SAE Aerospace
An SAE International Group

AEROSPACE RECOMMENDED PRACTICE

SAE ARP5416 REV. A

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Superseding ARP5416

Aircraft Lightning Test Methods

RATIONALE

With the original release of the document, many new test methods were provided to account for aircraft operational experience and changing aircraft technology, including more reliance on electronic data and control systems and increasing use of composite materials in aircraft structures. As experience is gained with these test methods, some changes and clarifications are needed to ensure consistency across test organizations, particularly regarding high voltage tests and integrated system functional upset tests. Also, ignition source detection methods have historically relied upon the use of Polaroid film as the standard. Since this film's source of supply is rapidly disappearing, photographic methods using modern camera technologies needs to be included in the recommended practice.

FOREWORD

This SAE Aerospace Recommended Practice (ARP) has its origins in the SAE AE-4L Committee's "Blue" book issued in 1978 and titled "Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware." Subsequent to the issuance of the "Blue" book, the SAE AE-4L developed MIL-STD-1757 for the United States military dated 1981 and titled "Lightning Qualification Techniques for Aerospace Vehicles and Hardware." In MIL-STD-1757, the committee placed the test methodology contained in the "Blue" book into a more formalized format. This ARP is a significant refinement and expansion of the basic material from these sources, providing a more thorough and updated description of the test techniques.

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1. SCOPE

This document is one of a set covering the whole spectrum of aircraft interaction with lightning. This document is intended to describe how to conduct lightning direct effects tests and indirect system upset effects tests. Indirect effects upset and damage tolerance tests for individual equipment items are addressed in DO-160/ED-14. Documents relating to other aspects of the certification process, including definition of the lightning environment, zoning, and indirect effects certification are listed in Section 2.

This document presents test techniques for simulated lightning testing of aircraft and the associated systems. This document does not include design criteria nor does it specify which items should or should not be tested. Acceptable levels of damage and/or pass/fail criteria for the qualification tests must be approved by the cognizant certification authority for each particular case. When lightning tests are a part of a certification plan, the test methods described herein are an acceptable means, but not the only means, of meeting the test requirements of the certification plan.

Each test method is set out in a uniform format, describing the test purpose, test object, test setup, test waveforms (voltage and/or current), measurements and data recording, test procedure and data interpretation. Guidance is provided on how to select the appropriate test or series of tests, and how the test results can be assessed.

Natural lightning is a complex and variable phenomenon and its interaction with different types of vehicles may be manifested in many different ways. It is not intended that every test described herein be applied to every system requiring lightning verification tests. The document is written so that specific aspects of the environment can be called out for each specific program as dictated by the vehicle design, performance and mission constraints.

2. REFERENCES

2.1 Applicable Documents

The documents below provide various sources of information relevant to aircraft lightning testing including descriptions of the external lightning environment applicable to aircraft, methods of determining lightning zoning of aircraft, regulatory requirements, and guidance on certifying aircraft by analysis and test.

NOTE: 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 referenced document are also acceptable.

2.1.1 SAE Publications

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

ARP4754 Guidelines for Development of Civil Aircraft and Systems

ARP5412 Aircraft Lightning Environment and Related Test Waveforms

ARP5414 Aircraft Lightning Zone

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

Report AE4L-76-1 "Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware", (Blue Book), dated June 20, 1978

Report AE4L-81-2 "Test Waveforms and Techniques for Assessing the Effects of Lightning Induced Transients", (Yellow Book), dated December 15, 1981

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2.1.2 Federal Aviation Regulations (FAR)

Available from the U.S. Department of Transportation, Subsequent Distribution Office, Ardmore East Business Center, 3341 Q 75th Avenue, Landover, MD 20785, www.faa.gov.

US Code of Federal Regulations 14 CFR Parts 21, 23, 25, 27 & 29; Sections x.581, .610, .867, .899, .901, .903, .954, .1301, .1309, .1316, .1431 and .1529 (as applicable)

2.1.3 FAA Advisory Circulars (AC)

Available from the U.S. Department of Transportation, Subsequent Distribution Office, Ardmore East Business Center, 3341 Q 75th Avenue, Landover, MD 20785, www.faa.gov.

AC 20-53A "Protection of Airplane Fuel Systems Against Fuel Vapor Ignition Due to Lightning", dated April 12, 1985, Rev B issued June 5, 2006. 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 20-136 "Protection of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning", dated March 5, 1990, Rev B issued September, 7, 2011

AC 21-16D RTCA Document DO-160D, dated July 21, 1998, Rev G issued June 22, 2011

AC 23.1309-1C "Equipment, Systems, and Installations", dated March 12, 1999, Rev 1E issued November 17, 2011

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

AC 27-1B "Certification of Normal Category Rotorcraft", dated September 30, 1999, Change 3 issued September 30, 2008

AC 29-2C "Certification of Transport Category Rotorcraft", dated September 30, 1999, Change 3 issued September 30, 2008

2.1.4 RTCA, Inc. Publications

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

RTCA/DO-160D "Environmental Conditions and Test Procedures for Airborne Equipment", dated July 29, 1997, including Change No. 1, dated December, 2000, Change No. 2, dated June, 2001 and Change No. 3, dated December, 2002, Rev G issued December 8, 2010

2.1.5 EASA Publications

Available from European Aviation Safety Agency, Postfach 10 12 53, D-50452 Koeln, Germany, Tel: +49-221-8999-000, www.easa.eu.int.

CS Parts 21, 23, 25, 27 & 29; Sections x.581, .610, .867, .899, .901, .903, .954, .1301, .1309, .1316, .1431 and .1529 (Parts and Sections as applicable)

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2.1.6 EUROCAE Publications

Available from EUROCAE, 102, rue Etienne Dolet, 92240 Malakoff, France, Tel: +33.1.40.92.79.30, www.eurocae.net.

EUROCAE ED-14D "Environmental Conditions and Test Procedures for Airborne Equipment", dated July, 1997, including Change No. 1, dated December, 2000, and Change No. 2, dated June, 2001 and Change No. 3, dated December, 2002, Rev G issued May, 2011

EUROCAE ED-79 "Certification Considerations for Highly Integrated or Complex Aircraft Systems", dated April, 1997, Rev A issued December, 2010

EUROCAE ED-81 "Certification of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning", dated May, 1996, including Amendment No. 1, dated August 26, 1999

EUROCAE ED-84 "Aircraft Lightning Environment and Related Test Waveforms Standard", dated August, 1997, including Amendment No. 1, dated October 19, 1999, including Amendment No. 2, dated May, 2001, including Amendment No. 3, dated June, 2006

EUROCAE ED-91 "Aircraft Lightning Zoning Standard", dated July, 1998, including Amendment No. 1, dated September 6, 1999, including Amendment No. 2, dated June, 2006

2.1.7 ANSI Publications

Available from American National Standards Institute, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, www.ansi.org.

ANSI Z540.1 "General Requirements for Calibration Laboratories and Measuring and Test Equipment", dated 1994

2.1.8 IEC Publications

Available from Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112.

IEC 60060-2 "High-Voltage Test Techniques - Part 2: Measuring Systems", dated November, 1994

2.2 Definitions, Abbreviations, and Acronyms

2.2.1 Definitions

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

ACTUAL TRANSIENT LEVEL (ATL): The level of transient voltage and/or current that 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.

ARC ROOT: The location on the surface of a conducting body at which the lightning channel is attached while high current flows.

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

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

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

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

DISCHARGE: Relative to High Voltage (HV) or High Current (HC) impulse generators, the transfer of charge from the storage capacitors. This action may or may not cause an electrical breakdown of the gap between the electrodes connected to the output terminals of the generator.

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 item, or wire bundles that interconnect equipment.

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

EXTERNAL ENVIRONMENT: Characterization of the natural lightning environment for design and certification purposes as defined in ARP5412/ED-84.

FACILITY GROUND: Reference ground plane (electrical) for the experiment or test configuration.

FLASHOVER: The condition when the arc produced by a gap breakdown passes over or close to a dielectric surface without puncture.

GAP BREAKDOWN: The electrical breakdown of the gap between the electrodes connected to the generator output terminals. This breakdown is caused by the discharge of the capacitors of an HV or HC impulse generator.

GENERATOR: A set of equipment (waveform synthesizer amplifiers, couplers, etc.) that delivers a voltage or current waveform, via direct or indirect coupling to the equipment under test (EUT).

HOT SPOT: A surface in contact with fuel/air mixtures that is heated by the conduction of lightning currents to a temperature which will ignite the mixtures.

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 two clouds, or between cloud and ground. It can consist of one or more return strokes, plus intermediate or continuing currents.

LIGHTNING HIGH VOLTAGE WAVEFORMS (A, B, C, AND D): Different standardized high voltage waveforms. For details refer ARP5412/ED-84.

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

LIGHTNING STRIKE ZONES: Aircraft surface areas and structures classified according to the possibility of lightning attachment, dwell time and current conduction. See ARP5414/ED-91 for reference.

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

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LOCAL GROUND: Any ground strap or conductor that is connected to the equipment and the same part of airframe structure in which that equipment is installed. The ground strap or conductor would, therefore, be bonded to the same ground plane that the equipment is mounted to and, during a lightning strike, would be at the same potential as the equipment.

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). 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.

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

PUNCTURE: Localized irreversible breakdown of insulation properties of a solid dielectric material.

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

SHIELDED CABLE (WIRE) BUNDLE: A wire bundle that contains one or more shields. Such wire bundles may include SOME unshielded wires.

STREAMER: Branch-like ionized paths that occur in the presence of a direct stroke or under conditions when lightning strokes are imminent.

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.

SYSTEM: A combination of two or more parts or equipment, generally physically separated when in operation, and such other units, assemblies, and basic parts necessary to perform an operational function or functions.

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.

THERMAL SPARKS: Burning particles emitted by rapid melting and vaporization of conductive materials carrying current through a point contact.

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

UNSHIELDED CABLE (WIRE) BUNDLE: A wire bundle that contains no shields.

UPSET: (See System Functional Upset).

V_{OC} AND I_{SC}: Open circuit voltage and short circuit current from a test generator for a particular primary excitation of the generator. The ratio (V_{OC}/I_{SC}) of the two quantities denotes the source impedance (see ARP5415 for reference).

VOLTAGE AND CURRENT TEST/LIMIT LEVELS (V_T, I_T, V_L AND I_L): Voltage and current excitation thresholds for generators used for testing of systems and equipment. For details, refer to ARP5412/ED-84, ARP5415, and DO-160/ED-14.

VOLTAGE SPARK: An electrical breakdown of a gaseous dielectric between two separated conductors.

ZONING (1A, 1B, 1C, 2A, 2B, AND 3): The process (or end result of the process) of determining the location on an aircraft to which the components of the external environment are applied. For details, refer to ARP5414/ED-91.

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2.2.2 Abbreviations

A	amperes
AC	alternating current
C	CAPACITANCE
cm	centimeters
d or D	distance or diameter
dB	decibel
DC	direct current
f or F	frequency
ft	feet
GΩ	gigaohms
Hg	mercury
Hz	hertz
i or I	current
K	constant
kA	kiloamperes
kHz	kilohertz
kV	kilovolts
L	inductance
m	meter
mA	milliamperes
MHz	megahertz
μH	microhenries
μJ	microjoules
μs	microseconds
mm	millimeters
mmHg	millimeters of mercury
MΩ	megohms
nH	nanohenries
p	pressure
P	power
pF	picofarad
ps	picoseconds
Ω	ohms
Q	resonance characteristics
R	resistance
s	seconds
V	voltage or volts
W	watts
Z	impedance

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2.2.3 Acronyms

AC	Advisory Circular
ANSI	American National Standards Institute
AOA	Angle-Of-Attack
ARP	Aerospace Recommended Practice
ATL	Actual Transient Level
CFC	Carbon Fiber Composite
CFR	Code of Federal Regulations
CFRP	Carbon Fiber Reinforced Plastic
CN	Coupling Network
CS	Certification Specification
CW	Continuous Wave
EED	Electro-Explosive Device
EASA	European Aviation Safety Agency

EFIS	Electronic Flight Information System
EM	Electromagnetic
EMC	Electromagnetic Compatibility
ETDL	Equipment Transient Design 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
FFT	Fast Fourier Transforms
FHA	Functional Hazard Assessment
FRP	Fiberglas Reinforced Plastic
HIRF	High Intensity Radiated Fields
HV	High Voltage
ICAS	Integrated Crew Alerting System
ICOLSE	International Conference on Lightning and Static Electricity
IEC	International Electrotechnical Commission
IMA	Integrated Modular Avionics
IR	I * R (structural current times resistance)
LISN	Line Impedance Stabilization Network
LRU	Line Replaceable Unit
MIL-STD	Military Standard
NIST	National Institute of Standards and Technology
RF	Radio Frequency
RTCA	RTCA, Inc., formerly Radio Technical Committee on Aeronautics
SLPM	Standard Liters Per Minute
SSA	System Safety Assessment
TCL	Transient Control Level
TLD	Time-Limited Dispatch

3. LIGHTNING EFFECTS

The lightning effects to which aircraft are exposed and the effects that should be reproduced through laboratory testing with simulated lightning waveforms can be divided into direct and indirect effects.

Direct effects include burning, eroding, blasting and structural deformation caused by lightning arc attachment, which includes high-pressure shock waves, magnetic forces and thermal effects produced by the associated high currents.

Indirect effects are those resulting from the interaction of the electromagnetic fields accompanying lightning with electrical/electronic equipment in the aircraft. These fields are the results of aperture coupling and structural IR (current times resistance) voltage rise due to lightning currents in aircraft.

In some cases both direct and indirect effects may occur to the same component of the aircraft. An example would be a lightning flash to an antenna which physically damages the antenna and also injects large currents directly into the transmitter or receiver signal and power lines. In this document the physical damage to the antenna will be treated as a direct effect, whereas the voltages and/or currents that couple from the antenna into the radio/radar equipment will be treated as an indirect effect.

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3.1 Direct Effects

The major examples of direct effects due to lightning are categorized and listed below.

a. Dielectric Puncture

The puncture of a dielectric skin covering electrically conductive elements may cause holes ranging from pinholes to large diameter holes. These holes may result in the direct attachment of the lightning channel to the enclosed equipment. The likelihood of puncture is a function of the distance to the conductor underneath the dielectric, the thickness and dielectric strength of the skin, the condition of the dielectric surface, and the proximity of other conductors. A puncture of the dielectric skin will generally occur unless the voltage to puncture the dielectric at any point is significantly greater than the voltage required to cause flashover to the nearest conducting point on the airframe.

b. Arc Root Thermal Damage and Heating Effects

Burn through and material erosion can occur at the arc root. In metal, this is a function of current and time. In the arc root area, there is a large thermal input from the arc root itself, as well as a concentration of ohmic heating due to the high current densities. Most of the energy is generated at or very close to the surface of the metal. If the heat generated in the immediate arc root area is in excess of that which can be absorbed into the metal by conduction, then the excess is either lost in melting and vaporizing the metal or is re-radiated. There is a minimum charge transfer within a minimum time for a given thickness of any given metal below which melt-through cannot occur.

In carbon fiber composites the thermal effects are more pronounced. The thermal conductance and electrical resistance cause resin melting, vaporization, and ply delamination. This leads to an increase in “affected-area" in relation to the physical depth of damage. The arc root burning voltage of carbon is higher than that of metals. This effect, plus the high bulk resistivity, generates more heat in the immediate arc root area and the hot spots remain for a longer period than for most metals.

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For metallic surfaces it is primarily the combination of the intermediate and continuing current phase of the lightning flash that can exceed the minimum requirements of both current and duration for burn through or severe erosion. In the case of carbon fiber composites, however, short duration high action integral pulses as well as low current, long duration pulses produce high thermal inputs, and so all phases of the lightning flash are significant.

(1) Hot Spot Formation

Hot spot formation may occur on the inner surface of the aircraft skin opposite to the lightning attachment point. The effects of hot spots are significant primarily with regard to ignition of fuel and other highly flammable vapors.

(2) Ohmic Heating

The energy dissipated as heat in a conductor due to an electrical current is $\int i^2R*dt$ (watt-seconds). Where ‘i’ is the time varying current and ‘R’ is the ohmic resistance of the conductor. The ohmic heating generated by the complete lightning pulse is the ohmic resistance of the lightning path through the aircraft multiplied by the action integral of the pulse and is expressed in Joules or watt-seconds. In a lightning discharge, the high action integral phases of the lightning flash are of too short a duration for any heat generated in an aircraft structure by ohmic heating to disperse significantly.

(3) Exploding Conductors (Disruptive Forces)

Conductors may vaporize explosively if they have insufficient cross sectional area to carry lightning currents. The associated shock wave can give rise to severe damage particularly in confined spaces. This failure mechanism is particularly significant in electric wiring connected to external equipment (e.g., navigation lights, antennas, pitot tube heaters, etc.). If these are not adequately protected and are confined in or pass through closed compartments in the aircraft, they can present a significant hazard.

(4) Direct Effects Sparking

Two types of sparking can occur: thermal sparking and voltage sparking. Thermal sparks occur when currents pass through the interface joint between two parts and there is insufficient cross-sectional area to support the current. Voltage sparks occur when the voltage between two separated electrodes exceeds the breakdown level and discharge results. Voltage sparks are usually the result of induced voltages in the structure or wiring.

Most thermal sparking occurs near the edges of high spots on the mating surfaces where the interface pressure is at or close to zero. The primary causes are high current density and inadequate interface area and pressure. Thermal sparks consist of burning electrode material.

c. Acoustic Shock Wave Damage

The interaction of the arc and the aircraft surface can also produce a shock wave. The severity of the shock is dependent upon both the peak current value and the rate of rise of the current. In general, the damage due to acoustic shock wave is not significant on metal skins. Metal skins may be dented but generally not punctured. Stiff composite skins can suffer cracking and ruptures.

d. Magnetic Force

Charged particles in motion in a magnetic field experience a force that for a current flowing in a wire can be expressed as $F = (I \times B) L$, where F is the force, I is the current, L is the length of the wire, and B is the magnetic field. F, I, and B are vectors. For lightning currents flowing in aircraft, this force can manifest itself in various ways. One is a force on the surface of a conductor carrying lightning current. This effect can be explained as an element of current on one portion of the conductor producing a magnetic field that causes all other current elements to experience a force. The equation yields a force that is directed inward on all sides of the conductor. This force is only significant when the surface current density is greater than several kilo-amperes per millimeter. For example, a conductor of 5 mm diameter carrying a pulse of 200 kA peak current would experience a surface pressure of 1000 atmospheres. In some cases even relatively small forces can be significant. One such case is that of metal braid bonding straps. These can be compressed to near solid conductors leading to metal embrittlement and subsequent mechanical failure.

Another more common concern is that considerable magnetic forces can exist from currents flowing on separate conductors or from different sections of the same conductor where the lightning current is forced to change direction. The action of the force is to draw the separate conductors together or straighten out the single conductor. This force can also exist between current in the aircraft and the arc channel. This force is usually only of significance where the lightning current is confined to small-cross section conductors as might occur in some externally mounted equipment. Due to a change in current magnitude affecting both terms on the right side of the equation, the peak value of the force is proportional to the square of the peak current (i^2). The ultimate effect on the test object depends on the mechanical response of the test object.

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3.2 Indirect Effects

Indirect effects are the result of the interaction of the electromagnetic fields accompanying a lightning flash with the aircraft which creates a transient lightning internal environment for the duration of the flash. This internal environment causes voltages and currents on interconnecting wiring which, in turn, appear at equipment interfaces.

Indirect effects result from the following coupling mechanisms:

a. Apertures

Apertures are defined as electromagnetically transparent openings in the structure. Examples include windows, canopies, radomes, gaps, non-conductive panels, etc. Coupling of voltages and currents to internal wiring results from the fields that pass through apertures.

b. Diffusion

Diffusion is the process by which electromagnetic fields penetrate through the thickness of a conductive material. It results in internal fields that reflect a lengthened waveform of the external driving current to the vehicle. For highly conductive structures like aluminum, this generally results in a coupled current of insignificant amplitude. For more resistive materials like carbon fiber composites, the amplitude of the coupled current can be significant.

c. Structural IR Voltages

These result from the current flow through the impedance of the structure between two ends of an electrical circuit. For highly conductive structures like aluminum the magnitude of this voltage is generally insignificant. For more resistive structures like carbon fiber composites, the magnitude of this voltage can be significant.

d. Conductive Penetrations

Any conductor that is partially external and partially internal to the structure can form a path to directly conduct currents to the interior of the vehicle. Examples are wiring from external elements such as antennas, lights and heaters, and mechanical cables or tubing that is conductive. If such penetrations are not well bonded or isolated at penetration points, they can conduct significant currents inside the vehicle.

4. PLANNING OF LIGHTNING EFFECTS TESTS

Before conducting tests on airborne equipment and systems for lightning effects, careful planning for conducting the tests should be accomplished. Many aspects of the testing need to be determined in advance to ensure a high quality and valid test. Some of these items are determination of the lightning zone where the hardware is located, the waveforms that need to be applied, the type(s) of configuration(s) and number of samples for each configuration, the location and number of test points, and success criteria. Other hardware items that are needed to simulate an actual installation such as adjacent support structure or objects located under dielectric surfaces need to be located or manufactured.

An important part of the planning process involves developing documentation to support the actual testing. This documentation may include a separate “test plan” and “test procedure,” or the concepts of both may be combined in a single document. A test plan will typically provide the purpose, general scope and aspects of the planned testing to help various program and customer personnel deal with issues associated with planning, budgeting for, and supporting the test. The test procedure typically is a much more involved document that provides details on the test object, zoning, applicable waveforms, laboratory test equipment, success criteria, step-by-step procedures for each individual test, and any other relevant aspects. The test procedure should adapt and refine the applicable tests contained in this ARP to the particular hardware being evaluated. Since this ARP deals with details of testing, it generally refers to material that should be contained in a test procedure rather than a test plan. It should be recognized that the terms “test procedure” and “test plan” have often been used interchangeably in the past. Past documents have also used a test plan to define ‘Why’ and ‘What’ is being tested and a test procedure to define ‘How’ the test article is being tested.

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4.1 Test Object Conformity

Three types of tests are typically done:

a. Development - Evaluation of non-conformed, built-up or off the shelf parts. Data from these tests does not meet the requirements of qualification or certification tests, but may lead to further refinements in design intended for certification.

b. Qualification - Data taken with quality assurance agreement as to the test set-up and part number. Data typically used for overall system certification. Test is run to specification and data approved by the cognizant airworthiness authority.

c. Certification - Contains all qualification data and part conformity paperwork. Test data approved by the cognizant airworthiness authority and submitted as a part of aircraft lightning certification package.

Engineering or evaluation testing may be performed on any system or unit prior to a certification. However, when conducting a certification test the system is required to meet conformity requirements. Test objects which are of a computer nature must have verified and documented software installed. The process of conformity can take some time. The applicant is advised to start the process early in order to ensure that the proper levels of conformity requirements have been achieved prior to conducting the test. If not addressed early it may impact the test schedule or proper credit for test results may not be obtained. Due to the fact that conformity requirements may vary depending upon the type of testing being conducted as well as the type of certification sought, it is recommended that the applicant coordinate these requirements with the certification authorities with a view to reach an agreement, well in advance of actual testing.

Any differences between the configuration of the test article and the final production configuration should be analyzed to show that the differences do not impact the test. Conformity requirements should be reviewed in detail prior to discussion with the authorities and submission of the test documentation and test schedule.

4.2 Test Procedure

An outline of a typical test procedure is shown below. The content of a specific test procedure may contain more or less material, based on the nature of the testing. It is recommended that the applicant coordinate with the certification authorities well in advance of the final formulation of the procedure.

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a. INTRODUCTION

- Scope
- Objective (include whether Certification is goal)
- Test Location
- Test Witnessing

b. TEST OBJECT

- Description
- Conformity Aspects

c. TEST EQUIPMENT

- Description
- Calibration

d. SAFETY CONSIDERATIONS

e. TEST REQUIREMENTS

- Detailed Description of each Test, using this ARP as the basis
- Pass/Fail Criteria
- Operating Modes For Electrical/Electronic Equipment and Evaluation Techniques

f. TEST REPORT REQUIREMENTS

4.3 Measurement Set-Up Calibration

Test and measurement equipment requiring calibration should be calibrated before lightning tests.

The outputs of generation apparatus such as HV generators and amplifiers should be verified before every test sequence.

Background levels should be verified and noise levels minimized. In addition, care should be taken to avoid spurious coupling, for example, by the use of optical fibers.

Some examples of calibration methods can be found in IEC 60060-2.

4.4 Test Safety Aspects

Testing for the direct and indirect effects of lightning requires high-energy electrical equipment that will be charged to lethal voltages during their operation. Therefore, all safety precautions relevant to this test apparatus must be complied with. All tests should be conducted in a controlled access area by personnel experienced in high voltage/high current testing. Special consideration should be given to personnel safety including the use of safety barriers/interlocks, well-documented safety procedures and logs, as well as eye and ear protection. In addition, relevant signage and audible warning of impending discharges may be appropriate. Fire suppression equipment may be required by local or company ordinances, and are recommended for any test where explosions and fire may occur.

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4.5 Test Set-Up

4.5.1 Test Object Design

It should be recognized that the test object set-up, design (size, build-up, coating) is one of the most important aspects of any test, whether it is an engineering test, or certification test. While utilizing full scale, built to drawing parts may seem the easiest and most 'fool proof' way of testing, it can be very expensive. Tests should be run on representative part build-ups, of appropriate size and shape, to accurately mimic the actual design and installation. Test object set-up is important to insure that bonding and grounding are properly implemented so test currents flow along representative paths and that test part mounting is consistent with actual installation of the part. This is of particular importance on smaller test objects where edge effects and surrounding structure may influence test object current distributions and affect test results.

Surface and corrosion inhibitive coatings are very important parts of the set-up process. Surface coatings can affect the way in which the arc disperses across the test object, and corrosion inhibitive coatings will affect the bond paths and grounding of surfaces and parts. These aspects should be reviewed prior to test set-up and it should be determined if they adequately represent the installation.

For example, a full large airliner wing to body fairing need not be tested to determine whether a Zone 2A current waveform will punch though the lightning protection and panel. Reasonably sized and grounded panels will suffice for the direct attachment test. A panel of sufficient size built to represent the thinnest portion of the middle of the panel may be adequate (worst case build-up). Because current would theoretically be flowing in all directions from the point of attachment, circumferential grounding may be fine. Experience has shown that 18 x 18 inches is of a large enough size of a flat panel to give reasonable data. Smaller sizes are acceptable if one recognizes that blast pressures and edge effects may skew test results.

4.5.2 Waveform Scaling

Multiple joint build-up parts should also be carefully constructed to mirror the actual intended installation. In addition, installation location and sizing must be taken into account in case current level scaling is required. For example, if a part is going to be tested with two fasteners holding two parts together that represents an installation of many fasteners holding two parts together, a full scale waveform may not be appropriate. Scaling the waveform to show what the effect of the current division among the fasteners would be appropriate.

4.5.3 Waveform Application

For high current direct effects and fuel system tests, the appropriate waveforms as identified in ARP5412/ED-84 are typically applied in combination for a given test shot. For example, a Zone 2A direct arc attachment test would consist of a current component D followed by the B and C* current components within the same test shot, rather than applied as individual, distinct test shots. The purpose of this is to more closely simulate possible combinations of effects that may occur due to a real lightning event. For high voltage direct effects tests only one waveform is applied at a time, though more than one waveform may ultimately be applied to the test configuration to assess different conditions. For indirect effects tests, typically one waveform or waveform set is applied for a given test except that multiple pulses or repetitions are often required as called out in the test methods.

4.5.4 Concurrent Testing

Using the same test object for two concurrent test conditions may be difficult. If a Zone 1B arc entry test and a Zone 3 conducted current test is to be performed concurrently on a test specimen representing a large control surface that has many latches but the test panel has only two latches, the latches will be overtested because only two are available to carry the current. If the actual installation only has two latches holding it on, then, this would be a valid test. This is assuming all surfaces and surrounding structures were included in the test.

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5. DIRECT EFFECTS TEST METHODS

The Direct Effects Test Methods outlined in this section are:

- High Voltage Strike Attachment Tests (5.1)
    - Initial Leader Attachment Test (5.1.1)
    - Swept Channel Attachment Test (5.1.2)
    - High Voltage Strike Attachment Test on Models (5.1.3)
- High Current Physical Damage Tests (5.2)
    - Arc Entry Tests (5.2.1)
    - Aircraft Non-Conductive Surfaces Test (5.2.2)
    - Conducted Current Test (5.2.3)
- Induced Transients In External Mounted Hardware (5.3)
    - Measurement of Injected Transients in External Hardware (5.3.1)
    - Voltage Stress Assessment Of Circuit Insulation (5.3.2)

These tests evaluate direct effects protection and issues, except for fuel ignition considerations which are addressed in Section 7. The high voltage attachment tests are applied to determine specific lightning strike attachment points and breakdown paths across or through non-conducting materials. Since the currents that flow during these tests are typically low, the attachment tests are not intended to show possible damage from a lightning strike. The high current physical damage tests are used to assess actual damage from lightning currents. The high current transient tests address cases where electrical wiring installed within structures or externally mounted hardware may be susceptible to direct injection of lightning currents. However, the effects due to indirect coupling onto wiring (indirect effects) are addressed in Section 6 of this document. This section includes testing that can be applied to both an overall aircraft and particular components on aircraft.

5.1 High Voltage Strike Attachment Tests

These tests are used to determine lightning attachment points and breakdown paths across or through non-conducting materials.

5.1.1 Initial Leader Attachment Test

5.1.1.1 Test Purpose

This test is normally applicable to parts of aircraft that are located in initial leader attachment regions within Zones 1A and 1B, as described in the ARP5414/ED-91. Examples are wing tips fabricated of non-conducting materials, radomes, and large antenna fairings. This test can be used to assess:

- locations of possible leader attachment locations on full size structures,
- evaluation of radome wall materials,
- optimization of the location of protection devices,
- flashover or puncture paths, along or through dielectric surfaces, and/or
- performance of protection devices, such as radome diverter strips.

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5.1.1.2 Test Object

The test object should be full-scale production line hardware or a representative prototype. Any paint finishes, in particular any coats of anti-static paint or dielectric coverings on electrically conductive elements, should be included to ensure realistic development of corona and streamering from the conducting elements.

Electrically conducting objects, such as antenna elements and lights, normally enclosed by non-conducting test objects should be represented within the test objects. These may be actual devices, or geometrically correct mockups whose surfaces are at least as electrically conductive as the items they represent. These items must be positioned at the same locations within the test object as they would be in the aircraft installation. If the conducting objects may be oriented in several positions, those that represent worst cases should be represented in the tests. Normally these are the positions that result in the smallest distances to the non-conducting skins, or the strongest electric field intensities in directions normal to the aircraft surface.

Other conductors such as mounting fasteners, frames, hinges and latches must also be represented.

All conducting objects that are normally bonded (i.e., grounded) to the airframe must be electrically connected to the support structure and mocked up adjacent aircraft surfaces. Anti-static paint should be bonded to the support structure in a representative manner.

5.1.1.3 Test Setup

There are three test arrangements, designated Test Setup A, Test Setup B and Test Setup C, that can be used. Test Setups A and B are most appropriate for tests on complete production or prototype test objects, such as a radome. Test Setup C is most appropriate for developmental tests to evaluate skin panel construction and diverter strip configurations. Each test arrangement is intended to result in initiation of electrical activity, such as corona and streamering, at the test object (and not at the external electrode) as occurs in flight just before a lightning strike attachment. Once ionization of the air in the test object is initiated, the streamer will progress toward the other electrode which is to be a large geometry shape intended to represent an electric field equipotential surface some distance from an aircraft extremity. In this way the influence of the external test electrode on test results is minimized.

Overviews of the test arrangements showing the high voltage generator, test object, and external electrode in Test Setups A, B, and C are illustrated in Figure 1 through Figure 6.

The general test arrangement for Test Setup A is illustrated in Figure 1.

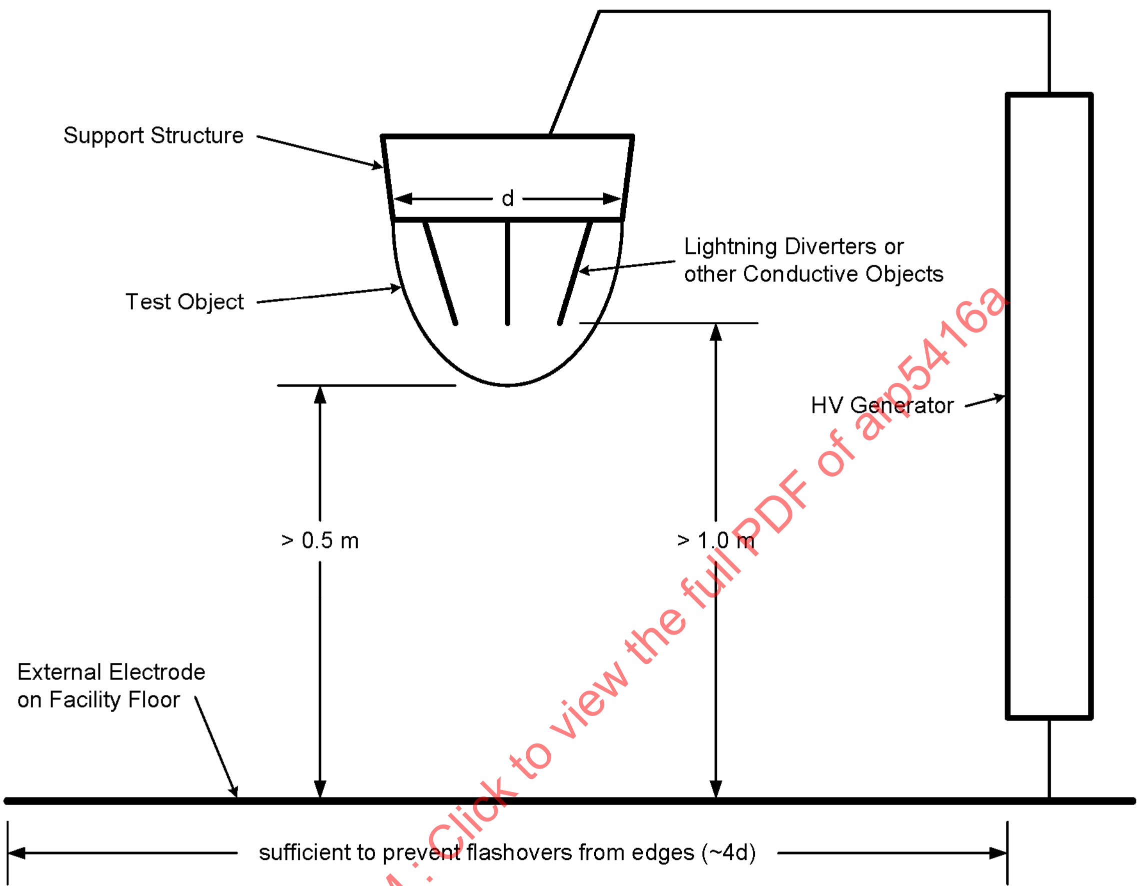

FIGURE 1 - INITIAL LEADER ATTACHMENT TEST SETUP A

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The test object is elevated above the external electrode which is a large area ground plane placed on the facility floor. The dimensions of the ground plane and spacing between the test specimen and the ground plane are dependent upon the size of the test object, as indicated in Figure 1. The test object should normally be tested with two or more orientations, to represent electric field directions that this part of the aircraft may experience in flight.

Four conditions should apply for a valid test:

(1) The external electrode should be at least 1 m from the closest conductive element (inside or outside of the test object).

(2) The external electrode should be at least 0.5 m from the test object skin.

(3) Connection of the streamers should occur in the air away from the test object (this can be confirmed by photographs of the flashovers. The leader connection point is shown in Figure 2.

(4) The streamer from the external electrode must not originate from the edge of the electrode.

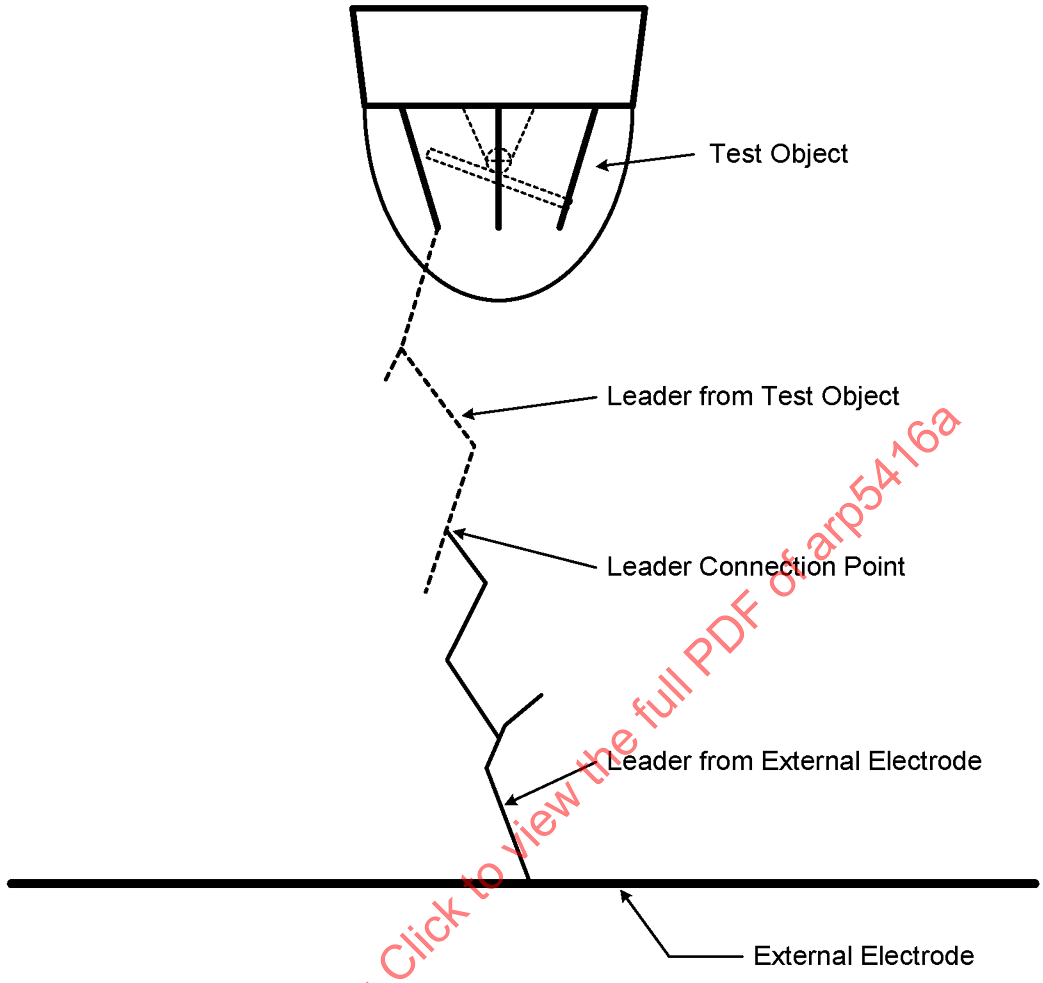

FIGURE 2 - LEADER CONNECTION POINT

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Specific dimensions and test object orientations should be described in the test procedures.

The general test arrangement for Test Setup B is illustrated in Figure 3.

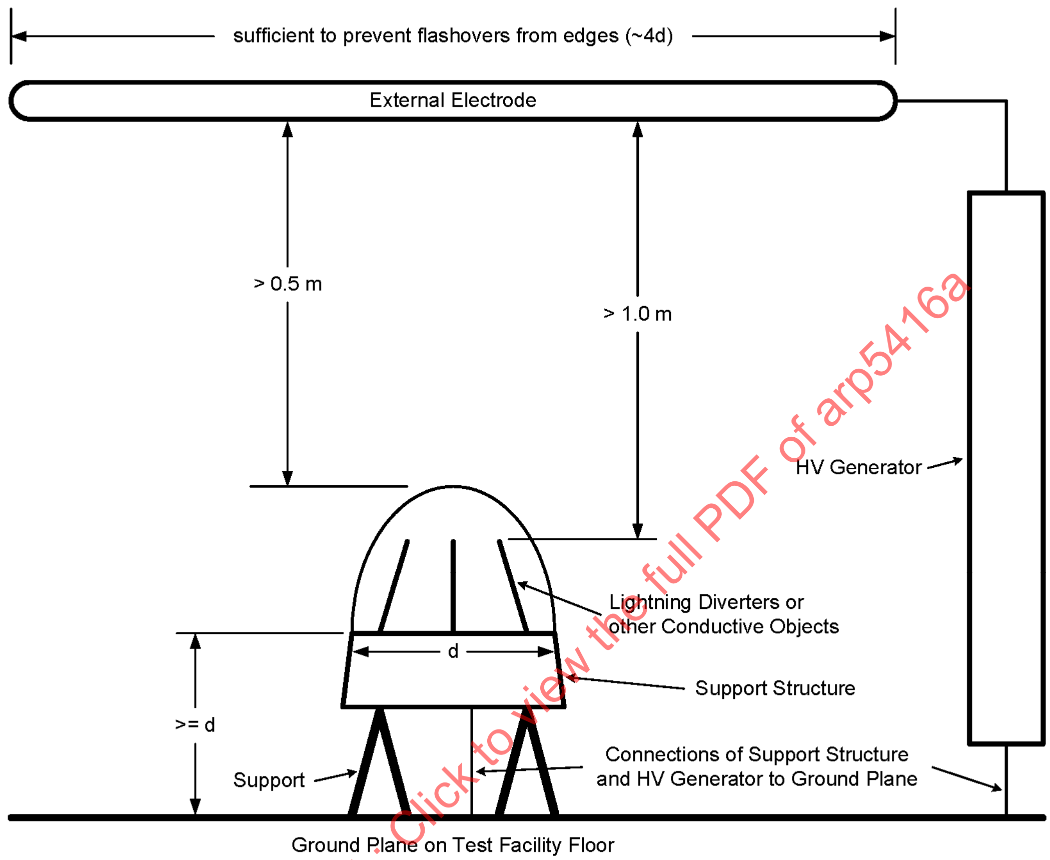

FIGURE 3 - INITIAL LEADER ATTACHMENT TEST SETUP B

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The test object is elevated above the ground plane on supports by a distance greater than the width of the test object 'd' to minimize influence of the ground plane on test results. The external electrode is suspended above the test object and at high potential when the test is applied. The dimensions of the external electrode and spacing between the test object and the external electrode are dependent upon the size of the test object, as indicated in Figure 3. The test object should normally be tested with two or more orientations, to represent the possible electric field directions that this part of the aircraft may experience in flight.

Small test objects such as low profile antennas have sometimes been mounted on a flat plate electrode for test as shown in Figure 3. To prevent flashovers from the edges of the high voltage electrode, increasing the size of this electrode as suggested in Figures 1 and 3 may be insufficient as flashovers may still occur from the edges. For such cases the high voltage electrode may be lowered until flashovers are initiated at the test object. This modification is acceptable if the connection between leaders originating at the test object and at the high voltage electrode are observed to connect in the air gap between test object and electrode.

Alternately, the fixture on which the test object is mounted should be profiled in a representative manner or have de-stressed edges.

Figures 4 and 5 show an example of test setup for externally mounted equipment. Width/diameter of the HV should be sufficient such that flashovers from its edges do not occur.

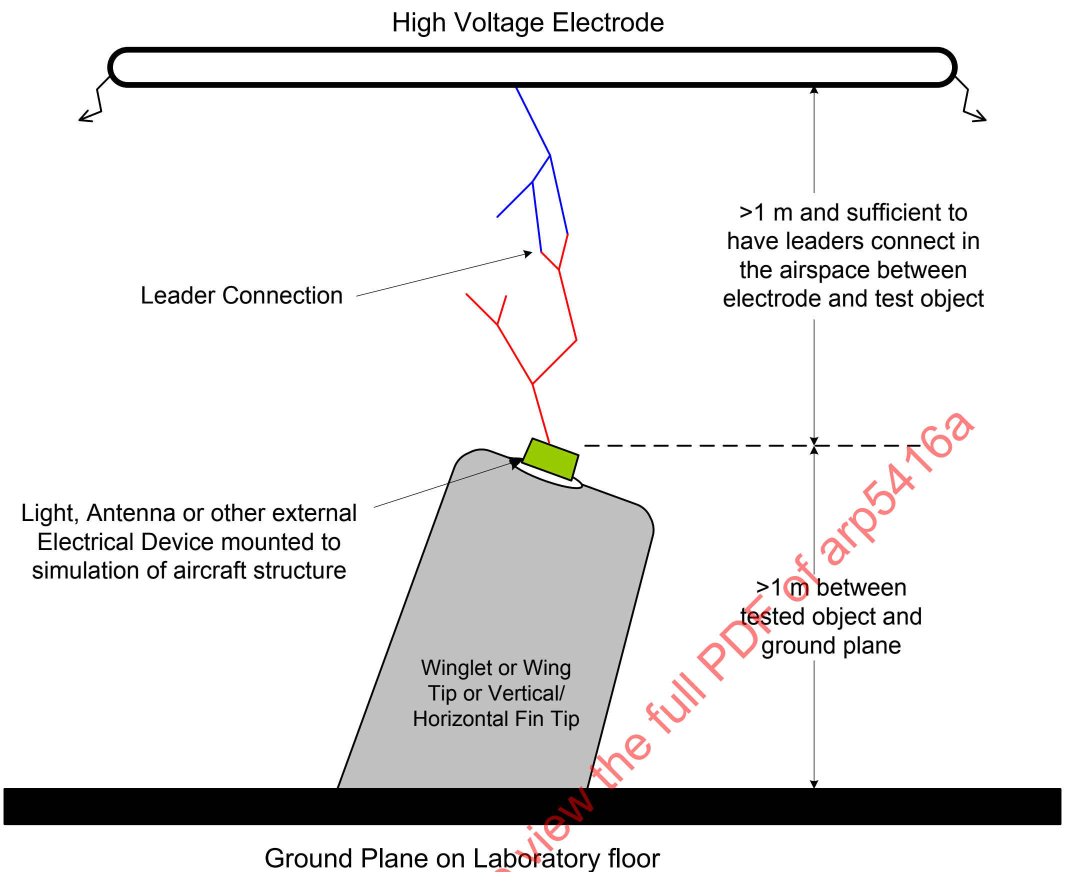

FIGURE 4 - INITIAL LEADER ATTACHMENT TEST SETUP B, OF EXTERNALLY MOUNTED EQUIPMENT

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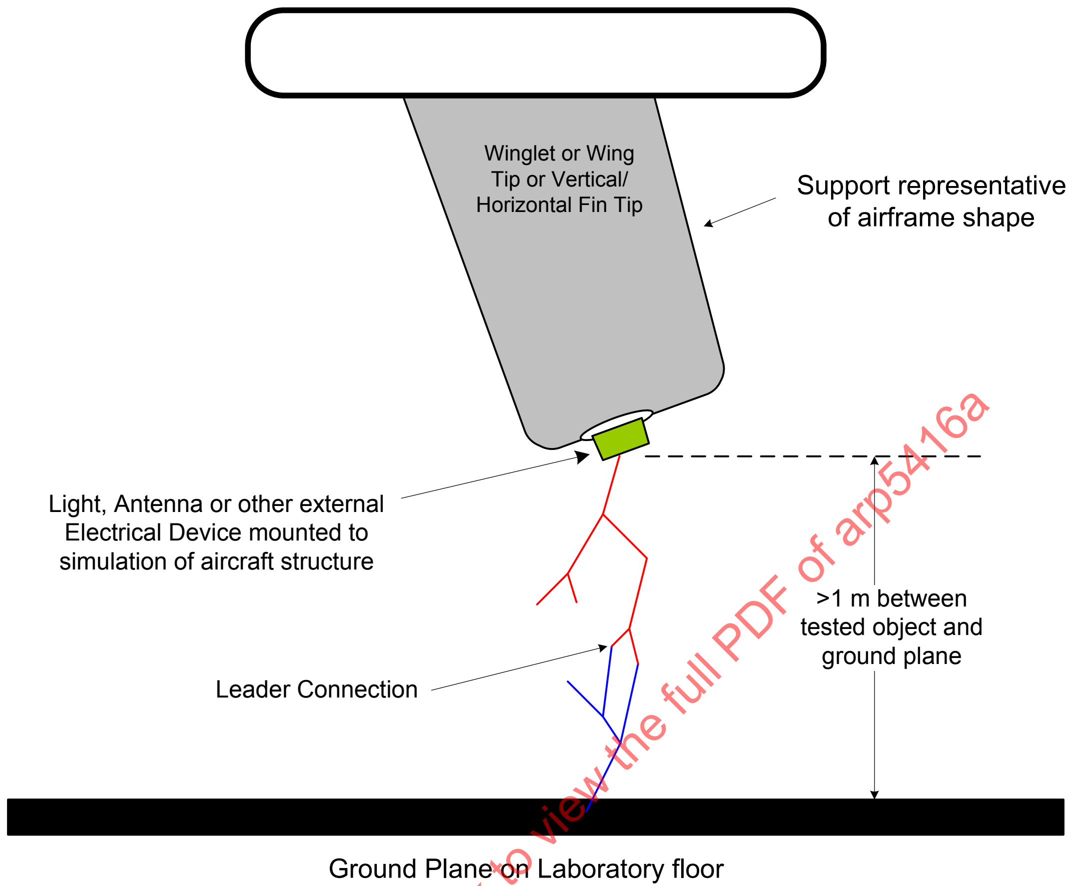

FIGURE 5 - INITIAL LEADER ATTACHMENT TEST SETUP B, OF EXTERNALLY MOUNTED EQUIPMENT SUSPENDED ABOVE GROUND PLANE

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Five conditions should apply for a valid test:

(1) The external electrode should be at least 1 m from the closest conductive element (inside or outside of the test object).

(2) The external electrode should be at least 0.5 m from the test object skin.

(3) Conjunction of the streamers should occur in the air away from the test object, as illustrated in Figure 2.

(4) The streamer from the external electrode must not originate from the edge of this electrode.

(5) The aircraft end termination of the diverter strip or other conductive object must be elevated above the ground plane by a distance greater than the width of the test object ‘d’ to minimize influence of the ground plane on test results.

Additional guidance for HV generator settings:

(a) When the flat HV electrode shown in Figure 3 or 4 is at positive polarity, the average electric field required to produce a flashover is ~950 kV/m. This will often produce leaders from the edges of the HV electrode in Figure 3 or 4 that will make this arrangement impractical unless the test specimen is mounted on a simulated aircraft structure that extends ~1 m above the ground plane as illustrated in Figure 5. If the support structure is not de-stressed (resulting in attachment to the support structure), the gap may be reduced until flashovers occur to the test object rather than the support structure.

(b) When the HV electrode as shown in Figure 3 or 4 is at negative polarity, the average electric field required to produce a flashover is ~500 kV/m.

Specific dimensions and test object orientations should be described in the test procedures.

The general test arrangement for Test Setup C is illustrated in Figure 6.

In this arrangement candidate protective devices and device locations on a non-conductive skin specimen can be evaluated prior to establishing a protection design and installing such devices on a production or prototype test object.

A typical skin panel would be 1 m square, although other sizes and shapes would be acceptable, sufficient to accommodate a full scale arrangement of protection devices. Production - like skin materials, surface finishes and paints should be applied. A typical use of this test is to determine the spacing ‘D’ of diverter strips to be installed on a radome or antenna fairing. The diverters should be as long as they would be in the aircraft installation. A mockup of any conductive items behind the protective surface should be placed an appropriate position behind the skin at the distance ‘d’. The protection devices are normally at facility ground potential and the electrode is at high potential. In order to apply a realistic test condition, experience has shown that the electrode should be positioned midway between the diverter strips, as in the example of Figure 6, to prevent attachment around the edge or an unrealistic result. The electrode should be elevated above the panel surface by a distance equal to the dimension of the panel if square, or the smaller dimension of a rectangular panel. The diverter strips may be repositioned at a greater or smaller spacing to optimize the design and still prevent puncture.

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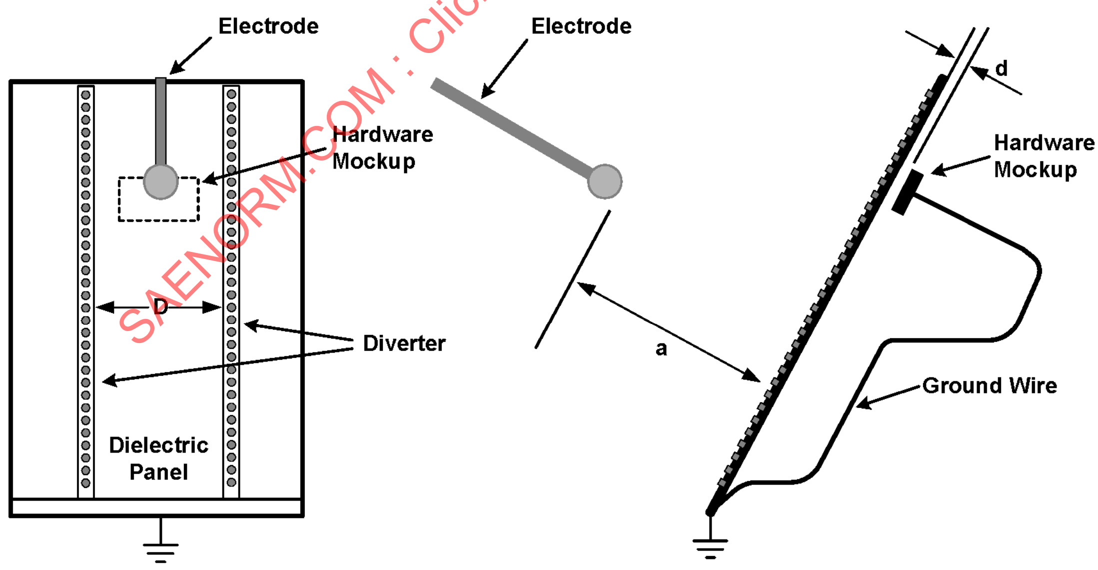

Determining Distance 'D' as a Function of Proximity 'd' to an Internal Conductor
Distance 'a' is the shorter dimension of the panel's width or height

FIGURE 6 - ARRANGEMENT FOR PROTECTION DEVICE EVALUATIONS TEST SETUP C

The arrangement of Figure 6 is not equivalent to the verification test arrangement of Test Setups A and B, but experience has shown that diverter spacing determined from development tests as illustrated in Figure 6 have proved successful in subsequent verification tests of test objects, such as radomes, employing similar diverter spacing.

Test Setup A is the most desirable arrangement, since it usually allows a larger dimension external electrode (i.e., a conductive surface on the laboratory floor) to be provided; however this arrangement necessitates that the test object be suspended from the laboratory ceiling.

Test Setup B is intended to create a similar electric field arrangement about the test object while allowing larger or heavier test objects and support structures to be placed on the laboratory floor. In this arrangement a large diameter electrode must be suspended above the test object.

Test Setup C is most appropriate for developmental tests to evaluate skin panels and diverter strips. However, tests of flat panels should not be employed for verification of protection designs, since the flat panel specimens do not represent significant features of the non-conducting structures being verified.

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Test Setup A

(1) Mount the test object to a support structure containing mocked-up surfaces (or actual structure if available) representative of the adjacent vehicle surfaces. Ensure that electrical bonding of the test object to the support structure represents the actual installation.

(2) Electrically connect all conductive hardware on or within the test object that is normally grounded to the airframe to the support structure.

(3) Suspend the supporting structure and test object above the ground plane. The distance from the test object to the ground plane should be as described in Figure 1.

(4) Electrically connect the output of the HV generator to the support structure.

Test Setup B

(1) Mount the test object to a support structure containing mocked-up surfaces (or actual structure if available) representative of the adjacent vehicle surfaces, as for Test Setup A. Ensure that electrical bonding of the test object to the support structure represents the actual installation.

(2) Electrically connect all conductive hardware on or within the test object that is normally grounded to the airframe to the test support structure.

(3) Elevate the supporting structure and test object above the ground plane. The distance from the test object to the ground plane should be as described in Figure 3.

(4) Electrically connect the support structure to the ground plane.

Test Setup C

(1) Mount the test panel to non-conducting support structure. A mockup of any conductive items behind the panel should be placed an appropriate distance behind the panel at the appropriate position. Place the test panel and support structure on a conducting ground plane.

(2) Position the HV electrode above the test panel as shown in Figure 6.

(3) Electrically connect all conductive hardware on or behind the test panel that is normally grounded to the airframe to the ground plane.

(4) Electrically connect the output of the HV generator to the HV electrode.

All Test Setups

(1) Electrically connect the HV generator return to the ground plane.

(2) Be sure that the elevated connections between the HV generator and the test object are farther away from the ground plane than the test object.

(3) Note that whereas it is necessary for all electrical connections normally present between the test object and the aircraft to also be included in the test setup, it is not necessary that any specified electrical bonding resistances be met for these high voltage strike attachment tests. Electrical continuity is important, but connections via low resistance bonds are not.

(4) Set up sensing and recording equipment. This includes a HV divider, a recording oscilloscope and cameras to photograph the flashovers. Additional instrumentation, to measure discharge current and to photograph streamering within or behind the test object may also be included.

5.1.1.4 Test Waveforms

Voltage waveform D as defined in ARP5412/ED-84 should be applied for Test Setups A and B, since this is most representative of the electric field at an aircraft extremity during an initial leader attachment. Either voltage waveform A or D should be applied for Test Setup C. Waveform A is added since this is most representative of the electric field associated with lightning re-attachment to aircraft surfaces, radome, located in swept leader and swept channel zones. The test voltage should be applied at both polarities. Normally, two discharges in each polarity should be applied in each test object or electrode orientation.

If the HV generator discharge current exceeds the range of typical leader current of up to 2000 A it may produce unrealistic effects which are beyond the scope of this test.

5.1.1.5 Measurements and Data Recording

- Photographs and description of each test setup.

- Waveform plots of the test voltage and, if appropriate, current waveforms.

- Photographic records of all high voltage discharges. These should have complete coverage of the tested surface. One camera should enable immediate preliminary analysis of the test shot to be made so that any punctures are identified immediately.

- Photograph of each electrode configuration.

- Photographs of puncture locations or other significant effects.

- Records of laboratory environmental data (such as temperature, pressure and humidity), dates of testing, personnel performing and witnessing the tests, and test location.

- Record of any deviations from the test procedure.

- Records of the results of each discharge showing polarity, voltage amplitude, and waveforms.

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5.1.1.6 Test Procedure

This test procedure is applicable to all test setups (A, B, and C).

(1) Measure laboratory environmental conditions.

(2) Review and implement safety procedures. Some areas of concern are as follows. Test areas must be safe and clear of personnel prior to charging of test equipment. Capacitor banks must be shorted out after tests and prior to re-entry of personnel into the test area. Eye and ear protection must be appropriate.

(3) Calibrate the HV generator and instrumentation as follows:

(a) Carefully inspect the test object for any blemishes that might later be confused with effects of the tests, and identify these so that they are not confused with subsequent test results.

(b) Drape the test object with a conductive foil.

(c) Select the initial polarity and initiate a test to the foil, while measuring the applied voltage. It is advisable for the initial test object polarity to be positive (+), regardless of being in Test Setup A or Test Setup B. Experience has shown that this condition results in a lower probability of puncture of non-conducting materials since streamers originating from the test object protective devices progress further into the air gap before being joined by opposing streamers from the negative electrode. In some cases, Test Setup B will not allow proper attachments when configured for positive polarity. If this is the case, then it is allowable to reconfigure the test object to Test Setup A for the positive polarity test.

(d) If the waveform is not per the requirements of ARP5412/ED-84, adjust the generator parameters or electrode spacing as necessary to obtain the specified waveform.

(e) Repeat steps (c) through (d) as necessary to obtain the required conditions.

(f) Remove the foil from the test object.

(4) Clean test object with appropriate technique to remove dust, debris, and other contaminants which could affect test results.

(5) Apply a discharge to the test object, while measuring the applied voltage and taking photographic evidence of the path of the flashover. Ensure that the discharge still occurs on the rising wave front before the crest of the voltage waveform.

(6) If environmental conditions and materials are such that static charge may accumulate on the dielectric surfaces, charge levels should be measured with a field mill and, if significant, be removed with a grounding stick before proceeding.

(7) Inspect the test object and document the results.

(8) If puncture has occurred, perform an assessment to determine if the test object has failed. If it is deemed to have failed, then the test sequence may need to be terminated.

(9) Repeat steps (5) through (8), if more than one test under the same conditions is required.

NOTE: Since the dielectric properties of the test object may progressively degrade, the total discharges should be limited to two (2) at any particular combination of HV electrode and test object positions. If more data is required, the symmetry of the object may be used to relocate the HV electrode for additional tests.

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(10) Switch the polarity of the HV generator.

(11) Repeat steps (4) through (7).

(12) Reposition the HV electrode and test object, as required by the test procedure.

(13) Repeat steps (4) through (11), as required by the test procedure.

5.1.1.7 Data Interpretation

Test objects should undergo a thorough post-test evaluation to determine the adequacy of the design against the acceptance criteria.

5.1.2 Swept Channel Attachment Test

5.1.2.1 Test Purpose

This test is normally applicable to parts of an aircraft that are located in Zone 1A but not exposed to initial leader attachment. That is, those portions of Zone 1A where initial leader attachment is predicted should use test method as described in 5.1.1; those extensions of Zone 1A defined by aircraft movement relative to the established lightning channel should use this test method. See ARP5414/ED-91 for guidance on defining initial leader attachment locations and Zone 1A extensions due to sweeping leader effects. This test is also applicable to areas in Zones 1C, 2A, or 2B that are exposed to the effects of sweeping lightning channels as described in ARP5414/ED-91. This test can be used to assess:

- possible puncture locations on non-conducting (i.e., dielectric) surfaces,
- flashover paths over non-conducting surfaces, or
- performance of protection devices, such as diverter strips on antenna fairings.

This test is normally conducted with a high voltage generator that is not capable of producing the current components that would flow into the test object in accordance with the lightning strike zone that the test object is to be located within. However, if equipment is available to produce the required test voltage followed by the applicable current components, then the high current physical damage test of 5.2 can be conducted together with this test.

5.1.2.2 Test Object

The test object should be full-scale production line hardware or a representative prototype. Any paint finishes, including any coats of anti-static paint or dielectric coverings on electrically conductive elements, should be provided to ensure realistic development of corona and streamering from the conducting elements. Anti-static paint should be bonded to conducting structure in a representative manner.

The test object may also be a non-conducting surface, such as an access cover or antenna fairing that is integral with the airframe. In this case the test object would also be a production item or representative prototype, installed in a panel that is representative of the surrounding aircraft surface.

5.1.2.3 Test Setup

- An overview of a typical test arrangement showing the test object and typical test electrode position is illustrated in Figures 7 and 8. For large test objects, of dimensions on the order of 0.25 m or more, tests usually are applied from several electrode positions, as illustrated on Figure 7. Smaller test objects can usually be tested from one test electrode location centered over the test object, as illustrated in Figure 8. The sphere gap spacing, g, and the test electrode spacing, d, are determined during the test set-up calibration.

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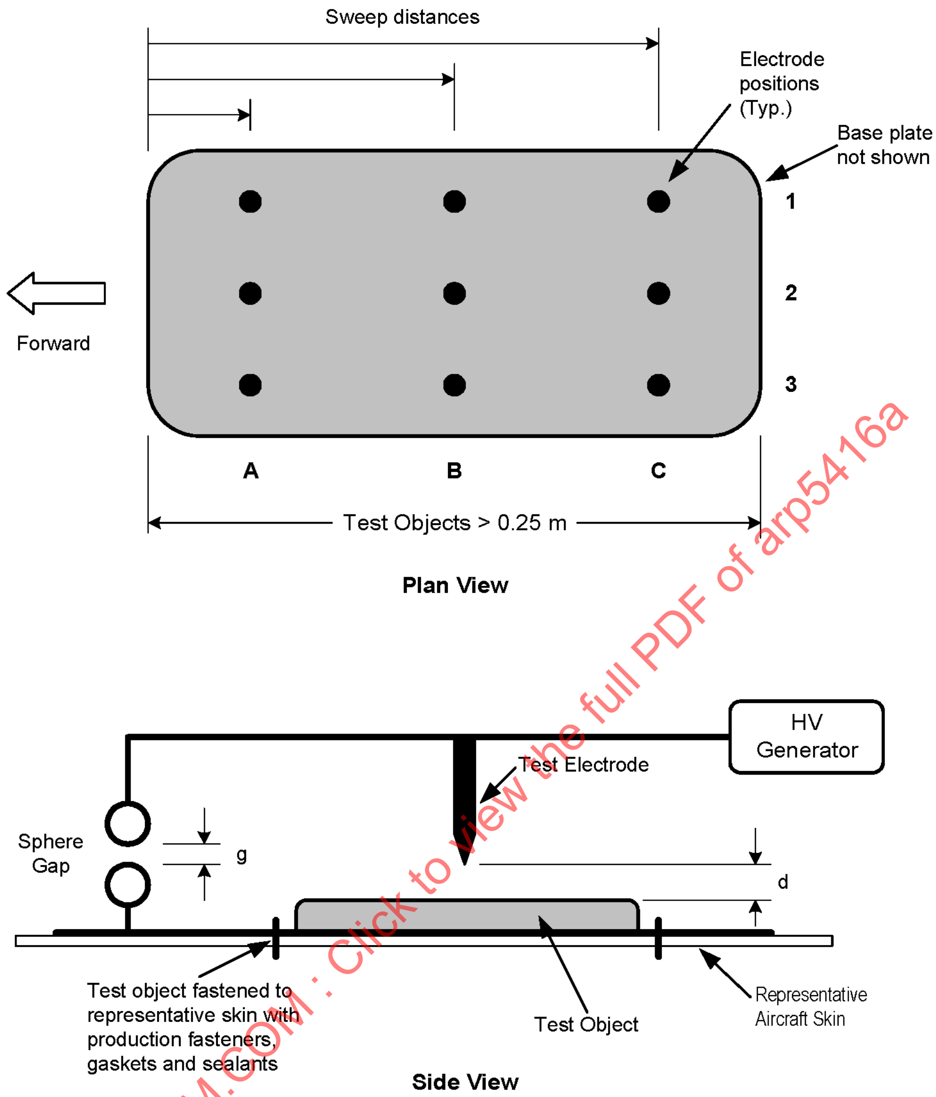

FIGURE 7 - ARRANGEMENT FOR SWEPT CHANNEL TEST OF LARGE TEST OBJECTS

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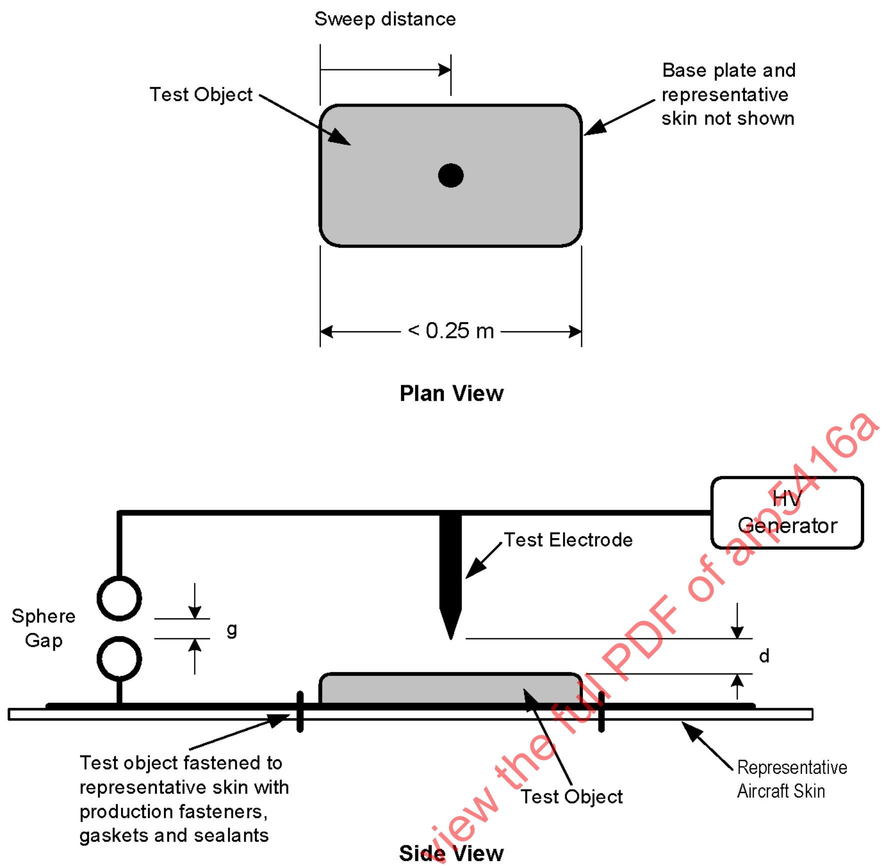

FIGURE 8 - ARRANGEMENT FOR SWEPT CHANNEL TEST OF SMALL TEST OBJECTS

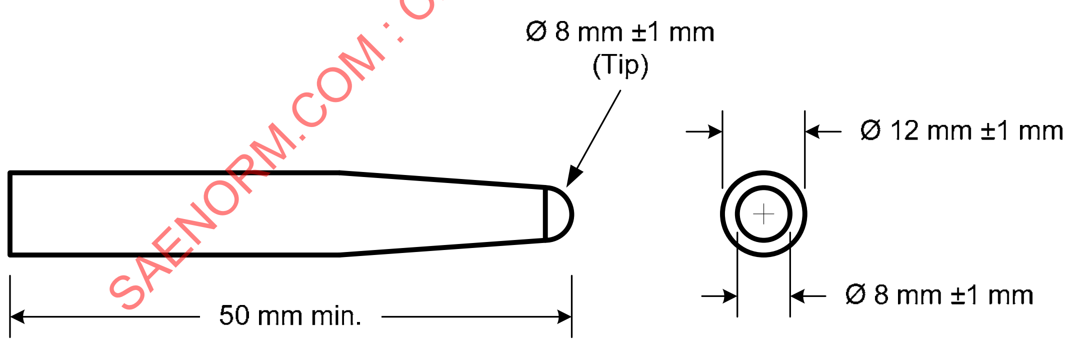

FIGURE 9 - TEST ELECTRODE FOR SWEPT CHANNEL TEST

- Mount the test object to a surface representative of the actual vehicle region under test. Ensure that electrical bonding to the surrounding surface represents the actual installation. Production hinges or fasteners, surface finishes, gaskets and sealants should be present.

- Ground all hardware to the test object structure that is normally grounded to the airframe or electrically connected to other equipment in the aircraft installation.

- Connect the output terminal of the HV generator to the high voltage electrode. The test electrode should be as shown in Figure 9, with an electrode tip radius of 4 mm ± 0.5 mm.

- Setup equipment to measure and record the test voltage and current.

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5.1.2.4 Test Waveforms

Voltage waveform A as defined in ARP5412/ED-84 should be applied.

5.1.2.5 Measurements and Data Recording

- Photographs and description of each test setup and electrode position.
- Photographic records of all tests. Cameras should provide 360 degree coverage of the test object. One camera should enable immediate preliminary analysis of the test shot to be made so that any punctures are identified immediately.
- Photographs of puncture locations or other significant effects.
- Records of laboratory environmental data (such as temperature, pressure and humidity), dates of testing, personnel performing and witnessing the tests, and test location.
- Records of any deviations from the test procedure.
- Records of the results of each test showing voltage polarity, amplitude, and waveform.

5.1.2.6 Test Procedure

(1) Measure laboratory environmental conditions.

(2) Review and implement safety procedures. Some areas of concern are as follows. Test areas must be safe and clear of personnel prior to charging of test equipment. Capacitor banks must be shorted out after test and prior to re-entry of personnel into the test area. Eye and ear protection may be appropriate.

(3) Carefully inspect the test object for any blemishes that might later be confused with effects of the tests, and identify these so that they are not confused with subsequent test results.

(4) Calibrate the generator and instrumentation as follows:

(a) Determine the desired test voltage based on a 140 kV/m multiplied by the sweep distance. For sweep distances less than 0.5 m the desired test voltage shall be 70 kV. The high voltage generator shall be configured to produce Voltage Waveform A as defined in ARP5412/ED-84.

NOTE: High voltage generators configured to produce voltage waveform A may yield a noisy waveform at low test voltages. High voltage generators configured for waveform B with a high crest voltage may be used to maintain the 1000 kV/µs (±500 kV/µs) requirement of waveform A.

(b) Set up the sphere gap (g), as shown in Figure 7, and set the sphere gap to spark over at a voltage that is 120 to 130% of the desired test voltage. Operate the high voltage generator such that a flashover occurs at the sphere gap. The sphere gap sparkover should occur on the wavefront of Waveform A. Record the breakdown voltage for the sphere gap. If necessary, adjust the spacing of the sphere gap such that the sphere gap breaks down at 120 to 130% of desired test voltage and repeat the sphere gap breakdown voltage demonstration. If the required waveform is not correct, adjust the generator parameters or electrode spacing as necessary to obtain the specified waveform.

(c) Connect the output terminal of the high voltage generator to the high voltage test electrode. The test electrode should be as shown in Figure 9.

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(d) Install the test object underneath the test electrode such that the electrode is over one of the test locations. Ground the test object to the high voltage generator return. Place a sheet of metal foil over top of the test object and ground the foil to the high voltage generator return. The electrode should be placed 50 mm away from the surface (d) of the test object to represent the voltage applied by a lightning channel sweeping over the surface of the test object.

(e) Operate the high voltage generator such that a flashover occurs at the test electrode. Record the breakdown voltage for the test electrode. For desired test voltages below 140 kV, the spacing (d) may need to be reduced such that the electrode breaks down at the desired test voltage (-0/+10%). Repeat the electrode breakdown voltage demonstration as needed. The maximum test electrode spacing shall be 50 mm.

(f) Remove the metal foil from the test object.

(5) Clean test object with appropriate technique to remove dust, debris and other contaminants which could affect test results.

(6) Apply test voltage to the electrode, while measuring the applied voltage and taking photographs of any flashovers that occur.

NOTE: If no flashover occurs to the test object the test has been successfully applied. This is an indication that insulating sursfaces of the test object can successfully withstand the lightning channel voltage.

(7) Inspect the test object and document the results. Mark and photograph any punctures or other effects on the test object.

(8) If puncture has occurred, perform an assessment to determine if the test object has failed. If it is deemed to have failed, then the test sequence may need to be terminated.

(9) Repeat steps (4) through (7) for each of the tests, electrode polarities and electrode positions called for in the test procedures.

NOTE: Since the dielectric properties of the test object may progressively degrade due to repeated electrical stressing, experience leads to the recommendation that an acceptable number of tests are two (2) at each polarity at a particular electrode position.

5.1.2.7 Data Interpretation

Test objects should undergo a thorough post-test evaluation to determine the adequacy of the design against the Pass/Fail criteria.

5.1.3 High Voltage Strike Attachment Test on Models

5.1.3.1 Test Purpose

The test is used to locate the initial leader attachment regions on an aircraft. This is the first step in the method for determining lightning zones by test, as described in ARP5414/ED-91. In some cases, tests on models need to be supplemented by other means to determine detailed initial leader attachment locations. This case is particularly true of aircraft involving large amounts of non-conductive structural materials.

Two test setups are described to simulate either a naturally approaching leader or an aircraft initiated strike.

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5.1.3.2 Test Object

The test object should be an accurate model of the vehicle exterior that is not less than one meter in its largest dimension. Exterior surfaces of the model should be electrically conductive, even though some surfaces of the aircraft, such as a radome and windshields, are made of non-conducting materials. Model tests cannot determine detailed attachment locations on non-conductive surfaces. Therefore, the entire model is provided with conductive surfaces and the test determines which surfaces would be potentially susceptible to initial leader attachments. High voltage strike attachment tests of full scale non-conductive structures as described in 5.1.1 and 5.1.2 must be applied to establish detailed strike locations, surface flashover or puncture possibilities, or the effectiveness of protection devices.

If more than one vehicle configuration exists or is planned, the various possible configurations should be modeled separately.

5.1.3.3 Test Setup

- Mount the model on electrically insulated stand-offs or suspend it from non-conducting lines such that it is positioned in space between a high voltage electrode and a ground plane.

- To simulate a naturally occurring leader the upper electrode may be a rod or small sphere not exceeding 50 mm diameter to represent a leader approaching the aircraft.

- To represent an aircraft initiated strike, a large flat plate should be used to represent the ambient field condition preceding the formation of bi-directional leaders from the aircraft. The flat plate electrode should be sufficiently large so that field concentrations at electrode edges do not influence test results (i.e., flashovers should occur to the flat surfaces and not the edges of the electrode and ground plane. This typically requires that electrode and ground plane dimensions be a minimum of three times the largest dimension of the model. Figure 10 shows a typical setup for the naturally occurring leader case. Figure 11 shows the arrangement to represent the aircraft initiated strike.

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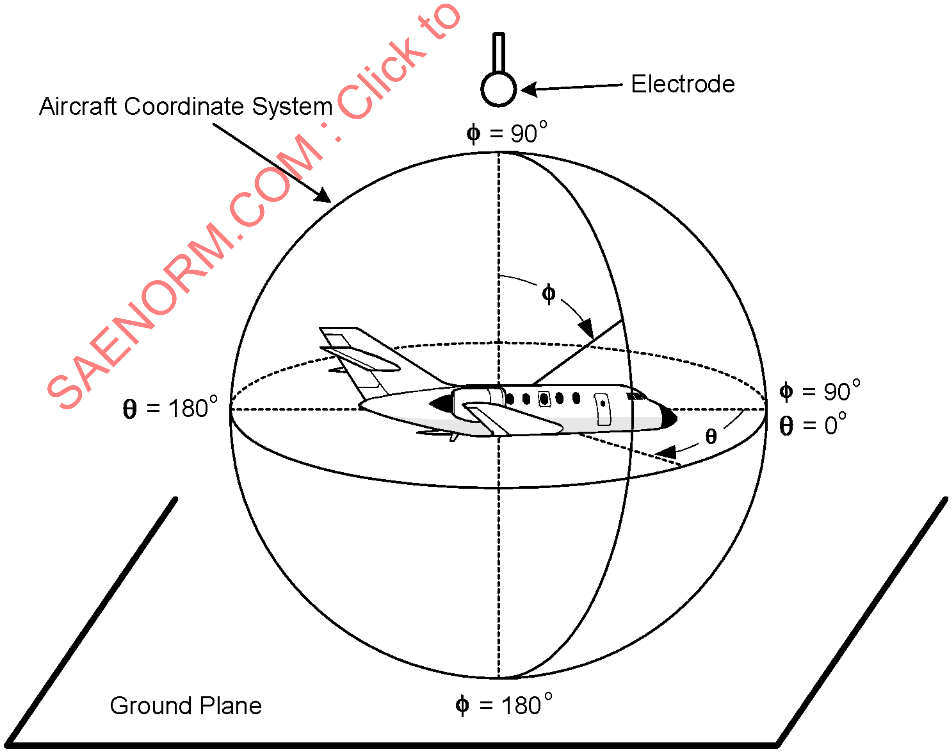

FIGURE 10 - TEST SETUP TO DETERMINE INITIAL LEADER ATTACHMENT LOCATIONS ON MODELS NATURALLY OCCURRING LEADER SIMULATION SHOWN

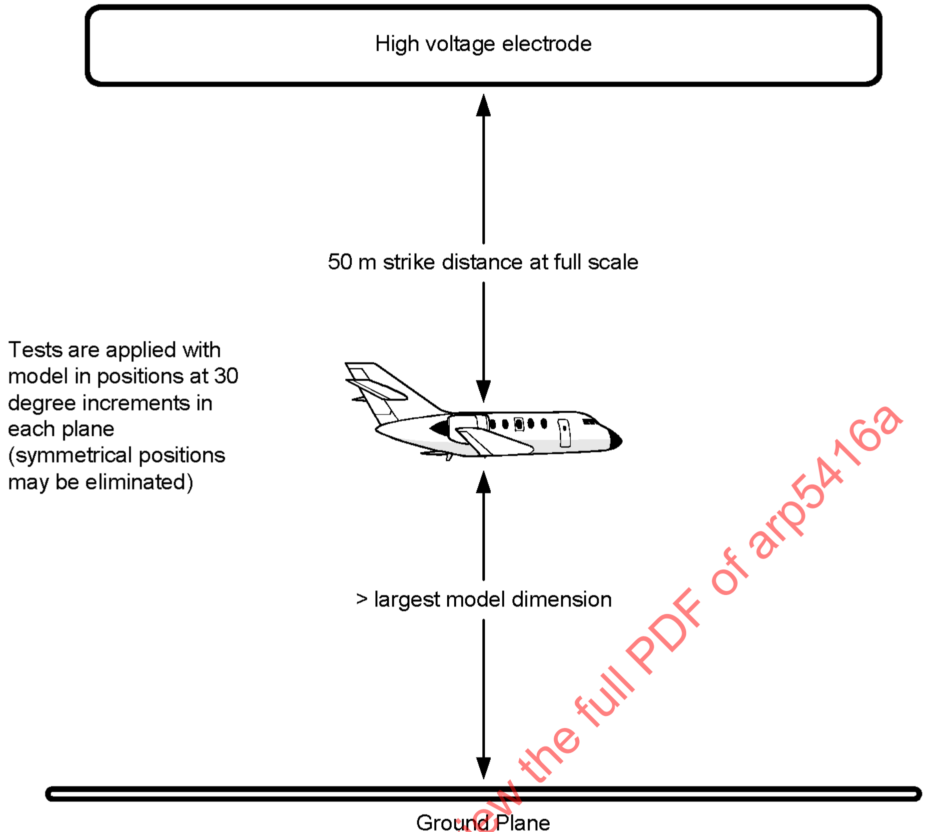

FIGURE 11 - TEST SETUP TO DETERMINE INITIAL LEADER ATTACHMENT LOCATIONS ON MODELS AIRCRAFT INITIATED STRIKE SIMULATION SHOWN

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- For determination of locations where approaching leader attachments are possible, tests should be applied that represent lightning leaders approaching from all possible directions expected in flight. If the aircraft initiated strike locations are being determined, the model should be capable of being exposed to ambient electric field directions possible in flight. In most cases it is more practical to change the orientation of the model rather than to reposition the electrodes. Since lightning leaders and ambient electric fields may occur from all directions, the model must usually be positioned at many orientations with respect to the electrodes. Experience has shown that tests of the model in 30 degree incremental positions about the airplane roll, pitch and yaw axes usually identify all of the initial leader attachment locations experienced by similar shaped aircraft in flight. Some additional orientations, representing directions intermediate from the reference planes may be advisable when evaluating strike possibilities to areas such as engine nacelles. Adjust the position of the electrode and the model for the following conditions.

- For the approaching leader case the high voltage electrode should be positioned to represent a striking distance of 50 m from the nearest model surface. The striking distance is scaled by the same factor as the model. Thus if a 1/30 model is tested the HV electrode would be positioned 50/30 = 1.67 m from the model. The distance from the model to the ground plane is less important, since the ground plane in fact represents an equipotential plane anywhere in space. Typically this distance has been a minimum of the largest dimension of the model, measured from the closest extremity of the model in any of its positions. Reorientation of the model to new positions may necessitate adjustment of the HV electrode location so as to maintain the modeled 50 m striking distance, but the height of the model to the ground plane need not be changed. For each model orientation the electrode should be positioned over the center of the model.

- For the aircraft initiated leader case the model is positioned midway between the HV electrode and the ground plane. The distances from the model to the electrode and ground plane should represent the 50 m striking distance to the closest extremity of the model, but the electrode need not be repositioned when the model is oriented such that the distances to the electrode are greater than the scaled 50 m striking distance.

- Strike locations associated with flashovers from the HV electrode may be considered initial leader ‘entry’ points; whereas locations from which flashovers proceed to the ground plane may be considered ‘exit’ points; however there is no real significance to these definitions. All places where test strikes either ‘entered’ or ‘exited’ the model should be considered as initial leader attachment points that could actually be either entry or exit locations on the aircraft.

- Select an initial polarity and connect the test voltage generator to the electrode and ground plane.

- Set up cameras to photograph the test strikes, and equipment to record the test voltage waveshape. Two cameras should be used that are at right angles to each other, so that strike locations on the model are clearly identified.

5.1.3.4 Test Waveforms

Tests to determine naturally occurring strike locations should be conducted with voltage waveform C, at an amplitude set to produce flashover to the model in 2 μs as defined for this waveform in ARP5412/ED-84. Variations in times to flashover (i.e., breakdown) of ±1 μs are acceptable for these tests.

Tests to determine locations of aircraft initiated leaders should be conducted with voltage waveform D. The amplitude of this waveform should be set to produce flashovers to the model at times between 50 and 250 μs as defined for this waveform in ARP5412/ED-84. The aircraft initiated leader tests may also be conducted with DC voltage, applied gradually until flashovers to the model occur.

5.1.3.5 Measurements and Data Recording

- Photographs and description of the basic test setup.

- Photographic records of the electrode configurations and flashovers to the model for each test.

- Records of laboratory environmental data such as temperature, pressure and humidity, dates of testing, personnel performing and witnessing the tests, and test location.

- Records of any deviations from the test procedure.

Results of each test, including oscillograms of typical test voltages applied in each polarity at each model position. It is not necessary that oscillograms of each individual test voltage be recorded, since voltages in each test condition will be similar.

5.1.3.6 Test Procedure

(1) Measure laboratory environmental conditions.

(2) Review and implement safety procedures. Some areas of concern are as follows: Test areas must be safe and clear of personnel prior to charging of test equipment. Capacitor banks must be shorted out prior to entry of personnel into the test area. Eye and ear protection may be appropriate.

(3) Calibrate the generator and instrumentation by applying test voltages and monitoring flashover times until flashovers are occurring within the time limits in 5.1.3.4. Strike locations on the model need not be recorded during these trials.

(4) While maintaining the orientation of the test model, apply a series of tests (typically ten) to the test model, until confidence is obtained that all of the possible leader attachment points for that model orientation and voltage polarity are obtained.

(5) Rotate the model 30 degrees to the next position, in accordance with the test procedures.

(6) If rotation of the model significantly changes the (model/electrode) gap length, adjust the electrode gap to maintain the desired gap distance as described in 5.1.3.3.

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(7) Repeat steps (3) through (5) until all of the model positions have been tested. This usually means that the model will have been rotated through 360 degrees in increments of 30 degrees. Note that the model may have to be rotated through 180 degrees in the roll axis since the left and right sides of most airplanes are symmetrical. In this event, if the test data is to be analyzed statistically to obtain attachment probabilities the data obtained in the roll positions should be multiplied by 2 to normalize it to the data obtained from positions in the yaw and pitch planes.

(8) Change the polarity of the generator.

(9) Repeat steps (3) through (7).

NOTE: To minimize testing time, a default assignment of attachment points can be made in situations where the test result is obvious, such as when the wings are in the direction of the electric field and all strikes occur to the wing tips.

5.1.3.7 Data Interpretation

Data obtained from positive and negative polarity tests should be combined to identify all of the possible initial leader attachment locations.

The attachment points identified in this testing are used to help locate possible initial lightning attachment regions on the aircraft as part of the process of locating the lightning strike zones as described in ARP5414/ED-91. Where the tests result in attachments to surfaces that are non-conductive on the aircraft, testing of these full scale skins and structures in accordance with 5.1.1 and 5.1.2 should be performed to determine if puncture or flashover would occur at these surfaces.

It should be noted that model tests are used only to establish initial leader attachment locations, and not the complete lightning strike zones, since lightning attachment locations are not limited to initial leader attachments.

5.2 High Current Physical Damage Tests

These tests are used to determine the effects due to a lightning attachment to an aircraft surface and current flow away from such an attachment. These effects can be evaluated at the point of attachment or along the path taken by the lightning current.

5.2.1 Arc Entry Test

5.2.1.1 Test Purpose

This test is applicable to structures located in Zones 1A, 1B, 1C, 2A, and 2B, as described in ARP5414/ED-91. The test is used to determine the direct effects that may result at the locations of possible lightning channel attachment to an aircraft or where high current and energy densities may flow away from a point of entry during a lightning strike. Examples are aircraft surfaces or components exposed to direct or swept lightning strike effects, internal structural elements that may conduct lightning currents, and externally mounted components that may experience direct strike or conducted current effects. The test can be used to assess:

- arc root damage,
- hot spot formation,
- melt-through behavior,
- adequacy of protection layers,
- behavior of joints and hardware attachments,
- voltage and current at points of interest.

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5.2.1.2 Test Object

These tests may be performed on a full-scale production item or a representative prototype. These tests may also be performed on panels, coupons, or subsections of the aircraft part. The panels, coupons or subsections should be fabricated with the appropriate manufacturing processes, paints and other finishes, joints, and materials. For protection devices that require a specific voltage to ionize, such as segmented diverter strips, the voltage of the generator should be sufficient to ionize the test object during the high current test. The primary focus of the high current test is on the ability of the attachment hardware to transfer the current to the aircraft structure.

5.2.1.3 Test Setup

- Mount the test object in a fixture or aircraft structural section.
- Ground all hardware to the test object structure that is normally grounded.
- Connect the generator return to the assembly such that the lightning currents are conducted away from the test object in a manner representative of when the aircraft is struck by lightning. Ensure that magnetic forces and other interactions associated with current flow within the setup are controlled such that they represent the natural situation.
- Orient a test electrode 50 mm or greater above the area of the test object that is to be evaluated. For most arc entry tests the electrode should be the 'jet diverting' type, as shown in Figure 13. If blast or shock wave effects are not of concern, a rod electrode with rounded tip and a diameter of 5 mm or greater can be used.
- Set the generator polarity to negative in order to produce maximum damage. If only current components A or D are being evaluated, positive polarity is acceptable.
- A fine metallic wire, not exceeding 0.1 mm diameter, may be used, if desired, to direct the arc to a specific point of interest on the test object. This approach is helpful for generators that use lower voltages. Test results should not be adversely affected. The wire should end a few millimeters from the test object. To achieve this, a tape "hinge" can be used as shown in sketch at left in Figure 12. The wire should not be taped to the test object (sketch at right).

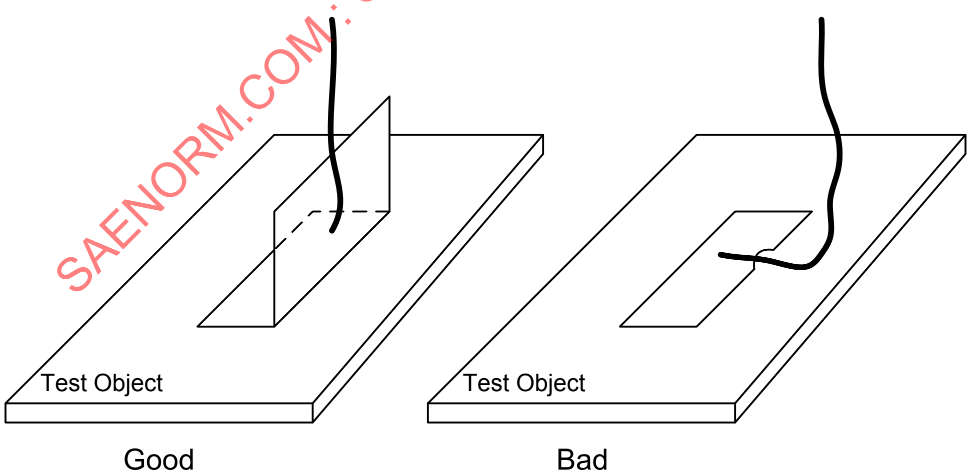

FIGURE 12 - TEST WIRE POSITIONING

- Set up sensing and recording equipment.

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5.2.1.4 Test Waveforms

A subset of current components found in Table 3 of ARP5412/ED-84 are used for this test, depending upon the aircraft zone where the test object is located.

5.2.1.5 Measurement and Data Recording

- Photographs and description of the test setup.
- Photographs of the test object both before and after each discharge.
- Photographs and description of damage to the test object.
- Records of laboratory environmental data (such as temperature, pressure and humidity), dates of testing, personnel performing and witnessing the tests, and test location.
- Record of any deviations from the test procedure.
- Records of the results of each discharge showing polarity, currents amplitudes, waveforms, action integrals and charge transfers at applicable test points.

NOTE: Indirect effects measurements are frequently required for external electrical hardware (see 6.1). If desired, some of these measurements can be made during the direct effects tests, as long as key waveform parameters, such as peak rate of rise, are correct or otherwise accounted for.

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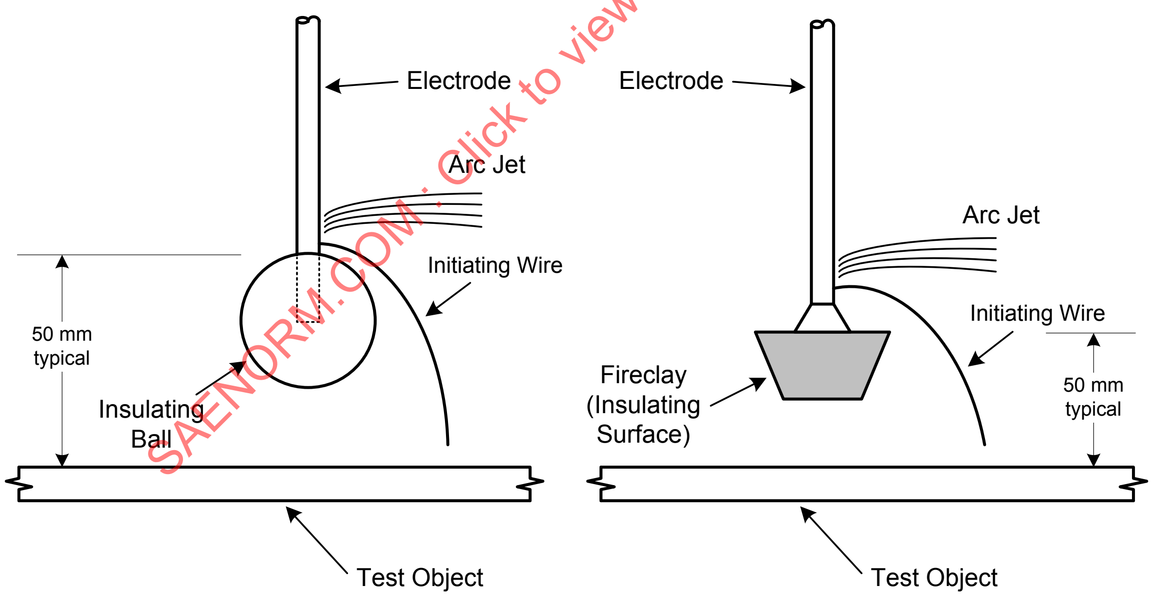

FIGURE 13 - TYPICAL JET DIVERTING TEST ELECTRODE

5.2.1.6 Test Procedure

(1) Measure laboratory environmental conditions.

(2) Review and implement safety procedures. Some areas of concern are as follows. Test areas must be safe and clear of personnel prior to charging of test equipment and capacitor banks must be shorted out prior to entry of personnel into the test area. Eye and ear protection may be appropriate.

(3) Calibrate the generator and instrumentation as follows:

(a) Insert a conductive bar over the test object with material properties similar to the test object, such that a generator discharge will not damage the test object.

(b) Connect the bar to the generator return.

(c) Initiate a discharge to the bar, while measuring the applied current waveform(s).

(d) If the current level or waveform(s) are not correct, adjust the generator parameters.

(e) Repeat steps (c) thorough (d) as necessary to obtain the required waveform(s).

(f) Remove the bar.

(4) Initiate a discharge to the test object.

(5) Inspect the test object and document the results.

(6) If required, orient the electrode in a new position and repeat steps (4) through (5).

5.2.1.7 Data Interpretation

Test objects should undergo a thorough post-test evaluation to determine the adequacy of the design with respect to Pass/Fail criteria.

5.2.2 Aircraft Non-Conductive Surfaces Test

5.2.2.1 Test Purpose

This test is normally applicable to aircraft surfaces located in Zones 1A, 1C, and 2A. This test is used to determine the effects of a lightning channel sweeping over aircraft optical transparencies, antenna fairings and other non-conductive surfaces. If a dielectric coating is present which will be easily punctured, such as a de-icing boot overlaying conductive structure, the arc entry test in 5.2.1 is more appropriate. For dielectric fairings, where a puncture and subsequent attachment to an underlying antenna could occur, the swept channel attachment test in 5.1.2 should also be performed. If puncture does occur, the arc entry test of 5.2.1 should be performed. This test can be used to assess:

- Shock wave damage and thermal effects.
- Effects of arc attachment to buried or internal wires.
- Effects on the inside plies which could produce 'spall'.
- Effects on transparency attachment to the frame.
- The magnitude of voltages and currents induced or directly coupled onto internal conductors.

5.2.2.2 Test Object

The test object should be a full-scale production item or a representative prototype. The assembly should be sufficiently complete to evaluate possible damage without affecting the test results. If the intent of the test is to compare different designs, all samples should have the same size, cross section, mounting and method of any de-icing or anti-icing, application of surface finishes or anti-static coatings, and the method of grounding the de-icing or anti-icing elements.

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5.2.2.3 Test Setup

- Mount the test object in a fixture or aircraft structural section. Figure 14 shows a test object mounted in a generic test frame that supports the test object simulating the angle of the transparency. The metal flashing attached in front of the test object simulates the fuselage in front of the transparency. This type of test arrangement can provide spall information at a crew station. Figure 15 shows a full-scale windshield mounted in a section of aircraft structure (or test fixture that duplicates the structure). This arrangement is sometimes used if the lightning damaged windshield is to be pressure tested. If moisture is judged to be a factor, windshields should be tested in both the wet and dry conditions.

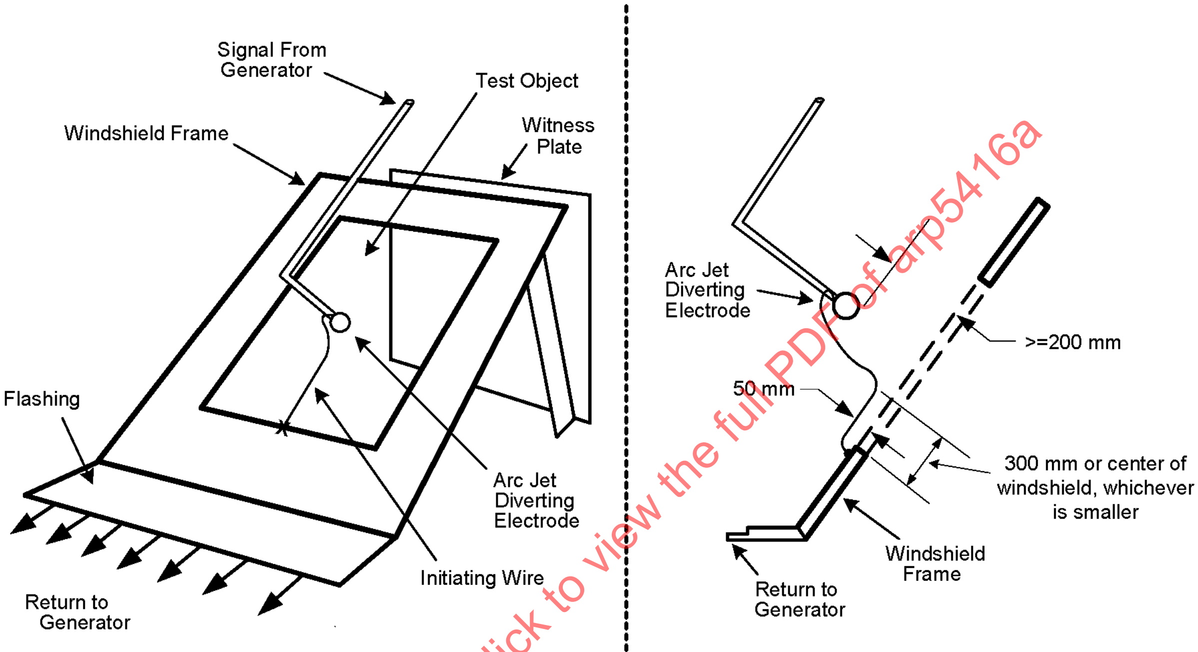

FIGURE 14 - TEST ON TRANSPARENCY MOCK-UP

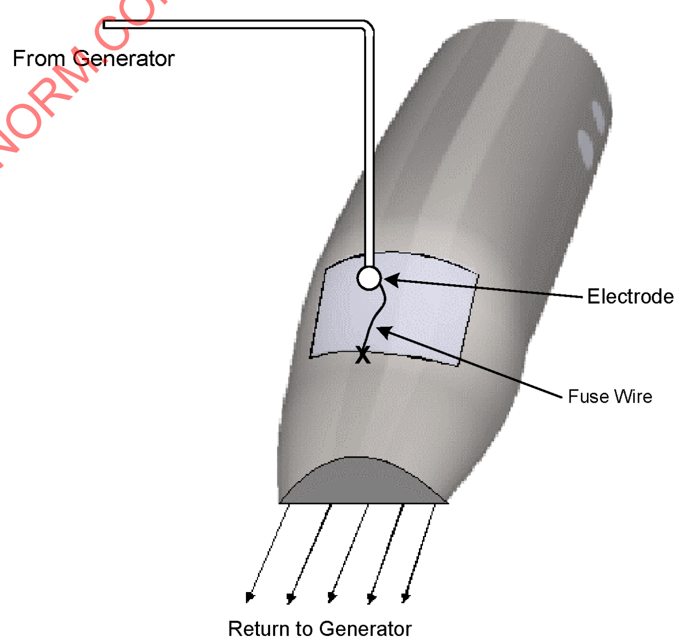

FIGURE 15 - TEST ON WINDSHIELD

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- Ground all hardware to the test object structure that is normally grounded.

- Connect the generator return to the assembly such that the lightning currents are conducted away from the test object in a manner representative of when the aircraft is struck by lightning. Ensure that magnetic forces and other interactions associated with current flow within the setup are controlled such that they represent the natural situation.

- Orient a 'jet diverting' electrode (see Figure 11) 200 mm or greater above the area of the test object that is to be evaluated. For a transparency, the electrode should be centered on the transparency.

- For a transparency, the electrode should be positioned 300 mm from the leading edge of the transparency or half way between the leading and aft edge of the transparency whichever is the smaller.

- Connect the high side of the generator to the electrode.

- For this test either positive or negative polarity can be used.

- A fine metallic wire, not exceeding 0.1 mm diameter, should be used to direct the arc to a specific point of interest on the test object. The fuse wire path should be from the electrode directly toward the non-conductive surface. Then at a distance of 50 mm above the surface, it should travel approximately parallel to the surface forward to the aircraft structure (or flashing) directly in front of the non-conductive area. Typical wire attachment points are aircraft structure, heads of mounting screws, windshield wiper shafts or arms, or windshield anti/de-ice bleed air nozzles.

- Set up sensing and recording equipment.

5.2.2.4 Test Waveforms

Current waveform A/Ah or D of ARP5412/ED-84 is used for this test depending on the aircraft zone where the test object is located. Components B & C* may be used if it is felt necessary to assess thermal effects on the surface of the test object.

If it is necessary to evaluate the thermal effects of components B & C* on, for example, acrylic windscreens, an additional test may be conducted with the electrode moved closer to the leading edge of the transparency, thereby shortening the initiating wire to enable these components to be applied across a shorter distance of the test object.

5.2.2.5 Measurements and Data Recording

- Photographs and description of the test setup.

- If applicable, description and photographs of instrumentation probes for windshield heater circuit and harness arrangement.

- Photographs of the test object both before and after each discharge.

- Photographs and description of damage to the test object.

- Description and photographs of the orientation of heating wires with respect to the fuse wire.

- Records of laboratory environmental data (such as temperature, pressure and humidity), dates of testing, personnel performing and witnessing the tests, and test location.

- Record of any deviations from the test procedure.

- Records of the results of each discharge showing polarity, current amplitudes, waveforms, action integrals and charge transfers at applicable test points.

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- If applicable, records of amplitude and waveforms of induced signals in heater circuits.
- If applicable, photographs of transparency spall pattern on witness plate.

NOTE: Some tests require that the degree of spall from the inner surface of the transparency at the crew station be evaluated. One method of determining the force and pattern of the spall is to place a witness plate behind the transparency at the crew's location. The witness plate is made of a soft material that will qualitatively record the amount, direction, and force of the transparency spall. Plastic modeling clay, artists modeling clay (in the pliable wet condition), soft Styrofoam insulation board spray painted with a contrasting color, or soft newsprint paper (no printing) are examples of possible witness plate materials.

5.2.2.6 Test Procedure

(1) Measure laboratory environmental conditions.

(2) Review and implement safety procedures. Some areas of concern are as follows. Test areas must be safe and clear of personnel prior to charging of test equipment and capacitor banks must be shorted out prior to entry of personnel into the test area. Eye and ear protection may be appropriate.

(3) Calibrate the generator and instrumentation as follows:

(a) Insert a conductive bar over the test object with material properties similar to the test object, such that a generator discharge will not damage the test object. For transparencies, ensure the arc blast pressure will not mechanically damage the transparency.

(b) Connect the bar to the generator return.

(c) Initiate a discharge to the bar, while measuring the applied current waveform(s).

(d) If the current level or waveform(s) are not correct, adjust the generator parameters.

(e) Repeat steps (c) thorough (d) as necessary to obtain the required waveform(s).

(f) Remove the bar.

(4) Clean test object with appropriate technique to remove dust, debris, and other contaminants which could affect test results.

(5) Initiate a discharge to the test object.

(6) Inspect the test object and document the results.

(7) If required, orient the electrode in a new position and repeat steps (5) through (6).

5.2.2.7 Data Interpretation

Test objects should undergo a thorough post-test evaluation to determine the adequacy of the design with respect to Pass/Fail criteria. Photographs showing the arc path, entry point(s), and damage areas observed on the test object should be correlated to provide an understanding of damage effects.

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5.2.3 Conducted Current Test

5.2.3.1 Test Purpose

This test is applicable to aircraft structure located in Zone 3, as described in ARP5414/ED-91. This test can be used to assess:

- physical damage,
- arcing and sparking,
- magnetic force effects,
- thermal effects.

5.2.3.2 Test Object

The test object should be full-scale production like sections or subsections of structures that include interfaces between structural members or assemblies, such as adhesive bonded joints, fastened joints, hinges, bearings in actuators, and fuel tank access panels. The specimens should be large enough to represent a sufficient cross section of the airframe to allow representative lightning current distribution to be achieved.

5.2.3.3 Test Setup

- Mount the test object in a fixture.
- Ground all hardware to the test object structure that is normally grounded.
- Connect the generator high and return sides to the assembly such that the lightning currents are conducted through the test object in a manner representative of when the aircraft is struck by lightning. The polarity of the generator is usually not relevant. Ensure that magnetic forces and other interactions associated with current flow within the setup are controlled such that they represent the natural situation.
- Set up sensing and recording equipment.

NOTE: A semi-coaxial arrangement of the conductors and the test object can be used to minimize magnetic effects and distribute current flow. Figure 16 shows a typical test arrangement for testing small material samples using this technique. Also, measurements of induced voltages into wiring as described in 6.1 can sometimes be combined with this test method.

5.2.3.4 Test Waveforms

A subset of current components found in Table 3 of ARP5412/ED-84 are used for this test. The amplitude levels must be scaled based on a determination of the expected current density for all possible lightning current paths through the airframe structure containing the area simulated by this test object. Current densities can be estimated by computer analysis or low-level swept CW tests that have been transformed to give the response due to lightning waveform. Note that the current densities on the edge of the test panel could be three times the current in the center due to magnetic field effects. This situation might not be representative of the aircraft installation.

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5.2.3.5 Measurement and Data Recording

- Photographs and description of the test setup.
- Photographs of injection points.
- Photographs of the test object both before and after each discharge.
- Photographs and description of damage to the test object.
- Records of laboratory environmental data (such as temperature, pressure and humidity), dates of testing, personnel performing and witnessing the tests, and test location.
- Record of any deviations from the test procedure.
- Records of the results of each discharge showing polarity, current amplitudes, waveforms, action integrals and charge transfers at applicable test points.

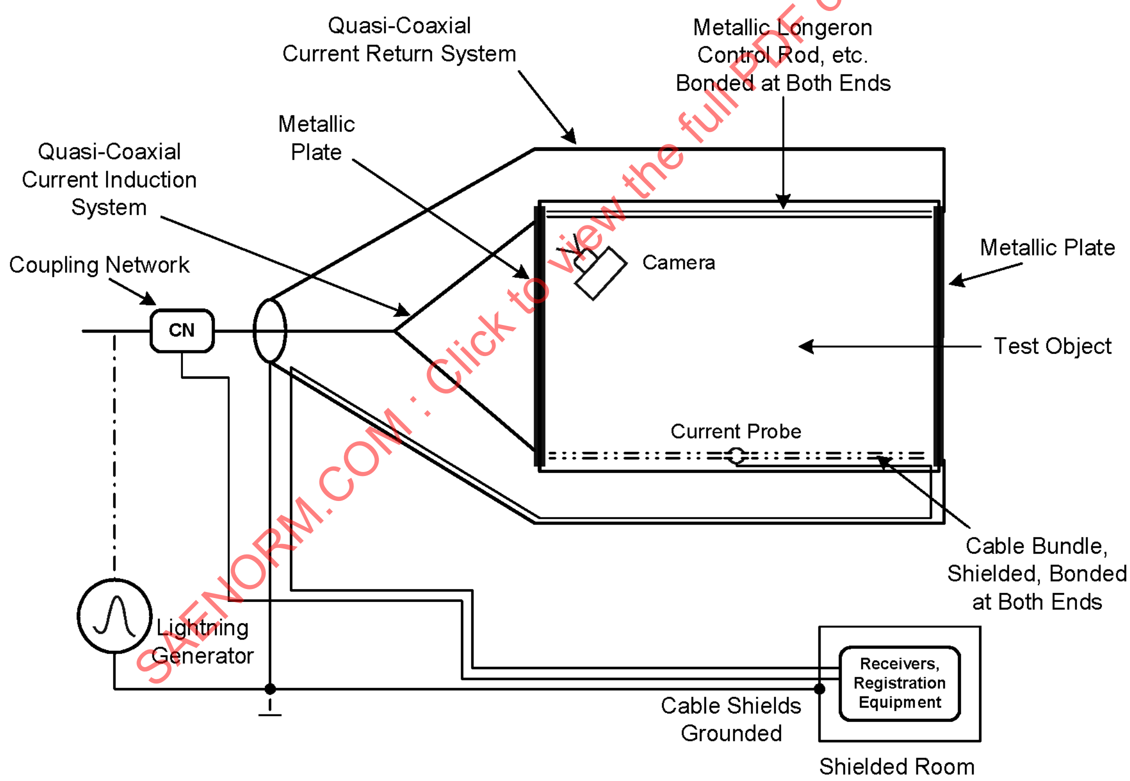

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FIGURE 16 - TYPICAL SETUP FOR DAMAGE TEST WITH POWER LEAD LAYOUT

5.2.3.6 Test Procedure

(1) Measure laboratory environmental conditions.

(2) Review and implement safety procedures. Some areas of concern are as follows. Test areas must be safe and clear of personnel prior to charging of test equipment and capacitor banks must be shorted out prior to entry of personnel into the test area. Eye and ear protection may be appropriate.

(3) Calibrate the generator and instrumentation as follows:

(a) Detach the generator high and return from the test object and connect them to a conductive bar near the test object. The bar should have material properties that are similar to the test object.

(b) Initiate a discharge to the bar, while measuring the applied current waveform(s).

(c) If the current level or waveform(s) are not correct, adjust the generator parameters.

(d) Repeat steps (b) thorough (c) as necessary to obtain the required waveform(s).

(e) Remove the bar and reattach the generator high and return to the test object.

(4) Clean test object with appropriate technique to remove dust, debris, and other contaminants which could affect test results.

(5) Initiate a discharge to the test object.

(6) Inspect the test object and document the results.

5.2.3.7 Data Interpretation

Test objects should undergo a thorough post-test evaluation to determine the adequacy of the design with respect to Pass/Fail criteria.

5.3 Induced Transients in External Mounted Hardware

The tests in this section evaluate induced electrical transients that are closely associated with direct effects.

5.3.1 Measurement of Injected Transients in External Hardware

5.3.1.1 Test Purpose

This test is applicable to externally-mounted aircraft components located in Zones 1A, 1B, 1C, 2A, and 2B that have electrical circuits which may have voltages and currents injected into them from direct lightning attachment. Such components include antennas, icing detectors, angle-of-attack (AOA) sensors, electrically heated pitot tubes, navigation lights and electrical de-icing heaters. This test may be accomplished in combination with the arc entry test of 5.2.1 or conducted current test of 5.2.3. This test may be used in addition to full aircraft indirect effects tests in 6.1 that are used to determine induced voltage and current on wires connected to the externally-mounted aircraft components due to Zone 3 conducted currents.

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5.3.1.2 Test Object

The test object should be full-scale production line hardware or a presentative prototype. The structure, wiring, and equipment installation should be electromagnetically similar to the intended production configuration. The test object should include installation provisions such as gaskets, bonding jumpers, paint and sealants. Electrical wire bundles representative of the aircraft installation should be included.

5.3.1.3 Test Setup

- Mount the test object to a test fixture that is representative of the airframe structural and wiring harness interfaces. Figure 17 shows a simple aluminum test chamber. The test object is installed on a panel that is representative of the actual aircraft structure. The actual aircraft structure material, such as aluminum, fiberglass reinforced plastic (FRP), carbon fiber composite (CFC) or titanium should be used for the test panel.

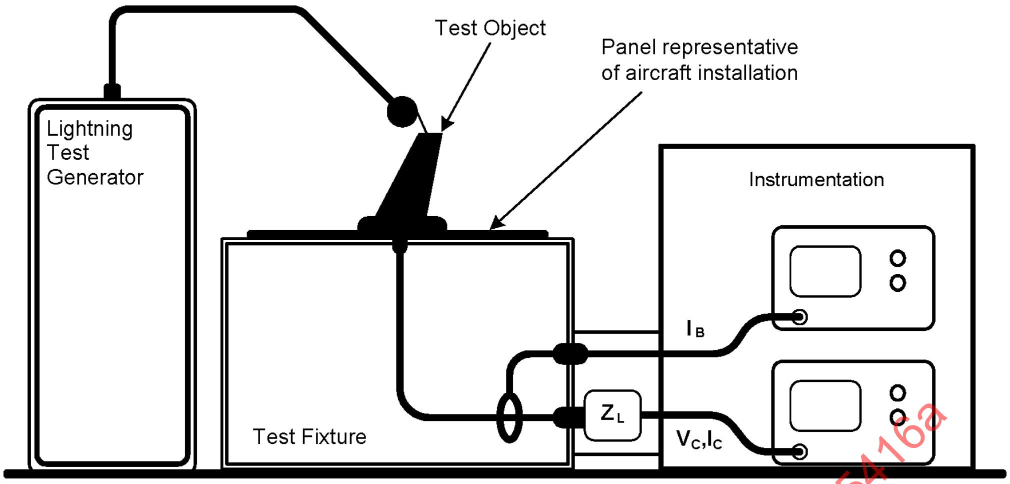

FIGURE 17 - TYPICAL METAL SKIN INSTALLATION

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- Ground all test object hardware to the test fixture as specified for the aircraft installation.

- Select the initial test polarity and connect the return side of the high voltage generator to the test fixture. Ensure that the connection position will result in test current being conducted away from the test object in a manner representative of when the aircraft is struck by lightning.

- Orient a test electrode 50 mm or greater above (or attach it directly to) the test object at a probable attachment point expected from natural lightning. For most arc entry tests the electrode should be the 'jet-diverting' type, as shown in Figure 13.

- Set up the current and voltage measurement probes and recording equipment.

- Provide shielding for any measurement probes and recording equipment to minimize measurement noise. A suitably shielded instrument cable or optical fiber link should be used between the induced transients measurement probes and the recording equipment.

- Terminate the test object wires in appropriate loads (Z_L). There are two general approaches to terminating the wires when measuring induced voltages V_C and currents I_C. The first approach consists of terminating the wires with open and short circuits to measure the open circuit voltage (V_{OC}) and the short circuit current (I_{SC}) for a given interface circuit. This approach produces values that are worst case levels, which are useful for performing computations on circuits with differing load impedances. However, this requires two separate pulse tests, one with each termination condition. The second approach consists of terminating the wires with actual circuit impedances, to measure the induced voltage and current transients with these actual circuit impedances. Bulk wire bundle current (I_B) measurements are possible with either approach.

5.3.1.4 Test Waveforms

Current components found in Table 3 of ARP5412/ED-84 are normally used with the particular waveforms being dependent on the aircraft lightning zone where the test object is located in the actual installation. These waveforms are used (with current waveforms B and C being excluded) because the key waveform parameters relative to indirect effects coupling are associated with the specified waveforms, including peak current and peak rate of rise. See 5.1.3.7.

5.3.1.5 Measurement and Data Recording

- Photographs and description of the test setup.

- Photographs and descriptions of instrumentation probes for electrical circuits and harness arrangement.

- Photographs of the test object both before and after each discharge.
- Photographs and description of damage to the test object.
- Records of laboratory environmental data (such as temperature, pressure and humidity), dates of testing, personnel performing and witnessing the tests, and test location.
- Record of any deviations from the test procedure.
- Records of the results of each discharge showing polarity, currents amplitudes, waveforms, action integrals and charge transfers at applicable test points.
- Records of amplitude and waveforms of voltages/currents at the terminals of electrical circuits in the test object. The recording instrument should have a minimum bandwidth of 30 MHz.

5.3.1.6 Test Procedure

(1) Measure laboratory environmental conditions.

(2) Review and implement safety procedures. Some areas of concern are as follows. Test areas must be safe and clear of personnel prior to charging of test equipment and capacitor banks must be shorted out prior to entry of personnel into the test area. Eye and ear protection may be appropriate.

(3) Calibrate the generator and instrumentation as follows:

(a) Detach the high side of the generator from the test object and connect it to a conductive bar that is connected to the generator return point of the test object. The bar should have material properties that are similar to the test object.

(b) Initiate a discharge to the bar, while measuring the applied current waveform and the induced levels in the electrical circuit instrumentation.

(c) If the current level or waveform is not correct, adjust the generator parameters.

(d) If the induced noise levels in the instrumentation circuit are above those expected, modify the instrumentation setup to reduce the induced levels.

(e) Repeat steps (b) thorough (d) as necessary to obtain the required conditions.

(f) Remove the bar and reattach the generator to the test object.

(4) Initiate a discharge to the test object, while measuring the applied current waveform and the induced transients on the electrical wires.

(5) Inspect the test object and document the results.

5.3.1.7 Data Interpretation

The measured transient voltage and current responses and any test object malfunction or damage should be evaluated relative to the defined pass/fail criteria. The measured voltage or current waveforms and amplitude should be compared to the specified transient control level (TCL) defined for the system. If tests were conducted at levels less than the applicable lightning threat level, the measured current and voltage responses must be extrapolated to the threat levels using the guidelines specified in 6.1.6.6. For extrapolation, the peak amplitude, rate-of-rise or integral related responses of the measured current or voltage waveforms must be identified. If the test current waveforms do not correspond to the required A, D or H waveform, different extrapolation factors for peak amplitude, rate-of-rise or integral related responses may be required.

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5.3.2 Voltage Stress Assessment of Circuit Insulation

5.3.2.1 Test Purpose

This test is an indirect effect assessment due to a direct effect. This test is applicable to areas of the aircraft (possibly any lightning zone) where induced voltages might cause flashover or breakdown of insulated electrical wiring to surrounding structures due to changing magnetic flux and voltage drops in structural resistances. An example is the voltage, $V_{induced}$, which may appear between a pitot heater element and the pitot tube during a strike to a radome mounted pitot tube as illustrated in Figure 18. If breakdown occurs, the impedance at the breakdown point will be very low and the pitot heater circuit may be exposed to very high voltages in excess of those measured during the indirect effects testing of Section 6.

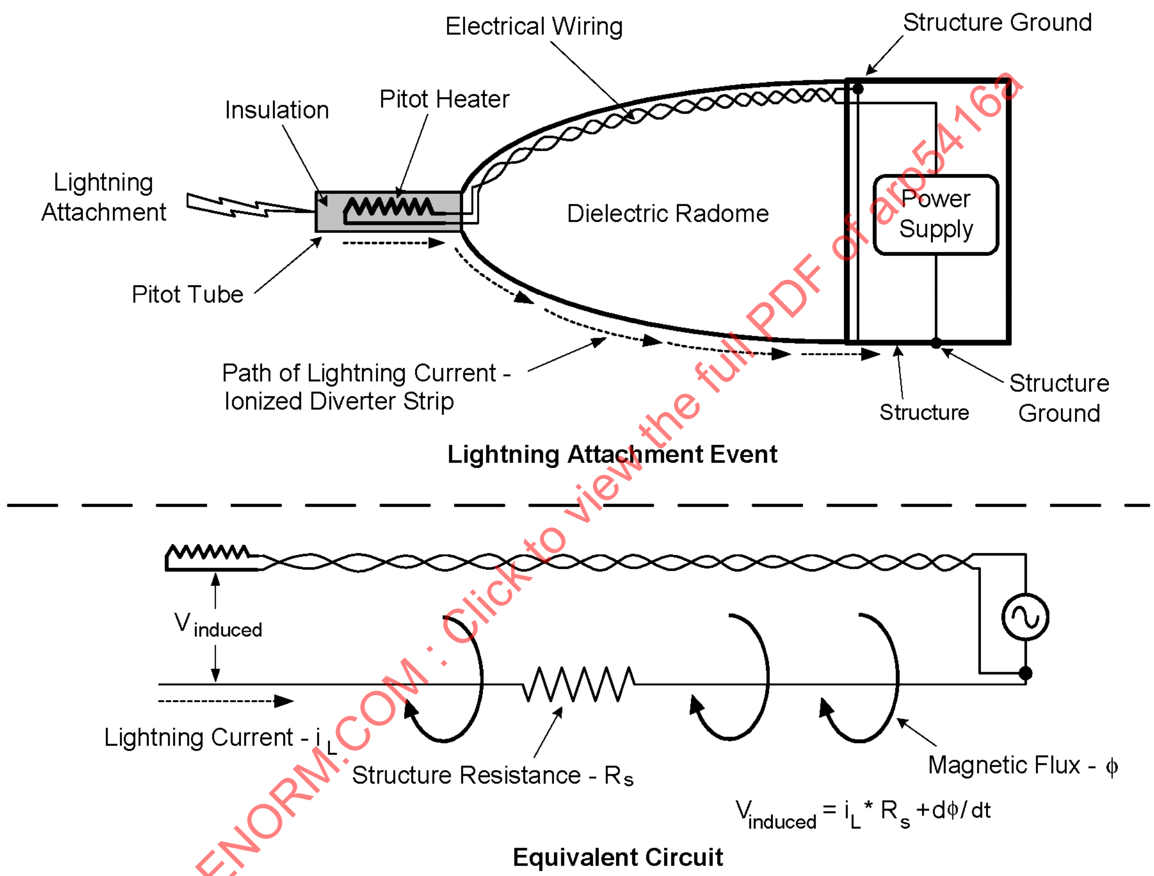

FIGURE 18 - LIGHTNING INDUCED VOLTAGE APPEARS AT PITOT HEATER INSULATORS

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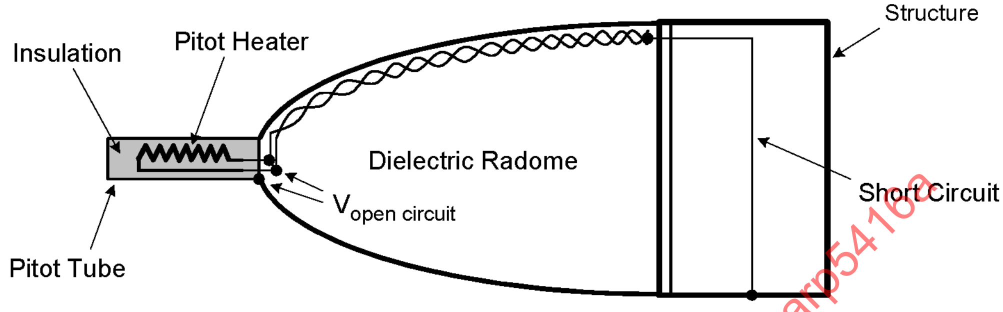
5.3.2.2 Test Object

The test object should be a full-scale production item or a representative prototype. The test object should be fully representative in relation to the system wiring of interest and the type and installation of equipment, wire runs, and wiring relevant to the tests to be made.

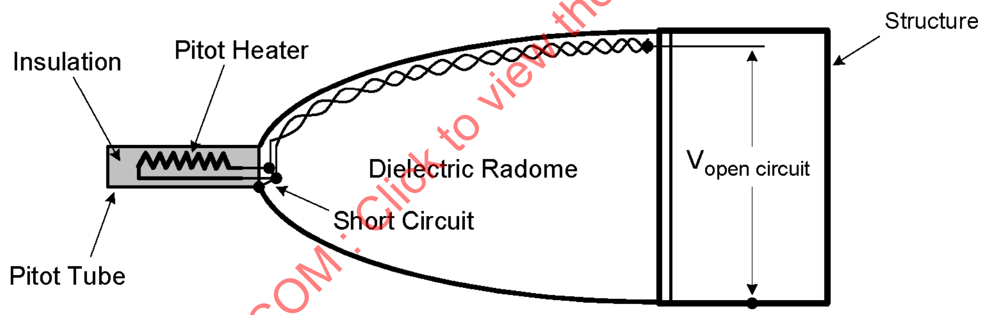
5.3.2.3 Test Setup

- Use the setup of 5.3.1 or 6.1, whichever is appropriate.

- Place a temporary short circuit at one end of the circuit as shown in Figure 19. Set up the instrumentation to measure of the open circuit voltage at the other end of the circuit.



Common Mode Voltage Measurement at Pitot Heater



Common Mode Voltage Measurement at Power Supply

FIGURE 19 - INDUCED VOLTAGE MEASUREMENT LOCATIONS

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5.3.2.4 Test Waveforms

Current waveforms A, D, and H of ARP5412/ED-84 are normally used with the particular waveforms being dependent on the aircraft lightning zone where the test object is located in the actual installation.

NOTE: These waveforms are used (with current waveforms B and C being excluded) because the key waveform parameters relative to indirect effects coupling are associated with the specified waveforms, including peak current (for diffusion/resistive coupling) and peak rate of rise (for aperture coupling). The test current waveform should be the stroke current component appropriate to the zone in which the structure is located. This test may be conducted with non-representative waveform parameters, and in this case the measured voltage should be extrapolated to correspond to the full threat.

5.3.2.5 Measurement and Data Recording

Use the measurements and data recording material of 5.3.1 or 6.1, whichever is appropriate.

5.3.2.6 Test Procedure

Use the test procedure material of 5.3.1 or 6.1, whichever is appropriate.

5.3.2.7 Data Interpretation

The measured levels should be reviewed to determine the adequacy of the design with respect to Pass/Fail criteria. If tests were conducted with waveform parameters different than the applicable lightning threat waveform, the measured values need to be extrapolated to the threat levels using the guidelines specified in 6.1.6.6. For extrapolation, the dI/dt and IR components of the measured test current waveform need to be identified. If the test current waveforms do not correspond to the required waveform, different extrapolation factors for dI/dt or IR related voltages might be applicable. If the peak voltage exceeds the insulation withstand voltage, sparkover should be expected and damaging currents may flow into the conductors.

6. INDIRECT EFFECTS TEST METHODS

The indirect effects test methods outlined in this section are for lightning induced transients in aircraft wires and wire bundles:

a. Aircraft Tests to measure lightning induced transients (6.1),

b. Tests for Equipment and Systems (6.2),

c. Wire Bundle Shield Transfer Function Tests (6.3), and

d. Shield/Connector Current Handling Tests (6.4).

6.1 Aircraft Tests

The two basic types of aircraft tests are swept frequency tests and current pulse tests. These aircraft tests may be used to acquire engineering data to support aircraft lightning protection design, or they may be used to acquire lightning protection effectiveness data to support aircraft or engine certification.

6.1.1 Test Purpose

Aircraft tests are used to determine the actual transient levels (ATLs), including the transient waveforms, induced into aircraft electrical/electronic systems wiring. These induced transient current and voltage amplitudes and waveforms are typically measured on installed wire bundle shields and individual wires. The measured ATLs can be used to define or verify the associated lightning protection TCLs and ETDLs. Transients may also be measured on non-electrical system conductors such as control cables; fuel, hydraulic, and pneumatic lines; and structural elements, for fuel system and structure lightning protection design and certification.

6.1.2 Test Object

The aircraft test may be performed on a complete and functioning aircraft, a major section of an aircraft, or an engine assembly. If the test is performed for aircraft or engine certification, a production aircraft or engine should be preferred, otherwise justification for results applicability may be required. A production aircraft or engine with no flight test wiring installed is preferred. If flight test wiring is present, this wiring should be disconnected on both ends and the connectors and shields isolated from the structure during testing. The aircraft or engine may be subject to conformity inspections by the appropriate regulatory authority prior to the test.

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If the test is performed to develop engineering design data, a prototype, mockup, or major aircraft or engine section may be used. The structure, wire bundles, and equipment installation should be electromagnetically similar to the intended aircraft or engine production configuration. If an engine assembly or major section of an aircraft is used for the test, additional conductors may be required to simulate current flow on the rest of the aircraft that was not included in the engine assembly or major aircraft section.

Aircraft tests are typically conducted with the aircraft systems unpowered. The power contactors, circuit breakers, and equipment power switches may need to be configured to maintain power circuit continuity.

The aircraft or engine may require minor modification to install lightning test instrumentation and probes. These modifications should be designed and installed so that they do not affect the lightning current paths, or create additional openings in the aircraft. For example, a special window panel may be installed to allow instrumentation wires or fiber optic cables inside the aircraft without opening an aircraft door or hatch.

For aircraft major section or engine tests, the aircraft major section or engine must include lightning current paths to the rest of the aircraft in order to get realistic current flow and accurate induced transient measurements. These current paths may include system components such as mounting brackets, fuel and hydraulic lines, flight control and electrical conduits/wires, bonding straps, and structural elements.

For engines, all lightning current paths between the engine, nacelle, pylon, strut, and airframe should be considered, and may be included in the test setup. These current paths include engine mounts, fuel and hydraulic lines, electrical wire bundles, push rods, ground straps, safety lock wires, and any other design features intended specifically for EMC, HIRF, or lightning protection.

Any fuel, electro-explosive devices (EEDs), and pyrotechnics should be removed or made safe prior to tests. EEDs may be replaced by equivalent instrumented devices. Flammable fuel vapor should be eliminated, by filling the fuel tanks to reduce vapor volume, and by filling the remaining fuel vapor space with an inerting gas such as nitrogen.

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6.1.3 Return Conductor Arrangement

The test setup includes the aircraft, a suitable return conductor arrangement, the current generator, and current generator controls and monitoring instruments, and induced transient measurement instruments.

Lightning interaction with an aircraft depends on the lightning attachment points. The lightning attachment points are represented by the current generator and return conductor attachments to the aircraft. Typically, several attachment configurations are required to adequately characterize the aircraft ATLs. The lightning attachment configurations used for the aircraft tests should be based on likely lightning attachment points, and the routing and location of systems and wiring in the aircraft. Table 1 gives a list of typical attachment configurations for an aircraft. For example, a measurement made on a wire routed between the flight deck and the left wing navigation light should be made with the nose and the left wing tip attachment points. In this configuration, the simulated lightning current would flow through structure where the wiring of interest is routed, thereby inducing the maximum transients in that wiring.

TABLE 1 - TYPICAL TEST CURRENT ATTACHMENT CONFIGURATIONS

Current Generator Attachment Point	Return Conductor Attachment Point
Aircraft	
Nose	Tail
Windshield Post	Tail
Nose	Wing Tip
Nose	Engine
Nose	Landing Gear
Nose	Vertical Tail
Wing Tip	Tail
Wing Tip	Wing Tip
Engine Inlet	Engine Exhaust
Engine Inlet	Tail
Helicopter	
Main Rotor Blade	Tail Rotor Blade
Main Rotor Blade	Landing Skid
Main Rotor Blade	Nose
Tail Rotor Blade	Landing Skid
Tail Rotor Blade	Nose

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The number of current generator and return conductor configurations may be reduced by using analysis to show that the selected current generator and return conductor configurations achieve the most severe lightning transients for the aircraft test points. The analysis and models used in the analysis should be validated by comparison with lightning test results.

The return conductors and current generator attachments should be configured to simulate the important characteristics of the lightning and aircraft interaction. The current distribution on the test aircraft should simulate as much as possible the current distribution that would exist on the aircraft during an in-flight lightning strike.

The return conductor arrangement will be dependent on the aircraft shape. The aircraft and return conductors cannot be considered uniform transmission lines, such as a coaxial transmission line, except in the crudest approximation. So the aircraft and return conductor arrangement should be configured to provide repeatable test results, with a representative current distribution on the airframe.

This may be achieved using the aircraft on the ground and an assembly of return conductors. The preferred installation would be to use return conductors about the aircraft fuselage, wings and tail boom, which would encourage a representative current distribution in the aircraft. As a minimum, the return wires should be arranged as a ground plane under the aircraft fuselage, wings, and tail boom. This may be the most practical return conductor configuration for large transport aircraft. This will exaggerate the current density on the lower part of the aircraft nearest the ground plane. This is typically satisfactory for wing-mounted wiring and systems, and for aircraft where the critical wiring, systems, and key coupling points (such as doors and hatches) are on the lower part of the aircraft. But this configuration produces lower current density on the higher parts of the aircraft, such as the top of the fuselage and near the cockpit windows.

Practical aircraft and return conductor configurations form a non-uniform transmission line. The characteristic impedance of this complex non-uniform transmission line typically ranges from 70 to 150 Ω. The aircraft and return conductors are driven at one lightning attachment point by the test current generator. The aircraft and return conductors are typically shorted together at the other lightning attachment point for that test configuration. This aircraft and return conductor arrangement will produce a drive point impedance that has low resistance at low frequencies, is inductive in the range of 10 kHz up to a high-Q quarter-wavelength resonance frequency of the aircraft/return conductor transmission line, and then with multiple transmission line resonances at higher frequencies.

This differs from the characteristics of natural lightning attachment to aircraft. Lightning return stroke characteristic impedance or surge impedance have been estimated to range from 1000 to 6000 Ω, with some longitudinal resistance in the lightning channel. Therefore, the aircraft during a natural lightning strike will not exhibit a high-Q quarter-wavelength resonance, but will exhibit a lower-Q half-wavelength resonance related to the lightning current path length through the aircraft.

The aircraft and return conductor arrangement may be terminated with matching resistors instead of shorting the aircraft and return conductors. Matching the transmission line may eliminate the quarter-wavelength transmission line resonant response that is test configuration dependent. However, for most lightning attachment configurations, the aircraft and return conductor are much too complex to be represented as a uniform transmission line. Even if the aircraft and return conductor transmission line can be terminated in a matched impedance, the matching load resistance is generally so high that it reduces the amplitude of the input current that can be injected into the aircraft with a given current generator. This results in an unacceptable signal-to-noise ratio and hampers the ability to measure induced transients in wiring. It also reduces the normal half-wavelength resonance typical for a natural lightning strike to an aircraft.

With the aircraft and return conductor shorted at one attachment point, the quarter-wavelength transmission line resonance provides conservative induced transient measurements at the resonant frequency. The quarter-wavelength resonance occurs at a frequency that is lower by half compared to the half-wavelength resonance. The defined lightning environment spectra decrease 40 dB per decade or 12 dB per octave as frequency increases in the airframe resonance frequency range. So the induced transient response due to the quarter wavelength resonance may be higher than an induced transient response due to a half wavelength resonance.

For helicopters with avionics in the nose area, the highest lightning transients tend to result from the nose to tail rotor blade current generator and return conductor configuration, as shown in Figure 20. Current generator attachment to main rotor blades may result in the highest lightning transients for wiring and systems installed on the engine and gearbox. With the main rotor blade current generator and return conductor configuration, a coaxial return may be impractical and a simplified configuration may be used. However, additional analysis may be required to account for differences between transients measured in the test configuration and expected transients in flight.

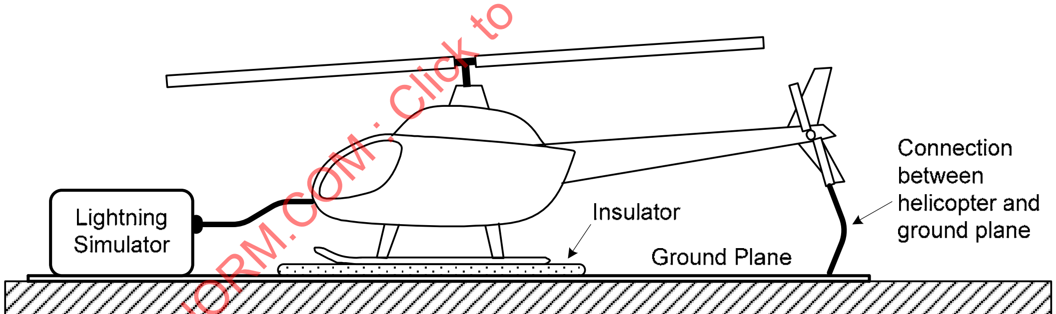

FIGURE 20 - HELICOPTER GROUND PLANE ARRANGEMENT

For small aircraft, conductors surrounding the aircraft uniformly spaced from its surface may be the most effective return conductor arrangement. This arrangement, shown in Figure 21, provides reasonably representative current distribution between the top and bottom surfaces of the aircraft. Additional analysis to represent the in-flight current distribution should not be necessary in this arrangement, except to consider the resonance of a short circuit return connection compared to the expected impedance of the lightning channel for an in-flight lightning attachment.

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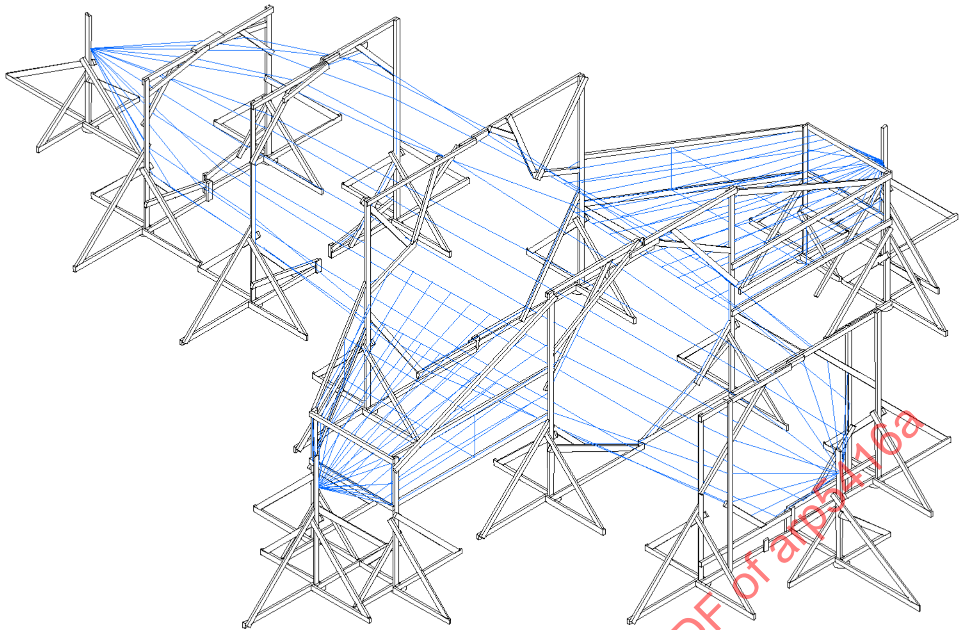

FIGURE 21 - SMALL AIRCRAFT RETURN CONDUCTOR ARRANGEMENT

For large aircraft, the return conductor arrangement may be more complex, and it may not be practical to have conductors above the aircraft. Therefore, additional analysis may be necessary to assess the aircraft current distributions in the test configuration and in the normal in-flight lightning attachment. The analysis should determine the effect of the test return conductors, and the effect of the return conductor termination on the aircraft surface current distribution. Analysis should determine the differences between test current distribution and the expected surface current distribution for an aircraft in-flight lightning attachment. Method of moments, finite-difference time domain, and finite element models are all effective tools for assessing the lightning surface current distribution on large aircraft.

Localized return conductors may also be used for lightning induced transient response for wiring in specific areas of the aircraft, such as the stabilizers or engines. Figure 22 shows localized return conductors for measurements associated with wiring in the vertical stabilizer.

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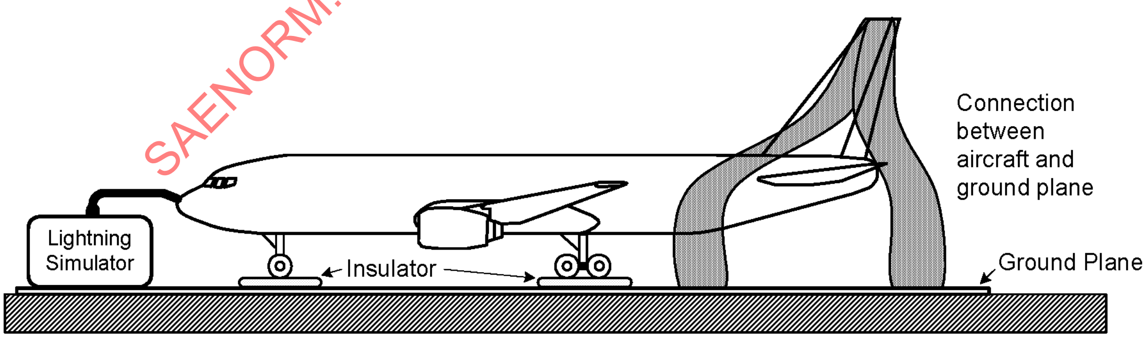

FIGURE 22 - LARGE TRANSPORT AIRCRAFT RETURN WIRE ARRANGEMENT

The test aircraft must be isolated from the return conductors except at the current generator and return conductor attachment points. The tires or helicopter skids must be isolated from the ground plane return conductors using insulating pads or stands. The insulating pads or stands must withstand the voltages developed between the aircraft and return conductor, particularly during high current pulse tests.

The ground plane should preferably be single point grounded to facility ground near the test generator ground point to meet health and safety requirements. Care should be taken to minimize traveling wave effects or spurious oscillations between the return arrangement and the facility (i.e., hangar). This might be accomplished by careful selection of the ground point, or by grounding the return arrangement to the facility via resistors to damp out such resonances, or by grounding the arrangement via a low DC resistance connection which has a high impedance at high frequencies.

6.1.4 Measurements

The aircraft tests provide induced transient responses that may be used to determine the ATLs that can be compared to the TCLs and ETDLs. Therefore, the aircraft lightning measurements should be chosen to match the method by which the aircraft TCLs and the equipment or system ETDLs are defined. For example, if the TCLs are defined as individual wire open circuit voltages and individual wire short circuit currents, then aircraft measurements should include individual wire open circuit voltages and wire short circuit currents. Or, if the TCLs are defined as overall wire bundle currents, then the aircraft measurements should include overall wire bundle currents.

Also, the aircraft lightning measurements should provide data that can be directly compared to the ETDLs and corresponding equipment qualification tests. For example, if the ETDLs and corresponding equipment qualification tests are based on the DO-160/ED-14, Section 22 wire bundle injection tests, the wire bundle injection tests levels are based on open circuit loop voltages and/or wire bundle currents. Therefore, the full aircraft lightning measurements should include open circuit loop voltages and short circuit 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) and any other shields in the same wire bundle should be grounded in 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.

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 measurement configurations described in a. through e. are shown in Figure 23. The loaded wire measurements described in d. and e. above are usually made only in special cases, such as navigation light and window heater circuits, and power distribution buses, 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. Surge protection devices installed in aircraft wiring should be considered. Surge protection devices would be in the conducting state from induced voltage due to natural lightning strikes, but would not conduct during tests with lower test currents.

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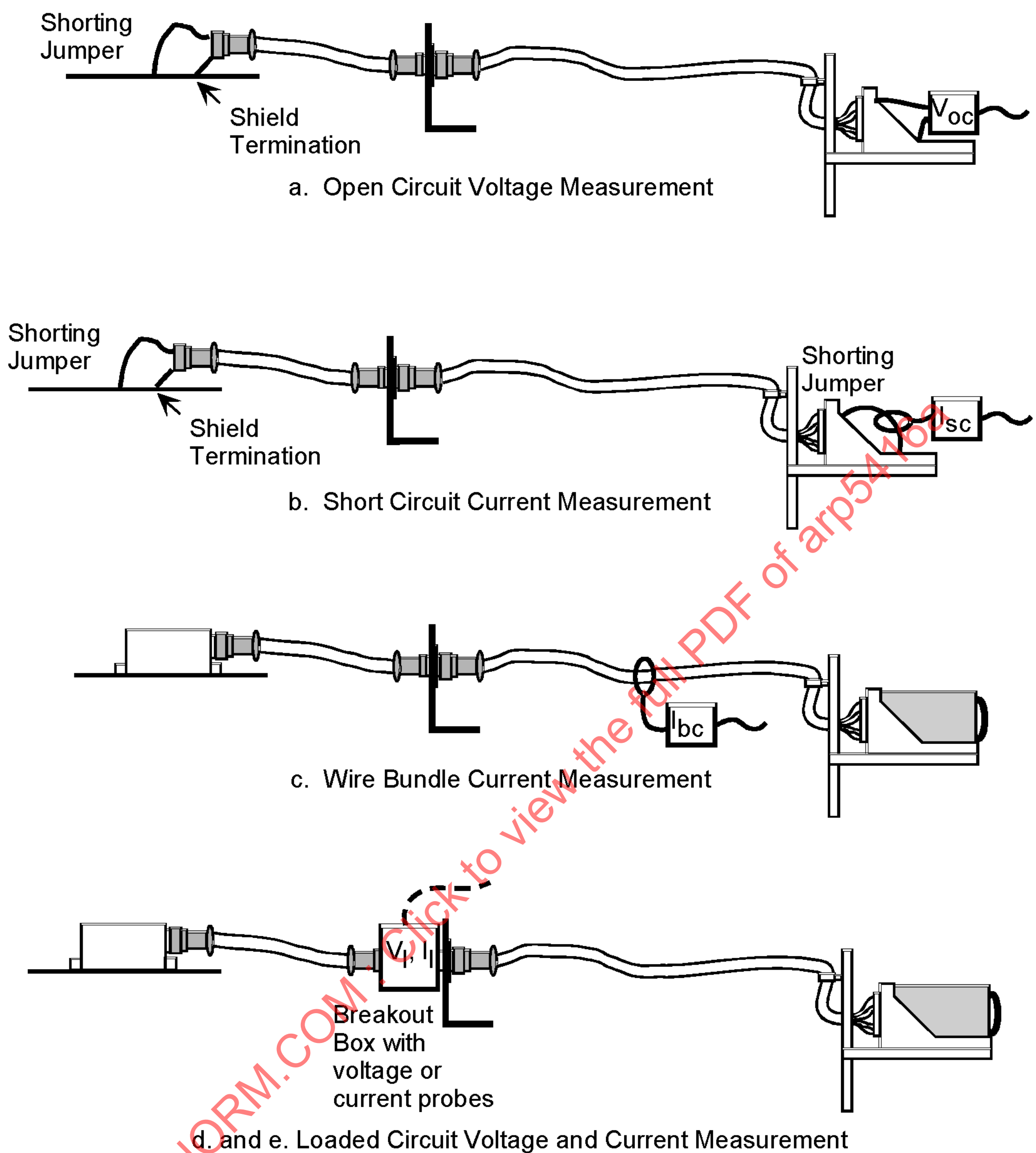

FIGURE 23 - SCHEMATIC REPRESENTATION OF MEASUREMENT TYPES

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Figure 23 gives a schematic representation of these measurement types. The first three measurement types are most commonly used, 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. and b., a Thevenin equivalent circuit can be derived for each measured aircraft circuit, from which the ATLs can be determined. The last two methods d. and e. typically require more complex breakout boxes to install the voltage and current probes without affecting circuit and wire bundle shield characteristics.

For open circuit voltage and short circuit current measurements, the aircraft wiring of interest is disconnected from the LRU at both the measurement and remote ends. The remote ends are grounded to nearby airframe structure by using jumper wires. The jumper wires length should be minimized to prevent magnetic coupling from influencing test results. Grounding the aircraft wire at one end allows all of the voltage induced in the wire to be measured at the other end. High input impedance voltage probes should be used for these open circuit measurements. Short circuit current measurements are made by installing an additional grounding jumper at the measurement end, so that both ends of the wire being measured are shorted to the aircraft structure. Currents flowing in the wire are then measured using a current transformer placed around the grounding jumper at the measurement end.

Additional measurements may include voltages induced by magnetic fields passing through apertures, lightning currents flowing through structural resistances, and surface current density. Both magnetically induced and structural voltages may be measured by installing a test wire in the aircraft where the particular voltage measurements are desired. For both magnetically induced and structural voltage measurements the test wire is electrically bonded to aircraft structure at one end and the open circuit voltage is measured at the other end of this wire. This is similar to measurement a. above. For magnetically induced voltage, the wire is positioned so as to enclose magnetic fields penetrating through apertures. For structural voltage, the wire is routed near the structure of interest. The space between the wire and structure should be minimized to reduce magnetic field coupling to the test wire. Surface current density may be measured by installing surface current density probes at selected locations on the aircraft external surfaces. These measurements are helpful to characterize the current distribution around the aircraft. The results may be used to correct differences between the aircraft and return conductor current distribution and predicted aircraft current distribution during a natural lightning strike. These measurements are also helpful to characterize the induced transient coupling mechanisms in particular areas of the aircraft. This is especially important when determining the appropriate scale factors to use for pulse test measurements if the standard test waveform(s) (component A and H) are not applied.

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.

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.

6.1.5 Swept Frequency Aircraft Tests

Swept frequency aircraft tests are used to measure transfer functions of induced transient voltage or current relative to the current injected into the aircraft. The frequency-domain transfer functions are multiplied by the appropriate lightning environment spectrum, and Inverse-Fourier transformed to produce the resulting time-domain lightning response. Swept frequency aircraft tests typically use low amplitude injection current, and the transfer functions, including amplitude and phase, are measured using vector network analyzers.

6.1.5.1 Test Setup

The aircraft and return conductor arrangement is set up as described in 6.1.3. Since the swept frequency aircraft tests do not generate high voltage between the aircraft and return conductors, the separation distance between the aircraft and return conductors should be chosen for current distribution uniformity, not voltage standoff requirements. Preferably, the impedance of the generator should be matched by terminations of similar impedances at each end on the aircraft. If it is not possible with this arrangement to drive sufficient current through the aircraft to obtain suitable measurements at low frequencies (i.e., below 1 MHz) the remote extremity of the aircraft may be terminated in a short circuit to the return conductor arrangement. A sketch of a general test setup is shown in Figure 24.

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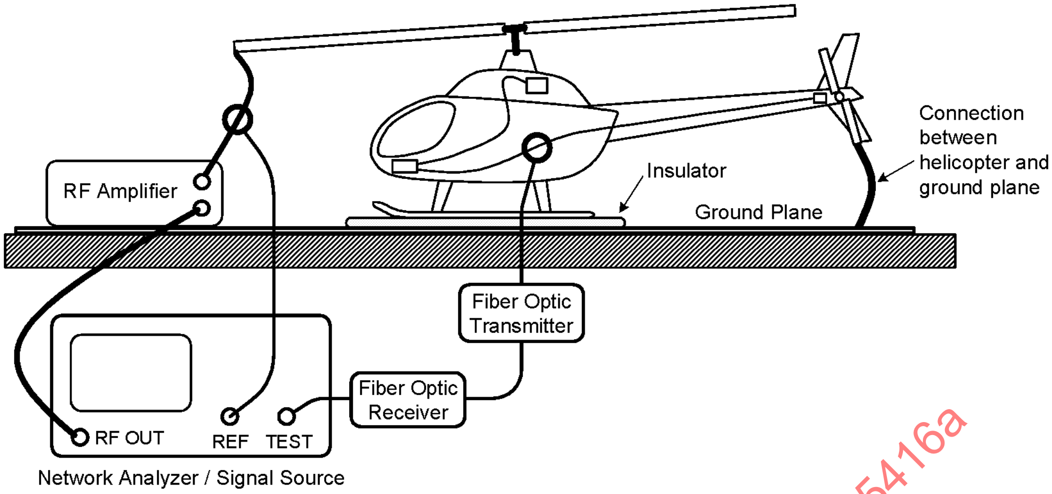

FIGURE 24 - SWEPT FREQUENCY TEST SETUP

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Swept frequency tests use relatively low current, which develop relatively low voltages across joints or other interfaces that could potentially arc during natural lightning strikes. Because of this, it may be necessary to use low-impedance jumpers across joints and interfaces to simulate the expected lightning current paths. For example, control surface actuators may be nonconductive at low amplitude test currents but may conduct during full threat lightning strikes. If the actuator control or position sensor system transients are being measured, one test configuration may incorporate jumpers across the actuator.

6.1.5.2 Test Waveforms

Swept frequency tests use low amplitude sinusoidal current that is injected at an aircraft attachment point. The current is frequency-swept or frequency-stepped in a defined frequency range. The frequency range needed to characterize lightning induced transients depends somewhat on the aircraft, the coupling mechanisms between the airframe injected current and the internal areas of the aircraft, and the interaction with wires in the aircraft. But in general, the lowest frequency of the range should be of the order of 100 Hz to determine the diffusion and structural voltage characteristics. The highest frequency should be on the order of 50 MHz, to determine aircraft and wire bundle resonance effects. Coupling and resonant effects above this frequency are not significant for lightning because the lightning environment spectra are decreasing at 40 dB per decade at these frequencies.

The injected current amplitude should be high enough to measure transfer functions with adequate signal to noise ratio. The injected current with a given RF power amplifier output power rating will vary with frequency. The injected current will be high at low frequencies where the aircraft and return conductors have low resistance. At higher frequencies, the injected current will decrease as the inductive impedance of the aircraft and return conductor circuit increases. Through the aircraft resonances the injected current will vary widely.

6.1.5.3 Instrumentation

A swept- or stepped-frequency signal generator is the current source. The signal generator output is typically amplified by a wide-band RF power amplifier to produce the current injected into the aircraft at one attachment point. The RF power amplifier must operate into a highly mismatched load, since the impedance of the aircraft and return conductors typically is low-resistance and inductive at lower frequencies, but then varies widely through the airframe resonances.

A current transformer is installed on the conductor that connects the output of the RF power amplifier and the aircraft. This current transformer is connected to the reference channel of the network analyzer, which measures the injected current. In some cases more than one current transformer may be used, to provide adequate operating bandwidth for the frequency span of approximately 100 Hz to 50 MHz.

The test probe is installed to measure shield current, wire current or wire voltage, depending on the desired transfer function. The test probe may be a current transformer or voltage probe, and once again, more than one probe may be used for a single test point to provide adequate operating bandwidth and sensitivity over the entire frequency range.

The measurement instrument is typically a vector network analyzer that measures the amplitude and phase of the test probe relative to the reference current injection probe. Most vector network analyzers use phase-locked detectors, narrow measurement bandwidth, and repetitive sampling to assure adequate signal to noise and dynamic range. In the case where a current transformer probe is used, care must be taken that the measurement not be influenced by the insertion impedance, especially at the low frequency part of the spectrum.

Wide-band analog fiber optic links are often used to connect the current or voltage test probe to the network analyzer. A short coax cable is then used between the test probe and the analog fiber optic transmitter. The output of the fiber optic receiver then drives the network analyzer input. The fiber optic link eliminates unwanted current on the test probe wires between the aircraft and the instrumentation. These currents can be a significant source of measurement noise. The analog fiber optic link must have operating bandwidth the same as the desired transfer function bandwidth.

6.1.5.4 Measurement and Data Recording

The induced transient responses are measured as transfer functions relative to the input current at the attachment point of the aircraft. As such, the transfer function is independent of the lightning current component. It can be used to determine the induced transient response on aircraft wiring by multiplication by the A, D, D/2, or H frequency spectrum and inverse-Fourier transforming the product. It is very important that data is taken at enough frequency points to accurately characterize the frequency-domain transfer function. That is, the data must be well sampled in frequency to capture the transfer function. This generally requires fewer data points at low frequency (20 to 50 points per decade) where the transfer function does not change rapidly, and requires many more data points at high frequency (100 to 200 points per decade) in the transfer function resonance frequency region. The division between high and low frequency is approximately 1 MHz.

An important part of swept frequency measurements is the instrumentation system calibration. This is not the individual test equipment calibration, but an end to end measurement of the probes, interconnecting coax cables, and amplifiers. This calibration characterizes the frequency dependent responses of the probes, wires, network analyzer, and amplifiers. The calibration transfer function $H_C(f)$ should be repeated for each probe and measurement configuration, and the results stored so that these responses can be extracted from the desired test point responses. Both amplitude and phase data should be measured for the calibration transfer function, so that loss (or gain) and line length effects can be compensated for in the aircraft transient transfer functions.

The test point response transfer function $H_T(f)$ is the ratio of the test point response X(f) to the injection current I(f) so that:

$$H_T(f) = \frac{X(f)}{I(f)} \qquad \text{(Eq. 1)}$$

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where:

$H_T(f)$ = the test point response transfer function

X(f) = the test point response

I(f) = the injection current

This test point response transfer function must be corrected to remove the amplitude and phase characteristics of the probes, wires, network analyzer, and amplifiers. The corrected transfer function $H_{TC}(f)$ is:

$$H_{TC}(f) = \frac{H_T(f)}{H_C(f)} \qquad \text{(Eq. 2)}$$

where:

$H_{TC}(f)$ = the corrected test point response transfer function

$H_T(f)$ = the test point response transfer function

$H_C(f)$ = the correction factor

The data set for a swept frequency test point consists of transfer function data recorded as frequency, magnitude, and phase. The data set may be plotted as magnitude (usually in dB) versus frequency on a logarithmic frequency scale. Phase versus frequency can also be plotted. Modern network analyzer allow the number of frequency data points to be specified in frequency ranges such that the entire transfer function measurement will be well sampled.

System noise transfer functions should be measured for each type of lightning transfer function measured, in each general measurement location of the aircraft. Noise transfer functions for shield or wire currents are typically measured with the current transformer removed from the shield or wires, and placed adjacent to the wires in that aircraft location. The current transformer should be isolated from the aircraft structure.

Noise transfer functions for wire voltages are typically measured with the voltage probe disconnected from the aircraft test point and grounded to the voltage probe shield. For unbalanced, common-mode voltage probes, the voltage probe shield should be connected to the same aircraft reference point, such as structure, that was used during the test point transfer function measurement.

6.1.5.5 Measured Data

Typical measurement types consist of the following:

(1) Measurement system calibration transfer functions $H_C(f)$

(2) Wire bundle shield current transfer functions

(3) Individual wire voltage transfer functions

(4) Individual wire current transfer functions

(5) Voltage noise measurement transfer functions

(6) Current noise measurement transfer functions

(7) Input Impedance for each attachment configuration

(8) Aperture or structural voltage transfer functions

(9) Surface current density transfer functions.

A current amplitude transfer function is shown in Figure 25, along with the related noise amplitude transfer function.

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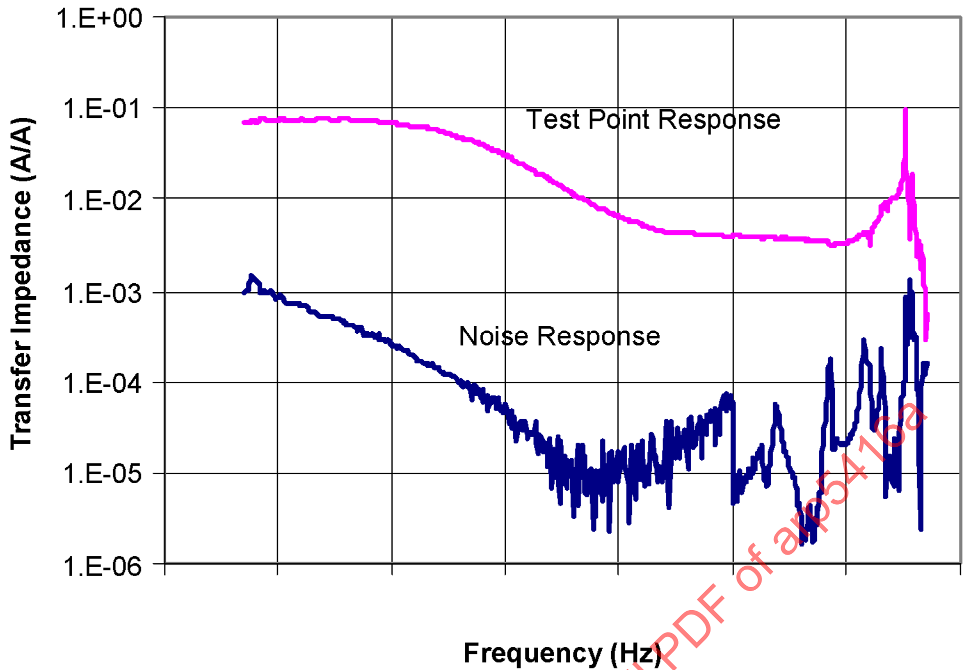

FIGURE 25 - TRANSFER FUNCTION EXAMPLE

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6.1.5.6 Data Processing

The transfer function data must be processed to determine the time-domain pulse response transients for each test point. Each transfer function is multiplied by the lightning current component frequency spectrum. This product is then inverse-Fourier transformed to determine the pulse response. The lightning current frequency spectra generated at the same frequencies as the measured transfer functions simplify the multiplication.

The inverse Fourier transform must have high fidelity to deal with the wide frequency bandwidth (over five decades), and large dynamic range of the transfer functions. Typically, this means that the inverse Fourier transform must have high numerical precision, and must handle unequally spaced frequency samples in the transfer function. Many commercially available Inverse Fourier transform computational routines are based on Fast Fourier Transforms (FFT) geared to repetitive signals, with uniformly spaced frequency samples. These may be less suitable for transforming the transfer functions than special purpose integral Fourier transform routines. The selected inverse Fourier transform routine should be validated with analytical transfer functions that have similar characteristics, including frequency sample spacing, as the transfer functions that will be measured.

Additional processing may be performed to correct the data for aircraft current distribution effects caused by the return conductor configuration, or for aircraft termination impedance mismatches. Corrections are usually made by combining the measured transfer function with an analytically generated transfer function.

6.1.5.7 Data Assessment

Interpretation of the transient waveforms derived from swept frequency transfer functions is done by comparing these ATLs to the ETDLs and determining whether the requirements are being met considering margins and uncertainties. The data may also be processed to account for any differences between the test return conductor/aircraft current distribution and in-flight current distribution.

The measured transient waveforms are commonly more complex than the standardized waveforms, and may need to be approximated by a combination of two or more standardized waveforms. Figure 26 shows an example of the appropriate peak levels that would be recorded relative to the standardized waveforms.

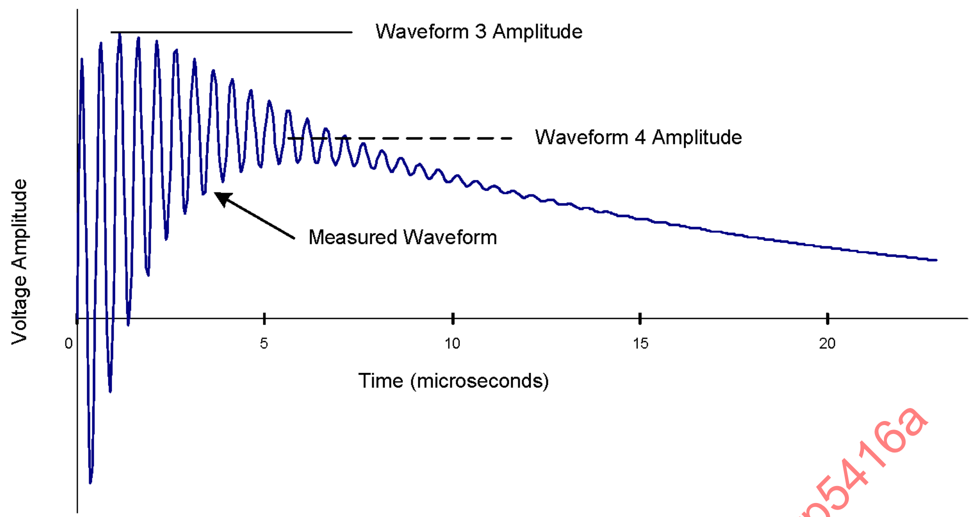

FIGURE 26 - EXAMPLE FOR ESTABLISHING TRANSIENT LEVELS OF STANDARD WAVEFORMS

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The measured transfer functions should be compared to the appropriate noise transfer function. The measured transfer function should exceed the noise transfer function by a factor of 2, or 6 dB, over the desired frequency range. If the measured transfer function does not exceed the noise transfer function over the entire frequency range, then the measured transfer function and noise transfer function should be transformed into the time domain and again compared. Here the transformed measurement should exceed the transformed noise by a factor of two, or the transformed noise should be a factor of ten lower than the TCL for that test point.

The drive point impedance of the aircraft and return conductors should be assessed. The quarter-wavelength resonance of the aircraft (or ½ wavelength resonance if a termination impedance is used) and return conductor for that attachment configuration should be obvious and near the frequency calculated for that current path length. If there are other resonant effects that show up at frequencies below the quarter-wavelength resonance, there may be interaction between the aircraft, return conductors, and nearby conductors, such as the facility ground system, hangar structures, or reinforcing bars in the floor. These effects may be mitigated by changing the location of the connection between the return conductors and facility ground, or by terminating the return conductors to facility ground with matching resistors.

6.1.6 Pulse Test

Aircraft current pulse tests are used to measure induced transient voltage or current waveforms and amplitude. Current pulse tests with amplitudes less than the defined component A, D, or H are acceptable, because comparisons between measurements from full amplitude aircraft tests and lower-amplitude tests show reasonable agreement if appropriate scale factors are used. Pulse test waveforms with peak current amplitude in the range of 1 to 20 kA are typically used. Occasionally, tests at higher test current amplitudes may be applied. Full amplitude component A, D, or H waveforms are usually impractical and may cause damage to the aircraft and/or equipment.

6.1.6.1 Test Setup

Aircraft current pulse tests are normally conducted with systems unpowered if reduced current amplitude pulses are used. A sketch of a general test setup is shown in Figure 27.

However, if moderate to high amplitude component A, D, or H waveforms are used, then the aircraft may be tested with the systems operating to enable system responses to be monitored, necessitating the use of external power. External power may also be needed to enable some measured circuits to be representative of flight conditions. If external power (either electrical or hydraulic) must be connected to the aircraft, these power sources must be connected to the aircraft in such a manner to ensure there are no additional conducting or flashover paths to the return conductors or to local ground. This needs to be verified by making comparisons between transient measurements performed with and without external power. These external power sources must have electrical isolation that will withstand the maximum voltage levels appearing between the pulse generator, aircraft and return conductor circuit.

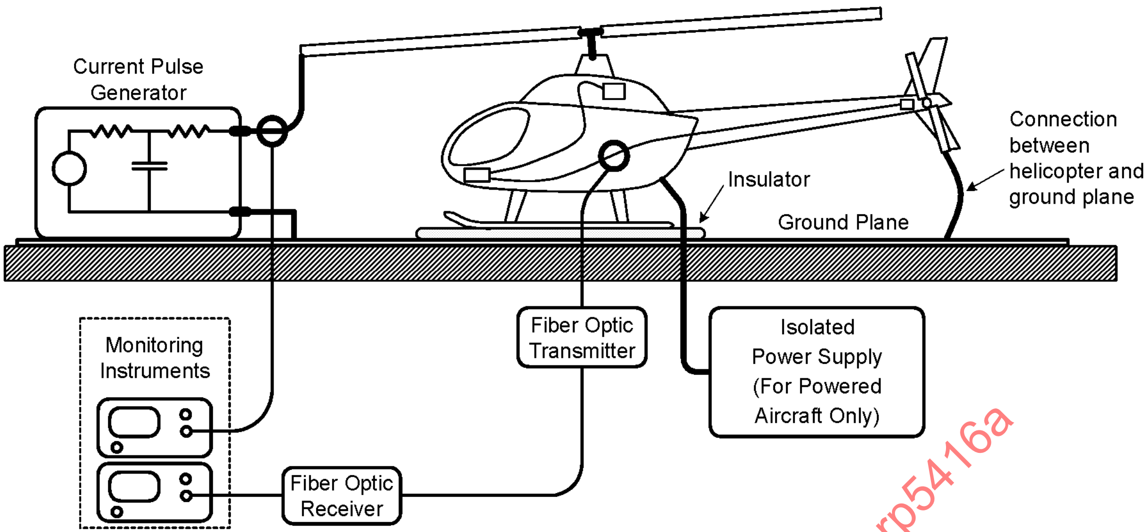

FIGURE 27 - PULSE TEST SETUP

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The current pulse generator should incorporate series resistance between the pulse generator and the aircraft to reduce pulse generator switching noise, and to provide a consistent impedance for the pulse generator. Resistance of 1 to 2 Ω is typical.

A wire connects the current pulse generator and the aircraft at one lightning attachment point, and the return conductors and aircraft are connected at the other lightning attachment point for the selected attachment configuration. The return conductors should be arranged to provide the desired aircraft current distribution. The spacing between the return conductors and the aircraft should be large enough to prevent arcing and flashover between the aircraft and return conductors for the voltages anticipated during the pulse tests.

Reduced current amplitude pulse tests develop lower voltages across joints or other interfaces that could potentially arc during natural lightning strikes. Because of this, it may be necessary to use low-impedance jumpers across joints and interfaces to simulate the expected lightning current paths. For example, large control surfaces such as ailerons may have arcing between the extremities of the aileron and the adjacent wing structure, particularly if the actuators and hinges are not located at the aileron extremities. If the actuator control or position sensor system transients are being measured, one test configuration may incorporate jumpers between the outboard end of the aileron and the adjacent wing structure.

6.1.6.2 Test Waveforms

The pulse generator should produce the standard test waveforms, so that measurements can be extrapolated linearly to the appropriate component A, D, or H waveform as defined in ARP5412/ED-84.

It is important to try to obtain the correct test current waveshape to facilitate the extrapolation process.

The current components A, D, and H are defined in ARP5412/ED-84. Practical pulse generators cannot instantaneously turn on the current. There may be traveling wave currents superimposed on the test current due to mismatches in the transmission line associated with the aircraft and test current return conductors. The peak rate of rise at the airframe during the turn-on switching should be accurately characterized, since this may affect the waveform 3 induced transient response for aircraft circuits.

6.1.6.3 Instrumentation

A high-voltage current pulse generator is the current source. Pulse generators with peak current amplitude in the range of 1 to 20 kA are typically used. A current transformer or current viewing resistor should be installed on the conductor that connects the output of the test current generator to the aircraft. For some high voltage pulse generators, the current transformer or current viewing resistor may be installed in the connection between the pulse generator and the return conductors to minimize the voltage that the probe is exposed to. The pulse generator current monitor probe system should have sufficient bandwidth to accurately measure the injected waveform.

The test probe is installed to measure shield current, wire current or wire voltage, depending on the desired transient response. The test probe may be a current transformer or voltage probe, with bandwidth appropriate for the anticipated response. Since a single probe may not have adequate bandwidth to capture all possible transient responses, a low frequency probe and a high frequency probe may be used on single test point on subsequent pulse tests, to ensure that the appropriate transient response is recorded.

The transient measurement instrument is typically a digital storage oscilloscope or a transient digitizer. The oscilloscope or digitizer should have adequate bandwidth to record the appropriate transient response. The effective operating bandwidth should be 100 Hz to 50 MHz. Many digital storage oscilloscopes specify their bandwidth for repetitive waveforms, not single transients. Therefore, the digital storage oscilloscopes should have sample rates that are five to ten times faster than the highest frequency response anticipated. So for a 20 MHz resonance the digitizer or digital storage oscilloscope should sample at 100 to 200 million samples/second.

The digital storage oscilloscope or transient digitizer may be installed in the aircraft near the test point being measured. The coax cable from the test probe to the digital storage oscilloscope or transient digitizer should be short and well-shielded. Wide-band analog fiber optic links may be used to connect the current or voltage test probe to the digital storage oscilloscope or transient digitizer. Then the digital storage oscilloscope or transient digitizer may be located outside the aircraft. A short coax cable is then used between the test probe and the analog fiber optic transmitter. The output of the fiber optic receiver then drives the digital storage oscilloscope or transient digitizer input. The fiber optic link eliminates unwanted current on the test probe wires between the aircraft and the instrumentation. These currents can be a significant source of measurement noise. The analog fiber optic link must have operating bandwidth the same as the desired transient response bandwidth.

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Care must be taken to shield the measurement system from radiated and conducted noise. The measurement system should be placed in shielded enclosures to minimize the coupling of extraneous noise in the instrumentation. The measurement system should also be positioned adjacent to the measurement location and grounded to the airframe as close to the measurement location as possible. The auxiliary power supplied to measurement devices in the shielded box should be filtered using feed-through filters mounted on the side of the box. To avoid ground loops, the AC or DC power should be provided through appropriate isolating devices (e.g., isolating transformers for AC sources or inverted and filtered power from DC sources). Measurement leads for the voltage and current probes should be shielded. Probes to measure differential voltages should be chosen for their electrical characteristics and small physical size for use in confined areas. Currents on individual conductors and on wire bundles can be measured by the use of current transformers, preferably with split cores that would not disrupt installed harness arrangements.

6.1.6.4 Measurement and Data Recording

The induced transient responses are measured as the test current is applied to the aircraft. The data set for a pulse test point consists of transient response data recorded as amplitude versus time, and the applied test current.

System transient noise responses should be measured for each type of lightning transient measured, in each general measurement location of the aircraft. Noise responses for shield or wire currents are typically measured with the current transformer removed from the shield or wires, and placed adjacent to the wires in that aircraft location. The current transformer should be isolated from the aircraft structure.

Noise responses for wire voltages are typically measured with the voltage probe disconnected from the aircraft test point and grounded to the voltage probe shield. For unbalanced, common-mode voltage probes, the voltage probe shield should be connected to the same aircraft reference point, such as structure, that was used during the test point response measurement.

6.1.6.5 Measured Data

The following are typical measurements:

(1) Wire bundle shield current

(2) Individual wire voltage

(3) Individual wire current

(4) Voltage noise

(5) Current noise

(6) Drive current

(7) Aperture or structural voltage

(8) Surface current.

Typical transient voltage and current responses in interconnecting wiring experiencing the effects of the lightning current component A current in the airframe are shown in Figure 28, Figure 29, and Figure 30.

Figure 28 illustrates that measured transient waveforms are commonly more complex than the 'standardized' (waveforms 1, 2, 3, etc.) used to represent such induced transients.

6.1.6.6 Data Processing

If the test current waveshapes are the same as those defined for components A, D, and H as defined in ARP5412/ED-84 then the measured pulse transients should be extrapolated by an extrapolation factor which is the ratio of the full threat current amplitude to the test current amplitude.

If the defined test current waveshapes A, D, or H have not been duplicated then the dominant coupling mechanisms applicable to each of the measured transients must be determined. This will determine whether the induced transient response should be scaled by peak current, peak current rate-of-rise or integral of current. Some induced transient responses may have significant contributions from more than one parameter. For example, many transient responses show significant structural resistance and aperture contributions, so the scaling would be dependent on both peak rate of rise and peak current. In such cases, a more exact method such as Fourier analysis should be used, rather than simply multiplying by a single scale factor.

6.1.6.7 Data Assessment

The induced transient responses should be reviewed to ensure that damped oscillatory responses are actually related to the aircraft, and are not resonances due to interaction between the return conductors and the facility ground system, hangar structure, or floor reinforcing bars. Any resonances which are at a frequency lower than that appropriate to the quarter-wavelength resonance of the aircraft should be investigated and accounted for.

The measured transient responses should be compared to the appropriate noise measurements. The measured transient response should exceed the noise measurement by a factor of two. Or, the measured noise should be a factor of ten lower than the TCL for that test point.

Voltages and currents induced in aircraft wiring are several orders of magnitude lower than the injected pulse currents. This means that the measurement instruments must be sensitive enough to measure relatively low level test point voltages and currents, but reject high amplitude undesired magnetic and electric fields and ground currents.

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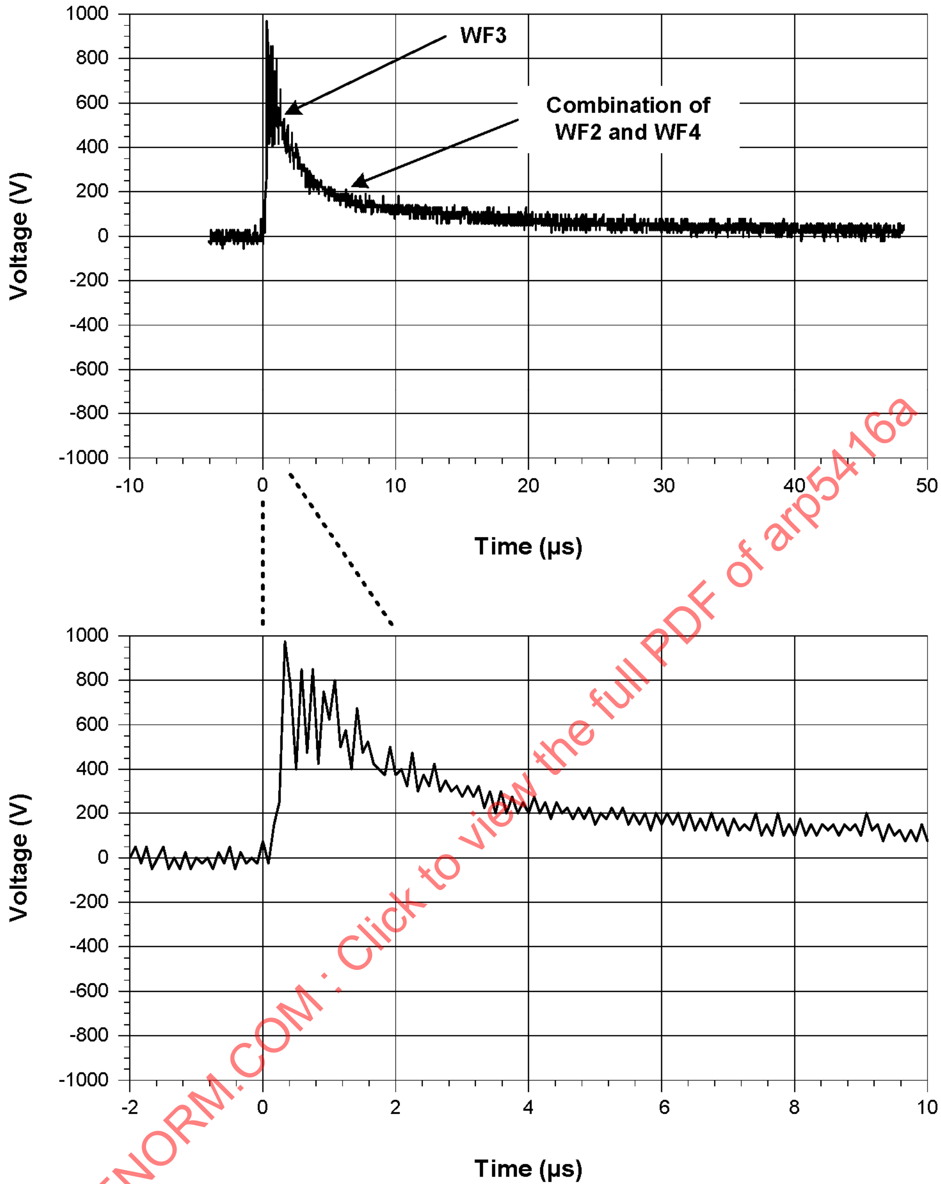

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FIGURE 28 - TYPICAL CONDUCTOR OPEN CIRCUIT VOLTAGE DUE TO CURRENT COMPONENT A

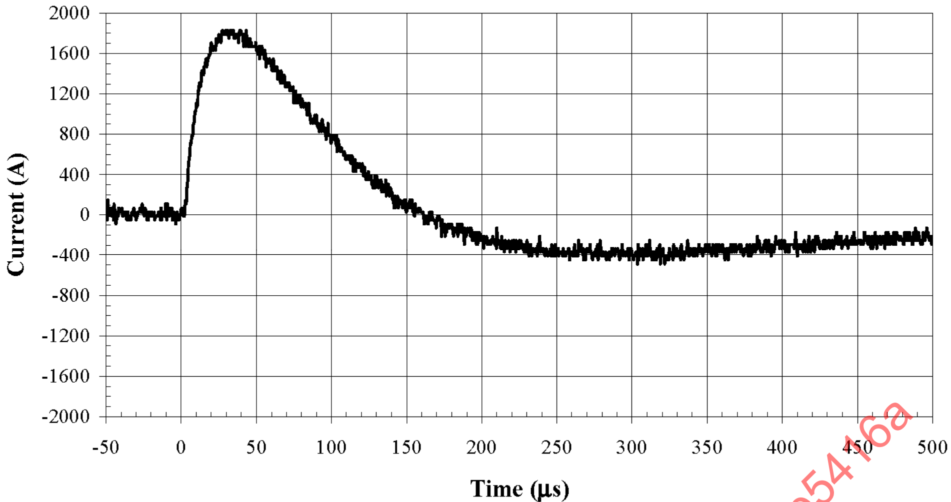

FIGURE 29 - TYPICAL WIRE BUNDLE SHORT CIRCUIT CURRENT DUE TO CURRENT COMPONENT A

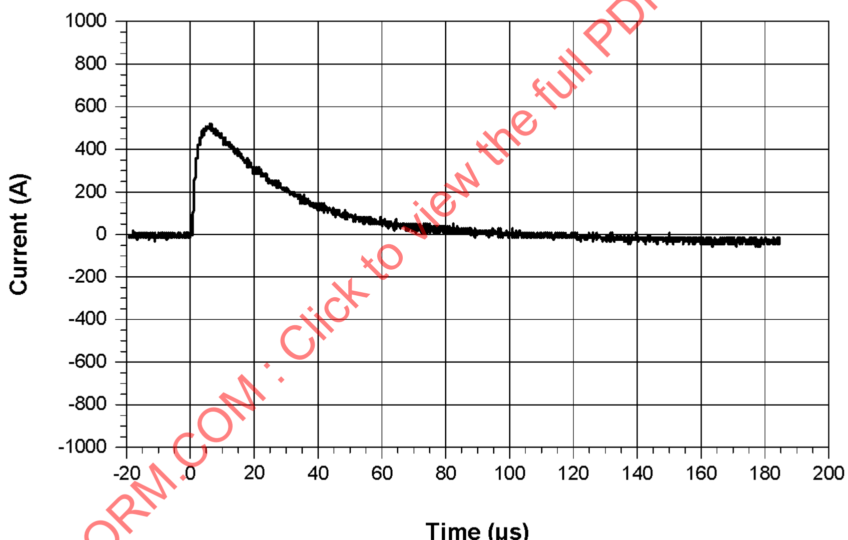

FIGURE 30 - TYPICAL CONDUCTOR SHORT CIRCUIT CURRENT DUE TO CURRENT COMPONENT A

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6.2 Tests for Equipment/Systems

These test methods and procedures apply transient voltage and current waveforms to verify the capability of individual items of equipment or systems comprised of more than one piece of equipment interconnected with wire harnesses to withstand effects of lightning induced electrical transients.

Two types of tests may be used for systems/equipment qualification or engineering evaluation. The first is a damage tolerance test that is usually conducted using the pin injection method, but sometimes conducted using the wire bundle method, to verify that circuit elements within a piece of equipment can tolerate the applied transients without damage. The second group of tests evaluates the functional upset tolerance of systems usually comprised of more than one item of equipment when single stroke, multiple stroke and multiple burst transients are applied to interconnecting wire bundles.

6.2.1 Equipment Damage Tolerance Tests

The procedures for damage tolerance tests of individual items of equipment are addressed in DO-160/ED-14, Section 22, and not here.

6.2.2 Equipment Functional Upset Tests

The procedures for evaluating functional upset to individual items of equipment due to the single stroke, multiple stroke and multiple burst environments are also described in DO-160/ED-14, Section 22, and are not addressed in this document. Tests that evaluate the susceptibility of systems comprised of more than one item of equipment to functional upset due to the single stroke, multiple stroke and multiple burst environments are described in 6.2.3.

6.2.3 System Functional Upset Tests

System level functional upset testing is the primary means for verifying that a Level A system does not have any adverse effects, including failures and malfunctions, when exposed to the aircraft internal lightning environment. The equipment, wiring, connectors and system operation should be representative of the system installation and operation in the aircraft. The test waveforms and levels should be determined by aircraft lightning transient measurements, use of data from tests on an existing aircraft shown to be similar, analysis, or, for Level A display systems, test levels defined in AC 20-136B. Test levels should include appropriate margins.

6.2.3.1 Test Purpose

The purpose of system functional upset tests is to verify performance in accordance with applicable CFR/CS requirements during and after exposure to the aircraft internal lightning environment associated with the Single Stroke, Multiple Stroke and Multiple Burst lightning environments as defined in ARP5412/ED-84. Tests described in this section are applied most frequently to systems comprised of multiple items of equipment providing critical functions with catastrophic failure conditions (Level A Systems). Systems performing less critical functions may also need to be tested if they are integrated with critical functions.

Lightning transients must be applied in the Multiple Stroke (MS) and Multiple Burst (MB) waveform sets, since these environments are more likely to produce system upsets than are single transients. Where these system functional upset tests do not adequately assess damage resistance of individual interfaces to the voltage or current levels specified it is expected that the system equipment will have damage tolerance verified by other tests (per 6.2.1, DO-160/ED14 Section 22).

6.2.3.2 Test Object

The test object is the system under test, including all equipment and interconnecting wire bundles, sensors, transducers, and power sources that are necessary for the system to perform its intended function(s). An item of equipment may be omitted if its function can be represented by a simulated data input, dummy load or be interfaced with a diagnostic equipment as long as such a substitution does not affect system function or susceptibility to a lightning related upset. Any substitution of system equipment should be assessed for its effect on the system under test, documented in the test plan and approved by the certification authorities prior to conducting the test.

Many lightning certification Level A systems are complex and/or integrated which can make it very difficult to appropriately define and bound the test object. A complex system is a system whose operation, failure modes, or failure effects are difficult to comprehend without the aid of analytical methods. An integrated system is one that incorporates a number of separate functions within a single implementation. Either of these systems may perform multiple functions of different criticality levels and have failure modes potentially leading to unsafe aircraft operating conditions. Because of this, large numbers of equipment and wire bundles may be involved and it is usually not practical to test these systems and functions simultaneously. Therefore, simultaneous injection into all the various wire bundles may not be possible.

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Some systems, especially those supplying digital signals may be adequately represented without the additional systems interface being part of the test. An example of this could be the FADEC supplying Integrated Crew Alerting System (ICAS) information to the Electronic Flight Information System (EFIS) display system. The FADEC could be tested separately, showing that when the lightning-induced transient level is applied to the FADEC, it outputs good data to the EFIS system. The EFIS system could then be tested separately with the input from the FADEC simulated. The EFIS system would then be monitored to show that good data was properly displayed when the lightning-induced transient level was applied.

Test plans shall be developed that define the extent of the system to be tested, and the transient test levels. Due to the highly integrated nature of some systems, it is very likely that the systems perform functions of several criticality levels (e.g., Hazardous, Major, Minor, etc.) or are connected to equipment that perform functions with various criticality. Therefore, when performing testing on functions with catastrophic failure conditions (Level A Systems) and susceptibilities occur to these lesser functions, it is allowable to reduce the test levels to those appropriate for those functions. However, it is also important to note that if a failure occurs to a function with hazardous or major failure conditions (Level B or Level C Systems), a careful assessment must be made to determine any interaction with the function with catastrophic failure conditions and apply appropriate performance criteria to the less critical function that meets the regulatory requirements. The expected level of performance for any functions included in the system test should be defined in the test plan.

Power should be supplied through line impedance stabilization networks (LISNs). Further guidance on LISNs characteristics are found in DO-160/ED-14, Section 22. Other services such as pressurized air, hydraulics, temperature and speed sources may also be required to enable the tested system to operate in a realistic manner. Software must be capable of exercising all the functional aspects being tested and with appropriate configuration control and validation. The system should be operated and tested in appropriate modes representing all flight conditions, where functional performance is required, unless a worst case mode of operation can be justified. Details of elements included in the tested system, simulations, power and other inputs along with operational modes should be included in the test procedure.

6.2.3.3 Test Setup

(1) Where practical, the general layout of the equipment and wiring on the test bench should be similar to the layout of equipment and wiring in the aircraft. Wire bundles may be zigzagged back and forth on the test bench in situations where insufficient test bench space is available for straight wire runs.

(2) Bonding strap dimensions and composition should be as in the final installation to achieve similar electromagnetic performance, except that some intermediate connectors may be ungrounded to allow test current to flow through the entire lengths of shielded cables.

(3) Actual aircraft equipment racks should be used where appropriate.

(4) When external terminals are available for ground connections to equipment, the terminal should be connected to the test bench to ensure that the equipment is grounded in a manner similar to the aircraft installation and that the equipment operates properly and in safe condition during the test, unless otherwise specified in the test procedure. The lengths of the ground connections defined in the aircraft installation instructions should be used.

Interconnecting Wiring - General: Testing of the equipment on an integrated system rig must provide an accurate electromagnetic representation of the final aircraft installation. System interconnecting wiring should be in accordance with the applicable wire harness specification, installation, and interface control drawings or diagrams. In general, the wire bundle should be built using the same build techniques and materials as the aircraft installation. The intent is that the interconnecting wire bundles used during the laboratory tests develop transient voltages and currents on the system circuits that are representative of the transients that occur on the aircraft. Important features that should be considered for the interconnecting wiring bundles:

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(a) Wire bundle length should be representative of the aircraft installation; ideally, the wire bundle length should be the same as the aircraft. Wire bundle length is defined as the distance from an EUT to another EUT/load/sensor including any disconnects that are in the aircraft wire bundle. However, limited space on the table or test equipment limitations may necessitate that shorter or longer wire bundles be used. It is allowable that short wire bundle lengths be extended up to the minimum length required to properly perform the test (e.g., allow for current probe placement, connector wire separation, etc.).

(b) Shield termination techniques or policies should be defined and used on the interconnecting wiring. Worst case tolerances allowed with shielding techniques should be used in the test wire bundle.

(c) Wire composition and size should be representative of the aircraft installation.

(d) Connectors of the test wire bundles should be terminated with the same or similar connectors to be used in the aircraft. If bulkhead connectors and/or intermediate connector breaks are included in the system, these should also be included in the test setup. For practical reasons, if used, these connectors may be deliberately not grounded to the test bench in order to achieve the desired test current on both sides of the connector.

(e) Remote power return grounds that are normally routed in the wire bundle should remain in the bundle. Local power returns or external ground terminals should be connected to the ground plane if the terminal is normally grounded in the installation. The lengths of the ground connections defined in the aircraft installation instructions should be used.

Test Bench Wiring of Significantly Shorter Lengths Than Aircraft Wiring: If a very long aircraft harness is to be represented but is not available or impractical to test because its impedance would prevent injection of the required test current into its shield, a shorter harness may be used. In this case the harness must be tested at the corresponding shielded conductor transient level that results in the same core wire voltage levels and waveforms that would be expected on the aircraft. This can be accomplished simply by removing all shields from the wire bundle and testing to the required core voltage. If shields are to be left on during the test, an alternate method is to use the shield wire transfer function test to determine the proper bundle current necessary to develop the core wire voltage. In any case, with shorter wire bundles, shield termination techniques should still apply. The test procedure should state whether the transients are to be applied to the wire bundle shields or to the shielded core wires with shields disconnected.

Some aircraft wiring bundles are not shielded and in this situation the core wires are exposed to the loop voltages appearing between the wire bundles and the airframe, which is represented in the test by the test bench. In this situation the injected loop voltage would be the same as expected in the aircraft wire bundle(s) regardless of aircraft wire bundle length.

6.2.3.4 Test Waveforms

System functional upset tests are to be performed with designated transient test waveforms and levels for Single Stroke, Multiple Stroke and Multiple Burst waveform set test applications. Specific transient waveforms, levels and waveform set sequences should be described in the test procedure. The injected transients should be a loop voltage, a shield current, or a combination of loop voltage and shield current. The test procedure should provide for voltage and current levels and limits, as follows:

- When all conductors are unshielded, and there are no interface protection devices (i.e., when all conductors have high impedance to ground) the intent of the test is to drive the test voltage in the unshielded wire bundle(s). Therefore, a current limit may not be needed since the test voltage level will be achieved. This voltage level is established by measurement or analysis in the system harness installed in the aircraft.

- When some conductors have low impedances (e.g., shielded, or protection devices) and others high impedances (e.g., unshielded) there should be a test current level and/or a test voltage level with corresponding voltage and current limits respectively.

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- When all conductors are shielded or when there are protection devices in all of the circuits (i.e., low impedance loop) then the intent of the test is to drive the test current in the shielded wire bundles. Therefore, a voltage limit is not relevant since the test current level will be achieved. This current level is based on measurements or analysis of actual transients in system harnesses installed in the aircraft, which is the basis for establishing the system test condition.

6.2.3.5 Measurement and Data Recording

The following data as a minimum should be recorded during the tests and included in the test report.

- Photographs and description of each test setup.
- Records of the transients injected into each wire harness and branch of the system under test.
- Descriptions of system operational modes.
- Records of dates of testing, personnel performing and witnessing the tests, and test location.
- Record of any deviations from the test procedure.
- Records of the results of each test configuration showing voltage and current amplitude, and waveforms, pulse shape/characteristics and adverse effects (if any).
- Records of system responses (including videos of displays, control surface motions, annunciator panels, computer print-outs of control parameters and other data.

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6.2.3.6 Test Procedure

The procedures for damage tolerance tests of individual items of equipment are addressed in DO-160/ED-14, Section 22, and not here. The procedures for evaluating functional upset to systems due to the single stroke, multiple stroke and multiple burst environments are also described in DO-160/ED-14, Section 22 and are not addressed in this document. Procedures for performing simultaneous and individual injection on complex systems are included in the following subparagraphs.

6.2.3.6.1 Individual Injections

The standard methodology of complying with the requirements of AC 20-136B is the injection of the lightning transient, either by wire bundle induction or ground injection, on each individual connector of the equipment under test. This is applicable to both system and individual components.

Procedures for performing individual harness injection are addressed in DO-160/ED-14. Tests should be applied individually to each bundle at its assigned test and limit levels (if applicable).

Caution must be taken when performing individual injection on a complex system to ensure that susceptibilities are not masked. For example, when testing a two-channel system, (e.g., a dual channel FADEC), one of the channels may be turned off and not be tested if the system can function on one channel. In this case channel switch-over cannot be enabled to allow the second channel to continue performing the function if the first channel becomes upset. This approach can enable the test to be performed using individual bundle injection. The analysis to determine if individual injection is appropriate should take into account the system architecture (e.g., independence of channels) and the topology (e.g., risks of cross-coupling increased when transients appear simultaneously throughout the system).

When the single channel test approach is used it is generally assumed that any susceptibility that occurs on the single active channel will appear at the same time in all channels, which may not be the case if the functioning within the two channels is skewed so that their susceptibilities are not the same. Thus it is possible that approaches that simplify the tested configuration could result in failure conditions that may not be present in the actual installation.

It should also be noted that power conductors may conduct lightning-induced transients from different locations in the aircraft. Thus they frequently are assigned different test levels from other harnesses interfacing with the same equipment. Power conductors may be tested as part of the bundle if they have not been assigned a different ETDL than the wire bundle(s).

6.2.3.6.2 System Level Testing Using Simultaneous Injections

As stated in 6.2.3.6.1, the requirement is injection into each wire bundle connector individually, however, it is also desirable to excite large portions of the system simultaneously. While the ideal case is injection into all the systems branches simultaneously, this typically is not practical. Though it may not be possible to inject the proper levels into all branches, a limited level system test is still very desirable to perform. This can be accomplished by the simultaneous injection onto several bundles or branches of wire bundles by wire bundle induction using multiple injection cores or by ground injection directly into the case of one of the components of the system. Wire bundle induction allows for the injection of current and/or voltages on the system wire bundles. Ground injection applies currents and voltages to the case or cases of equipment under test and allows the current to flow through the wire bundles based on the loop impedances (between wire bundles and test bench) of the bundles.

Wire bundle induction uses transformer cores to inject voltages into the loops that exist between the wire bundles and the test bench, and currents into the shields or conductors of shielded wire bundles.

Ground injection applies an impulse voltage between an item of equipment and the test bench that injects a voltage in the loops between the wire bundles connected to the injected equipment and the test bench, and drives currents into the shields or conductors of the wire bundles.

In either method the amounts of voltage or current that are injected depend on the impedances of the wire bundles. Fully shielded bundles have low impedances and accept current. Unshielded wire bundle conductors that are terminated with high impedances to ground in the connected equipment do not conduct much current but experience the loop voltage, which appears at the connected equipments in accordance with their impedances to ground. Basic aspects of wire bundle induction and ground injection methods are contained in RTCA DO-160/ED14 Section 22 and the User's Guide to that section.

An example of how a limited system level test on a low impedance wire bundle configuration can be applied is the ground injection method used on a dual channel FADEC. In the case of the FADEC, it is often desired to test the unit with one channel disabled and if during the test, the FADEC attempts to switch channels, it is considered a failure. It is possible to ground inject into the FADEC a low level signal, while monitoring the various current levels of the interconnecting harnesses. Once the lowest impedance wire bundle is determined, then the signal level is increased until that individual wire bundle test level is reached and the test conducted at that generator setting. It is understood that the other wire bundles will not reach the full requirement, however there will be a limited excitation in all branches with the level depending upon the loop impedance of the individual branches.

With the generator set at this level testing is conducted at both polarities and with the proper number of environment applications (10) in each polarity.

It is required to repeat this procedure for each current waveform and environment (Single Stroke, Multiple Stroke and/or Multiple Burst) that is applied in this manner.

It should also be noted that it is still required to conduct the test on any individual connector that did not reach the required test level during simultaneous injection.

Figures 31 and 32 show the concepts of wire bundle injection and ground injection methods.

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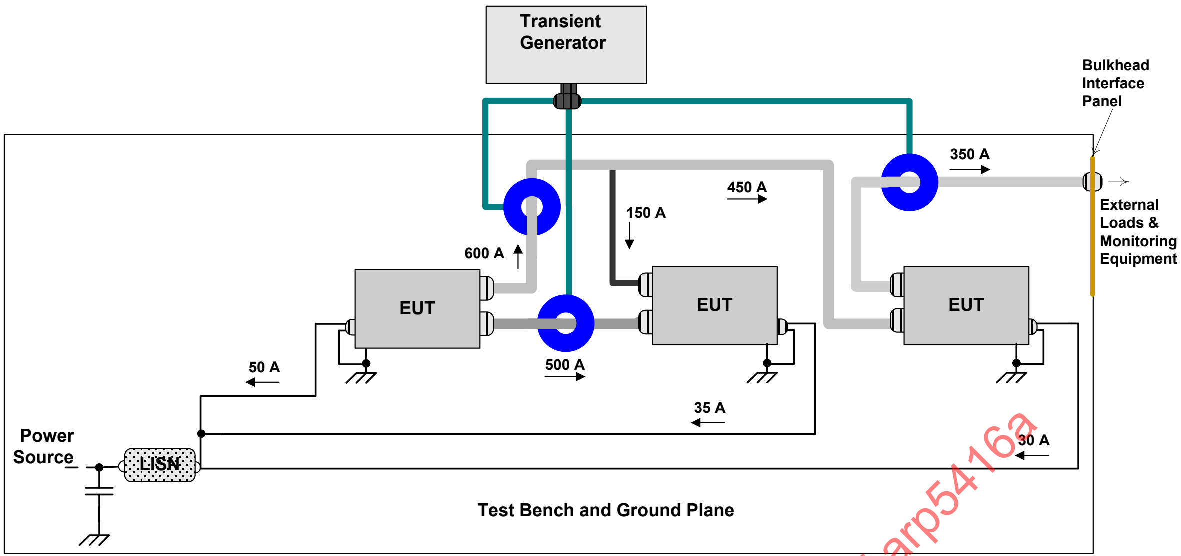
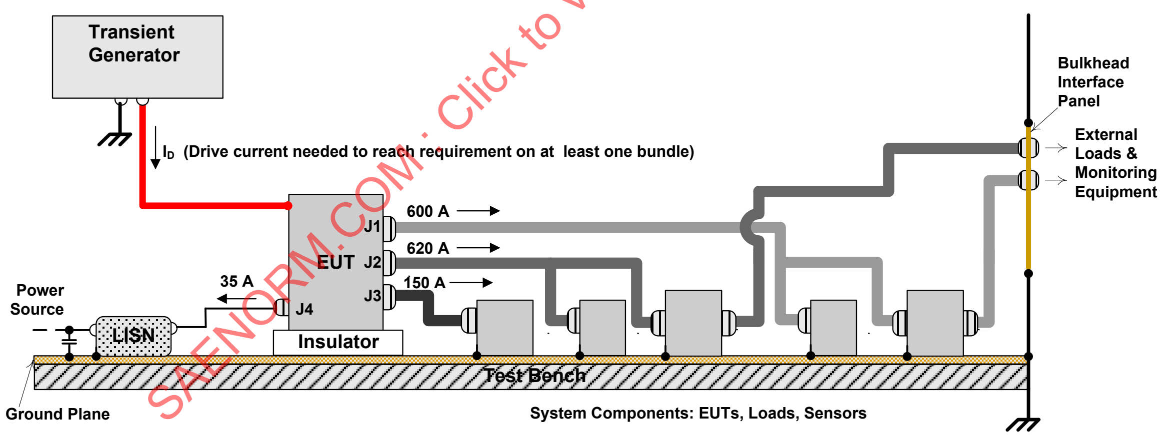


Notes
- Limited level system test of all system branches.
- Test level in this example is 600 A for interconnect bundles, 60 A for the individual power conductor.
- Requirement met on one branch with limited level test on remaining branches.
- Remaining system branches require individual injections at applicable test levels.

FIGURE 31 - SIMULTANEOUS WIRE BUNDLE INDUCTION - EXAMPLE



Notes
- Limited level system test of all system branches.
- Test level in this example is 600 A for interconnect bundles, 60 A for the individual power conductor.
- EUT in this example is a dual channel FADEC.
- J1 Bundle (Channel A) and J2 Bundle (Channel B) have nearly the same impedance, making it possible to simultaneously meet the requirement on both branches (FADEC channels).
- J3 Bundle and J4 Bundle require individual injections at applicable test levels.
- Power connections to additional system components are not shown for simplicity; typically, a single LISN for all system components is sufficient.

FIGURE 32 - SIMULTANEOUS INJECTION USING GROUND INJECTION - EXAMPLE

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Typically ground injection cannot be applied to equipment that needs to be grounded directly to the test bench for functionality, however, it is often possible to put a large impedance, such as an inductor into ground lines for DC operated equipment. This is more difficult with AC powered equipment.

Ground injections to multiple equipments in order to achieve simultaneous injections may be impractical and is typically used to test multiple wire bundles of the same unit. If multiple LRUs are to be tested at the same time then the wire bundle injection method is more appropriate in these situations.

The magnitudes of test voltage/current injected into each branch of a system may be controlled by varying the following test parameters:

- the transient generator parameters,
- the turns ratio of the injection cores on each harness branch,
- the impedances between equipment and the test bench,
- the locations of the injection cores.

The test procedure should specify the test voltages/currents which are to be injected into major harnesses at specified levels, and that the injected currents divide naturally in accordance with harness branch impedances. Alternately, the test procedure may specify the amount of voltage/current to be injected into each branch of the tested system, however, achievement of specified levels in all branches of a wire bundles is usually impractical. Transients in all branches should be measured and those receiving less than the specified levels should be tested separately after the simultaneous injection tests are completed.

If the system is built with a reconfiguration process in case of failure, it is important to test all configurations or to test at least the most critical configurations including the normal and last available (with all redundancies off) configurations.

Some aircraft have systems that incorporate separate redundant control or data channels, and the aircraft operating procedures allow dispatch with one or more channels inoperative. For example, some full authority electronic engine controls allow dispatch with one engine control channel inoperative under time-limited dispatch (TLD) procedures. For these types of systems, the system test should include configurations with the channel inoperative according to the TLD procedures. The system configurations for the tests should include the normal full-up operating configuration and the TLD channel inoperative configuration. It is important to note, that the test procedures and test set ups outlined below are general in nature and, therefore, must be adapted to fit the system under test.

6.2.3.7 Data Interpretation

The test results shall be evaluated with reference to the pass/fail criteria which are derived from the System Safety Assessment process and specified in the test procedure.

6.3 Wire Bundle Shield Transfer Function Test

Shield or overbraid transfer functions may be required for the following purposes:

- If the aircraft ATLs were determined based on the wire bundle shield current, and the ETDLs were based on unshielded wire bundles.

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- If the aircraft wire bundle is not available for a system test and a substitute wire bundle must be used instead. In such a case the transients induced in the substitute wire bundle will have to be set to represent those induced in the aircraft wire bundle. An example would be, if an unshielded wire bundle is to be used for a system test in place of a shielded wire bundle that is in the aircraft and credit is taken for the shielding effectiveness of the shield or overbraid. With wire bundle shield transfer functions, the open circuit voltage and short circuit current on wires within a shielded wire bundle can be calculated for a given shield current. The wire bundle shield transfer functions quantify the effectiveness of the shield. The wire bundle shield effectiveness is frequency-dependent, so if the transfer function measurement is done in the time domain this measurement is valid only if the waveform used corresponds to the intended wire bundle current waveform. If frequency domain measurements are performed it should be ensured that the frequency range of the intended wire bundle transfer function test covers the spectrum of the intended wire bundle current waveform.

Two test methods may be used to determine shield transfer functions of a shielded wire bundle. Shield transfer functions indicate the relative attenuation of the shield, and are typically expressed as the attenuation as a function of frequency. One method, pulse injection, is conducted by injecting a lightning pulse on the wire bundle and measuring open circuit voltage and short circuit current coupled into the internal wires. The responses are then used to determine the transfer function. The second method uses swept frequency measurements, injecting currents of a few amperes from a network analyzer or similar source through an amplifier, onto the shielded wire bundle and measuring the coupled responses into the internal wires. The result is the ratio of the response voltage or current to the drive current as a function of frequency, which directly indicates the shield transfer function. Figure 33 shows an example of shield transfer impedance, which is the ratio of the internal wire response voltage to the current on the shield.

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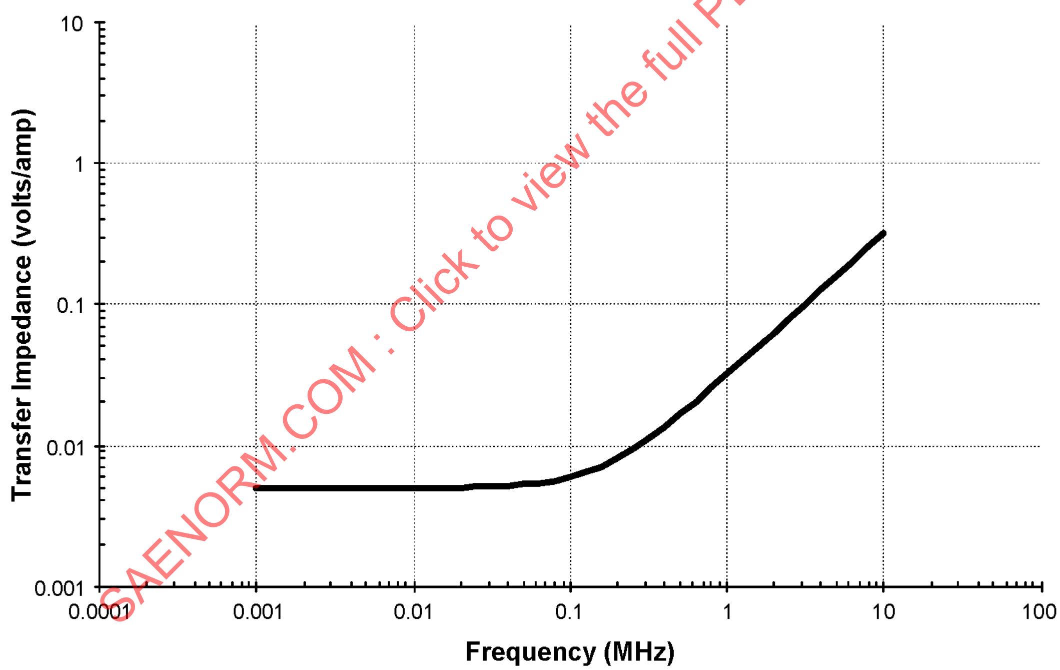

FIGURE 33 - WIRE BUNDLE SHIELD TRANSFER IMPEDANCE EXAMPLE

Normally, an actual aircraft wire bundle is used as the test article. In some cases the actual wire bundle may be too long or too complex to use. Since the transfer function of a wire bundle is a combination of the transfer function of the shield (usually measured in Ω/m over the frequency range) and the transfer function of the connectors (usually measured in Ω over the frequency range), individual tests can be done on a short section of shielded wire bundle and on a connector. The actual transfer function of the aircraft shield can then be determined by multiplying the shield transfer function by the wire bundle length and adding twice the connector transfer function.

6.3.1 Wire Bundle Shield Transfer Function Using Lightning Pulse Injection Method

6.3.1.1 Test Purpose

The purpose of this test is to determine the shield transfer function of a shielded wire bundle. The test is typically conducted with open circuit or short circuit wire terminations at the wire bundle ends. The shield transfer function is estimated by comparing the response and drive current waveforms.

6.3.1.2 Test Object

The test object includes the wire bundle to be tested, and the appropriate mating connectors for the wire bundle. The wire bundle may be single shielded (e.g., a twisted shielded pair) for which the transfer function is the open circuit voltage or short circuit current per unit ampere in the shield. Or it may be a wire bundle that is comprised of several individual shielded wires together with other unshielded wires. In this latter case, the transfer function may be defined as an individual conductor open circuit voltage or short circuit current as a function of total wire bundle current.

In some cases, the test article can be a short section of shielded wire or a single connector (see 6.3).

In the case for wires terminated with open circuits at one end and short circuits at all other ends, the transfer function is referred to as the shield transfer impedance.

6.3.1.3 Test Setup

The wire bundle under test should be positioned above a conducting ground plane, supported approximately 50 mm above the ground plane and connected as shown in Figure 34. For a complex wire bundle with multiple branches, the branches should be kept separated. Only the two connectors for the branch that is under test should be connected with the shield terminated to the ground plane. All other branch connectors should be isolated from the ground plane so that the full current is applied to the branch under test. The other branches should be tested separately.

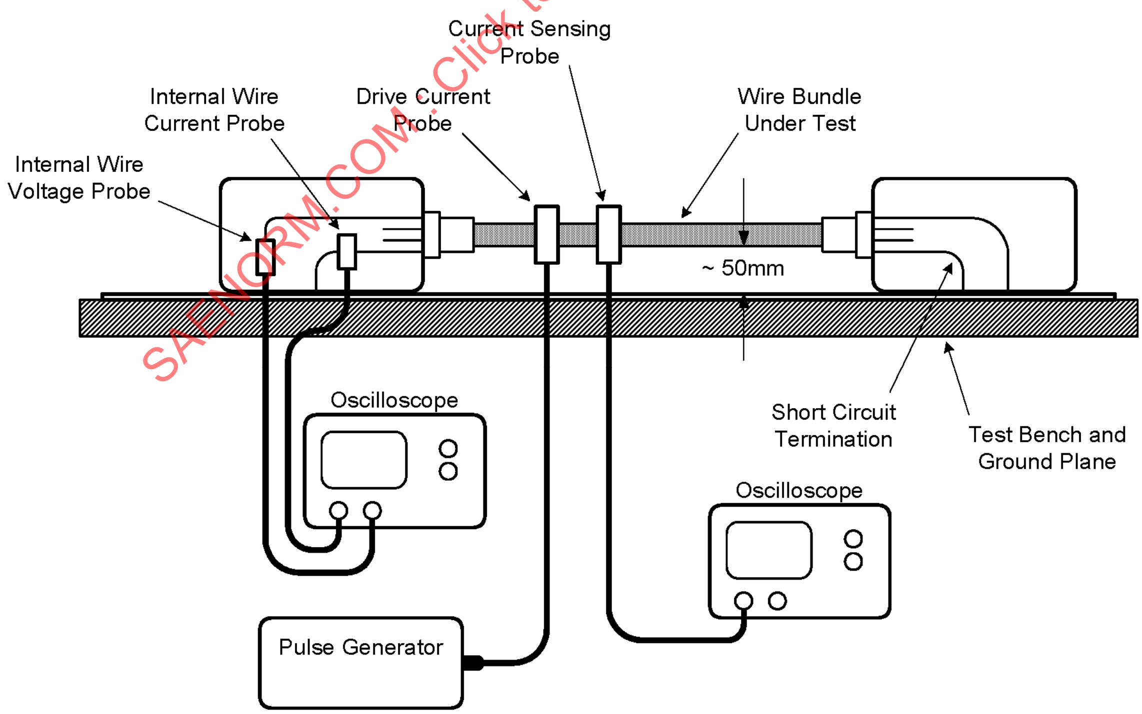

FIGURE 34 - WIRE BUNDLE SHIELD TRANSFER FUNCTION PULSE INJECTION TEST SETUP

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A shielded enclosure with the appropriate mating connector should be connected to the measurement end of the wire bundle and bonded to the ground plane. The shielded enclosure should allow access to the connector pins either to short them to ground for short circuit current measurements, or to measure open circuit voltage. At the other end of the branch under test a shielded enclosure with the appropriate mating connector should be connected and bonded to the ground plane. The connector pins should be shorted to ground as shown in Figure 34. As an alternative, the actual system LRU may be connected at this end of the shielded wire bundle and bonded to the ground plane. However, this alternative should only be used if the system LRU circuit impedances are known over the frequencies of interest, typically from a few kilohertz to a few megahertz. The test configuration and termination at both ends of the wire bundle should be identified in the test procedure. The wires within the wire bundle under test where the voltage and current will be measured should be identified in the test procedure.

The voltage and current probes should have adequate bandwidth for the anticipated transfer function. Typically the probe bandwidth should extend from approximately 100 Hz to 10 MHz.

The probe bandwidths are different than for aircraft tests because in these tests there is no need to assess resonances.

6.3.1.4 Test Waveforms

Waveform 1 or 3 defined in ARP5412/ED-84 with a peak level of 100 A to 1 kA should be used for this test.

6.3.1.5 Measurement and Data Recording

The following data should be recorded:

- Bonding resistance measurements before and after the test
- The actual current amplitude and waveform injected on the wire bundle
- Open circuit voltage and short circuit current waveforms measured on the selected wires within the wire bundle.

6.3.1.6 Test Procedure

(1) Lay out the wire bundle and all test components and loads on the ground plane, including ground straps, as specified in the test procedure.

(2) Disconnect all connectors at the branch ends except for the two connectors of the branch under test.

(3) Connect the connectors for the branch under test as shown in Figure 34.

(4) Short circuit the selected wires inside the shielded enclosure at one end of the branch under test.

(5) Connect the voltage probe in the shielded enclosure at the other end of the branch for shield transfer impedance measurements. Short circuit the selected wire to ground and install the current probe for current transfer function measurements.

(6) Inject the appropriate lightning pulse waveform on the shielded wire bundle, and measure open circuit voltage and short circuit current waveforms on the pins.

(7) Calculate wire bundle shield transfer function.

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6.3.1.7 Data Interpretation

The shield transfer function is determined by comparing the drive current and the response. If the response waveform and the drive waveform have similar waveshapes, considering the time to peak and duration, then the transfer function can be expressed by the ratio of the peak response to the peak drive current. However, if the two waveforms have different characteristics, then a more detailed assessment is needed.

Typically the voltage response for a wire in a shielded bundle is related to the drive current rate of rise. Therefore, the drive current peak rate of rise must be used to calculate an appropriate transfer impedance factor. It is not appropriate to use the ratio of the response and drive current amplitudes for these types of responses. The voltage response will reach its peak much sooner than the drive current. The drive current probe must have adequate bandwidth to measure the drive current peak rate of rise.

6.3.2 Wire Bundle Shield Transfer Function Using Swept Frequency Tests

6.3.2.1 Test Purpose

The purpose of this test is to determine the shield transfer function of a shielded wire bundle. The test is typically conducted with open circuit or short circuit wire terminations at the wire bundle ends. The swept frequency tests directly measure the shielding transfer function.

6.3.2.2 Test Object

The test object includes the wire bundle to be tested, and the appropriate mating connectors for the wire bundle. The wire bundle may be single shielded (e.g., a twisted shielded pair) for which the transfer function is the open circuit voltage or short circuit current per unit ampere in the shield. Or it may be a wire bundle that is comprised of several individual shielded wires together with other unshielded wires. In this latter case, the transfer function may be defined as an individual conductor open circuit voltage or short circuit current as a function of total wire bundle current.

In some cases, the test article can be a short section of shielded wire or a single connector (see 6.3).

In the case for wires terminated with open circuits at one end and short circuits at all other ends, the transfer function is referred to as the shield transfer impedance.

6.3.2.3 Test Setup

The wire bundle under test should be positioned above a conducting ground plane, supported approximately 50 mm above the ground plane and connected as shown in Figure 35. For a complex wire bundle with multiple branches, the branches should be kept separated. Only the two connectors for the branch that is under test should be connected with the shield terminated to the ground plane. All other branch connectors should be isolated from the ground plane and left open so that the full current is applied to the branch under test. The other branches should be tested separately.

A shielded enclosure with the appropriate mating connector should be connected to the measurement end of the wire bundle and bonded to the ground plane. The shielded enclosure should allow access to the connector pins either to short them to ground for short circuit current measurements, or to measure open circuit voltage. At the other end of the branch under test a shielded enclosure with the appropriate mating connector should be connected and bonded to the ground plane. The connector pins should be shorted to ground as shown in Figure 35. As an alternative, the actual system LRU may be connected at this end of the shielded wire bundle and bonded to the ground plane. However, this alternative should only be used if the system LRU circuit impedances are known over the frequencies of interest, typically from a few kilohertz to a few megahertz. The test configuration and termination at both ends of the wire bundle should be identified in the test procedure.

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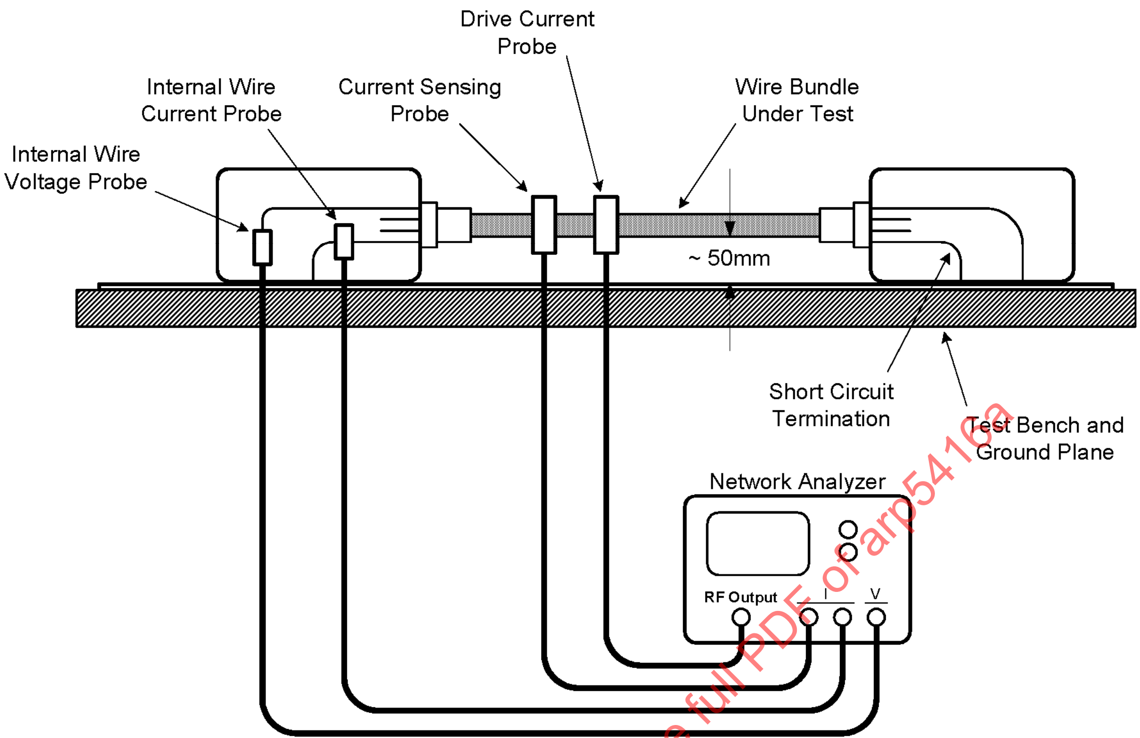

FIGURE 35 - SWEPT FREQUENCY WIRE BUNDLE SHIELD TRANSFER FUNCTION TEST SETUP

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The wires within the wire bundle under test where the voltage and current will be measured should be identified in the test procedure.

The voltage and current probes should have adequate bandwidth for the anticipated transfer function. Typically the probe bandwidth should extend from approximately 100 Hz to 10 MHz.

The probe bandwidths are different than for aircraft tests because in these tests there is no need to assess resonances.

6.3.2.4 Test Waveform

The current applied on the bundle should be swept or stepped from approximately 100 Hz to 10 MHz. If the frequencies are stepped, then use at least 10 measurements points per decade.

6.3.2.5 Measurement and Data Recording

The following data should be recorded:

- Bonding resistance measurements before and after the test
- Open circuit voltage and short circuit current measured on the selected wires within the wire bundle, relative to the injected current on the wire bundle. This will be the shielding transfer function as a function of frequency.

6.3.2.6 Test Procedure

(1) Lay out the wire bundle and all test components and loads on the ground plane, including ground straps, as specified in the test procedure.

(2) Disconnect all connectors at the branch ends except for the two connectors of the branch under test.

(3) Connect the connectors for the branch under test as shown in Figure 35.

(4) Short circuit the selected wires inside the shielded enclosure at one end of the branch under test.

(5) Connect the voltage probe in the shielded enclosure at the other end of the branch for shield transfer impedance measurements. Short circuit the selected wire to ground and install the current probe for current transfer function measurements.

(6) Inject the RF Output on the shielded wire bundle, and measure open circuit voltage and short circuit current waveforms on the pins.

(7) Calculate wire bundle shield transfer function.

6.3.2.7 Data Interpretation

The transfer function represents the ratio of the selected wire voltage or current and the current injected on the wire bundle. This transfer function is used to calculate the transient response of the voltage or current on the selected wire. The spectrum of the actual wire bundle lightning current waveform, measured during a full aircraft lightning test or calculated from an analytical model of the aircraft, may be multiplied with the transfer function. The result of this product of the transfer function and the wire bundle current waveform spectrum can then be processed through an inverse Fourier transform to calculate the actual voltage or current transient on the shielded wire within the wire bundle.

6.4 Shield/Connector Current Handling Test

6.4.1 Shield/Connector Current Handling Test

6.4.1.1 Test Purpose

This test is to verify the ability of a shield or a connector or a shield to connector interface to conduct the lightning-induced currents.

6.4.1.2 Test Object

The test object may be a single shielded (e.g., twisted shielded pair), a wire bundle shield, a connector (bulkhead and/or mating), a shielded junction box, or any combination of these. The shields, connectors, and the junction boxes may be of metallic or non-metallic material with or without metallic plating.

6.4.1.3 Test Setup

The wire bundle under test will be mounted 50 mm above a ground plane and connected at both ends to test fixtures representative of the bonding configuration of the shield to the fixtures or to the ground plane in an actual installation. Examples of the test setup are shown in Figures 36 and 37. The generator should be connected to drive the required current from end to end of the wire shield.

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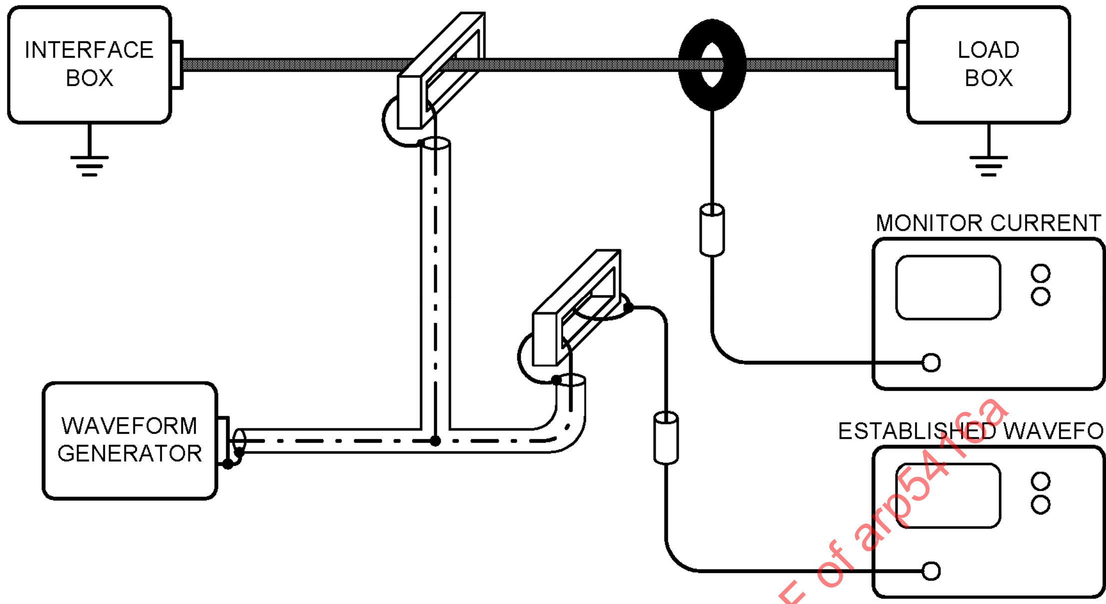

FIGURE 36 - HARNESS CURRENT HANDLING CAPABILITY TEST SETUP - WIRE BUNDLE INJECTION

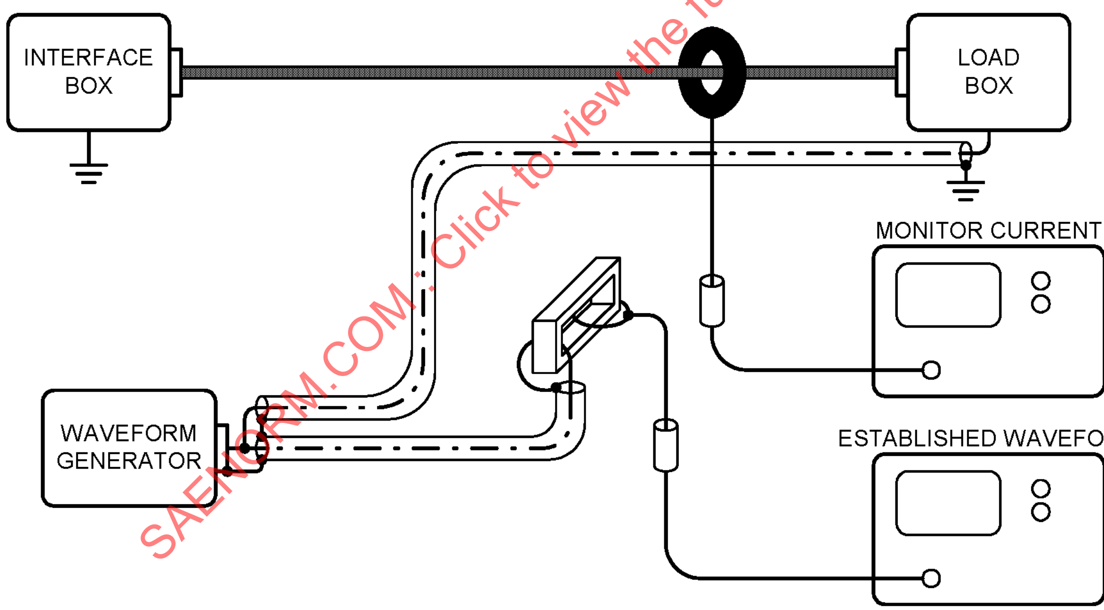

FIGURE 37 - HARNESS CURRENT HANDLING CAPABILITY TEST SETUP - GROUND INJECTION

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6.4.1.4 Test Waveforms

Test current waveform (for details, see ARP5412/ED-84) should be applied for this test.

6.4.1.5 Measurements and Data Recording

The following data should be recorded:

- Dielectric strength of wire insulation before and after test (dielectric strength of insulation can be obtained either from wire specifications or determined for a prototype wire)
- DC resistance measurements before and after the test
- The calibrated short circuit current waveform
- The actual current injected on the overbraid

6.4.1.6 Test Procedure

(1) The transient generator should be adjusted to drive the required short circuit current waveform.

(2) The DC resistance of the required path (such as harness backshell to backshell, or wire shield to box or to ground plane) should be measured and recorded.

(3) The transient generator amplitude control should be set to the calibrated short circuit current level.

(4) The calibrated transient generator signal should be applied directly on the wire shield. A total of 10 pulses minimum should be applied.

(5) The DC resistance of the same pre-tested path should be measured and recorded.

6.4.1.7 Data Interpretation

The damage is to be evaluated based on pre-/post-test DC resistance measurements and the dielectric insulation degradation, as well as visual inspections for evidence of arcing or sparking. The limits of pre-test and post-test values should be indicated in the test procedure.

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7. FUEL SYSTEM TEST METHODS

These types of tests apply to regions of the aircraft where concentrations of flammable fuel vapors may be present, and where ignition of such vapors could constitute a hazard. Their purpose is to demonstrate that ignition sources will not be produced by lightning arc attachments or by the resulting conduction of lightning currents.

7.1 Test Objectives

The objective of the test is to demonstrate that ignition sources do not exist. Ignition sources which might arise include, but are not limited to:

a. Voltage Sparks. A voltage spark is an electrical breakdown across a gap within the fuel vapor space. It may take place for example between parts of the structure separated by a small gap, or to the structure from wiring which enters the fuel tank from another location on the aircraft.

b. Arcs and Thermal Sparks. An arc is an electrical plasma within the fuel vapor space, which may be accompanied by burning particles (thermal sparks) that are ejected from interfaces when such interfaces are inadequate to conduct the lightning currents to which they are exposed.

c. Melt Through or Puncture. Contact of fuel vapors with the lightning arc at a hole melted completely through a metal skin or a puncture through a composite skin.

d. Hot Spots. A hot spot is a surface in contact with fuel vapors that is heated to a temperature which could ignite the mixtures in the fuel vapor space.

e. Streamering at Fuel Vent Outlets or within Non-Conductive Fuel Tanks. Ionized air which develops into extended electrical streamers due to strong electrical field intensities at the vent and drain outlets.

Ignition source detection methods which are described in detail in 7.7 should be chosen so as to reliably detect the potential ignition sources which have been identified.

7.2 Tests and Specimen Types

7.2.1 Test Types

In order to demonstrate that the ignition sources defined above do not arise, three types of tests are identified:

a. Conduction Tests (7.3):

- Conduction tests to complete tanks or complete tank subassemblies (7.3.1)
- Conduction tests on fuel tank coupon specimens (7.3.2)
- Conduction tests to fuel system components (7.3.3)

b. Direct Strike Tests (7.4):

- Direct strike tests on complete tanks or tank sections (7.4.1)
- Direct strike tests on coupon specimens (7.4.2)
- Direct strike tests to externally mounted fuel system equipment (7.4.3)

c. Voltage Breakdown Tests (7.5):

- Voltage breakdown tests of small gaps (7.5.1)

d. High Voltage Corona and Streamer Test (7.6):

- HV streamer test (7.6.1)

e. Methods for Detection of Ignition Sources (7.7):

- Photographic method (7.7.1)
- Ignitable mixture (flammable gas) test method (7.7.2)

These tests should be applied to the various components of the fuel system according to Table 2 if they are exposed to direct strikes, conducted lightning currents or other effects such as induced voltages. If a component is not exposed to one or more of these effects the assessment test is not applicable.

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TABLE 2 - EXAMPLES OF APPLICATIONS OF FUEL SYSTEM TESTS

Test Objects	High Current Tests			High Voltage Tests	
	Conduction Test (7.3)	**Direct Strike Test (7.4)**	**Attachment Test (Note 1.)**	**Voltage Breakdown Test (7.5)**	**Corona & Streamer Test (7.6)**
Fuel Tank:					
Access panels	X	X	X		
Skin panels	X	X	X		
Structural joints	X	X	X		
Bladders					
Filler cap	X	X	X		
System Components Within Tanks (other components installed within the tank skins**):**					
Fuel vent lines and fittings	X	X	X		
Fuel transfer lines and fittings	X				
Fuel pumps and installations	X	X	X		
Fuel drain installations	X	X	X		
Fuel Quantity Gauging System	X	X	X	X	
Fuel temperature sensors	X	X	X	X	
Electrical wiring				X	
Fuel tank inerting system plumbing	X				
Vent fire suppression system	(functional test, in presence of lightning initiated flames)				
Insulating link				X	
Fuel vent outlets		X	X		X
Interconnect valves	X				
Fuel vent and transfer lines and fittings	X				
Fuel flow monitors	X				
Flame arresters installation	X	X	X		
Fuel dump outlet installation	X	X	X		X
Fuel sump drains	X	X	X		
Fuel dump measuring sticks	X	X	X		

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NOTES:

1. For composite or non-conductive components or test units, attachment tests per 5.1.1 or 5.1.2 may be used to validate probe placement for Direct Strike Tests in 7.4.