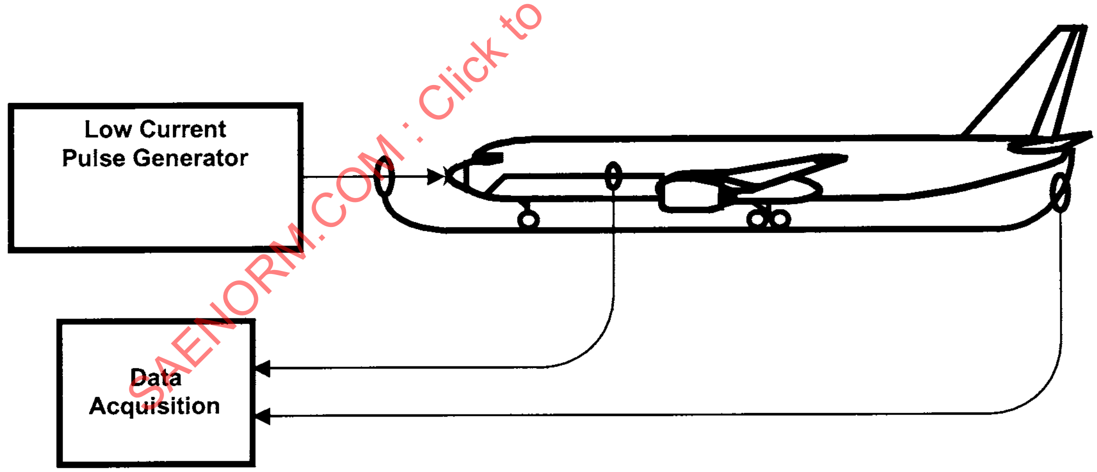


FIGURE 11 - Low Current Pulse Test Setup

4.6.2.2 (Continued):

Pulse current generators operate at high voltages (typically 10,000 to 50,000 V) so care must be taken to assure that personnel and the aircraft are safe from electric shock and sparking hazards. The instrumentation, including the probes, recording oscilloscopes and (usually) optical fiber links must have adequate operating bandwidth and dynamic range for these measurements (similar considerations apply to the instrumentation employed for the swept CW tests). Care must be taken to minimize response contamination from unintentional coupling to the instrumentation system. The same considerations with respect to arcing current paths and potential non-linearities as described for the swept CW method apply.

After the voltage and current transients have been measured and appropriately extrapolated to ATLs, then these ATLs can be compared to the ETDLs for appropriate systems. Considerations for incorporating appropriate margins should be used when comparing the ATLs and ETDLs.

Nonlinearity in the aircraft response should be considered. With an injected current of 1000 A used to represent current Waveform A with peak current of 200 kA, the extrapolation would be a factor of 200. The results have shown that the extrapolation process usually gives worst case results, because, in general, nonlinear effects tend to reduce resulting equipment interface transients. Nonlinear effects are generally caused by coupling resistance of bonds and joints that is reduced by large current flow. In certain cases, natural lightning may cause arcing between aircraft parts. This arcing may result in higher transients on parts than if the arcing did not occur. The low level test currents may not produce those arcs. Therefore, in using low level test methods, the applicant should consider these factors in performing this assessment.

One method to address the nonlinearity is by insuring good electrical bonding between aircraft parts, which is particularly effective on aluminum aircraft. On aircraft without effective electrical bonding or with extensive use of composite structures, structural voltages should be measured. If the extrapolated structural voltages exceed approximately 3000 V, additional bonding may need to be considered or temporary bonding jumpers may be added where arcing is anticipated to simulate the arcing conditions during the low level current tests.

4.6.2.3 High Current Pulse Tests: High current pulse tests may be used to measure wire and wire bundle voltages and currents. During these tests, the aircraft is subjected to high amplitude current pulses with waveshapes representative of current Waveforms A and H. Current amplitudes range from 10 to 200 kA, with fast current rise times.

The high current pulse waveform should be the defined threat current waveform. That is, the test waveform should have the same double exponential waveform. The peak current and peak rate of rise should be proportional to the external environment waveforms, current Component A and H. Responses to current Components D and D/2 are usually derived from the responses to current Component A.

The multiple stroke and multiple burst environments are not required to be applied to the full vehicle in a test. The multiple stroke and burst internal environment may be determined by testing using a single current component to obtain the transfer function of interest, or to obtain the actual transient response level.

4.6.2.3 (Continued):

The pulse generator attachment point and the current exit point attached to the current return should be selected based on entry and exit points defined from the aircraft zoning assessment. The current return should be configured to approximate a parallel or coaxial transmission line with the aircraft. This is necessary to provide a low inductance path for the current pulse generator. The short circuit pin current, wire bundle current, or shield current are typically measured with calibrated current probes. Open circuit pin voltages or equipment circuit voltages can be measured using high impedance voltage probes. The measurements of actual transients are made on wires, wire bundles, or wire shields for the appropriate systems to determine the ATL. If the tests were carried out with a reduced external environment level, the measured transients are then extrapolated. In most cases, a linear extrapolation is used to estimate the levels that would be induced by full-threat components A, D, D/2 and H currents. If the extrapolated structural voltages exceed approximately 3000 V, additional bonding may need to be considered or temporary bonding jumpers may be added where arcing is anticipated to simulate the arcing conditions during the high level current tests. Figure 12 shows a typical high current pulse test setup.

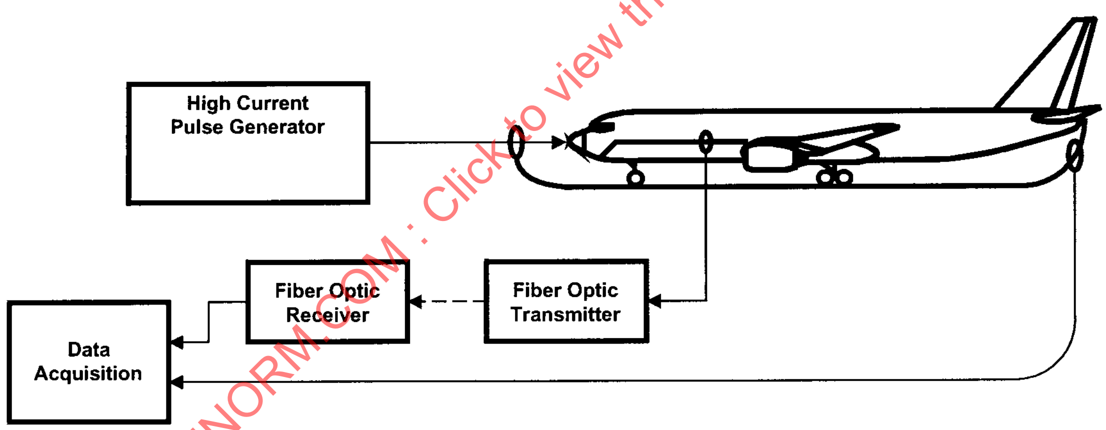


FIGURE 12 - High Current Pulse Test Setup

There are several key considerations for high current pulse tests. The current pulse generator must be capable of producing the appropriate current and current rate-of-rise. This typically requires a pulse generator and aircraft test setup with very low inductance. These pulse generators often operate at very high voltages to create the appropriate peak current and rate-of-rise. There are significant personnel hazards associated with this class of current pulse generators. The instrumentation, including the probes, wire bundles and fiber optic links, must have adequate operating bandwidth and linearity for these measurements. Often wide bandwidth analog fiber optic links are used between the voltage or current probe and the transient waveform recorders. This is to minimize response contamination from unintentional coupling to measurement wire bundles.

4.6.2.3 (Continued):

After the voltage and current transients have been measured and appropriately extrapolated to ATLs, then these ATLs can be compared to the ETDLs for appropriate systems. Considerations for incorporating appropriate margins should be used when comparing the ATLs and ETDLs.

Nonlinearity in the aircraft response should be considered. However, experiments investigating the linearity of scaling for the high-level test approach have shown that the extrapolation process is quite linear. With an injected current of 10 to 50 kA used to represent current Waveform A with peak current of 200 kA, the extrapolation would be a factor between 4 and 20. This high-level pulse method has the least extrapolation factor of the three methods described in this section. In addition, nonlinearity effects become less of a factor because with the high level current tests, the aircraft structure and wire bundles are subjected to relatively high voltages and currents, so that arcing would occur similar to the arcing from natural lightning.

4.6.2.4 Test Aircraft: The test aircraft should be a production aircraft. It is usually one of the flight test airplanes. If a prototype airplane is to be used the wiring configuration, wire routing, equipment installation and aircraft structure must be shown to be electrically similar to a production aircraft. If flight test wiring is present, this wiring should be capped and stowed on both ends during testing.

The aircraft should be positioned to allow the maximum clearance possible between the aircraft extremities and the surrounding building structure if it is to be tested indoors. Electrically insulating pads should be placed under the aircraft tires or skids to provide electrical isolation between the aircraft and the surface the aircraft is parked on. The current return path to the current pulse generator or RF amplifier should be arranged so that the return conductors have minimal influence on airframe current distribution and test results. More details of return conductor arrangements are described in ARP5416 (Draft).

Test current entry and exit points on the aircraft should be specified in the test plan. These should be selected to conduct test current through those portions of the airframe that contain the wiring being measured, as long as the selected points are realistic lightning entry and/or exit locations as determined from the aircraft lightning strike zones. For example, a measurement made on a wire routed between the cockpit and the left wing navigation light is made when the test current is conducted between the left wing tip and the nose. The test current would then flow through portions of structure containing the wiring being measured, thereby inducing the maximum voltages or currents in this wiring. Table 3 defines some common current entry and exit pointers that can used during the tests.

TABLE 3 - Common Test Entry/Exit Points

ENTRY:	EXIT:
NOSE RADOME	TAIL
NOSE RADOME	WING TIP
NOSE RADOME	LANDING GEAR
NOSE RADOME	VERTICAL TAIL/ HORIZONTAL STABILIZER
WING TIP	TAIL
WING TIP	WING TIP
ENGINE NACELLE	OPPOSITE WINGTIP/ TAIL/ THRUST REVERSER

4.6.2.5 Measurements: The measurements made during the aircraft tests provide the ATLs that are used to determine the acceptability of the TCLs and ETDLs. Therefore, the measurements should be chosen to match the way the aircraft TCLs and the equipment and/or system ETDLs are defined. For example, if the TCLs are defined as individual wire open circuit voltages and short circuit currents, the aircraft measurements should include these same parameters. Alternately, if the TCLs are defined as wire bundle currents, then the aircraft measurements should include wire bundle currents. Also, the measured parameters should be those that are applied in equipment or system tests. Therefore, if the ETDLs and corresponding equipment qualification tests are based on the DO-160/ED-14, Section 22 wire bundle tests, the wire bundle injection tests levels are based on open circuit loop voltages and wire bundle currents. Therefore, the aircraft tests should include measurements of cable-to-airframe loop voltages and wire bundle currents.

Several types of measurements can be made. These include:

a. Open circuit voltages (V_{OC}), which are induced voltages measured between an individual open-ended wire and adjacent aircraft ground, with the other end of the wire grounded at the remote equipment location using a low-impedance ground termination. Equipment at either end of the measurement wire is disconnected from the wire bundle, but shields of the measured wire. (if present) any other shields in the same wire bundle should be grounded on the normal fashion, either locally or to equipment connectors, if such shields are normally grounded at each end in the installation.

b. Short circuit currents (I_{SC}), which are induced currents measured on individual wires with both ends of the wire grounded using low-impedance ground terminations. Other conditions are as described in paragraph A.

4.6.2.5 (Continued):

c. Wire bundle currents (I_{bc}), which are induced currents measured in a wire bundle, with the aircraft equipment that use the wire bundle installed in their normal manner and the wire bundles connected to the equipment at each end, in the normal manner.

d. Loaded circuit voltages (V_l), which are induced voltages measured between a wire and adjacent aircraft ground, with both ends of the wire terminated normally, and with the aircraft equipment installed in their normal manner.

e. Loaded circuit currents (I_l), which are induced currents measured on individual wires with both ends of the wire terminated normally, and with the aircraft equipment installed in their normal manner.

The loaded wire measurements described in D and E above are usually made only in special cases, such as NAV light and De-Ice heater circuits, and power distribution busses, since such measurements would otherwise require elaborate breakout boxes whose presence could affect the measured transients. Also, loaded circuit measurements would probably have to be conducted with the system powered up, to account for non-linear load impedances. Finally, care would have to be taken to account for the presence of surge protection devices which would be in the conducting state in the presence of a full scale induced voltage but would not conduct during tests with scaled down test currents.

Figure 13 illustrates these measurements. The first three measurement are most commonly made, because they can be easily related to the ETDLs verified with DO-160/ED-14, Section 22 tests, and because the measurement can be performed using relatively simple circuit shorting devices. With the first two measurements, a Thevenin equivalent circuit can be derived for each measured aircraft circuit, from which the ATLs can be determined. The last method typically requires more complex breakout boxes to install the voltage and current probes without affecting circuit and wire bundle shield characteristics.

The bulk wire bundle currents can be used to establish ATLs on entire wire bundles installed in the aircraft. These measurements can be made with the bundle in various configurations (i.e., both ends grounded, equipment installed, determining effects of adjacent low impedance conductor etc.).

The specific circuits and wire bundles to be measured and the locations where these measurements are to be made should be described in a test plan, together with other information regarding equipment configuration and aircraft test conditions. These should be derived from study of the system function(s), circuit diagrams and installation drawings and inspection of the aircraft to be tested.

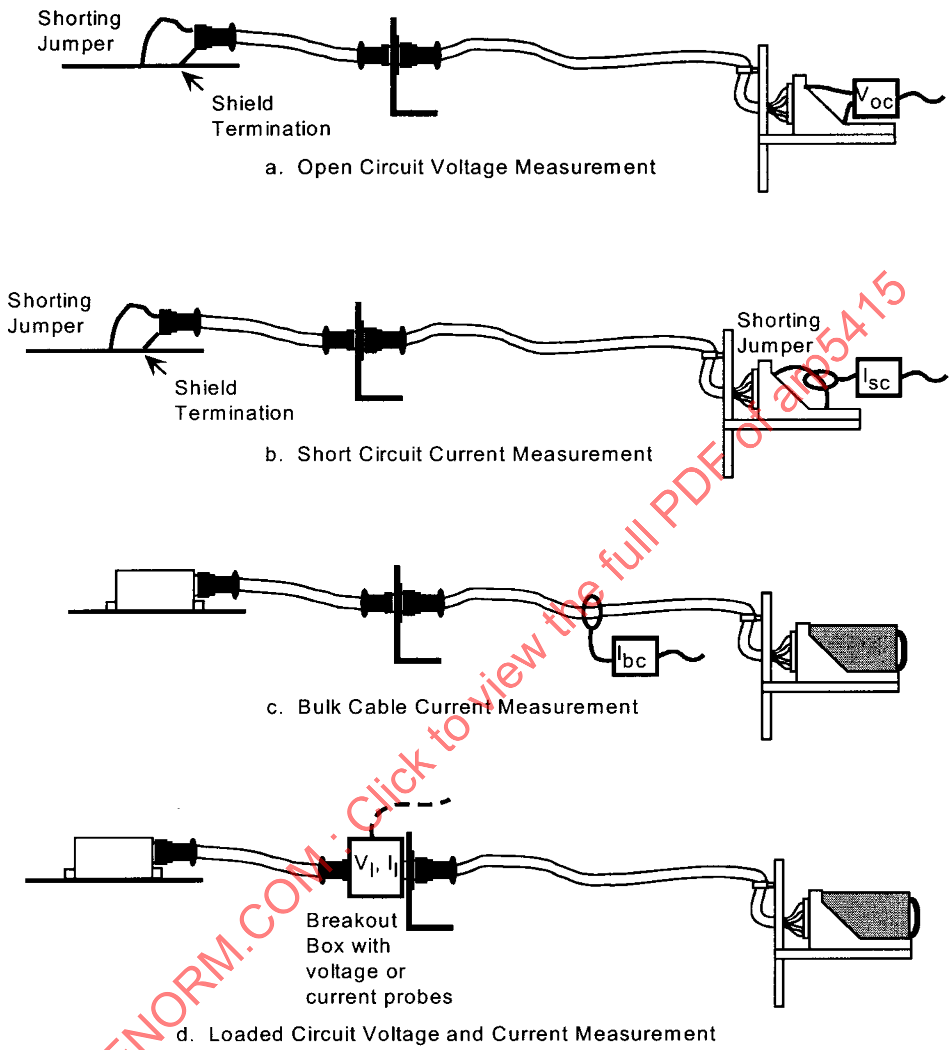


FIGURE 13 - Schematic Representation of Measurement Types

4.6.2.5 (Continued):

The voltage and current test points should be on selected wires for all Level A systems. Similarity of equipment interface circuits, wire bundle lay-up, shielding status and routing may be used to minimize the number of measurement points. These should be selected to determine the ATLs for the wire and equipment installations assessed to have the most severe exposure to lightning induced transients. The wire bundle lengths, locally high lightning current distributions, wires routed in exposed locations, or wires routed with other wires subject to high lightning transients should be considered during test planning.

4.6.2.5 (Continued):

For Levels B and C systems, the route to compliance does not always employ aircraft tests. However, ATL data on typical circuits employed for level A functions may also be used to verify that the appropriate system or equipment ETDLs were selected for level B systems. Further discussions of certification of systems performing level B and C functions is contained in 7.2.

The open circuit voltage and short circuit currents measured are the maximums that may be induced in the interconnecting wiring. Equipment interface circuit impedance may reduce both voltage and current appearing at equipment to lower levels. The actual voltage and current that enter the LRU circuits can be determined by analysis if the aircraft wiring is viewed as a Thevenin equivalent circuit whose voltage source is the measured open circuit voltage and whose series impedance is determined by dividing the measured open circuit voltage by the short circuit current. This Thevenin equivalent may then be connected to equipment interface circuit impedance to determine the actual voltage and current expected to appear at equipment interface circuits.

Locations of LRUs and associated interconnecting wiring should be identified using aircraft system installation drawings and aircraft installation inspection. The wire shielding status should also be determined from the drawings. Any shield at the measurement end, which is normally grounded either by the connector backshell or through one of the connector pins to a ground within the LRU, should be grounded to the airframe. A convenient location should be selected close to the disconnected LRU for grounding the shield during the induced voltage measurements.

The measurement instrument, such as an oscilloscope or network analyzer, may be placed inside the aircraft to measure the induced voltages and currents in the aircraft wiring. The measurement instrument should be placed in a shielded enclosure to help minimize unwanted noise in the measurements. The shielded box should be placed near the measurement point and grounded to the airframe as close to the measurement point as possible. AC power supplied to the measurement device should use a filtered feed-through connector mounted in the side of the shielded box. An isolation transformer should be used to provide an isolated power. Measurement leads used to connect the voltage and current probes to the measurement device should be shielded with an overbraid.

The measurement instrument, such as an oscilloscope or network analyzer, may be located outside the aircraft. A shielded enclosure may be used to minimize unwanted noise in the measurements. Typically, wide-bandwidth analog fiber optic links are used to connect the measurement probe to the measurement instrument. Measurement instrumentation outside of the aircraft should not be hard-wired to probes inside of the aircraft. It is very difficult to control undesired coupling under this arrangement and the validity of any test results would be therefore questionable.

4.6.2.5 (Continued):

Voltage and current probes, oscilloscopes, and network analyzers should have appropriate high and low frequency response to adequately characterize the test point response. Currents on individual conductors and on wire bundles can be measured by the use of current transformers. Wire bundles, which can not be easily disconnected, should be measured using a current transformer with a split core, so that a wire bundle does not have to be disconnected for installation of the probe.

Instruments used to record and measure specified test voltages and currents, such as network analyzers, oscilloscopes and probes, should be calibrated to standards traceable to the appropriate national standards body, such as the U.S. National Institute of Standards and Technology (NIST), using procedures and processes approved by the appropriate national standards body.

4.6.2.6 Instrument Noise Measurements: Voltages and currents induced in aircraft wiring are several orders of magnitude lower than test current generator voltages and currents. This means that the measurement device must be sensitive enough to measure low level probe output voltages in areas where significant electrical and magnetic fields are present. The measurement system must be adequately shielded from this radiated and conducted noise. Instrumentation noise should be measured at each of the test points locations to characterize the noise. The results of the noise measurements should be compared to the intended measurements to ensure that there is adequate signal compared to the noise.

To minimize noise content in measurements several precautions should be implemented throughout the tests:

a. The measurement instrument, such as oscilloscope or network analyzer, should be placed inside a shielded enclosure.

b. Voltage and current probe lead lengths should be minimized.

c. Current probes should include electric field shields.

d. Consider using wide bandwidth fibre-optic links to electrically isolate the measurement probes on the aircraft from the measurement instruments in the shielded enclosure.

Instrument noise levels should be measured at each airframe test point location. For common mode wire voltage test points, noise levels are typically measured with the voltage probe disconnected from the test point, and short circuited to the test probe signal return. The test probe return should also remain attached to aircraft ground. For wire current test points, noise levels are typically measured with the current transformer removed from the wire, placed adjacent to the wire, but electrically isolated from the wire.

4.6.3 Verification by Analysis: System lightning protection certification compliance can be verified by analysis. Typically, the analysis is used to calculate the actual transient levels (ATL) that exist on aircraft wiring. The ATLs may be voltage or current on conductors and wire bundles. Many techniques exist for calculating the actual transient levels. The techniques range from simple calculations based on first principles to complex three-dimensional electromagnetic models of the aircraft and interconnecting wiring installation solved using computer programs. Computer-based electromagnetic modeling programs generally use techniques in the following categories:

a. thin wire method of moments analysis,
b. finite-difference analysis,
c. method of moments patch analysis,
d. finite element analysis, or
e. transmission line modeling.

The analytical model used to determine the ATLs during the verification step may be the same model that has been used during the design process to assist in establishing the TCLs and ETDLs associated with the system. Analytical models have the advantage that the effects of in-flight conditions can be simulated, without the influence of the ground plane or ground return system that are present during aircraft lightning tests. Also, application of both of the lightning current components (A and H) would be very straightforward. With test, each current component typically requires a separate pulse generator. On the other hand, in the analytical model it is rarely possible to represent all of the aircraft electrical features, such as structural joint and connector resistances and the myriad of adjacent electrical conductors usually present in typical aircraft. This means that a higher margin between TCLs and ETDLs must usually be incorporated, even though some of the factors that are not modeled may actually reduce the measured transient levels. Any analysis method selected must have been verified by comparison of its computed results with test results.

Two key aspects of verification by analysis are the fidelity of the model, and validation of the modeling technique. The analytical model must accurately represent the appropriate aircraft, system, and wiring features that are important for the lightning protection. Although the existing analytical techniques provide accurate solutions, the quality of the input data for the model is the most important element of the analytical solution. Developmental tests on pre-production airframes, mockups, or existing aircraft often provide data that will support development of the analytical model for certification compliance verification. The key items that must be included in the analytical model should be identified. These items may include structural material electrical parameters, aperture descriptions, shield transfer impedance, circuit loads impedance, etc.

The analytical model and analysis technique should be validated based on known aircraft transient responses. Validation should address how appropriate the particular analytical model and analysis techniques are for the given lightning environment and the aircraft and system features modeled. The validation should also address the sensitivity of the model input data. Typically, validation is based on verifying the computation accuracy using models that can be verified using other analytical data. The validation should also compare results of aircraft and system analysis to test data on the same aircraft. This validation may be performed using models of existing aircraft and system installations and comparing the results to actual test data for that aircraft.

4.6.3 (Continued):

If analysis is used to verify lightning protection compliance, an overview of the analysis methods proposed should be contained in the Certification Plan recommended by ARP5413, and an Analysis Plan should be prepared for review and approval by the certifying authorities prior to commencement of the analysis. This plan should provide information on:

a. The analysis technique(s) proposed,
b. Key analytical model input data required,
c. Source of the model input data,
d. Validation approach for the model,
e. Validation approach for the analysis technique,
f. Sensitivity of the model and technique to input variations, and
g. TCL, ATL and ETDL margins required to account for model sensitivity and input variations.

Details of each of above activities should be provided in the Analysis Report, together with results of the analyses.

4.6.4 Similarity Assessment: Similarity may be used as a means to verify compliance with the lightning certification requirements. ARP5413 provides guidance on how to evaluate similarity between a previous certified system and installation and a new system or installation. Similarity of design and installation features that influence susceptibility to lightning direct and indirect effects must be shown if verification of compliance with the lightning protection regulations by similarity is proposed. The degree of similarity is related to the hazard classification for the system. If the new system and installation is performing a Level A control function, relevant design features must be shown. If the system is performing a level B function, some differences in equipment design and/or installation can be accepted, as long as they do not result in sufficient increases in susceptibility or vulnerability to lightning effects which may compromise their ability to meet acceptance criteria.

Important features of airframe design which must remain similar are structural materials, number and locations of electromagnetic apertures (i.e., windows, non-conducting doors and access panels), locations of wiring, status of shields, locations of grounds to the airframe, system architecture and circuit designs. Features of the equipment designs include interface circuits, EMI filters, surge suppression devices, equipment locations in the aircraft, equipment racks, enclosures and housings (i.e., box design and materials), equipment grounding, and the ETDLs to which the new equipment has been previously qualified (or TSO'd). Software similarity is also important, including features such as fault tolerance, watchdog timers, parity checks, data sample rates and window times, channel A/B communications, and data processing speeds.

If differences in either the hardware or software aspects described above are discovered, the effects of these differences on susceptibility to lightning-induced effects must be evaluated. This includes particularly damage tolerance, and the susceptibility to upset by the multiple stroke and multiple burst environments.

4.6.4 (Continued):

The similarity assessment should be approached systematically. For example, if similarity is used to verify compliance for an aircraft that is a derivative of an existing certified aircraft, the similarity assessment should address all changes from the existing aircraft to the new aircraft. The list of changes may identify change requests, revision records, or part number changes. Each change should be assessed for its impact on the lightning certification, and the impact identified. It is very useful to list the change reference number, description of change, and impact in a table, if there are a number of changes.

For changes where the impact is uncertain, or where the impact reduces the lightning protection margins, further assessment may be required. This additional assessment may include analysis or engineering tests to support the similarity claim. However, if significant analysis or tests are required to support the similarity claim, this implies that there is not obvious similarity between the existing aircraft installation and the new aircraft installation. Therefore, verifying compliance by certification analysis or certification tests may be more appropriate. Also, if the similarity assessment shows that the change significantly reduces lightning protection margin, compliance verification by certification tests or detailed analysis may be required for that change.

4.7 Corrective Measures:

If the verification tests and/or analyses show that the interconnecting wiring in fact experiences higher amplitude transients than are allowed by the TCL(s) assigned to this wiring or that equipment can not tolerate the ETDL(s) assigned to it, changes should be made in either the wiring designs or installation, or in the equipment designs, to enable the necessary margin to exist between TCL(s) and ETDL(s). The following approaches may be considered:

a. Redesign either the wiring or the equipment.

   For the wiring this usually means improving the shielding by reducing pigtail lengths on existing shields, or replacing unshielded wiring with shielded wiring, or adding an overbraid shield to a group of individually shielded circuits.

   For the equipment this usually means adding surge suppression devices to interface circuits (often only one or two such interfaces may require this). Other modifications may include changes in the designs of EMI filters (to accommodate higher transient voltage levels), and addition of series impedance. If the incompatibility was associated with system functional upset, software changes such as the addition of error detection and watchdog timers may be considered.

b. Select a different set of TCLs and ETDLs, with both being either higher or lower than the original levels.

   The margin between TCLs and ETDLs is preserved, but each level may be increased (if the original TCL(s) was not met) or reduced (if the original ETDL(s) was not met). The revised levels may be more compatible with existing wiring and/or equipment designs.

4.7 (Continued):

The verification tests or analyses applicable to any parts of the wiring or equipment designs or installations that have been modified must be repeated to confirm that these systems (or portions thereof) meet the applicable TCL(s) and ETDL(s). Specific steps should be proposed in revisions to the original certification plan and to the test or analysis plans that were applicable to the original system. These need to be reviewed and approved by the certifying authority prior to commencement of the verification activities. Appendix C provides additional detail on design protection.

5. EFFECTS OF INDUCED TRANSIENTS:

Induced transients may be characterized by voltages impressed across or currents flowing into equipment interfaces. Equipment interface circuit impedance(s) and configuration(s) will determine whether the induced transient(s) are predominantly voltage or current. These transient voltages and currents can degrade system performance permanently or temporarily. Component damage and system functional upsets are the primary types of degradation. Component damage is a permanent condition while functional upset refers to an impairment of system operation, either permanent or momentary (e.g., a change of digital or analog state, which may or may not require manual reset) that may adversely affect flight safety.

5.1 Component Damage:

The ability of electrical and electronic components to tolerate the damaging effects, such as insulation breakdown, or burnout, of electrical transients is known as damage immunity. Damage immunity of electrical/electronic components is a consideration that is part of the equipment and circuit design process. Damage immunity will be influenced by:

a. amplitude of interface transients,
b. impedance of that remote portion of the installation interfacing with the circuit and
c. impedance of the circuit interface itself.

Devices, which may be susceptible to damage due to electrical transients, are

1. active electronic devices, such as diodes, transistors, and integrated circuits,

2. passive electrical and electronic components, such as resistors, capacitors, solenoids, temperature, pressure and position sensors, especially those of very low power or voltage rating,

3. transient protection devices,

4. electro-explosive devices such as squibs and detonators and

5. electromechanical devices such as indicators, actuators, relays and motors.

5.1 (Continued):

Damage mechanisms for electronic components subjected to electrical transients include dielectric breakdown and thermal effects, which can result in semiconductor junction, resistor and interconnection failures.

Breakdown can occur in all types of insulation if the voltage stress is high enough and applied for a sufficient time. Breakdown may occur across a surface or through the interior of a device, such as a puncture. The voltage at which dielectric breakdown occurs is a function of the material and its thickness. The voltage at which surface breakdown occurs is also a function of environmental factors such as humidity and altitude (air pressure). Surface breakdowns can also occur between circuit board traces and across connector wafers, and these items should be shown capable of tolerating the same ETDL(s) as the electrical or electronic component(s) they are associated with. If the surface(s) mentioned above are exposed to ambient air (as would usually be the case if the equipment is installed in non-pressurized regions of the aircraft) ability of the surface(s) to tolerate the assigned ETDL voltage should be demonstrated at the air pressure associated with the certified flight altitude. For example, at 33,000 ft (10,000 m) the air pressure is approximately 200 mm Hg, as compared with 760 mm Hg at sea level. This means that air and surfaces exposed to air will withstand approximately 1/3 the voltage which the same surface (or air gap) will withstand at sea level. Failure to account for the influence of reduced air pressure on surface and gap voltage withstand capabilities has resulted in failures of such insulation under in-flight lightning strike conditions.

Thermal effects result from transient current flow, which dissipates excessive energy in the component. This is a major cause of semiconductor failure. Thermal effects can cause resistor burnout, failure of semiconductor junctions, spot welding of relay contacts, detonation of electro-explosive devices and even failure of transient protection devices.

Interconnection type failures can occur due to induced electrical transients that increase the temperature sufficiently to melt metal surface connections, beam leads within integrated circuits and the wire in wire-wound resistors. Integrated circuits and discrete active components such as diodes, transistors and MOSFETs are, in general, the most vulnerable components.

Circuit design, circuit component selection and installation architecture can be employed to enable equipment input and output interfaces to tolerate assigned ETDLs and minimize application of terminal protection devices (TPDs) such as diodes and metal oxide varistors (MOVs).

5.2 System Functional Upset:

Functional upset usually applies to a system compromised of two or more items of equipment, although some systems may be incorporated in a single “box” or within a single rack in which each part of the system is an individual circuit card. Permanent or momentary upset of a signal, circuit, or a system component can adversely affect system performance to a degree, which may degrade ability of the system to perform its intended function. In general, functional upset depends on circuit design and operating voltages, signal characteristics and timing and system and software configuration. Systems or equipment which may be susceptible to functional upset due to electrical transients, include (1) computers and data or signal processing systems associated with cockpit displays, (2) electronic engine and flight controls and (3) power generating and distribution systems.

“System Functional Upset” is an impairment of system operation, either permanent or momentary (e.g., a change of digital or analog state) which may or may not require manual reset. Upset, itself, can take the form of a diverse group of actions or reactions such as a single discrete change of state, system re-initialization, or a change in amplitude (either in range or out of range) of an analog output. Ultimately, system functional upset must be addressed if it can affect safety of flight. In some cases, such as non-critical system functions, upset or perturbation may be acceptable.

Functional upset can be a particularly important issue for digital processor based systems. Systems of this nature are designed to process data using signals having a pulse format and can respond to the electrical pulses in aircraft wiring produced by lightning. The upset of a digital processor is a statistical event and verification based upon testing or analysis of single pulse effects would not be adequate. Since lightning induced transients have time durations in the microsecond range, upset is most prevalent in digital subsystems. Upset can sometimes occur in analog systems, for instance with a sample and hold circuit.

Since many electrical/electronic systems are comprised of components that are distributed throughout the aircraft, verification of compliance relative to functional upset involves considering the overall lightning environment to which the system is exposed. The multiple stroke and burst aspects of the external lightning environment, defined in ARP5412 are intended for use in functional upset of systems. It is necessary that these environments be translated into corresponding internal environments in order for assessments of their effects on systems to be made. Usually verification of system tolerance of these environments is done by tests in which multiple stroke and burst transients are injected into a functioning system, usually on a bench. Sometimes system tolerance of the multiple stroke and burst effects can be shown by analysis.

When an assessment of upset is being performed by analysis a description of the complete system architecture, including hardware, interconnections, and software procedures for handling data is usually necessary. An analysis of multiple stroke and burst transient effects should clearly establish the reasons why a particular system will not experience functional upset when exposed to the lightning environment. If this can not be established by analysis, a combination of tests and analysis may be appropriate. Lightning can induce transients simultaneously on all the wire bundles and conductors throughout a system. It is therefore important to evaluate the effects of simultaneous application of induced transients at all system interfaces.

5.2 (Continued):

An assessment of functional upset involves making pass/fail judgments regarding any effects of the multiple stroke and burst tests (or analysis) results as they relate to the continued performance of the system's intended function(s) and continued safe operation of the aircraft. These acceptance criteria may rely upon the results of the FHA, a key step in the system safety process. This is a system design and validation issue requiring the application of systems engineering disciplines.

For analog computer based architectures, immunity can be achieved through circuit design measures, but for digital computer based designs, architectural (fault tolerance, software, etc.), as well as, circuit design measures need to be used.

Upset control must be addressed in a multi-tiered effort. It may require circuit, internal packaging, systems and software design coordination. As with a damage assessment, upset control begins at external electronic interfaces, which are directly stimulated by lightning induced transients.

Hardware design must focus on practical methods to minimize the potential of upset. Circuit and control loop bandwidths should be limited to the minimum necessary for functional requirements. The use of differential-balanced inputs will also minimize the potential of upset.

Layout of circuits and conductors or internal packaging must also be controlled to minimize coupling to more sensitive buried circuits. In the most severe cases, it may be necessary to apply suppressors on external input/output signals at their point of entry. Also, in many cases, designing the input circuits with adequate time constants so that the input does not respond to short lightning pulses should be considered as alternative means of protection from upset.

Systems and software engineering must address the potential of lightning-induced transient errors such that system performance is not compromised by upset. System architectures and associated equipment must, therefore, be designed for the potential of errors and fault accommodation to ensure system performance throughout the lightning event.

Software filtering and constantly refreshing data (never re-use data taken in one cycle for multiple cycle operations or calculations) are methods which typically minimize error. Limiters, rate checks, parity checks and check-sums are typical methods employed to detect upset.

Once erroneous data is recognized or detected, automatic methods of maintaining a system function might entail using a last-good-stored value or re-calculation using alternate parametric inputs or synthesized parameters. Fault latches inhibit automatic recovery and should be avoided.

Since upset can be a function of transient amplitude, rate of change, pulse spacing, or even repetition frequency, establishment of susceptibility to upset is more complex than establishment of susceptibility to damage. In some cases, a system could have one type of susceptibility (upset) associated with transient amplitude, another associated with transient rate of change and yet another type of susceptibility associated with the repetition rate of transients such as that defined for the multiple stroke and multiple burst environments. An ETSL may be assigned for amplitude susceptibility, but may not be relevant to frequency or timing susceptibilities.

5.2 (Continued):

The determination of timing susceptibilities may be based on an analytical assessment of the multiple stroke and multiple burst threats. The timing and the repetition rates should be applied analytically to the equipment by the system designer in an effort to locate areas of susceptibility. This process must be applied until the system designer is assured of an error-free design. Alternately, timing susceptibilities might be determined through extended tests (example: continuous multiple burst applications well beyond the normal 2 s environmental occurrence time, between 5 to 10 min for example).

Circuit tests, while primarily used to assess damage, might also be used to determine a worst case response, its effect on system performance and ultimately the ETSL. Such worse case responses might, then, be used as a stimulus (example: input interface) in a large scale closed loop system model to determine ultimate system performance and the ETSL. When circuit tests are utilized as an evaluation tool, the equipment manufacturer should consider a sample size sufficient to develop confidence and, especially for complex integrated circuits, should consider affects for alternate or second sources since internal circuit differences could alter the worst case response. In addition, the synergistic effects of lightning induced transients can be important.

However, experience has shown that the consideration of synergistic effects is not always necessary for upset evaluation as long as sufficient protection is applied to a given interface circuit. From a damage point of view, for example, damage typically occurs on those electronic components that interface a given circuit with its corresponding external wire bundle and therefore the effects of other wire bundles are not significant.

Lightning attachment to an aircraft can produce transients simultaneously on all the wire bundles and connections attached to any given equipment. It is therefore important for those responsible for lightning protection to evaluate the equipment and determine if this synergism, (simultaneous excitation of all interfaces) could be a factor. As previously indicated, the control or elimination of system functional upset will ultimately require close hardware design and system and software engineering coordination.

6. MARGINS AND VERIFICATION METHODS:

Margins are incorporated to account for the uncertainties involved in the verification process. Margins are defined as the difference between the ETDL and the TCL as shown in Figure 1 of ARP5413. The magnitude of the margin required is usually dependent upon several factors. These include the confidence placed on the methods used to establish and verify the TCLs and ETDLs and the criticality of the function provided by the system.

When establishing the acceptance criteria for Level A, B and C systems it should be remembered that compliance applies to maintaining the functions and not necessarily to continuing the operation of all components or parts of the system, provided the function is maintained. Thus some components of a system could be upset or damaged, providing that the required functions are maintained.

6. (Continued):

The amount of the margin depends upon the degree of assurance with which the specified TCL and ETDL levels are verified. If verification is done by analysis only, or analysis supported by minimal test data on a Level A system, the margin should be large, perhaps separating ETDL from TCL by a factor of 10. On the other hand, if aircraft tests are conducted to verify the amplitudes of transients in wiring and the ability of equipment to tolerate the ETDLs is also verified by equipment tests on a Level B system, margins may be less, perhaps as low as 50%. In this latter case, for example, a TCL might be 300 V and a corresponding ETDL might be 450 V.

Another situation where higher margins are appropriate is in the prediction of the ATLs during the design of a completely new system and the absence of test data from similar systems or airframes. The possibility exists that some conductors or circuits will experience higher transients than those which have been predicted by analysis during the design phase or those which have been measured during tests of a full vehicle if that vehicle is not sufficiently similar to the installation being certified. Even when tests are conducted on a representative vehicle, it is never practical to measure transients in every single wire due to time constraints.

Other uncertainties are inherent in the specification of the natural lightning environment and the methods of simulating this environment for verification test purposes. The margin, which is defined as the difference between the TCL and the ETDL, is the value that is used to account for all of these factors. It is the only margin that should be applied, since it does encompass all of the uncertainties involved in the verification, along with an adequate safety factor. It should be noted that the lightning environment definitions do not themselves include a margin. It is known that each of the defined lightning environments is exceeded occasionally in natural lightning strikes.

Even though the specific value established for the margin is an engineering judgment, the margin must be agreed upon with the certification authority. If the margin is too large, then penalties in weight and cost will be inflicted upon the design. If the margin is too small, then the likelihood of a lightning-strike encounter resulting in system damage or functional upset becomes unacceptably high.

The size of the margin is inversely proportional to the confidence given to the TCL and ETDL selection and verification methodology. One method of verification would, in theory, be to subject an actual operating aircraft to a simulated full-threat lightning strike. With this method of verification, a comparatively small margin would be required, to account only for environment simulation uncertainties. Considerations of personnel and equipment safety, as well as test facility limitations prevent such an approach. There are no facilities capable of performing such a test, except perhaps on very small aircraft.

6. (Continued):

The most common method of verification of TCLs is utilizing low-level full-vehicle test and analysis, or an analysis method, which has been verified by test on another vehicle. The testing may be accomplished either by time domain, pulse testing, or by frequency domain methods utilizing variable frequency continuous wave (CW) testing. An analysis is then performed in which results of these low-level tests are extrapolated linearly to the levels which would be produced by a full-threat lightning-stroke current (current Component A) as defined in ARP5412. For these methods of verification, a margin of approximately 2:1 should be sufficient. The analysis would also include consideration of current Component D from the multiple stroke environment and current Component H from the multiple burst environment.

Another type of verification is utilizing an analysis method, which has been previously verified to yield acceptable results for a dissimilar aircraft type. Such an analysis would be based on first principles of electromagnetics and electric circuits. However, because of difficulty in describing complex circuits within a complicated airframe in a manner suitable for analyses, such methods cannot be depended upon to yield numerically accurate results. Orders of magnitude of induced transients can be predicted, but more specific results are often not possible. For these cases, margins of up to 10:1 are not unrealistic.

The method(s) of verification of TCLs, whether by full-vehicle test, analysis, or some combination thereof should be described in the certification plan - together with the actual TCLs and ETDLs selected, for concurrence by airworthiness certifying authorities. Selection of the most appropriate method often depends on airframe availability, schedule and cost factors.

7. MAJOR ELEMENTS OF COMPLIANCE:

As noted or implied in Section 3.6 of this User's Manual and Appendices B and C, optimum electrical/ electronic immunity from lightning effects is achieved by designing it in from the start of an aircraft development program.

This section is based on the 5 levels recognized by ARP5413, Levels A through E as described in 4.1. If a system with its associated equipment is determined to be Level D or E, no further test or analysis is required. Thus there are four levels of rigor relative to compliance demonstration:

1. Level A control
2. Level A display
3. Level B
4. Level C

In applying the major levels of compliance it is necessary to equate the level of rigor to the level of the potential failure.

7. (Continued):

For Level A control systems, unless similarity to a previously certified aircraft or analysis can be employed to verify that actual transient levels in interconnecting wire harnesses do not exceed the TCLs assigned to the wiring associated with systems performing Level A control functions, a full aircraft test must be performed to verify that the ATLs in this wiring do not exceed the TCLs assigned to this wiring.

For Level A display systems, TCLs and ETDLs for most system installations can be selected from among the standard transient levels defined for individual conductors/pins and wire bundles given in Tables 22-2 and 22-3, respectively, of DO-160/ED-14, Section 22, using the installation descriptions provided in Section 7.a.2.(c) of ARP5413 as a guide instead of an aircraft test. However, this cannot be done by comparison with the guidance of 7.a.2(c) by itself. Substantiating evidence must be provided to validate the selected TCLs/ETDLs.

The "substantiating evidence" noted above may be references to previous aircraft test data, detailed review of the installation, or analysis based on first principles of coupling physics, to predict the ATLs in the wiring installations being certified. This represents a reduction in the rigor of compliance for Level A display systems as compared with Level A control systems.

Whatever verification methods are proposed should be described in the Certification Plan and presented to the certifying authorities for review and approval prior to proceeding.

NOTE: Control system failures and malfunctions can more directly and abruptly contribute to a catastrophic event than display system failures and malfunctions. It is, therefore, appropriate to require a more rigorous Lightning verification method for Level A control systems than for Level A display systems.

Because the loss of a Level B and/or Level C system has less effect on safe operation of the aircraft, default test levels have been provided in ARP5413. This reduction in rigor is based on the following:

1. Loss of Level B and/or Level C systems, by definition, does not lead directly to loss of the aircraft.

2. The default levels are based on measurements of induced transients during full vehicle tests of conventional metal aircraft, and margins of 1.5 to 2 over the average of these measured transients in typical circuits. (Some measured transients have been higher than the default levels.)

When analysis or similarity is used, the level of rigor should be consistent with the level of criticality. For example, the use of similarity for a Level A control system would require a nearly identical installation for a nearly identical system on a nearly identical aircraft. Whereas, for Level B and C systems, a representative installation of a representative system on a representative aircraft is all that is required.

7. (Continued):

These concepts will be elaborated on in the following sections.

NOTE: The following terms are found in Section 7 of ARP5413:

- adversely affected
- sufficiently similar
- minimal differences
- adverse changes
- adverse effects
- substantiating evidence
- timely manner

The detailed meaning of these terms is subjective in nature and will depend upon the system being addressed and the installation affected. It is therefore necessary to define the meanings of these terms with respect to the specific system(s) to be certified and include these, as applicable, in certification plan(s) which are presented to certification authorities for review and approval prior to proceeding with the certification activities proposed in the plan(s).

7.1 Level A Requirements:

The primary concern is the continuation of the Level A function in flight without adverse effects. Any susceptibility cannot affect the safe operation of the aircraft.

Level A functions are further categorized into two groups. One group involves functions for which the pilot will not be part of the operational loop. These are classified as Level A control functions and include FBW and FADEC systems. These systems are usually classified as Level A functions for both IFR and VFR operation.

The second group involves functions for which the pilot will be within the loop through pilot/system information exchange. These are defined as Level A display functions, and include, for example, EFIS and EICAS systems. Some other cockpit displays may also be included in this classification.

If a function is performed by multiple systems, or a single system that includes multiple redundant channels, then loss of one or more of the systems or channels during exposure of the aircraft to lightning shall not result in the loss of the function. It is necessary to keep in mind that lightning strikes may induce similar transients in all channels of a multiple channel system so that similar effects may be experienced in each channel. Therefore, redundancy is usually not sufficient to maintain the function during the lightning event unless it can be shown that the common induced effects of lightning will not adversely affect each of the redundant systems or channels at the same time.

7.1 (Continued):

The acceptance criteria applicable to a specific system depends upon the function being performed by that system. In some cases, some degradation in performance may be acceptable, at least for a limited period of time. For other systems, only a very short upset, within tolerable limits, and recovery without pilot intervention in a limited time may be accepted. The acceptance criteria is usually developed as an output of the FHA, and is described in the Certification Plan that is recommended in ARP5413, for review and approval by the certifying authorities.

While it is normally desirable to have automatic recovery to normal operation, operational or functional requirements of individual systems may preclude such recovery. While the function may recover eventually, it may not recover in a timely manner or without crew intervention.

7.1.1 Level A Control Systems: An acceptable process for verifying compliance of Level A control systems with the lightning protection requirements is outlined in Figure 2 in ARP5413.

It should be noted that the verification process for Level A control systems is somewhat more rigorous. This process can also be used for all other function classifications (i.e., Level A Display, Level B and Level C).

One type of system, which at first review might be considered as a Level A Control “System”, is the Automatic Flight Control System (AFCS). The term “Automatic Flight Control” is commonly used to define systems, which perform a controlling function with respect to one or more of the primary axes of pitch, roll, or yaw of the aircraft in flight. The main systems, which perform these controlling functions, are AFCS and FBW Flight Control Systems.

One example of the AFCS is the autopilot. The hazard categories assigned to the functions performed by autopilots can range from minor to catastrophic and are very much dependent upon the installation and the amount of control granted to the autopilot system in various aspects of flight. In typical installations an AFCS has varying levels of command over control surface movements and/or power levels, closed loops, system failures may have catastrophic influences such as flight control hardovers. The issues that must be considered in categorizing autopilots and establishing applicable acceptance criteria are whether or not failures, due to a lightning encounter are passive and do not result in an undesired and unmonitored aircraft control surface movement or change in power level. Another consideration in the validation process would be the need to demonstrate that any autopilot failure, due to a lightning encounter does not (1) cause a command to a control surface that exceeds the structural integrity of the aircraft and (2) that the “rate of change” of the flight control servo does not place the aircraft in a position from which the pilot cannot recover. This includes a standard “recognition” time (normally 1 s in landing and 3 s in cruise).

The main purpose of this example is to point out the need to carefully examine the System Safety Analysis from the perspective of the function being performed on the particular aircraft being certified and not just the system by itself when determining the criticality category of any system. Similar reasoning can be used in determining the requirements for any system on the aircraft.

7.1.1 (Continued):

For FBW installations the safety analysis must consider the possibilities and consequences of partial or total loss of function on continued safe flight and landing of the aircraft. A FBW control system must survive a lightning encounter without loss of function and remain operational in a manner, which will allow continued safe flight and landing of the aircraft. Deviations of control and asymmetry of control surfaces such as flaps and slats must be shown to be within acceptable limits.

Lightning protection design for a system may employ partitioning of channels of the systems to aid in the immunity from loss of the total system. However, it should be noted that like redundancy, partitioning, in and of itself, might not provide sufficient protection for functions performed by identical systems.

In the case of redundant systems, an installation using wire bundle and LRU separation can provide a lower probability of equivalent response. Examples are where wire bundles are routed on opposite sides of the aircraft fuselage, under floor boards, or above the head liner, etc. and where LRU positioning is in different equipment bays.

7.1.1.1 Level A Systems - Similarity: The primary difference between Level A control and Level A display is in the amount of change that is acceptable. All changes must be explained to the certification authorities. Changes to TCL and ETDL values for Level A control systems may be acceptable if suitable safety margins remain. In practical applications, greater latitude is allowed in similarity arguments for Level A display systems than for Level A control.

When analysis or similarity is used, the level of rigor is consistent with the level of criticality. For example, the use of similarity for a Level A system performing control functions would require a nearly identical installation for a nearly identical system on a nearly identical aircraft. Whereas, for Level B and C systems, a representative installation of a representative system on a representative aircraft is all that is required.

CAUTION: Similarity is a subjective area and similarity justifications must be negotiated with the cognizant airworthiness certification authorities. While ARP5413 provides a list of points to cover for the assessment, Table 4 illustrates examples of situations where similarity arguments may be considered.

TABLE 4 - Examples of Similarity Applications

	Generally Considered Similar	**Generally Not Considered Similar**
Aircraft Type	A simple stretch Adding winglets, delta fins	General Aviation to Transport aircraft 2-engine narrow body to 4-engine wide body
Equipment Location	Going from an unprotected (external to pressure vessel) to a protected area (internal) Moving away from an aperture	Going from a protected (inside pressure vessel) to an unprotected area (external) Moving to a location near an aperture
Airframe construction	Same material	Different material - dissimilar such as aluminum to composite
Apertures	Deleting a door/window or equivalent apertures Decreasing the largest dimension of equivalent aperture	Addition of a large cargo bay door or other aperture Increasing the largest dimension of an aperture
Systems interfaces	Adding a small number of circuits the same as existing circuits	Changing from analog to digital or vice versa Changing from wire to optical fibers
Wire size and routing	Comparable exposure of wiring Wire runs moving from a less protected area to a more protected area	Changing from wire to optical fiber Wire runs moving from a protected area to a less protected area
Connectors	Going from pigtails to properly terminated backshell Shortening a pigtail Going from a smaller connector to a larger connector as long as the wire bundle does not change	Going from a properly terminated backshell to pigtails Increasing the length of a pigtail Changing from metal to a material with less bulk conductivity (conductive coated plastic/stainless steel)
Wire bundle shielding/Wire type	Going from untwisted wires to twisted Going from unshielded to properly terminated shields Installing a higher performing shield	Going from twisted wires to untwisted Going from shielded to unshielded Installing a lower performing shield
Grounding	Using dedicated returns	Not using dedicated returns
Bonding	**Any change must be reviewed. Assume not OK until proven otherwise.**	
System modification status: Hardware, Software, Firmware	**Any change must be reviewed. Assume not OK until proven otherwise.**	

7.1.2 Level A Display Systems: Methods of achieving compliance of Level A display systems to lightning protection requirements are outlined in Figure 3 in ARP5413.

Based on the fact that display system failures and malfunctions do not contribute as directly or as abruptly to catastrophic failures as do control systems failures, a different verification method is applicable. This method in which verification of TCLs by similarity to previous test data, as represented by the transient levels in Tables 22-2 and 22-3 of DO-160/ED-14, Section 22 in place of full vehicle test or analysis of the present avionics installation, is provided. Selection of the appropriate level(s) from Section 22 is to be substantiated by some analyses or references to test data from similar installations, however.

Level A display systems perform functions with failure condition classifications considered to be catastrophic. However, for Level A Displays, the flight crew is in the loop and the catastrophic event is a result of some action taken by the crew as a result of hazardously misleading or missing information provided by the display. Typical examples of information provided by Level A display systems are attitude, altitude and airspeed. As aircraft size and complexity increase other display systems such as Engine Indication and Crew Alerting Systems (EICAS) could also fall within this classification.

7.2 Level B and Level C Requirements:

The aircraft test or analysis methods used to determine the TCLs and ETDLs for Level A systems are also acceptable for the determination of TCLs and ETDLs for Level B and C systems. Alternately, Level 3 as defined in D0-160/ED-14, Section 22 may be used for most Level B systems. For Level B systems and associated wiring installed in more severe electromagnetic environments such as areas external to the fuselage, areas with composite structures demonstrating poor shielding effectiveness, and other open area, select a level appropriate to the environment.

Level 2 as defined in D0-160/ED-14, Section 22 may be used for most Level C systems. For Level C systems installed in more severe electromagnetic environments such as areas external to the fuselage, areas with composite structures demonstrating poor shielding effectiveness, and other open area, use Level 3.

7.3 Example 1 - System Test Levels Developed from Low Current Pulse Test:

Example 1 utilizes data from aircraft tests on a similar aircraft (see 7.1.1.1 for similarity requirements). The data shown in this example is based on a fictitious light business jet, with primarily metal structure. It is important to remember that this data is simply given as an example to show how the data from a previous aircraft test is used to develop test levels.

The method outlined below provides an example of how aircraft test data can be used to determine the test levels for a Level A (Level A control or a Level A Display Level B or Level C system and associated equipment. However, as has been noted, less rigid methods are available for the determination of Level A Display, Level B and Level C systems test levels than those for Level A control systems. These less rigid methods will be expanded upon further in later sections.

7.3 (Continued):

Usually the test levels are developed by transient analysis testing conducted on either a full aircraft or aircraft section. There are several methods for conducting these type of tests and the procedures are outlined in ARP5416 (Draft). The result of this testing is used to support the development of test levels of installed equipment.

In most cases, this type of data is tabulated to show the following:

a. Worst case coupling (i.e., open circuit voltage/short circuit currents) of various wire routings throughout the aircraft or test article.

b. Effects of wire shielding.

c. The effect of adjacent low impedance conductors.

d. Bulk current measurement to show the expected current flow on wire bundles of various lengths.

By analyzing the tabulated data, test levels for indirect effects tests can be produced for any installed equipment/system if the wire routing and composition of the wire bundle is known.

The results of the lightning transient analysis described above provides information that serves two purposes:

a. Provide voltage and current levels for various types of interconnecting circuits within the airframe.

b. Provide data to determine bulk wire bundle currents in bundles if the routing and number of low impedance conductors are known.

These levels represent the TCLs, which will be induced in interconnecting wiring, and appear at the equipment interfaces. Normally these levels are defined in terms of open circuit voltage (V_{OC}) and the short circuit current (I_{SC}). In accordance with ARP5413, it is also required to establish the ETDL which is the amplitude of voltage and/or current that the equipment installed is required to tolerate and remain operational without damage or system upset. These levels are set higher than the TCLs. The difference between the TCL and ETDL is the margin. This margin will vary depending upon the actual installation and therefore only the TCLs are covered by this analysis.

To develop the TCLs, a comparison is made of the intended installation and the test data from the aircraft test. This comparison is based upon parameters such as the wire routing, number of low impedance conductors in the wire bundles, shielding techniques and overall length. An example of the type of data normally provided by the aircraft test is given in Figure 14 and Tables 5 through 12.

7.3 (Continued):

Figure 14 shows the current values measured in the aircraft test for various lengths of multiple conductor wire bundles, with multiple low impedance conductors routed in exposed areas of the aircraft. For the same exposure area the longer wire runs have much more inductance than the shorter wire runs and therefore have higher impedances at lightning frequencies. Therefore the longer wire runs will have less current induced on them. However, for wire runs which are exposed over their entire lengths, the longer wire runs will have the higher induced currents. For example, the 35-ft. wire bundle might be routed from the nose to the tail for a small business jet and contain anywhere from one to greater than nine low impedance conductors. In the establishment of the test level for the installation a comparison is made of wires of similar lengths and routing along with the number of low impedance conductors then a margin is added to establish the test levels. This data can also be used in the establishment of attenuation values for various waveforms in regard to both low impedance conductors as well as attenuation due to length of the conductors. Table 5 and 6 provide these attenuation values for various wire bundle lengths.

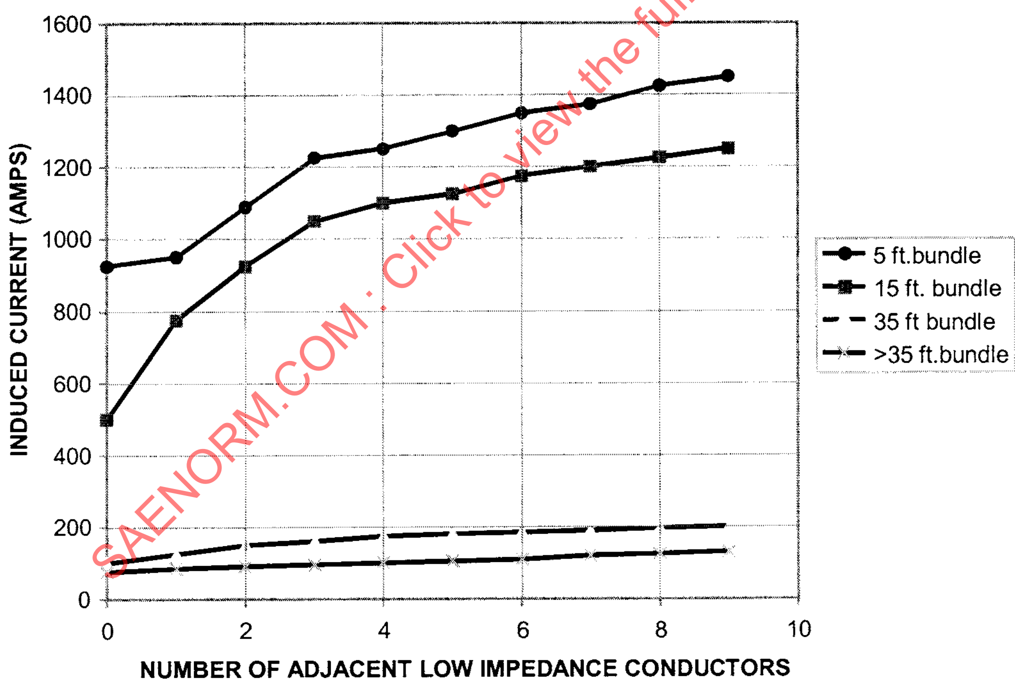


FIGURE 14 - Bulk Wire Bundle Current for Various Wire Bundle Lengths and Adjacent Low Impedance Conductors

In addition, to the Bulk Wire Bundle Currents shown in Figure 14, the aircraft test normally also provides data dealing with the open circuit voltage and short circuit current present at the interfaces of equipment for various routing within the aircraft with similar exposure areas. Tables 7 through 12 provide examples of this type of data. The values are given for both shielded and unshielded configurations.

TABLE 5 - Attenuation Provided by Shielding for Various Wire Lengths

Length of Shielding Run	Waveform 1 Shielding (dB)	Waveform 2 Shielding (dB)	Waveform 3 Shielding (dB)	Waveform 5 Shielding (dB)
0 to 15 Feet	-3.2	-22	-15	-3.2
15 to 35 Feet	-8.0	-19	-21	-3.2
≥ 35 Feet	-3.2	-19	-19	-8.0

TABLE 6 - Attenuation Due to Adjacent Low Impedance Conductors for Various Wire Bundle Lengths

Wire Bundle Length	Number of Adjacent Low Impedance Conductors	Waveform 1 Reduction in Signal Strength (dB)	Waveform 3 Reduction in Signal Strength (dB)
0 - 15 Feet	1	-6.0	-11.0
	3	-10.0	-15.0
	5	-13.0	-15.4
	9	-16.0	-18.0
15 - 35 Feet	1	-2.2	-4.0
	3	-6.0	-10.0
	5	-9.0	-12.0
	9	-12.0	-18.0
≥ 35 Feet	1	-2.3	-3.5
	3	-5.4	-9.0
	5	-8.6	-11.0
	9	-11.0	-13.0

TABLE 7 - Single Shielded Wire Waveform 1 (I_{SC})

AREA	A	B	C	D	E	F	G	H	I
A	665								
B	374	320							
C	650	200	22						
D	688	38	35	22					
E	688	38	35	35	22				
F	N/A	N/A	285	285	340	*			
G	723	728	200	83	83	N/A			
H									
I	N/A	N/A	N/A	250/8	250/8				

NOTES:

N/A NOT APPLICABLE
* Data not available
/ First Number - Externally Mounted Device
Second Number - Internally Mounted Device

TABLE LEGEND:

A FORWARD NOSE AREA
B MID NOSE AREA
C COCKPIT AREA
D AFT CABIN AREA
E FUSELAGE TAIL AREA
F ENGINE
G WING
H LANDING GEAR
I VERTICAL TAIL / HORIZONAL STABILIZER

TABLE 8 - Single Shielded Wire Waveform 2 (V_{OC})

AREA	A	B	C	D	E	F	G	H	I
A	62								
B	102	10							
C	102	15	17						
D	136	34	34	17					
E	136	34	34	34	17				
F	240	240	225	225	225	*			
G	170	71	50	33	33	N/A	33		
H									
I	N/A	307/36	400/16	400/16	400/16				

NOTES:

N/A NOT APPLICABLE
* Data not available
/ First Number - Externally Mounted Device
Second Number - Internally Mounted Device

TABLE LEGEND:

A FORWARD NOSE AREA
B MID NOSE AREA
C COCKPIT AREA
D AFT CABIN AREA
E FUSELAGE TAIL AREA
F ENGINE
G WING
H LANDING GEAR
I VERTICAL TAIL / HORIZONAL STABILIZER

TABLE 9 - Single Shielded Wire Waveform 3 (V_{OC})

AREA	A	B	C	D	E	F	G	H	I
A	266								
B	157	48							
C	198	24	21						
D	239	40	42	21					
E	239	40	42	42	21				
F	420	420	382	382	382	*			
G	270	115	75	225	95	N/A	95		
H									
I	N/A	480/64	688/39	688/39	688/39				

NOTES:

N/A NOT APPLICABLE
* Data not available
/ First Number - Externally Mounted Device
Second Number - Internally Mounted Device

TABLE LEGEND:

A FORWARD NOSE AREA
B MID NOSE AREA
C COCKPIT AREA
D AFT CABIN AREA
E FUSELAGE TAIL AREA
F ENGINE
G WING
H LANDING GEAR
I VERTICAL TAIL / HORIZONAL STABILIZER

FIGURE 10 - Single Unshielded Wire Waveform 1 (I_{SC})

AREA	A	B	C	D	E	F	G	H	I
A	940								
B	940	480							
C	940	480	55						
D	995	55	50	55					
E	995	55	50	50	55				
F	2000	2000	840	840	2000	*			
G	1045	760	280	120	120	N/A	120		
H									
I	N/A	N/A	N/A	N/A	N/A				

NOTES:

N/A NOT APPLICABLE
* Data not available
/ First Number - Externally Mounted Device
Second Number - Internally Mounted Device

TABLE LEGEND:

A FORWARD NOSE AREA
B MID NOSE AREA
C COCKPIT AREA
D AFT CABIN AREA
E FUSELAGE TAIL AREA
F ENGINE
G WING
H LANDING GEAR
I VERTICAL TAIL / HORIZONAL STABILIZER

TABLE 11 - Single Unshielded Wire Waveform 2 (V_{OC})

AREA	A	B	C	D	E	F	G	H	I
A	780								
B	910	130							
C	910	130	150						
D	1210	300	300	150					
E	1210	300	300	300	150				
F	2130	2130	2000	2000	2000	*			
G	1510	630	500	300	300	N/A	300		
H									
I	N/A	2730/290	2600/160	2600/160	2600/160				

NOTES:

N/A NOT APPLICABLE
* Data not available
/ First Number - Externally Mounted Device
Second Number - Internally Mounted Device

TABLE LEGEND:

A FORWARD NOSE AREA
B MID NOSE AREA
C COCKPIT AREA
D AFT CABIN AREA
E FUSELAGE TAIL AREA
F ENGINE
G WING
H LANDING GEAR
I VERTICAL TAIL / HORIZONAL STABILIZER

TABLE 12 - Single Unshielded Wire Waveform 3 (V_{OC})

AREA	A	B	C	D	E	F	G	H	I
A	1500								
B	1770	270							
C	1770	270	230						
D	2130	360	370	230					
E	2130	360	370	370	230				
F	3670	3670	3400	3400	3400	*			
G	2400	1020	750	850	850	N/A	850		
H									
I	N/A	4270/570	4000/300	4000/300	4000/300				

NOTES:

N/A NOT APPLICABLE
* Data not available
/ First Number - Externally Mounted Device
Second Number - Internally Mounted Device

TABLE LEGEND:

A FORWARD NOSE AREA
B MID NOSE AREA
C COCKPIT AREA
D AFT CABIN AREA
E FUSELAGE TAIL AREA
F ENGINE
G WING
H LANDING GEAR
I VERTICAL TAIL / HORIZONAL STABILIZER

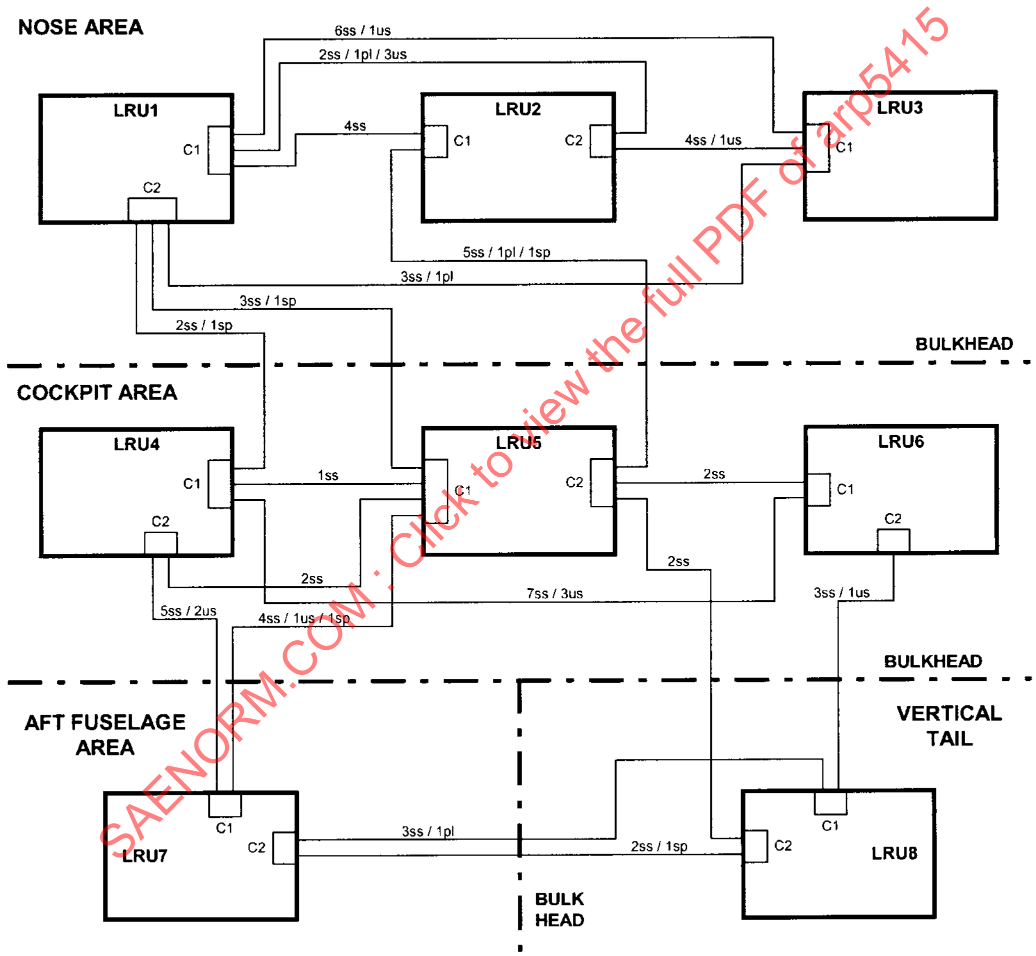
7.3 (Continued):

As stated above, in establishing the test levels using this type of data a comparison is made of the routing of the wires and then the level provided in the table is multiplied by the number of wires in the bundle to establish the current value. In regard to the voltage level, the worst case value for all the various routing contained within the wire bundle is used for the test value.

The following example is based upon a simple system but as stated above the method is the same regardless of the type of system.

7.3 (Continued):

Figure 15 provides the block diagram of the installed system. In using the data from the aircraft testing, it is required that the block diagram includes the number of wires into each connector, the number of low impedance conductors that are contained in each branch and the length of each branch. Figure 14 can then be used, in conjunction with Tables 5 through 12 to develop the TCLs for each connector.



SYMBOL	DESCRIPTION
ss	Single Shielded Wire
sp	Shielded Pair
us	Unshielded Wire
pl	Power Line

FIGURE 15 - Example Avionics Installation

7.3 (Continued):

In the example given the following assumptions concerning the length of the wire bundles are made:

Wire bundles running within the Nose Area: ≤5 ft
Wire bundles running within the Cockpit Area: ≤5 ft
Wire bundles running from Nose Area to Cockpit Area: 5 ft ≤ X ≤ 15 ft
Wire bundles running from Fuselage Tail Area to Nose Area: ≥35 ft
Wire bundles running from the Fuselage Area to Cockpit Area: 15 ft ≤ X ≤ 35 ft
Wire bundles running within the Fuselage Tail Area: 5 ft ≤ X ≤ 15 ft
Wire bundles running from Vertical Tail to Fuselage Tail Area: 15 ft ≤ X ≤ 35 ft
Wire bundles running from Vertical Tail to Cockpit Area: ≥35 ft

Based upon these assumptions, the requirement for each connector can be established:

Since these wire bundles contain shielded wires then Waveform 1 and Waveform 3 are applicable (NOTE: In other installations other waveforms may apply).

It should be noted that the margin selected (i.e., 6 dB) for the various examples is simply a level selected and in no way should be taken as a requirement. Other margins have been accepted by the authorities to show compliance.

Waveform 1 requirements:

LRU1 connector C1:

Total Low Impedance Conductors routed within the Nose Area:
= 6ss + 2ss+ 4ss + 1pl
= 13 wires @ 320 A (from Table 7)
= 4160 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -16 dB (from Table 6)
0.158 * 4160 = 660 A
Add 6 dB for margin: Total Test Current required: 1320 A

LRU1 connector C2:

Total Low Impedance Conductors routed within the Nose Area:
= 3ss +1pl
= 4 wires @ 320 A (from Table 7)
= 1280 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -10 dB (from Table 6)
Total Current for these lines = 0.316 * 1280 = 405 A

7.3 (Continued):

Because this LRU has wires routed from the Nose to the Cockpit a similar analysis must be conducted on those lines:

Total Low Impedance Conductors routed from Nose to Cockpit:
= 5ss + 2sp
= 7 wires @ 200 A (from Table 7)
= 1400 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤ 5 ft: -13 dB (from Table 6)
0.224 * 1400 = 313 A
Total current for wires running into LRU1 connector C2 = 405 A + 313 A = 718 A
Add 6 dB for margin: Total Test Current required: 1436 A

LRU2 connector C1:

Total Low Impedance Conductors routed within the Nose Area:
= 4ss
= 4 wires @ 320 A (from Table 7)
= 1280 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -10 dB (from Table 6)
Total Current for these wires = 0.316 * 1280 = 404 A

Because this LRU has wires routed from the Nose to the Cockpit a similar analysis must be conducted on those lines:

Total Low Impedance Conductors routed from Nose to Cockpit:
= 5ss + 1sp + 1pl
= 7 wires @ 200 A (from Table 7)
= 1400 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -13 dB (from Table 6)
= 0.224 * 1400 = 314 A
Total current for wires running into LRU2 connector C1 = 404 A + 314 A = 717 A
Add 6 dB for margin: Total Test Current required: 1434 A

7.3 (Continued):

LRU2 connector C2:

Total Low Impedance Conductors routed within the Nose Area:
= 4ss + 2ss + 1pl
= 7 wires @ 320 A (from Table 7)
= 2240 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -13 dB (from Table 6)
Total Current running into LRU2 connector C2 = 0.224 * 2240 = 502 A
Add 6 dB for margin: Total Test Current required: 1004 A

LRU3 connector C1:

Total Low Impedance Conductors routed within the Nose Area:
= 13ss + 1pl
= 14 wires @ 320 A (from Table 7)
= 4480 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -16 dB (from Table 6)
Total Current for these lines = 0.158 * 4480 = 708 A
Add 6 dB for margin: Total Test Current required: 1416 A

LRU4 connector C1:

Total Low Impedance Conductors routed within the Cockpit Area:
= 8ss
= 8 wires @ 22 A (from Table 7)
= 176 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -13 dB (from Table 6)
Total Current for these wires = 0.224 * 176 = 39 A

Because this LRU has wires routed from the Nose to the Cockpit a similar analysis must be conducted on those lines:

Total Low Impedance Conductors routed from Nose to Cockpit:
= 2ss + 1sp
= 3 wires @ 200 A (from Table 7)
= 600 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -10 dB (from Table 6)
= 0.316 * 600 = 190 A
Total current for wires running into LRU4 connector C1 = 39 A + 190 A = 229 A
Add 6 dB for margin: Total Test Current required: 458 A

7.3 (Continued):

LRU4 connector C2:

Total Low Impedance Conductors routed within the Cockpit Area:
= 2ss
= 2 wires @ 22 A (from Table 7)
= 44 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -6 dB (from Table 6)
Total Current for these wires = 0.5 * 44 = 22 A

Because this LRU has wires routed from the Cockpit to the Fuselage Tail Area a similar analysis must be conducted on those lines:

Total Low Impedance Conductors routed from Cockpit to Fuselage Tail Area:
= 5ss
= 5 wires @ 35 A (from Table 7)
= 175 A
With attenuation due to adjacent low impedance conductors for wire bundle 15 ft ≤ X ≤ 35 ft: -9 dB (from Table 6)
= 0.355 * 175 = 59 A
Total current for wires running into LRU4 connector C2 = 22 A + 59 A = 81 A
Add 6 dB for margin: Total Test Current required: 162 A

LRU5 connector C1:

Total Low Impedance Conductors routed within the Cockpit Area:
= 3ss
= 3 wires @ 22 A (from Table 7)
= 66 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -10 dB (from Table 6)
Total Current for these wires = 0.316 * 66 = 21 A

Because this LRU has wires routed from the Cockpit to the Fuselage Tail Area a similar analysis must be conducted on those lines:

Total Low Impedance Conductors routed from Cockpit to Fuselage Tail Area:
= 4ss + 1sp
= 5 wires @ 35 A (from Table 7)
= 175 A
With attenuation due to adjacent low impedance conductors for wire bundle 15 ft ≤ X ≤ 35 ft: -9 dB (from Table 6)
= 0.355 * 175 = 59 A

7.3 (Continued):

Because this LRU has wires routed from the Cockpit to the Nose Area a similar analysis must be conducted on those lines:

Total Low Impedance Conductors routed from Cockpit to the Nose Area:
= 3ss + 1sp
= 4 wires @ 200 A (from Table 7)
= 800 A
With attenuation due to adjacent low impedance conductors for wire bundle 15 ft ≤ X: -10 dB (from Table 6)
= 0.316 * 800 = 253 A
Total current for wires running into LRU 5 connector C1 = 21 A + 59 A + 253 A = 333 A
Add 6 dB for margin: Total Test Current required: 666 A

LRU5 connector C2:

Total Low Impedance Conductors routed within the Cockpit Area:
= 2ss
= 2 wires @ 22 A (from Table 7)
= 44 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -6 dB (from Table 6)
Total Current for these wires = 0.5 * 44 = 22 A

Because this LRU has wires routed from the Cockpit to the Vertical Tail Area a similar analysis must be conducted on those lines:

Total Low Impedance Conductors routed from Cockpit to Vertical Tail Area:
= 2ss
= 2 wires @ 43 A (from Table 7); Note: since there is no data directly from the Vertical Tail to the cockpit, the current from the Vertical Tail to the Tail Fuselage (8 A/Internal device) is added to the current from the Tail Fuselage Area to the Cockpit (35 A).
= 86 A
With attenuation due to adjacent low impedance conductors for wire bundle ≥35 ft: -2.3 dB (from Table 6)
= 0.767 * 86 = 66 A

7.3 (Continued):

Because this LRU has wires routed from the Cockpit to the Nose Area a similar analysis must be conducted on those lines:

Total Low Impedance Conductors routed from Cockpit to the Nose Area:
= 5ss + 1pl + 1sp
= 7 wires @ 200 A (from Table 7)
= 1400 A
With attenuation due to adjacent low impedance conductors for wire bundle 15 ft ≤ X: -13 dB (from Table 6)
Total current for these wires = 0.224 * 1400 = 314 A
Total current for wires running into LRU5 connector C2 = 22 A + 66 A + 314 A = 402 A
Add 6 dB for margin: Total Test Current required: 804 A

LRU6 connector C1:

Total Low Impedance Conductors routed within the Cockpit Area:
= 2ss + 7ss
= 9 wires (≤5 ft) @ 22 A (from Table 7)
= 198 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -16 dB (from Table 6)
Total Current for wires running into LRU6 connector C1 = 0.158 * 198 = 31 A
Add 6 dB for margin: Total Test Current required: 62 A

LRU6 connector C2:

Total Low Impedance Conductors routed from Cockpit to Vertical Tail Area:
= 3ss
= 3 wires @ 43 A (from Table 7); Note: since there is no data directly from the Vertical Tail to the cockpit, the current from the Vertical Tail to the Tail Fuselage (8 A/internal device) is added to the current from the Tail Fuselage Area to the Cockpit (35 A).
= 129 A
With attenuation due to adjacent low impedance conductors for wire bundle ≥35 ft: -5.4 dB (from Table 6)
Total current for wires running into LRU6 connector C2 = 0.537 * 129 = 69 A
Add 6 dB for margin: Total Test Current Required: 138 A

7.3 (Continued):

LRU7 connector C1:

Total Low Impedance Conductors routed from Fuselage Tail Area to the Cockpit Area:
= 9ss + 1sp
= 10 wires @ 35 A (from Table 7)
= 350 A
With attenuation due to adjacent low impedance conductors for wire bundle (15 ≤ X ≤ 35 ft): -12 dB (from Table 6)
Total Current for wires running into LRU7 connector C1 = 0.25 * 350 = 88 A
Add 6 dB for margin: Total Test Current Required: 176 A

LRU7 connector C2:

Total Low Impedance Conductors routed from Fuselage Tail Area to the Vertical Tail Area:
= 5ss + 1pl + 1sp
= 7 wires @ 8 A (from Table 7/ Internal Device)
= 56 A
With attenuation due to adjacent low impedance conductors for wire bundle 15 ft ≤ X ≤ 35 ft: -9 dB (from Table 6)
Total Current for the wires running into LRU7 connector C2 = 0.355 * 56 = 20 A
Add 6 dB for margin: Total Test Current Required: 40 A

LRU8 connector C1:

Total Low Impedance Conductors routed from the Vertical Tail Area to the Cockpit Area:
= 3ss
= 3 wires @ 43 A (from Table 7); Note: since there is no data directly from the Vertical Tail to the cockpit, the current from the Vertical Tail to the Tail Fuselage (8 A/internal device) is added to the current from the Tail Fuselage Area to the Cockpit (35 A).
= 129 A
With attenuation due to adjacent low impedance conductors for wire bundle ≥35 ft: -5.4 dB (from Table 6)
Total Current for these wires = 0.537 * 129 = 69 A

7.3 (Continued):

Because this LRU has wires routed from the Vertical Tail Area to the Fuselage Tail Area a similar analysis must be conducted on those lines:

Total Low Impedance Conductors routed from Vertical Tail Area to the Fuselage Tail Area:
= 3ss + 1pl
= 4 wires @ 8 A (from Table 7/Internal Device)
= 32 A
With attenuation due to adjacent low impedance conductors for wire bundle 15 ft $\leq$ X $\leq$ 35: -6 dB (from Table 6)
Total current for these wires = 0.5 * 32 = 16 A
Total current for wires running into LRU8 connector C1 = 69 A + 16 A = 85 A
Add 6 dB for margin: Total Test Current required: 170 A

LRU 8 connector C2:

Total Low Impedance Conductors routed the Vertical Tail Area to the Cockpit Area:
= 3ss
= 3 wires @ 43 A (from Table 7); Note: since there is no data directly from the Vertical Tail to the cockpit, the current from the Vertical Tail to the Tail Fuselage (8 A/internal device) is added to the current from the Tail Fuselage Area to the Cockpit (35 A).
= 129 A
With attenuation due to adjacent low impedance conductors for wire bundle $\geq$35 ft: -5.4 dB (from Table 6)
Total Current for these wires = 0.537 * 129 = 69 A

Because this LRU has wires routed from the Vertical Tail Area to the Fuselage Tail Area a similar analysis must be conducted on those lines:

Total Low Impedance Conductors routed from Vertical Tail Area to the Fuselage Tail Area:
= 2ss + 1sp
= 3 wires @ 8 A (from Table 7/Internal Device)
= 24 A
With attenuation due to adjacent low impedance conductors for wire bundle 15 ft $\leq$ X $\leq$ 35: -6 dB (from Table 6)
Total current for these wires = 0.5 * 32 = 12 A
Total current for wires running into LRU8 connector C2 = 69 A + 12 A = 81 A
Add 6 dB for margin: Total Test Current required: 162 A

7.3 (Continued):

Waveform 3 requirements:

This same analysis must be accomplished for Waveform 3, but since the process is exactly the same, only a limited amount of examples will be provided showing how the levels are developed:

LRU1 connector C1:

Total Low Impedance Conductors routed within the Nose Area:
= 6ss + 2ss + 4ss + 1pl
= 13 wires @ 48 A (from Table 9)
= 624 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -18 dB (from Table 6)
= 0.126 * 624 = 81 A
Add 6 dB for margin: Total Test Current required: 162 A

LRU1 connector C2:

Total Low Impedance Conductors routed within the Nose Area:
= 3ss + 1pl
= 4 wires @ 48 A (from Table 9)
= 192 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -15.4 dB (from Table 6)
Total Current for these lines = 0.170 * 192 = 33 A

Because this LRU has wires routed from the Nose to the Cockpit a similar analysis must be conducted on those lines:

Total Low Impedance Conductors routed from Nose to Cockpit:
= 5ss + 2sp
= 7 wires @ 24 A (from Table 9)
= 168 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -15.4 dB (from Table 6)
= 0.170 * 168 = 29 A
Total current for wires running into LRU1 connector C2 = 33 A + 29 A = 62 A
Add 6 dB for margin: Total Test Current required: 124 A

7.3 (Continued):

LRU2 connector C1:

Total Low Impedance Conductors routed within the Nose Area:
= 4ss
= 4 wires @ 48 A (from Table 9)
= 192 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -15 dB (from Table 6)
Total Current for these wires = 0.178 * 192 = 34 A

Because this LRU has wires routed from the Nose to the Cockpit a similar analysis must be conducted on those lines:

Total Low Impedance Conductors routed from Nose to Cockpit:
= 5ss + 1sp + 1pl
= 7 wires @ 24 A (from Table 9)
= 168 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -15.4 dB (from Table 6)
= 0.170 * 168 = 29 A
Total current for wires running into LRU connector C1 = 34 A + 29 A = 63 A
Add 6 dB for margin: Total Test Current required: 126 A

LRU5 connector C1:

Total Low Impedance Conductors routed within the Cockpit Area:
= 3ss
= 3 wires @ 21 A (from Table 9)
= 63 A
With attenuation due to adjacent low impedance conductors for wire bundle ≤15 ft: -15 dB (from Table 6)
Total Current for these wires = 0.178 * 63 = 11 A

Because this LRU has wires routed from the Cockpit to the Fuselage Tail Area a similar analysis must be conducted on those lines:

Total Low Impedance Conductors routed from Cockpit to Fuselage Tail Area:
= 4ss + 1sp
= 5 wires @ 42 A (from Table 9)
= 210 A
With attenuation due to adjacent low impedance conductors for wire bundle 15 ft ≤ X ≤ 35 ft: -12 dB (from Table 6)
= 0.251 * 210 = 53 A

7.3 (Continued):

Because this LRU has wires routed from the Cockpit to the Nose Area a similar analysis must be conducted on those lines:

Total Low Impedance Conductors routed from Cockpit to the Nose Area:
= 3ss + 1sp
= 4 wires @ 24 A (from Table 9)
= 96 A
With attenuation due to adjacent low impedance conductors for wire bundle 15 ft ≤ X: -15 dB (from Table 6)
= 0.178 * 96 = 17 A
Total current for wires running into LRU5 connector C1 = 11 A + 53 A + 17 A = 81 A
Add 6 dB for margin: Total Test Current required: 162 A

LRU8 connector C2:

Total Low Impedance Conductors routed the Vertical Tail Area to the Cockpit Area:
= 3ss
= 3 wires @ 39 A (from Table 9/Internal Device)
= 117 A
With attenuation due to adjacent low impedance conductors for wire bundle ≥35 ft: -9 dB (from Table 6)
Total Current for these wires = 0.355 * 117 = 42 A

Because this LRU has wires routed from the Vertical Tail Area to the Fuselage Tail Area a similar analysis must be conducted on those lines:

Total Low Impedance Conductors routed from Vertical Tail Area to the Fuselage Tail Area:
= 2ss + 1sp
= 3 wires @ 39 A (from Table 9/ Internal Device)
= 117 A
With attenuation due to adjacent low impedance conductors for wire bundle 15 ft ≤ X ≤ 35: -10 dB (from Table 6)
Total current for these wires = 0.316 * 117 = 40 A
Total current for wires running into LRU8 connector C2 = 42 A + 40 A = 82 A
Add 6 dB for margin: Total Test Current required: 164 A

A summary of these current levels for Waveform 1 and Waveform 3 are provided in Table 13 In addition, the data from the aircraft test can also be analyzed to determine what the voltage limitation should be when accomplishing the testing. As stated at the beginning of the analysis the worst case open circuit voltage of the unshielded configuration of any of the wire routings should be used as a voltage limitation level (with a 6 dB margin). For the example provided this open circuit voltage is taken directly from Table 11 (with a 6 dB margin) for the worst case for each of the routings analyzed.

TABLE 13 - Summary of Current Levels for Example A

LRU	CONNECTOR C1 WAVEFORM 1 (current/voltage)	CONNECTOR C2 WAVEFORM 1 (current/voltage)	CONNECTOR C1 WAVEFORM 3 (current/voltage)	CONNECTOR C2 WAVEFORM 3 (current/voltage)
1	1320/260	1436/260	162/260	124/260
2	1434/260	1004/260	126/260	114/260
3	1416/260	N/A	170/260	N/A
4	458/300	162/600	84/600	130/600
5	666/600	804/600	162/600	186/600
6	62/600	138/600	48/600	84/600
7	176/600	40/320	106/320	138/320
8	170/600	162/600	182/600	164/600

7.3 (Continued):

It should be noted that all the requirements are based on the 200 kA initial strike. This method allows for testing of the single stroke as well as the multiple stroke. Under this method the follow on pulses are defined as 1/4 amplitude of the initial pulse (i.e., one 200 kA pulse followed by thirteen 50 kA pulses). If multiple stroke testing is to be accomplished separately, then the first pulse would be based upon the 'D' waveform (100 kA) and the follow on pulses would be 1/2 amplitude of the initial multiple stroke pulse (i.e., one 100 kA pulse followed by thirteen 50 kA pulses).

7.4 Example 2 – System Test Levels Developed from Low Current Pulse Test:

Example 2 shows the development of TCLs using a combination of mathematical analysis and low current pulse test to provide the aircraft data.

This example deals with an installation where some data are available from testing of similar aircraft but the installation also contains elements for which such test data are not transferable. One such instance might be a FADEC installation, where the FADEC computers are not located on the engine itself but rather within the aircraft fuselage. The engines are mounted on the fuselage with all of the sensors mounted on the engine and cabling is routed through the pylon firewall and into the fuselage. The wire bundles to be used are all overbraided. The overbraid, as well as the individual wire shields, are terminated in the connector backshell and controlled by an electrical bonding requirement. In the development of the threat levels for the engine FADEC system, an analysis is performed on the installation. This analysis examined all of the conductors (engine beam, hydraulic lines, wire bundles, etc.) which pass through the firewall. This was accomplished to determine the physical area available to carry the lightning current from the engine into the fuselage during a swept stroke attachment to the engine. Since the engines are located in Zone 2, the requirement is considered to be 100 kA (i.e., engine swept stroke attachment and aft aircraft detachment).

7.4 (Continued):

It is possible to only look at the physical dimension because the majority of the energy from a lightning strike (current component A) is contained within the lower frequency spectrum and the skin effect is minimized (i.e., current division closely approaches that of a DC current).

Figure 16 shows the block diagram of the FADEC system that is installed on the aircraft and Figure 17 shows the pylon firewall with all of the interconnecting lines. Table 14 provides the effective cross sectional area of all these interconnecting lines/devices.

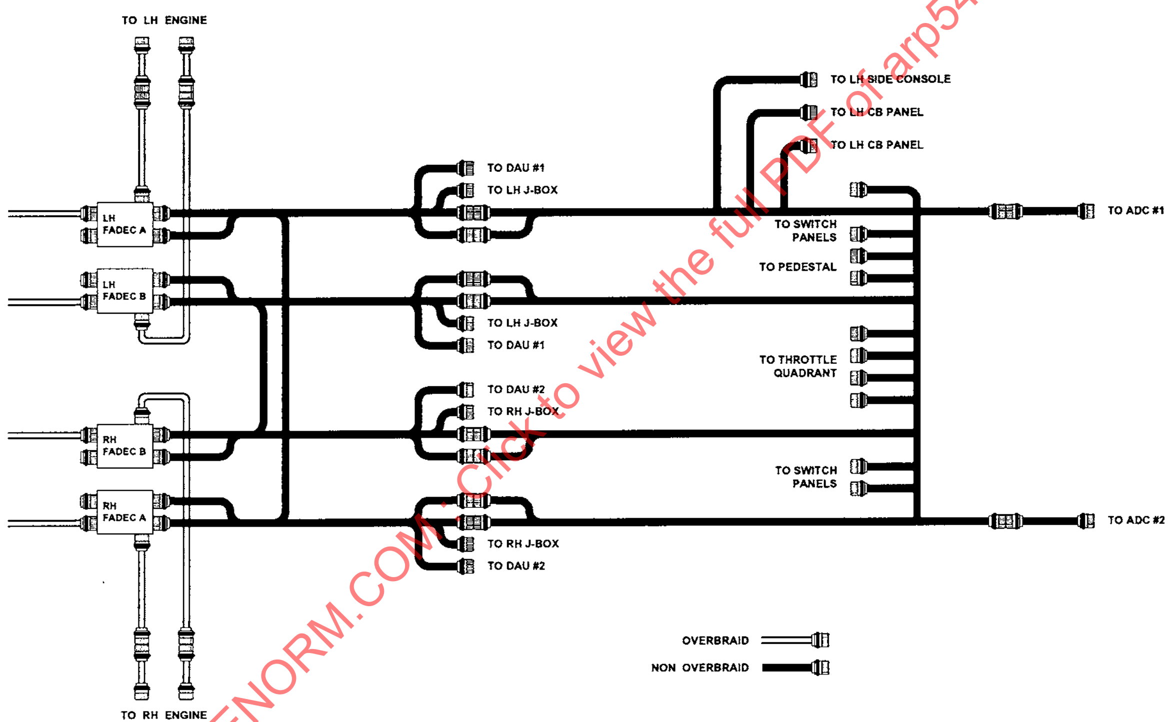


FIGURE 16 - FADEC System Block Diagram

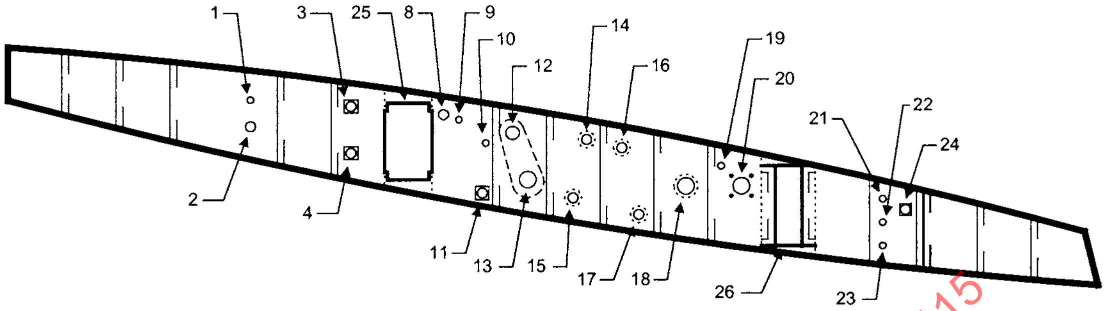


FIGURE 17 - Fire Wall Penetration

TABLE 14 - Fire Wall Penetration and Effective Cross Sectional Area (Skin Effect)

Pylon Firewall Penetration Description	Tube Diameter (Diameter in inches)	Total Effective Cross Sectional Area (in square inches)	% of Effective Cross Sectional Area
1) Fuel Line Motive Flow	0.625	0.165	2.664
2) Fuel Line Engine Feed	1.00	0.283	4.569
3) FADEC "B" (External Overbraid)	0.80	0.220	3.552
3a) FADEC "B" (Internal Wires)	23 wires, each 0.085	0.131	2.115
4) DAU (External Overbraid)	0.80	0.220	3.552
4a) DAU (Internal Wires)	23 wires, each 0.085	0.131	2.115
8) Hydraulic Pressure	0.625	0.165	2.664
9) Fire Extinguisher	0.75	0.204	3.294
10) Hyd. Drain	0.25	0.047	0.759
11) Hyd. Suction	1.00	0.283	4.569
12) Engine Anti-Ice	1.00	0.283	4.569
13) LP Bleed	2.00	0.597	9.638
14) FADEC "A" (External Overbraid)	0.80	0.220	3.552
14a) FADEC "A" (Internal Wires)	23 wires, each 0.085	0.131	2.115
15) Main Engine Bundle (Overbraid)	0.50	0.126	2.034
15a) Main Engine Bundle (Internal Wires)	12 wires, each 0.085	0.068	1.098
16) Active Mount (Overbraid)	0.80	0.220	3.552
16a) Active Mount (Internal Wires)	23 wires, each 0.085	0.131	2.115
17) Active Mount (Overbraid)	0.50	0.126	2.034
17a) Active Mount (Internal Wires)	12 wires, each 0.085	0.068	1.098
18) HP Bleed	1.50	0.440	7.104

TABLE 14 - Fire Wall Penetration and Effective Cross Sectional Area (Skin Effect) (Continued)

Pylon Firewall Penetration Description	Tube Diameter (Diameter in inches)	Total Effective Cross Sectional Area (in square inches)	% of Effective Cross Sectional Area
19) Service Air	0.50	0.126	2.034
20) ATS	2.00	0.597	9.638
21) Thrust Reverser Hyd. Press.	0.375	0.086	1.388
22) Thrust Reverser Hyd. Return	0.375	0.086	1.388
23) Thrust Reverser Hyd. Latch	0.25	0.047	0.759
24) Thrust Reverser Elec. Bundle (Overbraid)	0.75	0.204	3.294
24a) Thrust Reverser Elec. Bundle (Internal Wires)	20 wires, each 0.085	0.113	1.824
25) FWD Beam Bonding Jumper "A"	0.637	0.169	2.728
26) FWD Beam Bonding Jumper "B"	0.637	0.169	2.728
27) AFT Beam Bonding Jumper "A"	0.637	0.169	2.728
28) AFT Beam Bonding Jumper "B"	0.637	0.169	2.728
Totals		6.194	100.00

7.4 (Continued):

The development of the threat levels for the engine to the FADEC wire bundles, as mentioned above, is based upon:

1. The physical area available to carry the lightning current between the aircraft and engine, and
2. the FADEC wire bundle's percentage of that area.

The percentage of the FADEC's cross-sectional area in comparison with the total can then be used to determine the percentage of the lightning current that will flow on the FADEC wire bundle.

In order to make this analysis as simple as possible, several assumptions are made:

1. All interfaces are metal to metal.
2. All the materials are the same (i.e., same conductivity).
3. All the conductors are electrically bonded at the firewall interface.
4. All of the tubes and overbraid have a skin thickness of 0.1 inch.

7.4 (Continued):

This will result in a fairly even distribution of the lightning current. Another important consideration are the engine beams. Since these beams are of a large area, it is natural to assume that they would carry the majority of the current, engine beams are normally connected by the use of bonding jumpers across the upper and lower section of the forward and aft attachment points and therefore only the area of the bonding jumpers are used in the calculation.

The calculation of the various tubes are based upon the 'metallic' physical area available for current flow and does not incorporate any current carrying ability of the fluids within the tubes (i.e., hydraulic or fuel). In addition, the electrical bundles physical area is calculated from both the effective physical cross-sectional area of the overbraid and the combined effective physical cross-sectional area of the wire bundle contained within the overbraid.

The formula used to calculate the effective cross sectional area of the tubes is equal to the cross sectional area of the outer tube minus the cross sectional area of the inter tube as shown in Figure 18.

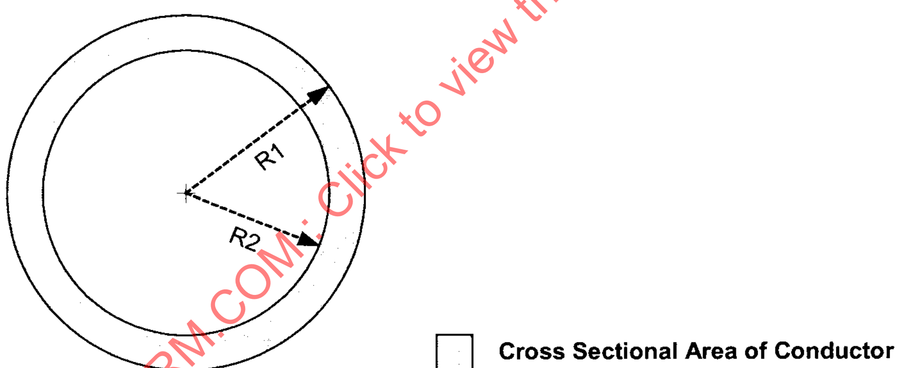


FIGURE 18 - Effective Cross Sectional Area of a Tube

As can be seen from Table 14, the FADEC "A" wire bundle has an outer over-braid effective cross sectional area of 0.22 in^2 which is 3.552% of the total area and the internal wire bundle shields have an effective cross sectional area of 0.131 in^2 which is 2.115%. When these two are added together, the total of 5.667% represents the percentage of current that will flow on the FADEC "A" wire bundle during a lightning strike.

7.4 (Continued):

Since all the conductors are used in the calculation, the amount of current flowing on the FADEC “A” wire bundle is:

$$I_{FADEC} = I_T * (\%OB + \%IW) \qquad \text{(Eq. 11)}$$

where:

I_{FADEC} = Current on FADEC “A”, in amperes
I_T = Total Current Available, in amperes
%OB = FADEC “A” Over-braid percentage of total cross sectional area
%IW = FADEC “A” Internal Wire Bundle percentage of total cross sectional area

Therefore:

I_{FADEC} = 100,000 * (3.552% + 2.115%)
= 100,000 * (5.667%)
= 5667 A

The test level for testing the entire wire bundle would then be 5667 A or 5.667 kA.

If the wire bundle was tested without the over-braid then the test level would be:

$I_{Internal\ wire\ bundle}$ = IT * (%IW)
$I_{Internal\ wire\ bundle}$ = 100,000 * (2.115%)
$I_{Internal\ wire\ bundle}$ = 2115 A = 2.115 kA

The same analysis would then be performed on FADEC “B”.

It should be noted that this analysis is extremely conservative due to the fact that it is very unlikely that if the engine did have a direct swept stroke attachment that all of the current would pass through the firewall. In most cases the majority of the current would exit out of the aft section of the engine and only the current due to the magnetic field coupling would flow on the FADEC wire bundles. As a result of this method being so conservative, no margin should be necessary in applying the test levels.

7.4.1 FADEC Computers to the Aircraft and FADEC to FADEC: In the determination of the threat levels for the wire bundles that are routed from the FADEC to the other areas of the aircraft as well as those which run between the FADEC units, a comparison was made based upon wire routing, number of low impedance conductors in the wire bundles, shielding techniques and overall length. This method is described in detail in the above sections. However, for this case the use of the data provided in Figure 14 can be used. Figure 14 shows the current values measured in the aircraft test for various lengths of multiple conductor wire bundles routed in exposed areas of the aircraft. For example, if 35 ft wire bundles are routed along the fuselage wall directly under the windows and around the door and escape hatch which expose them to the maximum amount of coupling and while for the wire bundles in this example, the FADEC wire bundles are routed under the floor and against the fuselage wall providing much greater shielding. Data taken in the aircraft test can show a comparison between this type of routing and can be used to provide margin for the test levels. In this example we will allow for a reduction of greater than 20 dB of the ATL for wire bundles routed under the floor panels for similar length bundles compared to those routed above the floor and close to the window (10 A versus 100 A for a single shielded conductor). In establishing the test level for the FADEC wire bundles of similar lengths and routing, the worst case coupling of the poorly shielded wire bundle of similar length (200 A) is used to establish the test levels as shown for the FADEC wire bundles attached to J2 and J5. As stated above, these wire bundles are of similar lengths, approximately 35 ft (FADEC “B”) and 33 ft (FADEC “A”) and contain well in excess of 10 low impedance conductors (>21 shielded). The wire bundle connected to J3 (FADEC to FADEC) is overbraided and is routed completely under the floor for both sets of FADECs, which provides excellent shielding. In comparing this wire bundle to the worst case coupling of the aircraft test, the 15-ft wire bundle was used. The J3 bundle is approximately 12 ft in length and contains eight (8) low impedance conductors. When the overbraid is taken into account and only the current flowing on the inner wire bundle is analyzed, the worst case ATL would be approximately 850 A. A test level of 1.1 kA is used for this bundle and with the shielding provided by the bundle’s installation, a margin of well over 10 dB is achieved.

In addition to the individual wire bundles, the 28 VDC power line is tested to simulate a transient on the power bus. This test level was also established from the aircraft test. The data can be analyzed for effect on the loaded system to determine the ATL (in this example we will chose a value of approximately 70 A for Waveform 1) and 6 dB was added to this measured level in determining the test requirement for the FADEC system.

The test levels for Waveform 3 and Waveform 5 can also be developed from the aircraft test in a manner similar to that detailed above. For Waveform 3 the level of 600 V/24 A is used for all wire bundles in the installation because it represents a worst case (with a 6-dB margin) of the levels measured in the aircraft test as shown in Table 9. For Waveform 5 a test level of 150 V/150 A is used for the 28 VDC distribution system and a level of 50 V/300 A and 50 V/200 A are used for the other wire bundles. Waveform 5 seen in this type of installation is a result of diffusion currents through the overbraid or in the case of the 28 VDC system, which is an extremely complex system routed throughout the entire airframe. These values were also taken from the aircraft test and provide approximately 6 dB of margin.

7.4.1 (Continued):

All of the test requirements for the FADEC system interface connectors are shown in Table 15 (only the initial pulse levels are shown, which are based on the 200 kA initial strike). This method allows for testing of the single stroke as well as the multiple stroke. Under this method the follow on pulses are defined as 1/4 amplitude of the initial pulse. If the multiple stroke testing is to be accomplished separately then the first pulse would be based upon the 'D' waveform (100 kA) and the follow on pulses would be 1/2 amplitude of the initial multiple stroke pulse (per environment standard).

TABLE 15 - FADEC Initial Strike, Multiple Stroke and Multiple Burst Test Levels

Waveforms (Vp/Ip)				
Interface Connector	**Multiple Stroke**			**Multiple Burst**
	1	**3**	**5A**	**3**
J2	900/200	600/24	50/300	250/10
J3	900/1100	600/24	50/300	250/10
J4	900/2890	600/24	50/200	250/10
J5 (except 28VDC)	900/200	600/24	50/300	250/10
J5 (28VDC)	900/150	600/24	150/150	250/10

7.5 Example 3 – System Test Levels Developed from Swept Frequency Tests:

This example shows the development of Levels for a Major Derivative of an existing transport category aircraft originally certified several years before. As part of the derivative, a new engine was to be certified on the aircraft. The new engine has a FADEC control with no hydraulic or mechanical backups. This aircraft has never had a Level A control system installed before.

The aircraft is a twin engine commuter turboprop with a seating capacity of 30 passengers.

Along with the 30-passenger version, two minor derivatives of the aircraft were also planned. First, a stretched version with a seating capacity of 38 passengers was planned. And second, a shortened version with 25 passenger capacity was planned.

7.5.1 Early Efforts: The first of the models to certify was the 30-passenger version. This aircraft is a major derivative of an aircraft that was certified more than 10 years ago. The new turboprop engines will use a FADEC controller with no hydraulic or mechanical backups. The previously certified aircraft has never had a Level A control system installed.

Each engine's FADEC was a dual channel controller with the wiring for both channels running from the engine, up the strut, down the wing leading edge and into the forward electronics bay.

Early in the program, a functional hazard assessment (FHA) was performed to establish the criticality category of all aircraft electronic/electrical systems. Due to the fact that the FADECs were full authority and had no hydraulic or mechanical backups, the analysis determined that the FADEC units were performing Level A Control functions.

Also, early in the program, the aircraft was zoned for lightning attachments. The aircraft zones show that the possible lightning strike entry and exit locations that would expose the FADEC system to the highest levels of induced transients are a strike "entering" the propeller on one wing and "exiting" the from the opposite wing tip.

The acceptance criteria for the FADEC system was established from the FHA.

The FADEC system engineer determined the pass/fail criteria for the FADEC to be that the FADEC did not stop functioning correctly.

Minor anomalies such as loss of BITE were acceptable because they would not have any affect on the engine performance in flight.

A Certification Plan was prepared and sent to the FAA for review and approval. The main points in the plan were:

a. The TCLs and ETDLs applicable to the FADEC system were provided in tabular form.

b. Ability of the FADEC system to tolerate the assigned ETDLs would be verified by equipment and system tests at assigned ETDLs two times higher than the ATLs in the FADEC to FADEC wiring (i.e., the intra-engine wiring) and also the FADEC – Aircraft interconnecting wiring.

c. The ATLs would be verified as not exceeding the ETDLs by an aircraft test applied using the Low Level Swept Continuous Wave test with Fourier analysis to translate test results into the equivalent time domain transient voltage (V_{oc}) and current (I_{sc}) waveforms. (Alternately, a low level pulse test could be performed on the aircraft to determine the time domain ATL voltages, currents and waveforms in the system interconnecting wiring.

7.5.2 Setting ETDLs and TCLs: The FADEC controls on these engines had previously been qualification tested in the lab to lightning transients of 600 V. This qualification was done for another manufacturer's aircraft certification. The test reports were reviewed to determine their applicability to the new aircraft certification. The test set up, pass/fail criteria and test anomalies were reviewed. After reviewing the test report for these tests, it was determined that these tests could be used for certifying the new aircraft.

The aircraft manufacturer also had existing aircraft test data from a similar type aircraft that showed they could expect around a 300 V transients at the FADEC without any wire shielding.

Since the FADEC was qualified to a 600 V transient and the expected worst case in flight transient was 300 V, it was decided not to add any wire shielding or additional structural protection to the aircraft.

Because this was a major derivative, the first aircraft available for lightning tests would not be ready until late in the program. This meant that there would be a certain amount of risk in the lightning certification program. The actual worst case in flight transients would not be known until very close to the certification date.

7.5.3 Aircraft Tests: Late in the program, a full aircraft Low Level Swept Continuous Wave test was done to determine the worst case in flight transient on the FADEC.

The aircraft was placed over a ground plane. The aircraft was isolated form the ground plane by placing a sheet of 1 in thick dry plywood under each set of tires. A network analyzer drove the aircraft through an amplifier using the ground plane as the current return. The aircraft was driven at the propeller hub and the opposite wing tip was grounded to the ground plane. This simulated a propeller hub to opposite wing tip lightning attachment.

The network analyzer provided a current to drive the airframe and simultaneously measured the induced open circuit voltage at the FADEC pins versus the drive current. The drive current was swept from 1 kHz to 50 MHz.

The resulting data was a frequency domain response in V/A (i.e., Volts at the FADEC pin versus Amperes into the propeller hub). The test set up allowed real time data reduction to get the time domain transients.

The data was multiplied (in the frequency domain) by the known spectrum of a particular lightning component (in this case current Component A). These lightning spectrums are in A/Hz, so the resulting data is in V/Hz. By inverse Fourier transforming this, the result is the time domain voltage transient the FADEC pin would see due to that particular lightning current Component.

As it turned out, the measured time domain transient at the FADEC pins due to lightning current Component A was about 350 V. Since the FADEC was only qualified to 600 V, there would not be a 6 dB margin.

7.5.3 (Continued):

Several methods of increasing the margin were investigated. First, the FADEC wiring outside the fuselage could be shielded. The lightning test had shown that this wiring accounted for most of the induced voltage. Second, the FADEC could be re-qualified to 700 V thereby increasing the margin to 6 dB. And a final method was to add a metal foil layer to the fiberglass wing leading edge over the FADEC wiring.

The last method was determined to be the most cost-effective solution. A 2-mil aluminum foil was added to the inside surface of the fiberglass wing leading edge. A lightning re-test was conducted and the FADEC transient was found to be reduced to about 250 V. This met the 6-dB margin with something to spare.

7.5.4 Certification: Documentation provided to the certifying authorities (i.e., FAA, JAA) should include the results of both TCL and ETDL verification activities. For the TCL verification, reports should be provided of results of full vehicle test or analyses conducted in accordance with approved Test/Analysis Plans to verify that the ATLs are less than or equal to the TCLs presented in the Certification Plan that has been approved previously by the authorities. For the ETDL verification, the documentation should include damage tolerance and system functional upset test and/or analysis reports, demonstrating that the system tolerates the ETDLs from the damage tolerance and system functional upset standpoints, in accordance with approved Test/Analysis Plans and acceptable criteria set forth in the Certification Plan.

7.6 Example 4 – System Test Levels Developed from Similarity and Analysis:

After the certification of the original 30-passenger model, a stretched version was introduced. The stretch consisted of two 5 ft fuselage plugs. One was added forward of the wings and one aft of the wings. This increased the seating capacity to 38.

A software change in the FADEC increased the maximum thrust rating of the engine. An analysis determined that software change had no effect on the HIRF/Lightning susceptibility of the FADEC. Therefore the original FADEC qualification test data was used.

The main wire runs for the FADEC went from the engine, up the strut, down the wing leading edge and forward inside the fuselage to the forward electronics bay. Therefore, the only change in FADEC wiring for the stretched model was the additional 5 ft of internal wiring in the forward fuselage plug.

The coupling to the internal fuselage wiring was known to be minimal from the lightning ground test on the earlier model. The internal fuselage coupling was no more than 10% of the coupling from the external wiring on a per unit length basis.

An analysis was performed using the data from the earlier model ground test. The analysis showed that the additional 5 ft of internal wiring added about 20 V to the induced transients. Therefore, the maximum lightning transient this model would see in flight would be 270 V. This still met the 6-dB requirement since the FADEC had been qualified to a 600 V transient.

7.6 (Continued):

A certification report including the analysis and previous FADEC qualification test data was prepared and sent to the FAA for approval.

7.7 Example 5 – System Test Levels Developed from Generic Data Base:

An alternative method for the development of test levels for Level A display systems is also provided for in ARP5413. This method uses the generic database provided in DO-160/ED-14, Section 22 for wire bundle test.

In using this method an analysis is performed upon the installation using the guidelines provided in ARP5413.

This example will use the simple system provided in Figure 19. The system is installed in an aircraft with no bulkhead between the radome and avionics bay, all shields and current carrying conductors are terminated at cockpit and aft fuselage bulkheads and equipment connectors. The cockpit has no special shielding measures (i.e., composite glareshield with no embedded screen, no EMI gaskets used around the doors etc.) but all shields are terminated at bulkheads and equipment connectors. The equipment installed in the AFT Fuselage area, as well as the Vertical Tail area are within the metal fuselage area and all shields and current carrying conductors are terminated at various bulkheads and at the equipment connectors.

For the wire bundles routed entirely within the nose area with no other wires coming from other areas Level 4 would be applicable because of the lack of a bulkhead between the radome and the avionics bay. Level 4 provides Waveform 1 levels of 1500 A with a default voltage of 750 V.

For wire bundles routed from the nose to the cockpit as well as those routed within the cockpit, from the cockpit to AFT Fuselage Area or Cockpit to Vertical Tail, Level 3 would be applicable because the current carrying conductors are terminated at the bulkhead and equipment connectors and the equipment is installed within the metal fuselage. Level 3 provides a Waveform 1 level of 600 A with a default voltage of 300 V and with Waveform 3 having a level of 120 A with a default voltage of 600 V.

For wire bundles routed from the AFT Fuselage Area to the Vertical Tail Area, Level 2 would be applicable because the current carrying conductors are terminated at the bulkhead and the equipment is mounted in a well shielded area. Level 2 provides a Waveform 1 level of 250 A/125 V with Waveform 3 having a level of 50 A with a default voltage of 250 V.

The following table provides the test levels based upon the above example using the generic database for the example system.

The margin between ETDLs and TCLs (or ATLs) utilized in these examples is inherent in the selection of the levels from the generic data based upon the guidance given in ARP5413 and as such no additional margin is required.

7.7 (Continued):

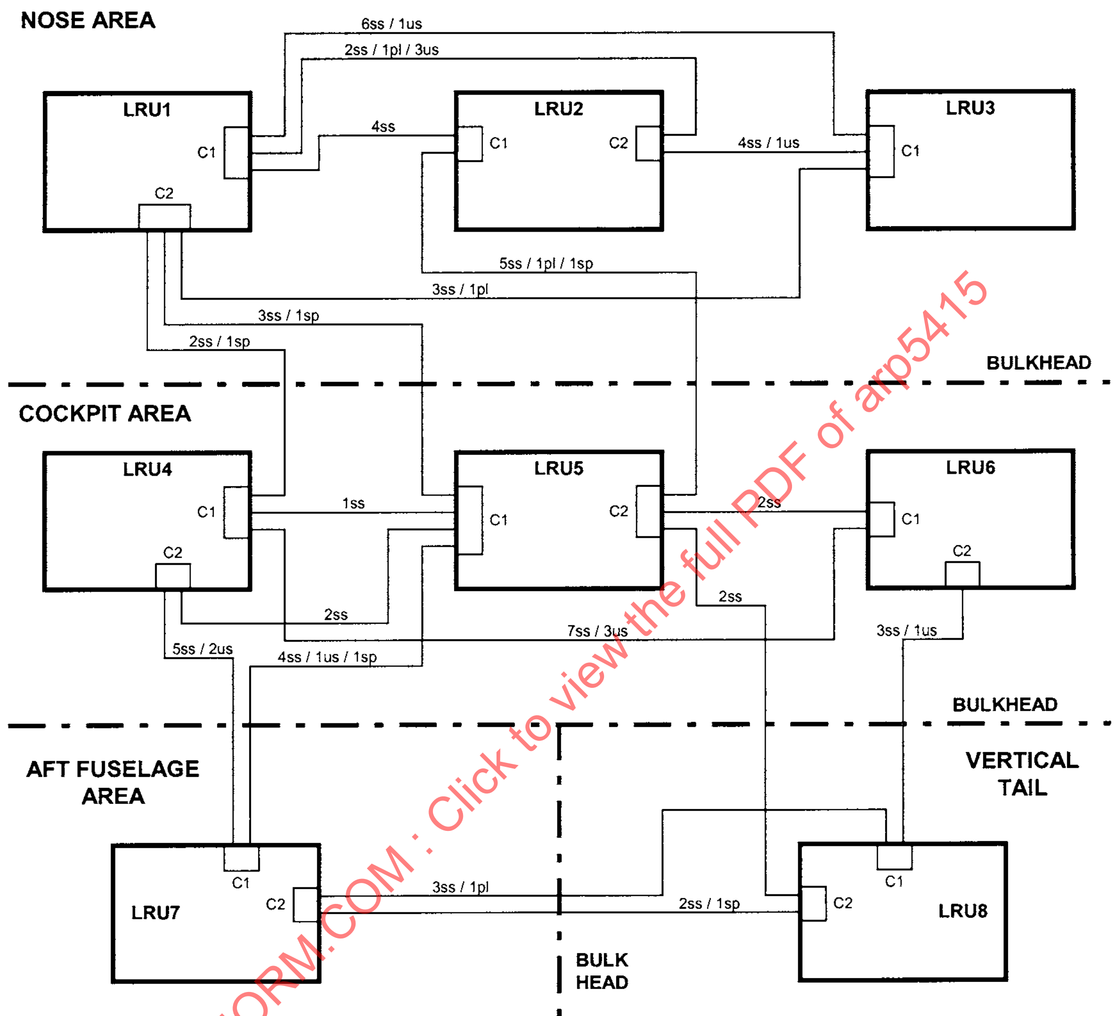
The TCLs and ETDLs described in this example are based on the external environment component A (i.e., 200 kA). This method allows for the single stroke as well as the multiple stroke testing. Under this method the follow on pulses are defined as 1/4 amplitude of the initial pulse. If the testing is to be accomplished separately (i.e., damage tolerance testing accomplished using only single stroke testing and system upset testing accomplished using the multiple stroke/multiple burst environment) then the first pulse for the multiple stroke environment would be based upon the “D” waveform (100 kA) and the follow on pulses would be 1/2 amplitude of the initial multiple stoke pulse.

The transient levels associated with the Components D, D/2 and H external environments are fractions of the component A related transients, as described in ARP5412. As stated above, the component A related transients are employed for damage tolerance verification purposes and all of the transient levels are employed for assessments of system functional upset purposes in the multiple stroke and multiple burst modes, as defined in ARP5412. Specifically, the Component H related transients are applied in the multiple burst mode and the Component A (or Component D) and D/2 related transients are applied in the multiple stroke mode. The amplitudes of the follow on pulses in the multiple stroke mode are determined based upon the predominant coupling mechanism, also as described in ARP5412.

Table 16 shows the ETDLs (and embedded TCLs) test levels for the above example. These were derived from the generic database that was considered applicable for the example system.

TABLE 16 - Summary for Level A Display Functions Example

LRU	CONNECTOR C1 WAVEFORM 1 (V/I)	CONNECTOR C2 WAVEFORM 1 (V/I)	CONNECTOR C1 WAVEFORM 3 (V/I)	CONNECTOR C2 WAVEFORM 3 (V/I)
1	750/1500	750/1500	1500/300	1500/300
2	750/1500	750/1500	1500/300	1500/300
3	750/1500	N/A	1500/300	N/A
4	300/600	300/600	600/120	600/120
5	300/600	300/600	600/120	600/120
6	300/600	300/600	600/120	600/120
7	300/600	125/250	600/120	250/50
8	300/600	300/600	600/120	600/120



SYMBOL	DESCRIPTION
ss	Single Shielded Wire
sp	Shielded Pair
us	Unshielded Wire
pl	Power Line

FIGURE 19 - Example Avionics Installation

7.7 (Continued):

Since the Component H induced voltage transients are of short duration as compared with transit times in typical wire harness, the associated currents are related to the induced voltages by the characteristic impedance's of the wire harnesses. These typically are in the 100 Ω range, however the relationship between Waveform 3 (i.e., traveling wave) voltages and currents in ARP5412 for multiple burst test applications is implied as 25 Ω, resulting in the ETDL assignment of 600 V/24 A. (NOTE: The frequency of the applied Waveform 3 must be 5 MHz or higher for use in the Multiple Burst application)

For some cases, where a portion of the installation involves very short shielded wire bundles terminated to the airframe, the waveform of the current in the shield can approach current Waveform 6_h (see 4.4.2).

8. MAINTENANCE, SURVEILLANCE, REPAIR AND MODIFICATIONS:

8.1 General:

The lightning maintenance program is developed to ensure that the designed lightning protection is maintained throughout the life of the aircraft. Degradation of the lightning protection should be detectable through scheduled maintenance. The scope and level of the maintenance program depends on the detailed lightning protection design approach and the level of criticality associated with the systems addressed by the maintenance program.

This chapter provides general guidelines on how to define maintenance procedures for aircraft lightning protection features. In keeping with the normal aircraft design and certification process, the aircraft maintenance program should address those features, which are required for the lightning protection scheme of the aircraft and its systems.

This chapter also provides guidelines on lightning protection assurance programs developed to ensure that the defined protection maintenance program adequately detects lightning protection degradation. The section describes the role of engineering validation, tests and surveillance in the lightning protection assurance program.

Section 8.1.1 defines the general terms, which are used in the following sections related to maintenance, repair and modification. Section 8.2 discusses how lightning protection requirements may affect maintenance and repairs. Section 8.3 discusses maintenance for aircraft modifications. Section 8.4 discusses the lightning protection assurance program. Section 8.5 describes test techniques, which may be used for in-service maintenance.

8.1.1 General Definitions: Maintenance actions ensure the continued airworthiness of the aircraft and its systems during in-service operation.

Maintenance is defined as those actions required for restoring or maintaining an item in serviceable condition, including servicing, repair, modification, overhaul, inspection and determination of condition.

8.1.1 (Continued):

This definition of maintenance includes repairs and modifications, but it is useful to define these terms separately, since they are derived differently.

Repair is defined as making an item serviceable by replacing or processing failed or damaged parts. It typically consists of replacing a (damaged) item by another (undamaged) identical or functionally equivalent item.

A Modification is defined as a change or alteration to a part of the aircraft or its systems, which is effected through rework and/or installation or removal of an item. Typically, a modification is a design change that alters the original state of the aircraft or its systems.

It is also useful to distinguish between scheduled and unscheduled maintenance.

Scheduled Maintenance is performed at defined intervals to retain an item in a serviceable condition by systematic inspection, adjustment, etc.

Unscheduled Maintenance is performed in order to restore an item to a satisfactory condition by correcting a known malfunction and/or defect.

Maintenance tasks and procedures are defined by the aircraft maintenance program and are discussed in 8.2. Maintenance associated with repairs and modifications is discussed in 8.4 and 8.5.

8.1.2 Inspection Definition: Currently visual inspection is accomplished at the following levels.

General Visual (Surveillance) Inspection is a visual examination of an interior or exterior area, installation, or assembly to detect obvious damage, failure or irregularity. This level of inspection is made under normally available lighting conditions such as daylight, hangar lighting, flashlight or droplight and may require removal or opening of access panels or doors. Stands, ladders or platforms may be required to gain proximity to the area being checked.

Detailed Inspection is an intensive visual examination of a specific structural area, system, installation, or assembly to detect damage, failure, or irregularity. Available lighting is normally supplemented with a direct source of good lighting at an intensity deemed appropriate by the inspector. Inspection aids such as mirrors, magnifying lenses, etc. may be used. Surface cleaning and elaborate access procedures may be required.

A Visual Check is an observation to determine that an item is fulfilling its intended purpose. It does not require quantitative tolerances. This is a failure finding task.

A Functional Check is a quantitative check to determine if one or more functions of an item performs within specified limits.

8.1.2 (Continued):

The word "inspect" is used to describe a task where it is judged whether the detail, component, system, or area inspected is:

a. At the time of inspection, free from any observed defects likely to affect airworthiness.

b. Will remain serviceable until the next scheduled inspection of that detail, component, system, or area.

c. Is in a condition that requires a report or recording.

Further guidance on inspection definitions can be obtained in the ATA Maintenance Program Development Document MSG-3. Inspection/check requirements can be found in the applicable section of the Instruction for Continued Airworthiness (ICA), as required by local regulatory requirements, which usually consists of a Aircraft Maintenance Manual and other associated manuals.

8.2 Maintenance Procedures and Lightning Protection:

8.2.1 General: The initial aircraft maintenance program is defined by the aircraft manufacturer as a normal part of the aircraft design and certification process. The maintenance program is typically developed by the manufacturer together with regulatory authorities and aircraft operators.

Visual inspection is the first and generally most important step in lightning maintenance. It is important to note that lightning protection design philosophies may employ concepts and protection methods not previously encountered by maintenance personnel. Because of this, lightning hardness degradation can be unintentionally introduced during normal maintenance and repair activities (e.g., paint overspray, errors in re-assembly of connectors). It is important to provide adequate guidance to allow detection of incorrect installations that could adversely impact the lightning protection features.

Scheduled maintenance tasks should not be defined in order to protect against incorrect assembly and repair.

8.2.1.1 Relationship Between Design And Maintenance: Maintenance requirements for aircraft lightning protection should be defined as an integral part of the initial aircraft maintenance program and adjusted as the program is developed in accordance with service experience. The procedures can only be defined with a detailed knowledge of the design. The primary design features used to ensure aircraft systems operate satisfactorily when exposed to a lightning environment involves three complementary hardening features:

- Aircraft structure - (aircraft skin and frame)
- Electrical wiring installation protection - (solid or braided shielding/ connectors)
- Equipment protection - (LRU case, electronics I/O protection)

8.2.1.1 (Continued):

In theory effective protection could be achieved by either of the two design extremes:

a. large contribution to overall protection from conductive aircraft structure and extensive wiring shielding, but with no specific protection of the electronic equipment, or

b. no specific protection provided by the aircraft structure and no specific shielding of the aircraft wiring, but with extensive protection of the equipment and its interfaces.

In practice, typical designs will lie between these two extremes; the design choice is generally a combination of both. The relative combination will have a direct impact on the resultant maintenance procedures. The maintenance program will depend on the specific aircraft system architecture, aircraft structure design, system design and lightning protection allocation.

Increased time between maintenance checks may be achieved by redundant protection. System architecture, which results in system redundancy, contributes to overall lightning protection and can reduce the impact of protection degradation. If sufficient redundancy can be shown to exist then scheduled maintenance of lightning protective features may not be required. However, degradation common to multiple levels of redundant protection, such as corrosion, should be considered.

Further details on maintenance of shielding and equipment protection is given in 8.2.3 and 8.2.4.

8.2.1.2 Development of Scheduled Maintenance Procedures: The maintenance program, established by the aircraft manufacturer or maintenance board, should identify the following:

- Applicable systems.
- lightning protection features and their locations.
- Potential failure modes of these features and their effect on system operation.
- Maintenance techniques which are applicable for these features.

The development of scheduled maintenance procedures comprises two phases; identification and selection of applicable tasks and determination of task intervals (periodicity).

1. Identification And Selection of Applicable Tasks

   Once the lightning protection features have been identified for a particular installation or system, applicable and effective maintenance tasks should be selected for that particular installation or system. These tasks may be selected from the initial systems and powerplant, structure and zonal maintenance programs. Table 17 gives some guidance to the maintenance tasks that may be applied to certain types of electromagnetic protection features.

TABLE 17 - Applicable Maintenance Tasks for Lightning Protection Measures

PROTECTION TYPE	WIRE BUNDLE SHIELDING	AIRCRAFT STRUCTURE SHIELDING					CIRCUIT PROTECTION DEVICES
DESCRIPTION	Over braid shield, critical individual wire bundle shield	Raceway, conduits	RF gaskets	Shield for non-conductive surfaces	Structural bonding		Lightning protection devices
EXAMPLES	Metallic conduit, braid	Raceway, conduits	Removable panels	Conductive coating	Contact bonds, rivet joints	Bonding leads/straps, pigtails	Resistors, Zener diodes, EMI filters, filter pins, etc.
DEGRADATION OR FAILURE MODE	Corrosion, damage	Corrosion, damage	Corrosion, damage, deformation	Damage, erosion	Corrosion, damage	Corrosion, damage, security of attachment	Short circuit, open circuit
MAINTENANCE OPERATIONS	Visual inspection, measurement of wire bundle shielding/bonding	Visual inspection, bonding measurement	Visual inspection of gaskets, bonding leads/straps	Visual inspection, shielding effectiveness measurement, bonding measurement, surface resistivity, etc.	Visual inspection, bonding measurement	Visual inspection for corrosion attachment and condition, bonding measurement	Check at test/repair facility in accordance with maintenance or surveillance plan

8.2.1.2 (Continued):

Visual inspection may suffice for the observation of deterioration of the protective feature, dependent upon the design philosophy. Where assurance of the protective integrity standards cannot be maintained adequately by such measures then specific testing may be required. These techniques should make use of easy to apply quick-look portable devices, which can be readily integrated into the normal maintenance operations.

2. Determination of Task Intervals

The periodicity of any maintenance tasks selected for the lightning protection features should be determined by considering the following criteria:

- Relevant operating experience gained in the past with the same or similar installations. This should already be reflected in existing maintenance programs for similar installations. For new installations, or where relevant operating experience does not exist, the aircraft manufacturer can establish monitoring/sampling programs so that an acceptable and adequate database can be established.

- Exposure of the installation to any adverse environment (e.g., humidity, marine climate, etc.) and possible degradation of any protection features.

- Susceptibility of the installation to damage. Note that this is determined by the feature itself and by its location. For example, RF gaskets may be more fragile than bonding leads and bonding leads fitted from structure to moving parts (e.g., doors, flap track fairings) may be more susceptible to damage than leads fitted between fixed structural points.

- Criticality of each protective feature within the overall protection scheme.

- The reliability of protective devices fitted to installed equipment.

8.2.2 Maintenance of Aircraft Structure Shielding: The design lightning analysis or test will have clearly identified the main items, which contribute to the overall lightning protection of systems. Since aircraft structure contributes to lightning protection, this aspect should be considered when the aircraft maintenance requirements are developed and should be adequately addressed in the aircraft maintenance and structural repair manuals.

8.2.2 (Continued):

The following are examples of items, which will typically need to be considered for inclusion in the maintenance program to ensure acceptable protection retention:

- Primary structure:

  Electrical continuity between main parts, e.g., wing/fuselage, pylon/wing, fin/fuselage, tailplane/fuselage, etc.

- Secondary structure:

  Electrical continuity between secondary structure, if used as a shielding feature and the primary structure, e.g., bonding of cowls, doors, access panels, etc.

Degradation or failure modes of structure, both metallic and non-metallic, are assessed as a normal part of maintenance program development. The most significant degradation effect that structure can have on lightning protection arises from a decrease or loss of electrical continuity. This can be caused by corrosion, accidental damage, etc. Existing structural maintenance techniques (based primarily on visual inspections, supplemented as necessary by electrical bonding checks) have proven to be effective at detecting such degradation.

The items in Table 18 may need to be addressed during visual inspection.

Where equipment racks, shelves and doorways are designed to contribute to the protection standard of installed equipment or systems there should be appropriate inspection procedures applied.

8.2.3 Maintenance of Electrical Wiring Installation Protection: The design lightning analysis or test will have clearly identified the relative contribution of each of the main items, which contribute to the overall wiring protection. Since the aircraft wiring installation features contribute to the lightning protection this aspect should be considered when the aircraft maintenance requirements are developed and should be adequately addressed in the aircraft maintenance manual.

Electrical wiring protection is achieved mainly by shielding, shielding of bundles, or individual wire bundle shielding. An integral part of wiring shielding is termination of the shielding. Note that this section addresses maintenance for wiring shields, which contribute to lightning protection.

The examples in Table 19 are typical of items that may need to be addressed during visual inspection.

TABLE 18 - Aircraft Structure Shielding

ITEM	INSPECTION
Bonding Straps	**Check and/or inspect as necessary for:** • Damage, • Chafing, • Deformation, • Security of attachment, • Corrosion, • Degradation due to electrical discharge.
Conductive Gaskets	**Check and/or inspect as necessary for:** • Damage, • Corrosion, • Wear, • Water, • Brittleness • Hardening, • Fluid contamination, • Evidence of continuous contact between gasket and associated panel/enclosure.
Flame Sprayed Surfaces	**Check and/or inspect as necessary for:** • Damage, • Erosion, • Corrosion, • Retaining screws in contact with surface.
Raceways	**Check and/or inspect as necessary for:** • Damage, • Security of attachment and corrosion.
Finger Stock	**Check and/or inspect as necessary for:** • Damage, • Deformation, • Corrosion.

TABLE 19 - Wiring Installation Protection

ITEM	INSPECTION
Wire Bundle Shielding	**Check and/or inspect as necessary for:** • Damage, • Chafing, • Birdcaging, • Wear, • Corrosion, • Fluid contamination.
Bonding Straps	**Check and/or inspect as necessary for:** • Damage, • Chafing, • Deformation, • Security of attachment, • Corrosion, • Fluid contamination, • Degradation due to electrical discharge.
Connector Backshells	**Check and/or inspect as necessary for:** • Damage, • Security of attachment, • Corrosion, • Fluid contamination.
Wire Bundle Shield Pigtails	**Check and/or inspect as necessary for:** • Damage, • Chafing, • Deformation, • Corrosion, • Wear, • Security of attachment.
Finger Stock	**Check and/or inspect as necessary for:** • Damage, • Deformation, • Corrosion.

8.2.4 Equipment Maintenance: Lightning protective features may be designed into equipment in such a way to preclude meaningful in situ testing of the protective features. In a large percentage of these cases, the failure of a protective feature in the equipment will result in a loss of function. In that case, the protection feature will be restored to normal by the resulting maintenance action. However, in some cases, the protective feature's failure is latent and is not easily detected. In those cases, the reliability of those features should be orders of magnitude greater than the reliability of the equipment itself, which would result in a reasonable assurance that the protective feature remains available for the life of the equipment. Other equipment protective features include design architecture, such as differential circuits. In those cases, no maintenance activity is required to verify the operation.

Normally, maintenance of lightning protective features in equipment can be accomplished within the existing scope of maintenance activities for the equipment, without specific protective device testing. However, the equipment manufacturer may require a specific test of a lightning protective feature, during equipment repair or maintenance, if they find that test necessary to preclude a loss of lightning protection. This is most appropriate for equipment which supports highly critical functions, such as equipment in a Level A system, where the lightning protection failure is latent, or where the reliability of the lightning protection feature is not significantly more reliable than the equipment as a whole.

8.3 Aircraft Modification and Lightning Protection:

During the design phase of a modification, an assessment should be made of the impact on the overall lightning protection of the aircraft, to ensure that the overall electromagnetic hardness will not be compromised. In particular, those modifications and repairs that may introduce discontinuities in areas of the aircraft's skin, or cause a decrease in the aircraft structural shielding, should be evaluated. This evaluation should ensure that the structural shielding of equipment or wiring has not been compromised.

Changes in wiring type, connectors, bonding, shielding and LRU modifications should be evaluated to ensure that they do not compromise the protection of Level A, B or C systems. The routing of the wiring should not be modified without re-assessing the impact on the protection that is already provided. The methods used for assessing the protection levels should be accomplished in accordance with current lightning certification requirements.

Any modification should ensure that the segregation provided for wiring associated with systems of differing criticality is not compromised by the modification.

Where modification is proposed which requires an interface to a Level A, B or C system, the applicant should verify that the lightning protection of that system is not degraded or compromised. Additional lightning protection measures may need to be introduced to support the certification of such a modification. If the appropriate information is not available from the aircraft manufacturer or OEM, additional lightning tests or analysis may be required to support the modification certification.

8.4 Protection Assurance Program:

The maintenance program should be validated to ensure that the maintenance actions detect and effectively restore lightning protection features that may degrade in service. The lightning protection maintenance assurance program is a desirable element of the aircraft continuing airworthiness for lightning protection. The protection assurance program should focus on the protection adequacy of Level A systems.

The aircraft, engine and equipment lightning protection features are typically designed to be effective over the life of the aircraft or equipment. Laboratory environmental tests for vibration, humidity, temperature and salt exposure are often conducted on protection elements and equipment and previous service experience on other aircraft models or configurations is typically considered when developing the maintenance program.

However, laboratory environmental tests, previous service experience on other aircraft or configurations and visual inspections have not always been adequate to assure that the lightning protection will be maintained. Therefore, a protection maintenance assurance program may be necessary to validate the effectiveness of the defined maintenance program.

In addition, the maintenance program activities may not directly determine the lightning protection effectiveness, but may look for indirect indications that would represent degradation. For example, visual inspections may look for connector corrosion that would indicate the potential for increased shield bonding resistance. But the shielding effectiveness itself can only be determined by direct measurement, which may be accomplished by the assurance program.

If a protection assurance program is required then the following sections provide guidance on how the program is to be planned.

8.4.1 Protection Assurance Program Goals: The protection assurance program is an engineering evaluation of the protection maintenance program, which supports the instructions for continued airworthiness. The intent of the protection assurance program is to validate the scheduled and unscheduled maintenance actions, to confirm that the maintenance intervals are appropriate and to detect unanticipated protection degradation that is not detected in the maintenance program. Results from this program may be used to justify changes to the scheduled and unscheduled maintenance program.

Elements of the protection assurance program are described below.

Protection assurance plan. This plan describes the general approach for the aircraft lightning protection, types of surveillance actions, the number of aircraft that will be under surveillance, the time intervals between surveillance actions and the overall duration of the surveillance program. The plan should include the expected acceptance or pass/fail criteria for the results of the surveillance. The protection assurance plan should be prepared as part of the aircraft certification, to validate compliance with the instructions for continued airworthiness.

8.4.1 (Continued):

Protection surveillance. The protection surveillance may include full aircraft lightning tests, shielding effectiveness tests, resistance measurements, or connector or structure teardown. The protection surveillance for avionics black boxes may include checks for filter effectiveness and transient suppression performance.

Protection maintenance program modifications. The results and findings of the protection surveillance should be reviewed and incorporated into the protection maintenance program. These could include changes to the maintenance intervals or changes to the maintenance actions.

8.4.2 Scope of Surveillance: The extent of the surveillance program depends on the scope of the aircraft maintenance program. A surveillance program is needed if the maintenance program does not directly determine the effectiveness of the lightning protection. For example, the maintenance program may rely upon visual inspections to determine if wire shielding or raceways continue to provide effective protection. Then the surveillance program should include direct measurements on an agreed-upon set of protection features.

In contrast, if the maintenance program incorporates direct measurement of the protection elements, then the surveillance program may not be required for these elements. Again, an example is if the maintenance includes scheduled or unscheduled shield and connector loop resistance measurements, a surveillance program is not necessary for the shield and connector protection effectiveness.

Full aircraft tests are a method to determine the overall lightning protection effectiveness. Full aircraft tests include low-level swept frequency tests, low current pulse tests, or high current pulse tests. The results of these tests can be directly compared to the original lightning certification data. The disadvantage of full aircraft tests is that these tests do not provide information on the location or extent of individual protection element degradation. For example, a full aircraft test could indicate degradation, but could not determine that the cause is an individual connector or shield termination. A further disadvantage is that full aircraft tests require dedicated access to the aircraft, generally at a specific test site.

Detail bonding resistance measurements are effective for determining changes to connector bonding resistance, panel bonding or bonding jumper performance. The disadvantage is that additional evaluation is required to assess whether bonding resistance changes are affecting the lightning protection. Bonding resistance on certain components may have more effect on the lightning protection than bonding resistance on other components. Also, traditional bonding resistance measurements are not effective for detecting wire shield degradation, particularly for complex wire bundles with many branches and terminations. Bonding resistance measurements can often be performed during other aircraft maintenance activities and do not require that the aircraft be located at a specific test site.

8.4.2 (Continued):

Loop resistance or impedance measurements are effective for determining changes to the protection afforded by wire bundle shields and connectors. The loop measurements are particularly good for complex wire bundles. As with bonding resistance measurements, additional evaluation is required to assess whether loop resistance or impedance changes have any real effect on the lightning protection margin. Higher loop resistance on certain wire bundles may have more effect on the lightning protection than high loop resistance on other wire bundles. Loop resistance or impedance measurements can often be performed during other aircraft maintenance activities and do not require that the aircraft be located at a specific test site.

Tear-down inspections that are not part of the maintenance program may be part of the surveillance program. For example, disassembly of selected connectors may be part of the surveillance, to detect corrosion or shield termination failure that would not be visible during the maintenance inspections.

The selection of lightning protection features for surveillance should be based on the class of shielding, hardware type, physical environment and lightning environment. Sufficient measurements should be made on Level A systems to include a significant sample of all hardware and environment combinations. If lightning protection features for some Level A systems are covered by surveillance on other Level A systems with similar configuration, hardware and exposure, then surveillance may not be required for all Level A systems.

A separate surveillance program may be set up for individual avionics systems, electrical equipment or electronic engine controls to assess lightning protection elements within the equipment that cannot be effectively assessed by aircraft tests or equipment acceptance tests. Avionics, electrical equipment, electronic flight control, or engine control inspections or tests may be required to determine the effectiveness of the avionics lightning protection features. For example, if the maintenance program for a specific item of avionics does not specify tests to assure functionality of lightning filters, based on an assumed reliability of the filters, then the surveillance program could include tests to validate the assumed reliability.

8.4.3 Selection of Aircraft: The surveillance program typically uses selected aircraft, not the entire fleet. The selection of the aircraft for surveillance should consider high operating time and high flight cycle aircraft. The operating environment should also be considered in selecting aircraft for surveillance. Use of aircraft that operate in extreme temperatures, corrosive environments like salt spray, or harsh environments is recommended.

More than one aircraft should be used in the surveillance program. The number should be based on the considerations above and should be agreed upon with the regulatory authorities. For example, when dealing with aircraft models with expected fleet sizes that exceed 500 aircraft, an initial sample size for surveillance of five to ten aircraft should be acceptable to the regulatory authorities.

A separate surveillance program may be set up for individual avionics systems, electrical equipment, electronic flight controls, or engine controls for lightning protection elements within the equipment that cannot be effectively verified by aircraft tests.

8.4.4 Frequency and Duration of Surveillance Program: The surveillance activities are normally scheduled with heavy maintenance activities, such that an evaluation of in-service conditions is possible. Surveillance typically requires access panel removal to gain access to lightning protection features, which can be scheduled along with the heavy maintenance activities. Surveillance activities scheduled every four to five years on the selected aircraft have been acceptable to the regulatory authorities. The duration or the frequency may be amended based on the results of the protection assurance program.

8.4.5 Allowable Lightning Protection Variations: The manufacturer should define the acceptable lightning protection effectiveness tolerances that are due to production variations and in-service aging. The tolerances may be developed by analysis, tests with intentionally degraded protection features, by margin tests, or other methods. The measurement techniques and accuracy for monitoring the lightning protection effectiveness should be assessed to ensure that these tolerances can be detected.

8.5 In-Service Maintenance Test Techniques:

This section aims to provide general guidance on the methods, which may be used to determine the effectiveness of typical lightning protection measures, employed in aircraft. Available methods are discussed in the following paragraphs. The tests selected should be appropriate for the level of system criticality and the architecture and allocation of the aircraft lightning protection.

The first step in maintenance is almost always visual inspection for damage and corrosion. In many cases visual inspection may suffice for the observation of deterioration of the protection feature, dependent upon the design philosophy. Where the protection integrity standards cannot be assured adequately by such simple measures then specific testing may be necessary.

The test techniques, which may be performed in an airline maintenance environment, are:

a. DC resistance measurement
b. Low frequency loop impedance measurement
c. Equipment protection tests

The milliohm-meter is often used to measure the ground path resistance of grounding straps or bonding. This technique is limited to the indication of only single path resistance values.

Low frequency loop impedance testing is a useful method complementary to DC bonding testing. A visual inspection of wire bundle shields complemented by a low frequency loop impedance test gives good confidence in the integrity of the shielding provisions.

8.5 (Continued):

Low frequency loop impedance testing is a method developed to check that adequate bonding exists between over braid (conduit) shields and structure. To achieve the shielding performance required it often is necessary that both ends of a wire bundle shield are bonded to aircraft structure. In such cases it is hard to check bonding integrity by the standard DC bonding test method. If the bond between shield and structure at one end is degraded while the other one is still good, there is little chance of finding this defect by performing DC bonding measurements. The remaining bond still ensures a low resistance to ground but the current loop through the shield is interrupted causing degradation of shielding performance. The fault, however, can be detected by performing a low frequency loop impedance test.

The loop impedance test is performed by injecting a low frequency signal into the wire bundle and determining the voltage/current relationship that results.

Where dedicated lightning protective devices are used in electrical and electronic equipment installed in the aircraft, the manufacturer may develop test techniques to check those devices. Those tests could include checking the functionality of filters with impedance bridges, etc. These tests may also include temporary disconnecting the protection devices.

APPENDIX A
FARS AND JARS RELATED TO LIGHTNING PROTECTION

The documents below include descriptions of the external lightning environment applicable to aerospace vehicles and provide additional guidance.

NOTE: Whenever a reference document appears in this report, it carries the minimum revision level of the reference document acceptable to meet the intended requirements. Later versions of the reference document are also acceptable but earlier versions are not acceptable. In all cases, other documents shown to be equivalent to the referenced document are also acceptable.

A.1 FARS/JARS PART 23:

A.1.1 FARs Part 23:

FAR 23.867 Electrical bonding and protection against lightning and static electricity.

a. The airplane must be protected against catastrophic effects from lightning.

b. For metallic components, compliance with paragraph (a) of this section may be shown by:

   1. Bonding the components properly to the airframe; or
   2. Designing the components so that a strike will not endanger the airplane.

c. For nonmetallic components, compliance with paragraph (a) of this section may be shown by:

   1. Designing the components to minimize the effects of a strike; or
   2. Incorporating acceptable means of diverting the resulting electrical current so as not to endanger the airplane.

FAR 23.954 Fuel System Lightning Protection.

The fuel system must be designed and arranged to prevent the ignition of fuel vapor within the system by:

a. Direct lightning strikes to areas having a high probability of stroke attachment;
b. Swept lightning strokes on areas where swept strokes are highly probable; and
c. Corona or streamering at fuel vent outlets.

A.1.1 (Continued):

FAR 23.1309 Equipment, systems, and installations.

a. In showing compliance with this section with regard to the electrical power system and to equipment design and installation, critical environmental and atmospheric conditions, including radio frequency energy and the effects (both direct and indirect) of lightning strikes, must be considered. For electrical generation, distribution, and utilization equipment required by or used in complying with this chapter, the ability to provide continuous, safe service under foreseeable environmental conditions may be shown by environmental tests, design analysis, or reference to previous comparable service experience on other airplanes.

A.1.2 JARs Part 23:

JAR 23.867 Electrical bonding and protection against lightning and static electricity.

a. The aeroplane must be protected against catastrophic effects from lightning.

b. For metallic components, compliance with sub-paragraph (a) of this paragraph may be shown by:

    1. Bonding the components properly to the airframe; or
    2. Designing the components so that a strike will not endanger the aeroplane.

c. For non-metallic components, compliance with sub-paragraph (a) of this paragraph may be shown by:

    1. Designing the components to minimize the effects of a strike; or
    2. Incorporating acceptable means of diverting the resulting electrical current so as not to endanger the aeroplane.

JAR 23.954 Fuel System Lightning Protection.

The fuel system must be designed and arranged to prevent the ignition of fuel vapor within the system by:

a. Direct lightning strikes to areas having a high probability of stroke attachment;
b. Swept lightning strokes on areas where swept strokes are highly probable; and
c. Corona or streamering at fuel vent outlets.

A.1.2 (Continued):

JAR 23.1309 Equipment, systems, and installations.

a. In showing compliance with this section with regard to the electrical power system and to equipment design and installation, critical environmental and atmospheric conditions, including radio frequency energy and the effects (both direct and indirect) of lightning strikes, must be considered. For electrical generation, distribution, and utilization equipment required by or used in complying with this chapter, the ability to provide continuous, safe service under foreseeable environmental conditions may be shown by environmental tests, design analysis, or reference to previous comparable service experience on other aeroplanes.

A.2 FARS/JARS PART 25:

A.2.1 FARs Part 25:

FAR 25.581 Lightning protection.

a. The airplane must be protected against catastrophic effects from lightning.

b. For metallic components, compliance with paragraph (a) of this section may be shown by:

   1. Bonding the components properly to the airframe; or
   2. Designing the components so that a strike will not endanger the airplane.

c. For nonmetallic components, compliance with paragraph (a) of this section may be shown by:

   1. Designing the components to minimize the effects of a strike; or
   2. Incorporating the acceptable means of diverting the resulting electrical current so as not to endanger the airplane.

FAR 25.1316 System lightning protection.

a. For functions whose failure would contribute to or cause a condition that would prevent the continued safe flight and landing of the airplane, each electrical and electronic system that performs these functions must be designed and installed to ensure that the operation and operational capabilities of the systems to perform these functions are not adversely affected when the airplane is exposed to lightning.

b. For functions whose failure would contribute to or cause a condition that would reduce the capability of the airplane or the ability of the flight crew to cope with adverse operating conditions, each electrical and electronic system that performs these functions must be designed and installed to ensure that these functions can be recovered in a timely manner after the airplane is exposed to lightning.

A.2.1 (Continued):

c. Compliance with the lightning protection criteria prescribed in paragraphs (a) and (b) of this section must be shown for exposure to a severe lightning environment. The applicant must design for and verify that aircraft electrical/electronic systems are protected against the effects of lightning by:

1. Determining the lightning strike zones for the airplane;
2. Establishing the external lightning environment for the zones;
3. Establishing the internal environment;
4. Identifying all the electrical and electronic systems that are subject to the requirements of this section, and their locations on or within the airplane;
5. Establishing the susceptibility of the systems to the internal and external lightning environment;
6. Designing protection; and
7. Verifying that the protection is adequate.

A.2.2 JARs Part 25:

JAR 25.581 Lightning protection.

a. The aeroplane must be protected against catastrophic effects from lightning (see JAR 25C899 and ACJ25.581).

b. For metallic components, compliance with sub-paragraph (a) of this paragraph may be shown by:

1. Bonding the components properly to the airframe; or
2. Designing the components so that a strike will not endanger the aeroplane.

c. For non-metallic components, compliance with sub-paragraph (a) of this paragraph may be shown by:

1. Designing the components to minimize the effects of a strike; or
2. Incorporating the acceptable means of diverting the resulting electrical current so as not to endanger the aeroplane.

A.2.2 (Continued):

JAR 25X899 Electrical bonding and protection against lightning and static electricity (see also ACJ 25X899).

The electrical bonding and protection against lightning and static electricity systems must be such to:

a. Protect the aeroplane, including its systems and equipment, against the dangerous effects of lightning discharges;

b. Prevent dangerous accumulation of electrostatic charge;

c. Minimize the risk of electrical shock to crew, passengers and servicing personnel and also to maintenance personnel using normal precautions, from the electricity supply and distribution system;

d. Provide an adequate electrical return path under both normal and fault conditions, on aeroplanes having earthed electrical systems;

e. Reduce to an acceptable level interference from these sources with the functioning of essential electrically-powered or signaled services (see also JAR 25.1351(b)(4) and JAR 25.1431(c)).

JAR 25.954 Fuel System Lightning Protection.

The fuel system must be designed and arranged to prevent the ignition of fuel vapor within the system (see ACJ25.954 and ACJ25X899):

a. Direct lightning strikes to areas having a high probability of stroke attachment;
b. Swept lightning strokes on areas where swept strokes are highly probable; and
c. Corona and streamering at fuel vent outlets.

JAR 25.1316 System lightning protection.

a. For functions whose failure would contribute to or cause a condition that would prevent the continued safe flight and landing of the aeroplane, each electrical and electronic system that performs these functions must be designed and installed to ensure that the operation and operational capabilities of the systems to perform these functions are not adversely affected when the aeroplane is exposed to lightning.

b. For functions whose failure would contribute to or cause a condition that would reduce the capability of the aeroplane or the ability of the flight crew to cope with adverse operating conditions, each electrical and electronic system that performs these functions must be designed and installed to ensure that these functions can be recovered in a timely manner after the aeroplane is exposed to lightning.

A.2.2 (Continued):

c. Compliance with the lightning protection criteria prescribed in sub-paragraphs (a) and (b) of this paragraph must be shown for exposure to a severe lightning environment. The applicant must design for and verify that aircraft electrical/electronic systems are protected against the effects of lightning by:

1. Determining the lightning strike zones for the aeroplane;
2. Establishing the external lightning environment for the zones;
3. Establishing the internal environment;
4. Identifying all the electrical and electronic systems that are subject to the requirements of this section, and their locations on or within the aeroplane;
5. Establishing the susceptibility of the systems to the internal and external lightning environment;
6. Designing protection; and
7. Verifying that the protection is adequate.

A.3 FARS/JARS PART 27:

A.3.1 FARs Part 27:

FAR 27.610 Lightning protection.

a. The rotorcraft must be protected against catastrophic effects from lightning.

b. For metallic components, compliance with paragraph (a) of this section may be shown by:

1. Electrically bonding the components properly to the airframe; or
2. Designing the components so that a strike will not endanger the rotorcraft.

c. For nonmetallic components, compliance with paragraph (a) of this section may be shown by:

1. Designing the components to minimize the effects of a strike; or
2. Incorporating acceptable means of diverting the resulting electrical current to not endanger the rotorcraft.

FAR 27.954 Fuel System Lightning Protection.

The fuel system must be designed and arranged to prevent the ignition of fuel vapor within the system by:

a. Direct lightning strikes to areas having a high probability of stroke attachment;
b. Swept lightning strokes on areas where swept strokes are highly probable; and
c. Corona and streamering at fuel vent outlets.

A.3.1 (Continued):

FAR 27.1309 Equipment, systems, and installations.

a. In showing compliance with paragraph (a), (b), or (c) of this section, the effects of lightning strikes on the rotorcraft must be considered in accordance with Section 27.610.

A.3.2 JARs Part 27:

JAR 27.610 Lightning protection.

a. The rotorcraft must be protected against catastrophic effects from lightning.

b. For metallic components, compliance with sub-paragraph (a) of this paragraph may be shown by:

   1. Electrically bonding the components properly to the airframe; or
   2. Designing the components so that a strike will not endanger the rotorcraft.

c. For non-metallic components, compliance with sub-paragraph (a) of this paragraph may be shown by:

   1. Designing the components to minimize the effects of a strike; or
   2. Incorporating acceptable means of diverting the resulting electrical current so as not to endanger the rotorcraft.

JAR 27.954 Fuel System Lightning Protection.

The fuel system must be designed and arranged to prevent the ignition of fuel vapor within the system by:

a. Direct lightning strikes to areas having a high probability of stroke attachment;
b. Swept lightning strokes on areas where swept strokes are highly probable; and
c. Corona and streamering at fuel vent outlets.

JAR 27.1309 Equipment, systems, and installations.

a. In showing compliance with paragraph (a), (b), or (c) of this section, the effects of lightning strikes on the rotorcraft must be considered in accordance with JAAR 27.610.

A.4 FARS/JARS PART 29:

A.4.1 FARs Part 29:

FAR 29.610 Lightning and static electricity protection.

a. The rotorcraft must be protected against catastrophic effects from lightning.

b. For metallic components, compliance with paragraph (a) of this section may be shown by:

   1. Electrically bonding the components properly to the airframe; or
   2. Designing the components so that a strike will not endanger the rotorcraft.

c. For nonmetallic components, compliance with paragraph (a) of this section may be shown by:

   1. Designing the components to minimize the effects of a strike; or
   2. Incorporating acceptable means of diverting the resulting electrical current to not endanger the rotorcraft.

d. The electric bonding and protection against lightning and static electricity must:

   1. Minimize the accumulation of electrostatic charge;
   2. Minimize the risk of electric shock to crew, passengers, and service and maintenance personnel using normal precautions;
   3. Provide an electrical return path, under both normal and static electricity on the functioning of essential electrical and electronic equipment.
   4. Reduce to an acceptable level the effects of lightning and static electricity on the functioning of essential electronic equipment.

FAR 29.954 Fuel System Lightning Protection.

The fuel system must be designed and arranged to prevent the ignition of fuel vapor within the system by:

a. Direct lightning strikes to areas having a high probability of stroke attachment;
b. Swept lightning strokes on areas where swept strokes are highly probable; and
c. Corona and streamering at fuel vent outlets.

FAR 29.1309 Equipment, systems, and installations.

a. In showing compliance with paragraphs (a) and (b) of this section, the effects of lightning strikes on the rotorcraft must be considered.

A.4.2 JARs Part 29:

JAR 29.610 Lightning and static electricity protection (see ACJ 29.610).

a. The rotorcraft structure must be protected against catastrophic effects from lightning.

b. For metallic components, compliance with sub-paragraph (a) may be shown by:

 1. Electrically bonding the components properly to the airframe; or
 2. Designing the components so that a strike will not endanger the rotorcraft.

c. For non-metallic components, compliance with sub-paragraph (a) may be shown by:

 1. Designing the components to minimize the effects of a strike; or
 2. Incorporating acceptable means of diverting the resulting electrical current to not endanger the rotorcraft.

d. The electric bonding and protection against lightning and static electricity must be such as to:

 1. Minimize the accumulation of electrostatic charge;
 2. Minimize the risk of electric shock to crew, passengers and servicing personnel, and also to maintenance personnel using normal precautions;
 3. Provide an electrical return path under both normal and fault conditions, on rotorcraft having earthed electrical systems;
 4. Reduce to an acceptable level interference from lightning and static electricity with the functioning of essential electrically-powered or signaled services (see also JAR 29.1351(b)(4) and JAR 29.1431(a)).

JAR 29.954 Fuel System Lightning Protection.

The fuel system must be designed and arranged to prevent the ignition of fuel vapor within the system by:

a. Direct lightning strikes to areas having a high probability of stroke attachment;
b. Swept lightning strokes on areas where swept strokes are highly probable; and
c. Corona and streamering at fuel vent outlets.

JAR 29.1309 Equipment, systems, and installations.

a. Compliance with the requirements of sub-paragraph (b)(2) of this paragraph must be shown by analysis and, where necessary, by appropriate ground, flight or simulator tests. The analysis must consider:

 1. Possible modes of failure, including malfunctions and damage from external sources;
 2. The probability of multiple failures and undetected failures;
 3. The resulting effects on the rotorcraft and occupants, considering the stage of flight and operating conditions; and
 4. The crew warning cues, corrective action required, and the capability of detecting faults.

APPENDIX B
LIGHTNING TRANSIENT COUPLING

Determining the aircraft actual transient levels (ATLs) can involve analysis, tests, and data comparison in a complementary fashion as illustrated in Figure B1. This appendix provides a discussion of coupling mechanisms, analytic simulation ("Rapid/Virtual Prototyping" of aircraft EM configurations and lightning protection) technology and results from test and analysis combinations. Actual measured lightning transient amplitudes are also presented, based on the results of tests on three business jets.

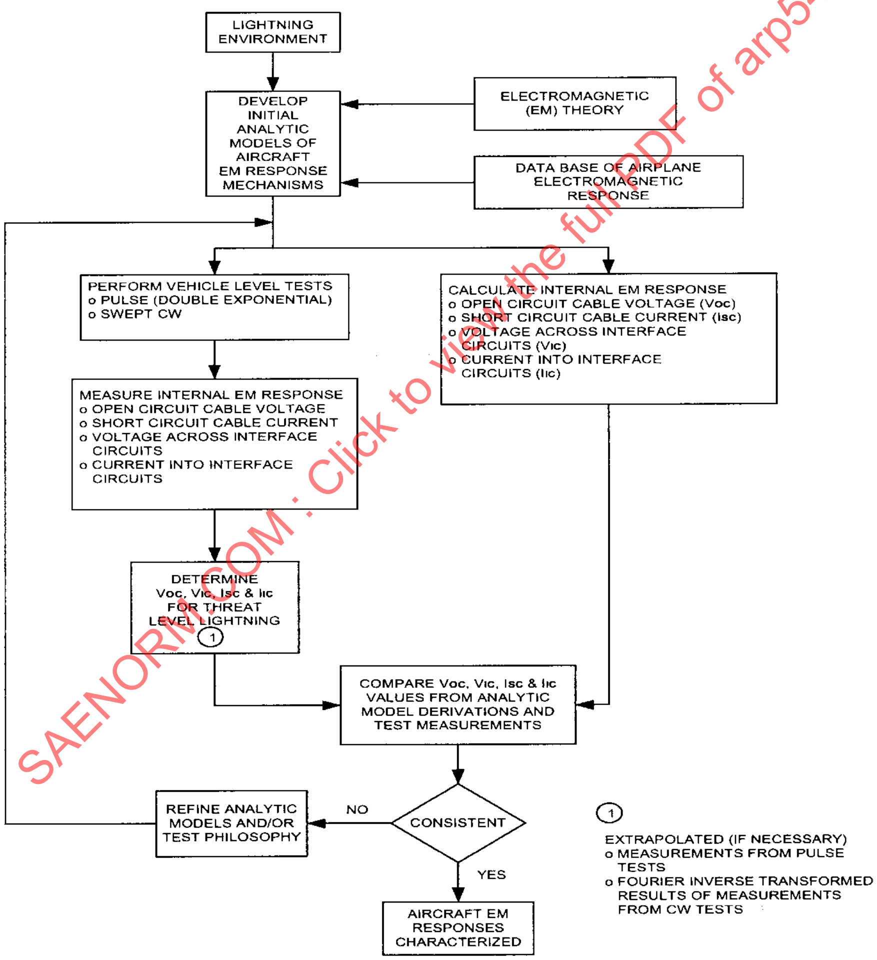


FIGURE B1 - Analysis and Test Process

Testing of a complete aircraft containing complex, flight-safety electronics in various configurations can be time consuming. An aircraft test carried out over an extended time is likely to investigate only a small number of possible combinations of system modes and lightning attachment configurations. It is unusual for a complete aircraft to be made available for many weeks of ground testing prior to production certification. A more complete assessment can be accomplished using analysis for the effectiveness of protection and resulting system immunity. An analytical approach can mitigate undesirable impacts on the aircraft certification program.

In addition to allowing more comprehensive assessments than testing alone, analysis can directly support testing. Two examples of such direct support are:

- Defining and selecting the test methodologies
- Assessing the completeness and validity of the test results (i.e., assessing the impact of the approximations made during testing).

The simulation of the propagation of lightning EM energy into electrical/electronic systems is complex and involves a detailed understanding of the EM interactions involved. The design of test arrangements to provide required excitation of the aircraft is heavily dependent on being able to analyze the empiric simulation in detail. Furthermore, a quantitative assessment of impact of the unavoidable approximations in the test setup can be achieved using detailed analyses. In general, airworthiness certification should be achieved through a combination of test and analysis.

Analytical methods aimed at the problem of protecting the aircraft against lightning effects primarily involve calculation of electromagnetic field coupling to aircraft wiring bundles and calculation of circuit responses.

Detailed analyses can identify problem areas of system installation and electrical design. The measurement program during the airworthiness testing can be planned to concentrate on those areas. High quality measurement data can be obtained for these areas and used to validate the analysis. If validation is achieved, then many of the combinations of system modes and attachment configurations can be considered by analysis only. In this way, a more thorough lightning protection certification is achieved as well as possible reduction in test time.

Until recently, full aircraft detailed modeling and analyses of induced currents and voltages in wiring bundles, conduits, LRU cases, and various structural components was not feasible with any accuracy. However, the development of three-dimensional computer codes which can be run on machines of increasing speed and efficiency now has made such analyses viable. Furthermore, the trend towards the extensive use of non-metallic airframe materials (lower shielding), coupled with the increasing reliance on electronic (sensitive devices, etc.) systems for functions whose failure impacts safe aircraft operation, has made the task of Level A system design for immunity to lightning effects very difficult and expensive to accomplish. The level of confidence required in the modern aerospace industry for system installation design, airframe design, and airworthiness certification cannot be easily accomplished without using analytical methods. In general, errors in analysis are comparable to test errors. Efficient design processes offload expensive testing with less expensive analysis.

It is advisable that the process of validation of the analysis methods employed be confirmed by test as soon as there is a complete airframe available with some systems installed. At every opportunity throughout the development program, the design verification database can be expanded. This analysis and test process identifies potential design weaknesses early in the development process. Corrective measures can be taken immediately thereby making rectification more cost-effective and the body of evidence to support certification can be developed. Testing of the final standard production aircraft should be little more than a confirmatory check to ensure that there have been no significant changes between prototype and production.

Detailed and high quality analysis of the lightning protection has a significant role to play in the design and development of modern aircraft. However, testing will always be required in order to ensure that the very early assumptions were correct. In addition, the many features of the airframe and system which are not deliberately designed to provide lightning protection must be investigated for their impact on lightning protection performance.

Analytic EM simulation technology has been developed to predict electromagnetic coupling to electronic systems and to determine the effects on system operation. The technology ranges in complexity from large state-of-the-art numerical simulations suitable for modeling entire aircraft to more simple numerical implementations of specific analytical models of lightning energy coupling. In addition, circuit analysis tools appropriate and useful in determining the circuit level response to lightning-induced transients have been developed. Some of these computer codes are suitable for use on microcomputers, such as desktop PCs. Some are only practical for more powerful workstation or mainframe computers. Some of these codes represent commercial products and are available from the developer for a fee. Desktop PC technology has evolved to the point such that presently they are becoming excellent platforms for EM simulation technology.

The analytic simulation role is emerging (empiric simulation is a well established practice) and the following is only a partial list of codes that are available. Some design consulting companies have in-house codes and tools that are available as a part of their services, but are not included in this list.

Three Dimensional Time Domain Codes

This group of codes represents the proven state-of-the-art in modeling entire complex aircraft electromagnetic features in three dimensions. All codes mentioned here solve Maxwell's equations directly via a numerical algorithm that employs finite difference techniques spatially and temporally. Models of aircraft may include both exterior and interior detail, accounting for both non-metallic (composite, dielectric, plastic, etc.) and metallic materials.

Mathematically, these codes model the aircraft as a spatial mesh, equivalent to a lattice of nodes. Electric fields, magnetic fields, and currents are computed anywhere within the mesh. This calculation is done for each time step specified. Mesh size determines the fidelity of the results, and also strongly influences computer run times and computing resources required. Small increases in model fidelity require significant increases in both computation time and required computer memory.

Examples of these codes are listed below:

- EMA3D: EMA3D is a full 3D solution of Maxwell's equations based on the time domain finite difference method. It solves both the exterior and interior coupling problems simultaneously (self consistently) by directly meshing the entire aircraft. As a result, EMA3D allows the user to analyze the response of an aircraft to lightning, HIRF, or other EMC environments. It can also be used to perform antenna pattern computations and intrasystem EMC. The computations are done in the time domain, and wide-band frequency domain results are obtained by Fourier methods. Extensive post-processing facilities allow the user to obtain ffts, transfer functions, S-parameters, input impedances, complex input/output power, and others. Sources include lightning currents, plane waves (e.g., HIRF), voltage drivers for antennas, and others. EMA3D uses a thin wire formalism to model bulk wire harnesses and cables in the aircraft. Isotropic frequency dependent materials, composite materials, and anisotropic materials can be included. An air chemistry algorithm can be used to model the breakdown of air, as occurs in lightning situations. EMA3D has a Graphical User Interface (GUI) which can import IGES CAD files from any CAD system, such as CATIA, IDEAS, and others. Direct interfaces to some native CAD file formats are available. The GUI also has an extensive solid modeling capability, and can also export IGES files. All of the meshing and EMA3D problem definition and setup is done in the GUI in a user-friendly environment. Post-processing results visualization can be done in terms of 3D color images and surface plots, animations, zoom, rotations and simple x-y plots. EMA3D is available in various UNIX, Windows NT, and some supercomputer environments. EMA3D is available commercially from Electro Magnetic Applications, Inc., Denver, Colorado.

- TSAR (Temporal Scattering and Response): TSAR uses a suite of modules to accomplish its modeling tasks. A CAD module is used to generate the shape of the aircraft, both exterior and interior. The CAD module can import data from other CAD models with IGES form. A finite difference mesh is generated from the CAD model and Maxwell's equations are solved directly in the time domain. Solutions are obtained in three dimensions. Lightning transients coupling in terms of fields and currents is obtained, both in the exterior and interior. Solutions account for penetrations through composite structures, apertures, seams, and exposed conductors. Solutions account for materials media that include dielectric, composite, metallic, and lossy. TSAR is a code that was developed by the government and is available for a nominal charge to qualified contractors from Lawrence Livermore Laboratories in Livermore, California. The code can be run on several operating systems (UNIX and VAX/VMS) and is suitable for use on work stations, minicomputers, mainframes, and supercomputers. TSAR is not commercially supported.

- TLM (Transmission Line Modeling): TLM implements a numerical technique which is used for predicting electromagnetic fields, surface currents, and wire currents in a variety of problems. TLM models structures with a network of transmission lines and makes use of the equivalence between this network and Maxwell's equations. The solution of the network can be solved exactly, and gives a stable time-stepping numerical routing. The frequency range appropriate to the technique depends on the spatial separation used. At least six nodes/wavelength are required. Diakoptics is an extension of the TLM method and allows a large structure to be broken down into smaller substructures with differing grid sizes as required. The code is available from Kimberly Communication Consultants, Nottingham, U.K.

Three-Dimensional Frequency Domain Codes

These codes implement the method-of-moments (MOM) algorithm for the solution to Maxwell's equations. Rather than directly solving Maxwell's equations in the time domain, either a frequency domain electric field integral equation (EFIE) form of Maxwell's equations, and/or a magnetic field integral equation (MFIE) form is solved using the MOM algorithm. Complex aircraft structures are modeled either as a structure of wires (in the case of the EFIE solution), as patches (in the case of the MFIE solution), or as a combination of the two. Solutions are provided at specific frequencies. Dielectric materials are difficult to account for with these codes. MOM codes are generally only appropriate for modeling external coupling. These codes do not have a GUI and no solid modeling capability.

- NEC (Numerical Electromagnetic Code): This code implements the MOM technique to the solution of Maxwell's equations in the frequency domain. It can be used to predict EM fields and surface currents for a variety of problems. The frequency range the technique covers depends on the size of the model relative to the excitation wavelength. (The smaller the wavelength, the more model components required.) The code was developed by the government and is available for a fee from Lawrence Livermore Laboratories, Livermore, California to qualified contractors. NEC is not commercially supported.

- GEMACS (General Electromagnetic Analysis of Complex Systems): GEMACS is a hybrid analysis program comprised of a MOM module, a geometrical theory of diffraction (GTD) module, and a finite element/difference module. It is included in this category of codes, since it is often used as a MOM code that is augmented by the GTD module in the higher frequency regimes to alleviate the need for excessive MOM model elements. The code can model three dimensional structures with apertures. It has been developed by the government and is available from Rome Air Development Center, Rome AFB, NY to qualified U.S. companies in VAX and PC formats. GEMACS is not commercially supported.

Electrical/Electronic System Installation Wiring Analysis

- MHARNESS: MHARNESS is a time domain finite difference solution of the multi-conductor transmission line equations, useful for both HIRF and lightning applications. Frequency domain results are obtained by Fourier methods with post processing utilities. It can model complex wire harnesses consisting of multiple conductors, multiple branches, and multiple shielding layers. It can be used to evaluate the effectiveness of various shield designs, connectors, and bonding impedances. It can be used to determine core wire voltages/currents for lightning, HIRF, and signaling and crosstalk applications. It can also predict the EMI fields radiated from a harness. A GUI simplifies the creation of MHARNESS models. It also has an interface with Mentor Graphics Logicable CAD software for wiring tables. The interface format can be easily changed for other wiring list formats, also. MHARNESS is available in UNIX or Windows NT environments. MHARNESS is available commercially from Electromagnetic Magnetic Applications, Inc., Lakewood, Colorado.

Circuit Analysis Codes

Numerous circuit analysis codes exist for taking lightning induced transients on wires and cables and calculating their effects on a unit's electronic circuitry. Many of these codes are available commercially and are suitable for the PC environment.

- SPICE (Simulation Program with Integrated Circuit Emphasis): SPICE was developed at the University of California at Berkeley and released in 1972. It has become the dominant analog circuit simulator for virtually every type of electronics application. Though upgraded several times, the core algorithm has remained essentially unchanged. Semiconductor devices are modeled using Gummel-Poon parameters.

- IS_SPICE: IS_SPICE is a commercial version of SPICE offered by Intusoft, San Pedro, California. It operates in the PC (386 or higher) or Macintosh environment and offers advanced features including graphics output and post processing.

- XSPICE: XSPICE is a version of SPICE developed under contract to the United States Air Force and is available through Georgia Tech Research Corp. XSPICE is an enhanced and extended version of SPICE version 3C1 and has both analog and digital simulation capabilities. The two advancements of XSPICE over SPICE are (1) The basic R, L, C, diode, and transistor library has been extended to include over 40 devices, including summers, integrators, digital gates, s-domain transfer functions, and digital state machines; and (2) a set of programming utilities allows model creation in the C programming language. System level simulation is possible with this program. The code is written for UNIX operating system and work station platforms. XSPICE is not commercially supported.

B.1 LIGHTNING TRANSIENT COUPLING MECHANISMS AND WAVEFORMS:

Coupling of lightning transient energy to aircraft systems and associated wiring can result in complex voltage and current waveforms on the system wiring and circuits. The coupling and resulting waveforms depend on many aircraft features such as structural materials, openings in the structure and skins, wire routing, shielding characteristics, and circuit characteristics. However, the complex coupling mechanisms can be broken into simpler descriptions of the coupling.

B.1.1 Lightning Transient Coupling Mechanisms:

A lightning strike to an aircraft will result in lightning currents that are conducted on the aircraft skin and major structure. This external current will then produce voltage and current on wires inside the aircraft. For example, coupling that results from current flowing past an opening or aperture in a conducting cylinder is illustrated in Figure B2. These are typical responses for wires within a metal aircraft fuselage that has door, window and access hatch openings. Using lightning current Component A waveform, the resulting current and voltage on a wire within the cylinder are shown. In Figure B3, the voltage and current waveforms for various wire, shield, and circuit impedance arrangements are shown.

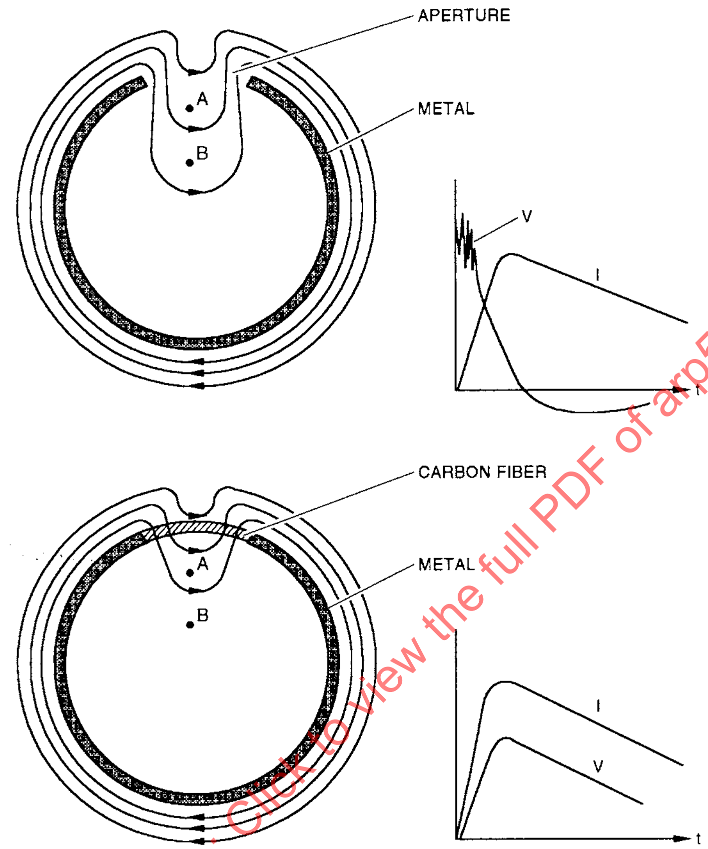


FIGURE B2 - Aperture Coupled Fields

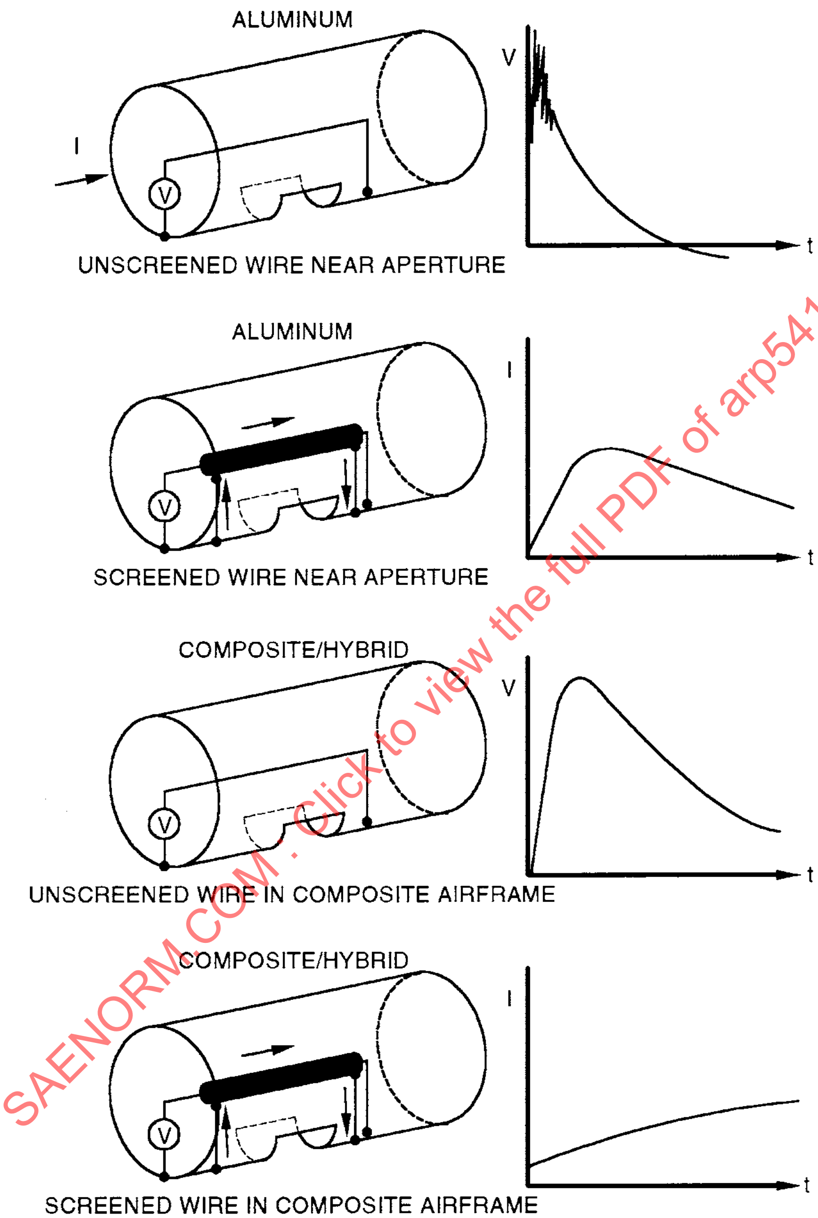


FIGURE B3 - Field Topology Effects on Coupling Mechanisms

B.1.1 (Continued):

Figure B4 illustrates the coupling mechanisms for a single wire routed along conducting structure. For the lightning transient current, I_1 (current Component A), flowing through a conducting structure, the wire, circuit loads and coupling can be represented by lumped-element networks in Figures B4B and B4C. The transfer inductance, L_{12}, represents coupling of magnetic fields from the current in the structure into the loop formed by the wire and conducting structure. The resistance, R_{12}, represents the resistance of the conducting structure below the wire.

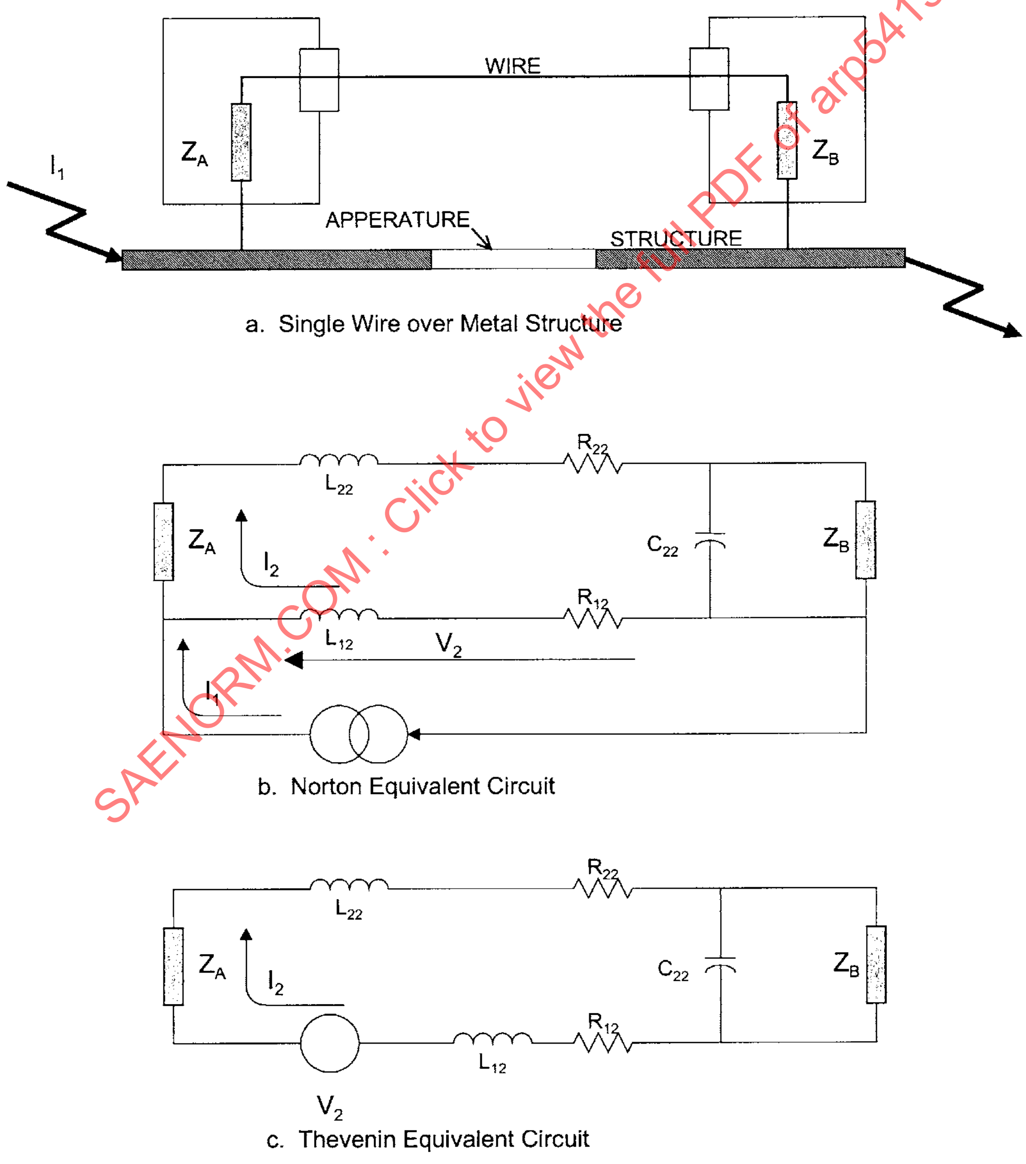


FIGURE B4 - Wire and Circuit Coupling Mechanisms

B.1.1 (Continued):

During the early times in the lightning waveforms, such as current Component A waveform, the voltage, V_2, is mostly due to the magnetic coupling for wiring terminating in a high impedance. So the voltage follows an amplitude/time curve proportional to the rate of change of the current waveform. Hence, test Waveform 2 reasonably approximates this voltage. This voltage appears as a source in series with the wire and structure loop, as illustrated in Figure B4C. Figure B4B is the Norton equivalent circuit and Figure B4C is the Thevenin equivalent circuit.

For wires with both ends terminated in a low impedance, the magnetic field would produce a current with an amplitude/time curve proportional to the magnetic field amplitude. Thus, test Waveform 1 reasonably approximates this current.

Very often, the wire is completely enclosed by a conducting shield. This could be in the form of a conduit mounted on the wing, through which the wire is routed. Or, it could be an outer shield of a multi-wire bundle. In either case, the configuration of a wire in a conductive shield along a highly conductive structure would be as illustrated by Figure B5A, and the circuit model would be as Figure B5B.

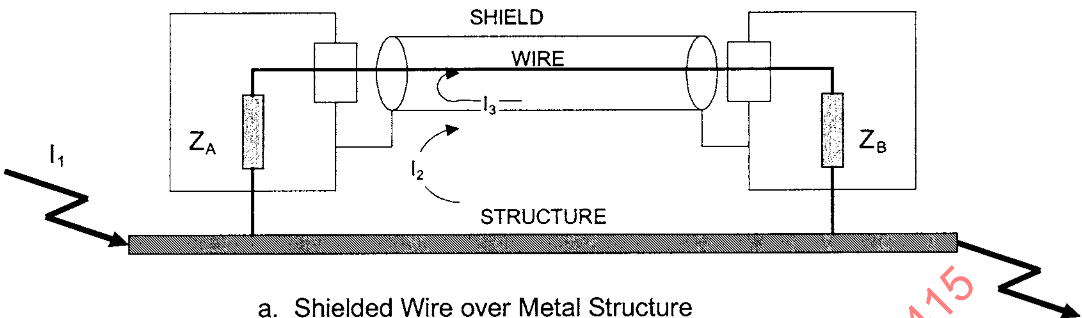
The current in the shield would have essentially the same waveform as the current Component A waveform in the structure; hence, the incorporation of test Waveform 1. Figure B5C is a circuit model, assuming a current source, where I2 is transient Waveform 1.

For the wire, there is a voltage source V_3 in the wire/structure loop, as illustrated in Figure B5D. This voltage is the same as that developed across the shield resistance by the current I_2.

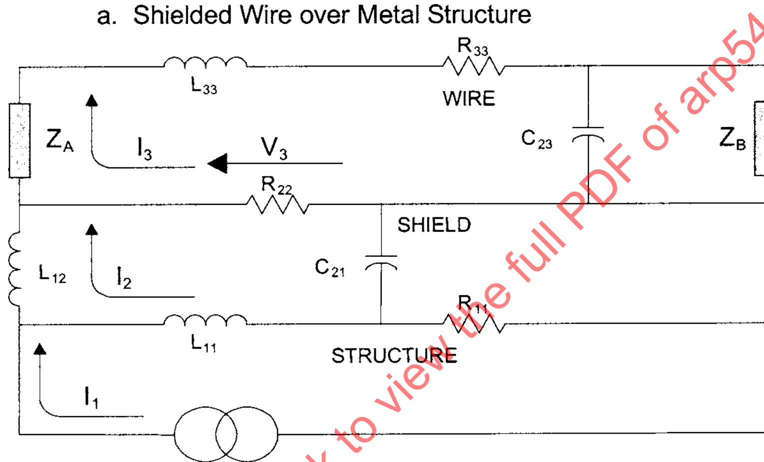
Where the airframe is constructed of conductive composite such as CFC, the circuit model remains the same. Figure B6A illustrates a single shielded wire routed within a section of structure. This can be represented by Figure B6B where I_1 is the lightning current Component A, and I_3 is the current in the wire. As with the previous examples, Z_A and Z_B represent the terminating impedances.

The circuit model for the wire and shield is illustrated in Figure B6C. Here, the current I_2 in the shield/structure loop will have a much longer time to the peak, and an even longer time to decay to half-peak. This can be described as the current redistributing into the shield, and is represented by test Waveform 5. As before, this current in the resistance of the shield will create a voltage in the wire/shield loop, as illustrated in Figure B6D.

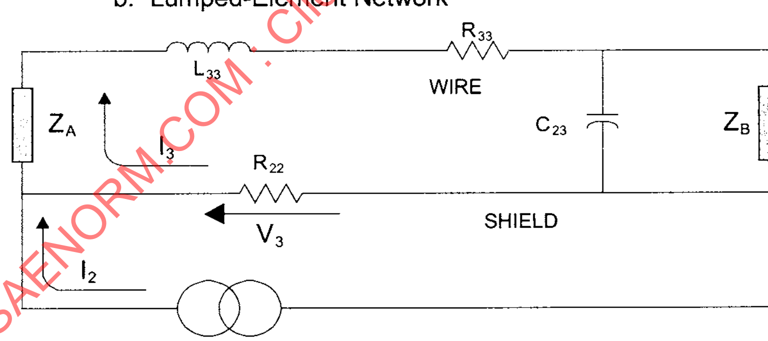
Thus, as shown in Figures B4, B5 and B6, the lightning current Component A waveform occurring at an attachment point can produce current Waveform 1 and voltage Waveform 4 sources. These sources drive internal wire responses and can produce current and voltage waveform responses ranging from Waveform 1 and 4 to responses having Waveform 5 or even longer waveforms. In addition to the waveform/response to the magnetic field produced by the current Component A waveform, voltage Waveform 2 can also be a response (see Figures B2, B3 and B4) to this Waveform A magnetic field.



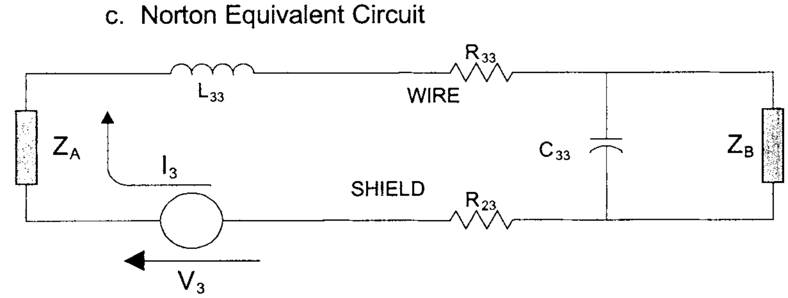
a. Shielded Wire over Metal Structure



b. Lumped-Element Network

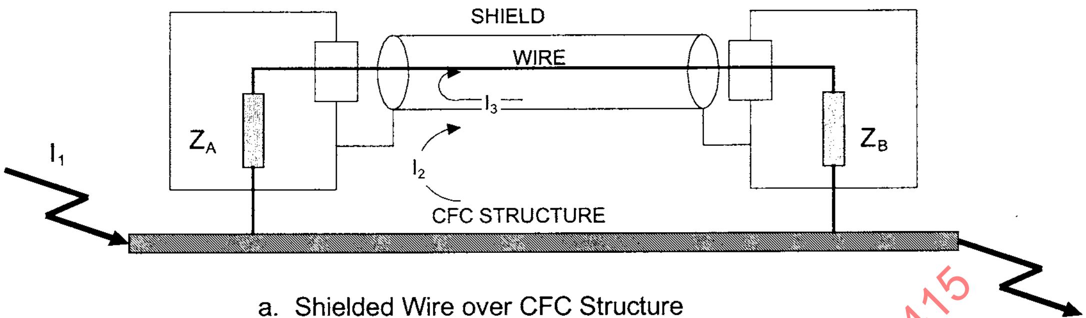


c. Norton Equivalent Circuit

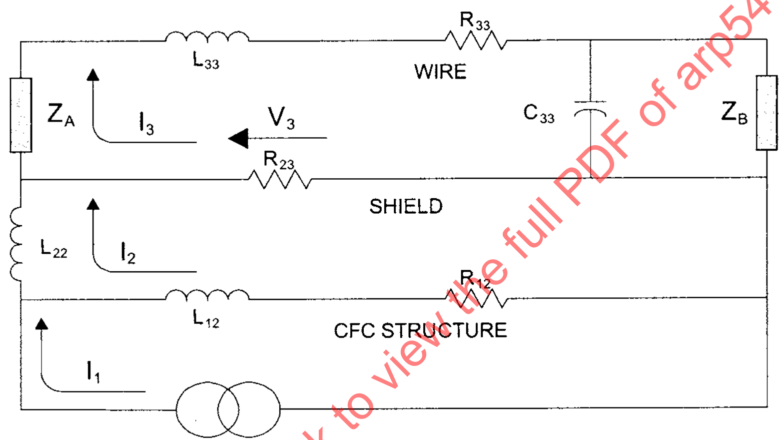


d. Thevenin Equivalent Circuit

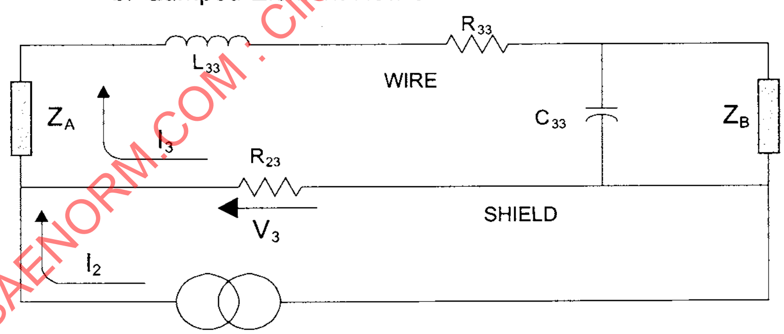
FIGURE B5 - Wire in a Conductive Shield



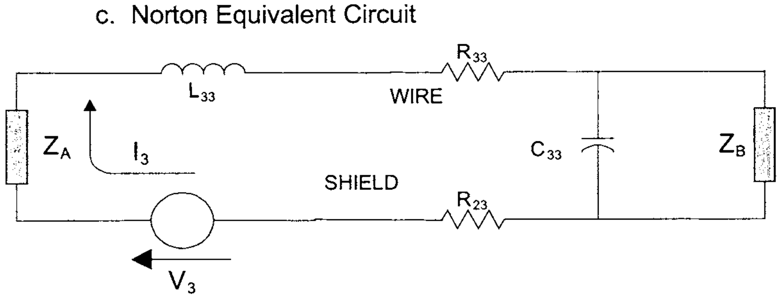
a. Shielded Wire over CFC Structure



b. Lumped-Element Network



c. Norton Equivalent Circuit



d. Thevenin Equivalent Circuit

FIGURE B6 - Structure Section

B.1.2 Forced Transient Response:

The electromagnetic processes and associated coupling mechanisms may be described by simple algebraic relationships:

V = RI and ø = LI

or ordinary differential equations having forms ranging in complexity from:

$$V = d\Phi/dt \qquad \text{(Eq. B1)}$$

to:

$$A_u\frac{d^uV}{dt^u} + \ldots + A_1\frac{dV}{dt} + A_oV = B_w\frac{d^wI}{dt^w} + \ldots + B_1\frac{dI}{dt} + B_oI \qquad \text{(Eq. B2)}$$

where:

I = Current Component A
Φ = Magnetic flux produced by current waveform
V = Interface voltage
L = Inductance
R = Resistance
C = Capacitance
A and B are functions of L, R and C

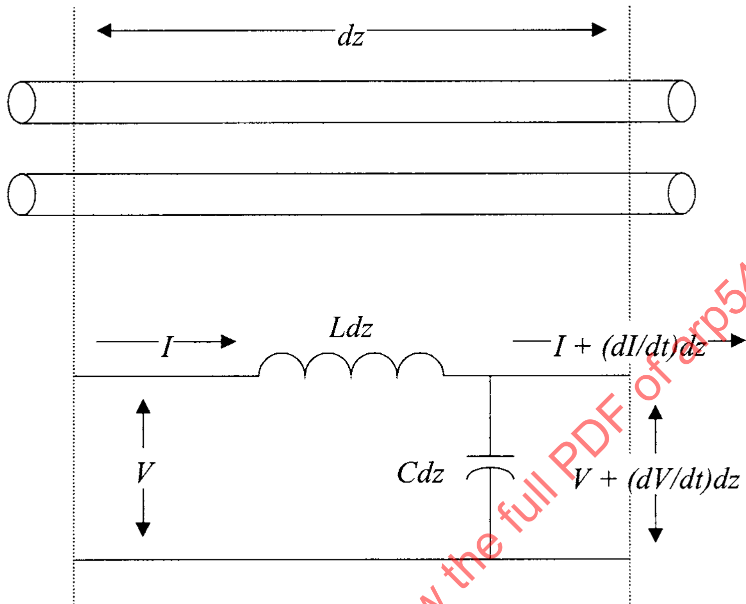
Test Waveforms 1, 2, 4 and 5 are representative solutions to these equations.

B.1.3 Oscillatory Transient Response:

There are typically discontinuities in the aircraft structures, as well as impedance mismatch between the aircraft and the lightning channel. These discontinuities and mismatches give rise to reflections, and to oscillating currents in the structure. These reflections result in a mixture of damped sinusoidal responses with different frequencies. The damped sinusoidal waveform responses can be represented by traveling wave solutions to the partial differential equations for electromagnetic transmission lines. Each frequency is a function of the length of the section of aircraft structure or wires. The lowest frequency is typically associated with the longest distance between discontinuities. This is often the length of the current path on the aircraft between lightning attachment points.

In addition to being driven by the lightning current waveforms conducted on the aircraft structure, aircraft wires have their own natural resonance at frequencies associated with their lengths when they are excited by the lightning waveforms. The wires and the adjacent conducting structure can be represented as an electromagnetic transmission line.

Transmission line segment



Partial differential equation representation

$$\frac{\partial V}{\partial z} = -L\frac{\partial I}{\partial t}$$

$$\frac{\partial I}{\partial z} = -C\frac{\partial V}{\partial t}$$

FIGURE B7 - Fundamental Transmission Line Segment

B.1.3 (Continued):

Figure B7 shows the fundamental transmission line segment and associated partial differential equations. From the partial differential equation for voltage and current change along the transmission line segments, the traveling wave solutions are developed.

$$\frac{\partial^2 V}{\partial z^2} = LC\frac{\partial^2 V}{\partial t^2} \text{ and } \frac{\partial^2 I}{\partial z^2} = LC\frac{\partial^2 I}{\partial t^2} \quad \text{(Eq. B3)}$$

$$V = F_1(t - \sqrt{LC}\, z) + F_2(t + \sqrt{LC}\, z) \quad \text{(Eq. B4)}$$

and:

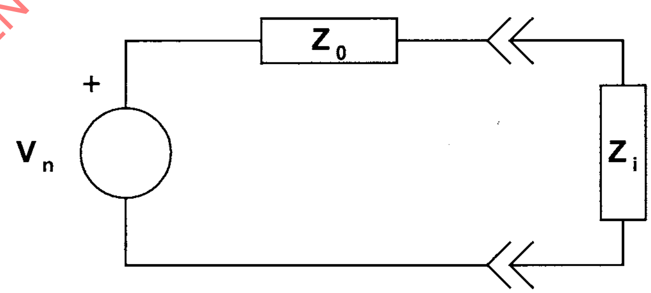
$$I = \frac{F_1(t - \sqrt{LC}\, z)}{Z_o} - \frac{F_2(t + \sqrt{LC}\, z)}{Z_o} \quad \text{(Eq. B5)}$$

where:

$$Z_o = \sqrt{\frac{L}{C}} \quad \text{(Eq. B6)}$$

As can be seen, Z_0 is the ratio of voltage to current for a single traveling wave at any given point and time along the transmission line. This traveling wave representation provides insight relative to the role Z_0 plays in providing a bound on those interface currents that are damped sinusoid responses resulting from traveling waves (see Figure B9).

Unlike forced response Waveforms 1, 2, 3, 4, and 5, a circuit representation for energy application to the circuit at either end of a system interface due, to travelling wave (natural) response Waveform 3, could be simply:



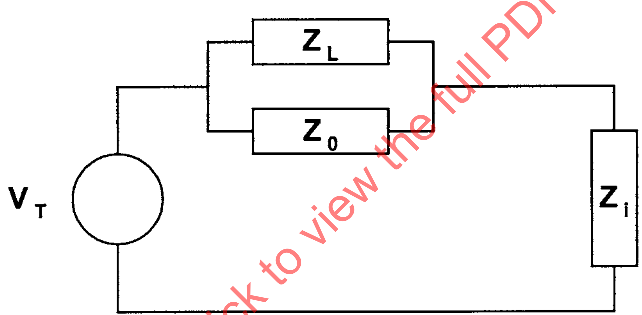
where: V_n is the natural response (traveling wave) voltage = $F_1 + F_2$, Z_i is either Z_A or Z_B

FIGURE B8 - Natural Response Energy Application to an Interface Circuit

B.1.4 Total Lightning Transient Response:

The total response induced by lightning current such as Waveform A is made up of the forced and natural responses. The total lightning transient response is then the actual transient level (ATL). The quantitative relationship between the lightning current and the corresponding total lightning transient response induced in aircraft wiring can be expressed in either the frequency domain or time domain.

A representation for energy application to an interface circuit (either and of a system interconnection) from a total response (contains the appropriate composite from the possible Waveform 1, 2, 4, and 5 forced responses and a significant Waveform 3 natural response) could be:



where:

$V_T = V_f + V_n$

V_f = composite forced responses

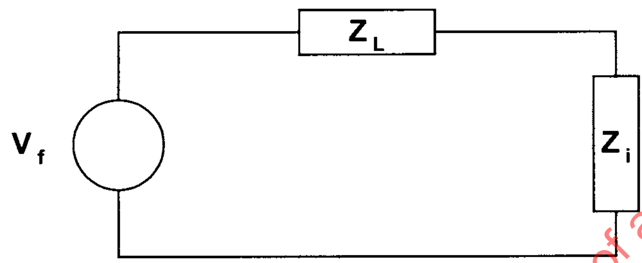
Z_L = loop impedance

FIGURE B9 - Total Response Energy Application to an Interface Circuit

Since Z_0 will only have a relatively small variation, when a significant natural response is present, Z_0 will provide a lower bound on current (during the Waveform 3 transient, current will not be able to go lower than V_n/Z_0).

B.1.4 (Continued):

When compared to the forced response, if the natural response does not occur or is insignificant, the current representation for an interface circuit reduces to:



where V_f is composite forced response which could also contain waveform 3

FIGURE B10 - Forced Response (Only) Energy Application to an Interface Circuit

A transfer function for the open circuit configuration of a 1-m long wire above a ground plane is shown in Figure B11. This transfer function includes the frequency range (below resonance) where the response could be approximated by $V = \frac{d\phi}{dt}$. This simpler equation would yield the double exponential derivative (Waveform 2) open circuit voltage.

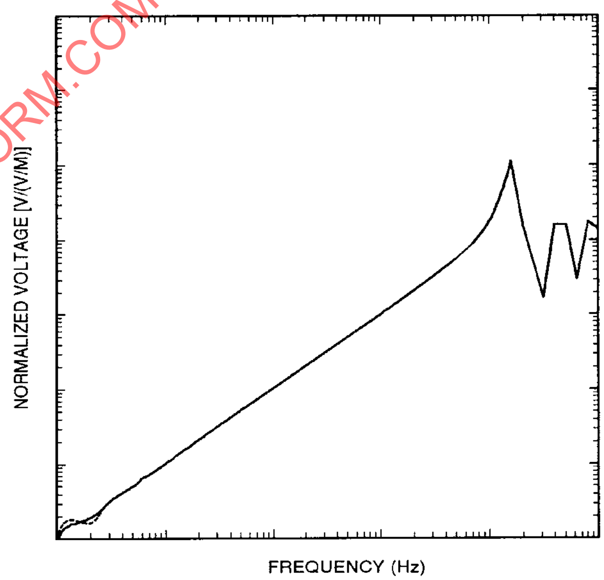


FIGURE B11 - Transfer Function - Open Circuit Configuration of a 1-Meter Long Wire Above a Ground Plane

B.1.4 (Continued):

A transfer function such as this would also represent the time domain ordinary differential equation for the total response (natural and forced) to the lightning current which would have the form:

$$D_n\frac{d^nV}{dt^n} + ... + D_1\frac{dV}{dt} + DoV = Em\frac{d^nI}{dt^n} + ... + E_1\frac{d^2I}{dt^2} + Eo\frac{dI}{dt} \quad \text{(Eq. B7)}$$

where:

V = Voltage at any particular point
I = Current Component A
D and E are functions of L, R and C

As can be seen in the plots for solutions, shown in Figures 12 through 15, to the differential equation, the damped sinusoid waveform response would be the natural response seen in the early time response, of the various solutions, where the forced response would be seen at the later time, following the damped sinusoid.

It is important to recognize that the differential equation for the total response needs to contain additional terms for fidelity, an upper limit of 6 for n (order of the differential equation) should provide sufficient granularity, of the response associated with the early time resonance. Except for some relatively simple electrical configurations, the D and E parameters are not analytically determined. The quantitative response of complex aircraft electrical and electronic systems may need to be determined through an iterative process employing numerical and experimental methods.

Figures B12 through B16 show the early and late time response for a double exponential lightning pulse electromagnetic field (substantial aperture) coupled to a wire suspended above a ground plane. Also note that, from the transfer function of Figure B11, in which natural resonant frequencies can be identified, it is evident that the voltage associated with an open circuit loop could contain a significant traveling wave (Waveform 3 resonances) component in its response. In the plots of Figures B12 through B16, amplitudes are normalized to L_R (reference length) and time is normalized to:

$$\frac{L_n}{\pi c} \quad \text{(Eq. B8)}$$

with:

$\frac{L_n}{L_R}$ = 0.1, 0.01, 0.001, 0.0001; $\frac{\tau_r}{T_L}$ = 0.1, 1, 10, 100, 1000
L_n = Wire lengths (L_1, L_2, L_3, L_4) associated with the plots of Figures B9B through B9E
L_R = Reference length giving $\frac{\tau_r}{T_L} = 1$
$\tau_r = \frac{1}{\beta}$ from the double exponential equation

B.1.4 (Continued):

$\alpha << \beta$ (lightning current component A)
$\beta = 6.5 \times 10^5$
$\tau_r = 1.5 \times 10^{-6}$
$T_L = \frac{L}{c}$
$\pi = 3.14159265$
$c = 3 \times 10^8$ m/s

From the plot of Figure B12 $\left(\frac{\tau_r}{T_L} = 0.1, \frac{L_R}{L_R} = 1\right)$ it can be seen that the response to a double exponential excitation is strongly oscillatory with more distortion relative to the sinusoids of the other plots of Figures 12 through 16, due to higher modes, being somewhat more evident. The plot of Figure B13 $\left(\frac{\tau_r}{T_L} = 1, \frac{L_1}{L_R} = 0.1\right)$ still shows a strong oscillatory response. The plots of Figure B14 $\left(\frac{\tau_r}{T_L} = 10, \frac{L_2}{L_R} = 10^{-2}\right)$, Figure B15 $\left(\frac{\tau_r}{T_L} = 100, \frac{L_3}{L_R} = 10^{-3}\right)$ and Figure B16 $\left(\frac{\tau_r}{T_L} = 1000, \frac{L_4}{L_R} = 10^{-4}\right)$ show an oscillatory (early time) response on top of a double exponential derivative (longer time) response. The double exponential response is particularly dominant in Figure B16 (top plot).

As can be seen, the plots of Figures B14, B15 and B16 include the later time portion of the response (some portion of time after the sinusoid has damped out). Note, that for the relatively short wire (Figures B15 and B16), it could be easy to miss the "more" intense "early" time damped sinusoid. Because of the time duration for the top plot of Figure B15, the early time damped sinusoid appears to be questionable 'hash'. Even for the relatively shorter time duration (top plot) of Figure B16, the peak value (of the sinusoid) was not captured.

Structural voltage drop (Waveform 4) would be given by:

$$V = RI \quad \text{(Eq. B9)}$$

where:

V = Voltage between two points along the structure
I = Current Component A
R = Structure impedance (where structure impedance is dominated by resistance)

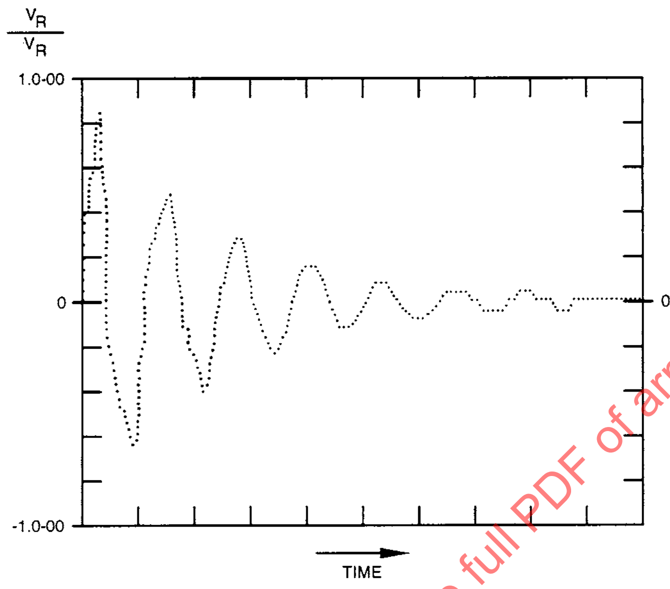


FIGURE B12 - Early Time Response of Electrically Very Long Wire

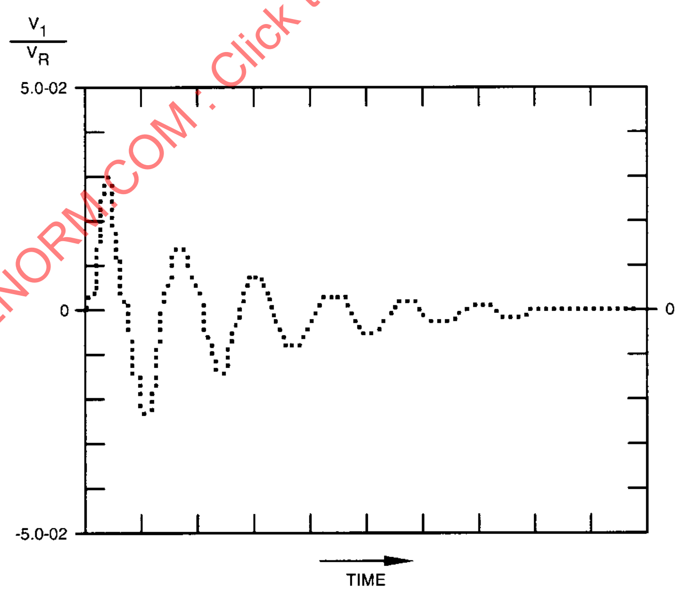


FIGURE B13 - Early Time Response of Electrically Long Wire

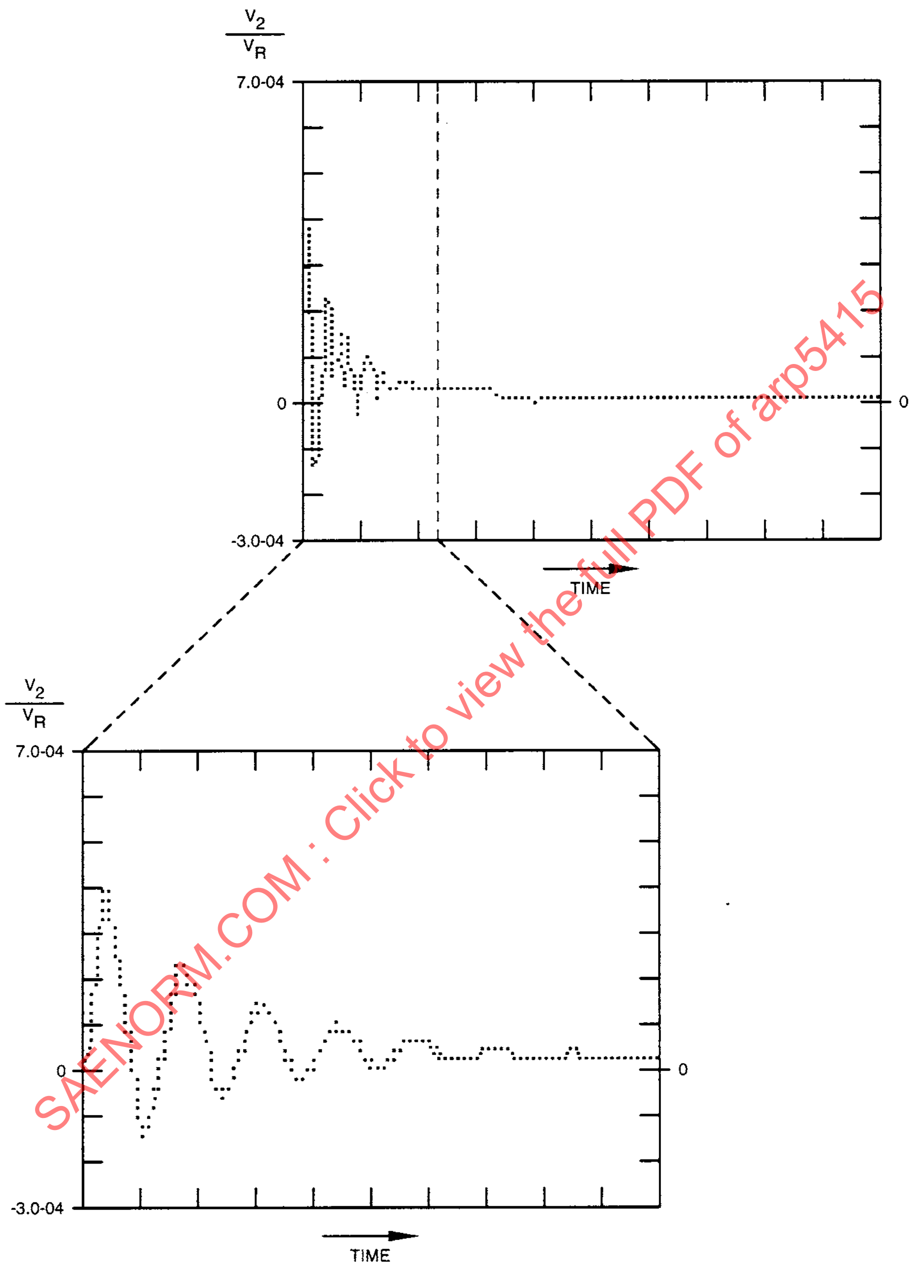


FIGURE B14 - Time History of Intermediate Length Wire

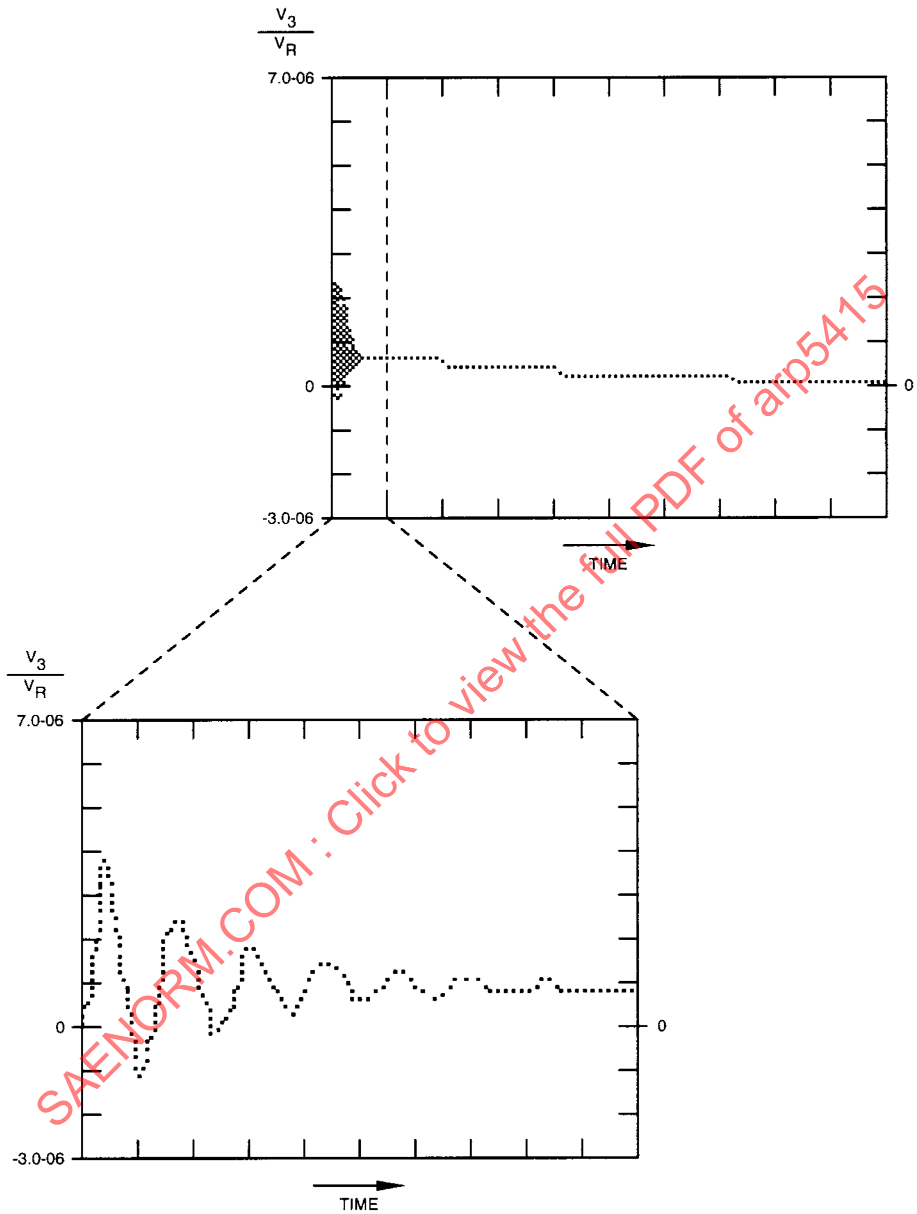


FIGURE B15 - Time History of Electrically Short Wire

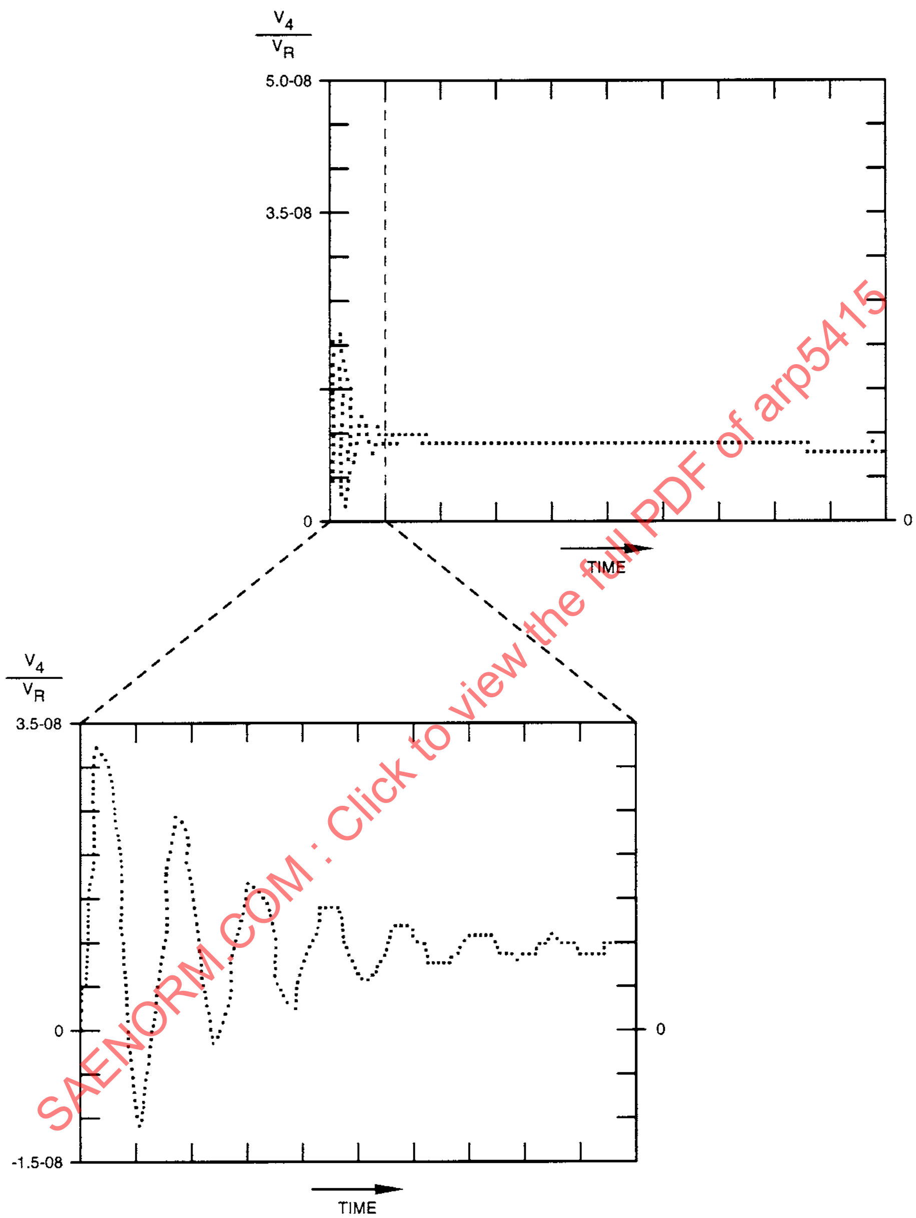


FIGURE B16 - Time History of Electrically Very Short Wire

B.1.4 (Continued):

In general, current (Waveforms 5A and 5B, for instance) and voltage responses in "buried" (several layers of shielding, etc.) wiring could be given by:

$$A_u\frac{d^uV}{dt^u} + \ldots + A_1\frac{dV}{dt} + A_oV = B_w\frac{d^wI}{dt^w} + \ldots + B_1\frac{dI}{dt} + B_oI \qquad \text{(Eq. B10)}$$

where:

I = Current Component A
V = Interface voltage
Aand B are a function of L, R and C

A transfer function for the short circuit configuration of a wire above a ground plane is shown in Figure B17. A transfer function such as this would also represent the simple algebraic equation:

$$\Phi = LI_1 \qquad \text{(Eq. B11)}$$

Where I_1 is the current induced in the wire. This equation would yield the double exponential (Waveform 1) short circuit current.

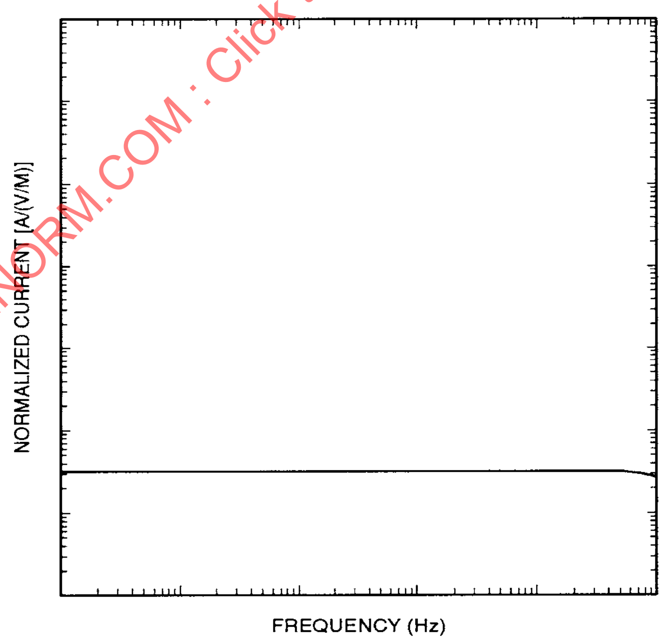


FIGURE B17 - Transfer Function - Short Circuit Configuration of a Wire Above a Ground Plane

B.2 EXAMPLE: AIRCRAFT TIME DOMAIN FINITE DIFFERENCE MODELING:

This example illustrates a very cost-effective application of the time domain finite difference (TDFD) method[4] for the lightning validation of a complex carbon fiber wing on a digital fly by wire aircraft.[5] The basic problem with validating the wing was that the wing is a sealed geometry, and no probes could be placed inside to make measurements. One could build an entire wing with imbedded probes to make measurements, but this is extremely expensive. The approach which was taken was to build a section of the wing with imbedded probes, perform a TDFD analysis of the section, perform a lightning test of the section, and then compare test and analysis results. If they compare favorably, then the TDFD method would be applied to the entire wing. This is in fact what was done.

The wing box (Figure B18) was 2.6 m long, 0.7 m wide and 0.1 m thick. The top and bottom skins, the side, the internal spars and one of the ribs were made of CFC. One rib, four stripes and the ends of the box were made of aluminum. Thicknesses were as follows:

Top and bottom CFC skins: 6 mm
CFC spars: 2 mm
Aluminum spar: 2 mm
CFC rib: 2 mm

The wing box included a fuel pipe, fuel pipe bell and wire conduit, these being numerically modeled as perfect conductors. The insulated fuel pipe couplings were modeled as gaps. The wire conduit was connected to the box at both ends and in the middle with bonding straps, assumed in the numerical model to be perfect conductors.

During tests, current was injected into one end of the wing box, the test geometry being as shown in Figure B19. Voltages and currents were measured at the points shown in Figures B20 and B21. Voltage and current probes were built into the test object when it was made, the current density in skin materials being measured by passing some of the skin material through Rogowski coils, a form of current transformer.

4. Rudolph, T. H., "Application of Finite Difference Techniques to Electromagnetic Scattering Problem," EMA-93-R-009, December 2, 1992.
5. Wahlgren, Bo. I. and Rosen, Jonas W., "Finite Difference Analysis of External and Internal Lightning Response of the JAS39 CFC Wing," presented at the 1988 International Aerospace and Ground Conference on Lightning and Static Electricity, April 19-22, 1988, Oklahoma City, Oklahoma.

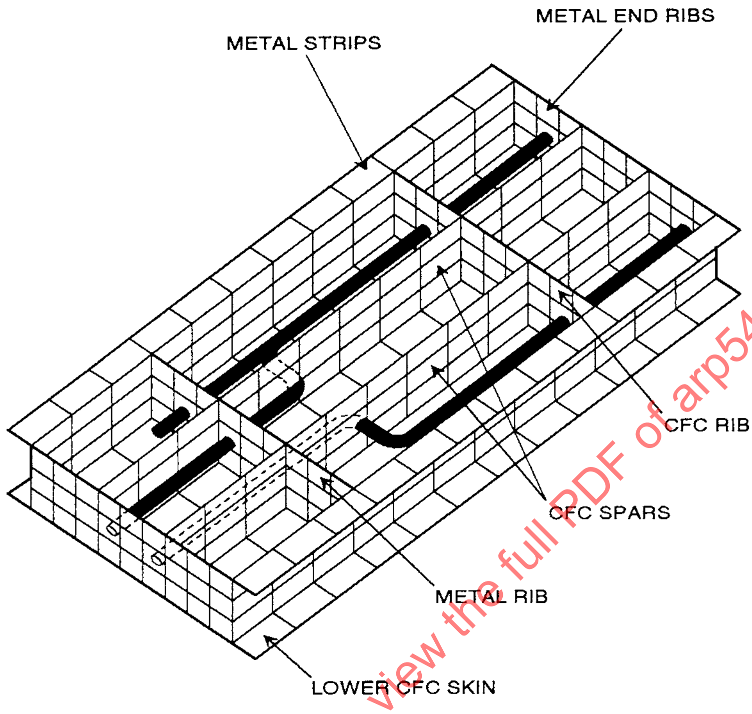


FIGURE B18 - Wing Box Analyzed With TDFD Technique

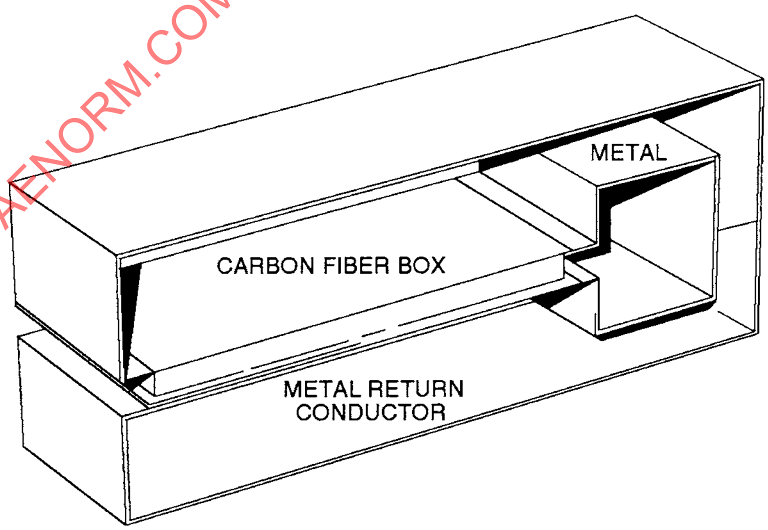


FIGURE B19 - Setup for Tests on Wing Box

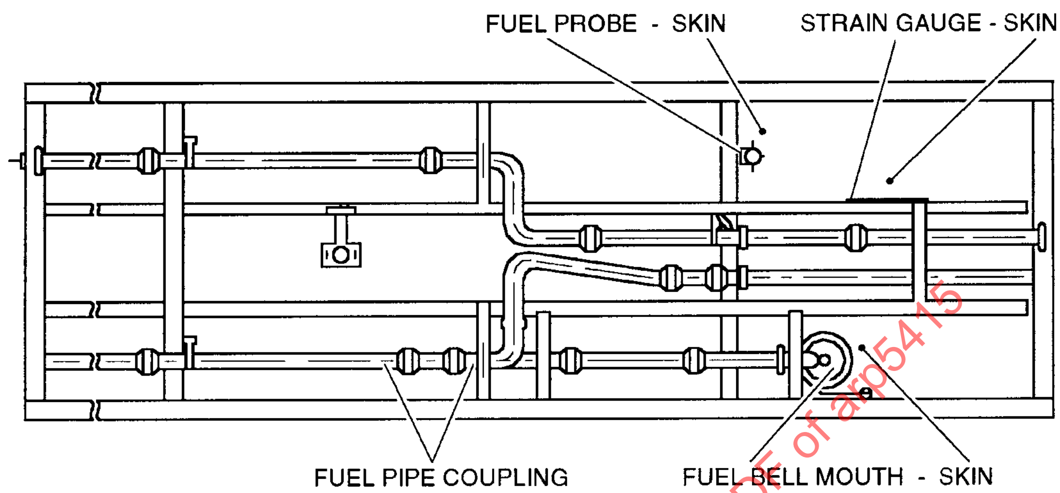


FIGURE B20 - Locations Where Voltages Were Measured

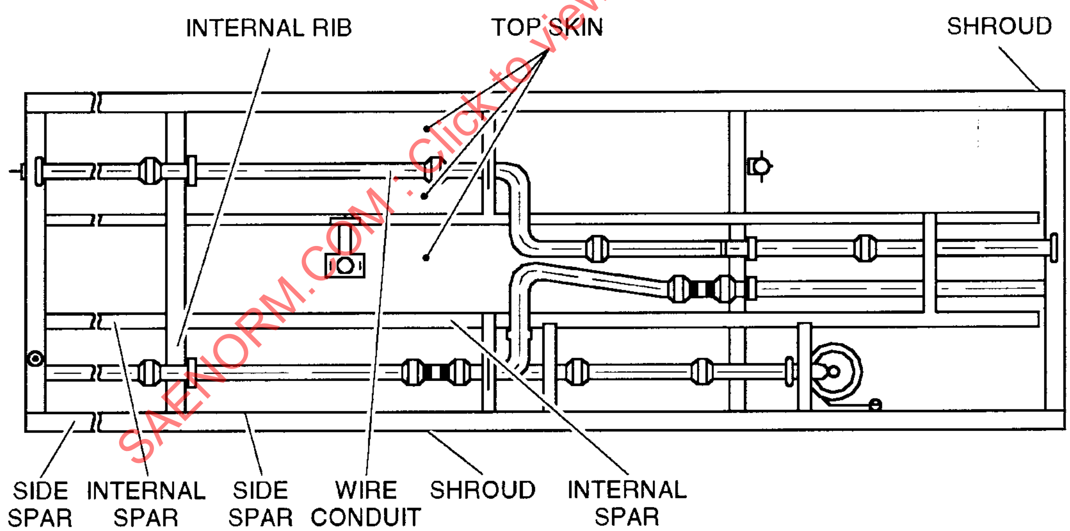


FIGURE B21 - Locatioins Where Currents Were Measured

B.2 (Continued):

Test and analysis conditions: Analysis and tests were done for two different conditions:

TABLE B1

Low level test:	400 A peak 0.25 μs rise time 1.0 μs decay time
High level test:	200 kA peak 10 μs rise time 150 μs decay time

The analysis was done with the TDFD techniques described earlier. The CFC surface and transfer impedances were modeled by the approach described in [6], though modified somewhat to conserve computer time. The time and space resolution for the two cases were:

TABLE B2

Low level:	Δx = 10 cm Δy = 4 cm Δz = 2.5 cm Δt = 50 ps Volume = 60,680 cells Number of time steps = 60,000 Simulated time = 3 μs Bandwidth = 700 MHz
High level:	Δx = 20 cm Δy = 7 cm Δz = 4 cm Δt = 100 ps Volume = 17,600 cells Number of time steps = 30,000 Simulated time = 30 μs Bandwidth = 350 MHz

6. McKenna, P. M., Rudolph, T. H., and Perala, R. A., "A Time Domain Representation of Surface and Transfer Impedance Useful for Analysis of Advanced Composite Aircraft," International Aerospace and Ground Conference on Lightning and Static Electricity, June 26-28, 1984, Orlando, Florida.