SAE Aerospace
An SAE International Group

# AEROSPACE RECOMMENDED PRACTICE

SAE ARP5416

Issued 2005-03

## Aircraft Lightning Test Methods

### 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.





**TO PLACE A DOCUMENT ORDER:** **Tel: 877-606-7323 (inside USA and Canada)**
**Tel: 724-776-4970 (outside USA)**
**Fax: 724-776-0790**
**Email: custsvc@sae.org**
**SAE WEB ADDRESS:** **http://www.sae.org**

SAE 100
Leading Our World In Motion

TABLE OF CONTENTS

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 lighting 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 Documents: Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001 (Web-Site: www.sae.org).

| | |
|---|---|
| ARP4754 | “Certification Considerations for Highly Integrated or Complex Aircraft Systems”, issued November, 1996 |
| ARP5412 | "Aircraft Lightning Environment and Related Test Waveforms", issued August, 1999 |
| ARP5413 | "Certification of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning", issued August, 1999 |
| ARP5414 | "Aircraft Lightning Zoning", issued August, 1999 |
| ARP5415 | "User's Manual for Certification of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning", issued August, 2001, Rev A issued April, 2002 |
| 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 |

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 (Web-Site: 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 (Web-Site: www.faa.gov).

| | |
|---|---|
| AC 20-53A | *"Protection of Airplane Fuel Systems Against Fuel Vapor Ignition Due to Lightning"*, dated April 12, 1985. 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 |
| AC 21-16D | RTCA Document DO-160D, dated July 21, 1998 |
| AC 23.1309-1C | *"Equipment, Systems, and Installations"*, dated March 12, 1999 |
| AC 25.1309-1A | *"System Design Analysis"*, dated June 21, 1988 |
| AC 27-1B | *"Certification of Normal Category Rotorcraft"*, dated September 30, 1999 |
| AC 29-2C | *"Certification of Transport Category Rotorcraft"*, dated September 30, 1999 |

2.1.4 RTCA, Inc. Documents: Available from RTCA, Inc., 1140 Connecticut Avenue, NW, Suite 1020, Washington, DC 20036-4001 (Web-Site: 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 |

2.1.5 EASA Documents: Available from European Aviation Safety Agency, Ottoplatz, 1, D-50679 Köln, Germany (Web-Site: 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)

2.1.6 EUROCAE Documents: Available from EUROCAE, 17, Rue Hamelin, 75783 PARIS CEDEX 16, France, (Web-Site: www.eurocae.org).

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

EUROCAE ED-79 *"Certification Considerations for Highly Integrated or Complex Aircraft Systems"*, dated April, 1997

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

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

2.1.7 ANSI Documents: Available from ANSI Inc., 11 West 42 Street, New York, NY 10036.

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

2.1.8 IEC Documents: 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.

CALIBRATION LOOP: A heavy duty, low self-inductance, low resistance, single turn wire loop passed through the injection transformer to form an insulated secondary winding. It should be low enough in impedance to achieve the test level and waveform.

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

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

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.

2.2.1 (Continued):

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.

FUEL VAPOR REGIONS: A region in the aircraft that may have fuel or fuel vapor present.

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 HIGH CURRENT COMPONENTS (A, B, C, D, AND E): Different standardized high current waveforms. For details refer to ARP5412/ED-84.

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.

2.2.1 (Continued):

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.

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.

MONITOR LOOP: A close fitting, single turn, wire loop wound through the injection transformer to form an insulated secondary winding. It is used to monitor the induced wire bundle or calibration loop voltage.

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

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.

2.2.1 (Continued):

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.

SUB-SYSTEM: A division of a system that in itself has the characteristics of a system.

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.

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 |

2.2.2 (Continued):

| | |
|---|---|
| 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 |

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 |
| 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 |

2.2.3 (Continued):

| | |
|---|---|
| FHA | Functional Hazard Assessment |
| FRP | Fiberglas Reinforced Plastic |
| HIRF | High Intensity Radiated Fields |
| HV | High Voltage |
| 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 |
| SAE | Society of Automotive Engineers |
| 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 sends damaging voltages resulting from electromagnetic (EM) energy into the transmitter or receiver connected to that antenna. 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.

## 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.

3.1 (Continued):

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.

For metallic surfaces it is primarily the intermediate 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-sec). 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.

3.1 (Continued):

(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.

3.1 (Continued):

d. Magnetic Force

Charged particles in motion in a magnetic field experience a force that can be expressed for a current flowing as F = IL x B, where F is the force, I is the current, L is the length, and B is the magnetic field. F, L, 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 five millimeters 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.

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, nonconductive 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.

## 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.

4.1 (Continued):

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.

a. INTRODUCTION

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

b. TEST OBJECT

- Description
- Conformity Aspects

4.2 (Continued):

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.

Care should be taken to avoid spurious coupling by the use of optical fibers for instance, and noise levels should be verified.

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.

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 and ultimately lead to erroneous data. 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.

## 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)

5. (Continued):

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.

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, Figure 2, Figure 3 and Figure 4.

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

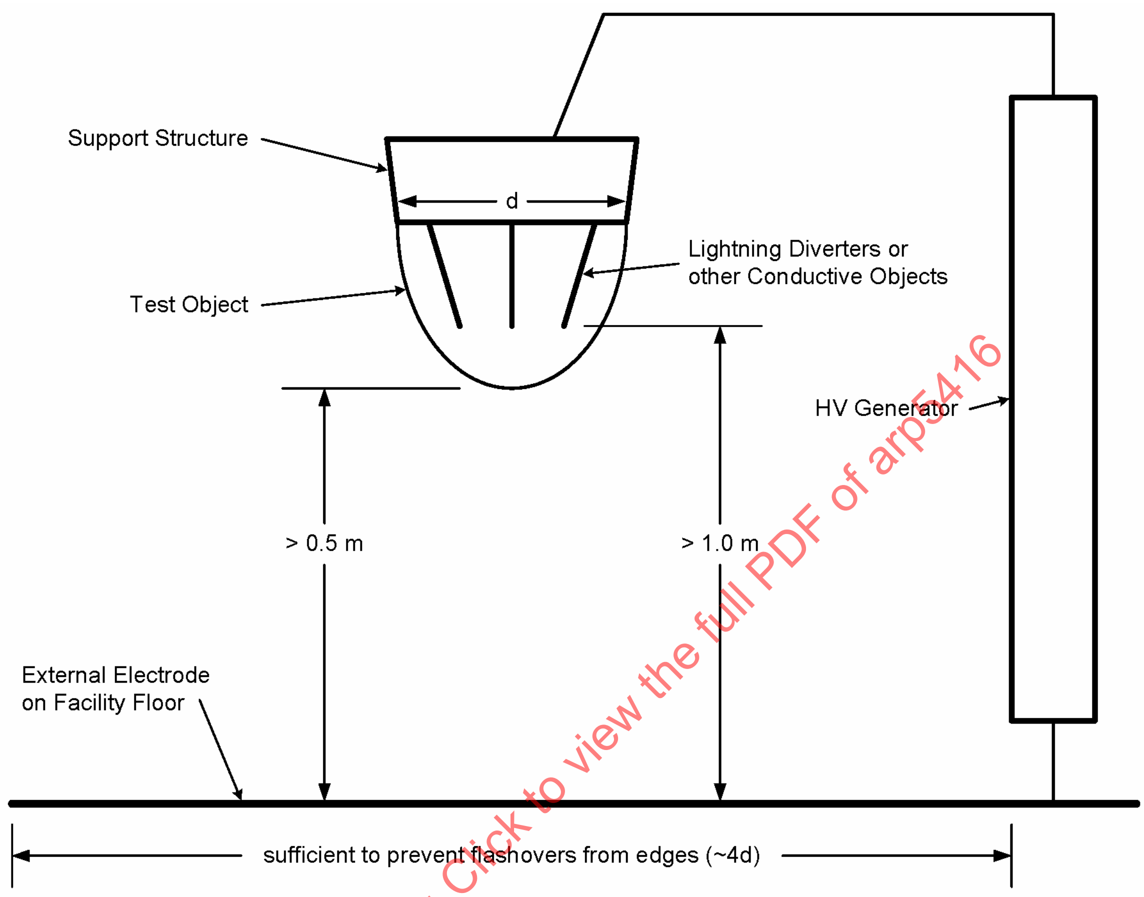


FIGURE 1 - Initial Leader Attachment Test Setup A

5.1.1.3 (Continued):

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.

5.1.1.3 (Continued):

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.

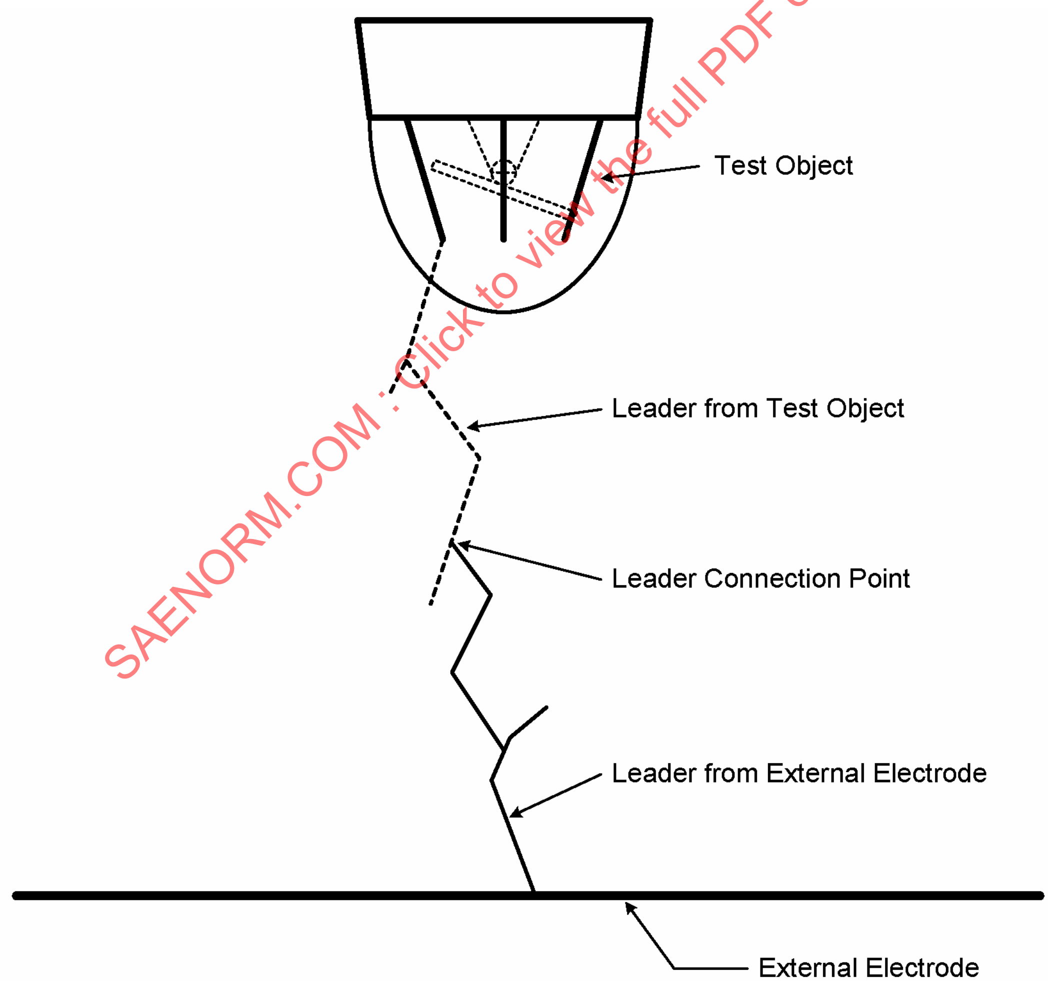


FIGURE 2 - Leader Connection Point

5.1.1.3 (Continued):

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.

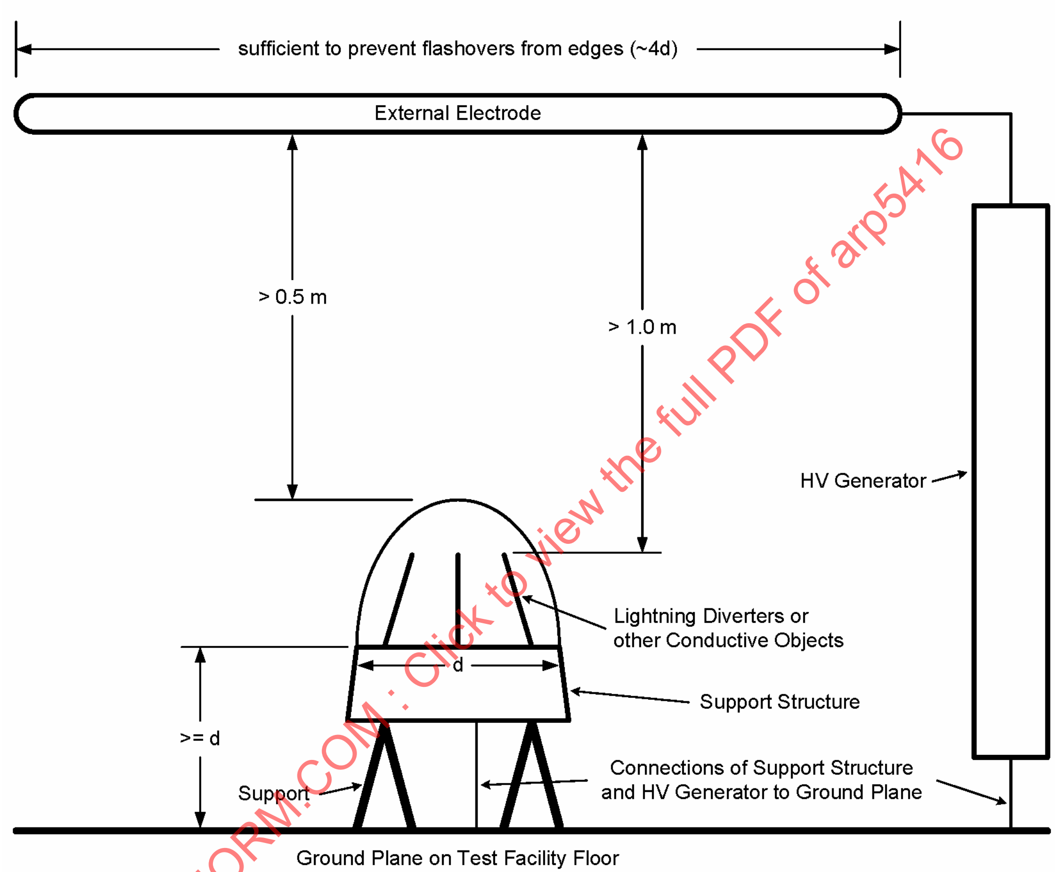




FIGURE 3 - Initial Leader Attachment Test Setup B

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.

5.1.1.3 (Continued):

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.

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 4.

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 1m 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 4, 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.

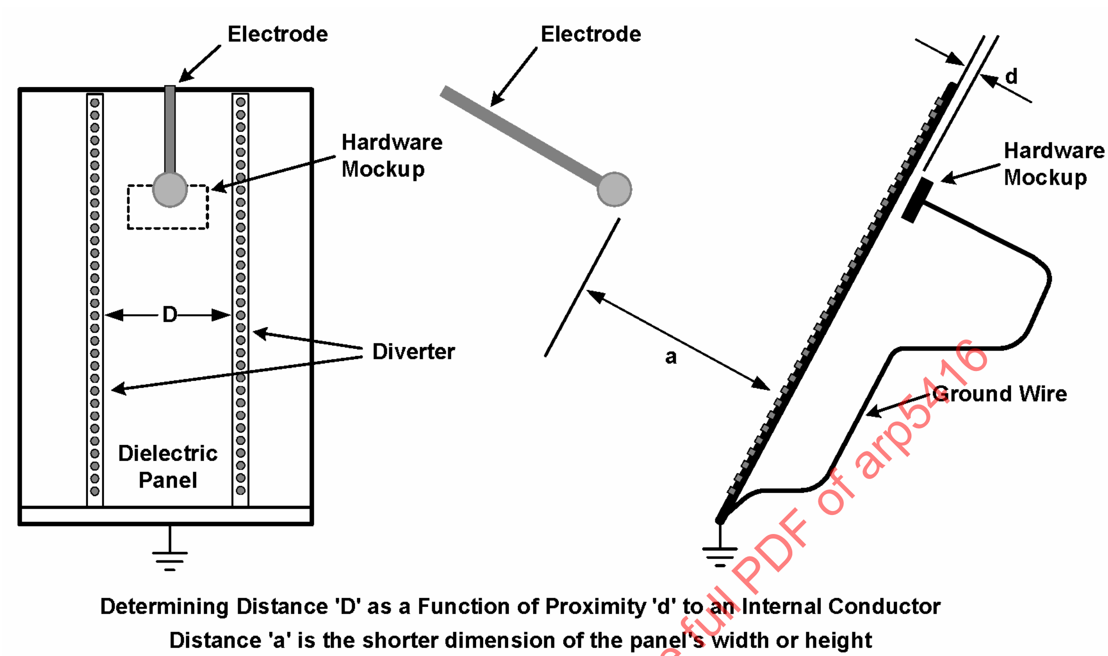


FIGURE 4 - Arrangement for Protection Device Evaluations Test Setup C



5.1.1.3 (Continued):

The arrangement of Figure 4 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 4 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.

5.1.1.3 (Continued):

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 4.

(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.

5.1.1.3 (Continued):

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 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.

5.1.1.5 (Continued):

- 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.

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 test object protective devices progress further into the air gap before being joined by opposing streamers from the negative electrode.

(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.

5.1.1.6 (Continued):

(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. A Tesla coil is useful for determining the location of small punctures that might be difficult to see with the naked eye.

(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.

(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 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 Figure 5 and Figure 6. Large test objects, of dimensions on the order of 0.25 m or more, usually that tests be applied from several electrode positions, as illustrated on Figure 5. Smaller test objects can usually be tested from one test electrode location centered over the test object, as illustrated in Figure 6. The sphere gap spacing, g, and the test electrode spacing, d, are determined during the test set-up calibration.

- 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 a round rod of no greater than 50 mm diameter.

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

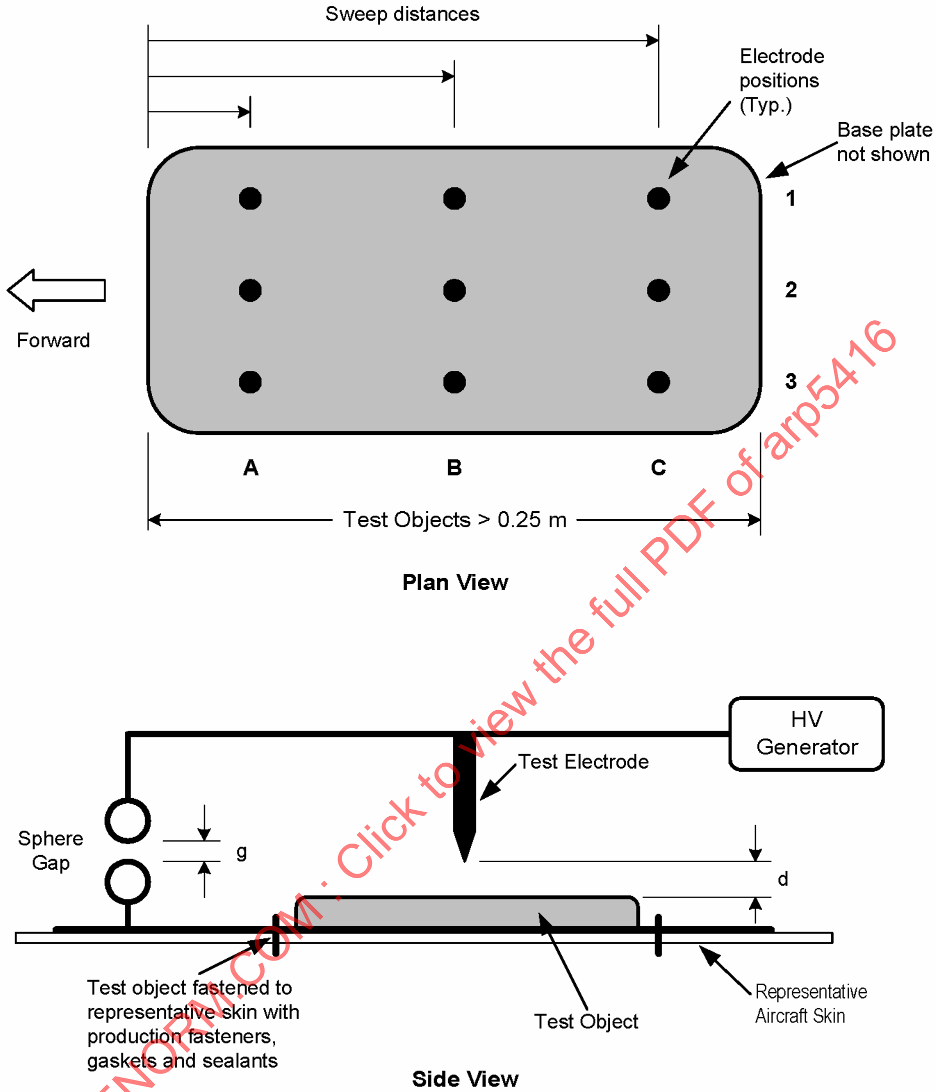


FIGURE 5 - Arrangement for Swept Channel Test of Large Test Objects

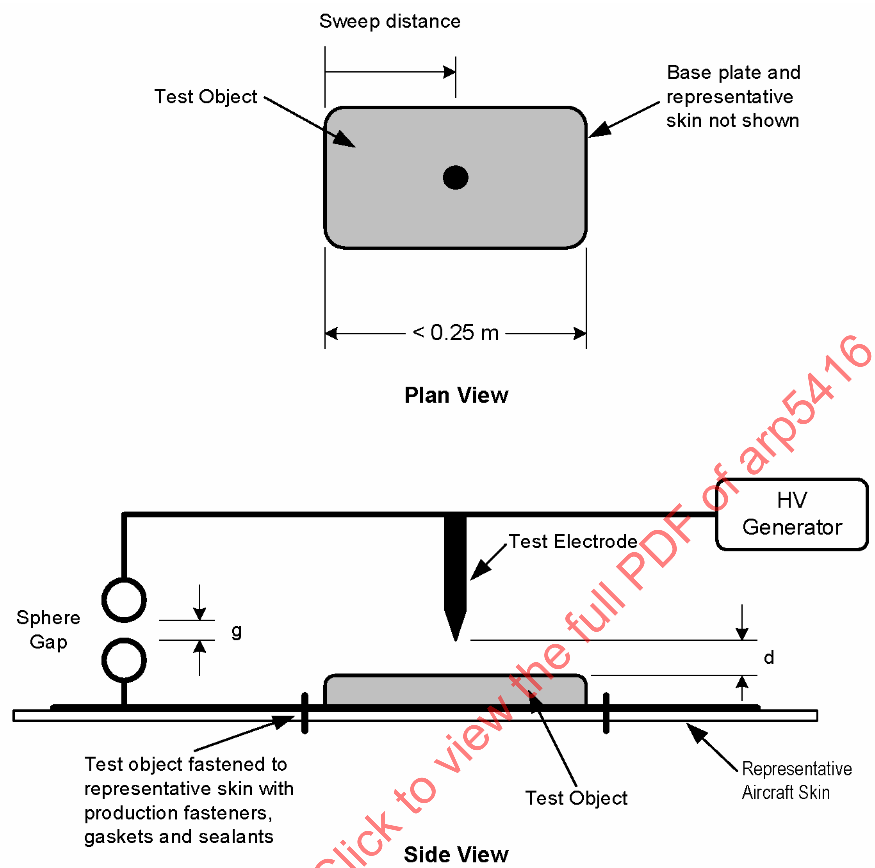


FIGURE 6 - Arrangement for Swept Channel Test of Small Test Objects



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.

5.1.2.5 (Continued):

- 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 140kV/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 5, 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.

5.1.2.6 (Continued):

(c) Connect the output terminal of the high voltage generator to the high voltage test electrode. The test electrode should be round rod of no greater than 50 mm diameter.

(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 overtop 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. If necessary, adjust the spacing (d) of the test electrode such that the electrode breaks down at the desired test voltage (-0/+10%) and repeat the electrode breakdown voltage demonstration.

(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 surfaces 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.

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 can not 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 7 shows a typical setup for the naturally occurring leader case. Figure 8 shows the arrangement to represent the aircraft initiated strike.

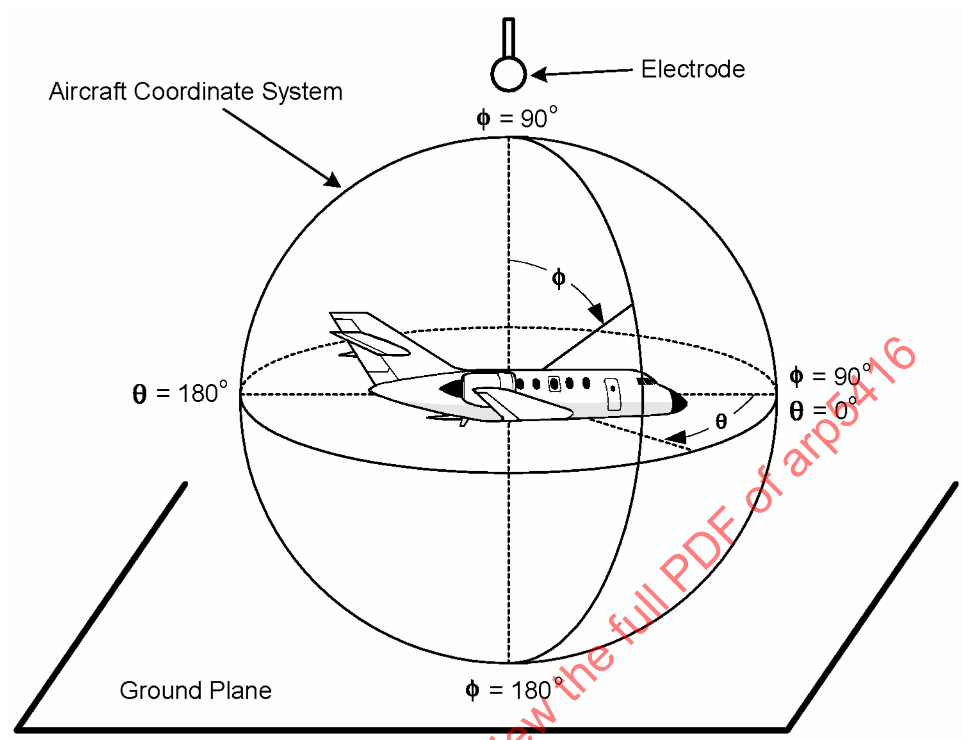


FIGURE 7 - Test Setup to Determine Initial Leader Attachment Locations on Models Naturally Occurring Leader Simulation Shown

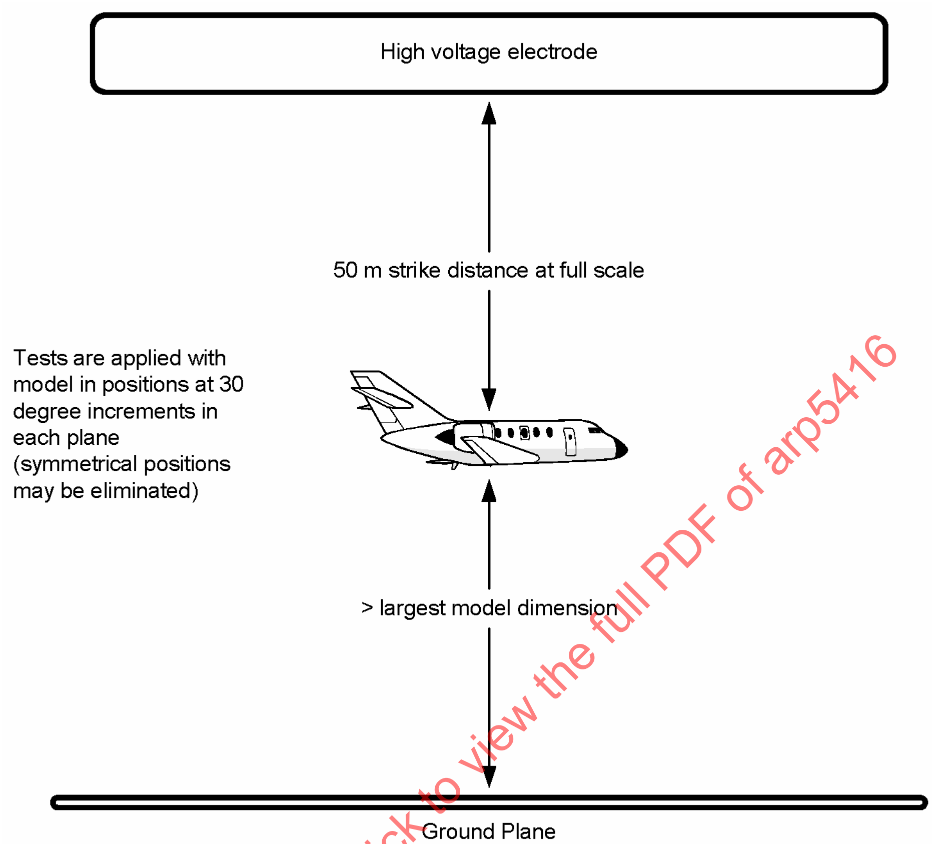


FIGURE 8 - Test Setup to Determine Initial Leader Attachment Locations on Models Aircraft Initiated Strike Simulation Shown



5.1.3.3 (Continued):

- 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.

5.1.3.3 (Continued):

- 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 μs 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° 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.

5.1.3.6 (Continued):

(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° in increments of 30°. Note that the model may have to be rotated through 180° 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.

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.

5.2.1.3 (Continued):

- 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 9. If blast or shock wave effects are not of concern, a rod electrode with rounded tip and a diameter of 50 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.

- Set up sensing and recording equipment.

5.2.1.4 Test Waveforms: A subset of current waveforms A, B, C and D 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.

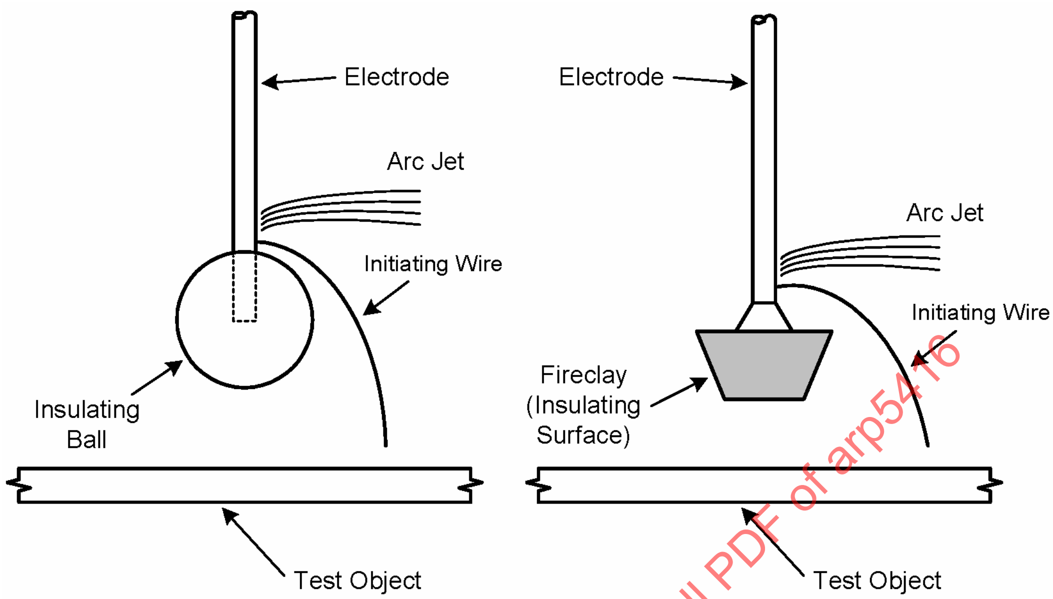


FIGURE 9 - Typical Jet Diverting Test Electrode

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.

5.2.1.6 (Continued):

(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.

5.2.2.3 Test Setup:

- Mount the test object in a fixture or aircraft structural section. Figure 10 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 11 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.

- 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.

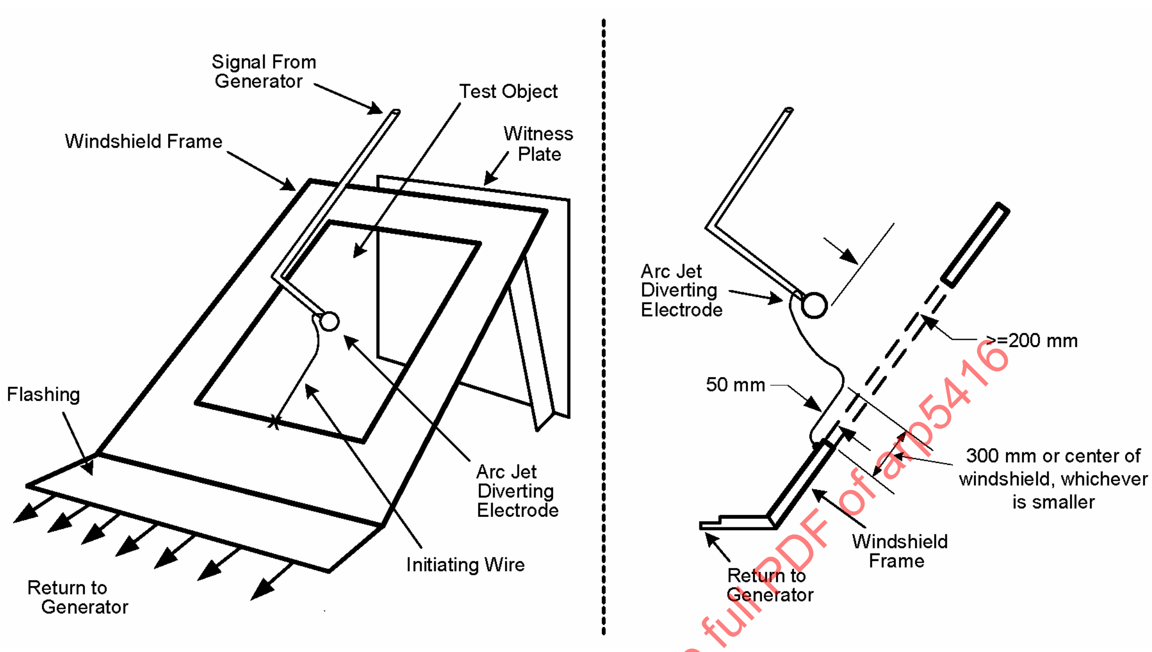


FIGURE 10 - Test on Transparency Mock-Up



5.2.2.3 (Continued):

- Orient a 'jet diverting' electrode (see Figure 10) 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.

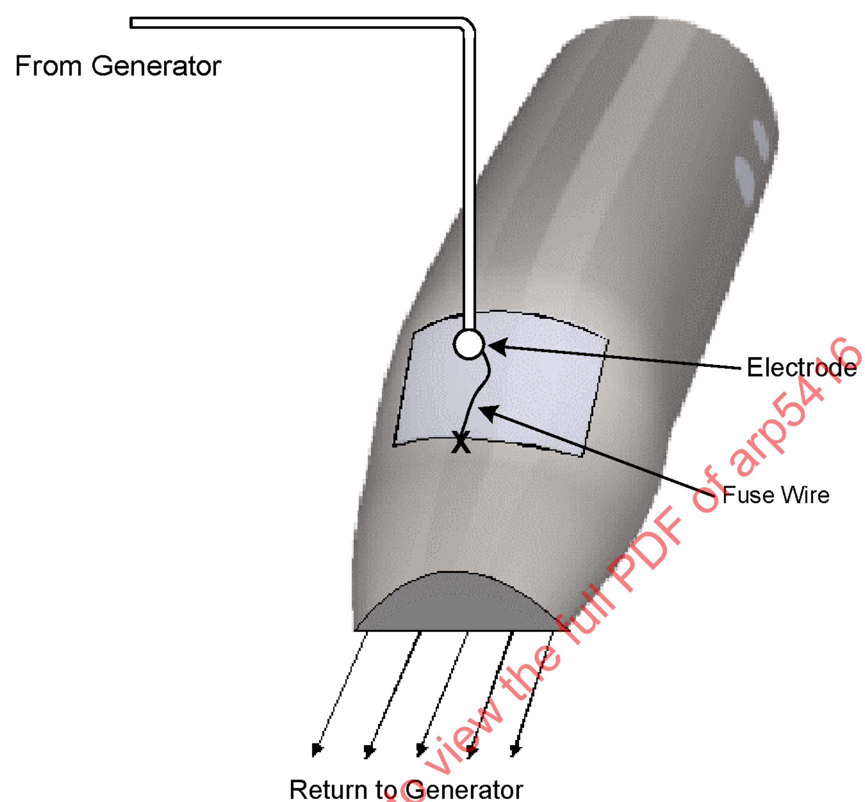


FIGURE 11 - Test on Windshield

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.
- 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.

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 12 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 waveforms A, B, C, and D 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.

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.

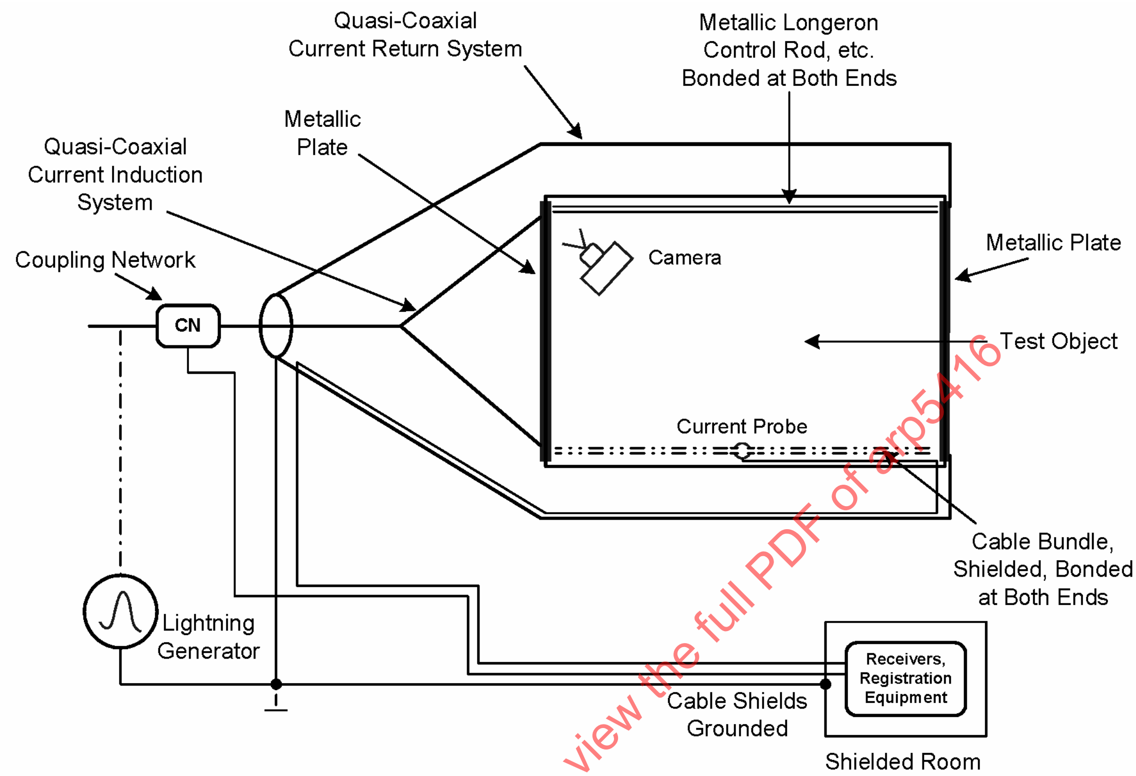


FIGURE 12 - Typical Setup for Damage Test with Power Lead Layout



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).

5.2.3.6 (Continued):

(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.

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 13 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.

- 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 9.

- 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.

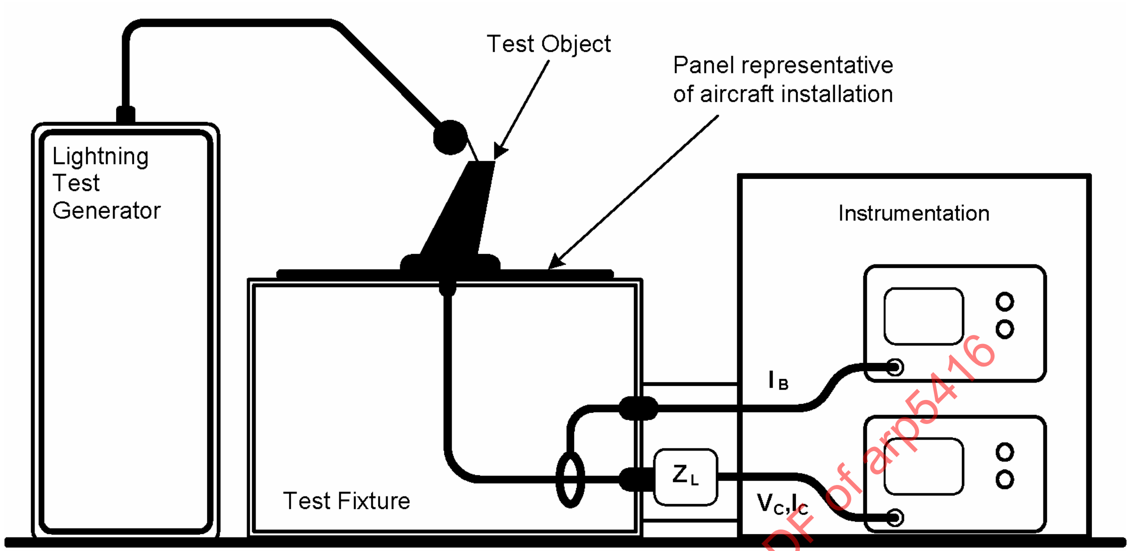


FIGURE 13 - Typical Metal Skin Installation



5.3.1.4 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. 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 5.3.1.7.

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.

5.3.1.5 (Continued):

- 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.

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 14. 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.

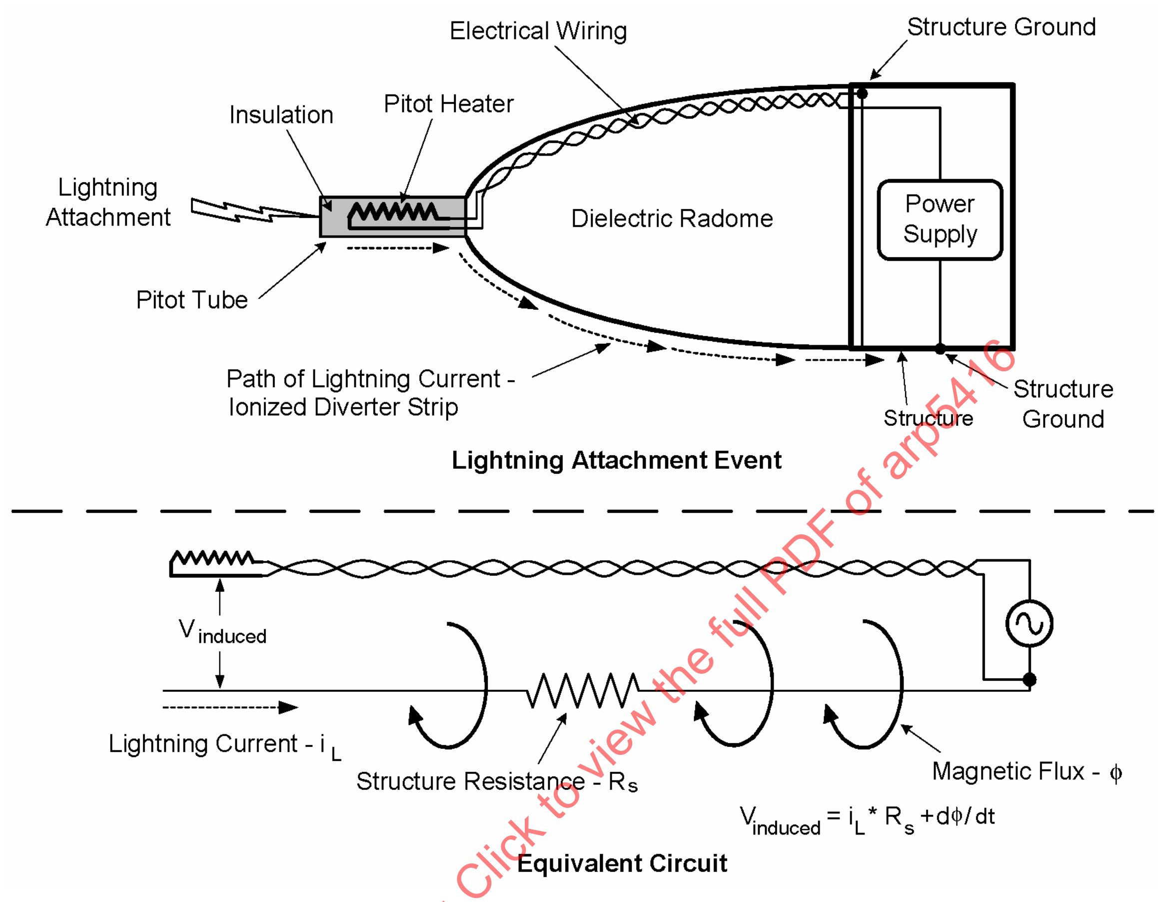


FIGURE 14 - Lightning Induced Voltage Appears at Pitot Heater Insulators



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 15. Set up the instrumentation to measure of the open circuit voltage at the other end of the circuit.

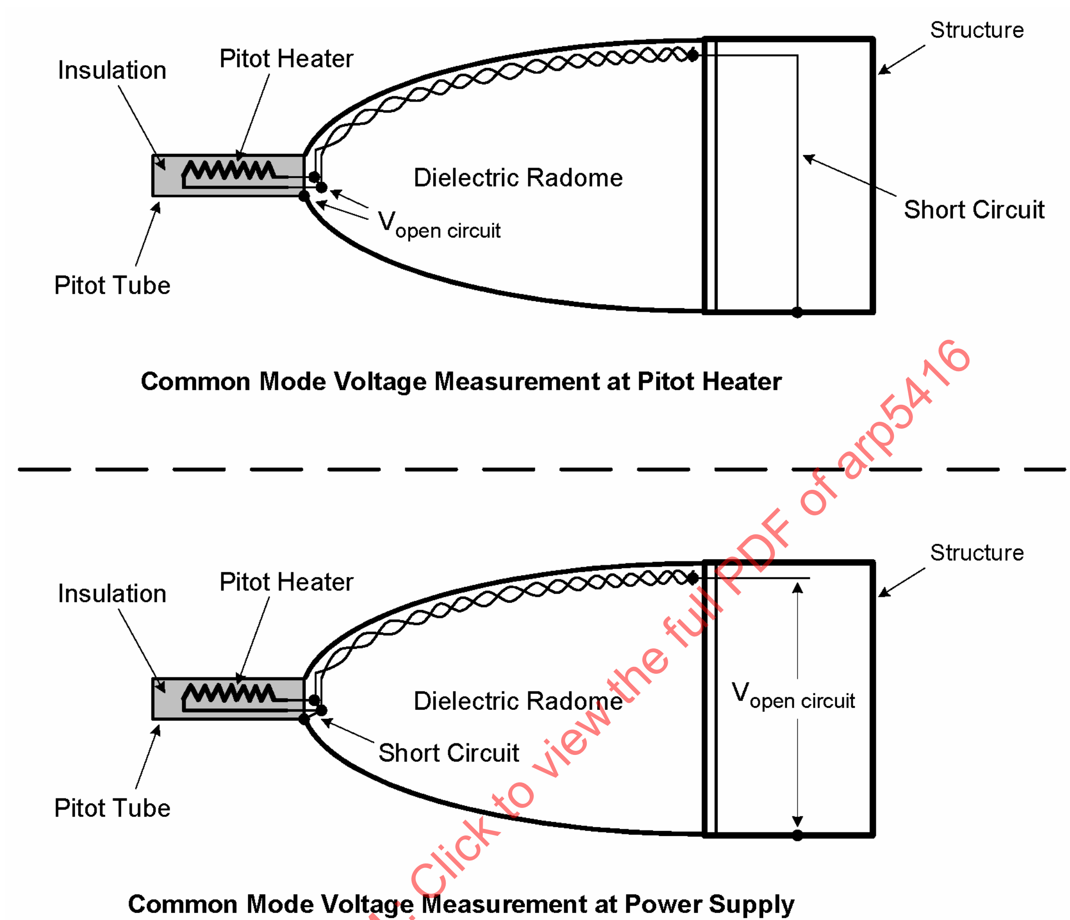


FIGURE 15 - Induced Voltage Measurement Locations

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 used. 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.

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.

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 |

6.1.3 (Continued):

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 uniform 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.

6.1.3 (Continued):

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.

A typical helicopter return conductor arrangement is shown in Figure 16. In this arrangement, a simple ground plane is used for the current return. Overhead return conductors are typically not required, because the main rotor blades will have the most significant effect on the current distribution in the helicopter.



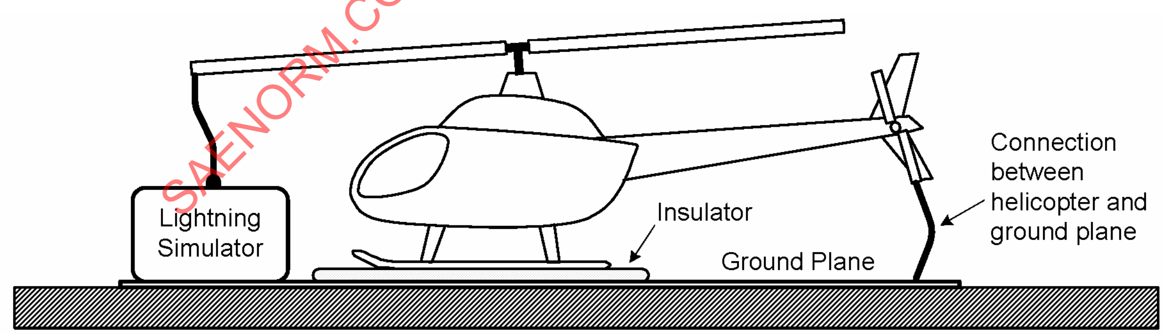


FIGURE 16 - Helicopter Ground Plane Arrangement

6.1.3 (Continued):

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 17, provides reasonably uniform 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.

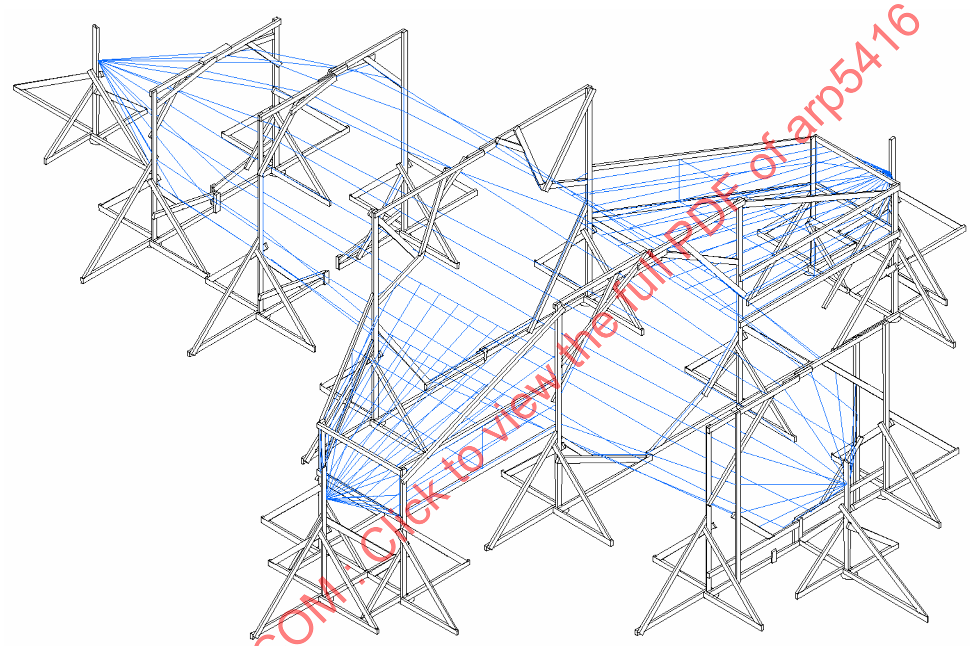



FIGURE 17 - Small Aircraft Return Conductor Arrangement

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.

6.1.3 (Continued):

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 18 shows localized return conductors for measurements associated with wiring in the vertical stabilizer.

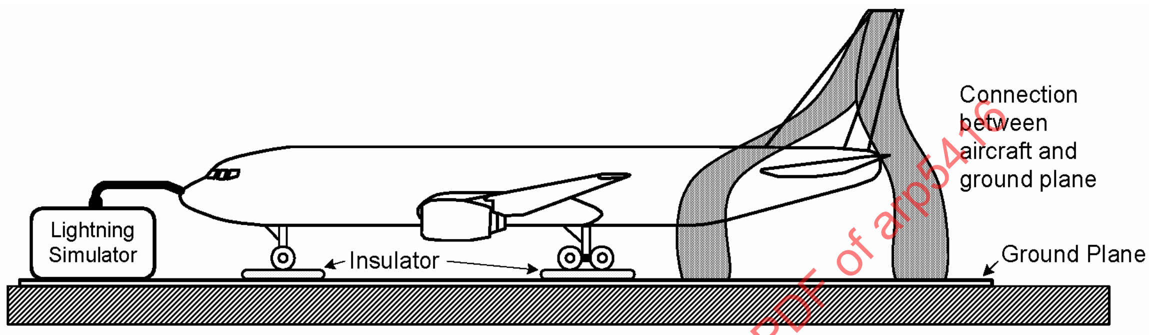


FIGURE 18 - Large Transport Aircraft Return Wire Arrangement

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.

6.1.4 (Continued):

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.

6.1.4 (Continued):

The measurement configurations described in a. through e. are shown in Figure 19. 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.

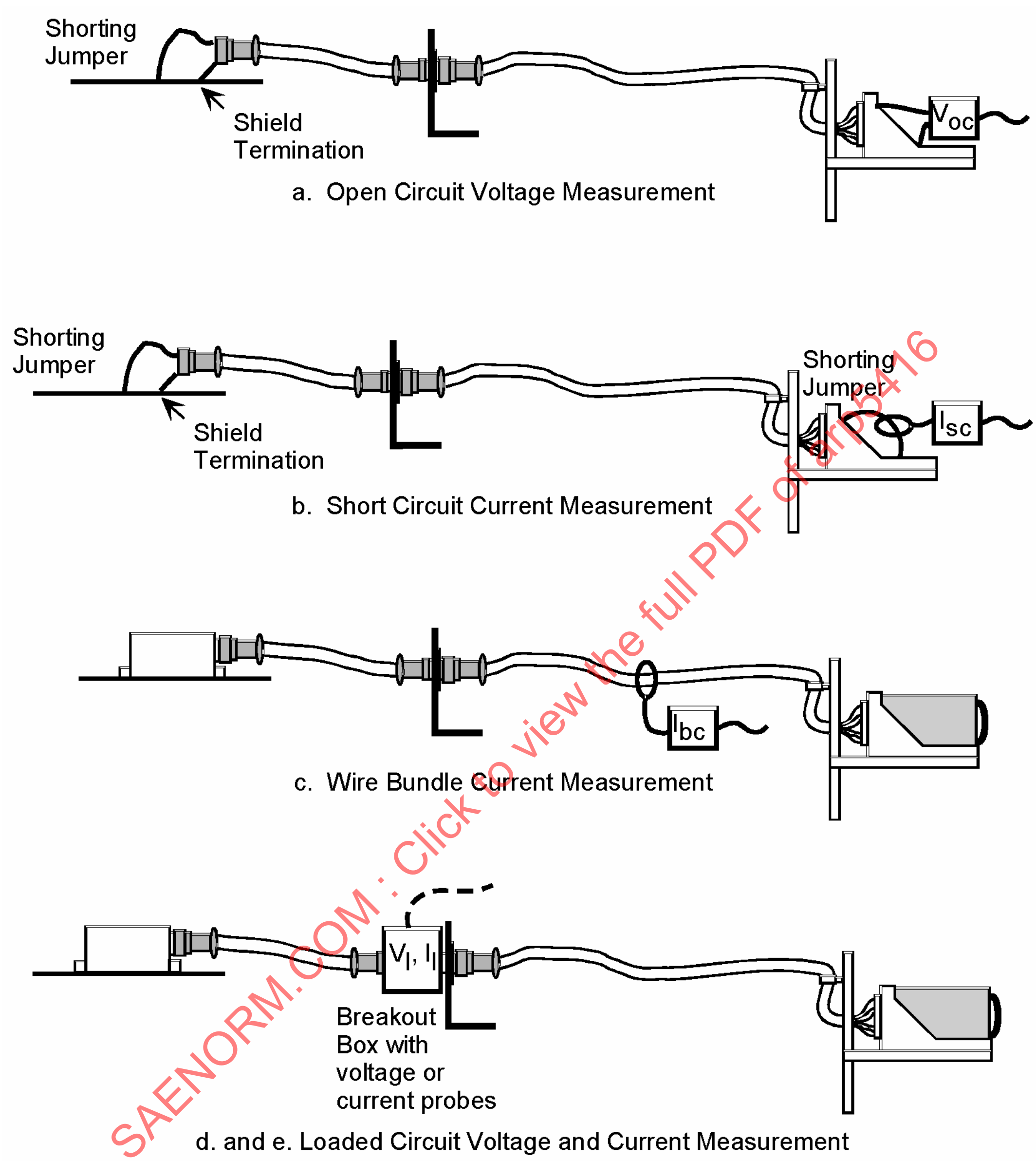


FIGURE 19 - Schematic Representation of Measurement Types

6.1.4 (Continued):

Figure 19 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.

6.1.4 (Continued):

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 one 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 20.

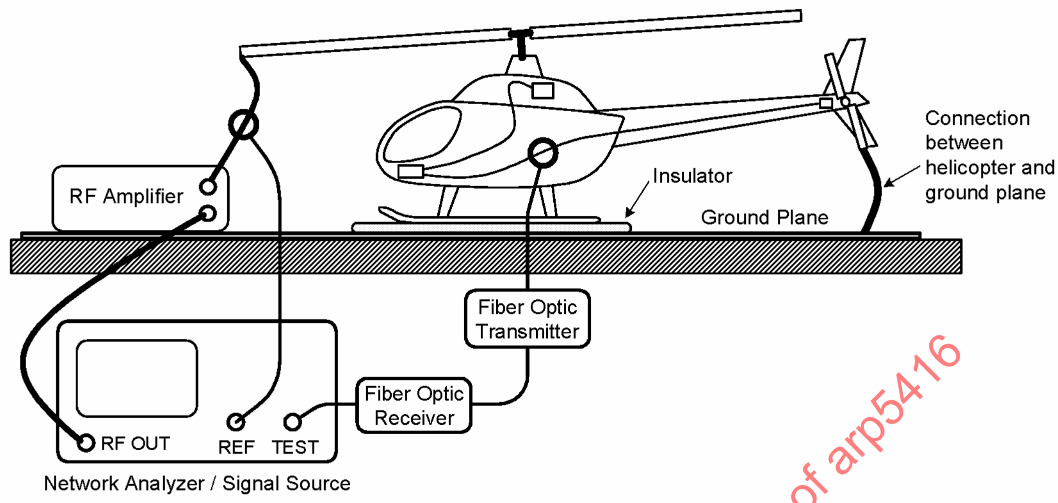


FIGURE 20 - Swept Frequency Test Setup

6.1.5.1 (Continued):

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 non conductive 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.

6.1.5.2 (Continued):

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:

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

where:

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

X(f) = the test point response

I(f) = the injection current

6.1.5.4 (Continued):

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:

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

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 21, along with the related noise amplitude transfer function.

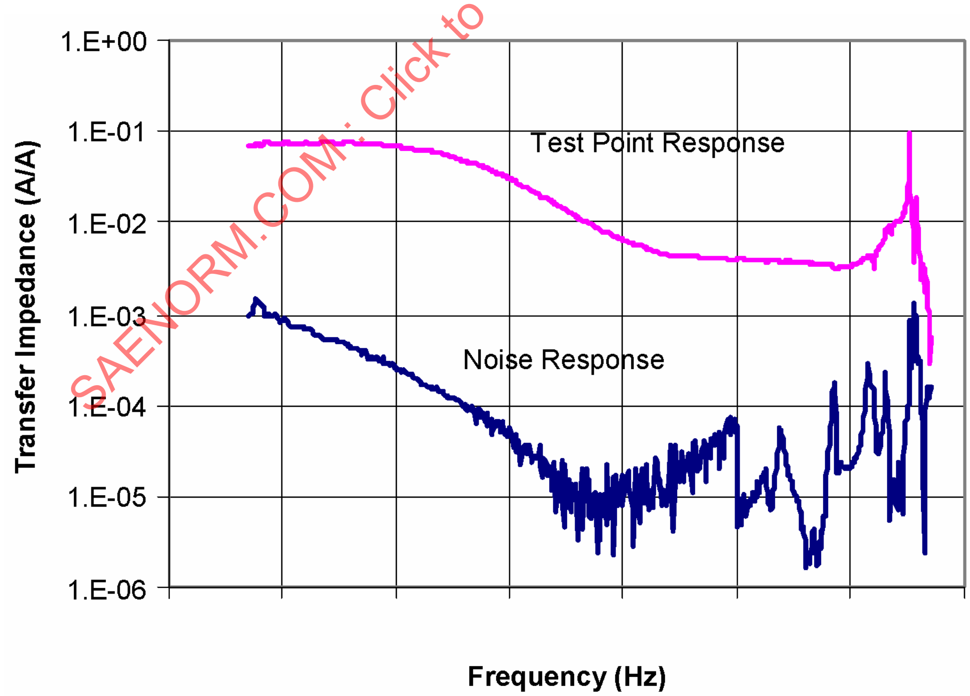


FIGURE 21 - Transfer Function Example

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 22 shows an example of the appropriate peak levels that would be recorded relative to the standardized waveforms.

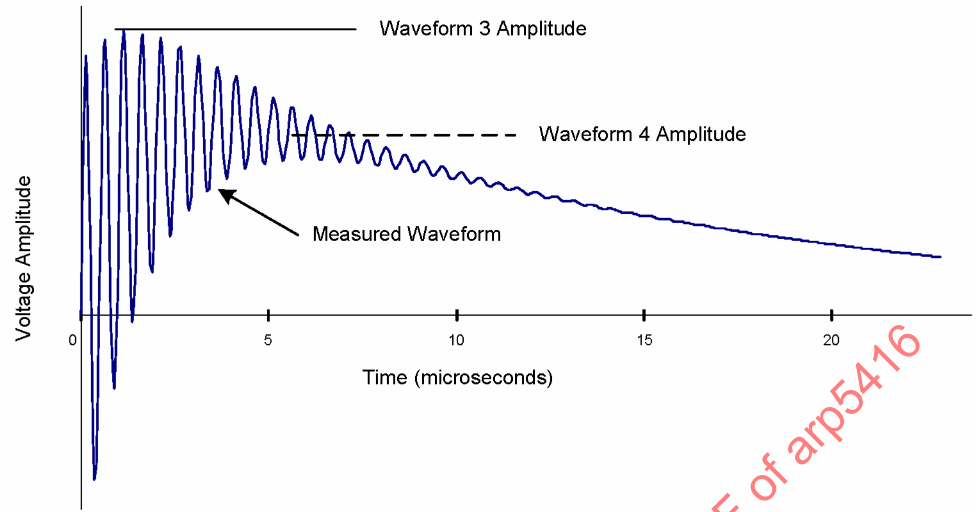


FIGURE 22 - Example for Establishing Transient Levels of Standard Waveforms

6.1.5.7 (Continued):

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 23.

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.

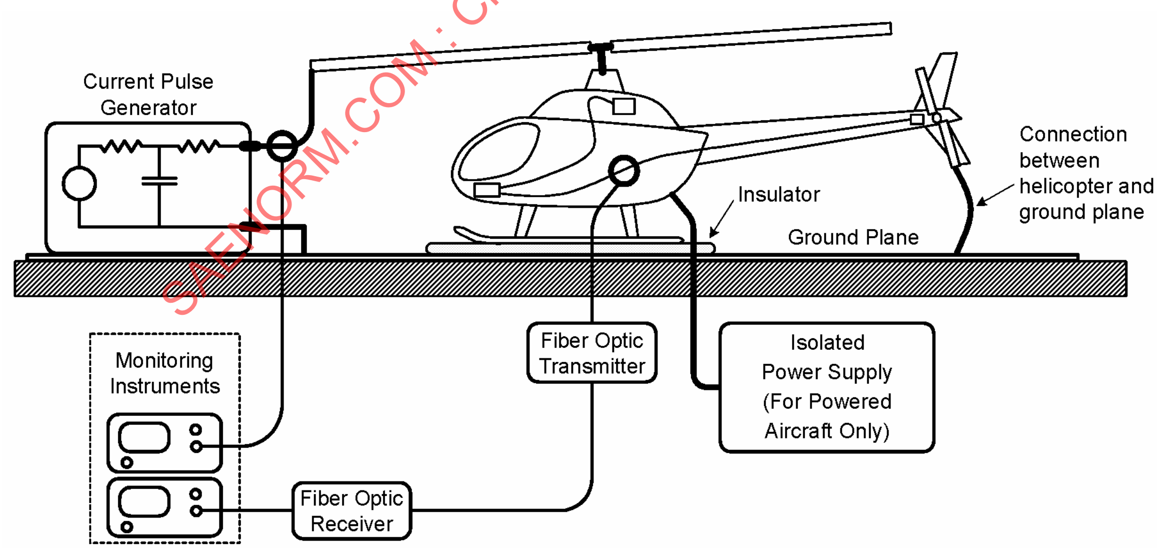


FIGURE 23 - Pulse Test Setup

6.1.6.1 (Continued):

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 one 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 defined components A, D, and H are double exponential waveforms. These idealized waveforms have maximum current rate-of-rise at the initiation of the waveform. 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 during the turn-on switching should be accurately characterized, since this may dominate the 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 effective bandwidth of 100 Hz to 50 MHz and sufficient i*t product capability.

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.

6.1.6.3 (Continued):

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 24, Figure 25 and Figure 26.

Figure 24 illustrates that measured transient waveforms are commonly more complex than the 'standardized' (waveforms 1, 2, 3, etc.) used to represent such induced transients.

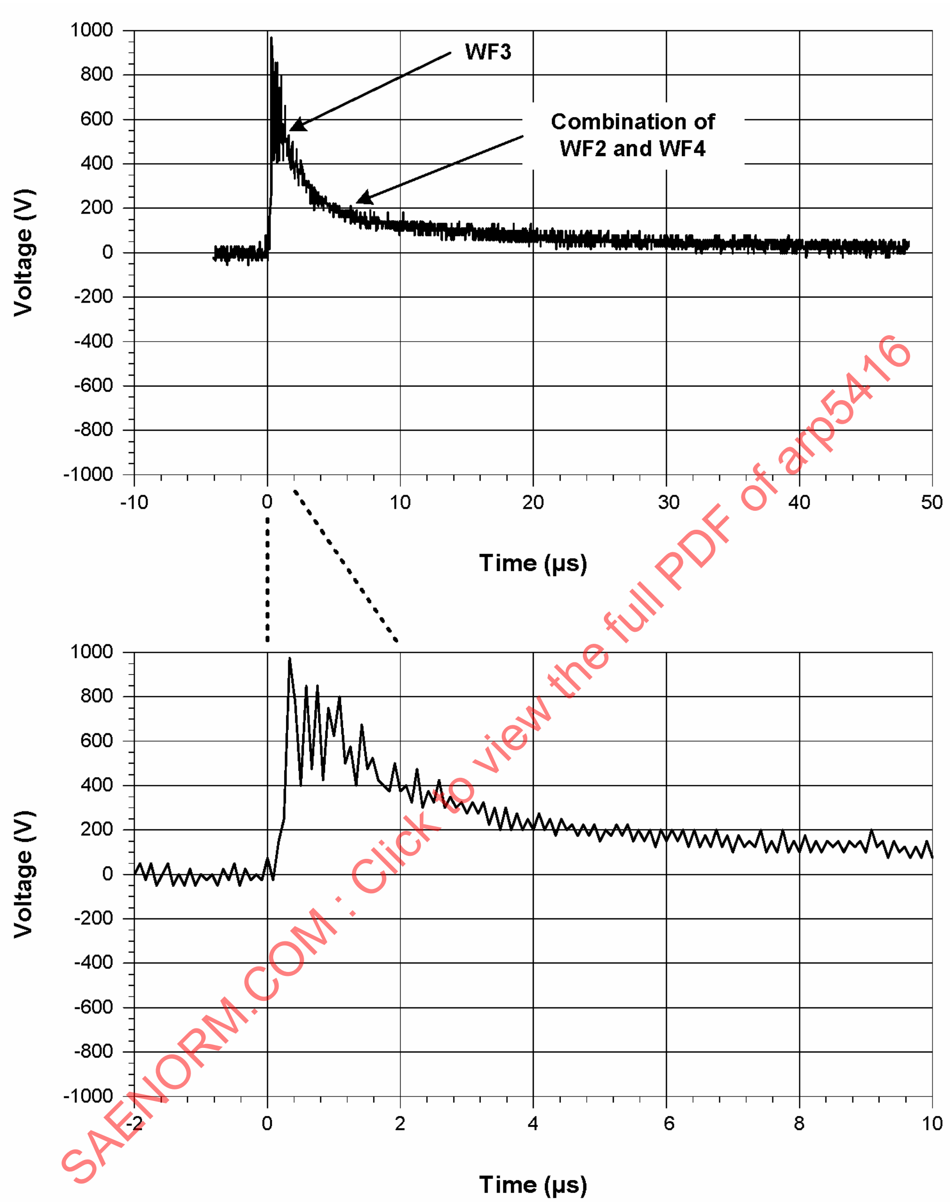


FIGURE 24 - Typical Conductor Open Circuit Voltage Due to Current Component A

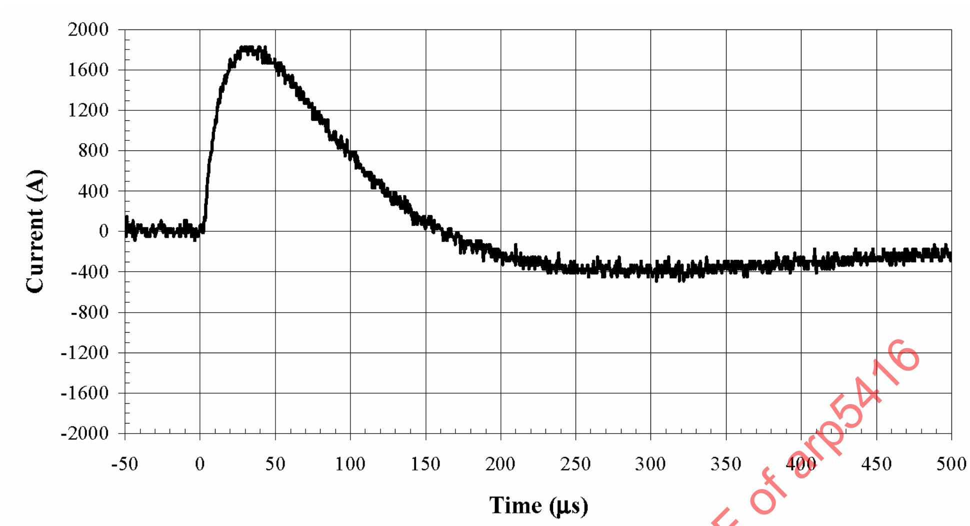


FIGURE 25 - Typical Wire Bundle Short Circuit Current Due to Current Component A

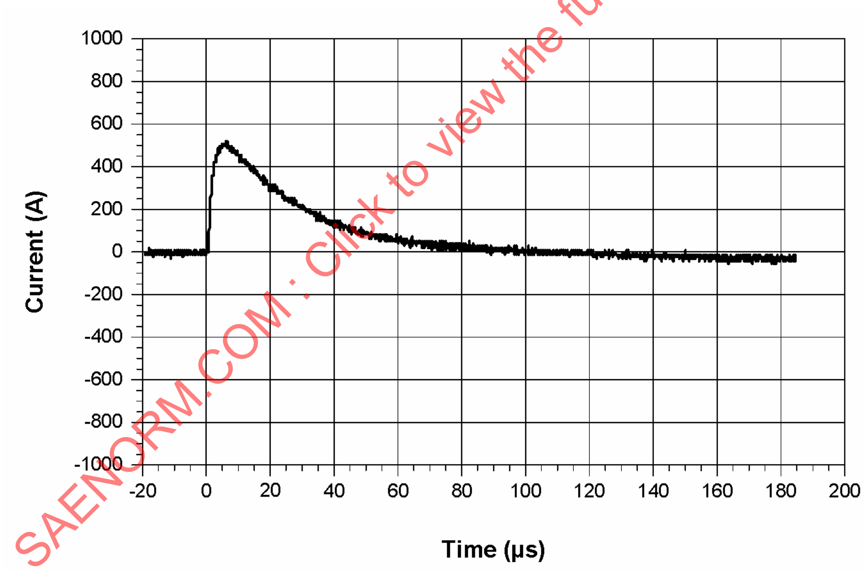


FIGURE 26 - Typical Conductor Short Circuit Current Due to Current Component A

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.

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 compromised 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: When evaluating systems with multiple bundles, particularly systems with multiple channels or integrated functions such as FADEC, IMA, and Fly-By-Wire flight controls, it may be necessary to simultaneously inject on multiple wire bundles to ensure that all aspects of the system are excited in a manner that represents what the system would experience in the actual installation. Simultaneous injection is accomplished by ground injection at the LRU(s) or by simultaneous transformer injection on the individual bundles.

The worst-case situations, represented by the highest amplitudes of induced voltages and currents, should be represented during the simultaneous injection test sequence. 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.

Alternative approaches to simultaneous injection can be used if the resultant test addresses the potential susceptibilities of the systems. For example, a multiple channel system may only test harnesses associated with one channel if the system is configured for single channel operation, assuming that any susceptibility that occurs on the single active channel will affect all channels the same. It should be noted that alternative approaches that simplify the test configuration could result in failure conditions that may not be present in the actual installation.

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. So the system configurations for the tests should include the normal full-up operating configuration and the TLD channel inoperative configuration.

6.2.3 (Continued):

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. Lightning current generators may not be able to simultaneously inject currents on multiple bundles when the sum of the individual bundle current levels exceed DO-160D/ED-14, Section 22 Level 5 wire bundle levels. In such cases, a limited multiple injection test, at the highest level possible for the lightning generator, should be accomplished. The multiple injection test should then be followed by individual single bundle testing to the required levels. Details of this approach should be coordinated with the certifying authority.

6.2.3.1 Test Purpose: The primary objective of system functional upset tests is to verify safe performance during and after exposure to the induced effects of 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 display or control functions.

6.2.3.2 Test Object: Ideally, the test object, i.e. the system under test, should contain all the pieces of equipment and interconnecting wire bundles. A piece of equipment may be omitted if its function can be represented by a simulated input, dummy load or be interfaced with a diagnostic equipment as long as such a substitution does not affect system susceptibility to a lightning related upset. Any substitution of system equipment should be analyzed for its effect on the system under test, documented in the test procedure and approved by the certification authorities prior to conducting the test.

Power should be supplied through line impedance stabilization networks (LISNs). Further guidance on LISNs characteristics are found in D0160, Section 22, paragraph 22.4 b(2) or ED-14, paragraph 22.4 b(2). If the aircraft power sources are protected from lightning-induced transients by transient protective devices, similar protective devices must be installed across the output of the power source(s) for the test because these devices influence the magnitude of transient voltage and current that may appear at system equipment power inputs during the test. 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 unless a worst case mode of operation can be justified.

Details of elements included in the tested system, simulations, power and other inputs, operational modes should be included in the test procedure.

6.2.3.3 Test Setup: The system should be arranged on the test bench so that test currents/voltages can be injected to flow in the same general path as it would happen in the system when installed in the aircraft during a lightning strike. In some cases, it is possible to conduct these tests on systems installed in an aircraft or on an engine.

- System Configuration - Control of wire configuration, wire length, system layout and system grounding should be commensurate with applicable installation control drawings as discussed in this section and the guidance in ARP5413/ED-81.

- External Ground Terminal - When external terminals are available for ground connections to equipment, the terminal should be connected to the test bench ground plane 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 length of the connections defined in the aircraft installation instructions should be used.

- Interconnecting Wiring - All system interconnecting wiring should be in accordance with the applicable wire harness specification, installation and interface control drawings or diagrams. Important features to be represented in the test setup are as follows:

  (1) Wire length

  (2) Wire shielding

  (3) Wire type and size

  (4) Shield terminations

  (5) Harness connectors

6.2.3.3 (Continued):

Where practical, actual wire harnesses and connectors intended for the aircraft installation should be used. If bulkhead connectors and/or intermediate connector breaks are included in the system, these should also be included in the test set up or their effects accounted for. For practical reasons, if used, these connectors may be deliberately not grounded to the test bench in order to achieve the desired current distribution on both sides of the connector. Where it is not practical to include aircraft wire harnesses in the test setup, other wire harnesses or shield arrangements may be used that produce similar induced transient responses when subjected to the test currents and/or voltages specified in the test procedure. For example, 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 instead, and tested at the corresponding shielded conductor transient level. In these cases, similarity of the resulting core wire transients to the levels and waveforms that would be induced by the applicable test current in the aircraft wire harness(es) should be established by wire transfer function tests or analysis (see 6.3 for test method). This analysis should be included in the test procedure and approved by the certification authorities prior to the test.

The test procedure should explicitly state whether the transient is to be applied to the shield of the core wire or to the core wire itself with adjusted transient levels and/or waveforms.



6.2.3.4 Test Waveforms: System functional upset tests are usually performed with designated transient test waveforms and levels for Single Stroke, Multiple Stroke and Multiple Burst waveform set test applications. Specific transient waveforms and levels and waveform set sequences should be described in the test procedure.

When the harnesses are comprised of combinations of shielded and unshielded conductors the test procedure will usually 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.

6.2.3.4 (Continued):

- When all conductors are shielded or when there are protection devices in all of the circuits (i.e. low impedances to ground) 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.

Simultaneous Harness Injections:

Simultaneous injection onto several bundles or branches of wire bundles is typically accomplished by wire bundle induction or ground injection. Wire bundle injection allows for the induction of current and voltages on particular portions of the system bundles. Ground injection applies currents and voltages to the case or cases of equipment under test and allows the current to flow through the bundles based on the impedances of the bundles. Wire bundle injection is normally used to apply Waveforms 2 and 3 to the system wire bundles. Ground injection techniques are typically used with Waveforms 1, 4 and 5.

Figure 27 and Figure 28 show typical transformer and ground injection test setups, respectively.



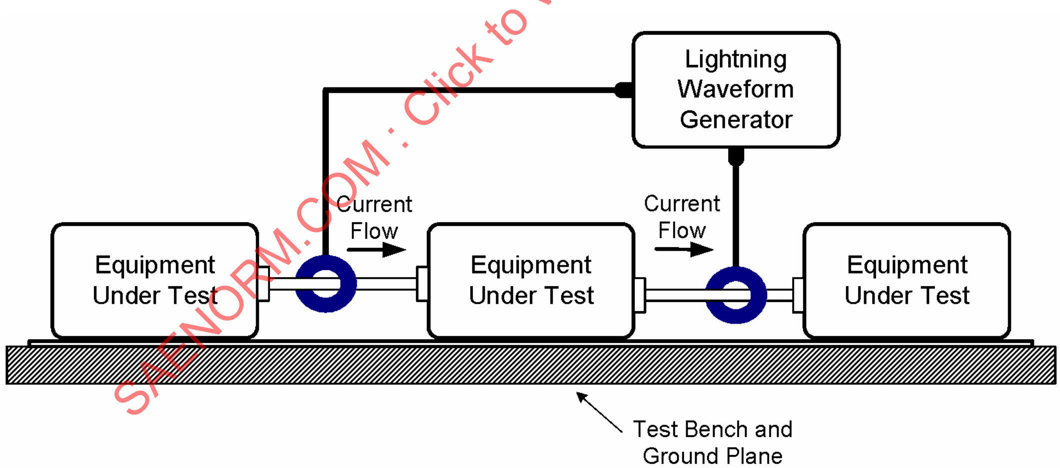


FIGURE 27 - Simultaneous Injection Using Transformer Injection

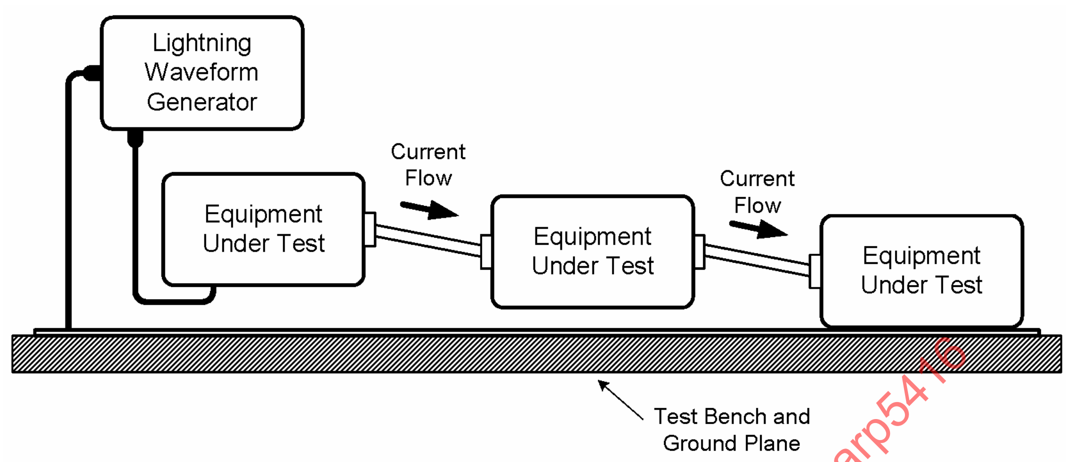


FIGURE 28 - Simultaneous Injection Using Ground Injection

6.2.3.4 (Continued):

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 transformers on each harness branch
- The impedances between equipment and the test bench
- The locations of the injection transformers

The test procedure may specify the test voltages/currents 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.

Individual Harness Injections:

Individual harness tests are applicable to systems with one interconnecting harness or in those cases where simultaneous harness injection is not possible. Specific procedures for performing individual harness injection are addressed in DO-160/ ED-14.

6.2.3.4 (Continued):

Tests should be applied individually to each bundle at its assigned test and limit levels (if applicable). If some bundles are routed to a common location such that common-mode threats are typical, then the current limit of each bundle should be added together. The voltage limit would remain the same.

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 cable bundle(s). Power conductors may also need to be tested in differential mode as well as common-mode since power conductors are often distributed throughout the aircraft and transients will appear line-to-line as well as between both (power and return) conductors and the local ground.

6.2.3.5 Measurement and Data Recording:

- Photographs and description of each test setup.
- Photograph or plots of each test configuration, including waveforms, voltage amplitude and pulse shape/characteristics.
- 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).

6.2.3.6 Test Procedure: 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.

6.2.3.7 Data Interpretation: The test results shall be evaluated with reference to the pass/fail criteria which are derived from the SSA 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.
- 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 29 shows an example of shield transfer impedance, which is the ratio of the internal wire response voltage to the current on the shield.

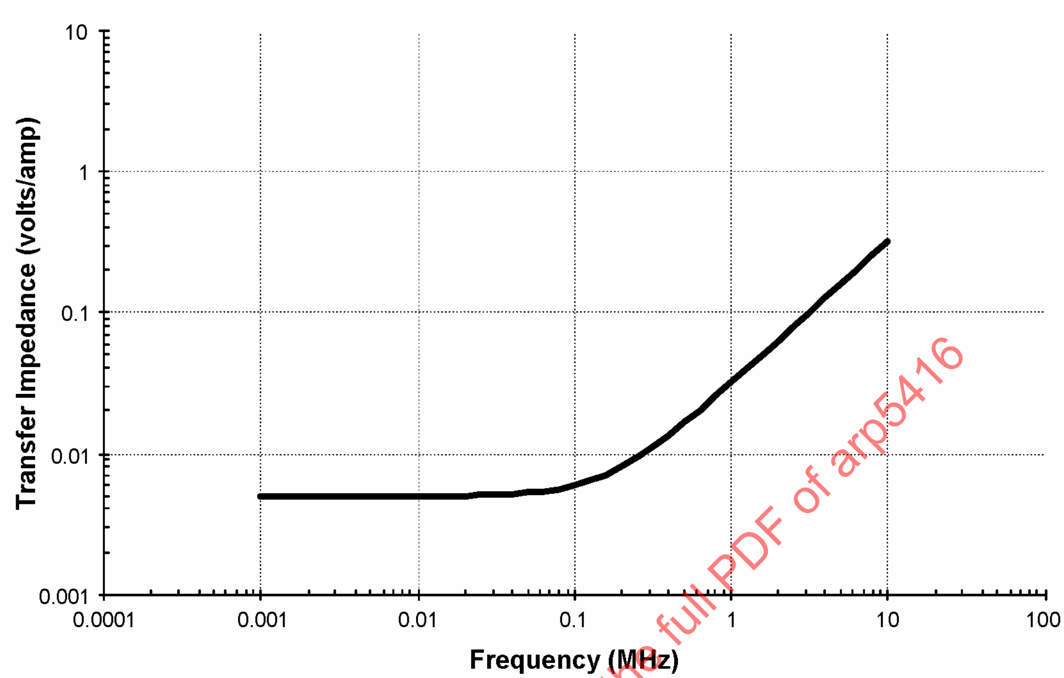


FIGURE 29 - Wire Bundle Shield Transfer Impedance Example



6.3 (Continued):

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 30. 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.

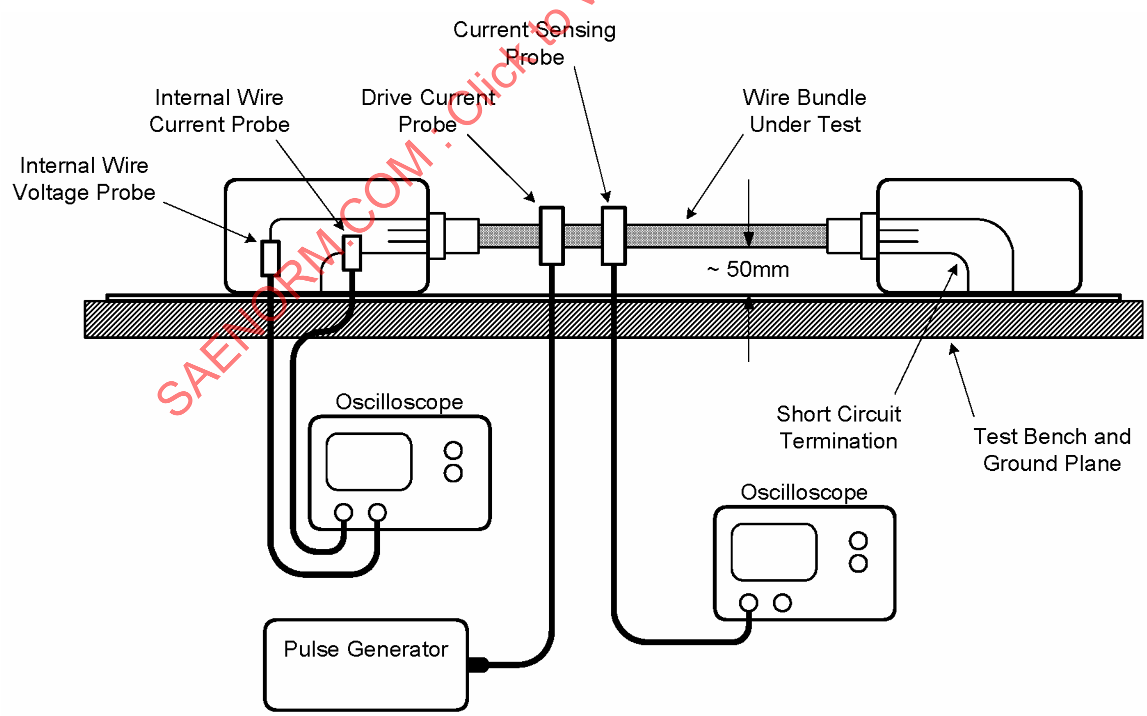


FIGURE 30 - Wire Bundle Shield Transfer Function Pulse Injection Test Setup

6.3.1.3 (Continued):

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 30. 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 30.

(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.

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 31. 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.

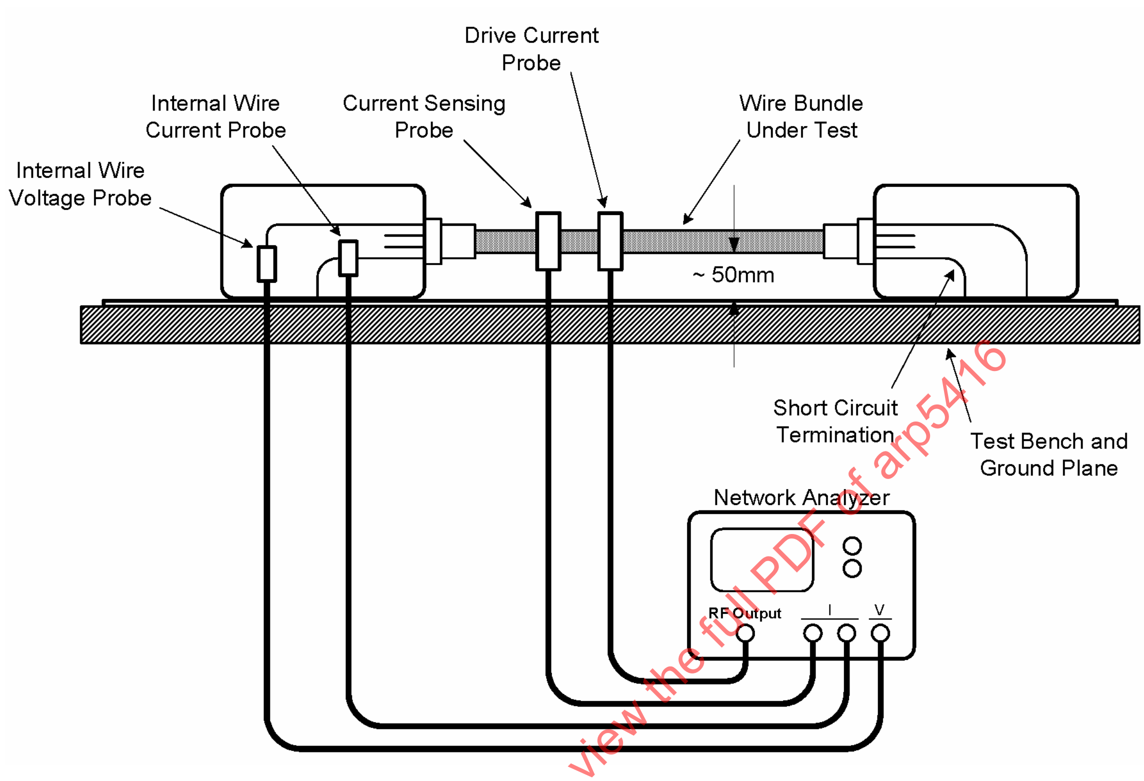


FIGURE 31 - Swept Frequency Wire Bundle Shield Transfer Function Test Setup



6.3.2.3 (Continued):

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 31. 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.

6.3.2.3 (Continued):

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 31.

(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 Figure 32 and Figure 33. The generator should be connected to drive the required current from end to end of the wire shield.

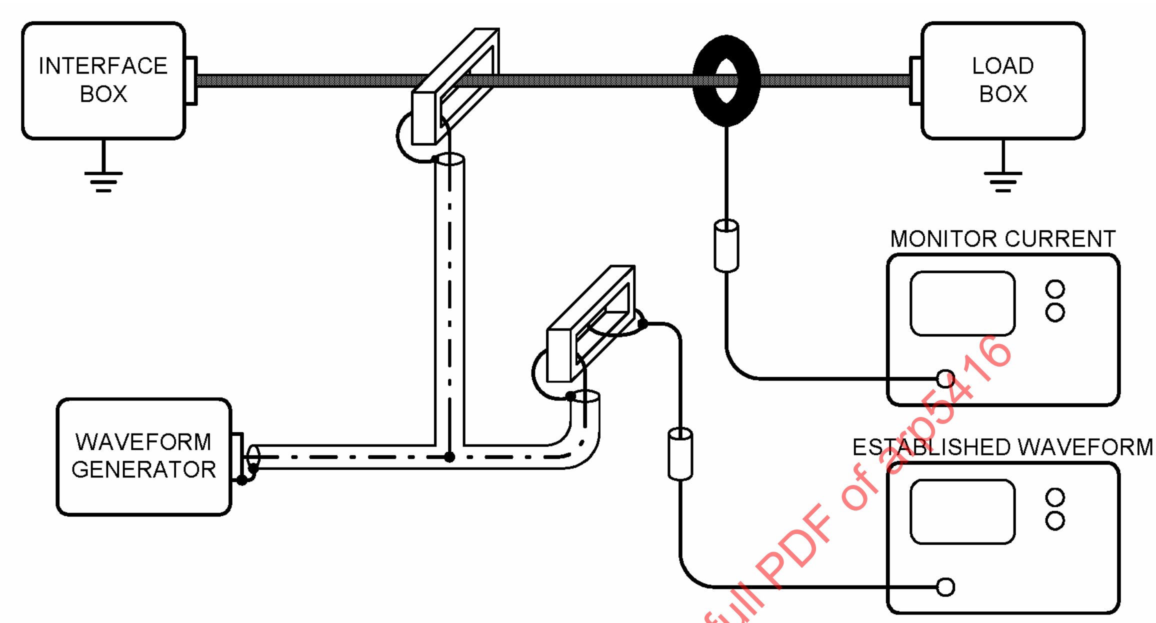


FIGURE 32 - Harness Current Handling Capability Test Setup - Wire Bundle Injection

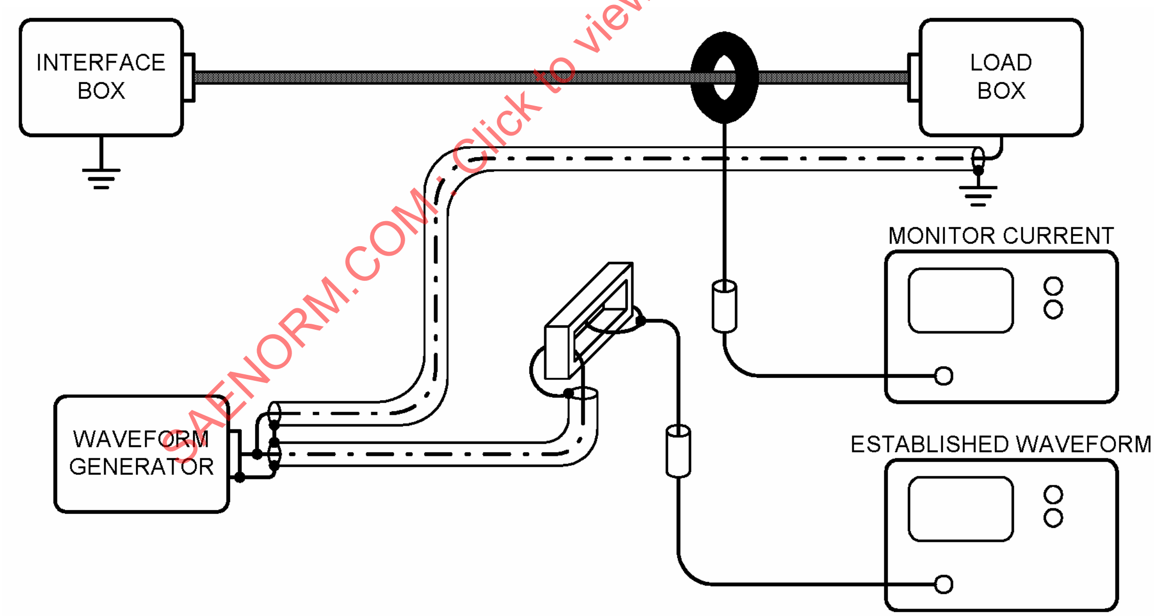


FIGURE 33 - Harness Current Handling Capability Test Setup - Ground Injection

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.

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)

7.2.1 (Continued):

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.

TABLE 2 - Examples of Applications of Fuel System Tests

| Test Objects | High Current Tests: Conduction Test (7.3) | High Current Tests: Direct Strike Test (7.4) | High Current Tests: Attachment Test (Note 1.) | High Voltage Tests: Voltage Breakdown Test (7.5) | High Voltage Tests: 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 | | |



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.