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Superseding ARP5415A

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

RATIONALE

This revision incorporates guidance material that is consistent with Federal Aviation Administration lightning certification regulations 14 CFR 23.1306, 23.2515, 25.1316, 27.1316, and 29.1316. This revision also incorporates changes throughout that are consistent with current guidance and practices in support of the FAA Advisory Circular AC 20-136. The contents were revised and greatly expanded to also be consistent with the Indirect Effects of Lightning related contents of ARP5416.

Due to the extensive re-work and re-organization of this revision, the standard "change bar" indications for the changes are not shown; therefore, an "R" has been placed before the document title.

TABLE OF CONTENTS

1.	SCOPE.....	7
1.1	Purpose	7
2.	REFERENCES.....	7
2.1	SAE Publications.....	7
2.2	Other Publications.....	8
2.2.1	FAA Publications.....	8
2.2.2	U.S. Regulations	8
2.2.3	EASA Publications	9
2.2.4	EUROCAE Publications.....	9
2.2.5	RTCA Publications	10
2.2.6	ANSI/NEMA Publications	10
2.3	Definitions, Abbreviations, and Acronyms	10
2.3.1	Definitions	10
2.3.2	Abbreviations	12
2.3.3	Acronyms	13
3.	BACKGROUND/EXPERIENCE	16
3.1	Aircraft Lightning Interactions	16
3.2	Lightning Indirect Effects.....	17
3.3	Prior Criteria	17
3.4	External and Internal Lightning Environment Criteria	17
3.5	Increased Attention to Indirect Effects Protection.....	18
4.	DESIGN CONSIDERATIONS.....	18
4.1	Structural Attenuation Design	19
4.2	Grounding	20

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4.2.1	Single Point Circuit Grounding	21
4.2.2	Multiple Point Circuit Grounds	23
4.3	Bonding	23
4.4	Wire Shielding and Cable Design	24
4.4.1	Termination Conflicts	27
4.5	Reduction of Coupling Through the Use of Fiber Optic Cables.....	28
4.6	System Installation and Equipment Architectures	29
4.6.1	Electrical/Electronic Equipment Location	30
4.6.2	Wiring Location	30
4.6.3	System Equipment Architectures	32
4.6.4	Circuit Design.....	34
4.6.5	Circuit Protection.....	37
5.	MAJOR ELEMENTS OF COMPLIANCE	40
5.1	Identify Systems to be Assessed	42
5.1.1	Considerations in the Safety Assessment	43
5.1.2	Additional Details Regarding Hazard Assessment	44
5.1.3	Aggravating Factors	45
5.1.4	System Availability and Integrity Considerations in the Safety Assessment	45
5.1.5	Lightning Safety Assessment Considerations for Combined Effects on Systems	45
5.2	Determine the Lightning Strike Zones for the Aircraft.....	47
5.2.1	Relationship of Lightning Strike Zones to Direct Effects.....	47
5.2.2	Relationship of Lightning Strike Zones to Indirect Effects	48
5.3	Establish the Aircraft Lightning Environment for Each Lightning Strike Zone	48
5.4	Determine the Lightning Transient Environment Associated with the Systems	48
5.4.1	Relationship between External and Internal Environment	49
5.4.2	Induced Transient Mechanisms	50
5.4.3	Determining Induced Transients	52
5.5	Establish Equipment Transient Design Levels (ETDLs) and Aircraft Actual Transient Levels (ATLs)	54
5.5.1	Definitions	55
5.5.2	TCL and ETDL Selection	56
5.5.3	Waveform Set Selection.....	61
5.5.4	Other TCL and ETDL Selection Considerations	63
5.5.5	TCL and ETDL Parametric Discussion	66
5.5.6	Multiple Pulse Waveform Sets	66
5.5.7	ATL Determination	67
5.6	Verify Compliance to the Requirements	67
5.6.1	Equipment and System Tests	68
5.7	Corrective Measures, If Needed	73
6.	AIRCRAFT LEVEL VERIFICATION.....	73
6.1	Aircraft Level Verification Methods	73
6.2	Uncertainty Considerations for Verification Methods	74
6.3	Nonlinearities	75
6.4	Complimentary Aspects of Testing and Analysis.....	76
6.5	Aircraft Level Verification by Test	76
6.5.1	Selection of the Test Object.....	77
6.5.2	General Test Approach	77
6.5.3	Test Considerations	77
6.5.4	Measurements:	78
6.5.5	Instrument Noise Measurements	81
6.5.6	Injection Set up and Return Conductor Configuration	81
6.5.7	Aircraft Pulse Current Injection Tests	82
6.5.8	Aircraft Swept Frequency Tests	83
6.6	Aircraft Level Verification by Analysis	84
6.6.1	Develop Analysis Approach and Produce an Analysis Plan.....	85
6.6.2	Compute ATLs and Other Results	93
6.7	Aircraft Level Verification by Similarity	94
6.7.1	Examples of Similarity Cases	95

6.8	Attainment of Aircraft ATLS Using Reduction.....	100
6.8.1	Waveform Reduction using Visual Inspection	103
6.8.2	Waveform Reduction using Waveform Norms.....	107
6.8.3	Waveform Reduction Examples.....	110
6.8.4	Summary Table of Example ATLS	132
7.	COMPLIANCE FOR LEVEL A SYSTEMS.....	132
7.1	Description of Level A Systems	132
7.2	System Test Level Selection.....	132
7.2.1	Test Level Development using Aircraft Lightning Transient Assessment.....	133
7.2.2	Test Level Development Using Existing Aircraft Test Data from a Similar Aircraft	135
7.2.3	Test Level Development Using Existing System Test Data from a Similar Aircraft.....	152
7.2.4	Test Level Development Using Standard Transient Levels for Level A Display Systems.....	152
7.2.5	Margins.....	154
7.3	Tests for Equipment/Systems	155
7.3.1	Equipment Standalone Tests.....	155
7.3.2	Level B/C Equipment Associated with Level A Systems	155
7.4	Integrated System Functional Upset Tests	155
7.4.1	Test Purpose.....	156
7.4.2	System Boundary Conditions.....	156
7.4.3	Interconnecting Wiring	170
7.4.4	General Setup Requirements	180
7.4.5	System Operation	181
7.4.6	Software Used During Lightning Tests	182
7.4.7	Individual Cable Bundle Tests	182
7.4.8	Multiple Simultaneous Cable Bundle Tests	185
7.4.9	Pass Criteria.....	187
7.4.10	Degraded Test Setup Considerations.....	188
7.4.11	Cable Bundle Shield Transfer Function Test.....	189
7.5	Level A Systems Certification by Similarity.....	201
7.5.1	System and Equipment Design Differences	202
7.5.2	Test Configuration Differences	205
7.5.3	Practical Use of Certification by Similarity	206
7.5.4	Test Level Development Using Existing System Test Data from a Similar Aircraft.....	206
7.6	System Tests on Aircraft.....	208
7.7	Certification Report	208
8.	COMPLIANCE FOR LEVEL B OR LEVEL C SYSTEMS	208
8.1	System Assessment and Definition	208
8.2	Certification by Similarity.....	209
8.3	Equipment Test.....	209
8.3.1	Pin Injection and Cable Bundle (Cable Induction/Ground Injection) Test.....	209
8.4	Immunity Assessment.....	210
8.5	Corrective Measures.....	210
8.6	IEL Protection Compliance	210
8.7	Considerations for Level B/C Equipment Integrated into Higher Level Systems.....	211
9.	MAINTENANCE, MODIFICATIONS, AND PROTECTION ASSURANCE	212
9.1	Purpose and Scope.....	212
9.1.1	Maintenance Definitions.....	212
9.1.2	Maintenance Procedures and Lightning Protection	213
9.1.3	Relationship Between Design and Maintenance	215
9.2	Development of Scheduled Maintenance Procedures.....	216
9.2.1	Aircraft Structure Protection.....	221
9.2.2	Electrical Wiring External Protection.....	224
9.2.3	Equipment Internal Protection.....	227
9.3	Development of Unscheduled Maintenance Procedures.....	227
9.3.1	Aircraft Structure Protection.....	228
9.3.2	Electrical Wiring External Protection.....	229

9.3.3	Internal Equipment Protection.....	229
9.3.4	Maintenance on Condition	230
9.4	Aircraft Modification and Lightning Protection	231
9.4.1	Aircraft Structure Modifications	231
9.4.2	Electrical Wiring Assembly or Installation Modifications	232
9.4.3	Equipment Modification.....	232
9.4.4	Impact of Modifications on the Maintenance and Protection Assurance Programs	232
9.5	Protection Assurance Program	232
9.5.1	Protection Assurance Program Goals.....	233
9.5.2	Scope of Surveillance	234
9.5.3	Selection of Aircraft.....	236
9.5.4	Frequency and Duration of Surveillance Program	237
9.6	In-Service Maintenance Test Techniques.....	237
10.	NOTES	238
10.1	Revision Indicator.....	238
Figure 1	Loop area multiple point and single point circuit grounding.....	22
Figure 2	Single point and multiple point circuit grounds	24
Figure 3	Shield terminations.....	27
Figure 4	Daisy chain termination.....	28
Figure 5	Cable bundle placement	31
Figure 6	Discrete circuit.....	36
Figure 7	Equivalent circuit.....	37
Figure 8	Relationships among transient levels	55
Figure 9	TCL and ETDL selection process	57
Figure 10	Waveform set selection flow	59
Figure 11	Simple system exposed to lightning induced effects	62
Figure 12	Aircraft current measurements on cable bundle at most exposed and other segments to equipment	64
Figure 13	Current-length product simplified approach when using the same wire types	65
Figure 14	Equipment pins with remote isolated circuit.....	69
Figure 15	Equipment pins with remote circuits referenced to case/aircraft structure	69
Figure 16	Equipment pins with remote transient voltage suppressors	70
Figure 17	Arcing	76
Figure 18	Schematic representation of measurement types	79
Figure 19	Current pulse test setup	82
Figure 20	Swept frequency test setup.....	83
Figure 21	Graphical user interface front end.....	87
Figure 22	Common terminology employed in the numerical simulation process.....	91
Figure 23	Three primary steps in the waveform reduction process	102
Figure 24	Satisfying visual inspection criteria	106
Figure 25	Waveform reduction using visual inspection.....	107
Figure 26	Standard test waveform norms	109
Figure 27	Five example waveforms selected to exhibit waveform reduction techniques	111
Figure 28	Waveform reduction example 1 response Waveform example 5	112
Figure 29	Response waveform reduction example 1 using visual inspection	115
Figure 30	Waveform reduction example 2	116
Figure 31	Response waveform reduction example 2 using visual inspection	119
Figure 32	Waveform reduction example 3	120
Figure 33	Response waveform reduction example 3 using visual inspection	123
Figure 34	Waveform reduction example 4	124
Figure 35	Response waveform reduction example 4 using visual inspection	127
Figure 36	Waveform reduction example 5	128
Figure 37	Response waveform reduction example 5 using visual inspection	131
Figure 38	Example avionics installation	134
Figure 39	System under test – example	157
Figure 40	Case 1: co-routing.....	160
Figure 41	Case 2: simulation of non-level a equipment.....	160
Figure 42	Case 3: simulation of level a equipment tested separately.....	162



Figure 43	Case 4: omission of redundant non-level a equipment.....	163
Figure 44	Case 5: omission of redundant level a equipment.....	165
Figure 45	Case 6: omission of redundant non critical interface wiring.....	166
Figure 46	Case 7: omission of non-level a equipment, associated interface types are not redundant	168
Figure 47	Test wiring harness design key considerations – aircraft length wiring	172
Figure 48	Test wiring harness design key considerations – shortening wiring	173
Figure 49	Test wiring harness design key considerations – disconnecting shields	174
Figure 50	Example of scaling injected currents in shielded cable bundles shorter than aircraft cable bundles	176
Figure 51	A single shielded cable bundle segment represents several aircraft cable bundle segments	178
Figure 52	Testing unshielded cable bundles shorter than aircraft installation	180
Figure 53	Example of a three test situation.....	184
Figure 54	Multiple simultaneous cable bundle induction – example	186
Figure 55	Ground injection on eut with multiple cable bundles – example	187
Figure 56	Shield transfer impedance measurement	191
Figure 57	Shielded bundle coupling impedance measurement	192
Figure 58	Cable bundle shield transfer function test setup pulse injection	195
Figure 59	Cable bundle shield transfer function test setup swept frequency	196
Figure 60	Pulse injection method data interpretation example	200
Figure 61	Routes to compliance – Level B and C systems	211
Figure 62	Development of a typical maintenance program	214
Figure 63	Contributors to the maintenance program	214
Table 1	Shielding effectiveness of aircraft skin materials	19
Table 2	Lightning failure conditions and certification levels	40
Table 3	Common test entry/exit points	78
Table 4	Examples of similarity cases	96
Table 5	Guidance on the use of similarity for changes of material	99
Table 6	Guidance on the use of similarity for changes to structural interfaces or structural bonding	99
Table 7	Guidance on the use of similarity for changes to apertures or slots in size/shape/number	99
Table 8	Guidance on the use of similarity for changes to electrical installations.....	100
Table 9	Standard test waveform norms	108
Table 10	Time domain response waveform with only pulse-like components norms.....	108
Table 11	Waveform reduction example 1 norms	114
Table 12	Waveform reduction example 2 adjusted norm values	118
Table 13	Waveform reduction example 2 adjusted norm values	118
Table 14	Waveform reduction example 3 norms	122
Table 15		126
Table 16	Waveform reduction example 5 norms	130
Table 17	Example table of ATLs	132
Table 18	Attenuation due to adjacent low impedance conductors for various cable bundle lengths (example only not generic data).....	137
Table 19	Single shielded wire Waveform 1 (i_{sc}), component A.....	138
Table 20	Single shielded wire Waveform 2 (v_{oc}), component A.....	138
Table 21	Single shielded wire Waveform 3 (i_{sc}), component A.....	138
Table 22	Single shielded wire Waveform 3 (v_{oc}), component A.....	139
Table 23	Single unshielded wire Waveform 1 (i_{sc}), component A.....	139
Table 24	Single unshielded wire Waveform 3 (i_{sc}), component A.....	139
Table 25	Single unshielded wire Waveform 2 (v_{oc}), component A	140
Table 26	Single unshielded wire Waveform 3 (v_{oc}), component A	140
Table 27	Shield measurements for one shield Waveform 1 (i_{sc}), component A	140
Table 28	Shield measurements for one shield Waveform 3 (i_{sc}), component A	141
Table 29	Shield measurements for one shield Waveform 1 (i_{sc}), component H	141
Table 30	Single unshielded wire Waveform 3 (v_{oc}), component H	141
Table 31	Summary of cable bundle ETDLS	149
Table 32	Summary of pin injection ETDLS.....	150
Table 33	Examples of system setup installation similarity applications	151
Table 34	Summary for level a display functions example	154

Table 35 Examples of system and equipment design similarity applications 204

Table 36 Aircraft structure and sub-structural shielding inspections 223

Table 37 Wiring installation protection inspections 225

1. SCOPE

This ARP provides detailed information, guidance, and methods in support of the Federal Aviation Administration (FAA) Advisory Circular (AC) 20-136. AC 20-136 provides a means, but not the only means, for demonstrating compliance with Title 14 of the Code of Federal Regulations (14 CFR) 23.1306 (Amendment 23-61), 23.2515 (Amendment 23-64), 25.1316, 27.1316, and 29.1316. It is also intended for this ARP to provide the same information, guidance, and methods, to the European Aviation Safety Agency (EASA) certification specifications CS 23.1306 (Amendment 23/4), 23.2515 (Amendment 23/5), 25.1316, 27.1316, and 29.1316, and associated Acceptable Means of Compliance (AMC) 20-136. This ARP provides references relevant to identifying: (1) acceptance criteria for the indirect effects of lightning compliance approaches, (2) verification (analysis and test) methods including those associated with multiple stroke and multiple burst, (3) recommended design options to optimize needed system immunity to lightning indirect effects, and (4) provide guidance in the areas of continued airworthiness of the lightning protection. Equipment hazards due to the indirect effects on equipment mounted on the aircraft exterior, equipment located within the aircraft interior as well as all associated interconnecting wiring are addressed. This ARP provides additional guidelines in the application of indirect effects of lightning tests identified in DO-160/ED-14 Section 22. The FAA and EASA regulations apply to all adverse effects of lightning for electrical and electronic systems. Refer to ARP5577 for guidance related to lightning direct effects on electrical and electronic systems.

1.1 Purpose

This ARP expands on the topics discussed in AC 20-136/AMC 20-136. Guidelines are provided which explain the approaches to compliance with the FAA regulations and the EASA certification specifications. Discussions are applicable to all categories of airplanes and rotorcraft. This ARP is not intended to provide mandatory approaches to compliance. In many cases, the path to compliance may use one or more of several methods. Applicants may elect to demonstrate compliance through alternative methods that are acceptable to their certifying airworthiness authority.

2. REFERENCES

The following publications form a part of this standard to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ARP4754	Guidelines for Development of Civil Aircraft and Systems
ARP4761	Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment
ARP5412	Aircraft Lightning Environment and Related Test Waveforms
ARP5414	Aircraft Lightning Zoning
ARP5416	Aircraft Lightning Test Methods
ARP5577	Aircraft Lightning Direct Effects Certification

2.2 Other Publications

2.2.1 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

AC 20-53	"Protection of Aircraft Fuel Systems Against Fuel Vapor Ignition Due to Lightning," Rev B issued September, 2011
AC 20-136	"Aircraft Electrical and Electronic System Lightning Protection," Rev B issued September, 2011
AC 23.1309-1	"System Design and Analysis," Rev E issued November, 2011. AC 23.1309-1 describes acceptable design practices for showing compliance with the requirements of amendment 41 to 14 CFR 23.1309
AC 25.1309-1	"System Design and Analysis," Rev A issued June, 1988. AC 25.1309-1 describes various acceptable means for showing compliance with the requirements of 14 CFR 25.1309, Equipment, Systems, and Installations.
AC 27-1	"Certification of Normal Category Rotorcraft," Rev B issued September, 2008. AC 27-1 covers policy on methods of compliance with Part 27 of 14 CFR, which contains airworthiness standards for normal category rotorcraft.
AC 29-2	"Certification of Transport Category Rotorcraft," Rev C issued September, 2008. AC 29-2 provides information on methods of compliance with Part 29 of 14 CFR, including methods of compliance in the areas of basic design, ground tests and flight tests.
AC 21-16G	"RTCA Document DO-160 versions D, E, F and G, Environmental Conditions and Test Procedures for Airborne Equipment," Rev G issued June, 2011
AC 33.28-1	"Compliance Criteria for 14 CFR §33.28, Aircraft Engines, Electrical and Electronic Engine Control Systems," issued June, 2001
AC 33.4-3	"Instructions for Continued Airworthiness: Aircraft Engine High Intensity Radiated Fields (HIRF) and Lightning Protection Features" (02/27/17, Change: 1)
AC 121-22C	"Maintenance Review Boards, Maintenance Type Boards, and OEM/TCH Recommended Maintenance Procedures" (8/27/12)
FAA Order 8900.1	"Flight Standards Information Management System (FSIMS)"

2.2.2 U.S. Regulations

The following documents can be obtained from the U.S. Government Publishing Office, 732 North Capitol Street, NW, Washington, DC 20401-0001, www.eCFR.gov.

US Code of Federal Regulations 14 CFR Parts 23.1306 [Amendment 23-61], 23.2515 [Amendment 23-64], 25.1316, 27.1316, 29.1316.

2.2.3 EASA Publications

Available from European Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany (for visitors and for mail over 1 kg) and Postfach 10 12 53, D-50452 Cologne, Germany (for mail 1 kg or less), Tel: +49 221 8999 000, www.easa.europa.eu.

CS 23.867, 23.954, 23.1306, 23.1309, 23.1529 (up to amendment 4). CS 23.2335, 23.2430, 23.2500, 23.2510, 23.2515, 23.2625 (as from amendment 5). CS 25.581, 25.899, 25.901, 25.954, 25.981, 25.1309, 25.1316, 25.1529, 25.1705. CS 27.610, 27.865, 27.954, 27.1309, 27.1316, 27.1529. CS 29.610, 29.865, 29.954, 29.1309, 29.1316, 29.1529. CS E.25, E.50, E.80, E.170, E.515. CS APU.30, APU.90. CS P.230, and CS P.230.

AMC as per Book 2 in CS 23, CS 25, CS 27, and CS 29.

AMC/GM to CS-23 – Issue 1

AMC 20-1	Certification of Aircraft Propulsion Systems Equipped with Electronic Control Systems
AMC 20-3	Certification of Engines Equipped with Electronic Engine Control Systems
AMC 20-29	Composite Aircraft Structure
AMC 20-136 (AMC-20/Amendment 13)	Aircraft Electrical and Electronic System Lightning Protection

2.2.4 EUROCAE Publications

Available from: EUROCAE Secretariat, 102 rue Etienne Dolet, 92240 Malakoff, France; Phone: +33 1 40 90 79 30, www.eurocae.net.

ED-12	"Software considerations in airborne systems and equipment certification" (Including Amendment N°1 – 19 October 1999), Rev C issued January, 2012
ED-14	"Environmental Conditions and Test Procedures for Airborne Equipment," Rev G issued March, 2011
ED-79	"Certification Considerations for Highly Integrated or Complex Aircraft Systems," Rev A issued December, 2010
ED-84	"Aircraft Lightning Environment and Related Test Waveforms Standard," issued August, 1997, including Amendment No. 1, issued October 19, 1999, including Amendment No. 2, issued May, 2001, including Amendment No. 3, issued June, 2006
ED-91	"Aircraft Lightning Zoning Standard," Rev A issued January, 2019
ED-105	"Aircraft lightning test methods," issued July, 2013
ED-113	"Aircraft Lightning Direct Effects Certification," issued September, 2002
ED-234	"User Guide Supplement to ED-14G," issued January, 2015. This document provides users of ED-14G additional background information for the associated test procedures and requirements in ED-14G.

2.2.5 RTCA Publications

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

DO-160	Environmental Conditions and Test Procedures for Airborne Equipment, Section 22 "Lightning Induced Transient Susceptibility," Rev G issued December 8, 2010. Section 22 provides basic test setups, levels, waveforms, and procedures for the evaluation of equipment to the indirect effects lightning.
DO-160	Environmental Conditions and Test Procedures for Airborne Equipment, Section 23 "Lightning Direct Effects," Rev G issued December 8, 2010. Section 23 provides environmental levels and procedures for testing of externally mounted equipment to the direct effects of a lightning strike.
DO-357	User Guide Supplement to DO-160G, issued December 16, 2014. This document provides users of DO-160G additional background information for the associated test procedures and requirements in DO-160G.
DO-178C	Software Considerations in Airborne Systems and Equipment Certification, dated December 13, 2011. This document is a standard for the design, development, and certification of software for airborne systems.

2.2.6 ANSI/NEMA Publications

Available from National Electrical Manufacturers Association, 1300 North 17th Street, Suite 900, Arlington, VA 22209, Tel: 703-841-3200, www.nmea.org.

WC 27500-2012	"American National Standard, Standard for Aerospace and Industrial Electrical Cable," issued 2012
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2.3 Definitions, Abbreviations, and Acronyms

2.3.1 Definitions

The following are definitions of terms as they are utilized in this ARP. Additional definitions related to Maintenance are listed in 9.1.1.

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

AIRCRAFT TEST: A full vehicle test for determination of the voltages and currents at the equipment interfaces and on the wiring due to the external environment, i.e., a test for determination of ATLs resulting from a lightning strike to a particular aircraft. Two basic approaches for performing aircraft tests are available; the "pulse injection" method involves injection of current pulses and the "swept frequency" method involves injecting low level (~1 A) sinusoid currents through the aircraft.

APERTURE: An electromagnetically transparent opening.

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

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

CONTINUED SAFE FLIGHT AND LANDING: The aircraft can safely abort or continue a takeoff, or continue controlled flight and landing, possibly using emergency procedures. The aircraft must do this without requiring exceptional pilot skill or strength. Some aircraft damage may occur because of the failure condition or on landing. For transport airplanes, the pilot must be able to land safely at a suitable airport. For Part 23 airplanes, it is not necessary to land at an airport. For rotorcraft, the rotorcraft must continue to cope with adverse operating conditions, and the pilot must be able to land safely at a suitable site.

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

DISPLAY FUNCTION: A function for which the pilot will be in the loop through pilot/system information exchange.

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

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

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

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

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

INTERNAL ENVIRONMENT: The electric and magnetic fields, currents, and voltages on and within the aircraft produced by a lightning strike to the aircraft.

LEVEL A DISPLAYS: a subset of Level A systems, which involve functions for which the pilot will be in the loop through pilot/system information exchange.

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

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

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

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

LOW-IMPEDANCE CABLE BUNDLE: A cable bundle expected to draw lightning currents during a lightning transient event such that the lightning current waveform is the dominant waveform that develops on the cable bundle under test. This may include shielded cable bundles terminated at both ends of the harness or unshielded cable bundles that have low impedance interfaces on both ends of the loop, such as transient suppression devices.

MARGIN: The difference between the Equipment Transient Design Level (ETDL) and the Actual Transient Level (ATL).

MULTIPLE BURST: A randomly spaced series of bursts of short duration, low amplitude current pulses, with each pulse characterized by rapidly changing currents (i.e., high di/dt). These bursts may result from lightning leader progression or branching, and are associated with the cloud-to-cloud and intra-cloud flashes. The multiple bursts appear to be most intense at the time of initial leader attachment to the aircraft. Refer to ARP5412/ED-84.

MULTIPLE STROKE: Two or more lightning return strokes occurring during a single lightning flash. Refer to ARP5412/ED-84.

OVER-SHIELDED BUNDLE: Cable bundle with shielded wires, unshielded wires, or both that is protected with a shield installed over the bundle and electrically bonded to ground at both ends; over-shielding is typically achieved by over-braiding, shielded conduits, or open sleeves.

RETURN STROKE: See Lightning Stroke.

SHIELDED BUNDLE: Cable bundle that contains one or more wires individually shielded with the shield electrically bonded to ground at both ends, potentially mixed with unshielded wires.

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

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

SYSTEM AVAILABILITY: Availability of a system's function during and after exposure to the effects of lightning. The system shall not suffer permanent nor temporary loss of function.

SYSTEM FUNCTIONAL UPSET: A malfunction of system operation due to exposure to the effects of lightning, either permanent or temporary (e.g., a change of digital or analog state) which may or may not require manual reset.

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

UPSET: See System Functional Upset.

2.3.2 Abbreviations

A	Amperes
C	Capacitance
cm	Centimeters
dB	Decibel
DC	Direct Current
f or F	Frequency
I	Current
K	Constant
kA	Kiloamperes
kHz	Kilohertz
L	Inductance
mA	Milli Amperes
MHz	Megahertz
μH	Microhenry
μs	Microseconds
mm	Millimeters

nH	Nanohenry
P	Power
ps	Picoseconds
Q	Resonance characteristics
R	Resistance
V	Voltage
W	Watts
Z	Impedance

2.3.3 Acronyms

14 CFR	Title 14 of the Code of Federal Regulations
AC	Advisory Circular
AC (power)	Alternating Current
AFHA	Aircraft Functional Hazard Assessment
AFWL	Air Force Weapon Laboratory
AMC	Acceptable Means of Compliance
ARINC	Aeronautical Radio Incorporated
ARP	Aerospace Recommended Practice
ATL	Actual Transient Level
AWG	American Wire Gauge
CAD	Computer Aided Design
CFC	Carbon Fiber Composite
CFR	Refer to 14 CFR
CMOS	Complementary Metal Oxide Semiconductor
CPU	Central Processing Unit
CRC	Cyclic Redundancy Check
CW	Continuous Wave
DAL	Development Assurance Level
DC	Direct Current
DME	Distance Measuring Equipment
DO	(RTCA) Document

DOT	Department of Transportation
EASA	European Aviation Safety Agency
ED	EUROCAE Document
EDAC	Errors Detected and Corrected
EEC	Electronic Engine Control
EFIE	Electric Field Integral Equation
EFIS	Electronic Flight Instrument System
EICAS	Engine Indication and Crew Alerting System
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EME	Electromagnetic Environment
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
ETDL	Equipment Transient Design Level
ETSL	Equipment Transient Susceptibility Level
ETSO	European Technical Standard Order
EUROCAE	European Organization for Civil Aviation Equipment
EUT	Equipment Under Test
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Engine Control
FBW	Fly-by-Wire
FHA	Functional Hazard Assessment
FMM	Fast Multipole Method
FO	Fiber Optic
GPS	Global Positioning System
GUI	Graphical User Interface
HIRF	High Intensity Radiated Fields
HMI	Hazardously Misleading Information
HUD	Head-up Display
IC	Integrated Circuit

ICA	Instructions for Continued Airworthiness
IEL	Indirect Effects of Lightning
IFR	Instrument Flight Rules
I/O	Input/Output
IR	$I * R$ (structural current times resistance)
LISN	Line Impedance Stabilization Network
LRU	Line Replaceable Unit
LTA	Lightning Transient Analysis
LVDT	Linear Variable Differential Transformer
MB	Multiple Burst
MIL-HDBK	Military Handbook
MIL-STD	Military Standard
MLFMM	Multi-Level Fast Multipole Method
MFIE	Magnetic Field Integral Equation
MOM	Method of Moments
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MOV	Metal Oxide Varistor
MRB	Maintenance Review Board
MS	Multiple Stroke
NASA	National Aeronautics and Space Administration
OEM	Original Equipment Manufacturer
PFD	Primary Flight Display
PMA	Parts Manufacturing Approval
RF	Radio Frequency
RTCA	Radio Technical Committee on Aeronautics
SFHA	System Functional Hazard Assessment
SLCL	System Lightning Certification Level
SSA	System Safety Analysis/Assessment
STC	Supplemental Type Certificate
TC	Type Certificate

TCL	Transient Control Level
TPD	Terminal Protection Device
TR	Technical Report
TSO	Technical Standard Order
USAF	United States Air Force
VFR	Visual Flight Rules
VHF	Very High Frequency
VOR	Visual Omnirange
WXR	Weather Radar

3. BACKGROUND/EXPERIENCE

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

3.1 Aircraft Lightning Interactions

All aircraft can experience lightning strikes. The various lightning environment components encountered during an aircraft interaction with lightning are discussed in ARP5412/ED-84.

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

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

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

3.2 Lightning Indirect Effects

Damage or interference due to lightning interaction can occur to on-board electronic components. In one study¹, this occurred in approximately 10% of the reported strike incidents, with the most frequent occurrence being temporary interference, with recovery of the affected item following the strike incident. Failures have ranged from damage to antennas, radios and engine instruments to burnout of components such as Electromagnetic Interference (EMI) filter capacitors and relay suppression diodes. In a few cases, power distribution circuit breakers have "tripped" indicating spark-over of insulation at terminal boards, connectors, relays, or circuit boards due to lightning-induced transients. In most cases, these spark-overs are across air gaps, which recover when the transient has passed and circuit breakers have been reset. In these cases, electric power has been lost temporarily and this has caused related upsets in other systems.

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

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

3.3 Prior Criteria

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

The employment of electrical/electronic systems to perform functions that can affect continued safe operation of the aircraft has increased the need to assure that equipment can safely tolerate the lightning environment within the specific aircraft for which they are intended. This begins with establishment of the ATLs expected within system interconnected wiring and is followed by designation of specific transient descriptions and levels which are to be withstood by system equipment. Verification of damage and upset tolerances is then accomplished by analyses, tests, or similarity with previously certified designs. Acceptable steps in this process are described in AC 20-136/AMC 20-136. Test methods and examples for accomplishing them are described in this ARP and ARP5416/ED-105.

3.4 External and Internal Lightning Environment Criteria

The transient waveforms and levels presented in Section 8 of ARP5412/ED-84 are based on actual transients measured in circuits of tested aircraft. The levels associated with these waveforms are also shown in Table 22.2 through Table 22.5 of Section 22 in DO-160/ED-14. A large amount of such data exists in the technical literature and was utilized to establish the transient waveforms and the amplitude levels. The lower levels (1, 2) are representative of transients observed in well-protected short cable bundles installed in metal airframes. The higher levels are more typical of longer cable bundles installed in less well shielded regions within metal or composite airframes. Other transients considerably different than those tabulated may occur and have also been observed. See 6.8 of this ARP for further information on the interpretation of aircraft measurement data.

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

The lightning environment specified in ARP5412/ED-84 is intended to represent the characteristics of a severe, but not the most severe, lightning flash. The peak amplitude and peak rate-of-rise parameters of the first return stroke are believed to be independently exceeded in less than 5% of recorded natural lightning flashes. However, such extreme parameter levels, present within the same stroke occur much less frequently than 5% of the time. Physical damage effects produced by lightning strike currents exceeding the intensities of those included in the external environment have been evidenced on aircraft struck in flight, yet not all of the defined parameters have appeared to be exceeded at once. Peak current amplitude and action integral may be exceeded, but rate of rise (di/dt) does not appear to be exceeded at the same time. In fact, recorded flashes to earth that have high action integrals usually do not have high rates of change.

The test waveforms provided in ARP5412/ED-84 are considered to be adequate for the demonstration of compliance for the protection of an aircraft and its systems against the lightning environment. They should be applied in accordance with the aircraft lightning strike zones in ARP5414/ED-91, test methods in ARP5416/ED-105, applicable FAA and EASA advisories, and other interpretive material.

3.5 Increased Attention to Indirect Effects Protection

As technology continues to advance, modern aircraft systems are becoming more reliant upon complex electronics to perform functions that in the past had been the work of mechanical or electromechanical devices. These systems are comprised of LRUs that are smaller than their mechanical predecessors. They are capable of receiving input from more sources (e.g., sensors, other LRUs, etc.) and can process complicated algorithms that result in a more efficient aircraft. All of this advanced technology also results in an aircraft that is more sensitive to environmental conditions such as lightning.

As these electronic systems shrink, their individual components are no longer capable of dissipating the power they are exposed to when the aircraft is struck by lightning. These components are also more sensitive to small changes in voltage which lightning can induce. The processors operate at speeds that allow them to respond to these voltage changes far faster than the mechanical systems they are replacing thus amplifying the potential impact those changes can have on the performance of the aircraft. All of these factors, as well as others, result in an even greater need for protecting aircraft electronic systems from the effects of lightning.

4. DESIGN CONSIDERATIONS

Designing aircraft electrical/electronic system immunity to lightning indirect effects, in the early stages of the design phase is the optimum approach to achieve compliance of such systems. Such a design objective should be the foundation for compliance demonstration to lightning regulations. Electrical/electronic system immunity to lightning induced transients should be optimized using system/equipment architectural design considerations, as well as design measures for environment reduction.

Some general considerations that are often overlooked are:

- a. It may be easier to design new electronic equipment to tolerate induced transients than it is to retrofit lightning protection into existing equipment.
- b. It is more practical to incorporate proven protection techniques into the basic electronic system design than it is to develop and retrofit new and improved protection techniques into an electronic system designed without consideration of lightning transient protection.
- c. The cost of adding transient protection into electronic equipment must be balanced with the cost of adding lightning protection to aircraft structure and interconnecting wiring.
- d. The system installation design should take advantage of inherent shielding from aircraft structure, and should avoid placing equipment and wiring in locations that have high lightning transient exposure.

The most commonly applied hardening techniques against the indirect effects of lightning are associated with the topics provided below:

- Structural attenuation design
- Grounding

- Bonding
- Wire shielding and cable design
- Use of fiber optics
- System installation and equipment architecture design

These hardening techniques and associated issues are addressed in the subsections below.

4.1 Structural Attenuation Design

The structural attenuation of each area of the aircraft containing electrical/electronic systems or wiring installations should be estimated as the initial design consideration. This can be used as part of test level development for systems. Then the following techniques should be considered to reduce the effect on the systems to a manageable level.

Early aircraft design employed a skin material comprised of continuous sheets of metal bonded to the metal frame. This provided good shielding of the interior from the external lightning environment. More recent aircraft designs may incorporate the use of less conductive materials and techniques which are less effective at shielding lightning energy. Listed below are materials in approximate descending order of effectiveness as shields against lightning energy entry.

Table 1 - Shielding effectiveness of aircraft skin materials

Material	Shielding Effectiveness
Aluminum – solid sheet	High
Titanium – solid sheet	Medium
Steel and other structural metals – solid sheet	Medium
Carbon or metal reinforced plastics	Low
Fiberglass – solid sheet	None
Kevlar – solid sheet	None

Openings in airframe compartments and other enclosures can be covered to provide shielding. In addition to the list above, common choices for such covers in descending order of their shielding effectiveness are:

- Metal wire mesh (backing or embedded),
- Conductively coated or plated composite,
- Conductively filled composite,
- Conductively filled plastic,
- Vacuum deposited metal-coated glass and acrylics.

The shielding effectiveness of a panel is degraded when either the panel material conductivity decreases or when the seam or joint conductivity between the panel and the compartment decreases. Such a decrease in conductivity may be caused by deterioration of a conductive coating or deterioration of a metal surface due to oxidation, corrosion, or loss of contact pressure between the surfaces due to loss or looseness of fasteners. Maintenance instructions (see Section 9) should address these issues. Metal surface contact also may be lost or impaired electrically due to manufacturing processes such as anodizing and paint overspray. This can be avoided if assembly drawings clearly identify critical bonding surfaces that must remain conductive. Openings in the aircraft skin, such as points at which wiring, tubing (fuel, hydraulic, pneumatic, etc.), or other mechanisms penetrate a surface such as a wing spar or bulkhead also permit lightning energy entry.

In practical aircraft designs, shielded compartments provide only limited amounts of shielding due to apertures, wire penetrations, seams, and other points of entry. Lightning energy may be transferred from one area to another by mechanisms such as wire coupling, raceway coupling, and other coupling paths.

Care must be taken not to compromise the shielding effectiveness of the structure when the wire cable bundles, mechanical linkages, and plumbing including pneumatic/fuel/hydraulic lines are exposed to the external lightning environment in areas of minimal protection. For example, wheel wells, cockpits, wings, and other apertures.

Location of these main areas of concern may be readily identifiable such as windows but the coupling survey should also look for less obvious coupling paths. For example:

- Wing/tail to fuselage fairings: These areas are frequently closed by composite (glass fiber, carbon fiber, etc.) panels, which provide little or no attenuation of the lightning environment.
- Engine pylon to wing/fuselage fairings: While these are often metal, non-conductive (e.g., silicon rubber) rubbing strips are used to allow relative movement. The slot so formed will allow lightning energy to penetrate into the inner cavity.
- Doors and hatches: Unless a good RF bond is formed around the whole periphery of the door or hatch, energy will penetrate.
- Seams: Seams closed with non-conductive sealant will allow the ingress of lightning energy.
- Wing trailing/leading edge devices: When these devices are operated (e.g., flaps and slats extended) a space appears at their base, which is unprotected. Any wire cable bundles in this area may require individual protection.
- Wire cable conduit/raceway: Unless well bonded at both ends and frequently down their length, these items can allow energy to couple into the cable bundles they are meant to protect.
- Cable Bundles running parallel to sensitive cable bundles: Non-sensitive cable bundles (e.g., from navigation or logo lights) which enter the fuselage or other shielded space from an unshielded area will carry substantial lightning induced voltages and currents. Should these wire cables run parallel to sensitive wire cable bundles, substantial energy will be inductively coupled into the sensitive cable bundles. Care should be taken to guarantee good separation of sensitive wire cables over their whole length.
- Landing Gear (extended or fixed): Offers little to no protection without adding protection into the design of the electrical/electronic component and wiring installation.

Although the basic design may be satisfactory for initial certification, the deterioration of the electromagnetic barrier with use over time may compromise the lightning protection in the future so entry point analysis should consider the effects of such deterioration on the level of protection.

In general, the total contribution of the aircraft structure to the attenuation of the lightning electromagnetic energy into areas containing the installed system(s) must be assessed.

4.2 Grounding

An overall grounding method should be developed for new aircraft. The method should specify the grounding requirements for both power and signal interfaces. It is important that equipment used on the aircraft comply with the aircraft grounding requirements even if it means a given piece of equipment that already has a Technical Standard Order (TSO) Authorization will have to be retested. The purpose of grounding extends beyond lightning considerations; HIRF, EMC, etc., also needs to be considered. Selected power and signal grounding during DO-160/ED-14 testing may produce entirely different susceptibility profiles than that associated with actual aircraft. Some aircraft ground the power return including phase neutral to chassis just outside the input/output (I/O) connector while others may require an “electrically long” wire to ground the power returns to chassis (e.g., wire that is longer than 1/2 the wavelength of the frequency of concern). A controlled grounding concept must be implemented and LRUs must be compatible with the selected scheme. An alternate method to reflect the LRU design approach, such as returning a local ground wire to the power source because that is how the LRU filtering is configured, could be implemented. This generally is much more difficult for the aircraft manufacturer.

In terms of signal returns, discrete signals often prove difficult to control. Discrete signals often use the airframe as the return. Large lightning magnetic field energy can couple through the large loop formed by the airframe and signal wire. In addition, large potential drops may exist between points along the airframe where system equipment is grounded. Properly specified signal returns can prevent lightning energy penetration.

Digital and analog signals are best protected when provided with a dedicated signal return lead for controlling/minimizing the effective signal loop area.

The dedicated return wire provides loop control even when both ends are terminated to chassis ground inside their respective LRUs. For example, rather than using a single wire to connect an output driver to an input device, a shielded twisted wire pair should be used with the return wire preferably connected to a signal reference at the output driver and signal reference at the input device. The shield should be grounded to the outside of both respective LRUs to complete the structure of the Faraday cage and minimize the loop area. The ideal situation would be isolation of the load with the dedicated return wire to minimize the loop area.

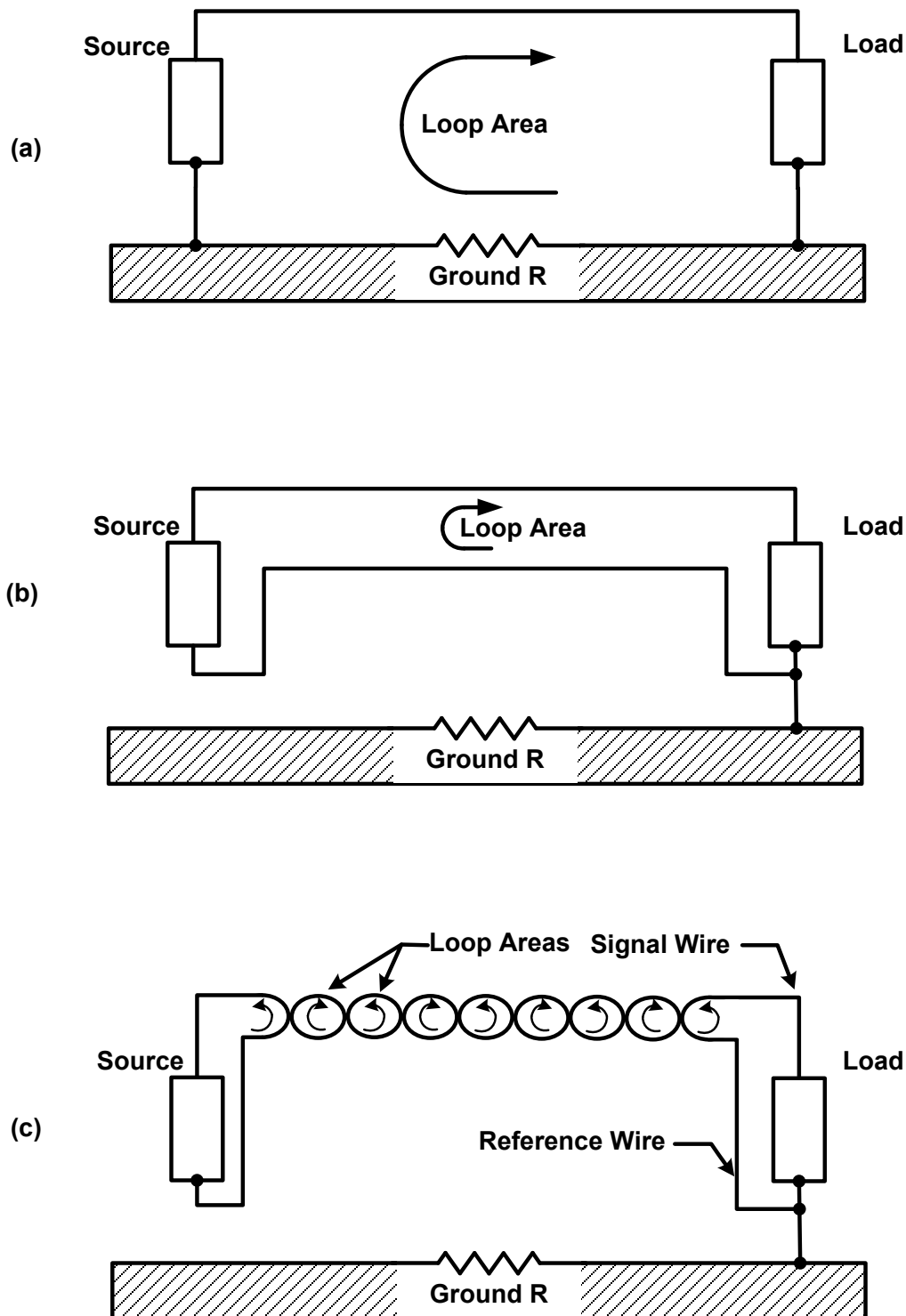
When a chassis or safety ground is required, this wire can be a point of lightning energy entry if it is not grounded immediately to the LRU chassis at the point of entry.

The aircraft integrator should avoid carrying a shield through equipment connectors and terminating the shield inside the equipment chassis, even in the case where such a pin is provided, unless such connection is specifically necessary to achieve manufacturer's specified performance.

In general, all wire shields should be terminated at the connector in such a manner that shield currents return to the aircraft structure without penetrating the equipment chassis. This also applies to cable bundles penetrating bulkheads, such as wing and body disconnects. If the cable bundle has an overbraid installed, it is still preferable for the interior signal shields to be terminated at the bulkhead even if the overbraid is peripherally terminated at the bulkhead. This is preferred because the individual signal shields can still carry significant lightning currents into protected areas of the aircraft.

4.2.1 Single Point Circuit Grounding

Multiple point circuit grounding (Figure 1a) can create ground loops that couple common mode currents and structural IR voltages into circuits. Single point circuit grounding (Figure 1b) prevents the low frequency common mode currents and avoids low frequency common mode structural IR voltages from coupling (only differential mode voltages) to circuits and should be used where possible. While only differential voltages appear across interface circuit, the common mode voltage on each end of an interface circuit could be significant. Single point grounding is most easily implemented for simple electromechanical devices, such as motors, servos, solenoids, potentiometer, lights, and switches. All of these devices can typically withstand several hundred or possibly a few thousand volts between the internal circuits and the case of the device.



(A) COUPLING OF COMMON MODE CURRENTS AND STRUCTURAL IR VOLTAGE

(B) ELIMINATING COMMON MODE CURRENTS AND AVOIDING STRUCTURAL IR VOLTAGE

(C) MINIMIZING INDUCED COUPLING OF VOLTAGES THROUGH THE USE OF TWISTED PAIR WIRING

Figure 1 - Loop area - multiple point and single point circuit grounding



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There are some problems with single point circuit grounds. While the single point ground concept prevents low frequency common mode current and avoids low frequency common mode structural voltage, low level electronic circuits may have insufficient common mode rejection for the higher amplitudes and frequencies in the lightning transient. Also, the high frequency lightning transients may still couple directly to the circuit. The common mode voltages may also exceed the electronic circuit breakdown limits between the circuit reference ground and signal circuits.

Added long reference leads, used in the single point ground approach, have inductance. Lightning induced magnetic fields cutting the circuit loop area may produce high voltages. To minimize these voltages, twist the added reference wire with its signal wire (see Figure 1c).

Investigations of lightning induced damage to electronic equipment frequently find that a single point ground concept was applied without consideration of the common mode voltage on the circuit.

4.2.2 Multiple Point Circuit Grounds

Single point circuit grounds, shown in Figure 2a, require that each LRU case be the single point reference for all internal circuitry. Each circuit or signal type is electrically bonded to local reference planes at multiple points and then each of these reference planes is electrically bonded to the chassis. The chassis is then electrically bonded to the nearest airframe grounding point.

Multiple point circuit grounds, shown in Figure 2b, may create ground loops or may subject input and output circuits to higher voltages than single point grounds. However, multiple point circuit grounds are often required because of circuit or safety requirements.

4.3 Bonding

Bonding is the method used to reduce both the DC resistance and impedance between two metallic surfaces or assemblies. This limits the voltage build up across them. Good bonding practices ensure low impedance paths for all lightning related currents.

Proper electrical bonding of equipment is necessary if electromagnetic effects are to be controlled, but there are many factors to be considered. Best practice for one aspect often conflicts with best practice for other aspects. The aircraft structure does not produce a true equipotential ground, and compatibility problems are not resolved just by making a wire connection to nearby structure. The closest approximation to an equipotential surface will be found on the inner surface of a shielding enclosure or the inner surface of a properly terminated wire shield, where the induced noise current density is low. Some basic electrical bonding considerations follow.

Typical electrical bonding practices may not be adequate for lightning. Lightning requirements usually demand low impedance bonds over a higher current amplitude and rate of change range than conventional bonding. It is of utmost importance to minimize the bonding impedance through such methods as case grounding the equipment or use of grounding straps, because of the currents produced by lightning. A purposely-engineered lightning bonding path is desired to provide electrical bonding. Safety grounds, or grounds provided by other aspects of the system (such as hydraulic tubing, flight control cables, lanyards, etc.) are not typically relied upon for lightning protection.

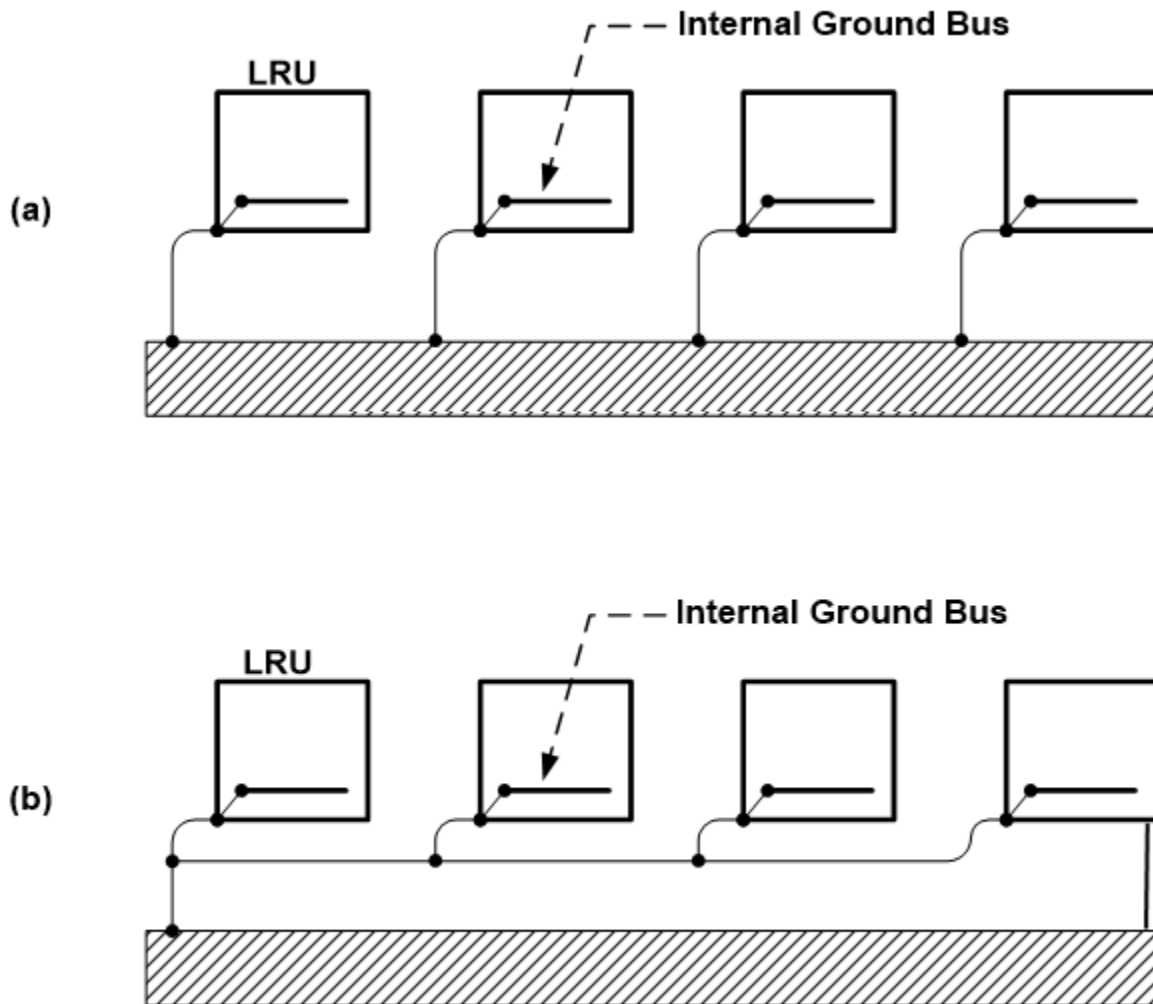


Figure 2 - Single point and multiple point circuit grounds

Equipment bonding to a mounting tray or airframe should be accomplished by direct metal to metal contact rather than a bonding strap. Bonding straps, if necessary, should be as short as possible and of low impedance throughout the frequency range where the equipment can adversely respond to lightning currents. Bonding strap length should be minimized; the impedance is a combination of DC resistance and high frequency impedance factors. The LRU design should provide a low impedance bonding means of its chassis to the aircraft. A length to width ratio of no greater than 5 to 1 will reduce the inductance per unit length of the strap to a reasonable level for use in high frequency applications. The important factor is the establishment of a low impedance bond between the wire cable shields, the shielded LRU housing, and aircraft structure.

4.4 Wire Shielding and Cable Design

Unshielded wires, exposed to high lightning transient magnetic fields and high structural voltages inside the aircraft structure, will develop high voltages or currents in electrical and electronic LRU interfaces. In order to protect an electronic system from the effects of lightning, it is often necessary to use shields on interconnecting wiring and to provide proper termination of these shields.

Solid metal shields inherently provide better shielding than a braided wire shield, and a spiral wrapped shield may provide poorer shielding than a braided shield. Braided shields with two overlapping layers of braid may provide shielding that approaches that of a solid metal shield. Generally shielding with higher optical coverage provides better shielding effectiveness against lightning currents. Rounded braid shields defined by WC 27500-2015 generally provide superior shielding effectiveness for lightning waveforms than flat braid shields defined by WC 27500-2015. This is due to the reduced mass of copper present in the flat braid shields, which provides weight savings.

Metal conduits should be carefully reviewed for their protection against lightning transient effects since they may or may not provide electromagnetic shielding. This is because conduits in aircraft tend to be used more for mechanical protection than for electrical protection of wires. The electrically conductive conduit must be electrically bonded to the aircraft structure at each end to carry current and thus provide shielding for the wires within the conduit. Conduits for mechanical protection are frequently installed with clamps that use rubber gaskets to prevent mechanical vibration and wear. Such clamps, of course, insulate the conduit from the aircraft structure and prevent it from having any magnetic shielding capability.

Clearly, non-electrically conductive conduits will not provide electromagnetic shielding and do not need to be electrically bonded.

Cable bundles routed in wing leading edges that are exposed to the full lightning environment during takeoff and landing may require cable bundle overbraids. The usual requirements for shields, such as high optical coverage (85%), should not be used to control cable bundle shielding performance. Cable bundle shielding is dependent on carrier diameter, number of picks per unit length, overall cable bundle diameter, carrier plating, and longitudinal pressure and not optical coverage. Only actual cable bundle shielding performance data should be specified, such as transfer impedance data and/or a set of tests to generate the shielding performance.

Additional cable bundle shielding can be provided by cable bundle raceways. A cable bundle raceway can be fabricated as part of the airframe by providing a partial (three sided) or fully enclosed metallic or metalically plated plastic raceway. The raceway may employ a top cover to permit access or be left open depending on the amount of protection needed. The duct could route from one major avionics bay to another or from the major avionics bay to the engines or from the cockpit to the avionics bay. Partitioning can be provided to separate sensitive cable bundles from noisy cable bundles within the raceway.

Routing or clamping cable bundles close to aircraft metallic surfaces or within raceways will minimize inductive pick-up in the "loop" created by the cable bundle and the aircraft lightning current conduction paths, including neighboring skin and structure.

The method of terminating a shield (or conduit) over a cable bundle can greatly affect its lightning transient protection effectiveness. Several methods of terminating cable bundle shields when groups of wires reach a connector to either an equipment or bulkhead are shown in Figure 3. These methods are discussed below.

360 Degree Termination

For best performance the overall cable bundle shield should be terminated on the back shell of a connector specifically designed for such termination as shown in Figure 3(a). The shield should make a 360 degree circumferential connection to the back shell of the connector and the connector shell itself should be designed to have low DC resistance, i.e., milliohms, to its mating panel connector. Most commonly, such low resistance mating requires the use of spring fingers within the connector shell. Connectors without such spring fingers frequently have high resistance between the mating shells, since the shells are frequently coated with an insulating coating to reduce problems of corrosion. The shell of the panel connector should also provide a 360 degree peripheral connection to the metal equipment case. Providing such a connection frequently requires that paint or other coatings on the case of the equipment be removed and the bare metal exposed.

Pigtail Termination

In the absence of a connector with 360 degree cable shield bonding, an external pigtail is often used for terminating the cable bundle shield or individual shields, as shown in Figure 3(b). Such pigtails are definitely inferior to the 360-degree connector because they force lightning transient current on the shield to flow through the pigtail. When the lightning transient current flows through the pigtail, a large magnetic field is created around it, which couples directly onto the wires, which are at this point not inside the shield. If such a pigtail cannot practically be avoided, it should be as short as possible, bound as closely as possible to the cable bundle, and should terminate on the connector backshell or the outside of the equipment case. A pigtail of only a very few inches in length may introduce more voltage onto the inner wires than a several foot section of the shield itself.

Termination to a Remote Point

Wire shields should be connected to the case upon which the connector is mounted and should not be connected to a remote ground point, as shown in Figure 3(c).

Termination Inside an LRU

Terminating an overall shield to the inside surface of an equipment case through a pigtail and a set of contacts in the connector (shown in Figure 3(d)) is less effective than the use of an external pigtail, partly because the length of the pigtail is inherently longer and partly because it brings currents directly to the inside of the case. Such termination of an overall shield should be avoided wherever possible and, in particular, must be avoided whenever the overall shield runs through a location where it will intercept a significant electromagnetic field.

Termination to Signal Bus

In no case should an overall shield be connected to a signal return bus as shown in Figure 3(e).

Terminating shields at both ends will provide significantly more effective protection than shields terminated at only one end. The presence of a shield terminated at only one end will not significantly affect the magnitude of the voltage induced by changing magnetic fields, although such a shield may protect against low frequency electric fields. While a shield may keep the voltage at the terminated end low, it will allow the common mode voltage on the signal wires to be high at the unshielded end.

Shielding against magnetic fields also requires the shield to be terminated at both ends, in order that it may carry a circulating current. It is the circulating current that cancels the magnetic fields that produce common mode voltages.

There is some value in staggering the spacing between multiple termination points on a wire shield, since it is theoretically possible that uniform termination can lead to troublesome resonances. Also, the wire may be exposed to a significant amount of magnetic field over only a small portion of its total length. If the shield has multiple terminations, the circulating currents will tend to flow along only one portion of the wire whereas, if it is terminated at only the two ends, current is constrained to flow the entire length of the wire.

Daisy chain pigtail shield terminations, as shown in Figure 4, should not be used. These daisy-chained pigtail terminations typically increase the overall length of the pigtail, and therefore increase the transient voltage that the wires inside the shield will be exposed to.

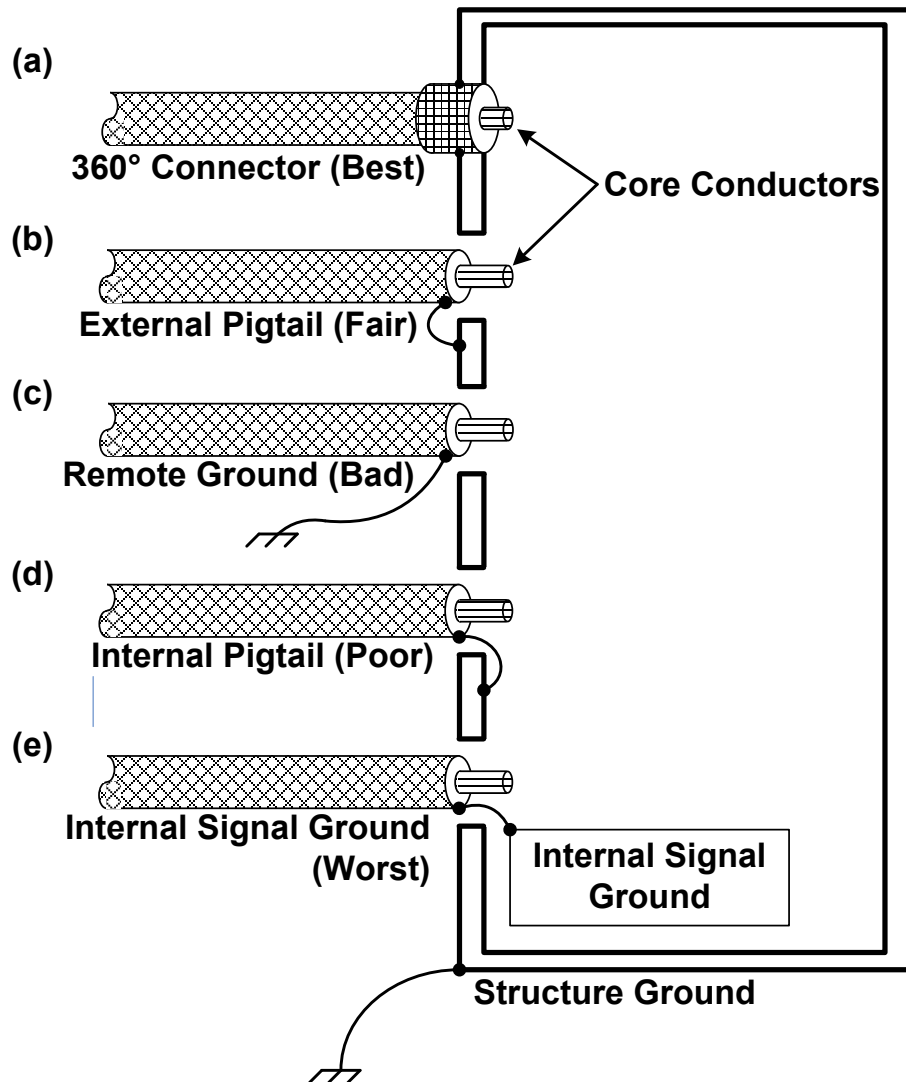


Figure 3 - Shield terminations

4.4.1 Termination Conflicts

The requirement that a shield intended for protection against lightning effects must be terminated at both ends may appear to raise the controversy about single-point or multiple-point termination of shields, but in reality it does not, since the single point circuits within the cable shields should have a ground return lead isolated from the overall shield at one end or the other. To be most effective, the shield must be terminated to the equipment connectors at both ends of the interface (a shielded twisted pair or Twinax can be effective for this application). This also allows the interconnecting equipment cases and connecting shields to be grounded in accordance with the wavelength based on the lightning spectrum or other severe electromagnetic requirements.

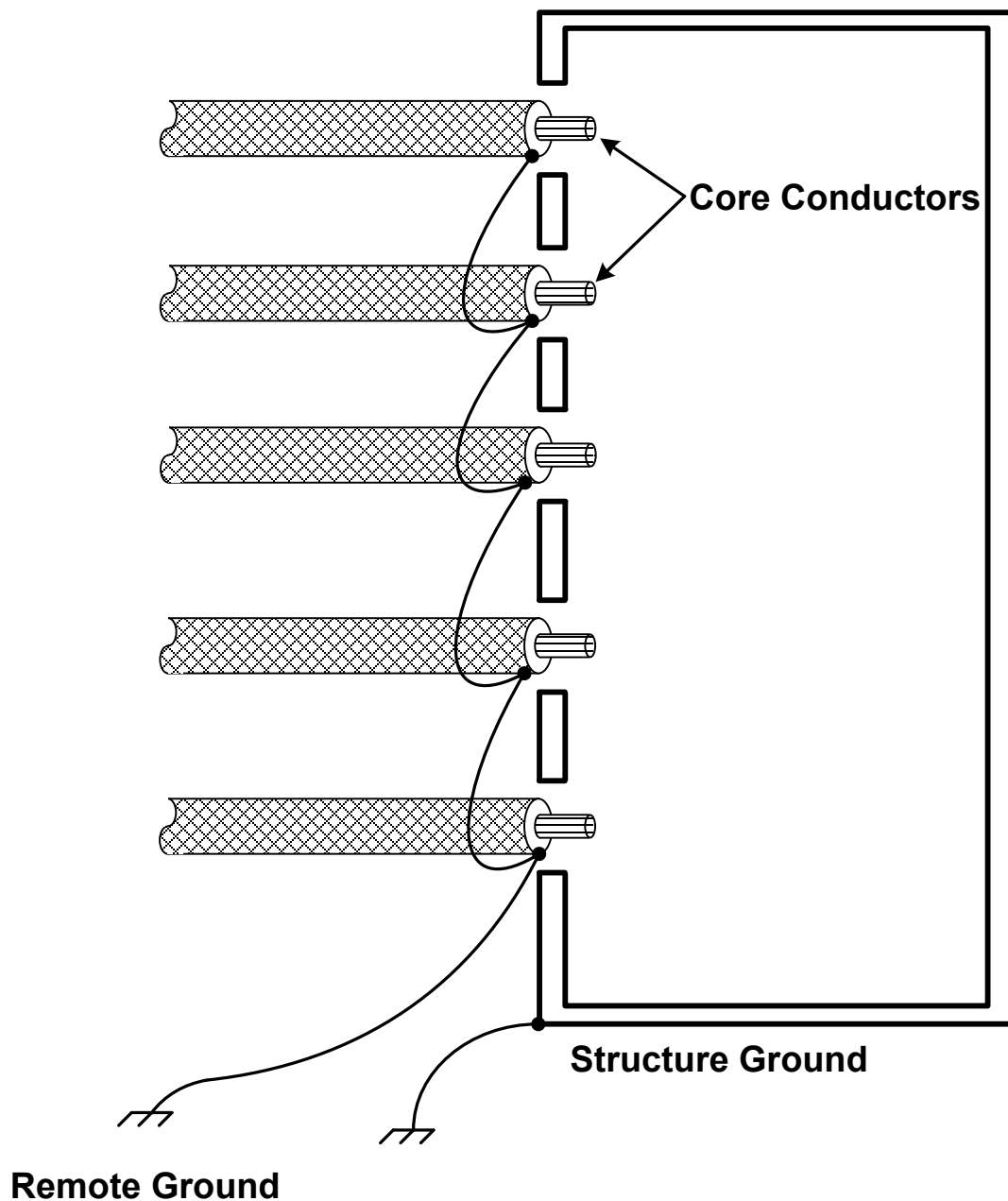


Figure 4 - Daisy chain termination

4.5 Reduction of Coupling Through the Use of Fiber Optic Cables

Fiber optics is a method of transmitting optical (light) signals over glass/silica or plastic fibers. Fiber optic (FO) transmission links do not respond to the magnetic field produced by lightning because of the nonconductive, dielectric nature of the fibers and because the RF and optical parts of the EM spectrum do not interact, making FO links the ideal I/O selection for aircraft with lower levels of shielding. FO links are available for the transmission of either analog or digital data. In terms of analog signal transmission, FO links are available off-the-shelf to transmit signal frequencies in excess of 1 GHz. As far as digital data is concerned, FO links designed to operate as RS 232 serial buses, or IEEE 488/Hewlett Packard interface bus (HPIB) parallel buses and more, are commonly available as standard commercial products.

The use of FO as a coupling solution for lightning magnetic fields introduces a new set of engineering problems in dealing with electro-optical components in an aircraft design.

Fibers are fabricated of silica, various glasses, and plastics as well as composite fibers consisting of plastic-clad glass or silica. Each has certain advantages and disadvantages. Pure silica fibers, which usually have a core doped with materials in order to increase the index of refraction, have the lowest signal attenuation values. Glasses and plastic fibers fabricated of acrylic or polystyrene have high signal attenuation. Composite fibers usually have a silica core with a suitable plastic cladding and have moderate signal attenuation. A disadvantage of plastic or plastic clad fibers is a limited temperature range.

The effectiveness of fiber optics in reducing lightning induced transients on exterior or interior cable bundles can be greater than 100 dB. This, however, does not imply that the entire data link is immune from the effects of lightning. The electronics associated with the link have a susceptibility threshold similar to any electronic system operating at a comparable signal level.

The major point of lightning energy susceptibility for a fiber optic data link is at the input of the receiver amplifier, especially for a receiver using a PIN diode photodetector. Under normal operating conditions the signal level at this point is low. Input currents can be in the nanoamp to sub-nanoamp range (1×10^{-9} A or less). Consequently, a very low lightning energy transient injected at this point can produce system upset by increasing the noise to signal ratio or the bit error rate.

Lightning energy hardening measures for fiber optic electronics include many general electronics hardening measures, such as:

- Select a fiberoptic link that has a specified resistance in the outer clad. The resistance level should not be any higher than 100 k Ω /cm. The clad needs to be bonded to the chassis or circuit card in such a way to provide a path to bleed off any static charge caused by the electric field generated by the lightning induced transient.
- Install the fiber optic transmitter (FOX) and fiber optics receiver (FOR) components in a high conductivity metal enclosure with good bonding and conductive gasketing.
- Eliminate all enclosure apertures except those that are absolutely necessary, such as that for the fiber optics, the seams due to the access cover, and the I/O connectors.
- Use nonconductors such as Kevlar or Aramid for strengthening fiber optic cables where necessary. Do not include metal conductor power or signal lines in the fiber optic cable.
- If an adequate connector can be found, use a metal fiber optic connector to run the fiber through a small diameter metallic tube which is peripherally attached to the enclosure and has adequate length to attenuate the local lightning magnetic field.

Some types of optical fiber use a metallic coating on the fiber to improve the efficiency of the fiber. These metal coated fibers should not be used as they will couple the RF energy through any aperture in shielded enclosures.

4.6 System Installation and Equipment Architectures

The overall system design should minimize the vulnerability of the system to high lightning energies. Special attention must be paid to system integration techniques. The layout of a system should be constrained to avoid low level signaling over long distances in the airframe. Signal waveforms which are required to be transmitted around the airframe must be carefully considered for their integrity in the harsh lightning produced environments. The design of the overall system architecture for the computers and software can have significant influence on the hardness of the system.

At the system level, a proven hardening technique is the use of dissimilar designs between redundant parts of the system. In all cases, any failure of a system component must not adversely affect an aircraft function such that safe operation of the aircraft is compromised. Use of a non-electronic back-up system (optical or mechanical) is a technique used in producing such an architecture.

The concept of different malfunction signatures can be used in the design and development process. Techniques for achieving this are:

- Dissimilar hardware (technology, electronic devices, circuit design, etc.).
- Dissimilar software.

- Different data sources.
- Different LRU locations.
- Different cable bundle routing and lengths.
- Avoidance of common points or paths between channels or components.
- Locate analog devices such as sensors or actuators as close as possible to their supporting control electronics (use short cables usually less than 1 m in length) whenever possible.
- Employ twisted shielded cables between the sensor/actuator and the control electronics unit with shield grounded coaxially at both ends for high lightning magnetic levels. The twisted shielded cable allows the shield to be non signal return current carrying. The inner conductors carry the entire signal pair current.
- Where redundancy is used, care must be taken with the devices used to exclude erroneous data; use virtual voters (no hardware) if a suitable voting algorithm can be produced.
- Distinct system architectures for “control” and “indication” functions, in which the “control” system is designed to provide an operational function (e.g., cabin pressurization), while the “indication” system monitors the health of the “control” system, and can initiate action (e.g., indication to pilot) to mitigate failures of the control system.

4.6.1 Electrical/Electronic Equipment Location

It is often possible to improve lightning transient protection by placing electronic equipment in locations where the electromagnetic fields are lowest and avoid placing equipment in the locations where the electromagnetic fields are highest. For example, since an important type of coupling from the outside electromagnetic environment to the inside of the aircraft is through apertures such as doors, hatches and windows, it follows that equipment should be located as far from these openings as possible.

Further, since doors with their imperfect bonding to structures are a major source of electromagnetic leakage; it follows that equipment should be located as far from such access doors as possible. In practice, this may be more easily said than done, because frequently the purpose of access doors is to provide ready access to electronic equipment. An added problem concerning access doors is the increased use of composite materials, which have little or no shielding capability.

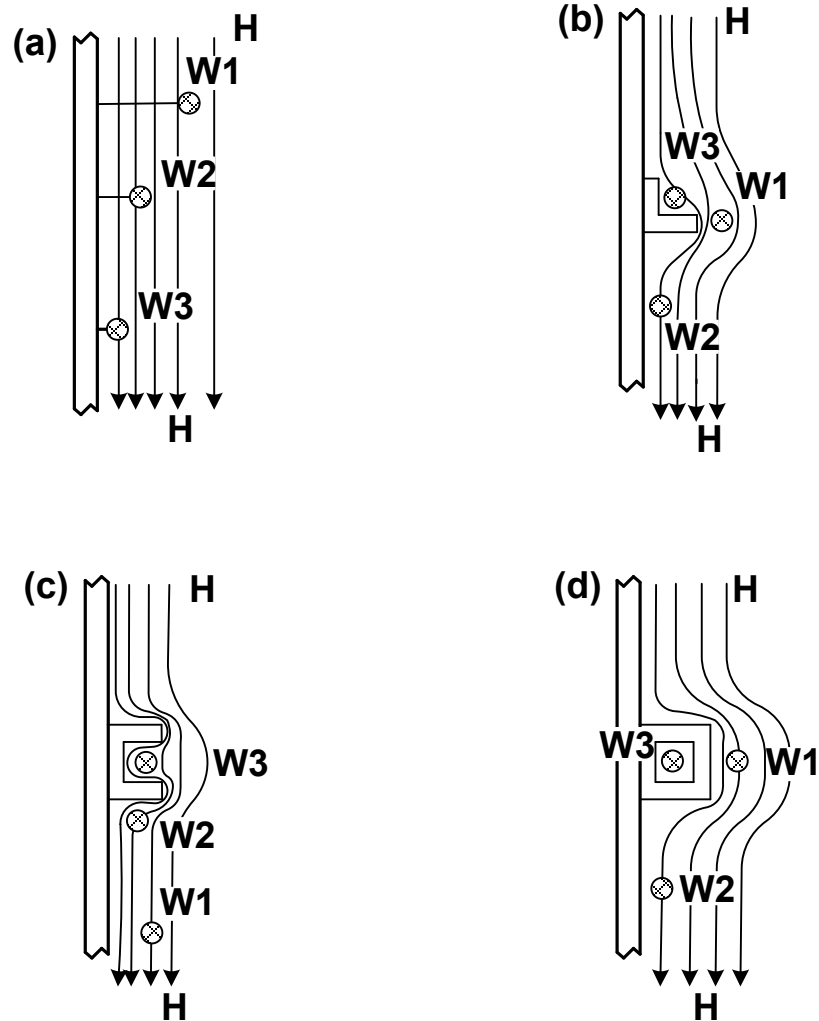
One main goal should be to locate electronic equipment toward the center of the aircraft structure rather than at the extremities and other areas of high current, since the EM fields will be lower where the conducted current is lower.

Another goal should be to locate electronic equipment away from the outer skin of the aircraft, particularly away from the nose of the aircraft, where the radius of curvature of a prime lightning current carrying path is smallest. Furthermore, if possible, electronic equipment should be located in shielded compartments.

One important factor that is under the designer's control is the type of shelf, rack, or mount upon which electronic equipment is to be located. This is particularly important for aircraft using large amounts of composite material for the structure. The shelves or racks are often used to provide electrical bonding points for electronic equipment and thus it is essential that they be highly conductive and be well bonded to the aircraft structure. They should either be made of metal or, if made from composite materials, they should be covered with aluminum or copper that is well bonded to the aircraft structure.

4.6.2 Wiring Location

Designers have somewhat more control over the routing of wiring used to interconnect equipment than over the location of the equipment itself. Wiring should be located away from apertures and away from areas where the radius of curvature of structural members or the outer skin is smallest. Moreover, wiring should be located as close to metal skin or structural members as possible. If the structural member is shaped or can be shaped to provide a trough into which the wiring may be placed, the member will provide more inherent shielding than it will if the wiring is placed on the edge of the member. Some examples of typical structural members and the best places for bundles of wiring are shown in Figure 5. In each case the structural member is assumed to be carrying current along its axis.



NOTE:

- (a) Wires over a plane
- (b) Wires near an Angle
- (c) Wires near a channel
- (d) Wires near a box

In each case pictured:

- W1 Highest flux linkages, worst
- W2 Intermediate linkages, better
- W3 Lowest linkages, best

Figure 5 - Cable bundle placement

The closer a wire is placed to a metallic plane, the less is the flux that can pass between that wire and the metallic plane. Magnetic fields are concentrated around protruding structural members and diverge in inside corners. Hence, wires located atop protruding members will intercept more magnetic flux than wires placed in corners, where the field intensity is weaker.

Fields will be weaker on the interior of a U-shaped member than they will be on the edges of that member. Fields will be lowest inside a closed structural member.

4.6.3 System Equipment Architectures

In a multi-processor architecture, one processor can monitor critical software functions and data flow in order to detect lightning induced anomalies of the other processor. Structured programs that have well defined loops (subroutine calls, etc.), control, and software with deterministic behavior are better at processing and correcting anomalies due to lightning.

Another approach is to use dissimilar software programs in redundant computers. Alternatively, dissimilar CPU types could host the software program resulting in unique processing environments for functions affecting safe operation of the aircraft.

The techniques of fault tolerant software systems provide another good means to design a system immune to the effects of lightning and could be programmed to fail in a passive or non-Catastrophic mode.

The sequence in which the software executes its process may be structured in such a manner to minimize the impact of the lightning effects. This method necessarily implies that updates to such software would need to be analyzed to ensure that the lightning protection has been maintained. In a redundant system, the different processors can interface with peripheral equipment in a dissimilar way in order to avoid each being affected by a lightning event at the same time. On a high level, multiple processing methods may be used such as two or more of the following: real time, monitored, background, foreground, sequential, prioritized, or interrupt driven.

4.6.3.1 Digital Computer Hardware Design

The source and load impedance, effective bandwidth, and characteristic impedance of the selected data cable of the technology to be employed is one of the most important factors. Each logic type has different circuit impedances, bandwidths, and noise thresholds, e.g., transistor/transistor logic (TTL), complementary metal oxide semiconductors (CMOS), or very large scale integration (VLSI). The same design precautions used for analog circuitry are generally used for digital circuits.

Internal wiring and printed circuit board trace isolation/segregation is important especially between I/O signals and sensitive internal analog and/or high speed digital circuits. Separating shielded cables from unshielded leads such as discrete leads among connectors is an important technique. Internal interconnect harnesses should not be routed over or near IC devices since that could result in direct coupling between them.

The following techniques can be classified in decreasing susceptibility:

- Level triggered signals,
- Edge triggered signals,
- Transition triggered signals such as Manchester bi-phase code,
- Sequence coded transition triggered signals, e.g., a transition is electrically encoded with a particular sequence such as ARINC 629, and
- Fault tolerance.

Bi-phase signals are inherently more immune than single-phase signals.

4.6.3.2 Digital Computer Software Design

Standard software design techniques may increase the system immunity to lightning effects. Such techniques include:

- Data Link Communication,
- Interrupts,

- Timers,
- Multi-processor,
- Redundancy,
- Dissimilar Programs,
- Processing Sequencing, and
- Fault Tolerance.

Generally, all the above mentioned techniques could be applied at the equipment level and/or the system level. The lightning influence should be considered when redundancy is being implemented to improve reliability and availability. Incorporation of lightning (also HIRF, EMC, etc.) tolerant software techniques may lead to a more robust system.

The CPU software interface with various input, control, and display devices may use one of a variety of techniques for maintaining data integrity in the presence of lightning produced environments. These may be:

- The data may be verified with the peripheral device.
- The data may be evaluated to determine if it is consistent with the previous and subsequent data communicated to or from the peripheral device.
- The data may be obtained over different interface channels with the same peripheral and compared for consistency.
- Likewise, the data may be obtained from different peripherals, but of similar capability and compared for consistency.
- Re-send tactics may be used if interference is detected.
- Error correction algorithms may also be used, e.g., CRC codes to recover erroneous digital information corrupted during the lightning strike.
- Software management of consolidation times in the acquisition of analog or discrete signals (time for which the signal value is sampled/averaged and validated for computations).
- Digital filtering in software (e.g., software filtering of quick rising transients for known slow variation analog signals like temperature data or introduction of noise rejection code to remove spurious data impossible to have in the real system).
- Adapting the max/min limits of detection for analog data (signal out of range) by means of the software.
- Avoid latching failures in the software that can be actually recovered after a lightning transient (e.g., not passing irreversibly to a degraded mode due to a failure that has been triggered by a transient in a signal, but consolidate the failure status only after several confirmation checks, in accordance with the system timing needs).

While the above paragraph mentions many techniques that improve performance with respect to lightning, it is important to remember the impact that software configuration can have on lightning protection. When changes are made to software, whether during initial certification or well into the product life cycle, performance in the event of a lightning strike is a required consideration when evaluating those changes for example in the following aspects:

- Changes made in the way that analog inputs are used.
- Modification of error handling routines and warning management.
- Modification of software that allows the activation of a part of the hardware that previously was not actively used.
- Change in the software signal gains or change to signal tolerances or thresholds.

- Change of the sampling rate of any analog or digital signal, or change in the refresh rate of data.
- Change to any software Watchdogs.
- Change in any software timer.

4.6.4 Circuit Design

In general, the hardware design is the most sensitive and cost effective step of the system design. It is important to separate the I/O circuitry and protection devices from the sensitive internal processing circuits. In addition, it is good practice to separate analog components from digital ones. If one uses relatively high resistance to isolate an LRU, one needs to be aware of the affect this may have on the HIRF and EMI protection performance. In general, it is important to ensure the lightning, HIRF, and EMI protection schemes are complimentary with one another.

Circuit design is important because good design minimizes requirements for additional protection methods, reducing weight and cost. Retrofit hardening is difficult and costly to achieve and should be avoided by considering lightning effects at the initial aircraft and/or equipment design phase. Typical design methods are:

- Input interface circuit impedance should be made reasonably high to provide inherent circuit immunity to damage by lightning induced transients.
- Balanced input circuitry should be used, in conjunction with twisted-pair wiring where practical, to minimize common mode interference problems.

When designing interface circuits for inherent immunity from possible induced transient damaging effects, in cases where component damage is due to heating, the following method is an example of the analytical techniques available to predict component damage thresholds due to electrical pulses. The Wunsch model for semiconductor failure relates the failure threshold in terms of power applied to the component as a function of rectangular pulse width. The relationship is expressed by the following equation:

$$P_F = K_1 T^{-1} + K_2 T^{-1/2} + K_3 \quad (\text{Eq. 1})$$

where:

P_F = power at failure in kilowatts

T = pulse width in microseconds

K_1 , K_2 , and K_3 are device-dependent constants

The three terms relate to adiabatic, quasi-adiabatic, and steady state heating, respectively. For pulses with time widths comparable to lightning induced pin/wire interface transients, semiconductor junction failures are primarily determined by the second term (K_2 , called the Wunsch damage constant), while resistor failures are primarily determined by the first term. The failure power is the product of the voltage across the components, V_F , and the current, I_F , through the component. To predict the failure power of semiconductor junctions requires knowledge of junction doping concentration and junction area. Detailed techniques for obtaining this data from published semiconductor data are given in the EMP Assessment Handbook (AFWL-TR-78-60) for diodes and both the emitter-base and collector-base junctions of transistors. The model used for all such junctions at damage levels is a resistor, R_S (surge resistance), in series with a battery whose voltage, V_{BD} , equals the breakdown voltage of the junction. Thus, the failure current and voltage at the terminals of the component are given by:

$$I_F = \frac{-V_{BD} + (V_{BD}^2 + 4R_S P_F)^{1/2}}{2R_S} \quad (\text{Eq. 2})$$

$$V_F = V_{BD} + I_F R_S \quad (\text{Eq. 3})$$

The applicant should note that junctions are less susceptible when forward biased. In this condition less power is developed when the injected current flows across the low amplitude forward bias voltage as opposed to the reverse biased case which is a product of the injected current and the reverse bias or breakdown voltage, V_{BD} .

Integrated circuits are modeled in the same way; however, the failure power for integrated circuits is better related to pulse width by the following more generalized empirical form:

$$P_F = At^{-B} \quad (\text{Eq. 4})$$

This technique has been extended to discrete resistors. The failure power (P_F) of resistors can be related as follows:

$$P_F = K(T)^A(P_R)^B(R_O)^C(\%\Delta R)^D \quad (\text{Eq. 5})$$

where:

P_F = pulse power in kilowatts

T = pulse width in microseconds

P_R = dc power rating in watts

R_O = initial resistance in ohms

$\%\Delta R$ = absolute value of percent resistance change

The constants A, B, C, and D have been determined by test for metal film, carbon composition, and wire wound discrete resistors and are documented in AFWL-TR-75-108.

The EMP Assessment Handbook (AFWL-TR-78-60), as well as the Aircraft Lightning Protection Handbook (DOT/FAA/CT-89/22), provide pulsed damage information and models for numerous components including devices such as capacitors and relays and, also, provide boundary constraints relative to this analytical method. As previously indicated, the failure power analysis is predicated on a rectangular pulse and, therefore, the applicant must either mathematically convert the induced stimulus or utilize conservative estimates. The EMP Assessment Handbook overviews the waveform conversion techniques and for a damped sinusoid with a Q of 24 defines the relationship to a rectangular pulse is as follows:

$$t = \frac{1}{2.4f} \quad (\text{Eq. 6})$$

where:

t = width of a rectangular pulse

f = frequency of a damped sinusoid

The following is an example of how the preceding method can be used to determine a component damage threshold. Consider the discrete circuit shown in Figure 6.

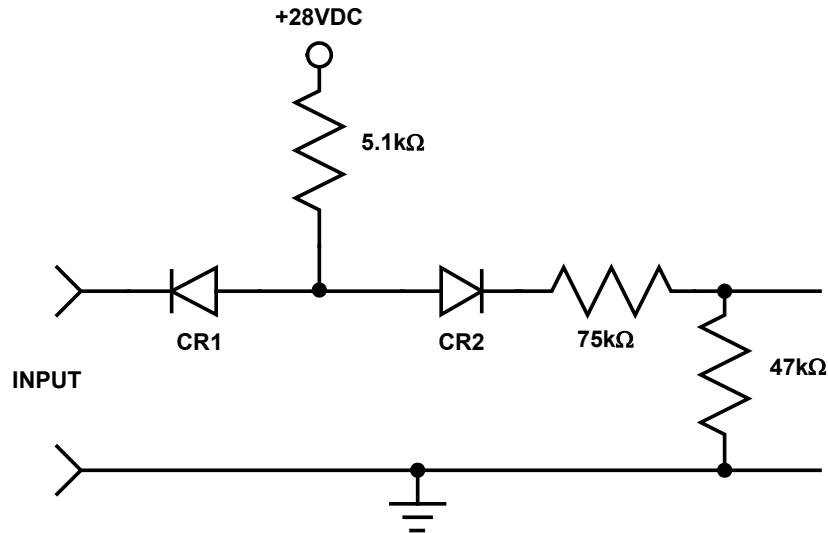


Figure 6 - Discrete circuit

For a 1N540 diode (CR1), the reverse breakdown voltage, V_{BD} , is 400 V and the damage constant, K , is 0.93. A typical reverse bias surge resistance for a diode is $25\ \Omega$. If the stimulus or induced waveform is a 1 MHz damped sine (approximate Q of 24), then the equivalent rectangular pulse is:

$$t = \frac{1}{2.4f} = 416.7\ \text{ns} \quad (\text{Eq. 7})$$

and the component failure power is:

$$\begin{aligned} P &= Kt^{1/2} = 0.93/(416.7 \times 10^{-9})^{1/2} \\ &= 0.93/6.45 \times 10^{-4} = 1441\ \text{W} \end{aligned} \quad (\text{Eq. 8})$$

The failure current, I_F , and failure voltage, V_F , would, then, be calculated as follows:

$$I_F = \frac{-V_{BD} + (V_{BD}^2 + 4R_S P_F)^{1/2}}{2R_S} \quad (\text{Eq. 9})$$

and

$$V_F = V_{BD} + I_F R_S \quad (\text{Eq. 10})$$

which yields:

$$I_F = 3.02\ \text{amp and } V_F = 475.5\ \text{volts} \quad (\text{Eq. 11})$$

Consider the equivalent circuit in Figure 7.

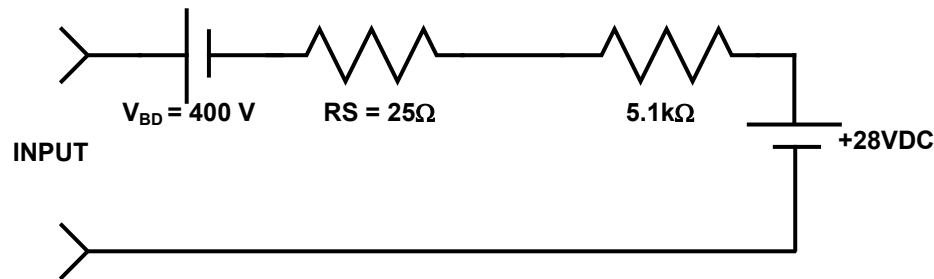


Figure 7 - Equivalent circuit

The pin test requirement is for a 1 MHz damped sinusoid waveform with an open circuit voltage of 600 V or a short circuit current of 24 A. Since the circuit loop impedance is high, 600 V will be attained first and the actual transient current is 33.6 mA. This qualification test level, when compared to the calculated circuit susceptibility level of 3.02 A, indicates substantial margin. A design margin of, at least, 10 to 1 is recommended when using analytical techniques of this type. However, larger margins may be necessary to account for the estimated or measured damage factors used.

While this analysis has focused on techniques using damage factors developed for the EMP, it should be noted that component selection based on manufacturer's steady state and pulsed ratings can be assessed using conventional analytical techniques and will produce the most reliable Equipment Transient Design Levels.

A functional disadvantage of most active protection is that while the voltage limiting devices are conducting, or reset functions are in process, desirable signal or information transfer is blocked. Other general disadvantages to active protection include increased equipment size, cost, and a reliability and maintainability burden for non-functionally related items.

4.6.5 Circuit Protection

The design objective is inherent electrical/electronic system immunity to lightning effects where reliance on dedicated protection for interface circuits is eliminated or minimized. These circuit protection techniques usually incorporate linear and/or passive elements, such as filters, transformers and resistors. The breakdown voltage of transformer windings, coupling capacitors, and various insulation barriers limit the degree of conducted isolation that can be provided to a lightning transient. These linear passive elements may also degrade the fundamental circuit performance as well, and must be considered during the basic circuit design.

Active protection for lightning entails hardware or software implementations designed to step in when a lightning transient is experienced. In this way, circuit damage or upset may be circumvented. Voltage or current limiting devices, referred to as terminal protection devices (TPDs), may be incorporated on electrical signal or power wires where they enter the equipment. Active TPDs typically perform no functional role during normal equipment operation. When a lightning transient of sufficient amplitude is experienced, these devices turn on and shunt or divert the energy until the pulse has sufficiently decayed.

Dedicated protection (not used during normal circuit operation) devices, whether active or passive, may result in a requirement for a surveillance plan (or maintenance plan). If needed, active devices that can be placed on equipment interface or power lines are available in many different technologies, response speeds, and power ratings. The following summary provides a topical guide to commonly employed devices.

TPDs may only be necessary for interfaces in which the ETDL is beyond the practical capability of inherent installation/circuit hardening techniques. In the component selection process, device voltage and current withstand ability is, typically, based on three data sources: manufacturer's parametric ratings, pulse test data, or pulse damage model assessments. Care should be taken to provide margin when utilizing the latter two approaches.

The following typifies the component selection process using manufacturer's ratings. Consider the case of a switch comprised of merely a power MOSFET. While the functional application may require a 28 VDC, 5 A switch, a 400 V/9 A MOSFET might be selected. A 2N7227 power MOSFET meets these requirements and, also, has a 56 A pulse/surge rating. This 400 V MOSFET switch is, then, capable of Level 2. For Waveform 4, then the ETDL is 125 V/25 A and the ETSL is 400 V/56 A. The switch has voltage and current design margins of 3.2 to 1 (10 dB) and 2.2 to 1 (7 dB) respectively.

When the ETSL is established through pulse tests, the quantity of devices should be sufficient to establish statistical confidence (part to part variation). In the case of integrated circuits, it may also be necessary to test multiple sources (manufacturers), especially where diverse technologies (example: bulk CMOS versus dielectrically isolated CMOS) and circuit topologies are to be employed. In all cases, device susceptibility may necessitate multiple parametric measurements. That is, a gross failure (open or short) may be preceded by a degradation (example: increased leakage beyond previously established ratings) which could be critical to its circuit function. In this case, the ETSL would be established at the amplitude where device parametric degradation exceeds circuit functional requirements.

In the third approach, which is also based in electronic component pulse testing, component/circuit withstand capability may be estimated using techniques developed for EMP assessments. The Aircraft Lightning Protection Handbook (DOT/FAA/CT-89/22) and EMP Assessment Handbook (AFWL-TR-78-60) provide detailed information and boundary constraints relative to this method. Discussion of the method with examples is provided above in 4.6.4. As indicated in the preceding examples, circuit design and component selection can be used to protect semiconductor devices from damage due to lightning induced transients.

As previously indicated, lightning induced transients can also damage passive components such as printed circuit boards, interconnects and electromechanical devices such as relays and solenoids. The more typical failure mode in these devices is a dielectric breakdown due to high voltage stress. These breakdowns can result in open circuits or short circuits due to metal re-deposition. These devices should, therefore, be designed with or selected for a dielectric withstand voltage rating equal to or in excess of the designated ETDL. The designer should also take note that long duration lightning induced currents such as Waveform 5A or 5B at Level 4 are capable of reaching the melting current of conductors such as printed circuit tapes. In such cases, circuits should be designed to include current limiting or printed circuit tapes, which must be sized to inhibit this thermal overstress.

While integrated circuits or active components are generally the focal point of a hardening program, all components must be addressed to preclude damage.

4.6.5.1 Spark Gaps

The high transient voltages associated with lightning events often allow the usage of controlled breakdown devices referred to as spark gaps. The spacing between the gap electrodes and the constituency of the gas employed within the gap enclosure determine the breakdown voltage. The gap is normally placed in shunt to ground at the entry point to be protected. The shunt voltage of the gap when fired (arcing) should be based on the desired equipment transient protection level. This number should be set by choosing a gap voltage that allows an adequate design margin over the actual lightning transient levels, while not risking breakdown due to normal signal voltage peaks.

Disadvantages in using spark gaps include slow response time (usually greater than 1 μ s) and lack of low voltage protection (less than 200 V). Spark gap advantages include low capacitance and high current withstanding levels. They are a good choice for RF lines from antennas that cannot tolerate high capacitance loads or AC power line protection where high operating line voltages exist.

4.6.5.2 Metal Oxide Varistors (MOV)

An MOV is similar in construction to a ceramic capacitor that has been manufactured using a sintering process, which allows a controlled voltage breakdown within the bulk ceramic. A metallic oxide is often used as the bulk material. Below breakdown, the device simply displays its characteristic capacitance. At threshold, a shunt current begins to flow through the weakest breakdown path. As the breakdown current increases, any voltage increase is met with more breakdown paths through the bulk of the device. In this way, the threshold voltage is approximately maintained as the device resistance varies inversely with breakdown current. MOVs are available in lower breakdown voltages than spark gaps and will withstand high current levels. The drawbacks to the MOV protection include the high device capacitance it exhibits and a relatively large size with respect to other protection devices. MOV protection is well suited for AC power lines and low frequency discrete control lines.

4.6.5.3 Semiconductor Protectors

Semiconductor devices that exhibit a threshold breakdown voltage, referred to as the Zener voltage, are very effective as transient protection devices. The fixed reverse breakdown voltage of the diode can be used, similarly to spark gaps or MOVs, to establish a higher protection voltage at a circuit interface. Common Zener diodes can be used for low current protection, and specifically designed transient absorbers, which employ the same mechanism, for higher transient current protection. Transient absorbers are available in unipolar (single junction) or bipolar (back to back junction) devices, making them suitable for DC and AC circuit interfaces.

In addition to reverse breakdown devices, artificially reverse biased diodes can also be employed. These circuits operate such that the diode goes into forward conduction when the transient level exceeds the reverse bias level. Semiconductor protectors in general exhibit low to moderate shunt capacitance, fast response time, and small size. Semiconductor protection devices can be used to solve most interface lightning protection problems, with the exception of those requiring very high standoff (signal) voltages, and very low junction capacitance.

4.6.5.4 Active Protection Applications

The following rules should be applied when incorporating active lightning protection:

- a. Mount terminal protection devices as close to the entry point (connector) as possible.
- b. Return the current from a shunt type protector to the periphery of the enclosure (case ground). Avoid shunt currents on any signal ground.
- c. Keep lead or trace lengths to and from a terminal protection device short, and incorporate low impedance shunt techniques whenever possible.
- d. Evaluate the switching time of the protection device with respect to the device being protected. If the protection device is not the lesser of the two by a significant margin, then isolation resistance or time delay is required between the two devices.
- e. Evaluate the physical breakdown voltage between interface wires that carry induced lightning transients and any neighboring wire, connector pin, transformer winding, circuit trace, or component. Take into account the operating signal voltage and operating altitude, as decreases in air pressure will reduce the breakdown threshold for a given separation distance. Ensure that lightning protection or circuit layout is adequate to prevent internal arc paths.
- f. Incorporate a pin assignment strategy to prevent lightning induced breakdown or coupling between connector pins when laying out an interface connector. Position critical balanced pairs equidistant to pins that may carry lightning transient currents.
- g. If spark gaps are to be incorporated on balanced pair transmission lines, incorporate three terminal type spark gaps to prevent a transient voltage differential from appearing between the lines due to single gap ignition.
- h. Evaluate the protected circuit for follow-on current. This occurs when power or signal current maintains conduction in the protection device after the lightning transient has passed. This is of particular importance when using spark gaps.
- i. Carefully isolate reset lines, or other lines that can generate single point error response, away from lightning transient or arrest current paths. Employ the longest possible decision time on critical edge-trigger circuits.
- j. Active devices can have latent failure modes. Therefore, periodic maintenance procedures may be needed to ensure function.
- k. System functionality must be considered since most active lightning transient protection components chosen for the design may adversely affect the system function being performed during the lightning strike event.

5. MAJOR ELEMENTS OF COMPLIANCE

This section provides details on the major steps to compliance of electrical/electronic systems to 14 CFR 23.1306, 23.2515, 25.1316, 27.1316, or 29.1316 as appropriate, or equivalent EASA CS requirements. Detailed guidance information or references to other sections of this ARP are provided to cover the complete process of certifying these aircraft systems for protection from the effects of lightning. As implied in Section 4, optimum electrical/electronic immunity from lightning effects is achieved by designing such from the start of an aircraft development program.

In the lightning regulations, the term “system” refers to the electrical and electronic equipment, associated software, and interconnecting wires installed on aircraft to perform a specific function. The term “function” refers to the action that the system performs. The lightning regulations in this section address only electrical and electronic systems, therefore systems that are only mechanical, pneumatic, or hydraulic are not subject to the lightning regulations listed. Electrical and electronic systems may be installed to augment mechanical, pneumatic, or hydraulic systems to perform a certain function. In some cases, the electrical and electronic systems may have different failure conditions than the mechanical, pneumatic, or hydraulic systems, particularly if the electrical and electronic systems have limited authority for that function.

The lightning failure conditions and System Lightning Certification Levels (SLCL) from AC 20-136 Table 1 are shown in Table 2 below. In the context of lightning certification and this ARP, the terms System Lightning Certification Level and Level are used synonymously. For example, the meaning of Level A System in this ARP is the same as SLCL A System. Note the SLCL is different from the Development Assurance Level (DAL), where DAL is used for eliminating design and development errors. SLCL is used for determining the lightning certification approach for the system, which includes both the means of determining ETDs and test methods.

Table 2 - Lightning failure conditions and certification levels

Lightning Requirement Provisions From 14 CFR23.1306, 23.2515, 25.1316, 27.1316, 29.1316, or equivalent EASA CS requirements	Failure Condition	System Lightning Certification Level
Each electrical and electronic system that performs a function, for which failure would prevent the continued safe flight and landing of the <i>aircraft</i> .	Catastrophic	A
Each electrical and electronic system that performs a function, for which failure would reduce the capability of the <i>aircraft</i> or the ability of the flight crew to respond to an adverse operation condition.	Hazardous	B
	Major	C

It should be noted that the Failure Condition Classification is related to the function performed by the electrical/electronic system under consideration. That function may be, but is not necessarily, an airplane-level function. That is, two independent systems whose individual failure conditions are, for example Hazardous, may have a combined functional failure that results in a higher integration level (i.e., airplane level) failure condition that is Catastrophic. In this case, neither system independently performs a function whose failure would prevent the continued safe flight and landing of the aircraft. However, the lightning safety assessment must consider common-mode failures, in which lightning exposure could adversely affect multiple systems in a manner that would lead to a more severe failure condition at a higher integration level, than the failure conditions of any individual system considered in isolation. In the example above, if the systems were not independent, but rather shared equipment or similar designs (e.g., susceptible power supplies) within separate equipment, the lightning safety assessment would need to consider the combined failure of each system when assigning the failure conditions listed in Table 2.

AC 20-136B paragraph 6.c.2.b discusses the multiple failure of Level B and C systems. In this ARP, 5.1.5 provides considerations on combined effects on systems.

There are three levels of rigor relative to compliance demonstration:

1. Level A Systems
2. Level B Systems
3. Level C Systems

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

Level A systems perform functions with failure condition classification(s) considered to be Catastrophic. Level A Display is a subset of Level A systems that perform functions with failure condition classification(s) considered to be Catastrophic and perform the function in such a manner that the flight crew is in the control loop. In the case of display systems, while the failure condition is considered to be Catastrophic, given quick action and the right choices by the flight crew, the effect of the failure may be lessened. This is not considered to be true for other Level A systems, such as control systems.

For Level A systems, an aircraft level evaluation must be performed to verify that the ATLs are less than ETDs by the agreed margin. This evaluation can be done by test, similarity to a previously certified aircraft, or analysis.

For the subset of Level A Display systems, ETDs for most system installations can be selected from among the standard transient levels defined for individual conductors/pins and cable bundles given in Table 22-2 through Table 22-5, respectively, of DO-160/ED-14, Section 22, using the installation descriptions provided in AC 20-136/AMC 20-136 as a guide, without specific aircraft test or analysis. For this option, AC 20-136 recommends the use of the following: *"You should use the information in Table 3 to evaluate your aircraft and system installation features to select appropriate ETDs for your system. Table 3 defines test levels for ETDs, based on RTCA/DO-160 Section 22, Tables 22-2 and 22-3. Provide the cognizant ACO with a description of your aircraft and display system installation features and compare these to the information in Table 3 to substantiate the ETD selected for your aircraft and Level A display system installation"*.

The aircraft manufacturer/system integrator may either select standard ETDs for Level A display systems as described above or, if wishing to choose levels lower than the standard ETDs, then use the Level A process (with agreed margin).

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

Because the loss of a Level B and/or Level C system has less effect on safe operation of the aircraft, recommended test levels have been provided in AC 20-136/AMC 20-136, although the levels selected should be consistent with the expected aircraft environment exposure for that system. This reduction in rigor is based on the following:

1. Loss of Level B and/or Level C systems, by definition, does not lead directly to loss of the aircraft.
2. The levels are based on measurements of induced transients during full vehicle tests of aircraft, with margins of 1.5 to 2 over the average of these measured transients in typical circuits. (Some measured transients have been higher than the standard levels.)

When analysis or similarity is used, the level of rigor should be consistent with the level of criticality. For example, the use of similarity for a Level A system would require a detailed justification of why similarity could be used. For further details on how and where to use similarity, see 6.7.

The regulations are not applicable to systems determined to have failure classifications of minor or no safety effect. However, equipment that interface with Level A systems need to be shown to not have lightning-induced susceptibilities that would adversely affect the Level A system qualifications.

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

1. Identify the systems to be assessed
2. Determine the lightning strike zones for the aircraft

3. Establish the aircraft lightning environment for each lightning strike zone
4. Determine the lightning transient environment associated with the systems
5. Establish equipment transient design levels (ETDLs) and aircraft actual transient levels (ATLs)
6. Verify compliance to the requirements
7. Corrective measures, if needed

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

Each of the elements numbered above is elaborated upon in the subsections to follow, in the order of appearance in the list above.

5.1 Identify Systems to be Assessed

One of the fundamental activities of identifying the system to be assessed is the aircraft safety assessment. This section describes processes and concepts for conducting a safety assessment which defines the scope of the applicable systems and equipment and their System Lightning Certification Levels. Applicants are encouraged to coordinate their specific Lightning Safety Assessments with the applicable certifying airworthiness authorities early in the product development stage to ensure the applicability of specific processes and concepts described in this section.

Depending upon failure effects, lightning protection requirements may apply to systems and equipment that are installed in an aircraft under the provisions of a new or amended Type Certificate (TC). They may also apply to systems and equipment installed under the provisions of a Supplemental Type Certificate (STC). A general path for demonstration of regulatory compliance for indirect effects of lightning is shown in the flow charts of AC 20-136 in Section 8, Figure 2 for Level A Systems and Section 9, Figure 3 for Level B/C systems. Lightning protection requirements for electrical and electronic systems are contained in 14 CFR Parts 23.1306, 23.2515, 25.1316, 27.1316, and 29.1316, or equivalent EASA CS requirements. Compliance with Technical Standard Order (TSO/ETSO) requirements or Parts Manufacturing Approval (PMA) as defined in CFR Part 21 does not ensure certification of the system on an aircraft via a TC or STC.

The Functional Hazard Assessment (FHA) is an integral part of the aircraft safety assessment. An aircraft FHA is conducted to identify all failures and classify them in functional and operational terms. An assessment of functional upset involves making pass/fail judgments as they relate to safe operation of the aircraft. Such pass/fail criteria fundamentally rely upon the results of the FHA, a key step of the aircraft safety assessment process. This is a system design and validation issue requiring the application of systems engineering disciplines and systems engineering participation. The aircraft safety analysis is important in the demonstration of regulatory compliance for the various types of aircraft systems. The failure condition classification of a function will determine the System Lightning Certification Level (SLCL) of a system. Reference documents are as follows: ARP4754/ED-79, ARP4761, AC 23.1309-1E, AC 25.1309-1A, AC 27-1A, and AC 29-2B. This analysis should be assessed to determine the impact of lightning induced effects on the systems and aircraft. Similarity to an existing system installation may be used to show compliance to the applicable lightning regulations and special conditions (as appropriate). Early coordination with the appropriate aviation certification authorities is recommended to ensure a timely certification process.

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

- a. Unique for each aircraft design,
- b. Applicable to overall aircraft installation configuration, not to the individual electrical/electronic equipment, and
- c. Cumulative, i.e., the criticality of a group of functions can be higher than the criticality of an individual function within the group.

When completed, the FHA provides:

- a. A list of the functions and their failure condition classifications, and
- b. Information for the identification of SLCLs associated with the systems providing such functions.

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

The definitions for each failure condition classification are provided in Section 6.c(2) of AC 20-136.

The terms Level A, etc., come from AC 20-136/AMC 20-136 and designate particular system lightning certification levels to be assigned to system implementations of those functions whose failures impact safety.

Systems and Equipment are assigned "lightning certification levels" based on failure condition classifications associated with aircraft-level functions implemented in the systems and equipment. The rigor and discipline needed in performing the activities supporting development processes will vary corresponding to the assigned lightning certification level.

5.1.1 Considerations in the Safety Assessment

Highly integrated electrical and electronic systems that perform multiple functions within an aircraft may have potential failure conditions during exposure to the lightning environments that are not identified in a standard 2X.1309 (23.1309, 25.1309, 27.1309, and 29.1309) system safety assessment. It is therefore necessary to conduct a safety assessment that is capable of identifying potential failures resulting from exposure to a lightning environment. The failure conditions due to exposure to the lightning environment must be assessed in a manner that demonstrates that exposure to the lightning environment will not result in adverse effects (which also include system failure effects) to the aircraft functional performance. The operation of systems separately and in combination with other systems should also be assessed with respect to the lightning environment.

When analyzing failure conditions associated with lightning, consideration must be given to the unique effects of lightning upon the aircraft functions since the presence of lightning environments may induce failures in ways not encountered under other operating conditions. For a standard system safety assessment, system redundancy typically reduces the probability of a functional failure. The lightning environment, however, may cause redundant electrical and electronic systems to suffer simultaneous effects (common mode failures).

Elements of the aircraft system safety analyses may be used as tools in conducting the safety assessment for lightning. For example, Aircraft level Functional Hazard Assessment (AFHA) and Systems Functional Hazard Assessment(s) (SFHA) are useful in defining aircraft functional hazards. From this, failure conditions due to exposure to the lightning environment can be identified to establish the Lightning Failure Conditions and the resulting System Lightning Certification Level. This is the Lightning Safety Assessment result.

Guidance on the processes for performing safety assessments are found in ARP4761.

For lightning compliance, if a certification applicant has not performed a Safety Assessment to classify the failure effect of the function being implemented by the system, it is required that the applicant demonstrate a suitable or equivalent process, which has been approved by the certifying airworthiness authority.

The safety assessment should include all significant modes of operation, functions with their failures, and their subsequent effect upon the aircraft, considering the stage of flight and operating conditions and the awareness of the crew to any failure or influence, and the corrective action required to maintain a safe condition. Functional failure and hazards (e.g., fire, rotor burst, bird strike, etc.) not induced by lightning do not need to be considered in this lightning safety assessment.

The Safety Assessment may show that some systems have different failure conditions in different phases of flight. Although different lightning failure conditions may be identified for the system in different phases of flight, the system should be certified for lightning considering the worst case failure condition independently of flight phases. The safety rating (e.g., integrity and availability) of the very same data (e.g., height above ground, or fuel quantity) may depend on the flight phases. It may for example be rated Major during cruise and Catastrophic during landing. In such an instance, the worst case failure condition shall be selected and demonstration made, at lightning Level A requirements that such failure mode does not occur. The same system may process and produce other data (e.g., annunciation to cockpit displays) which may be rated Hazardous, for example. This system, because of the Catastrophic rating of some failure conditions, shall be tested at the Level A lightning requirements and tests passed successfully for all the Catastrophic failure conditions. However, a Level B function is not required to pass when tested at the Level A requirements. For example, a malfunction of the annunciation function could be acceptable provided it passes successfully the Level B requirements for that function.

The lightning regulations address “adverse effects” to electrical and electronic systems and the functions they perform, not “all effects” to the functions and systems. Therefore, an important part of the safety assessment is to thoroughly define the adverse effects for the aircraft functions and systems. The definition of these adverse effects should be included in the safety assessment to identify and classify the failure conditions for the aircraft systems.

System monitors or comparators are often installed to reduce the consequences of undetected system failures. To mitigate the effect of undetected failures, these monitors or comparators are intended to alert the pilot in case of discrepancies in the system functions. When display alerts or pilot intervention are assumed during the evaluation of the hazard classification, the safety assessment should consider the consequences if lightning exposure prevents or limits pilot information originating from the system monitors, comparators and display alerts, or if lightning exposure prevents or limits pilot intervention. Electrical and electronic systems that are installed to monitor the function and integrity of mechanical, pneumatic, or hydraulic systems may be subject to lightning requirements, depending on the consequences of failure of the electrical and electronic monitor system.

Indication systems that alert the pilot to initiate defined action to over-ride or resume control, subsequent to errant control system operation that would otherwise result in a Catastrophic condition (either due to mal-control or non-control), may also be considered Level A Display systems, in lieu of classifying that (errant) control system as a Level A system. (In such cases, the system used by the pilot to over-ride or resume control would also need to be a Level A system). For example, in the case of an ice protection system, notifying the pilot to initiate action/control to maintain the continued safe flight and landing of the aircraft may be classified as Level A Display, in lieu of requiring Level A system functional operation of the ice protection system.

5.1.2 Additional Details Regarding Hazard Assessment

It is essential to define the boundaries of the system under assessment by identifying which equipment is required to perform the assessment. Since the integrated system assessment is a requirement linked to the criticality of the functions performed by the system, the proposed approach is based on:

- The Functional Hazard Assessment (FHA) and the Common Cause Analysis/Assessment (CCA) as defined in ARP4754/4761 and ED-79/135. This approach allows separating the system by functions and expansion on the corresponding system functional failures.
- The system architecture and equipment technologies.

Therefore, the list of system components required for the assessment of a complex system performing several functions may be established using the following instructions.

Based on the result of the safety assessment, the number of system components may be limited to the components which are involved in the function failure condition under consideration (top down analysis). The validity of this approach is ensured if any system upset leading to other failures conditions (of any criticality level) of the system have been assessed and that no adverse effect has been allowed. This implies that all failures conditions must be tested or analyzed, and that the consequences of any upset have been assessed (bottom up analysis). This approach may lead to more severe pass criteria than when the system is tested in its full integrity.

Based on the analysis of the system architecture and equipment technology, some equipment might be replaced by equivalent loads if the inputs do not have an active feedback or control loop and have been tested successfully to the relevant level.

NOTE: During the development process, it is necessary to define the associated pass criteria and to specify the levels for individual equipment which will be part of a critical system. This equipment (called critical equipment) should be developed so that at the relevant environment (system environment) any malfunction will not prevent the system from performing as intended.

5.1.3 Aggravating Factors

Aggravating factors may be driven from minimum availability requirements, which are driven by particular airworthiness requirements.

For an example, during the derivation of the lightning safety assessment, the worst case environmental flight condition is assumed. Typically, this is flight in IFR conditions, which include night, poor visibility and bad weather with possible lightning conditions. IFR conditions would provide further aggravating conditions to lightning effects in comparison to VFR operations.

One consideration for aggravating factors is system architecture and/or common technology effects. Typically, these situations present a significant risk of multiple failures of which the criticality may be worse than the loss of each individual function when considered independently, and/or may generate undue workload for the flight crew.

In particular, when performing the safety assessment, integration of LRUs performing multiple functions within a highly integrated system must be taken into account. Common-mode considerations must be taken into account for loss of Level B and Level C functionality performed by a single unit and the cascading effect of losing all of this functionality at once due to lightning common mode failures/susceptibility.

5.1.4 System Availability and Integrity Considerations in the Safety Assessment

System integrity and availability must be considered within the safety assessment. This aspect of the safety assessment considers the availability/recovery of the system in correlation to the system integrity, i.e., the availability/recovery needs of the system must be coupled with the integrity of the data provided by that system.

For example, it may be acceptable for a primary flight display to "red-X" due to a lightning event, providing that the information is available from another source, such as a stand-by display. If required by the safety assessment to recover its operation, the primary flight display must have the correct data displayed when recovered, i.e., no hazardously misleading information (HMI) upon recovery. In this example, the function availability is provided by the stand-by display and data integrity is covered by the display "red-X" which indicates to the pilot that the data is not valid and he/she must look at another source.

Another example is the "blink" versus "blank" issue with regards to primary flight displays. If the safety assessment requires continuous operation, then it may be permissible for a display to blink (screen goes "black" for 1 second or less) and display the correct data once it recovers. This addresses the data availability aspect as well as the data integrity because the time frame for loss of data (1 second) is considered acceptable, along with the fact that the data remains valid. However, in this case it is unacceptable for the display to rebuild the data being displayed after the lightning threat is removed, if the recovery is not accomplished in a timely manner.

5.1.5 Lightning Safety Assessment Considerations for Combined Effects on Systems

The system safety assessment should consider combined effects of lightning related failures or malfunctions on systems with lower failure classification that may impact the function of Level A systems.

It should be shown that any systems interfacing with Level A systems do not adversely affect the Level A functions performed by that system when exposed to the lightning environment. For example, equipment whose failures may monopolize communication or corrupt data on a data bus and prevent other systems on that data bus from performing functions which may lead to Catastrophic failure conditions should be assessed as a Level A system specifically for the failure that could monopolize communication or corrupt data. For an integrated system evaluation, it is best practice to include such interdependent functions in the integrated test set up.

In addition, the combined failure of multiple systems should not result in a Catastrophic event at the aircraft level. When simultaneous loss of all of these could result in Catastrophic consequences, then the combined loss should be classified as Catastrophic. Simultaneous and common failures due to lightning exposure do not have to be assumed for multiple Level B or C systems consisting of federated equipment installations. That is, for systems that are not identical and where each item of equipment is designed independently, simultaneous failure due to specific lightning exposure is unlikely. In addition, equipment and wiring installations are distributed throughout the aircraft. Aircraft tests and in-service experience has shown that these distributed installations are not simultaneously exposed to the maximum lightning fields. It is unlikely that all the equipment locations in the aircraft will be exposed simultaneously to the maximum lightning environment in flight when the equipment is distributed throughout the aircraft.

Specific examples where combined failures should be considered include:

- Failures due to lightning of identical components that are used in multiple systems. For example, solid-state relays may be incorporated as a replacement for electromechanical relays to provide power to systems. Lightning effects may include potential simultaneous loss of all solid-state relays used to provide power to multiple systems whose individual failure effect may have been classified as less than Level A. In this case, if simultaneous loss of all power to multiple systems could result in a Catastrophic failure, then the solid state relays should be considered Level A systems.
- Loss or malfunction of a Ground/Flight state sensor control system that provides ground/flight status to multiple systems. If loss or malfunction of the Ground/Flight state sensor control system could result in a Catastrophic failure, then the Ground/Flight state sensor control system should be considered a Level A system.
- Typically the non-restorable loss of all navigation and radio communication is considered a catastrophic event in IFR operation. Note that this classification is for part 25 airplanes. When the radio systems are federated so that the individual communication and navigation radios, such as VHF (Very High Frequency) communication, VOR (Visual Omnidirectional Range), or GPS (Global Positioning System), are not identical and where each item of equipment is designed independently, simultaneous failure due to specific lightning exposure is unlikely. In addition, the radios are installed in different areas of the aircraft, the lightning exposure simultaneously affecting all the radios and rendering them permanently inoperable is unlikely and therefore compliance may be shown by installation of individual radios having zonal separation. For installations that include integrated radios, integrated tuning control heads or where the communication and navigation radio systems (transceivers or tuning heads) are installed within the same aircraft area such that lightning exposure could illuminate all the radio systems and pose a potential for affecting all communication and navigation functions, then the applicant should comply with Level A requirements. In this case, the test only needs to show that the communication and navigation is available after test, since the Catastrophic conditions arise from the non-restorable loss of both communication and navigation.

Classification of functions and subsequently the system(s) performing each function resulting from the FHA usually follows predictable guidelines. Electrical/electronic systems that provide functions such as FBW flight controls and FADEC are usually examples of Level A systems. Attitude, altitude and airspeed sensing and display of these parameters are usually examples of Level A Display systems. As aircraft size and complexity increase, other systems such as Engine Indication and Crew Alerting Systems (EICAS), i.e., thrust rating, could also fall into the Level A Display classification. Level B and C systems generally include navigation, and displays providing heading, position and enroute data and communication. Emergency and/or warning systems, not identified as Level A, will generally be classified as Level B or C due to the potential for false indication/warning caused by lightning. Because external events unrelated to lightning (e.g., fire, rotor-burst) are not considered during the lightning safety assessment, lightning-induced loss of ability to provide for indication warning would not necessarily result in a classification of these systems as Level B or C.

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

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

Lightning effects on electrical and electronic systems are generally assessed independently from other system failures that are unrelated to lightning, and do not need be considered in combination with latent or active failures unrelated to lightning. Although a failure by itself may not be Catastrophic, Hazardous, or Major, it may be a contributing factor when combinations of failures are considered. For example, a latent or undetected failure caused by lightning could contribute to a Catastrophic, Hazardous, or Major failure condition when combined with one or more specific failures caused by lightning. Another example, as described above, is the loss of all communication systems and all navigation systems may be classified as a higher failure condition classification than the loss of only the communication system or only the navigation system. Therefore, combinations of failures caused by lightning must be considered.

5.2 Determine the Lightning Strike Zones for the Aircraft

Methods for identifying the lightning strike zones on an aircraft can be found in ARP5414/ED-91.

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

- Attachment to an aircraft nacelle containing a FADEC or similarly critical equipment.
- Attachment near the cockpit windows, thereby creating large electromagnetic fields in the cockpit region.
- Attachment to carbon fiber or other poorly conducting surfaces, thus providing especially large fields directly underneath the lightning attachment point. If the aircraft has a significant number/amount of non metal skins then large fields may also be found away from the lightning attachments.
- Attachment to wheel struts during landing or take off, thereby creating large fields in the wheel well as well as providing for large excitation of cable bundles along the wheel struts.

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

5.2.1 Relationship of Lightning Strike Zones to Direct Effects

Equipment mounted external to the fuselage, wings, or tail of the aircraft are exposed to the possibility of a direct lightning strike. Examples of such equipment are antennas, sensors, and probes. Antennas, sensors, and probes mounted behind a dielectric material integral to the aircraft skin may need to be protected from both direct and indirect effects. Section 23 of DO-160/ED-14 provides environmental levels and procedures for testing of such equipment to direct effects and ARP5416/ED-105 provides both direct and indirect effects lightning test methods for aircraft.

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

5.2.2 Relationship of Lightning Strike Zones to Indirect Effects

Some equipment may be located and installed in Zone 3. Zone 3 areas conduct current components of the lightning flash as well as multiple stroke and multiple burst waveform sets. Zone 3 currents are generally shared among all conductive aircraft components and low impedance cable bundles. There are cases such as some fuselage-mounted engines, which can be classified as being located in a Zone 2 region. Such a classification would replace exposure to the high amplitude current Component A by the re-strike current Component D. In these cases, the indirect threat is lower.

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

5.3 Establish the Aircraft Lightning Environment for Each Lightning Strike Zone

Once the aircraft lightning strike zoning has been determined it is necessary to establish the external lightning environment applicable for indirect effects assessment of the installed electrical/electronic systems. The accepted detailed definition of this environment is contained in ARP5412/ED-84 and consists of the current components (A, A_H, B, C, D, and H) which comprise the lightning flash. Those components which are important (for system assessments) to indirect effects are current Components A, D, and H since they will produce the largest transients in system wiring because of their large current magnitudes and/or rates of rise.

The lightning current flows through the aircraft between attachment points. For any given system there may be several attachment points which cause current to flow in a manner to couple to that system. The external environment applicable to a given system consists of those current components, which are to be applied at the aircraft exterior where coupling to systems can occur. The lightning/aircraft attachment configuration (entry and exit points for lightning current) i.e., zoning information is used to determine which components of the external environment are to be applied to the system under evaluation. Time domain and associated frequency domain plots of current Component Waveforms A, D, and H are described in Section 6 of ARP5412/ED-84.

In most cases, test levels will be based on current Component A. However, there may be some situations when systems equipment and wiring is installed exclusively within an area where structural lightning currents will be limited to Zone 2 levels. In these areas, it is acceptable to use test levels based on the Component D environment.

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

5.4 Determine the Lightning Transient Environment Associated with the Systems

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

Before system and equipment effects and system immunity can be assessed, the voltage and current transient amplitude and waveform characteristics must be determined. These voltage and current transient amplitude and waveform characteristics are the result of complex electromagnetic processes. The approach for establishing these characteristics may include test, analysis, comparison with similar aircraft data, or a combination of these. Whatever the approach, it must be based on methods that can be validated and can provide the appropriate data for ultimately verifying adequate lightning protection margins. Also, the methods must account fully for the aircraft structure, materials, apertures and arrangement of subsystems within the aircraft. The result of this complex process is used to determine equipment test levels for systems that are subsequently verified by aircraft level test. This process is discussed in detail in 5.5.

5.4.1 Relationship between External and Internal Environment

Many years of in-flight and ground-based data have led to an aircraft lightning certification environment definition. This definition takes into account the phenomenology of lightning and aircraft interaction and the characteristics associated with aircraft lightning strikes by severe cloud-to-ground and intracloud lightning flashes. Detailed information on the external lightning environment and typical induced voltages and currents in aircraft wiring is given in ARP5412/ED-84 and includes multiple stroke and multiple burst waveform sets. First return stroke attachment locations for the largest strikes are in lightning strike Zone 1A and Zone 1B. Systems located between other lightning strike zones may be subjected to a reduced number of strokes of the multiple stroke environment. This also means that the Zone 3 environment within structures, such as some fuselage mounted engine nacelles, whose surfaces are in Zones 2A or 2B, may not experience the induced effects of Current Component A as the worst case. Such systems would experience the effects of current Component D. Since most aircraft systems are installed in airframe sections that lie between Zone 1A and Zone 1B, or within an associated Zone 3, this usually exposes all system installations to current Component A and the total multiple stroke and multiple burst waveform sets.

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

The external environment described in 3.4 is defined as the external lightning current components, which are associated with their appropriate lightning strike zones. The interaction with these lightning strike zones results in electromagnetic fields on both the exterior and interior of the aircraft during the application of the lightning current components. When determining internal environments, it is frequently convenient to define the current and charge densities on the aircraft surface as the surface environment and the electromagnetic fields and structural currents within the aircraft interior as the internal environment. This separation of the interaction process is an approximation, which is valid when the surface environment is not significantly affected by the internal environment, so that the surface and internal environments are significantly decoupled. This is the case for all metal or mostly metal aircraft with small apertures. The word "aperture" is a general term. It not only involves openings in the skin such as glass windows, but it also includes seams, joints and composite panels, if these are significant contributors to the internal environment. In these cases, it is clear that changes to the aircraft internal structures and cable bundle layouts will not significantly affect the surface current and charge density on the metal exterior.

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

1. The first class includes aircraft which are largely open structures, such as certain helicopters. Although the basic structure may be metal, large portions of the skin may be glass, fiberglass, Kevlar, or other non-conducting material. In this case, the distinction between interior and exterior electromagnetic environments becomes less pronounced and one must therefore determine the entire environment (electromagnetic fields and cable bundle responses) simultaneously.
2. The second aircraft class for which the decoupled approximation is not valid includes aircraft which have large amounts of carbon fiber composite (CFC) structure, especially if the CFC structure is not protected by any metallization. Typically, the CFC structure surrounds metal substructure, hydraulic tubes, etc. By the process of redistribution, the current will initially flow on the exterior and gradually transfer to metal components. This process simultaneously involves both the external and internal features of the aircraft and cannot be separated into two distinct processes.

5.4.2 Induced Transient Mechanisms

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

Waveforms 1, 2, 4, and 5 of ARP5412/ED-84 may occur in aircraft wiring as responses to the external environment Current Component A waveform. Waveforms 1 and 4 are proportional to the Current Component A exponential waveform, and Waveforms 5A and 5B are lengthened exponential waveforms. Waveform 2 is proportional to the derivative of Current Component A. These waveforms will be significant in circuits using airframe return and also for circuits installed within non-metallic aircraft structures.

Waveforms 1, 2, 4, 5A, and 5B can be referred to as particular, fundamental, or forced responses to input excitation Current Component A and D, and are the responses expected in an interconnecting wire(s) whose total length is short when compared to the wavelength of the excitation pulse. It should be noted that this is true for all aircraft for component A and D waveform threats. An interconnecting wire is considered short when it is less than one tenth of the wavelength of the dominant frequencies in the excitation, i.e., less than 30 meters for Waveform 1. ARP5412/ED-84 shows that the internal Waveforms 1, 2, 4, 5A, and 5B can be derived from the external Current Component A and D, and there are other types of current waveforms in the structure and the effect of these should be considered.

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

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

When the aircraft is exposed to a lightning transient, cable bundles may be excited into electrical resonance and an initial oscillatory response may occur. The oscillations will damp out, in general, within 10 to 20 cycles. As cable bundle and/or aircraft lengths approach an electrically long condition, this oscillatory response becomes more dominant in the total response. A circuit becomes electrically long when the duration of an excitation pulse is very short when compared to the electrical wave transit time. For an electrically long circuit, the Waveform 3 traveling wave response dominates. Except for some unusual cases, the oscillatory response is always present, to some extent, in the total response. As discussed previously, the other components in the total response are referred to as forced responses. Thus, since the pulse duration for Current Component A is such that electrical circuit lengths associated with most aircraft and aircraft wiring lengths are not clearly electrically long, the total response to Current Component A could be a Waveform 3 combined with Waveform 1, 2, 4, 5A, or 5B.

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

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

These waveform sets are divided into two broad lightning transient coupling classes, based on airframe or airframe section construction. Any of the waveforms could produce component damage or functional upset. The current waveforms are more likely to cause component damage due to energy. The voltage waveforms are more likely to cause component damage due to dielectric breakdown in components such as capacitors.