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Engineering Standard Practice

DHC-8 Series 400 EMI/HIRF/ Lightning Control Plan

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1.0 SCOPE

1.1 Introduction

This document outlines the effort to be applied on the DHC 8 Series 400 aircraft to ensure that it will operate in its electromagnetic environment including externally generated High Intensity Radiated Fields (HIRF), Lightning, Tribolelectric Charging (P-Static), internally generated Electromagnetic Interference (EMI), and Electrostatic Discharge (ESD). This document describes the organizational structure of the program including responsibilites, lines of authority and control, implementation planning and milestones. *ESP 84 provides recommended design standards to ensure a common design protection methodology throughout the aircraft.*

Lightning/EMI/HIRF requirements for electrical/electronic systems are provided in ESP 89 (Electromagnetic Environmental Effects Requirements DHC-8 Series 400 Electrical/Electronic Systems and Equipment) and the DTRD (de Havilland Technical Requirements Document).

1.2 Applicability

This document is applicable to de Havilland as well as Suppliers responsible for systems and structures installed on DHC 8 Series 400 aircraft. This document will ensure that techniques intended to limit the effects of EMI, HIRF, Lightning, P-Static and ESD are uniform throughout the aircraft.

2.0 APPLICABLE DOCUMENTS

Documents listed form part of this document to the extent specified below and to the extent specifically referenced in other paragraphs. If a document is referenced as being applicable without specifying a particular paragraph then the document is applicable in its entirety. Where a particular issue or revision of a document is specified in the text, no other issue or revision shall be used. Where no revision is mentioned, the latest issue or revision shall be used. Publications and technical references listed below provide data and information on EMI, HIRF, Lightning, P-static and ESD control and should be used if further details on these subjects are required.

Government Documents

TCA Special Condition	High Intensity Radiated Field
FAA Special Condition	High Intensity Radiated Field
FAA AC 20-53A	FAA Advisory Circular: 'Protection of Airplane Fuel Systems Against Lightning'
FAA AC 20-136	Protection of Aircraft Electrical/ Electronic Systems Against the Indirect Effect of Lightning
FAA AC 20-107	Composite Aircraft Structure
FAA AC 25-1309-1A	Equipment, Systems and Installations
FAR 25.1316	Systems Lightning Protection
JAA CRI F-01	High Intensity Radiated Field
JAA CRI F-03	Systems Lightning Protection
JAA ACJ 25.581	Lightning Protection
JAA ACJ 25.603	Composite Aircraft Structure
JAA ACJ 25X899	Electrical Bonding and Protection Against Lightning and Static Electricity
JAA ACJ 25.954	Fuel Systems Lightning Protection
JAA AMJ 25-1309	Equipment, Systems and Installations
JAA ACJ 25.1353	Electrical Equipment and Installation
JAR 25X899	Electrical Bonding and Protection Against Lightning and Static Electricity

FAR/JAR 25.581	Lightning Protection
FAR/JAR 25.603	Materials
FAR/JAR 25.954	Fuel Systems Lightning Protection
FAR/JAR 25.1353	Electrical Equipment and Installation
FAR/JAR 25.1431	Electronic Equipment
RTCA/DO-160C	Environmental Conditions and Test Procedures for Airborne Equipment
DOT/FAA/CT-83-3	User's Manual for AC 20-53A Protection of Airplane Fuel Systems Against Fuel Vapor Ignition Due to Lightning
DOT/FAA/CT-89/22	Aircraft Lightning Protection Handbook
MIL-C-5541	Chemical Conversion Coatings on Aluminum and Aluminum Alloys
MIL-C-38373	Cap, Fluid Tank Filler
MIL-STD-285	Attenuation Measurements for Enclosures, Electromagnetic Shielding for Electronic Test Purposes, Method of
MIL-STD-461C	Electromagnetic Susceptibility and Emissions Requirements for the Control of Electromagnetic Interference
MIL-STD-889	Dissimilar Metals
MIL-STD-1757	Lightning Qualification Test Techniques for Aerospace Vehicles and Hardware
MIL-HDBK-419	Grounding, Bonding and Shielding for Electronic Equipment and Facilities

de Havilland (de Havilland) Documents

DTRD-8-010	de Havilland Technical Requirements Document- General DHC-8 Series 400 Aircraft
DTRD-8-020	de Havilland Technical Requirements Document Avionics Systems DHC-8 Series 400 Aircraft

DTRD-8-047	de Havilland Technical Requirements Document Windshield DHC-8 Series 400 Aircraft
DTRDs	de Havilland Technical Requirements Documents applicable to all structures and systems
ESP 64-400	DHC-8 Series 400 Protective Treatment Specification
ESP 89	Electromagnetic Environmental Effects Requirements, DHC-8 Series 400, Electrical/ Electronic Systems and Equipment
ESP 96	Cable Shield Transfer Impedance Data and Recommended Connector Backshells - DHC-8 Series 400 Aircraft.
AEROC 84.9.AC.1	DHC-8 Series 400 System Level Functional Hazard Analysis

General References

1. Ott, Henry W., Noise Reduction Techniques in Electronic Systems, John Wiley & Sons, 1988
2. Paul, Clayton R., Introduction To Electromagnetic Compatibility, John Wiley & Sons, 1992
3. Smith, A.A., Coupling of External Electromagnetic Fields to Transmission Lines, John Wiley & Sons, 1977
4. Vance, Edward F., Coupling To Shielded Cables, John Wiley & Sons, 1978

3.0 MANAGEMENT

Aircraft electromagnetic compatibility (EMC) is achieved by controlling the sources, paths and receptors of unwanted electromagnetic energy, with a minimum increase in bulk, weight, circuit complexity, cost and a minimum decrease in performance. The most effective and least expensive techniques are available to the designer when EMC is addressed early in the program. When EMC is neglected until a design is mature, compatibility is gained only through cost and schedule penalties and compromised performance. Figure 1 shows the cost and availability of electromagnetic control measures throughout the life cycle of the program.

EMC design features fundamentally affect structural and electrical considerations. The control methods and techniques described in this document should be considered before design begins and aimed at total EMC in the operational environment during the product life cycle.

3.1 Responsibilities and Activities

3.1.1 de Havilland

de Havilland, as the aircraft systems and structures integrator is responsible to control EMI in the aircraft and to ensure aircraft compliance to HIRF and Lightning certification requirements throughout the life of the product. de Havilland in conjunction with all system and structures Suppliers will establish an overall integrated electromagnetic environmental effects control program to ensure that EMC is addressed adequately and early in the program. de Havilland is responsible for the following:

a. Interfacing with airworthiness authorities including Transport Canada Aviation (TCA), Federal Aviation Administration (FAA) and Joint Airworthiness Authority (JAA);

b. Defining electromagnetic environment requirements and allocation to the systems and structure Suppliers;

c. EMC coordination of systems and structures Suppliers;

d. EMC design of in-house built structures and systems;

e. EMC design implementation of systems and structures installations;

f. Detail HIRF and Lightning Direct Effects certification test programs for de Havilland designed systems and structures;

g. Aircraft level EMI, HIRF and Lightning Indirect Effects certification test programs;

h. Preparation of the aircraft certification HIRF and Lightning Compliance Reports 84.8.AC.6 and 84.8.AC.7 respectively.

3.1.2 EMC Technical Review Meetings

The objective of ensuring aircraft electromagnetic compatibility is a complex process requiring the interaction of many technical disciplines. de Havilland will conduct EMC technical review meetings with the structures and systems Suppliers to ensure an integrated design protection methodology, address EMI/Lightning/HIRF related problems and design discrepancies as well as establish channels of coordination.

3.1.3 System and Structure Suppliers

Each Supplier is required to establish an EMC program. This program must address Electromagnetic Environmental Effects control requirements as described in DTRD-8-010, ESP 89 as well as the structures and systems DTRDs. As required in ESP 89, each Supplier shall prepare and submit a EMI/HIRF/Lightning Control Plan to de Havilland for review and approval. The contents of this Control Plan are described in ESP 89 and shall follow the design standards described in this document. Initial submission of the Control Plan will be no later than 2 weeks prior to the Preliminary Design Review (PDR). The Control Plan will be updated and re-submitted to de Havilland for final approval by the Critical Design Review (CDR). Sixteen weeks prior to certification, the Supplier shall provide to de Havilland an Assurance Plan which will describe the EMC design techniques and procedures that were actually incorporated into the system/ structure design. The contents of this Assurance Plan will be as described in ESP 89.

The system Supplier will submit to de Havilland for review and approval all the respective intra-system and inter-system cable shielding requirements and shield termination requirements. These requirements will be determined with the cooperation of de Havilland and will be based on the Electromagnetic (EM) environment described in the DTRDs and ESP 89 as well as the interface circuit design. These requirements will follow the design standards described in this document. de Havilland will ensure that the requirements are implemented so as to maintain aircraft design uniformity.

Each system Supplier will be responsible for defining to the structures Supplier, system to structure interface and installation requirements associated with the EMI, HIRF and Lightning requirements. The structure Supplier will be responsible for system installation design in accordance with the system Supplier requirements. de Havilland will review and approve these requirements to ensure aircraft design uniformity. de Havilland will be the prime coordinator for the flow of information and requirements between the Suppliers.

EMI, HIRF, Lightning, Grounding, Bonding and ESD will be addressed at Preliminary Design Reviews (PDR) and Critical Design Reviews (CDR) and, as required, at Product Integration meetings and EMC Technical Review Meetings.

Each system and structure Supplier will develop a test program to demonstrate the Electromagnetic Environmental Effects requirements described in ESP 89 and the DTRDs. Each Supplier will develop and submit to de Havilland for review and approval a Test Plan at least 90 days before test and a Test Report no later than 30 days following test completion. The Test Plan and Test Report contents will be as described in ESP 89.

3.2 de Havilland EM Organization

The Electromagnetic Environment Effects control management for the DHC-8 Series 400 aircraft will be carried out by the following EM engineers:

a. Peter Bootsma, Lead Engineer

b. Margarida Reeves, EMI and HIRF

c. Ian Chrimes, Lightning Direct and Indirect Effects

The EM group will provide support to the various team leaders in the areas of EMI, HIRF and Lightning design requirements and implementation. The EM group engineers will attend the regularly scheduled Product Integration meetings to participate in design activities.

3.2.1 EM Group Tasks and Activities

The EM group activities vary as the product goes through various phases including new product development, testing and certification, production and in-service operation.

The main tasks during the new product development phase are:

a. Evaluate product definition for EM effects considerations;

b. Prepare an EMC program plan and budget;

c. Define the aircraft EM environment including internal threat levels pertaining to HIRF and Lightning (ESP 89);

d. Allocate requirements to systems and structure Suppliers including Interface Control Drawing (ICD) support;

e. Define structure and systems design and installation requirements pertaining to EMI, HIRF and Lightning.;

f. Prepare an aircraft EMI/HIRF Lightning Control Plan (ESP 84);

g. Monitor and control the implementation of concepts and requirements described in the Control Plan. Review drawings and specifications;

h. Review Supplier Control Plans and design;

i. Perform development tests and analysis on risk areas;

j. Monitor Supplier development tests. Review development test plans and test reports;

k. Monitor Supplier qualification tests. Review qualification test plans and reports;

l. Analyze in-house and Supplier's test data for accuracy and its implication towards aircraft compatibility;

m. Provide inputs to maintenance plan such as scheduled and unscheduled maintenance procedures.

The main tasks during testing and certification phase are:

a. Develop an EMI test program and participate in EMI aspects of flight testing;

b. Produce Functional Test Engineering Requirements (FTER) and ensure each Supplier produces a Functional Test procedure (FTP) to meet electrical bonding requirements;

c. Develop aircraft level EMI, HIRF and Lightning test programs, including test plans and reports;

d. Identify, analyze and fix problem areas with respect to EMI, HIRF and Lightning;

e. Review design changes and ensure they are properly implemented.

The main tasks during the production phase are:

a. Monitor quality assurance activities during the production phase;

b. Support quality control of structures and systems;

c. Control of equipment changes and wiring installation;

d. Carry out any testing and design improvements as required.

The in-service phase requires quality control and maintenance precautions to ensure the protection design is not degraded throughout the life of aircraft. Some of the tasks during this phase include:

a. Implementation of EMC aspects of maintenance and training plans;

b. Monitoring of aircraft structure and system repairs to ensure an adequate level of protection is maintained;

c. Monitoring changes in wiring, connectors, equipment, structures shielding, as well as bonding and grounding to ensure an adequate level of protection is maintained.

3.3 Quality Control and Problem/Resolution

One of the most important tasks of the de Havilland EM group is to ensure that the EMI/HIRF and Lightning design standards listed in this document and in the Suppliers Control Plans and Interface Control Drawings/Documents are properly implemented during the development, design, production and in-service phases of the aircraft program. During aircraft development, the implementation of these standards will be monitored through drawing reviews, attendance to regularly scheduled Product Integration meetings as well as EMC Technical Review meetings. Any discrepancies encountered between the actual design and the EM standards will be addressed with the responsible design engineer and the Supplier representative where applicable. If a resolution is reached, design changes will be implemented as required. If the discrepancy cannot be easily resolved then the EM engineer will evaluate the impact on the EMI/HIRF and Lightning certification requirements. Concurrently the responsible design engineer or Supplier, with the support of the EM engineer, will develop solutions and trade-off studies and provide recommendations. A final solution should be reached by either the de Havilland team leader or management based on the EM engineer evaluation and the design engineer/ Supplier recommendations.

In order to ensure that the structure/system EM related design standards described in each Supplier Control Plan are adequate for structure/system compliance to the EMI, HIRF and Lightning requirements, analysis and/or development tests should be carried out. If problems are identified early in the program any required design changes will have a lower cost and schedule impact and there will be a higher probability that the system will meet all EM requirements during qualification testing. If the analysis and/or development test data show system/structure non-compliance to the EM requirements then a similar procedure to the one described in the previous paragraph will be followed.

4.0 REQUIREMENTS

Generators of electromagnetic interference for aircraft include:

a. Aircraft AC power line electric and magnetic fields

b. Computer and avionics microprocessor timing and control clock signals

c. Aircraft power switching regulators used to convert between different power levels

d. Electrical switching transients generated by the switching of aircraft lights, fans and pumps or the operation of control surfaces and landing gear

e. Transmitters of radio frequencies such as high frequency (HF), very high frequency (VHF) communication links, high energy sources located on the ground such as everyday frequency modulated (FM) radio or HF, VHF and ultra high frequency (UHF) broadcast stations, or ground radar.

f. Lightning strikes

g. Triboelectric charging (P-Static)

h. Electrostatic discharge (ESD)

Noise sources a) through d) are described in section 4.1 under Electromagnetic Interference (EMI) requirements. Paragraph e) is described in section 4.2 under High Intensity Radiated Fields (HIRF). Paragraph f) is described in section 4.3 and includes both a Lightning Direct and Indirect Effects requirements. Paragraph g) P-Static phenomena and requirements are briefly described in section 4.4. Paragraph h) ESD is addressed in section 4.5.

Additional requirements pertaining to aircraft structural shielding effectiveness are included in the applicable DTRD.

4.1 Electromagnetic Interference (EMI)

Aircraft electrical and electronics systems must show compliance with the following Federal Aviation Regulations (FAR) and Joint Aviation Requirements (JAR):

a. FAR/JAR 25.1431

b. FAR/JAR 25.1353

The aircraft electrical/electronic systems include intentional and unintentional receivers and emitters. Intentional emitters/receivers include radars, navigation and communication antennas. Table 1 lists all navigation and communication equipment for the DHC-8 Series 400 as well as the equipment fundamental frequencies. As described in sections 2.2.1.23-00 and 2.2.1.34-00 of DTRD-8-020 the Avionics System Supplier is to use antenna modeling and/or antenna pattern testing to achieve optimum aircraft antenna location and minimize interference between the various antennas.

TABLE 1. DHC-8, Series 400, Navigation/Communications Frequencies

EQUIPMENT DESCRIPTION	FREQUENCIES OF OPERATION
VHF Communications	118 to 136.975 MHz
VHF Navigation	108 to 117.95 MHz
Glideslope	329.15 to 335 MHz
Marker Beacon	75 MHZ
Automatic Direction Finder (ADF)	190 to 1799 KHz
HF	2 to 29.9999 MHz
Transponder, Air Traffic Controller (ATC)	TX: 1090 MHz RX: 1030 MHz
Microwave Landing System (MLS)	5031 to 5091 MHz
Distance Measuring Equipment (DME)	1025 to 1150 MHz 962 to 1213 MHz
Global Positioning System (GPS)	1227.6 MHz and 1575.42 MHz
Weather Radar	9.345 GHz
Radio Altimeter	4.3 GHz
Long Range Navigation (LORAN)	100 KHz
Omega/VLF	10.2 to 23.4 KHz
Emergency Locator Transmitter (ELT)	121.5 and 243 MHz
Aircraft Communication Addressing and Reporting System (ACARS)	VHF (TBD)
Flight Phone	UHF (TBD)

Unintentional emitters and receivers include all aircraft electrical/electronic systems, including navigation and communication systems and antennas at frequencies other than their fundamental frequencies, as well as all wiring. *In order to control electromagnetic susceptibility and emissions characteristics of the aircraft electrical/electronic systems, all electrical/electronic systems are required to meet RTCA/DO-160C and MIL-STD-461C, CE 07 requirement, as described in ESP 89.*

4.2 High Intensity Radiated Fields (HIRF)

The HIRF environment external to the aircraft penetrates the aircraft and establishes an internal EM environment to which electrical/electronic systems will be exposed. The resultant internal EM environment is developed from many factors such as seams and apertures in the aircraft construction, the effects of re-radiation from structures, systems and wiring internal to the aircraft as well as the characteristic aircraft electrical resonance. The resultant internal environment will be essentially frequency dependent and aircraft and zone specific.

The requirement for demonstration of HIRF compliance for any specific system or equipment installed in the aircraft is related to the criticality of the function(s) performed by the system/ equipment. The identification of systems/ equipment functional criticality will result from the System Level Functional Hazard Analysis, AEROC 84.9.AC.1, developed by the Reliability and Maintainability Group, in accordance to AC 25.1309-1A or AMJ 25.1309, and should be submitted for approval to the Airworthiness Authorities.

The effects of an encounter with HIRF must be assessed to determine the degree to which the aircraft and/or its systems may be affected with respect to continued safe flight as defined in AC 25.1309. The assessment should take into account:

a. Operation of systems, separately and in combination with and/or in relation to other systems

b. Include all modes of operation and of failures and their subsequent effect upon the aircraft, considering the stage of flight and operating conditions

c. The awareness of the crew to the failure

d. The corrective action required

A complete definition of the failure condition categories is provided in AC 25.1309-1A and AMJ 25.1309. A summary of these categories, Catastrophic, Hazardous/

Severe-Major, Major, Minor and No Effect, and the relation to the HIRF test requirements is provided in ESP 89.

To ensure an adequate level of protection against the effects of HIRF for those electrical and electronic systems whose functions may be necessary for the continued safe flight and landing of the aircraft, TCA, FAA and JAA have issued Special Conditions for use in the certification program. The TCA and FAA Special Conditions define an external threat environment as well as an optional equipment test environment. The JAA Special Condition defines an external threat environment. The DHC-8 Series 400 certification test requirements applicable to electrical and electronics systems as defined in ESP 89 are based on the worst case environment taking into account the TCA, FAA and JAA Special Conditions.

The HIRF requirements including the system/equipment criticalities and categories levels as provided in ESP 89

4.3 Lightning

4.3.1 Lightning Direct Effects

4.3.1.1 Airworthiness Requirements

For Lightning Direct Effects Protection, the DHC-8 Series 400 aircraft must show compliance with the following FAR and JAR regulations:

a. FAR/JAR 25.954a,b,c

b. FAR/JAR25.581a,b,c

c. FAR/JAR25.603 c.

d. JAR25X899a.

Acceptable Means of Compliance (JAA):

a. ACJ 25.581

b. ACJ 25.603

c. ACJ 25X899

d. ACJ 25.954.

Advisory Material (FAA):

a. AC 20-53A

b. AC 20-107A

Special Conditions and Interpretative Material:

JAA CRI F-02

4.3.1.2 Lightning Strike Zones

The Lightning strike zones are used in association with the predicted threat levels which represent the most important characteristics of a natural Lightning strike event.

This information should be used to establish which protection methods are necessary and to assess the adequacy of the protection by means of simulated Lightning test, similarity and/or analysis.

The Lightning strike zones for the DHC-8 Series 400 were developed in accordance with the guidelines given in the FAA AC 20-53A and are shown in Figure 9 and 10.

The Lightning zones are defined as follows:

Zone 1: Surfaces of the aircraft that have a high probability of an initial Lightning flash attachment (entry or exit). For example, Wing-tips, Empennage, Nose, Engine Nacelle Inlets. This is further sub-divided into two sub-zones:

Zone 1A - Initial attachment point with a low probability of hang-on.

Zone 1B - Initial attachment point with a high probability of hang-on.

Zone 2: Surfaces of the aircraft across which there is a high probability of a Lightning flash being swept away from the initial Zone 1 point of attachment. Namely a secondary or swept stroke attachment. For example, the fuselage. This is further sub-divided into the two sub-zones:

Zone 2A - Swept stroke area with low probability of hang-on.

Zone 2B - Swept stroke area with high probability of hang-on.

Zone 3: Surfaces of the aircraft where there is a low probability of any direct or swept stroke attachment. Areas may carry substantial amounts of electrical currents if they lie between the entry and exit points. Typical example of Zone 3 areas are wing surfaces inboard of the wing-tip.

4.3.1.3 Lightning Environment

The natural Lightning environment, which comprises a wide statistical range of current levels, duration and number of strokes, is represented by current components A, B, C and D as shown in Figures 11, 12 and 13. Table 4 below shows the current components which should be used to verify the adequacy of Lightning protection for each of the designated Lightning zones.

TABLE 2. Lightning Direct Effects Current Requirements

ZONE	CURRENT COMPONENTS			
	A	B	C	D
1A	X	X		
2A		X*	X*	X
2B		X	X	X
1B	X	X	X	X
3	X	X	X	X

NOTES:

X*: Use an average current of 2 KA ±10 percent for a period equal to the dwell time up to a maximum of 5ms. If the dwell time is more than 5ms, apply an average current of 400A for the remaining dwell time. The dwell time shall be determined previously through a swept stroke attachment test or by analysis. If such determination has not been made, the dwell time shall be taken to be 50ms.

High voltage testing should be carried out in accordance with RTCA/DO-160(C) and FAA AC 20-53A.

4.3.2 Lightning Indirect Effects

To ensure an adequate level of protection for electrical/electronics equipment against the Indirect Effects of Lightning, TCA and the FAA require that all electrical/ electronic equipment meet the requirements of 25.1316 as described in AC 20-136. The JAA has issued a Lightning Special Condition outlining similar requirements to 25.1316. Both of these requirements establish aircraft performance criteria for all electrical/ electronic equipment which perform Critical and Essential functions.

The requirement for demonstration of Lightning Indirect Effects compliance for any specific system or equipment installed in the aircraft is related to the criticality of the function(s) performed by the system/equipment. The identification of systems/ equipment functional criticality, as in the case of HIRF requirements, will result from the System Level Functional Hazard Analysis, AEROC 84.9.AC.1. Since Lightning and the Functional Hazard Analysis have different failure conditions terminology, Table 5 should be used to provide a cross reference between the two terminologies.

TABLE 3. Failure Condition Terminology

FAILURE CONDITION	NOMENCLATURE OF FUNCTIONS
Catastrophic	Critical
Hazardous/Severe Major	Essential
Major	Essential
Minor	Non-Essential

The aircraft internal Lightning environment is produced by the external Lightning environment resulting from the current flow through the airframe and penetration of electromagnetic fields. The resultant internal environment will induce current and voltages on wires with responses depending on the type of coupling, wire length, shielding, equipment location and grounding. The wire responses are defined by a combination of five waveform types and formulated in terms of single stroke, multiple stroke and multiple burst testing[1] described in AC 20-136. The resultant internal environment is essentially aircraft and zone specific. As described in ESP 89 the DHC-8 Series 400 aircraft has been divided into lightning EM regions, each having different current and voltage requirements. *The partner must refer to ESP 89 for Lightning Indirect Effects test requirements for all electrical/ electronic systems.*

[1] See ESP 89 for Multiple Burst Definition

4.4 Triboelectric Charging (P-Static)

An aircraft in flight can acquire an electrostatic charge as a result of triboelectric or frictional charging associated with flight through ‘dry’ precipitation (e.g. snow, ice crystals, sleet, hail). If the charges are left to accumulate, voltages and electric fields may reach levels where electrical discharges occur on the airframe. The following types of discharges, see Figure 14, can cause interference or static on aircraft systems:

a. Corona from aircraft extremities

b. Sparking from poorly bonded metal objects

c. Streamering from dielectric surfaces

P-Static is not usually a threat to flight safety, but due to its broad frequency content, as shown in Figure 15, it may interfere with air to ground communications as well as navigation systems. It may also become a problem if it disrupts air traffic control and communication with the plane is lost. P-Static persists for as long as the aircraft is being charged by impact with the precipitation and once the aircraft leaves such a region, the static quickly clears up and the aircraft potential reverts to that of its surroundings. Static charges originate along the leading edges and migrate along conductive surfaces to trailing edges and extremities where it accumulates or it is dissipated into the atmosphere. Charge buildup rate, and therefore charging current, is a function of the size and velocity of aircraft as well as the atmospheric composition. Any open circuit along the current path will cause RF noise. Techniques to reduce localized charge buildup by providing a continuous conductive path and encouraging charge dissipation along trailing edges or extremities are addressed in section 5.1.3.

4.5 Electrostatic Discharge (ESD)

Electrostatic Discharge (ESD) has become a hazard to most electronics. It has been recognized that thick and thin film solid state devices, metal-oxide semiconductor devices, and many discrete electrical parts such as film resistors, capacitors, crystals and bipolar ICs are susceptible to damage by ESD. Susceptibility to ESD usually increases as devices become smaller and faster.

The ESD environment specified in ESP 89 requires that the individual equipment be tested to demonstrate that equipment electrical components are immune to the effects of the electromagnetic coupling of a typical static discharge through the external case of the equipment. The test is representative of the electrical stress that could occur on the flight line or in service where ESD handling procedures are not available and ESD sensitive equipment are installed, replaced or inadvertently touched by personnel working in or near electrical equipment. This test is not applicable to the pins of equipment as they have connector covers that protect the pins from a direct discharge.

ESD control is a special case of the overall subject of EMC. The major difference between ESD and EMI control is the much larger currents and voltages involved with ESD. However both ESD and EMI can be controlled by the same techniques described in the following sections.

5.0 DESIGN TECHNIQUES AND PROCEDURES

The aircraft contains numerous electrical/ electronic systems. The aircraft should include a layout and topology that optimizes electromagnetic compatibility. The following is a list of the dominant EMC preferred designs which require early conceptual consideration, planning and layout:

a. Major subsystems are grouped together for an inline equipment design to achieve the shortest possible wire bundle routing

b. Major incompatible wiring groups are separated

c. Aircraft has a designed system-level shielding barrier combined with a designed, controlled equipotential ground plane system.

d. Interface circuits are protected and/or filtered

e. Installed systems meet the EMI/HIRF and Lightning qualification test requirements.

In order to achieve the EMI/HIRF and Lightning requirements specified in section 4, the following design processes should be considered:

a. Grounding and Bonding

b. Shielding

c. Filtering

d. Hardware electrical and electronic design, including device selection, interface circuitry, wiring/routing and printed circuit board design.

e. System architecture including dissimilar designs between redundant parts of the system

f. Software design

In most cases proper grounding reduces the need for shielding and filtering and good shielding minimizes the need for filtering. Grounding is part of the assembly process and does not usually require additional hardware. Although shielding requires additional hardware, its implementation is straightforward. Filters, on the other hand, are separate pieces of equipment, which must be specified, designed, tested and installed.

The EM environment which the aircraft electrical/electronic equipment and wiring are exposed is dependent upon resonant and attenuation characteristics of the airframe as well as structural and systems detail design. As shown in the aircraft electromagnetic architectural topology diagram (Figure 16), the sources of electromagnetic threats such as HIRF and Lightning Indirect Effects, present a hazard to electronic circuit functionality. As a result circuitry must be designed to be immune to hazardous operations. The EM protection topology will be implemented in a layer design. The following is a list of the required layers of protection:

a. Airframe primary structure shielding

b. Cable location/ routing, airframe secondary structural shielding such as shielded equipment bays, racks, floors, liners, trays and additional cable shields or overbraid

c. Systems shielding such as cable and equipment enclosure shielding

d. Interface design, such as balanced isolated circuits

e. Voltage and current limiting, such as filtering and/or transient protection devices

f. Software

The optimum protection occurs when the protection requirements are partitioned among the various options available such that the cost, weight, difficulty, and life cycle performance verification measures associated with each protection design are minimized and the immunity to EMI, HIRF and Lightning effects are maximized. Due to the aircraft structural complexity, cost and weight constraints as well as life cycle performance and maintenance, it is the goal of the EM topological design, for all electrical/electronics to achieve maximum value from the equipment circuitry design in order to achieve the specified performance for HIRF and Lightning with a minimum requirement for additional shielding applied to primary structure, cables or secondary structures. Paragraphs a) through c) will be addressed in section 5.1, under the Mechanical Design; Paragraphs d) through f) will be addressed in section 5.2, 5.3, and 5.4.

5.1 Mechanical Design

5.1.1 EMI/HIRF/Lightning Indirect Effects

5.1.1.1 Airframe Primary and Secondary Structure Shielding

The airframe primary structure which is fabricated from aluminum, forms the first level of shielding. Depending on the aircraft size and configuration, the airframe structure provides relatively good shielding to EM fields for frequencies below 1 MHz. But EM fields above 1 MHz can find their way into the aircraft through points of entry including:

a. Openings such as windshields, windows, composite structures and air inlets/outlets

b. Seams or discontinuities such as doors and access panels

c. Wiring which enters a shielded region from a non-shielded region (for example wiring from external electrical equipment, radomes, wheelwells, wings etc)

d. Metallic plumbing such as hydraulic lines, fuel lines, and de-ice lines as well as control cables

In order to reduce the level of leakage, the following should be incorporated as part of the airframe structure design:

a. Electrically conductive liners should be used on composite structures and panels. The windshields should include a electrically conductive coating. The conductive coating is only expected to provide shielding in the high MHz and GHz frequency range. The use of the windshield heater layer for shielding purposes should be considered as long as this coating can be AC grounded to structure. The AC ground should be achieved by seam overlap between the heater and structure such that the built-in capacitance between the heating film and structure is adequate to provide some shielding for frequencies above 400 MHz.

b. The use of secondary structures such as conductive equipment racks and floors as well as additional shielding enclosures to house equipment should be considered in areas where conductive liners and coatings cannot be easily incorporated in the airframe structure or where these liners and coatings cannot be adequately bonded to the structure. In the cockpit, metalization of the glareshield and side panels, metal or metallized floors and metal instrument panels with equipment directly bonded to the structure should be considered to compliment the windshield shielding capabilities. Due to the large number of windows, access doors and panels the fuselage is difficult to seal for EM fields. Additional shielding in the fuselage should be achieved from secondary structure shielding such as EMI designed racks or enclosures to house equipment and metal or metallized floor panels under which equipment can be located.

c. Cables should be routed close to aircraft structure away from large openings such as windows, doors and access panels. In the cockpit, cables should be located behind the instrument panels and below the glareshield, as close as possible to the metallic airframe and well below the windshields. In the case of the fuselage, wiring should be routed below the floor as close to metallic structure as possible. Figures 17 - 22 shows preferred cable routing locations. When cable routing cannot be maintained to within 5 cm from the aircraft structure or additional reduction of EM field cable coupling is required, the use of metal trays should be considered. The cable trays reduce the distance between the cables and the structure or ground plane and therefore reduce the level of field coupling to cables. These metal trays should be grounded at distances no more than one tenth of the smallest wavelength or highest frequency against which immunity is required. Cables routed in areas with large openings, or little primary structural shielding, should include an additional shield layer. This additional shield can be in the form of a shield over the individual cables in the bundle or an overbraid for the whole bundle. For practical reasons, such as ease of maintenance or implementation of additional wires, the use of overbraid should be avoided. Critical systems wiring routed external to the fuselage pressure vessel must be designed with two levels of shielding (see section 5.3.3). Critical systems wiring located within the fuselage cabin must be routed within metal cable trays. The cable trays must be electrically bonded to the airframe. As a minimum, the shield should be grounded to structure where the cable transitions from one EM region to another and at all bulkhead disconnects. The shield should be grounded to the connector using 360 ° peripheral contact as described in section 5.3.4.2.2.

d. Metal meshes or honeycomb structures should be used to cover air inlets/

outlets in primary and secondary structures which enclose EM protected areas.

All conductive penetrations such as hydraulic, fuel and de-ice pipes as well as control cables passing through pressure bulkheads and metals interfaces from an exposed EM region to a shielded EM region should be electrically bonded to structure. Electrical bonding should be 360 ° peripheral contact and should be as described in section 5.2.2.

5.1.1.2 System Mechanical Design

As described above, due to the aircraft structural complexity, cost and weight constraints and life cycle performance and maintenance, it is the goal of the EM topological design, for **all electrical/electronics equipment to achieve maximum value from the equipment circuitry design so as to achieve the specified performance for HIRF and Lightning with a minimum requirement for additional shielding applied to primary structure, cables or secondary structures**. The HIRF and Lightning environments are tailored for the criticality of the equipment. Higher levels of criticality may require additional shielding depending on the cable locations and secondary structural design elements of the aircraft.

In order to meet the EMI requirements described in section 4.1, the equipment may need to be shielded and properly bonded to structure and the I/O power and signal interfaces may require filtering as well as cable/connector shielding. To support these recommendations, it should be noted that a rapidly changing 1 volt signal on a number 20 AWG wire, one foot long, and two inches above a ground plane exceeds RTCA/DO-160C radiated emissions limits. As a result, clocks lines, continuous data signals could easily radiate from printed circuit boards and interconnecting wiring and exceed radiated emissions limits.

The design of electrical/electronic equipment for EMI/HIRF and Lightning environments require different degrees of complexity depending on the criticality level of the functions. However for Critical/Catastrophic systems some or all of the general EMC design considerations listed below may be required to some degree in order to achieve conducted and radiated susceptibility requirements as well as emissions requirements.

5.1.1.2.1 Hardware Equipment Design for Catastrophic/ Critical Functions

As a worse case, assuming no airframe primary and secondary structural shielding, equipment which perform Critical/Catastrophic functions require an EM attenuation of at least 80 dB.

The following are effective design measures to achieve an integrated equipment hardened design for EMI/HIRF and Lightning protection:

a. One piece cast or machined aluminum housing,

b. Metal honeycomb, mesh panels to cover ventilation openings,

c. Conductive coatings or fine wire meshes for display screens or other types of glass windows,

d. Careful bonding of seams and control of screw spacing, as described in section 5.1.1.3.2

e. Seal all covers and connectors with an EMI seal or gasket as described in section 5.1.1.3.2

f. Transient protection devices and feedthrough filters mounted in a shielded filter box as described in sections 5.3.5.3 and 5.3.5.4,

g. Power line filters for common mode and differential mode noise attenuation.

h. Separation and isolation of AC and DC power from signal circuits. Separation is most effective with a 360° EMI bulkhead and feedthrough filters.

i. Separation of noisy high level circuits, clocks, oscillators and digital data from sensitive low level circuits.

j. Short separate ground paths from each circuit, module, or subsystem to a central ground point or terminal.

k. Multilayer circuit board design with power and ground planes as described in section 5.4.2.6.

The package design should include EMC design techniques early in the program. The development of an EMC packaging design checklist should be considered to ensure that all areas of concern are addressed.

5.1.1.3 Shielding

A shield is a metallic partition placed between two regions of space and is used to control the propagation of electric and magnetic fields from one region to another. A shield can be used to contain electromagnetic fields within a region and it may also be used to keep electromagnetic fields out of a region. From an overall systems point of view, shielding the noise source is more efficient than shielding the receptor. However in the case of externally generated HIRF and Lightning the shielding of individual receptors is necessary. In the following sections, shielding is defined as the ratio of the incident to transmitted electric and or magnetic fields and is specified in dB . The design of a shielded enclosure should consider the shielding effectiveness of the shield material and the shielding effectiveness due to discontinuities and holes in the shield.

5.1.1.3.1 Shielding Materials

Material shielding effectiveness varies with frequency, shield material, geometry of the shield, position within the shield, type of field being attenuated, direction of incidence and polarization. This section discusses the shielding effectiveness provided by a plane sheet of conducting material. This example, due to its simplicity, can be easily used to describe general shielding concepts, identify which material properties determine shielding effectiveness, and to estimate the relative shielding ability of various materials. However, the example does not include effects due to the shield geometry.

Electromagnetic waves consist of an electric (E) field and a magnetic (H) field. The ratio of the E to H field is called the wave impedance. If the source current is large compared to its voltage it is a magnetic or low impedance source. If the source operates at high voltage with a small current then the wave is an electric or high impedance source. At large distances and/or high frequencies the wave impedance for both an electric field and magnetic field becomes a constant 377 ohms.

The shielding effectiveness of a conductive barrier is a function of the wave impedance, frequency, material conductivity and thickness. Shielding effectiveness may be considered in terms of reflection and absorption losses as shown in Figure 23. Detailed equations can be found in [1] and [2].

An EM wave striking a conductive surface is partially reflected and the transmitted portion is absorbed. In the case of an electric field source at lower frequencies, the wave impedance is much higher than the metal intrinsic impedance and therefore most of the wave is reflected. As the frequency increases, the electric field intrinsic impedance decreases, decreasing the reflection term, and the ratio between barrier thickness and skin depth increases, increasing the absorption term. For electric fields at high frequencies the absorption loss becomes the primary shielding mechanism. In the case of high frequency electric fields, thin conductive materials a few mils thick will provide more than adequate shielding.

If most of the shielding is due to reflection loss, as in the case of electric field sources, two or more layers of metal separated by dielectric materials and yielding multiple reflections, will provide greater shielding than the same thickness of metal in a single shield. The separation of the two layers of metal is necessary to provide for the additional discontinuous surfaces. The shielding effectiveness of a double shield is less than twice that of a single shield because of re-reflections.

In the case of a magnetic field source, the wave impedance is lower than the metal intrinsic impedance and therefore there is little or no wave reflection. The primary shielding mechanism for magnetic fields is absorption loss. Since the absorption and reflection loss are low at low frequencies it is more difficult to shield against low frequency magnetic fields. Under these conditions the use of magnetic materials should be considered if no alternatives exist. When selecting magnetic materials the following properties should be considered:

a. Permeability decreases with frequency especially for the higher permeability materials as shown in Figure 24. Higher permeability materials, such as mu-metal are most useful for frequencies below 10 KHz.

b. Permeability depends on field strength. Maximum permeability occurs at a medium level of field strength as shown in Figure 25. For field strengths above saturation permeability falls off rapidly.

c. Machining or working high permeability materials, such as mu-metal, may degrade their magnetic properties. This can also happen if the material is dropped or subjected to shock.

Care should be taken when selecting magnetic material because most of the manufacturer's specifications are for the best permeability, at optimum frequency and field strength, and therefore can be very misleading.

Figure 26 shows the shielding effectiveness of aluminum for both magnetic loop and electric dipole. Figures 27 and 28 show the magnetic attenuation for various metallic sheets. Figure 27 shows that magnetic materials such as steel and mu-metal make a better magnetic shield at low frequencies, below 100 KHz, but at higher frequencies good conductors, such as copper and aluminum, provide a better magnetic shielding.

Since HIRF fields are electric and plane wave fields, the aluminum skin and enclosure wall thickness do not require to be any more than a few mils thick. For Lightning induced, fast rise time magnetic fields, aluminum skin thickness typical of aircraft structures should provide adequate shielding.

Honeycomb structural shielding effectiveness is due to the use of waveguide below cut-off concept for each of the cells. The waveguide below cut-off effectively attenuates EM fields if there is no metal conductors going through the cell. A cell with a conductor through the center is like a coaxial line which has no cut-off frequency and therefore is not very effective for EM field attenuation. Honeycomb structures should have a cell diameter no greater than 1/20 of the smallest wavelength/largest frequency for which immunity is required. The cell length should be at least three times the cell diameter. In order to be effective, honeycomb structures should have a good electrical bond between cells.

The shielding effectiveness of screens and perforated metals foils takes into account the attenuation effects of individual apertures acting as waveguides below cut-off, reflection losses associated with aperture geometry, area of the openings in comparison to distance between the holes, skin depth effects and coupling between closely spaced openings. Expressions to estimate the shielding effectiveness for a mesh or perforated metal plate are provided in MIL-HDBK-419, volume 1, section 8.4.3. The principal shielding action of a mesh is due to EM field reflection. Tests have shown that meshes with 50 percent open area and 60 or more strands per wavelength introduces a reflection loss very nearly equal to that of a solid sheet of the same material. Figures 29, 30 and 31 shows the calculated and measured shielding effectiveness for various copper screens.

Apertures used for windows, visual displays, alphanumeric displays etc, requiring a high degree of optical transparency should use transparent conductive coatings and/or wire mesh screens. The transparent coatings thicknesses are on the order of microns and can be vacuum deposited onto plastic or glass. Since these coatings are very thin there is very little or no absorption loss and the primary shielding comes from reflection. Therefore those coatings are only effective for electric fields or plane waves. Figures 32 and 33 show the shielding effectiveness of coatings with a resistivity of 10, 50 and 200 ohms/square. For frequencies above 100 MHz where the field wave impedance is approximately 377 ohms, the shielding effectiveness is mostly due to reflection and becomes relatively constant. For a 10 ohms/square coating this value is on the order of 25 dB. Since the shielding effectiveness improves with increasing thickness and optical transparency deteriorates with increasing thickness, trade-offs must be made. Figure 34 shows optical transmission versus surface resistivity. Typical conductive coatings include gold or indium tin oxide (ITO).

Wire mesh screens can be laminated between two clear plastic or glass sheets. In all wire mesh screens, bonding of wires at the crossover is required for good shielding effectiveness. Knitted wire mesh screens range between 10 to 150 conductors per inch with optical transparency ranging from 65 to 98%. Shielding effectiveness for several screens are shown in Figure 35. These screens provide better shielding effectiveness and better optical transparency than conductive coatings but they can inhibit viewing due to diffraction. In order to minimize diffraction, the screen wire orientation should be placed at a specific angle.

The conductive window, screen or coating, must be mounted to ensure electrical contact to the mounting enclosure along the entire perimeter of the aperture. In the case of conductive coatings, silver bus bars are placed around the edges of the glass and used in conjunction with an EMI gasket to provide good electrical contact. Wire screens usually include an EMI gasket.

Plastics and composites can be made conductive by either coating them with a conductive material or by using conductive fillers. To be effective as electromagnetic shields, conductive plastics should have surface resistivities of a few ohms per square or less. Some of the more common methods of producing conductive plastics are:

a. Conductive paints: Mixture of as much as 80% metal, most commonly nickel, and only 20% organic binder. Can be easily applied with standard paint equipment.

b. Flame/arc spray: Aluminum or zinc melted in a special spray gun and deposited onto plastic, producing a dense and uniform coating of metal with excellent conductivity.

c. Vacuum metallizing: Pure metal, usually aluminum, boiled in a vacuum chamber and deposited onto the surface of the plastic parts producing excellent conductivity. Can be applied to complex parts.

d. Electroless plating: Metallic coating, usually nickel, deposited by a controlled chemical reaction producing uniform film-thickness with very good conductivity. Can be applied to simple or complex parts.

e. Metal linings: Materials include foils, expanded metals foils or metallized clothes laminated in the plastic part. Shielding effectiveness for the expanded metal foils can be estimated using equations in MIL-HDBK-419, volume 1, section 8.4.3. **For the DHC-8 Series 400, airframe primary and secondary composite structures shall use expanded aluminum foil embedded into the composite structure (DHMS P1.64 type 1 and 2).** A sheet of expanded aluminum foil 0.007 inches thick with an open area of no more than 60% and largest hole dimension of 1/16 inches will provide a minimum of 20 dB attenuation up to 10 GHz for an electric and plane wave field.

f. Conductive composites are produced by mixing a conductive agent, such as fibers, flakes or powders, with plastic resin prior to molding. Typical conductive fillers include carbon fibers, aluminum flakes, nickel-coated carbon fibers, or stainless steel fibers. Loading levels of conductive fillers may vary from 10 to 40% in order to get the required electrical properties. Since the conductive material is inside the plastic, the main disadvantage is that the surface may not be conductive. The control of conductivity across the seams and joints may become a problem and may require a secondary machining operation.

5.1.1.3.2 Shield Discontinuities

The total shielding effectiveness of a shielded enclosure is limited by the ability of the seams to make adequate electrical contact. The amount of leakage from shield discontinuities depends mainly on the following:

a. Maximum linear dimension (not area) of the opening

b. The EM wave impedance

c. The frequency of the source

A rectangular opening or seam may be modeled as a long narrow slot. Slot antennas can cause considerable leakage if the length is greater than 1/100 of wavelength. For a slot antenna, maximum radiation occurs when the length is equal to a half-wavelength. Figure 36 shows that slots or shield discontinuities, even if narrow but a few inches long, will severely reduce the shielding capability above 100 MHz. The impedance across a seam consists of a resistive and capacitive component in parallel as shown in Figure 37. The impedance of a seam depends on many factors such as the material interface, contact pressure and the overlap area. The following are guidelines for the seam design:

a. The overlap area should be as large as possible in order to increase the effective capacitance between adjacent surfaces. For a metal-to-metal interface seam, the overlap should be no less than five times the gap between the surfaces forming the seam.

b. The material on both sides of the seam should be electrically conductive. In order to minimize corrosion, seam materials selection should be as described in Table 10 of section 5.2.2.4.5. Table 7 lists some conductive finishes for aluminum and carbon steel. For stainless steel, passivation should be adequate. For further information on conductive finishes refer to MIL-STD-889 and ESP 64-400. Most other finishes such as anodizing and black chromate are non-conductive and should not be used. Figure 38 shows the shielding effectiveness degradation with surface finishes.

TABLE 4. Conductive Finishes for Metals

Aluminium	Carbon Steel
Clear chromate (iridite)	Zinc chromate
Yellow chromate	Zinc plate
Tin plate	Cadmium plate
Nickel plate	Tin plate
Alodine	Nickel plate
Conductive paints	Conductive paints

c. When good shielding characteristics are to be maintained, permanent mating surfaces or metallic members should be bonded by welding, brazing, sweating, swaging or other metal flow processes. Soldering may be used to fill a seam but should not be employed to provide bond strength.

d. Rivets and screws are considerably less effective. To minimize slot size, screw spacing should be no more than 1/20 of the smallest wavelength/

largest frequency for which shielding is required.

e. If high levels of shielding are required into the GHz frequency range, then the use of EMI gaskets should be considered. EMI gaskets include meshes, expanded metals and loaded elastomers. Gasket conductive materials include silver, copper, aluminum and monel with finishes like tinplating and nickel plating. The gasket materials should be compatible with mating surfaces to minimize corrosion. Figure 39 shows correct and incorrect ways to install an EMI gasket. Figure 40 shows different ways of installing EMI gaskets.

For the DHC-8 Series 400 EMI gaskets should not be used on primary structure. In addition, secondary structures such as the cockpit and fuselage floors should not use EMI gaskets. In both cases, shielding should be obtained by proper seam design described in paragraphs a) through d).

A measure of seam performance is usually provided in terms of an interface transfer impedance. Transfer impedance is the ratio of the voltage across the seam divided by the current density across the seam. The units are in ohms-meter. Figures 41 - 45 inclusive show values of interface transfer impedance for various seam designs and gaskets. The effects of applied pressure and environment (salt spray, temperature and humidity) are also shown.

5.1.1.3.3 Grounding of Shields

A solid shield with no external connections and completely surrounding a circuit, can be at any potential and still provide effective shielding. In most cases, the shield is not a complete enclosure and it does have connections to the outside world, either directly through signal and power leads, or indirectly through stray capacitance due to holes in the shield. In these cases, the shield must be grounded in order to prevent its noise potential from coupling to the enclosed circuitry. The potential of an ungrounded shield will vary with conditions and location and therefore the noise coupled to the circuitry inside will also vary. Grounding of the shield has a number of additional benefits as described section 5.2. For these reasons, shields should be grounded. Shield bonding should be as described in section 5.2.2.

5.1.2 Lightning Direct Effects

The Supplier must design the protection measures to ensure that a Lightning strike does not affect the continued safe flight and landing of the aircraft. The protection measures should also ensure:

a. Flight crew and passenger safety

b. Minimize damaging effects on structural components, and possible malfunction/damage to equipment

c. Ease of repair, maintenance and inspection

It is important that Lightning protection is optimized, with consideration given to the following factors:

a. Cost (manufacture and repair)

b. Weight penalty

c. Ease of application

d. Durability

e. Reparability

f. Drapability-ability to cover complex shapes and surfaces

g. Corrosion

h. Detection of degradation/damage.

i. Methods of joining and electrical bonding

The basic Lightning protection for the aircraft can be achieved by ensuring that adequate paths are available for conduction of the Lightning currents. To obtain these objectives, consideration must be given to the Direct Effects of Lightning on the following aircraft structures and systems:

a. Structure:

Metallic

Conductive composite (carbon fibre)

Non-conductive composite (glass/aramide fibre)

Hinges, Bearings, Actuators

b. Systems:

Fuel

Electrical

Hydraulic

Externally mounted equipment

5.1.2.1 Structure

The Direct Effect of Lightning on aircraft structures include the following effects that must be evaluated relative to the aircraft zones for assessing the components vulnerability.

Heating Effects:

The instantaneous power dissipated as heat in a conductor due to an electrical current is i^2R watts. The heat generated by the complete Lightning pulse is therefore the ohmic resistance of the Lightning path through the aircraft multiplied by the action integral of the pulse.

Explosive Forces:

Where conductors having a small cross sectional area are required to carry a substantial part of the Lightning current, they may vaporize explosively. The associated shock wave can give rise to severe damage particularly in confined spaces. This failure mechanism is particularly significant in electric wiring connected to external equipment, e.g. navigation lights, antennas, pitot heater, etc. In addition, current flow in small cross section metal foils encapsulated in a dielectric, such as an externally mounted blade antenna, or internal arcing that may result from the lightning penetration of a non-conductive cover such as a radome, can present a hazard from disruptive forces.

Arc Root Thermal Damage:

Burn through and material erosion can occur at the Lightning arc root. In metal, this is mainly a complex function of current and time. In the arc root area, there is a large thermal input from the arc root itself, as well as a concentration of ohmic heating due to the high current densities. Most of the energy is generated at or very close to the surface of the metal, and must therefore be dissipated by conduction. If the heat generated in the immediate arc root area is excess of that which can be absorbed into the metal by conduction, then the excess heat is lost in melting and vaporizing.

In carbon fiber composites the thermal effects are more pronounced due to the lower thermal conductivity and higher electrical resistance. This leads to an increase in damage area in relation to the depth of damage. The arc root burning voltage of carbon is higher than that of metals. This effect, plus the high bulk resistivity, generates more heat in the immediate arc root area and the hot spots remain for a longer period than for most metals. Thus, short duration high action integral pulses as well as low current, long duration pulses produce high thermal inputs, and so all phases of the Lightning flash are significant in producing arc root damage in carbon fiber composites.

Hot Spot Formation:

Hot spot formation may occur on the inner surface of the aircraft skin due to arc root attachment and local high current densities. The effects of hot spots are usually only significant with regard to ignition of fuel and other high flammable substances. For aluminum skins, puncture will usually occur before a hot spot can develop. However, carbon fibre skins and titanium skins may develop hot spots before burn-through occurs.

Acoustic Shock Wave Damage:

At the commencement of the first return stroke, there is a rapid pinching of the arc channel due to the increase in the magnetic field surrounding the channel which produces a radial acoustic shock wave. At the same time, the rapid heating of the arc channel itself produces an axial shock wave. The latter is probably the most significant in terms of its interaction with the aircraft. The severity of the shock is dependent upon both the peak current value and the rate of rise of the current. In general, the damage due to acoustic shock wave is significant on metal skins. However less malleable composite skins can rupture.

Magnetic Pressure:

This pressure is only significant when the surface current density is greater than several kilo amperes per millimeter. For example, a conductor of five millimeters diameter carrying a pulse of 200 kA peak current would experience a surface pressure of 1000 atmospheres. The pressure is proportional to the square of the current i^2 and the inverse square of the diameter. Doubling the diameter or halving the current would reduce the pressure to 250 atmospheres. However, in some cases even relatively small pressures can be significant, such as the case of metal braid bonding straps. These straps can be compressed to near solid conductors leading to metal embrittlement and subsequent mechanical failure.

Magnetic Interaction:

Considerable magnetic forces can exist from the interaction of the magnetic fields of two current carrying conductors. This force may exist between two separate sections of the same conductor where the Lightning current is forced to change direction or between the aircraft and the Lightning arc channel. This force is usually only of significance where the Lightning current is confined to small cross section conductors as might occur in some externally mounted equipment. The peak value of the force is proportional to the square of the peak current i^2. The force can cause distortion in current carrying conductors.

Direct Effects Sparking:

Direct effects sparking occurs when very high currents are forced to cross a joint between two conducting materials, or forced to take very convoluted paths. Two different types of sparking can occur; thermal sparking and voltage sparking. The most common type of sparking is thermal sparking which occurs between mating surfaces where the contact pressure is low and the current density is high. Thermal sparks consist of molten or vaporized materials and generally have a higher energy content and a longer duration than voltage sparks.

Dielectric Puncture:

The puncture of any dielectric skin covering electrically conductive elements may range from small pin holes to large diameter holes and could permit direct attachment of the Lightning channel to the enclosed equipment. The probability of puncture of a dielectric will be a function of the presence of any conductor underneath the dielectric (which raises the electric field stress), the thickness and strength of the dielectric, the condition of the dielectric surface, and the proximity of other conducting surfaces. As a general guide, puncture of the dielectric must be considered possible unless the voltage required to puncture the dielectric at any point is significantly greater than the voltage required to cause flashover to the nearest external conducting metallic structure. The conditions for dielectric puncture are generated in the pre-discharge phase and at the onset of the first return stroke phase of the Lightning flash. Puncture might also occur as a result of electric fields associated with a subsequent stroke, or a swept stroke reattachment.

5.1.2.1.1 Metallic Structure

Most metallic structure can be adequately protected from the Direct Effects of a Lightning strike by selecting the correct thickness of material. All possible Lightning paths across and through the aircraft must be taken into consideration. The worst case amplitudes/current densities must be taken into account as a basis for the analysis.

5.1.2.1.1.1 Damage at Lightning Arc Root Attachment (Zones 1 and 2)

Heating Effects (Thermal and Resistive)

Typical Damage:

a. Erosion

b. Vaporization

c. Pitting, melting

d. Hot spots (mainly carbon fibre and titanium materials)

e. Melt-through (puncture)

The extent of damage will depend on the material thermal and electrical properties.

Complete melt-through and hot spots are dependent upon the type of material, thickness, surface finish and location on the aircraft. Melt-through and hot spots must be prevented in areas containing flammable fluids or vapors. Figures 46 and 47 show melt-through and hot-spots thresholds for varying thicknesses of aluminum and titanium skins.

Protection Methods

For integral wing fuel tanks, located in a swept stroke zone 2A including the dry bay area adjacent to the inboard fuel tank boundary, an aluminum skin thickness of 0.08 inches has been accepted as giving adequate protection to prevent melt-through. Thinner metallic skins for the fuel tank may be acceptable using adhesively bonded aluminum skins. However, simulated Lightning tests should be performed to ensure that the design will prevent puncture and hot spots or arcing at joint positions.

For other structural components (e.g metallic fairings) puncture of the outer skin may be acceptable. However, if puncture occurs then it must be shown by test and/ or analysis that the integrity of the structure is maintained for the continued safe flight and landing of the aircraft and the time and cost of repair is minimized. Analysis should take into account the effects of mechanical loading (limit load) and also consider the aerodynamic forces flowing across or into the perforation or hole. In some cases, these forces can cause partial or total detachment of the component.

Non-conductive finishes such as anodizing and painting will affect the dwell time of the Lightning attachment. An increase in dwell time will result in more extensive localized damage (i.e depth and area of damage).

Mechanical Forces (Shock or Stress Waves)

Typical Damage:

a. Denting
b. Bending
c. Deformation.

Protection Methods

The material thickness and mechanical properties (e.g malleability etc.) as well as the mechanical support of the component are the most important factors in preventing this type of damage.

5.1.2.1.1.2 Damage at Joints and Interfaces (Zones 1, 2, 3)

Arcing and Sparking (Voltage and Thermal)

Typical Damage:

a. Pitting
b. Welding
c. Source of fuel vapor ignition
d. Damage or sparking at couplings/bearings.

Protection Methods:

Arcing and sparking must be prevented in areas containing flammable fluids or vapors. Protection can be provided by ensuring low impedance path(s) (metal to metal contact, fasteners, or bonding jumpers) across joints and interfaces.

The following methods are considered to be acceptable for the transfer of Lightning currents across main structural component joints:

a. Permanent Joint: welding/brazing

b. Semi-Permanent Joint: bolts (interference fit), screws, solid rivets

c. Metal to metal faying surfaces which are free of any non-conductive finishes

d. For structural components using clearance fit holes, conductive bolts [i.e metallic bolts with either no finish or a conductive finish e.g Ion Vapor Deposited (IVD) coated] should be used to ensure an adequate conductive path

e. Where a counter-sink bolt is used to connect a skin panel with an internal component (e.g stiffener/stringer) , the counter-sink should be free of all non-conductive finishes

Magnetic Forces (attraction and repulsion)

Typical Damage:

a. Buckling

b. Bending

c. Crimping

Protection Methods

The thickness of the material and the mechanical support structure of the component will be the most important factor in preventing this type of damage. Thin metallic trailing edge located in zone 1B/2B structures should be adequately reinforced to prevent crimping effects.

5.1.2.1.2 Conductive Composite (Carbon Fibre)

When a carbon fibre structure is struck by Lightning it suffers far greater damage than an equivalent aluminum alloy structure. The majority of areas utilizing composite structures may require additional protection in the form of metallic mesh or foil to reduce damage to an acceptable level.

The need to apply surface protection or not should take into account the criticality of the structure and its location relative to the Lightning zones determined for the aircraft.

Typical damage to a composite structure at the arc root attachment will be:

a. Burning/vaporization of resin

b. Delamination

c. Tufting

d. Puncture or development of hot spots

Although Zone 3 areas have a low probability of direct Lightning attachment, the event must be considered possible if any adverse consequences could affect the continued safe flight and landing of the aircraft.

5.1.2.1.2.1 Types of Protection

It is recommended that protection be applied to all carbon fibre structures in Zones 1 and 2 unless the structure can be designed to minimize the effect of a Lightning strike.

Lightning protection of composites can take many forms, but in general they involve adding metal to the outer ply surface. The following methods of protection are recommended for surface and trailing edge protection:

Surface Protection (Lightning Zones 1A or 2A):

Expanded aluminum foil should be incorporated in the outer ply. The installation must ensure that an adequate electrical connection between the foil and aircraft structure. This may be achieved by laying the foil in the counter-sink and bonding through the fastener installation. An insulating layer is required between the perforated aluminum foil and the carbon fibre to protect against corrosion.

Trailing Edge Protection (Zones 1B or 2B):

Solid aluminum strips with a minimum cross sectional area of 20mm^2 (AWG 4; 40,000 circ mils) should be used. This will limit the temperature rise to 100^{o}C for a

200 KA zone 1B attachment so as to protect the underlying structure from any significant damage. The diverter strip should be mounted externally to the structure. A larger cross-section may be required to meet the mechanical strength requirements. The trailing edge diverter strip should have adequate contact to the primary aircraft structure. This can often be achieved by using a picture-frame network of diverter strips which form a continuous path for the Lightning currents around the periphery of the structure being protected. A thin layer of insulation (i.e glass fibre scrim) is recommended between the carbon fibre surface and the metallic protection to reduce the extent of damage to the carbon fibre skin. This insulating layer will also provide protection against the possibility of corrosion. If bonding jumpers need to be used to connect across joints or hinges, then sufficient cross-section must be used (see section 5.1.2.1.4).

5.1.2.1.2.2 Protection Verification

Suppliers are responsible for demonstrating by test, similarity and/or analysis, that the Lightning protection incorporated in their designs can withstand the Direct Effects of Lightning. Verification of protection by analysis/similarity using data from previously certificated aircraft is acceptable subject to de Havilland approval.

All qualification tests should be conducted in accordance with MIL-STD-1757A to the test levels and waveforms shown in Table 4. Externally mounted electrical/ electronics equipment should be tested to RTCA/DO-160C, section 23.

5.1.2.1.3 Non-Conductive Composite [Glass/ Aramide Fibre (GFC/AFC)]

Lightning strike damage to a non-conductive composite (e.g glass or aramide fibre), such as radomes, fairings and control surfaces, may result in puncture and perhaps detachment of the component from the aircraft.

The probability of puncture will be a function of the presence of any conductor (e.g metallic pipes, cables, probes, antenna elements, etc.) located beneath the component as well as the thickness and dielectric strength of the component. As a general guide, puncture of the dielectric must be considered possible unless the voltage required to puncture the dielectric at any point is significantly greater than the voltage required to cause flashover to the nearest external metallic structure.

The need to apply surface protection should take into account the criticality of the structure and its location relative to the aircraft Lightning zones. Adequate protection shall be verified by high voltage and high current testing using a representative test article.

Although Zone 3 areas have a low probability of being struck, the event must be considered possible if any adverse consequences could affect the continued safe flight and landing of the aircraft.

5.1.2.1.3.1 Types of Protection

The surface protection used for carbon fibre structural components section 5.1.2.1.2.1 can also be used for glass aramide fibre components.

For dielectric covers which enclose equipment that require transparency to radio signals (e.g radome, antennas), the use of solid aluminum diverter strips (20mm2 minimum cross sectional area) are recommended. The strips are mounted on the outer surface of the component and electrically bonded to the aircraft structure. The configuration of the diverter strips must be optimized to meet both Lightning protection and equipment operating performance requirements. Typical diverter strip configurations are shown in Figures 48 and 49. Figures 50 and 51 show methods for grounding diverter strips to the airframe and give an optimized solution for protection of a radome from puncture.

In addition, the possibility of puncture may be reduced by coating any internal metallic objects with a non-conductive layer (e.g painting, plastic coating etc).

The use of segmented diverter strips is not recommended.

5.1.2.1.3.2 Protection Verification

Figure 52 shows a flow chart that should be utilized when verifying Lightning Direct Effects protection design.

5.1.2.1.4 Hinges, Bearings and Actuators

It is recommended that all hinges, bearings and actuators which may carry a portion of the Lightning current be protected by bonding jumpers to minimize the damage due to arcing at non-conductive joints and interfaces [e.g PTFE (teflon) lined bearings etc].

For components where there is only one transfer position between the component and the main airframe, it is recommended that a single tinned copper bonding jumper AWG 6 (13mm^2; 26250 circ. mils) is used. For components where there are two or more currents paths (e.g control surface hinges), a single tinned copper bonding jumper AWG 8 (8mm^2; 16510 circ. mils) should be used at each position. Care should be taken to ensure that bonding jumpers are installed in a manner which is as direct as possible so as to avoid magnetic interaction (see Figure 53). Bonding jumpers across poor or non conductive joints/bearings are also necessary to ensure an acceptable level of conductivity between the structural components and the main metallic aircraft structure to prevent the accumulation of electrostatic charge. Care should be taken to ensure that the installation of the bonding jumper does not create a potential hazard for jamming a movable mechanism.

In non-fuel tank areas, the MS25083 tinned copper bonding jumper is recommended. For most bonding jumper applications involving main structural components as well as equipment bonding, a flat bonding strap (i.e low impedance) is preferred over a circular type. Refer to EM group for flat bonding strap part numbers. For high temperature applications >300°F, consult the EM group for bonding jumper P/N.

5.1.2.2 Systems

5.1.2.2.1 Fuel Tank

Main fuel system components which must be considered for design and vulnerability assessment include the following:

a. Skin thickness and material
b. Fuel tank skin joints/structural interfaces
c. Magnetic fuel level indicators
d. Fuel vents/drains
e. Fuel pumps
f. Pressure refueling system
g. Manual filler caps
h. Access covers
i. Fuel quantity probes
j. Electrical equipment and wiring

k. Fuel pipes/fittings/couplings

A Lightning arc attachment or current flow in a fuel area can create the following major sources of fuel ignition hazard:

a. Puncture of the fuel tank skin

b. Heating of the fuel tank skin to a sufficiently high temperature to initiate a hot spot ignition. Aluminum skins will not develop hot spots as melting and puncture will occur before a hot spot will develop. However, highly resistive metals such as titanium and carbon fibre must be considered for hot spots.

c. Sparking occurring within the fuel air environment, typically at bolted joints, fuel pipe connections, access doors, filler caps, pumps, drains, fuel level indicators or electrical wiring/probes.

d. Arcing between conductive elements isolated from each other, due to potential differences arising from the flow of Lightning currents through the airframe.

e. Sparking due to current transfer between an interface that has insufficient contact area or has a high resistance or intermittent contact (see Figure 54).

f. Lightning attachment to a fuel vent, outlet or drain initiating flame front propagation into the fuel tank.

5.1.2.2.1.1 Protection Method and Design Considerations

In general fuel tank boundaries including surge tanks and dry bays should not be located in Lightning Zone 1A.

Integral tanks form part of the aircraft skin in areas such as the wings. For this reason the skin thickness must be adequate to prevent puncture and ignition due to direct Lightning attachment. In a Lightning Zone 2A a skin thickness of 0.080 inches has been generally accepted by experience based on in-service aircraft data as giving sufficient protection to prevent melt-through.

The following design considerations must be addressed to ensure fuel system Lightning protection:

a. If possible locate fuel system components in a Lightning Zone 3 area

b. Ensure that fuel tank structures and systems are electrically bonded to the aircraft structure and are capable of carrying Lightning currents without sparking

c. Ensure that any interfaces which may spark are sealed (e.g O'ring seal) to prevent the spark from entering the fuel area

d. Ensure sufficient gaps are provided inside the tank between aircraft structure and plumbing (0.25 inches minimum) to prevent voltage breakdown and sparking. It should be noted that determination of breakdown voltage must take into account the effects of altitude (i.e reduced air pressure at altitude will allow a lower breakdown voltage than sea level)

e. Use flush mounted NACA vents located in Lightning Zone 3 ensuring that all skin and joint interfaces are electrically bonded and are capable of carrying direct Lightning arc attachment currents or conducted Lightning currents without sparking

f. Incorporate a shroud to prevent a direct Lightning attachment to the exposed drain lines

g. Utilize non-conductive inserts in drain lines to prevent conduction of Lightning currents into the connected system or fuel tank

h. Ensure that fuel system pipes/couplings are well bonded to structure and are capable of conducting Lightning currents without sparking

i. Select components which have been Lightning tested and approved

The following sections provide more detailed design considerations for fuel system Lightning protection.

5.1.2.2.1.1.1 Access Doors and Panels

It is extremely important to establish an access door design which will transfer Zone 1A or 2A Lightning currents without creating sparks within the fuel or fuel vapor environment. Protection methods and design considerations include:

a. Provide an adequate electrical bonding path through the attachment screws or door/wing structure mating surfaces

b. Construct the door from aluminum of 0.080 inches minimum thickness.

c. Utilize the fuel seal (O'Ring) to isolate any interfaces which may spark, from the fuel environment

d. Use capped anchor nuts and ensure good oversealing (see Figure 55)

e. In some cases a metallic gasket may be used to ensure a good metal to metal interface between the access door and wing structure

It should be noted that for simulated Lightning test purposes, the sealant should be omitted from the internal nut positions so as to verify that the access door and fastener joint are spark free. The sealant should be used to provide an additional method of protection, but due to the problems associated with the consistency of application and integrity of the sealant during the life of the aircraft, the sealant should not be solely relied upon to prevent sparking.

5.1.2.2.1.1.2 Fuel Pipes/Fittings/Couplings

Fuel pipes may carry a proportion of the current during a Lightning strike. Attention must be paid to ensure that the flow of current does not cause arcing or sparking across pipe joints, couplings and interfaces to structure due to non-conductive finishes or poor metal to metal joints.

There are a number of options available to overcome this problem, each of which should be validated by suitable analysis and/or test (See Figure 131):

a. Ensure adequate bonding at all joints, interfaces and couplings by using inherently conductive materials such as aluminum or titanium and by removing non-conductive finishes such as anodize. In some cases, bonding jumpers may also be required to ensure a sufficient conductive path

b. Use non-conductive inserts or spark gaps (recommended 1 inch (25mm) minimum gap) to prevent current flow along the pipes. If a non-conductive insert is used, then it must be ensured that each section of pipe is electrically bonded to aircraft structure

c. Self bonded fuel tank couplings

d. All metallic plumbing must be electrically bonded to aircraft structure at the entry/exit point to the fuel tank

The loss of a single bonding jumper should not result in an unbonded section of pipe i.e. each pipe section should have a minimum of two bonding paths to aircraft structure.

Fuel line couplings, joints and interfaces to structure must be verified by high current tests to ensure that they can carry conducted Lightning currents safely without arcing/sparking. The tests shall be carried out at a minimum peak current of 1500 amperes using waveform B (FAA AC20-53A).

5.1.2.2.1.1.2.1 Fuel Probes

Fuel quantity probes may be subjected to high voltages due to the flow of Lightning currents along the wing structure and induced voltages in the associated cable harnesses. If a significant voltage (KV) is developed between the probe and structure, then there is the possibility of a voltage spark which could be of sufficient energy to ignite the fuel vapor/air mixture.

When determining the breakdown voltages of the Fuel Quantity Indicator (FQI) Probes, test voltages must be applied to all of the electrode combinations which may exist (see Figure 56). It must be demonstrated by test or analysis that the Lightning induced voltage existing between probe and structure is lower than the probe to structure sparkover voltage by a safety margin of five. A minimum air gap of 0.25 inches is recommended between the probe and aircraft structure including metallic objects connected to the aircraft structure such as bonding jumpers and brackets.

Test shall be carried out between the following probe elements and it must take into consideration the flight altitude of the aircraft:

a. High to low terminals
b. High to airframe
c. Low to airframe

5.1.2.2.1.1.2.2 Manual Filler Caps and Water Drains

Manual fuel filler caps must meet the Lightning requirements of MIL-C-38373. It is recommended that fuel/water drains have been Lightning qualified by the vendor.

New designs must be subjected to simulated Lightning strike tests to ensure that no sparking takes place in the presence of any ignitable fuel mixture. A simulated Lightning test or an adequate analysis must be carried out to verify that the filler cap/water drain to aircraft interface is either spark free or demonstrates that any sparking occurs outside the fuel area.

5.1.2.2.2 Electrical Systems

Electrical equipment and the interconnecting cables, may become part of the conducting path either by direct Lightning arc attachment or by the conduction of Lightning currents through the airframe. Adequate bonding of the equipment housing and the cable shields (where applicable), is usually sufficient to provide protection against the Direct Effects of Lightning. For equipment or cables exposed to flammable vapors, special bonding arrangements may be required (see fuel system section for specific requirements).

Electrical/electronic equipment must also meet the EMI, HIRF and Lightning requirements of ESP 89.

5.1.2.2.3 Hydraulic Systems

Hydraulic pipes and equipment often provide a path for conducted Lightning currents. To prevent sparking due to Lightning and static electricity hydraulic pipes should have adequate bonding provided from the pipe to structure as well as between sections of pipe. Hydraulic pipes should use conductive couplings which will allow the flow of Lightning currents without sparking. In order to eliminate sparking across a coupling or joint, it may be necessary to incorporate bonding jumpers of adequate cross-section. The adequacy of a coupling to carry Lightning currents, should be verified by test. If the flow of Lightning current through the pipe(s) is unacceptable, a non-conductive insert should be used which has a minimum spark gap of 1 inch.

For actuators and other hydraulic equipment that may carry Lightning currents, low impedance bonding jumpers should be used to prevent damage at any non-conductive interfaces (e.g. PTFE lined seal at piston etc).

5.1.2.2.4 Externally Mounted Equipment

As a functional requirement, some equipment must be installed outside of the main aircraft structure in areas that are susceptible to Lightning strikes.

The installation techniques and protection features of each item of equipment in this category must be analyzed to establish the effect of a direct Lightning strike or conducted Lightning current to ensure the continued safe flight and landing of the aircraft. In addition the protection features must minimize the extent of damage as well as the time and cost of repair.

As a general rule, external equipment should be located in a designated Zone 3 area of the aircraft structure.

The following items are considered within the scope of external mounted equipment:

a. Antennas

b. External lights

c. Sensors including pitot probes, static probes and air temperature probes

d. Drain masts

e. Waste water

f. Vents and outlets

g. Cockpit windscreen deicing

h. Landing gear

i. Access doors and panels (non-fuel areas)

Each Supplier shall identify, in their Control Plan, the structures, systems and components which may be affected and could cause a hazard to the aircraft.

5.1.2.2.4.1 Antennas

The main consideration for antennas is to divert the Lightning strike from the antennas to the aircraft structure, without injecting current or voltage transients into the cable looms and electrical equipment. In most cases this is achieved by electrically bonding the antenna to the metallic aircraft structure by means of the fixing screws in accordance with the manufacturers requirements.

In a number of cases, the antenna itself is located beneath a non-metallic cover. The cover should be designed to prevent puncture by a Lightning strike. High voltage and current testing should be performed in accordance with RTCA/DO-160C Section 23 to verify adequacy of protection. If puncture occurs during high voltage testing, then high current tests to the antenna element must be carried out to establish what effects a current or voltage transient will have on the connected cables and equipment.

Where direct attachment is possible, protection devices, such as surge arrestors, should be considered to prevent Lightning transients from being transmitted to interconnecting equipment.

5.1.2.2.4.2 External Lights

In order to minimize the probability of a direct arc attachment to the light filament, it is recommended that the metallic light housing and mounting brackets are electrically bonded to the aircraft structure using metal to metal contact.

High voltage and current testing must be performed in accordance with RTCA/DO-160C Section 23 to verify adequacy of protection. If puncture occurs during high voltage testing, then the high current test to the light element must be carried out to establish what effects a current or voltage transient will have on the connected cables and equipment.

5.1.2.2.4.3 Sensors

Sensors which are mounted on the external structure may be prone to a direct Lightning attachment.

Protection methods include:

a. Locate sensors in Lightning Zone 3

b. Flush mount where possible

c. Install to manufacturers requirements

If a direct attachment to the sensor is possible, then an analysis and/or test must be carried out to confirm the effect on the sensor and the interconnected equipment. Testing should be carried out in accordance with RTCA/DO-160C Section 23.

5.1.2.2.4.4 Drain Masts (Non Fuel)

Drain Masts should be located in Lightning Zone 3 where possible. Metallic drain masts should be electrically bonded to the airframe at the exit point to ensure that both P-Static and Lightning currents can be transferred to the airframe. All drain lines which are exposed to a direct or swept stroke attachment (i.e Zones 1 or 2), must be provided with either a non-conductive insert (minimum gap of 1 inch) to prevent current flow internal to the airframe or designed with a nonconductive shroud to prevent a direct Lightning attachment to the drain line.

Testing may be required to ensure that the joints and interfaces are spark free and that no hazard to the aircraft will result from direct Lightning attachment.

5.1.2.2.4.5 Vents and Outlets (Non Fuel)

Vents and Outlets must be located in Lightning Zone 3 where possible. If located in Zones 1 and 2, then precautions should be taken to prevent a direct Lightning attachment to the outlet or prevent current flow along the connected lines internal to the airframe..

Protection methods include:

a. Flush mount

b. Direct electrical bonding of vent or outlet (i.e metal to metal faying surface) to the airframe at exit position and/or

c. Use of non-conductive insert in section of pipe (minimum gap of 1 inch)

5.1.2.2.4.6 Cockpit Windscreen De-Icing

Cockpit windshields must be protected against the Direct Effects of Lightning and integrated with the protection for static electrification to reduce the risk of puncture and window shattering as well as the injection of transients into the windshield heating system.

The materials used to fabricate the windshields/windows must have a high dielectric strength and should incorporate design features to bleed static charge from the external surface of the window due to triboelectric charging of the aircraft. In addition, the windshield heating element must be designed to minimize the electric field concentration that could cause streamer initiation. In general, thin film designs may be more effective than a wire grid.

The heating circuit should be protected from Lightning induced voltage transients which may occur from a nearby or direct Lightning attachment to the heater element. Over-voltage transient protection devices as described in section 5.3.5.4 are recommended.

5.1.2.2.4.7 Landing Gear

The landing gear is exposed to direct Lightning attachment while in the extended position.

Protection of equipment located on the landing gear may be achieved by adopting the following design practices:

a. Metallic housings must be well bonded to the landing gear main structure
b. Cable protection should be provided using solid metal tubes and/or flexible metallic braid
c. All metal components of the landing gear should be electrically interconnected and electrically bonded to the aircraft preferably without reliance on the use of bonding jumpers

5.1.2.2.4.8 Access Doors and Panels (Non-Fuel Areas)

A direct Lightning attachment to an access door or panel, may create sufficient mechanical and magnetic forces to operate or in some cases weld latches and/or hinges. For example, a welded latch on a pressure relief door (engine nacelle) would need to be assessed to ensure that this would not affect continued safe flight and landing of the aircraft. The opening of an access door during flight as a result of a Lightning attachment could result in detachment of the door. These concerns may be overcome by ensuring adequate electrical bonding of the door latches and hinges and by providing a sufficient level of mechanical latching.

A piano type hinge is usually sufficient to ensure a good current path to the airframe. Bonding jumpers are required between the access door and airframe if adequate bonding is not ensured by the hinge and latch design.

5.1.3 P-Static

To prevent the accumulation of P-Static, described in section 4.4, the following techniques will be used:

a. In order to reduce the stored charge at the aircraft extremities, properly placed static dischargers will be used. Static dischargers dissipate the charge before it can buildup enough to cause corona discharge and RF noise. Dischargers typically reduce the discharge threshold by 90%. A discharger consists of a bundle of carbon or metallic fibers at the tip of a slender high resistance rod. The rod is coated with corrosion-resistant material and is attached to the aircraft structure through a metal base. Dischargers must be carefully bonded to the conductive surface of the aircraft. Bonding and DC bonding resistance requirements will be as described in Table 11 of section 5.2.2.5.1. The number and location of dischargers will be determined and provided to the Suppliers and designers by the de Havilland EM group.

b. All external conductive components and aircraft structure must be electrically bonded in order to ensure that all aircraft conductive structures (metal and conductive composites) are at the same electrical potential and therefore there is no possibility of sparking. For P-static, electrical bond DC resistance of several thousand ohms should be adequate to drain away static charges. However, in order to meet other EM requirements, the conductive component resistance and bonding resistance, in most cases, will be well below this value. Bonding techniques and requirements are described in section 5.2.2.

c. In order to minimize streamering, all external dielectric surfaces exposed to the airstream require an electrically conductive layer. Non-conductive composites will be coated with a conductive paint (unless a conductive layer has been incorporated for lightning protection). This conductive paint should be grounded to the adjacent airframe. The DC bonding resistance will be no greater than 300,000 ohms with the exception of the radome. The radome DC bonding resistance will be no less than 1 Mohm and no greater than 10 Mohms. The windshield P-static design protection will be determined and substantiated by the Supplier as described in DTRD-8-047.

5.2 Grounding and Bonding

Grounding is the process of connecting a conductive medium to a reference point such as on equipment enclosure, aircraft structure or ground plane. Electrical bonding is the process of joining two or more conductive surfaces in order to obtain an electrically conducting path.

Grounding and bonding are required for:

a. Electrical system performance by establishing a signal return path between source and load.

b. Electromagnetic compatibility by reducing potential differences between aircraft structures, and between aircraft structures and installed systems. Providing homogeneous and stable paths for signal and power returns and ensuring the method by which power and signal returns are implemented minimizes electrical noise.

c. Protection against Lightning by providing low impedance paths for the Lightning currents and therefore reducing the possibility of sparking and arcing.

d. Preventing static charge accumulation.

e. Providing fault protection by establishing a fault current return path.

Good grounding and bonding practices applied to an aircraft, system, subsystem and equipment will ensure a lower level of electromagnetic interference and will often be less expensive than other EMC measures. Shielding and filtering will seldom correct problems created by poor grounding. A uniform grounding approach used throughout the aircraft avoids common impedance coupling and minimizes ground loops (see Figures 57 and 58). Good bonding eliminates potentially hazardous conditions and ensures that existing EMC measures are effective.

5.2.1 Grounding

The general aircraft over-all grounding philosophy is described below and should be adhered to by systems and structure Suppliers.

5.2.1.1 Types of Grounding Systems

The proper ground system is determined by the type of circuitry, signal level and sensitivity (noise floor), frequency of operation and size of system (self contained or distributed). No one ground system is appropriate for all applications and most system grounding schemes are a combination of the various types of ground systems. When selecting grounding systems two things should be considered:

a. All conductors have finite impedance consisting of AC and DC resistances and an impedance. For conductor lengths less than one quarter of the wavelength this impedance is inductive. For higher frequencies the impedance behaves approximately as a short-circuit transmission line with large values at quarter wavelength and multiples.

b. Two physically separated ground points are never at the same potential.

Most ground schemes are a combination of the following two types of ground systems:

a. Single point ground system, also referred to as wired return, has circuits referenced to structure at a single point. Single point ground systems can be either in series or parallel as shown in Figures 59 through 62 inclusive. The series ground connection is, from a noise standpoint, the least desirable single point ground system but has the advantage of simple wiring. The series ground connection should not be used between circuits operating at widely different power levels because high level stages with large currents may adversely affect the lower level stages. When this system is used, the most critical/ sensitive stage should be the one closest to the single (primary) ground point. The parallel ground connection is the most desirable single point ground system with the ground potential of the circuit a function of its own ground current and impedance. Mechanically this system is cumbersome with large amounts of wire required. Single point ground systems are normally applicable for circuit dimensions less than 0.03 of the signal smallest wavelength or largest frequency. At higher frequencies the inductance of the ground conductors increases the ground impedance. At even higher frequencies the ground conductor will behave as a short circuit transmission line with very high ground impedances at odd multiples of a quarter wavelength.

b. Multipoint ground system, also referred to as common return, is used at high frequencies and in digital circuitry. In this system, as shown in Figure 63, the circuits are connected to the nearest available low impedance ground plane, usually the chassis or airplane structure. The low ground impedance is due to the lower inductance of the ground plane. The connections between the circuits and ground plane should be kept as short as possible to minimize their impedance. Multipoint ground systems are normally applicable for circuit dimensions greater than 0.15 of the signal smallest wavelength or largest frequency.

For circuit dimensions between 0.03 and 0.15 of the wavelength, the grounding scheme should be selected based on the circuit sensitivity and electromagnetic environment. In some cases a hybrid ground system as shown in Figure 64 may be considered. A hybrid ground system is a single point ground system with added capacitors between the circuitry and the local ground plane. This system acts as a single point ground system at low frequencies and a multipoint ground system at high frequencies. Capacitance should be chosen to avoid resonances with load or line inductances.

Most ground systems problems occur as the result of common impedance coupling and low impedance ground loops. Common impedance coupling occurs when two or more circuits share a small but significant impedance in their return path (see Figure 57). This common impedance interference problem can be solved by:

a. Eliminating or reducing the common impedance. A single point ground scheme provides separate ground paths for noisy and sensitive circuits.

b. The use of balanced differential circuits and therefore increasing the immunity of a circuit to ground potentials.

Ground loops result when a power or signal source is connected with one or more loads in a multi-point ground scheme. As shown in Figure 58, if the ground loop formed by the structure and signal return lead has low impedance, a magnetic field can induce a noise current proportional to the loop area and the magnetic field intensity. Ground loop problems can be eliminated or reduced by:

a. Breaking the loop by either removing one ground lead and converting the circuit to a single point ground scheme, or by the use of transformers, common-mode chokes and opto-couplers.

b. Using balanced circuits and thereby cancelling the effect of the ground loop voltage between two circuits.

c. Avoiding the use of multi-point ground schemes on low level sensitive circuits.

Typically single point ground systems are used in analog circuits where low level signals are involved. In these cases, millivolt and microvolt ground drops can create significant common impedance coupling interference problems for those circuits.

Single point ground systems are also typically employed in high level subsystems such as motor drivers, where the intent is to prevent these high level return currents from developing large voltage drops across the common ground. Digital systems, on the other hand, are less sensitive to noise from external sources but are quite susceptible to internal noise due to common impedance coupling and therefore the digital systems tend to use a multipoint ground scheme.

5.2.1.2 Grounds Classification

The aircraft will have a mix of the two basic grounding systems, multipoint and single point. Eventhough the aluminum structure of the aircraft is a large ground plane and a nearly perfect circuit reference with a fuselage DC resistance a fraction of a milliohm, it is not an acceptable circuit return for signals with spectral components above 1 MHz because of skin effect, reactance and resonance conditions. Also the currents in the structure associated with 400 Hz power are large enough to present troublesome potentials to any audio circuit.

Equipment, subsystems and systems should be grounded in a manner that will prevent ground loops and ground returns common to signal and power circuits.

The aircraft structure and equipment chassis should not be used as AC and DC power returns and signal returns.

The following separate ground systems should be maintained:

a. **Isolated Return-** AC power separate return wire
b. **Power Return-** DC power separate return wire
c. **Digital Return-** digital signal separate return wire
d. **Analog Return-** analog signal separate return wire
e. **Chassis Ground-** aircraft structure ground, electrical /electronic equipment enclosure or housing grounds
f. **Shield Ground-** aircraft structure or equipment enclosure

The following three sections address power, signal and chassis grounds. Shield grounds are addressed in section 5.3 under Interface Design.

When designing the grounding system for equipment, subsystem or system, a block diagram similar to Figure 65 is useful in determining the proper interconnection of the various circuit grounds and it should be developed and updated as required throughout the life of the program.

5.2.1.3 Power Grounds

When two or more loads share a power supply, good grounding practices may reduce interference caused by changes in demand. The power grounding scheme can be greatly improved by employing single point ground with separate ground returns between noisy circuits and sensitive circuits. This will eliminate common ground impedance.

The following are guidelines for the power supply grounding scheme:

a. The use of the aircraft structure as a power return should be avoided.

b. Primary AC power should employ a single point ground system. The AC power return or neutral should be kept isolated from structure/chassis at each load (see Figures 66 and 67). This will minimize the level of AC power current harmonics on the aircraft structure. The isolation resistance between power return and chassis should be no less than 1 Mohm.

c. The primary DC power should employ a single point ground system. The power return should be isolated from structure/chassis at each equipment load (see Figures 66 and 67). The isolation resistance between power return and chassis should be no less than 1 Mohm.

d. Secondary power derived from the AC or DC primary power within the equipment should have its ground isolated from primary power grounds. The isolation resistance should be no less than 1 Mohm. Each secondary power return should be returned to its source, and may be connected to chassis at one point. No secondary power currents should return through the equipment enclosure or structure.

e. A parallel single point ground system, with a separate power return for each equipment should be used rather than a series single point ground system (see Figures 60 and 62). This usually tends to increase the number of wires. As a compromise the final power ground system is usually a combination of parallel and series single point ground connections with the noisy circuits sharing a common ground path but isolated from sensitive circuits grounds.

f. A separate independent current return path for each isolated equipment power source should be used. AC and DC power returns should be kept separate as shown in Figures 66 and 67.

g. Primary AC and DC power returns should be isolated from signal returns. The isolation resistance should be no less than 1 Mohm.

h. If necessary the structure common return, multipoint system, should only be considered for the DC and control circuits involving switches, relays, lamps, anunciators and solenoids.

5.2.1.4 Signal Grounds

The use of the aircraft structure as a signal return should be avoided. Digital and analog signals should be provided with a dedicated signal return lead for controlling the effective signal loop area, minimize common impedance coupling, pick-up and/ or emissions.

The following are guidelines for the signal grounding scheme:

a. Signals should use a single point ground scheme. The preferred method for the interface design is to use balanced lines with all signal inputs and outputs balanced with respect to signal ground as shown in Figure 68. Where unbalanced signals must be used, the signal return must be grounded at one end only, usually at the source. If the source is floating, such as in the case of RVDTs, temperature sensors etc, than the return should be connected to chassis at the load. The use of balanced/differential interfaces and other ground isolation techniques, as described in section 5.3.5.2, should be considered.

b. Grounding for high frequency signals such as digital or pulsed signals, with bandwidths in the megahertz and higher frequency ranges, usually requires a multipoint ground system. The use of balanced/ differential interfaces, ground isolation techniques and/or cable shielding should be considered in order to reduce noise coupling mechanisms associated with multipoint ground systems such as common impedance coupling and coupling due to ground loop pick-up.

c. Each equipment signal should have a separate return especially in the case of low level analog signals and digital signals. For multiple digital interfaces of similar signal level and rate, a shared return may be considered. In this case the Supplier should demonstrate design adequacy. The routing of these returns should be evenly distributed in the cable and connectors so as to ensure the effective area between signal and return for all the signals is minimized.

d. The use of common returns for analog and other signals such as digital and high frequency, should be avoided.

5.2.1.5 Chassis Grounds

All metal and composite parts, structures, electrical/electronics equipment and cable shields should be electrically connected together as described in section 5.2.2 under Bonding.

When a safety ground is required for each power connector, this ground wire can be a point of entry or exit of noise into or out of the equipment enclosure. Therefore, this wire should be connected to chassis immediately upon entry of the equipment enclosure. In equipment that includes an EMI filter enclosure at its power interface, as described in section 5.3.5.3, this wire to chassis connection should be done inside the filter enclosure at the point of entry so as to ensure that noise picked-up by this wire will not be carried into or out of the equipment enclosure.

5.2.2 Bonding

Electrical bonding is the process of mechanically connecting metal and composite parts so that a low resistance path exists between the various conducting surfaces and components. Electrical bonding provides a conducting circuit by which electrical energy can pass between aircraft structures, components and equipment during certain operational or environmental conditions.

The use of the aircraft structure both for a current return path (see section 5.2.1.3) and for Lightning protection necessitates integrally bonded primary and secondary structural components. It is essential that a homogeneous grounding system be designed into the primary structure, control surface and system/equipment installations.

Where possible, the bonding methods detailed in this document should be adhered to in the designs by both the systems and structures Suppliers. This will ensure a uniformity of bonding practices and methods utilized throughout the aircraft.

The actual bonding methods selected will be influenced by such factors as forces holding the surfaces together, fatigue resistance, corrosion resistance, material resistivity, and temperature coefficients of materials.

In addition, the effectiveness of an electrical bond depends on the characteristics of its application such as frequency range, magnitude of current passing through it, and environmental condition such as vibration, temperature, humidity, and corrosive elements.

A summary of the types of electrical bonds are listed in Table 8.

TABLE 5. Types of Electrical Bonds

BONDING REQUIREMENT	PURPOSE	PROTECTION METHOD
Structural Joints	Provide an integrally bonded structure	Metal to metal faying surface bonding, conductive fasteners and rivets, bonding jumpers, conductive coatings
Lightning Protection	To ensure the safety of the aircraft against the catastrophic effects of Lightning and to reduce the damaging effects of Lightning to a minimum	Metal to metal faying surface bonding, conductive fasteners and rivets, bonding jumpers
Fire/Explosion Protection	Prevent the occurrence of ignition sources	Metal to metal faying surface bonding, dual path bonding
Shock Hazard	Eliminate electrical shock hazard to personnel	Metal to metal faying surface bonding, bonding jumpers
Antenna Installation	Provide a good ground plane	Metal to metal faying surface bonding
Equipment Installation	Provide chassis ground	Metal to metal faying surface bonding, connector contacts, terminals
Static Discharge	Prevent the accumulation of static	Conductive coatings, bonding jumpers, static dischargers, conductive tires

5.2.2.1 Responsibilities

The structures and systems Suppliers will be responsible for producing a design which meets the following basic requirements:

a. Ensuring that the design of the structure, sub-assemblies, systems and equipment can meet the bonding values specified in Table 11.

b. Defining the bonding requirements for all of the structural parts, sub-assemblies, systems and equipment installations interfacing with the primary structure of the aircraft.

c. Carrying out verification testing to ensure that the structure, system or equipment meets the bonding values as specified.

5.2.2.2 Main Objectives

The objectives are:

a. To ensure that both system and structure Suppliers provide adequate bonding interfaces and provisions that meet the overall bonding requirements of the aircraft.

b. To establish a standard approach to the bonding methods used while ensuring that the bonding method takes into consideration certain operational requirements such as fault current capability, frequency range etc.

With proper design and implementation, electrical bonds minimize differences in potential between points within the fault protection, signal referencing, shielding, and Lightning protection networks of an installation. Poor bonds can lead to a variety of hazardous and interference-producing situations. For example, loose connections in ac power lines can produce unacceptable voltage drops at the load and transient levels exceeding RTCA/DO-160C test standards. The heat generated by the load current through the increased resistance of the poor joint can be sufficient to damage the insulation of the wires which may produce a power line fault or develop a fire hazard.

Poorly bonded joints in Lightning protection networks can be particularly dangerous. The high current of a Lightning discharge may generate several thousand volts and the possibility of arcing across a poor joint. Arcing could present both a fire and explosion hazard and may possibly be a source of interference to equipment. The additional voltage developed across the joint will increase the likelihood of flash-over occurring to objects in the vicinity of the discharge path.

Loose or high impedance connections in signal lines will cause significant problems because of intermittent signal behavior such as decreases in signal amplitude and/or increases in noise level.

A degradation in system performance from high noise levels is frequently traceable to poorly bonded joints in circuit returns and digital referencing networks.

Bonding is also important to the performance of other interference control measures. For example, adequate bonding of connector shells to equipment enclosures is essential to maintain the integrity of cable shields and to retain the low loss transmission properties of the cables. The careful bonding of seams and joints in electromagnetic shields is essential to the achievement of a high degree of shielding effectiveness. Interference reduction components and devices (capacitors, filters) also must be well bonded for optimum performance.

5.2.2.3 Resistance Criteria

A primary requirement for effective bonding is that a low resistance path be established between the two joined objects. The resistance of this path must remain low with use and with time. The limiting value of resistance at a particular junction is a function of the current through the path. For example, where the bond serves only to prevent static charge buildup, a very high resistance, i.e., 50 Kohms or higher, is acceptable. Where Lightning discharge or heavy fault currents are involved, the path resistance must be very low to minimize heating effects (see Figure 69).

A bonding resistance of 1 milliohm is considered to indicate that a high quality junction has been achieved. Experience shows that 1 milliohm can be reasonably achieved if surfaces are properly cleaned and adequate pressure is maintained between the mating surfaces.

Higher values of resistance tend to relax the bond preparation and assembly requirement. These requirement should be adhered to in the interest of long term reliability. Thus, the imposition of an achievable, yet low, value of 1 milliohm bond resistance ensures that impurities are removed and that sufficient surface contact area is provided to minimize future degradation due to corrosion.

A similarly low value of resistance between widely separated points on a ground reference plane or network ensures that the junctions are well made and that reasonably adequate quantities of conductors are provided throughout the plane or network. In this way, resistive voltage drops are minimized which helps with noise control. In addition, the low value of resistance tends to force the use of reasonably sized conductors which helps minimize path inductance.

It should be recognized that a low DC bond resistance is not a reliable indicator of the performance of the bond at higher frequencies. Inherent conductor inductance and stray capacitance, along with the associated standing wave effects and path resonances, will determine the impedance of the bond. Thus, in RF bonds these factors must be considered along with the DC resistance.

5.2.2.4 Bonding Design

5.2.2.4.1 Direct Bonds

A direct bond is formed when two structural members are electrically connected without the use of an auxiliary conductor. The bond may be accomplished by the use of metal flow processes such as welding and soldering or, for accessibility and manufacturing reasons the clamping force may be achieved by fasteners such as bolts or rivets.

Properly constructed direct bonds exhibit a low DC resistance and provide an RF impedance as low as the configuration of the bond members will permit.

Direct bonding is always preferred. However direct bonds can be used only when the two members can be connected together and can remain so without relative movement. The establishment of electrical continuity across joints, seams, hinges, or fixed objects that must be spatially separated requires indirect bonding with straps, jumpers, or other auxiliary conductors.

The objective in bonding is to reduce the contact resistance to a value negligible in comparison to the conductor resistance so that the total path resistance is primarily determined by the resistance of the conductors.

5.2.2.4.1.1 Direct Bonding Design

Direct bonds may be either permanent or semi-permanent in nature. Permanent bonds may be defined as those intended to remain in place for the expected life of the installation and not required to be disassembled for inspection, maintenance, or system modifications. Joints which are inaccessible by virtue of their location should be permanently bonded and appropriate steps taken to protect the bond against deterioration.

All connections not permanently joined are defined as semi-permanent bonds. Semi-permanent bonds include those which utilize bolts, screws, rivets, clamps and other auxiliary devices for fasteners (see Figure 70). Many bonded junctions must retain the capability of being disconnected without destroying or significantly altering the bonded members. Junctions which should not be permanently bonded include those which may be broken for system modifications, for network noise measurements, for resistance measurements, and for other reasons. In addition, many joints cannot be permanently bonded for cost reasons.

The most common semi-permanent bond is the bolted connection. This type of bond provides the flexibility and accessibility that is frequently required. The bolt (or screw) should serve only as a fastener to provide the necessary clamping force to maintain the pressure required between the contact surfaces for satisfactory bonding. Except for the fact that metals are generally necessary to provide tensile strength, the fastener does not have to be conductive. Although the bolt or screw threads may provide an auxiliary current path through the bond, the primary current path should be established across the metallic interface. Because of the poor reliability of screw thread bonds, self-tapping screws should never be used for bonding purposes. The type of nut used for the bolted connection should be self-locking and should not be prone to loosening under vibration as this will degrade the bonded joint.

The size, number and spacing of the fasteners should be sufficient to establish the required bonding pressure over the entire joint area. The pressure exerted by a bolt is concentrated in the immediate vicinity of the bolt head. However, large, stiff washers can be placed under the bolt head to increase the effective contact area. Because the load is distributed over a larger area, the tensile load on the bolt should be raised by increasing the torque.

Where the area of the mating surfaces is so large that unreasonably high bolt torques are required, more than one bolt should be used. For very large mating areas, rigid backing plates should be used to distribute the force of the bolts over the entire area.

Riveted bonds are less desirable than bolted connections or joints bridged by metal flow processes. Rivets lack the flexibility of bolts without offering the degree of protection against corrosion of the bond surface that is achieved by welding brazing or soldering. The chief advantage of rivets is that they can be rapidly and uniformly installed with automatic tools. Where rivet bonds are used, the hole for the rivet must be a size that provides a close fit to the rivet after installation. The rivet hole through the bond members must be free of paint, corrosion products, or other non-conducting materials.

Permanent Bonds:

a. Welding - The most preferred method, providing a good corrosion-free bond over the long term.

b. Brazing (including silver soldering) - A good bonding method but more prone to long term deterioration due to corrosion.

c. Soft Solder - Provides a low resistance joint, but has little mechanical strength. Not to be used for bonding in high current areas or areas intended to carry Lightning strike currents.

Semi-permanent Bonds:

a. Bolts - The number of bolts (or other threaded fasteners) to be used depends on the nature of the assembly requiring bonding. Sufficient bolts and appropriate tightening torque should be used to prevent distortion of the mating surfaces, and subsequent loss of contact.

b. Solid Rivets - Require careful installation to ensure a good bond. Sufficient rivets and appropriate assembly methods should be used to prevent distortion of the mating surfaces, and subsequent loss of contact. Riveted joints, with the rivets equally spaced approximately 3/4 inch, are acceptable if the rivet holes are free of insulating material and a minimum of three rivets are used. More rivets are needed as current requirements increase. The rivets are part of the bond joint and must be finished with a MIL-C-5541 class 3 coating. Bonds of this type are limited by current and bond joint resistance; consequently their use is restricted by the quantity and size of rivets and the nature of the bond application. Solid rivet bonds are not suited for antenna installation, RF, or bond applications which carry more than 70 amperes, or for bond joints which must offer less than 0.0005 ohm resistance. Blind rivets are not suitable for providing a suitable electrical bond.

5.2.2.4.2 Indirect Bonds

When it is not possible to create a direct bond due to the distance between mating surfaces, or because the surfaces may be joined by a hinge, bonding straps or jumpers can be used to create an indirect bond (see Figure 71).

5.2.2.4.2.1 Bond Impedance

The resistance of an indirect bond depends on the resistance of the bonding strap (determined by the material used and the strap dimensions), and the resistance inherent in the method of attaching the strap. The most important features of a bond strap are its material, geometry, and thickness. It is recommended that DHC-8 Series 400 utilize the MS25083 tinned copper bonding jumper. Only aluminum jumpers may be used in fuel tank applications. Refer to the EM group where flat bend straps are required or low impedance RF grounds.

The geometrical configuration of the bonding conductor and the physical relationship between objects being bonded introduce reactive components into the impedance of the bond. The strap itself exhibits an inductance that is related to its dimensions. A certain amount of stray capacitance is inherently present between the bonding jumper and the object being bonded and between the bonded objects. The bond interface impedance can be modeled by a parallel LC network with resonance frequencies as low as 10 to 15 MHz. In the vicinity of these resonances, bonding path impedances are of the order of several hundred ohms and the bonded system may act as an effective antenna system which increases the pickup of the same signals which bond straps are intended to reduce.

In conclusion, bonding straps should be designed and used with care with special note taken to ensure that unexpected interference conditions are not generated by the use of such straps.

5.2.2.4.2.2 Indirect Bond Design

Bonding straps which are expected to provide a path for RF currents are frequently recommended to maintain a length-to-width ratio of 5 to 1 or less, with a ratio of 3 to 1 preferred.

In many applications, braided straps are preferred over solid straps because they offer greater flexibility.

The number of jumper bonds used shall be kept to a minimum. The lengths shall be the minimum required to allow for structure and system flexure, thermal expansion and other variables. Adding jumpers in series to increase overall length is prohibited.

Ground point locations shall be chosen to make the best compromise of mechanical and electrical properties. For best conduction, locate the ground on a primary structure. Generally, for structural reasons, holes shall not be drilled in primary structures. The ground shall be installed on a secondary structure or on a metal tab installed on the primary structure.

The jumper and attachment hardware shall be capable of carrying the fault current from the circuit breaker protecting the wiring to the equipment until the breaker interrupts. Aluminum bonding jumpers are not allowed for fault current return.

When designing jumper installations, position the jumpers to avoid interference with moving parts. Particular care must be exercised in installing jumpers on control surfaces, shockmounts and similar items involving motion between attachment points.

The jumper and attachment hardware shall be capable of withstanding the temperature, vibration and other environmental conditions (e.g. fuel or hydraulic fluid leaks). For example, copper-weld jumpers shall be used in high vibration areas or where considerable flexing occurs.

The materials used in the jumper and attachment hardware shall be electrochemically compatible. Table 9 lists the types of jumpers compatible with various materials.

Design Standard 127 shows the hardware stack-up that should be utilized for the installation of static ground and ground return assemblies.

Dry Film lube anchor nuts shall not be used where electrical bonding is required through the anchor nut.

Typical applications of indirect bonds are shown in Figure 73.

5.2.2.4.3 Composite Bonding

Conductive Composite - Bonding is accomplished by making a transition from graphite to metal, where most of the fibers contact a metal surface which is an integral part of the composite assembly. This metal part is then bonded in a conventional manner to another metal part. Galvanic compatibility is a matter of concern when graphite epoxy composites are utilized in combination with metallic structures.

Non conductive Composites - Surface metallization techniques are required for bonding of nonmetallic, non-conducting surfaces.

5.2.2.4.4 Surface Preparation

To achieve an effective and reliable bond, the mating surfaces must be free of any foreign materials, e.g dirt filings, preservatives, and non-conducting films such as paint, anodizing and oxides. Various mechanical and chemical means can be used to remove the different substances which may be present in the bond surfaces After cleaning, the bond should be assembled or joined as soon as possible to minimize contamination of the surfaces. After completion of the cleaning process, the bond region should be protected with MIL-C-5541 class 3 coating to prevent bond deterioration through corrosion of the mating surfaces. Surface preparation should be carried out in accordance with the appropriate production process standard.

5.2.2.4.5 Protection Against Corrosion

If dissimilar metals must be bonded, the materials of the bonding connection must be selected to minimize corrosion and the bond should be protected from moisture and air. If bonding members are widely separated on the activity table, plating should be used to reconcile the dissimilarity (see Table 10).

Corrosion can be avoided in one or more of the following ways:

a. Electroplating one or both members with compatible metals
b. Moderately dissimilar metals may be joined without appreciable corrosion occurring if the cathodic member is much smaller than an anodic member
c. Corrosion between dissimilar materials can be minimized by the application of sealant to exclude moisture from the joint space.
d. Hardware used for attachment of bonding jumpers should comply with the information provided in Figure 72

Where corrosion is difficult to control, it shall be limited to replaceable elements such as jumpers, washers and brackets rather than in the primary or secondary structures.

TABLE 6. Hardware Material Selection To Avoid Corrosion

Hardware Type	STRUCTURAL MATERIAL/HARDWARE MATERIAL				
	Aluminium	Stainless	Titanium	Magnesium	Graphite Composite
Bolt/Screw	Cadmium Plated	CRES-Passivated	CRES-Passivated	Cadmium Plated	CRES-Passivated
Pressure Washer	Cadmium Plated	CRES-Passivated	CRES-Passivated	Cadmium Plated	CRES-Passivated
Terminal	Tinned Copper	Nickel Plated Copper	Nickel Plated Copper	Tinned Copper	Nickel Plated Copper
Anti-Corrosion Washer	Aluminium Alloy (2024)	None	None	Aluminium Alloy (5052)	CRES-Passivated
Nut/Nutplate	Cadmium Plated	CRES-Passivated	CRES-Passivated	Cadmium Plated	CRES-Passivated

TABLE 7. Intermetal Compatibility (MIL-STD-889)

Group Code	Materials in Group	Compatible Groups		
			Add These Groups	
		in Sea Water	When in Marine Air	Additional for Industrial Air
T	Graphite	ST	JKLOPQR	GMN
S	Gold, Platinum, Palladium, Rhodium	RST	HJKLOPQ	GMN
R	Silver	HRS	GJKLMNOPQT	None
Q	SS AM350 (Passive) Titanium (Pure), Titanium 6-4	Q	HJKOPRST	GLMN

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TABLE 7. Intermetal Compatibility (MIL-STD-889)

Group Code	Materials in Group	Compatible Groups in Sea Water	Add These Groups When in Marine Air	Additional for Industrial Air
P	SS AM355 (Passive), SS A286 (Passive), SS316L, 321 (Passive), SS301, 304 (Passive), Nickel (Passive)	HP	FHJKLMNOQRST	G
O	Monel, Copper 110 (Pure) ETP	O	HJKMPQRST	GLN
N	Bronze-Phosphor, Copper-Nickel 715	N	HLMPR	GOQST
M	Bronze 220	M	HLNOPR	IJQST
L	Brass 464, 268	L	GHJMNPRST	OQ
K	SS410, 430 (Passive)	JK	GOPQRST	GH
J	Chromium (Plated)	JK	GLOPRST	HIM
I	Stainless Steels-Ferritic, Martensitic	I	G	JM
H	Tin, Tin-Lead, Indium	GHPR	LMNOPQS	JK
G	LEAD	GH	IJKLR	FNOPQST
F	Iron, Steel	F	P	G
E	Aluminium Alloys 2014, 2024	DE	BC	None
D	Aluminium 1100 (Pure) Aluminium Alloys 1160, 3003, 6061, 7075, A360 Aluminium Alloys 218, 7072, 7079, 5052, 5456	DE	BC	None
C	Cadmium (Plated)	BC	ADE	None
B	Zinc (Not for aircraft use)	BC	ADE	None

TABLE 7. Intermetal Compatibility (MIL-STD-889)

Group Code	Materials in Group	Compatible Groups		
			Add These Groups	
		in Sea Water	When in Marine Air	Additional for Industrial Air
A	Magnesium Alloys	A	BC	None
T = Least Active (Cathodic), A= Most Active (Anodic)				

5.2.2.5 Electrical Bonding Verification

The basic structure must be electrically conductive through the use of fasteners, metal to metal contact faying surfaces or bonding jumpers. The only exceptions to this are structural components and equipment that meet the following:

a. Small mechanical items (i.e no linear dimension greater than 3 inches) that have no electrical parts or connections and that will not carry any current (return or fault)

b. Not subjected to charging effects such as exposure to the external environment or subject to moving fluids or gases

c. Not directly in contact or likely to be in contact with any flammable fluid or gas (e.g fuel vapor).

Conductive composites and composites utilizing metallized coatings, foils, conductive meshes, metallic diverter systems, and anti-static coatings shall be provided with bonding attachment points to ensure an adequate bonding path to primary aircraft structure.

All bonded joints must be verified by test to the values specified in section 5.2.2.5.1. All structure and system Suppliers shall provide a Functional Test Procedure (FTP) document which specifies the required test and resistance values to be achieved. In addition, the Suppliers shall carry out electrical bonding tests on all production assemblies. Any bond which does not meet the specified bonding value should be reworked or replaced. If failure still results after rework or replacement, then the EM group must be consulted for further advice.

5.2.2.5.1 Resistance Values

DC bonding resistance values listed in Table 11 apply to conductive metallic components.

The resistance specified in Table 11, is based on highly conductive materials:

a. Copper

b. Aluminum alloy (excluding Aluminum Lithium alloy)

c. Magnesium alloy

d. Nickel.

Where highly resistive materials are used consult the EM group:

a. Aluminum Lithium alloy

b. Titanium

c. Corrosion Resistant Steel (CRES)

d. Non-Corrosion Resistant Steel.

TABLE 8. Bonding Requirements

Item	Preferred Connection	Maximum Resistance Value to A/C Structure (Milliohms)	Notes
Primary Structure (Metallic)	Faying	0.5	Resistance between Primary Structural Joints
STRUCTURAL COMPONENTS			
Metallic Doors & Access Panels (fixed & removable)	Faying or Jumper	10	Bonding via piano type hinge is acceptable provided that the bonding value specified can be achieved
Scoops, Ducts, Drains and Vents	Faying or Jumper	10	

TABLE 8. **Bonding Requirements**

Item	Preferred Connection	Maximum Resistance Value to A/C Structure (Milliohms)	Notes
Metallic Lightning Diverter System	Faying	10	Includes Radome and Trailing Edge Diverters
Miscellaneous Metallic Components Attached to External Structure (e.g., Fairings,Probes)	Faying or Jumper	10	
Composite Structures with Lightning Protection Layer	Faying or Attachment Fasteners	10	
Conductive Structures With Conductive Paint	Fasteners	300,000 ohms	
Glareshield	Fasteners	10	
Conductive Floor Panels	Fasteners	10	
POWER PLANT			
Engine Components	Faying or Jumper	10	
Nacelle Components	Faying or Jumper	10	
Engine Ground Straps	Jumper	2.5	Located between forward engine and nacelle
FUEL SYSTEM (Items located in or associated with Fuel Tank Area or associated with the transfer of fuel)			
Pipe Conductive Material (length >3ft)	Faying or Jumper	50	No bond path to structure must exceed 144 inches in length, see section 5.1.2.2.1.1.2 Figure 131
Pipe Conductive Material (length <3ft)	Faying or Jumper	10	See section 5.1.2.2.1.1.2 No bond to structure shall exceed 144 inches in length. Figure 131
Pipe Resistive Material (all lengths)	Faying or Jumper	500	See section 5.1.2.2.1.1.2 No bond to structure shall exceed 144 inches in length. Figure 131

TABLE 8. Bonding Requirements

Item	Preferred Connection	Maximum Resistance Value to A/C Structure (Milliohms)	Notes
Equipment with no Electrical Connection	Faying or Jumper	10	e.g. Valves
Equipment with Electrical Connection	Faying	5	Bonding via pin connection alone is not sufficieint. e.g. Valves, Pumps, Motors, etc.
Miscellaneous Mechanical Brackets and Supports	Faying	10	
Fuel Nozzle - Ground Receptacle AN3117	Faying	10	
Fuel Tank Access Doors	Faying or Fastener (e.g., Conductive Gasket)	2.5	Bond must ensure no sparking where fuel or fuel vapour may be present
Heat Exchangers	Faying or Jumper	5	
HYDRAULIC SYSTEM			
Pipes	Faying or Jumper	500	No bond path to main structure should exceed 144 inches in length Figure 131
Equipment with Electrical Connection	Faying or Jumper	10	Actuators, Valves, Pumps, etc.
Equipment with no Electrical Connection	Faying or Jumper	500	Valves, Accumulators, etc.
ELECTRICAL/ELECTRONIC SYSTEMS			
Antenna Mounts	Faying	0.5 (or as per Manufacturer's recommendations)	
Equipment Cases Including Mounting Shelves, Panels, Racks, etc.	Faying or Jumper	2.5 (per interface)	Where possible, faying surfaces should be used
Metallic Conduit (Solid and Braided)	Faying or Jumper	2.5	
Radio Noise Filters	Faying	0.5	

TABLE 8. **Bonding Requirements**

Item	Preferred Connection	Maximum Resistance Value to A/C Structure (Milliohms)	Notes
Static Discharger Base	Faying	100	
Galley and Lavatory Components, Lightning Fixtures	Faying or Jumper	10	
Electrical Connectors	Faying	2.5	Electrically bonded to equipment case and bulkhead penetrations
Instruments Instrument Panel	Faying or Jumper	2.5 (per interface)	
OXYGEN SYSTEM			
Pipes and Equipment Conductive Material	Faying or Jumper	10	No bond path to main structure should exceed 144 inches in length Figure 131
Pipes and Equipment Resistive Material	Faying or Jumper	100	No bond path to main structure should exceed 144 inches in length Figure 131
PNEUMATIC/AIR CONDITIONING SYSTEM			
Pipesand Ducts	Faying or Jumper	500	
Equipment with Electrical Connection	Faying or Jumper	50	
Equipment with no Electrical Connection	Faying or Jumper	500	
Heat Exchangers	Jumper	2.5 (per interface)	
FLIGHT CONTROLS			
Control Surfaces	Jumper	10	
Control Surface Position Transmitters (e.g., RVDT's, etc.)	Faying or Jumper	2.5 (per interface)	

TABLE 8. Bonding Requirements

Item	Preferred Connection	Maximum Resistance Value to A/C Structure (Milliohms)	Notes
Control Surface Actuators with Electrical Connection	Faying or Jumper	10	
Control Surface Actuators with no Electrical Connection	Faying or Jumper	500	
Miscellaneous Cables and Linkages in Pressurized Zone	Faying	500	
LANDING GEAR			
Landing Gear Structure	Faying	10	Ground point on gear
Electrical Equipment	Faying or Jumper	10	To ground point on gear
MISCELLANEOUS COMPONENTS			
Mechanical Items e.g., brackets, supports	Faying or Jumper	50	
Seat Rails	Faying	10	Cabin and Flight Compartment
Seats (crew only)	Faying	100	
Fire Extinguisher Bottles (non-portable)	Faying or Jumper	2.5 (per interface)	

NOTES:

Testing of installed equipment should be made prior to connecting any additional interfaces (e.g. electrical connectors, hydraulic lines etc.)

5.2.2.6 Materials

5.2.2.6.1 Aluminum

Aluminum joints provide stable, long-term, low resistance service when properly designed and prepared Aluminum conductors are not suitable for direct exposure to corrosive environments. Aluminum jumpers are not allowed as fault return current conductors. Aluminum jumpers are used in fuel tank electrical bonding applications.

5.2.2.6.2 Steel

Steels, including stainless and CRES alloys, are capable of stable, bonded joints although bulk resistivities are higher than aluminum.

5.2.2.6.3 Titanium

Titanium structures can be bonded by conventional means. However, due to the high bulk resistance, current return grounding to titanium structure is not acceptable. Bond joints shall be sealed with high-temperature sealant to prevent deterioration of the bond due to oxidation.

5.2.2.6.4 Magnesium

Magnesium structures are effective electrical conductors but are highly flammable and prone to corrosion. They can be bonded to aluminum if adequate corrosion protection is provided. Protective washers of aluminum alloy 5052 are required between components, and all bonded joints to magnesium shall be sealed to prevent deterioration. Magnesium structures shall not be used as current return paths due to severe fire hazard.

5.2.2.6.5 Composites

Composite materials have a high electrical resistance and low thermal conductivity. Static charge dissipation and Lightning protection may be provided by means of integral wire mesh, perforated foil, conductive coating, or similar means. They shall not be used in applications where they must serve as an electrical circuit current return path. Where composites are bonded to conducting structures, the conductivity characteristics of the electrical bonding joint shall not degrade with time or operational environment.

5.2.2.6.6 Design Rules

Suppliers shall use the following rules for bonding design:

a. Bonds must be designed into the sub-assemblies, systems, and equipment to ensure that the resistance value specified, can be achieved.

b. Bonds must maintain intimate contact between metal surfaces. The surfaces must be smooth and clean and free of non-conductive finishes. Fasteners must exert sufficient pressure to hold the surfaces in contact in the presence of the deforming stresses, shocks, vibrations associated with the equipment and its environment.

c. The effectiveness of a bond will depend on the particular application. The type of bond used should be selected based on the frequency and current magnitude that is expected to be transferred between the two items of structure or equipment.

d. Direct bonds are preferable to indirect bonds.

e. Corrosion in bonded joints should be controlled by choice of materials to be bonded, bonding hardware and protective finishes/sealants.

f. Units installed in the aircraft without the benefit of mounting racks shall be mounted such that good bonding to aircraft structure is achieved.

g. System Suppliers shall ensure that units installed in mounting racks, are bonded to structure when installed in the mounting rack.

h. Ensure equipment is installed on a surface that is electrically part of the aircraft structure.

i. Ensure that the non-conductive composites requiring HIRF, Lightning and P-static protection have a conductive layer or coating and are bonded to the aircraft structure.

j. Bond externally mounted equipment and antennas, to ensure that the equipment, antenna ground plane and aircraft skin maintain the same electrical potential.

k. Bond mounting racks to aircraft structure using at least one bonding strap. Shock mounts on racks cannot be relied on to provide good bonding.

l. Ensure that equipment racks are designed such that frequent removal and replacement of the equipment from the rack does not degrade the effectiveness of the equipment/rack bond.

m. System Suppliers shall be required to ensure that connectors fixed to equipment cases are bonded by direct electrical contact between the connector shell and the equipment case.

n. Equipment with lids, such as junction boxes, may require bonding gaskets between the lid and the box where required to ensure complete bonding.

o. The bonding gaskets and the quality of the bond should not deteriorate with use.

p. The utilization of basic structure for both a current return and for Lightning protection necessitates an integrally bonded structure throughout all the major structural components and joints.

5.3 Interface Design

Wiring is one of the main culprits of electromagnetic interference. Wiring may act as a transmitting antenna or a very efficient receiving antenna. Noise may also be introduced into circuits as a result of wiring carrying unwanted currents due to inappropriate grounding or poor bonding methods as described in section 5.2.

The following techniques should be used to minimize wiring interference:

a. Separation of wires, cables and/or harnesses according to signal/energy categories

b. Cable shielding

c. Proper grounding of shields

d. Interface, source and load, circuitry design and filtering

e. Development and adherence to an over-all grounding scheme

The most common building blocks to signal wiring quality include:

a. Twisted pair for minimum magnetic pick-up and emissions

b. Shielding for minimum electric field pick-up and emissions

c. Balanced isolated interfaces circuitry for minimum common impedance coupling.

Figure 74 shows various wiring configuration interactions with the EMI, HIRF and Lightning environments present in the aircraft.

The following sections address all these techniques with exception of the over-all grounding scheme which is addressed in section 5.2.1.

5.3.1 Wiring Classifications

Functional grouping on long wire runs may result in excessive coupling between noisy lines and susceptible or sensitive lines. In order to achieve an electromagnetically compatible aircraft, the EMC classification of each wire should be determined early in the design program. Circuits from the same EMC classification should have similar EMI radiating and susceptibility characteristics. Wires shall be coded in accordance with the following classifications:

I.	AC Power:	-115VAC, 400Hz, 3 phase and single phase
		-115VAC, 3 phase, variable frequency
II.	DC Power:	-28VDC primary power
		-DC power bus/distribution
III.	RF Sources:	-Transmitter power
		-Modulation signal for RF carrier
IV.	Discretes:	-Circuits which operate on 28VDC or secondary AC powered:(< 1 ampere)
		Switching circuits
		Hydraulic valves
		Motor drives
		Fuel systems
		Inductive loads
		Lights
		AC power control circuitry
		DC power control circuitry
V.	Digital:	-Digital circuits
		-Signal levels 0 to 5V
		-Digital data buses
		-Clocks
		-Digital discretes
		-Digital circuitry secondary power

VI. Analog:	-Low level sensitive circuits, noise floor millivolts, high source and load impedance
	-Single phase AC signals noise floor millivolts, high source and load impedance
	-Audio signals, frequencies between 50 Hz and 15 KHz, moderate source and load impedance
	-Analog circuitry power reference or DC secondary power (filtered)
VII. Communications:	-Analog video, frequencies greater than 100 KHz
	-Low level RF signals, RF receivers

5.3.2 EMI Control

Cable routing and shielding to achieve aircraft internal EMC should be determined based on possible noise coupling between wires of the different wire classifications as well as the emissions requirements described in section 4.1.

Wires from different wire classifications should NOT be routed together. Table 12 lists suggested wire separations.

TABLE 9. Wire Separation

Category	Circuits	Separations (inches)						
		VII	VI	V	IV	III	II	I
I	AC Power	4	4	2	2	2	2	-
II	DC Power	4	4	2	2	2	-	2
III	RF Power	4	4	2	2	-	2	2
IV	Discretes	4	4	4	-	2	2	2
V	Digital	2	4	-	4	2	2	2
VI	Analog	2	-	4	4	4	4	4
VII	Communications	-	2	2	2	4	4	4

In addition to the wire classifications of Table 12 wiring associated with interfaces that perform Critical/Catastrophic functions should be routed in a separate bundle. Implementation of this process is TBD.

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Although wire separation is not the best way to reduce noise between circuits, it is often necessary. Separation is very effective when used for isolation and redundancy. If the separation requirements listed in Table 12 are not feasible, due to space limitations, equipment connector pin allocation, or other constraints, wires from different categories may be bundled together by following the recommended cable shielding listed in Table 13. These shielding recommendations are for circuits to be contained in one cable and were based on the following worst-case coupling conditions between a noise source and receiver:

a. Receiver circuit unbalance.

b. Receiver circuit of high impedance, greater than 1 Mohm.

c. Adjacent source and receiver circuit wires.

d. Analog receiver circuits tolerating as low as 10 millivolts peak-to-peak without malfunction

e. Digital receiver circuits tolerating as low as 0.5 volts

f. Analog frequency response as wide as 100 KHz

g. Cable length of 100 ft or more.

Special knowledge of circuit compatibility, or specific cable interface design may permit deviation from the separation and/or shielding recommendations of Tables 12 and 13. The final interface shielding and routing requirements should be based on Supplier design requirements, analysis and testing described in their respective EMI/HIRF Lightning Control and Assurance Plans.

TABLE 10. Cable Shielding, Control of EMI

Category	Circuits	Shielding Requirements						
		VII	VI	V	IV (1)	III	II (1)	I (1)
I	AC Power (1)	Shield AC Power (2), (3)	Shield both (3)	Shield both (3)	No shield	Shield AC power (2), (3)	No shield	No shield
II	DC Power (1)	No additional shield (2)	Shield both	Shield both	No shield	Shield DC power (2)	No shield	No shield

TABLE 10. Cable Shielding, Control of EMI

Category	Circuits	Shielding Requirements						
		VII	VI	V	IV (1)	III	II (1)	I (1)
III	RF Power (2)	No additional shield (2)	Shield analog (2)	Shield digital (2)	No additional shield (2)	No additional shield (2)	Shield DC Power (2)	Shield AC Power (2)(3)
IV	Discretes (1)	Shield Discretes (2)	Shield both	Shield both	No shield	No additional shield	No shield	No shield
V	Digital	No additional shield (2)	Shield analog	No shield	Shield both	Shield digital (2)	Shield both	Shield both (3)
VI	Analog	No additional shield (2)	No shield	Shield analog	Shield both	Shield analog (2)	Shield both	Shield both (3)
VII	Communications (2)	No additional shield (2)	No additional shield(2)	No additional shield (3)	Shield discrete	No additional shield (2)	No additional shield (3)	Shield AC power (2) (3)

NOTES:

(1) AC, DC power and discretes assumed to have on/off transients.

(2) Assumed appropriate type of coaxial cable used. No additional shielding required for group III or group VII.

(3) AC power magnetic shields using high permeability material.

(4) Shield both: implies shield both the source and receiver interfaces

The following guidelines in conjunction with the requirements of Table 12 and 13 should be applied when selecting wires to be bundled in harnesses:

a. AC and DC main power feeders to be routed seperately.

b. The preferred method of obtaining adequate low frequency magnetic decoupling should be achieved by the use of twisted pairs as described in section 5.3.4, proper grounding as described in section 5.2.1 and proper wire separation as described in Table 12. Low frequency magnetic shielding, using high permeability shields should be avoided. AC power cables emissions, due to the low frequency high current signal, are magnetic in nature. Therefore AC power cables should not be included in harnesses with any other cables or wires since this would require the use of conduits and/or high permeability shields.

c. Discretes which are carrying large transients should not be included in harnesses with wires in classes V, VI, VII. If this is unavoidable both the transient carrying wires and other wires in the harness should be foil shields or double shielded braid.

d. If possible, coaxial cables should be routed individually.

e. Wiring for systems which for safety reasons have two or more redundant channels should be equally distributed on either side of the aircraft.

f. Wiring for each redundant multiple channel should be provided in separate harnesses.

g. As described in section 5.2.1 on Grounding, the preferred design is for all signals to have separate return lines since shared return lines can cause common impedance coupling. If this is not feasible signals of different EMC classifications, as defined in section 5.3.1, should not share return lines.

It is recommended that colored tyes are used to identify bundles routed together in accordance with the wiring classifications of section 5.3.1.

The following shielding guidelines should be followed to ensure compliance to radiated emissions requirements described in section 4.1

a. AC power, DC power and discretes which are filtered at equipment interfaces so as to meet the conducted emissions requirements should require little or no additional shielding to meet radiated emissions requirements.

b. The shielding requirements for interfaces performing Critical/Catastrophic functions and Essential /Hazardous -Severe /Major should be dictated by the HIRF and Lightning requirements described in section 5.3.3.

c. Depending on the interface signal type, level, frequency and interface circuitry design, the shielding requirements for interfaces performing Non-essential/Minor functions, may be dictated by emissions requirements. The level of shielding to be determined and specified by Supplier in cooperation with de Havilland.

5.3.3 HIRF and Indirect Effects of Lightning

Electromagnetic fields can couple to interconnecting wires and cause a system upset. The amount of energy coupled depends on the antenna efficiency of the cables and the level of electromagnetic environment.

For a wire in a uniform EM field the coupling on the wire is low when the wavelength is greater than four times the wire length and it is maximized when the wire length is one quarter or one half the wavelength. At higher frequencies due to transmission line effects and losses, interconnecting wires are no longer the primary coupling path. At these frequencies the only coupling that needs to be considered is on the wire close to the equipment enclosure as well as coupling through enclosure apertures and direct case penetration. Table 14 summarizes these coupling paths. For the case of a non-uniform EM field at the higher frequencies, transmission line effects may not cancel and coupling to the whole cable needs to be taken into account.

The electromagnetic field levels and Lightning Indirect Effects interface voltage and currents are dependent on the equipment location and the failure condition category of the equipment. A system/equipment with interfaces classified under different failure condition categories should be designed for the highest electromagnetic field levels and interface voltages and currents.

DC, low frequency, high voltage interfaces such as primary AC and DC power and discretes with fairly high susceptibility thresholds are in most cases low impedance interfaces and therefore the level of electromagnetic (EM) coupling tends to be low. For these interfaces the use of shields should be avoided. EM coupling to these interfaces should be addressed by proper interface grounding, interface circuitry design, filtering, and transient protection.

Interfaces performing Non-essential/Minor functions may not require shielding because there is no applicable Lightning Indirect Effects requirements and the HIRF field level requirements are ‘low’. If these interfaces are being routed from an exposed EM environment (e.g. wing rear spar) to a well protected EM region (e.g. inside fuselage) then the segment of wiring in exposed region should be shielded. This shield should be terminated peripherally to the connector at the bulkhead/ metal interface separating the two regions (see section 5.1.1.1 and Figure 72).

Shield grounding should be as described in section 5.3.4.2.2.

The shield transfer impedance and/or shielding effectiveness requirements are highly dependent on the interface cable, interface circuitry and filtering and therefore the final cable shield requirements and transfer impedance should be determined by system Supplier in cooperation with de Havilland. Cable shield transfer impedance data is provided in ESP 96.

Wiring associated with systems that perform essential functions must be shielded in Lightning EM Regions 1 and 2 (external to the fuselage pressure vessel). Wiring associated with systems that perform critical functions must be designed with two levels of shielding in Lightning EM Regions 1 and 2 (external to the fuselage pressure vessel). The EM group recommend an overall shield for the second level of shielding. Critical systems wiring located within the fuselage cabin must be routed within metal cable trays. The cable trays must be electrically bonded to the airframe.

TABLE 11. Wavelength, Radiation and Effects

Frequency	Wavelength	Type of Radiation	Effects/Threats
10 KHz 100 KHz	30km 3km	VLF CW with AM	A/C and wiring - very low coupling
100 KHz 1 MHz	3km 300m	Low frequencies CW with AM	A/C and wiring - low coupling
1 MHz 50 MHz	300m 6m	MF/JF CW with AM or SSB/DSB	A/C and wiring - high coupling
50 MHz 400 MHz	6m 75cm	VHF CW with AM or FM	A/C and wiring - low coupling
400 MHz 40 GHz	75cm 7.5mm	UHF, SHF CW with AM Radar pulsed	Coupling on wiring close to equipment. Coupling through apertures (falling off quickly with increasing distance from aperture to equipment) Direct equipment case penetration.

As described in section 5.1 all cable bundles should be clamped close to the aircraft structure to minimize the pick-up in the ‘loop’ created by the cable bundle and structure and all cables bundles should be routed away from apertures such as doors and windows.

5.3.4 Cable Design

Cable design should take into account the signal, level, characteristic impedance, frequency, the length of the cable and EMI/HIRF/Lightning susceptibility and emissions requirements.

Electromagnetic coupling to or radiation from wire interfaces should take into account differential-mode, between signal and return, and common-mode, between signal/return and chassis. To minimize coupling and or radiation to/ from interfaces the effective loop area between signal and return, and between signal/return and chassis should be reduced. This can be achieved by routing the signal with its return and the signal/return close to chassis or aircraft structure. Twisting the signal and return wires further reduces the differential-mode coupling and/or radiation. The use of single point ground configuration can further reduce the common-mode coupling or radiation by reducing the level of common-mode current. Figure 75 shows interface configurations susceptibility to electric and magnetic fields. The following sections provide guidelines for selecting cables and wiring configurations to minimize EMI and ensure HIRF and Lightning compliance.

5.3.4.1 Cable Type

Most commonly used cables are single wire, twisted wires or coaxial. Single wire should be used for signals referenced to the aircraft structure. According to section 5.2.1.3, it should be limited to DC powered control circuits involving switches, relays, lamps, anunciators and solenoids.

Shielded or unshielded, twisted pairs, triplets or quads, should be used for frequencies below 100 KHz, including DC power, AC power, analog and audio. The use of twisted wires can be extended to frequencies as high as 10 MHz. For frequencies above 1 MHz, because of the twisted pairs non-uniform characteristic impedance and depending on cable length, signal level and interface circuitry, cable losses should be taken into account. Twisting wires is effective for coupling control but only when the current in the wire set is balanced. Therefore the twisted wires should be grounded at one end only, as described in section 5.2.1. Under these conditions twisted wiring provides the most effective isolation from low frequency magnetic fields as well as the most effective way of reducing magnetic field emissions from AC power. Twisting should be continued as close to the connector/

terminals as possible and routed through adjacent contacts at connector/terminals. Clamping and bending of twisted wires should be avoided because it reduces cable symmetry and voids some of the radiation and coupling reduction benefits due to twisting. The length of the twist must be a small fraction of a wavelength to obtain satisfactory cancellation. For signal lines, twisting should be no less than 18 twists/ft. If twisted pairs are used at higher frequencies such that cable length is greater than one tenth of the signal smallest wavelength then the circuit should be terminated in its characteristic impedance.

Coaxial cables have more uniform characteristic impedance and low losses and therefore are useful from DC to as high as a few GHz. Coaxial cables use the shield as the signal return. At low frequencies noise current on the shield can produce a noise voltage in series with the input signal and cause interference at the interface. The use of double shielded or triaxial cables, with insulation between the two shields, eliminates this low frequency coupling. At frequencies above 1 MHz, skin effect conditions on the shield prevail and a coaxial cable acts as a triax with the noise currents running on the outer portion of the shield and the signal currents on the inside portion of the shield. In order to avoid the use of the heavier and more expensive triaxial cables, coaxial cables should be considered for high frequency use above 1 MHz only. Coaxial cables should, in all cases, be terminated in their characteristic impedance.

Coaxial cables are the most suitable for unbalanced circuits with the shield grounded and serving as one conductor.

5.3.4.2 Cable Shielding

5.3.4.2.1 Shield Characteristics

Cables shielding depends on the choice of shielding material, connectors and wire categories described in section 5.3.1. This section addresses the shielding materials. The most common methods for shielding cables include braid, flexible conduit, rigid conduit and spirally-wound shields. The general properties of five classes of cable shields are given in Table 15.

TABLE 12. Comparison of Cable Shields

	Single Layer Braid (b)	Double Layered Braid (b)	Foil (c)	Conduit (c)	Flexible Conduit
Shielding (a) Effectiveness (Audio Frequency)	Good	Good	Excellenrt	Excellent	Good
Shielding (a) Effectiveness (Radio Frequency)	Good	Excellent	Excellent	Excellent	Poor
Normal Coverage	60-95%	95-97%	100%	100%	90-97%
Fatigue Life	Good	Good	Fair	Poor	Fair
Tensile Strength	Excellent	Excellent	Poor	Excellent	Fair

NOTES:

a. Poor < 20dB; Fair 20-40 dB; Good, 40-60dB; Excellent > 60 dB

b. Effectiveness against magnetic field is poor

c. For effective magnetic shield, high permeability material must be used

Braid consisting of woven or perforated material is the most common used cable shielding. Advantages of braid shields over solid shields include ease of handling in cable make-up and lightness in weight. However, for radiated (electric) fields the shielding effectiveness of woven or braided materials decreases with increasing frequency and increases with density and configuration of weave angle.

Solid or flexible conduits may also be used to shield system cables and wiring from the RF environment. Solid conduit shielding effectiveness, for RF purposes, is comparable to the shielding effectiveness of a sheet of the same thickness and material (see section 5.1.1.3.1). Degradation of solid conduit shielding is usually caused by discontinuities in the cable terminations such as connectors and backshells. Flexible conduit may provide effective shielding at lower frequencies, but at higher frequencies openings in shield can degrade the shielding effectiveness.

Protection against primarily magnetic fields require the use of high permeability shielding materials. Iron and steel conduit provide better protection against magnetic fields than does aluminum or copper conduit. The use of annealed high permeability metal strips wrapped around the cables are often used. Low frequency magnetic shielding can be enhanced by using multiple shields as following:

a. Combine a highly conductive shield for good reflection loss with a high permeability shield for a good absorption loss

b. Combine a shield of moderate permeability but high saturation level with a shield of high permeability but lower saturation level

Multiple layers of spiral-wound nickel-iron or silicon-iron alloys or low carbon steel have been found effective. High permeability tape is also available with or without adhesive backing. Also a combination of high permeability, high conductivity tapes are available which provide both electric and magnetic shielding. As described in section 5.3.2 the use of high permeability cable shields should be avoided if other means are available to minimize coupling.

The shielding effectiveness of a cable shield depends on the type of the shield, the length of the cable and the cable terminating impedances. The cable shielding effectiveness is usually defined as: $SE(dB) = 20Log_{10} (I_s/I_c)$; where I_s is the shield current and I_c is the current in the conductor due to the current in the shield.

A better measure of the shield performance requirements is the shield transfer impedance. The shield transfer impedance, in ohms per meter, is defined as the ratio of the open-circuit voltage induced on the inner conductors by the shield current (see Figures 76 and 77).

$Z_t = E_c/I_s$, where E_c is the distributed voltage on the inner conductor in V/m.

At low frequencies, well below 1 MHz, the transfer impedance of any shield is approximately equal to the DC resistance of the shield. At higher frequencies, well above 1 MHz, the transfer impedance for solid shields decreases due to skin effect. At these higher frequencies for leaky shields, such as braided wire and tape-wound shields, the transfer impedance increases with frequency due to a mutual inductance term that takes into account coupling through holes and solenoidal current in the shield. The transfer impedance for leaky shields can be written approximately as

$Z_t \cong R_0 + j\omega M_{12}$; where R_0 is the shield DC resistance and M_{12} is the mutual inductance.

Expressions for transfer impedance of solid shields, braided wire shields, tape-wound shields, double and multiple shields are provided in [4]. These expressions have been found to be very accurate at low frequencies and within a factor of three or less at the high frequencies. The transfer impedance for several kinds of shields is shown in Figures 78 through 85. Table 16 lists the calculated transfer impedance of some commonly used cables. The shield transfer impedance requirements for each cable interface should be determined by the Supplier, in cooperation with de Havilland, based on the electromagnetic environment, interface configuration and field pick-up, and interface circuitry design and sensitivity. The cable shields selected should have controlled transfer impedance agreed to by Supplier and de Havilland.

Above 100 MHz, the shield transfer impedance is usually not used as a measure of cable shield requirements due to transmission line effects and non-uniform current flow in the shield. At these higher frequencies shielding effectiveness data is a better measure of cable shield attenuation.

5.3.4.2.2 Grounding of Shields

Shields should not be used as signal return with exception of RF coaxial interfaces. In RF coaxial interfaces the frequency is high enough such that skin effect conditions prevail and signal currents run on the inside of the cable shield and the external currents run on the outside of the shield.

Conditions that establish the grounding of the shields vary depending on the shield current frequency as well as interface signal level and frequency. The following should be used to select the proper shield grounding:

a. Analog signals and audio signals, susceptible to low frequency magnetic fields, should have the shields grounded at one end only. If the source is grounded, the shield should be grounded at the source. If the source is floating then shield should be grounded at the receiver. This shield is an internal electrostatic shield and it should be carried through enclosures, bulkheads and metal interface connectors on a pin as close as possible to the interface circuitry ground. The shield should be routed to a connector pin via a pigtail as shown in Figure 86. Pigtail termination and maximum lengths should be determined by the Supplier and should be based on the level of the noise source and circuit sensitivity.

b. Digital and wideband signal circuit shields should be grounded at both ends.

c. Shields which are a barrier to high frequencies, greater than 50 KHz, should be grounded at both ends.

d. Shields which are a barrier to transients should be grounded at both ends.

e. Analog/audio signals and high frequency shielding requirements may conflict. In these cases, the circuits and installation must be evaluated. The design options include: double shielded interfaces, with the inner shield grounded at one end only and the outer shield grounded at both ends; the interface and interface circuitry as balance differential with the shield grounded at both ends; or, balanced differential interface and interface circuitry, and double shields with the inner shield grounded at one end and the outer shield grounded at both ends.

f. Shields must be grounded so that any interference/noise currents on the shield can be isolated from sensitive circuitry or areas. Shields grounded at both ends, should be terminated through an EMI connector backshell with complete circumferential bonding as described in section 5.3.4.3. This method is a must for interfaces performing functions rated Critical/ Catastrophic. Recommended connector backshells are provided in ESP 96.

g. The use of pigtails to terminate shields, should be avoided. The effect of the exposed pigtail section is to allow the direct EM field coupling to the exposed wire as well as noise coupling between the shield current running in the pigtail and the same exposed wires. Figure 87 shows the various outer shield terminations and their respective performance rating. Figures 88, 89 and 90 show cable shielding effectiveness degradation due to pigtail cable shield termination. Pigtail shield terminations should only be used on interfaces performing Essential /Hazardous/Major and Non-essential/Minor functions if the Supplier can demonstrate by analysis and/or tests that interface cable shielding design is adequate. In this case the Supplier, in cooperation with de Havilland, should specify the cable shield requirements as well as the maximum pigtail lengths and terminating procedure. Recommended connector backshells are provided in ESP 96.

h. Grounding a number of shields by means of a single pigtail to a connector ground pin should be avoided, especially if pigtail lead length exceeds one inch or where circuits of different EMC categories are involved. Such a ground lead is a common impedance element across which interference voltages can be developed and transferred from one circuit to another.

i. Pigtail shield terminations should never use the daisy chain method shown in Figure 91. See comment in paragraph h) on common impedance coupling.

j. Shields, grounded at both ends, should be grounded at pressure bulkheads and other conducting structures. If pressure bulkhead or other metal structure are located between regions with different EM protection than grounding of shields should be via a bulkhead connector EMI backshell with complete circumferential bonding (see Figure 72). If pressure bulkhead or metal structures are located within one electromagnetic region then shield grounding should be as described in (f) for interfaces performing Critical/Catastrophic functions, and as described in (g) for interfaces performing Essential/Hazardous/Major and Non-essential/Minor functions.

k. Individual shields within a harness should be electrically isolated from each other at all points except at connector terminations or ground points.

5.3.4.3 Connectors and Backshells

In order to achieve aircraft EMC, care should be taken on the pin allocation for the connectors. The signal/power and respective return should be routed in the same connector through adjacent pins. Wires of different categories, described in section 5.3.1, should not use the same connector. If the same connector is used for signals in different EMC categories then the following guidelines apply:

a. Pin allocation should be as illustrated in Figure 92 with one row of pins left empty between wires of different EMC category. As further protection, the empty row of pins can become ground pins or used to connect, where applicable, the cable internal shield (see section 5.3.4.2.2).

b. Wires from the different EMC classifications should be separated as soon as they leave the connector.

Signals going to connectors should be grouped such that only shielded leads, which are not filtered, enter one connector while all unshielded leads, which require filtering, go through another connector. For further details see 5.3.5.3 on filtering).

Interfaces performing Critical/Catastrophic functions should be routed in separate connectors from all other interfaces performing a function rated at a lower criticality level.

TABLE 13. Coaxial-cable Shield Parameters

Cable Type (RG-)	Strand Dia. d (in)	Outside Dia. (in)	Carriers C	Ends N	Picks, P (in^{-1})	Weave Angle, ∝ degrees	Fill, F	Coverage K (%)	Wt. per Foot (lbs)	Stranding Factor	DC Resis-tance, R0 (mΩ/m)	Leakage Induct-ance, M12 (nH/m)	Leakage Capacit-ance C_{12}/C_1C_2(m/F)
6 I	0.0063	0.189	16	9	5.90	25.0	0.790	95.61	0.019	1.54	6.6	0.42	2.9 x 10^7
6 AI	0.0063	0.189	24	6	8.80	24.9	0.790	95.58	0.019	1.54	6.6	0.28	1.9
6 O	0.0063	0.214	16	9	8.79	37.7	0.886	96.23	0.022	1.98	7.5	0.36	1.9
6 AO	0.0063	0.214	24	6	13.00	37.6	0.885	96.18	0.022	1.98	7.5	0.25	1.3
11	0.0071	0.292	24	8	6.50	27.5	0.799	95.96	0.033	1.59	4.0	0.25	1.6
22 I	0.0063	0.291	24	8	9.10	35.9	0.763	95.27	0.028	1.95	5.5	0.34	1.9
22 O	0.0063	0.316	24	8	12.00	45.9	0.842	97.50	0.033	2.45	6.4	0.14	0.6
23 I	0.0063	0.394	24	9	10.50	48.2	0.799	95.95	0.039	2.82	5.9	0.29	1.2
25 I	0.0063	0.298	16	13	5.00	31.4	0.786	95.44	0.029	1.74	4.8	0.46	2.8
25 AI	0.0063	0.298	24	9	6.00	26.0	0.776	94.98	0.029	1.60	4.4	0.34	2.3
25 O	0.0063	0.355	16	15	5.00	35.8	0.887	96.29	0.036	1.88	4.4	0.35	1.9
25 AO	0.0063	0.355	24	11	5.00	25.7	0.799	95.96	0.035	1.54	3.7	0.25	1.6
35	0.0071	0.470	24	10	9.00	48.8	0.850	97.74	0.056	2.71	4.3	0.12	0.5
58	0.0050	0.120	12	9	7.70	27.7	0.746	93.57	0.089	1.71	14.2	1.0	6.6
58 A	0.0050	0.120	16	7	10.30	27.7	0.775	94.92	0.018	1.65	13.7	0.53	3.5
59	0.0063	0.150	16	7	8.20	27.6	0.780	95.14	0.015	1.63	8.6	0.49	3.2
59 A	0.0063	0.150	24	5	12.30	27.6	0.835	97.29	0.016	1.53	8.1	0.14	0.9

TABLE 13. Coaxial-cable Shield Parameters

Cable Type (RG-)	Strand Dia. d (in)	Outside Dia. (in)	Carriers C	Ends N	Picks, P (in $^{-1}$)	Weave Angle, ∝ degrees	Fill, F	Coverage K (%)	Wt. per Foot (lbs)	Stranding Factor	DC Resis-tance, R0 (mΩ/m)	Leakage Induct-ance, M12 (nH/ m)	Leakage Capacit-ance C_{12}/C_1C_2(m/F)
62	0.0063	0.151	16	7	8.20	27.8	0.776	94.98	0.015	1.65	8.7	0.52	3.4
62 A	0.0063	0.151	24	5	12.30	27.8	0.831	97.15	0.016	1.54	8.1	0.15	1.0
63	0.0071	0.295	16	12	4.30	27.6	0.792	95.66	0.033	1.61	4.0	0.42	2.7
63 A	0.0071	0.295	24	8	6.50	27.8	0.793	95.71	0.033	1.61	4.0	0.27	1.8
65	0.0071	0.295	24	8	6.50	27.8	0.793	95.71	0.033	1.61	4.0	0.27	1.8
108	0.0050	0.164	16	6	10.80	36.4	0.546	79.36	0.009	2.83	17.6	4.6	25.0
114	0.0063	0.295	24	8	7.00	29.4	0.718	92.07	0.020	1.83	5.1	0.70	4.4
119 I	0.0071	0.337	24	10	5.40	26.4	0.862	98.10	0.041	1.45	3.1	0.08	0.5
119 O	0.0063	0.367	24	8	10.60	46.5	0.737	93.06	0.033	2.86	6.5	0.65	2.8
122	0.0059	0.099	16	6	12.90	28.9	0.801	96.02	0.008	1.63	16.2	0.37	2.4
122 A	0.0059	0.099	24	5	12.20	19.2	0.928	99.48	0.010	1.21	12.0	0.01	0.08
130	0.0100	0.487	24	8	6.30	39.9	0.786	95.41	0.076	2.16	2.3	0.33	1.7
142 I	0.0059	0.121	16	7	11.50	30.6	0.791	95.61	0.010	1.71	14.1	0.43	2.7
142 O	0.0059	0.141	16	7	14.50	40.7	0.778	95.09	0.011	2.23	16.0	0.55	2.8
144	0.0063	0.290	24	8	9.20	36.1	0.787	95.47	0.029	1.95	5.5	.032	1.7
156 I	0.0063	0.290	24	8	11.20	41.6	0.851	97.77	0.031	2.10	6.0	0.11	0.55
156 O	0.0070	0.333	24	8	9.20	39.9	0.803	96.13	0.034	2.11	4.7	0.26	1.3
156 S	0.0063	0.413	24	8	14.00	57.3	0.838	97.38	0.043	4.10	8.3	0.17	0.51
157 I	0.0063	0.465	24	9	12.80	58.0	0.856	97.92	0.049	4.16	7.5	0.12	0.36

TABLE 13. Coaxial-cable Shield Parameters

Cable Type (RG-)	Strand Dia. d (in)	Outside Dia. (in)	Carriers C	Ends N	Picks, P (in^{-1})	Weave Angle, ∝ degrees	Fill, F	Coverage K (%)	Wt. per Foot (lbs)	Stranding Factor	DC Resis-tance, R0 (mΩ/m)	Leakage Induct-ance, M12 (nH/m)	Leakage Capacit-ance C_{12}/C_1C_2(m/F)
157 O	0.0070	0.500	24	10	7.30	44.5	0.729	92.67	0.046	2.69	4.1	0.70	3.1
157 S	0.0063	0.580	24	9	13.50	64.5	0.848	97.70	0.060	6.35	9.2	0.16	0.34
174	0.0040	0.063	16	4	16.30	24.4	0.630	86.33	0.003	1.91	36.5	2.3	15.8
179	0.0040	0.066	16	5	12.00	19.2	0.729	92.65	0.004	1.54	28.1	0.88	6.6
181 I	0.0063	0.215	24	7	8.80	27.7	0.836	97.30	0.023	1.53	5.7	0.14	0.9
181 O	0.0100	0.490	24	8	7.00	43.1	0.820	96.76	0.080	2.28	2.4	0.20	0.95
189 I	0.0100	0.635	48	7	6.00	27.2	0.918	99.33	0.114	1.38	1.1	0.008	0.06
189 O	0.0100	0.680	48	6	7.00	32.7	0.778	95.07	0.104	1.81	1.4	0.17	1.0
192 I	0.0100	1.725	48	11	5.87	53.3	0.806	96.22	0.265	3.47	1.1	0.14	0.49
192 O	0.0095	1.780	48	11	5.95	54.5	0.764	94.43	0.182	3.88	1.1	0.25	0.85
192 S	0.0100	1.890	48	11	6.03	56.4	0.796	95.84	0.289	4.11	1.2	0.17	0.53
193 I	0.0100	1.725	48	11	4.15	43.5	0.664	88.68	0.220	2.86	0.89	0.66	3.1
193 O	0.0095	1.780	48	11	5.50	52.3	0.726	92.50	0.225	3.69	1.2	0.39	1.4
193 S	0.0100	1.890	48	9	7.70	62.6	0.781	95.20	0.284	6.83	1.7	0.23	0.54
194 I	0.0100	1.725	48	11	4.15	43.5	0.664	88.68	0.220	2.86	0.89	0.66	3.1
194 O	0.0095	1.780	48	11	5.50	52.3	0.726	92.50	0.225	3.69	1.2	0.11	0.38
210	0.0063	0.151	16	7	8.20	27.8	0.776	94.98	0.015	1.65	8.7	0.52	3.4
210 A	0.0063	0.151	24	5	12.30	27.8	0.831	97.15	0.016	1.54	8.1	0.15	0.96
211	0.0080	0.625	36	10	5.60	32.1	0.844	97.56	0.082	1.65	1.7	0.09	0.48

TABLE 13. Coaxial-cable Shield Parameters

Cable Type (RG-)	Strand Dia. d (in)	Outside Dia. (in)	Carriers C	Ends N	Picks, P (in^{-1})	Weave Angle, ∝ degrees	Fill, F	Coverage K (%)	Wt. per Foot (lbs)	Stranding Factor	DC Resis-tance, R0 (mΩ/m)	Leakage Induct-ance, M12 (nH/ m)	Leakage Capacit-ance C_{12}/C_1C_2(m/F)
211 A	0.0080	0.625	48	8	5.60	25.2	0.843	97.53	0.082	1.45	1.5	0.06	0.40
212 I	0.0063	0.189	16	9	5.90	25.0	0.790	95.61	0.019	1.54	6.6	0.42	2.9
212 AI	0.0063	0.189	24	6	8.80	24.9	0.790	95.58	0.019	1.54	6.6	0.28	1.9
212 O	0.0063	0.214	16	9	8.70	37.7	0.806	96.23	0.022	1.98	7.5	0.36	1.9
212 AO	0.0063	0.214	24	6	13.00	37.6	0.805	96.18	0.022	1.98	7.5	0.25	1.3
213	0.0071	0.292	24	8	6.50	27.5	0.799	95.96	0.033	1.59	4.0	0.25	1.6
214 I	0.0063	0.292	24	6	16.6	52.9	0.786	95.44	0.029	3.50	9.9	0.37	1.3
214 O	0.0063	0.317	24	7	15.40	53.0	0.850	97.75	0.034	3.25	8.5	0.13	0.45
217 I	0.0071	0.380	24	10	5.40	29.1	0.788	95.49	0.042	1.66	3.2	0.30	1.9
217 O	0.0071	0.405	24	8	10.60	49.3	0.794	95.75	0.045	2.96	5.4	0.32	1.3
218	0.0100	0.690	24	14	3.10	30.0	0.869	98.29	0.118	1.53	1.2	0.07	0.44
218 A1	0.0100	0.690	36	9	4.00	26.4	0.811	96.41	0.110	1.54	1.2	0.14	0.92
218 A2	0.0100	0.690	48	7	5.60	27.5	0.849	97.72	0.115	1.50	1.1	0.05	0.35
220	0.0100	0.925	36	12	3.50	30.0	0.840	97.44	0.151	1.59	0.091	0.009	0.53
220 A	0.0100	0.925	48	9	4.20	27.5	0.820	96.76	0.148	1.55	0.89	0.09	0.59
222 I	0.0063	0.189	16	9	5.90	25.0	0.790	95.61	0.019	1.54	6.6	0.42	2.9
222 AI	0.0063	0.189	24	6	8.80	24.9	0.799	95.58	0.019	1.54	6.6	0.28	1.9
222 O	0.0063	0.214	16	9	8.70	37.7	0.806	96.23	0.022	1.98	7.5	0.36	1.9
222 AO	0.0063	0.214	24	6	13.00	37.6	0.805	96.18	0.022	1.98	7.5	0.25	1.3

TABLE 13. Coaxial-cable Shield Parameters

Cable Type (RG-)	Strand Dia. d (in)	Outside Dia. (in)	Carriers C	Ends N	Picks, P (in^{-1})	Weave Angle, ∝ degrees	Fill, F	Coverage K (%)	Wt. per Foot (lbs)	Stranding Factor	DC Resis-tance, R0 (mΩ/m)	Leakage Induct-ance, M12 (nH/m)	Leakage Capacit-ance C_{12}/C_1C_2(m/F)
223 I	0.0050	0.120	12	9	9.00	31.5	0.775	94.95	0.010	1.77	14.8	0.72	4.4
223 AI	0.0050	0.120	16	7	11.50	30.4	0.795	95.80	0.010	1.69	15.5	0.43	2.3
223 O	0.0050	0.140	12	9	10.00	38.1	0.729	92.63	0.010	2.22	16.0	1.3	7.0
223 AO	0.0050	0.140	16	7	15.00	41.5	0.793	95.71	0.011	2.25	16.2	0.45	2.2
225 I	0.0063	0.290	24	6	16.60	52.7	0.788	95.52	0.029	3.46	9.8	0.36	1.3
225 O	0.0063	0.315	24	7	15.40	52.9	0.852	97.80	0.033	3.22	8.5	0.12	0.44
226 I	0.0063	0.375	24	10	10.50	46.8	0.907	99.14	0.042	2.35	5.2	0.03	0.12
226 O	0.0063	0.400	24	8	10.50	48.6	0.706	91.33	0.035	3.24	6.6	0.92	3.7
301	0.0050	0.190	16	10	8.00	32.1	0.752	93.84	0.014	1.86	10.0	0.73	4.4
302	0.0050	0.151	16	7	11.50	36.0	0.684	90.04	0.010	2.23	15.0	1.5	8.4
303	0.0050	0.121	16	7	11.50	30.6	0.791	95.61	0.010	1.71	14.1	0.43	2.7
304 I	0.0063	0.190	24	5	14.50	37.6	0.749	93.71	0.213	2.12	9.0	0.52	2.8
304 O	0.0063	0.215	24	6	11.50	34.4	0.769	94.57	0.021	1.91	7.2	0.40	2.3
316	0.0040	0.063	16	5	4.50	7.2	0.723	92.32	0.004	1.41	26.8	0.88	7.7
326 I[0]	0.0035	0.550	24	27	6.46	43.3	0.890	98.80	0.042	2.12	5.9	0.05	0.22
326 O[0]	0.0035	0.566	24	27	6.46	44.1	0.877	98.49	0.043	2.21	6.0	0.06	0.30
328 I	0.0100	1.085	48	9	5.50	38.5	0.795	95.80	0.167	2.05	1.0	0.14	0.75
328 O	0.0070	1.125	48	12	6.70	45.0	0.796	95.85	0.111	2.51	1.7	0.15	0.66
328 S	0.0100	1.225	48	9	5.60	42.4	0.748	93.63	0.177	2.45	1.1	0.28	1.3

TABLE 13. Coaxial-cable Shield Parameters

Cable Type (RG-)	Strand Dia. d (in)	Outside Dia. (in)	Carriers C	Ends N	Picks, P (in^{-1})	Weave Angle, ∝ degrees	Fill, F	Coverage K (%)	Wt. per Foot (lbs)	Stranding Factor	DC Resis-tance, R0 (mΩ/m)	Leakage Induct-ance, M12 (nH/m)	Leakage Capacit-ance C_{12}/C_1C_2(m/F)
329 I	0.0100	0.390	24	7	5.90	32.3	0.772	94.80	0.060	1.82	2.4	0.38	2.3
329 O	0.0070	0.430	24	9	9.20	46.9	0.794	95.74	0.043	2.70	4.7	0.31	1.3
391	0.0063	0.307	24	7	16.30	53.8	0.891	98.82	0.034	3.21	8.1	0.05	0.17

The overall shielding effectiveness of the cable is often compromised by leakage at the connector or connector and backshell. If the effectiveness of the cable shield is to be maintained, the cable shield must be properly terminated. In an otherwise adequately shielded system, currents conducted along shields can be coupled to the system wiring by an improper cable termination. In a properly terminated shield, the entire periphery of the shield should be grounded to a low impedance reference, minimizing any potentials at the surface of the termination.

Leakage through shielded cable connectors, including backshells, can be described in terms of a transfer impedance, in ohms. Similar to the leaky cable shields described in section 5.3.4.2.1, this transfer impedance Ztc, can be represented by a DC resistance, R0, measured across the connector and a mutual inductance, M12, between the external shield circuit and the internal conductors of the cable as shown below:

$$Z_{tc} \cong R_0 + j\omega M_{12}$$

The transfer impedance of a connector can then be used as a lumped element in the overall cable shield circuit model, in contrast to the distributed nature of the transfer impedance of the cable shield. Connector transfer impedance cannot be easily calculated but it can be easily measured. Table 17 lists measured values of transfer impedance for some connector models. Measurements have shown that connector torque can have a big impact on the connector transfer impedance. Figure 93 shows that at the higher frequencies the transfer impedance can increase by as much as 60 dB if torque is reduced from 200 in-lb to 25 in-lb.

In order to maintain the shielding integrity of a connector, a connector with spring contacts inside one portion of the connector should be selected (see Figure 94) so that positive contact is made along the circumference of the mating parts. The advantages gained using circumferential spring fingers over bayonet coupling is illustrated in Figure 95. The shielding effectiveness or attenuation is as much as 55dB higher for connectors with spring finger than for bayonet connectors. Figure 96 illustrates the type of connector that should be used when a shielded cable assembly contains coaxial or individual shielded wires.

The interface between the connector and its mounting surface (e.g. equipment, bulkhead) should be low impedance. A DC resistance requirement is provided in Table 11. The use of EMI gaskets should be determined by the Supplier based on the interface shielding requirements.

Figure 94 illustrates a permanent termination of a cable outer shield to a connector. The shield is made continuous with the connector by a soldering or metal-forming bond. While offering the best bond this practice is not practical or cost effective. Methods of quick mechanical compression bonding of the cable shield to the connector shell have been developed by EMC connector and backshell manufacturers. The backshell serves as a form of strain relief and provides a peripheral shielded configuration around the cable assembly at the wire-connector interface. Many such backshells permit rapid assembly, require no special tools, are field repairable and permit environmental sealing. They are available in high conductivity or high permeability materials to shield against both electric and/or magnetic fields. If the interface harness is made-up of more than one shielded cable then a similar method to that shown in Figure 97 should be considered. The knitted mesh is used to ensure that there are no openings between the various shields and therefore each shield has a 360 degree bond Recommended connector backshells are provided in ESP 96.

MIL-C-38999 Series III connectors should be used for interfaces performing Critical/Catastrophic functions. They should also be used at bulkheads or metal structures located between different EM areas. In addition, they are qualified for high vibration at elevated temperatures.

TABLE 14. Transfer Impedance of Typical Cable Connectors

Connector	Identification	R_0 (ohms)	M_{12} (H)
Multipin Aerospace Connectors (Threaded)	Burndy NA5-15863	0.0033	5.7×10^{-11}
	Deutch 38068-10-5PN	0.15	2.5×10^{-11}
	Deutch 38068-18-31SN	0.005	1.6×10^{-10}
	Deutch 38060-22-55SN	0.023	1.1×10^{-10}
	Deutch 38068-14-7SN	0.046	5.0×10^{-10}
	Deutch 38060-14-7SN	0.10	8.2×10^{-11}
	Deutch 38060-14-7SN	0.023	6.7×10^{-11}
	Deutch 38068-12-12SN	0.0033	3.0×10^{-11}
	Deutch 38068-12-12SN	0.012	1.3×10^{-11}
	Deutch 38068-12-12SN	0.012	1.3×10^{-11}
	Deutch 38060-12-12SN	<0.001	2.5×10^{-12}
	Deutch 38068-12-12SN	0.014	3.5×10^{-11}
	AMP	0.0067	1.6×10^{-11}
	AMP	0.0067	1.5×10^{-11}
	AMP	0.0033	1.9×10^{-11}
Type N	UG 21B/U-UG58A/U	*	*
Type BNC (Bayonet)	UG 88C/U-UG1094/U	0.002	$4\text{-}8 \times 10^{-11}$
Anodized	MS 24266R-22B-55	5×10^{4}	$\omega M<R_0$ @20 MHz
Open shell	MS 3126-22-55	0.5-1	$\omega M<R_0$ @ 20MHz
Split shell	MS 3100-165-1P Ms 3106A-	0.001	$\approx 20 \times 10^{-11}$

* Too small to measure in presence of 4 inches of copper tube used to mount connector.

5.3.5 Interface Circuitry Design

5.3.5.1 Removing/ Reducing Ground Loops

Ground loops are often a source of noise. This is especially true if the multipoint grounds are separated by a large distance, or when low-level analog circuits are used. Figure 58 shows a system grounded at two different points with a potential difference between the grounds. This potential difference may be due to magnetic field pick-up or due to currents running on the ground plane between the two ground points. This potential difference causes common-mode type noise voltage. Disconnecting or floating one of the grounds, removes the ground loop but at the same time converts the system to a single point ground system. The second option is to eliminate or minimize the effect of multipoint grounds by isolation of the two circuits. Isolation can be achieved by :

a. Balanced circuitry as described in section 5.3.5.2

b. Transformers as shown in Figures 98 and 99. Transformers ensure that the noise voltage appears between the transformer windings and not at the input to the circuit. The only noise coupling is due to parasitic capacitance between the transformer windings. This capacitance can be reduced by placing a shield between the windings. The shield should be grounded as shown in Figures 98 and 99. Disadvantages of transformers are size, limited frequency response and no DC continuity.

c. Common-mode chokes as shown in Figure 100 can transmit DC and differential-mode signals while rejecting common-mode AC signals. The common-mode noise voltage appears across the windings of the choke and not at the input to the circuit. Since common-mode choke has no effect on the differential-mode signal, multiple signals can be wound on the same core without crosstalk.

d. Optical coupling (optical isolators or fiber optics) as shown in Figure 101, breaks the metallic path between two grounds. Optical coupling is useful when there are very large voltage differences between the two grounds up to 100 MHz. The noise voltage appears across the optical coupler and not across the input to the circuit. Optical couplers are especially useful in digital circuits. They are not so useful for analog circuits because of poor linearity through the coupler.

e. Frequency selective grounding as described in section 5.2.1.1. This is only useful if the noise voltages are at a frequency different from the desired signal.

5.3.5.2 Balancing

Balanced circuits, as shown in Figure 68, are another way to reduce the common-mode ground noise voltages. A balanced circuit is a two conductor circuit in which both conductors and all circuits connected to them have the same impedance with respect to ground and all other conductors. In this case, the common-mode voltages induce equal currents in both halves of the balanced circuit and the balanced source and load responds only to the difference between the two inputs. Figure 102 shows the noise rejection capability of different interface configurations. The better the balance, the larger the amount of common-mode rejection. The system balance is dependent on source balance, signal lead balance, load balance as well as the balance of stray or parasitic impedances. Typically 60-80dB of balance is reasonable to expect from a well-designed circuit within its frequency band. As frequency increases circuit balance tends to decrease because stray capacitances have a larger effect on the impedance of signal and return circuits to ground. A twisted pair is inherently a balance configuration and therefore they should be used for balanced interfaces. Since perfect balance is not possible additional protection can be achieved by cable shielding such as shielded twisted pair. A coaxial cable is inherently unbalanced. If coaxial cables must be used in a balanced system, two cables should be used. Another alternative to using two coaxial cables is the use of twinax, consisting of two shielded conductors with well controlled characteristic impedance and low attenuation.

Broadband analog, video or low-level signals should be designed as balanced circuits.

5.3.5.3 Filtering

The use of frequency limiting passive or active circuits can be effective to further reduce interface noise to and/or from equipment. In some designs filtering may be a more practical solution to EMC problems than shielding. Filters can only be used to protect lines where the spectral content of the interference is different from that of the desired signal. Filters are effective in reducing noise when the low pass cut-off frequency is about ten times higher than the fundamental frequency being transmitted by the cable. They are usually useful for power, discretes and analog interfaces but not so widely used for digital interfaces such as high speed data lines where data skewing problems can occur and lines where a precise waveform is required for timing accuracy. Some standard type analog video drivers are not able to drive filter capacitance and the necessary amount of capacitance, approximately 1000 pF, can limit the effective video bandwidth. In cases where filters are not feasible, good circuit design and cable selection should be used.

Filters are either placed between signal/power and return, to eliminate differential-mode noise and/or between signal/power and chassis as well as return and chassis to eliminate common-mode noise. Several types of filters eliminate conducted interference:

a. Conventional filters such as high pass, low pass, band pass and band reject.

b. Lossy filters such as lossyline filters (ferrite tubes), ferrite beads and pin or connector filters.

Depending on the level of filtering and filter cut-off frequency, most filters are a combination of one or more stages shown in Figure 103. The source and load impedances should be taken into account when choosing the type of filter to be used. These impedances are usually different from the source and load impedances used by the filter manufacturer in producing its performance curves. The following are guidelines to aid in the selection of the type of filter stages:

a. An inductor should be used in series with a low source or load impedance

b. A capacitor should be used in parallel with a high source or load impedances

The non-ideal characteristics of passive filter electronic components, such as capacitors, inductors and resistors can affect the performance of any filtering network. The following are guidelines for the selection of components to ensure the filter performs as expected throughout the required frequency band:

a. Capacitor selection should take into account the capacitor resistance and inductance as shown in Figure 104. The maximum effective frequency of a capacitor is usually limited by its inductance and the lead inductance. Figure 105 shows the approximate usable frequency ranges for various types of capacitors. The high frequency limit is determined by the capacitor self-resonance and the low frequency limit is determined by the largest practical capacitance available.

b. Inductors, usually modeled as shown in Figure 106, are categorized into air core, open magnetic core, and closed core. Close magnetic core inductors have the lowest emissions. Air or open magnetic cores are the least susceptible to magnetic fields but have increased emissions.

c. Ferrite beads, modeled as a resistor in series with an inductance as shown in Figure 107, should be considered for higher frequency filtering above 1 MHz.

d. Resistors, usually modeled as shown in Figure 108, are grouped into wirewound, film type and composition.

If filtering is being used to meet EMI/HIRF requirements then all interfaces in the same connector should be filtered. No leads including ground leads should go unfiltered. All leads routed to the same connector should be grouped such that only shielded leads which do not require filtering, enter one connector while all unshielded leads requiring filtering go through another connector.

Higher frequency filtering requires the placement of filters within a shielded compartment as shown in Figures 109 and 110 to prevent interference from coupling between the filter input and output leads. Feedthrough filters should be used for each conductor as it passes through the shielded compartment wall.

The filter insertion loss can be compromised by high impedance connections of filter capacitors, feedthrough filters and of the filter shielded enclosure to chassis. Discrete capacitor lead lengths should be kept as short as possible such that the capacitor is effective for the frequencies of interest. Bonding DC resistance of the filter enclosure to chassis should be no greater than 0.5 milliohms as described in Table 11 of section 5.2.2.5.1.

Good filters can not be designed or purchased without a complete filter specification. As part of the specification, measurement or description of interference to be filtered is required. A complete filter specification should include at least the following elements:

a. Insertion loss including the filter insertion loss, pass band and reject band losses, cut-off frequency and efficiency at power frequencies.

b. Grounding requirements including the maximum impedance between the filter components to the ground system at the noise frequency.

c. Impedance matching by specifying filter elements to match the source and load impedances. If the source and load impedances are unknown or variable, the filter should include terminating impedances so that its behavior is stable over the frequencies of interest.

d. Voltage and current rating taking into account possible large current switching and transients on the interface. The filter current rating should be matched to maximum continuous demand.

e. Filter enclosure shielding ensures that the filter is effective for conductive interference and does not become a good receptor for radiated interference.

A filter pin connector, rather than a filter shielded compartment, should be considered for weight and volume reduction. The filter pin connector is usually more expensive than the shielded compartment approach. The most reliable filter pin connectors employ a discoidal monolithic substrate. Multi-filter stages with small ferrite bead inductors add very little to the filter insertion loss but add to cost, weight and volume, and therefore should be avoided. The filter capacitance available for typical connectors can be as high as 1mF. Filter pin connectors work best at frequencies greater than 1 MHz. The ratio between largest to smallest capacitor value on the same connector should be no greater than 10 to 1. Care should be taken when filtering differential lines in terms of unbalancing the line to ground impedance. In this case the tolerances on the filter capacitance should be no more than 5% and capacitance value should be no more than 0.001 mF, depending on signal frequency. The filters should be specified to meet the current and voltage requirements for each signal and power interface.

Filtering can also be provided by lossy line wiring as shown in Figure 111. Lossy line contains a ferrite embedded layer over the wire or wires plus a shielded layer. The lossy line ferrite material provides a distributed common mode choke to the cable providing common-mode noise attenuation as a function of length. The following are guidelines for the use of lossylines :

a. Filter line wires should have a metallic shield surrounding them in order to achieve the expected attenuation shown in Figures 112 and 113. The attenuation of a single shielded filter line is always more than that of a bundle of filter lines with an overall shield (see Figure 114). Some attenuation can still be achieved for unshielded filter lines if the lines routed close to chassis.

b. The shield should be grounded to chassis at both ends using a 360 degree peripheral connection to the connector backshell (see section 5.3.4.3).

c. This filter should only be used for frequencies above 100 MHz.

d. All lines bundled in the same overall shield routed to the same interface connector should be filter line.

e. Filter lines cables within an overall shield should be positioned as close as possible to the shield wall.

f. Lossy line wiring is interchangeable with normal wire.

5.3.5.4 Transient Protection Devices

To complement filtering, non-linear clamping devices can also be used. These devices should be placed from line to line and/or from line to chassis. They should also be placed as close as possible to the connector interface. Equipment which includes EMI filter assemblies should place the transient protection devices inside this filter assembly. To provide transient protection for the filter components transient protection devices should be placed prior to any filter components. In the case of filter pin connectors, these devices should be added to the connector as part of the filter pins. Table 18 lists chararcteristics and features of available transient suppressor devices. The device lead lengths should be kept as short as possible to minimize lead inductance and ensure that the voltage across the leads is small compared to the total device clamping or breakdown voltages. Since these devices may fail open circuit, failure detection is a concern. Suppliers should ensure that procedures are in place to identify part failures.

TABLE 15. Characteristics and Features of Transient Voltage Suppressor Technology

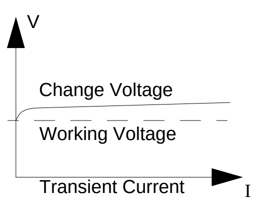
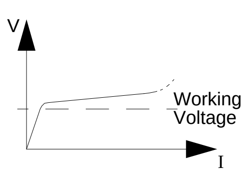
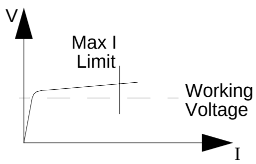
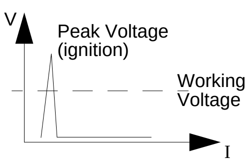
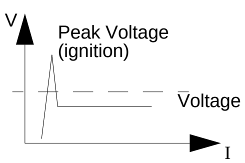
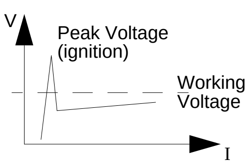
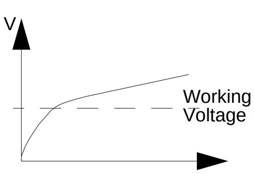
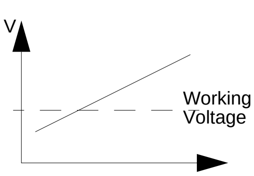
V-I Charasteristics	Device Type	Leakage	Follow on I	Clamping Voltage	Energy Capability	Capaci-tance	Response Time	Cost
	Ideal Device	Zero to Low	No	Low	High	Low or High	Fast	Low
	Zinc Oxide Var-sitor	Low	No	Moderate to Low	High	Moderate to High	Fast	Low

TABLE 15. Characteristics and Features of Transient Voltage Suppressor Technology

V-I Charasteristics	Device Type	Leakage	Follow on I	Clamping Voltage	Energy Capability	Capaci-tance	Response Time	Cost
	Zener	Low	No	Low	Low	Low	Fast	High
	Crowbar (Zener - SCR Combina-tion)	Low	Yes (Latching Holding I)	Low	Medium	Low	Fast	Moderat e
	Spark Gap	Zero	Yes	High Ignition Voltage Low Clamp	High	Low	Slow	Low to High
	Triggered Spark Gap	Zero	Yes	Lower Ignition Voltage Low Clamp	High	Low	Moderate	High
	Selenium	Very High	No	Moderate to High	Moderate to High	High	Fast	High
	Silicon Carbide Varsitor	High	No	High	High	High	Fast	Relative Low

5.4 Electrical/Electronics Design

5.4.1 System Architecture

At a system level, the use of dissimilar designs between redundant parts of the system should be considered to reduce system susceptibility. Two main techniques should be used in producing such an architecture:

a. Use of an non-electronic back-up system (optical or mechanical).

b. Provide a different frequency dependence of upset for the redundant parts which should result in different malfunction signatures. The different frequencies at which the lanes are most susceptible should be at least one octave apart. At system level integration, different routing of two wires or relocation can be sufficient to obtain different signatures. The different malfunction signatures can be achieved by different hardware (technology, devices, circuit design etc.), different software, different cable routing and lengths, avoiding common points or paths between lanes, providing data consolidation via different system parts, and by placing the system in physically different locations to achieve different environments at the higher frequencies.

5.4.2 Hardware Design

In general, the hardware design is the most sensitive and effective step of the system design. Good circuit design measures incorporated at the initial equipment design phase minimizes the requirement for additional protection methods and therefore reduces weight and cost. The following are general design measures that should be considered early in the system design:

a. Signal levels should be high enough to give good signal to noise ratio in the presence of the EM environment but not so high as to cause interference to other equipment.

b. The spectral content of the required signal should be the minimum required for correct circuit operation. In addition, circuitry should be designed to respond only to the required frequency range of the signal and should be band limited outside this range to minimize undesired response to interfering signals.

c. Circuit interface impedance should be low to minimize capacitive coupling from interfering signals and at the same time high enough to minimize inductive coupling.

d. Balanced input circuitry should be used where practical to minimize common mode interference problems.

e. Minimize coupling path by proper PCB design and wire routing.

In most cases devices that use large currents, such as rotary machines, solenoids, relays are not susceptible. Analog and digital circuitry which operate on very little current (low level or high impedance circuits) and have large bandwidth or have large loop gains are usually susceptible to nominal electromagnetic environments when connected to an efficient coupling path. Within this group, the analog circuitry is still more susceptible than the digital. Therefore separation of analog and digital devices should be considered. The following sections describe guidelines for the reduction of hardware emissions and susceptibility.

In order to minimize emissions and interference, circuitry design should always use the slowest and lowest level technology capable of doing the job. In order to minimize susceptibility, design should use the slowest but higher level technologies. Therefore circuitry selected should take into account EMI/HIRF/ Lightning requirements to ensure optimal design.

5.4.2.1 Analog Devices

Analog devices are primarily a source of susceptibility. Analog device response to in-band noise is linear and well defined by the device and circuit design. The level of in-band noise interference allowed should be estimated based on the circuitry performance requirements or noise floor. The main interference mechanism in the analog part of the system due to out-of-band interference, such as HIRF, is for the interfering RF signal to be demodulated causing a DC offset or a signal of the same frequency as the interfering signal modulation. Figures 115 through 117 show the susceptibility and damage thresholds for some common solid state devices. The operational amplifiers have the greatest sensitivity to RF interference. The following design precautions should be taken:

a. The system pass band should be restricted by using filtering.

b. Analog devices, such as sensors or actuators, should be located as close as possible to their analog interfaces.

c. High level balanced signals and balanced circuitry should be used. Signal and return should be routed together, preferably in twisted pair or coaxial cable depending on the circuitry frequency (see section 5.3.4.1).

d. In the case of redundant systems, the following techniques should be considered to exclude erroneous data:

- Virtual voters (no hardware) if a suitable voting algorithm can be produced.
- Data coherence verification techniques such as DC offset and scale limitation, AM and FM signals with carrier and center frequencies different from the HIRF modulations and internal aircraft modulations (e.g. 400 Hz, 1 KHz etc.) and monitoring of the signal reference.

5.4.2.2 Digital Devices

Digital and pulsed circuits are both a source of emissions and susceptibility. A square wave pulse has a very broad spectrum and contains significant energy at almost any frequency. Figure 118 shows the spectra of several common waveforms. Given an effective coupling mechanism almost any sensitive device will respond to a digital or pulsed signal. Digital circuits are susceptible to in-band and out-of-band interference. For in-band noise one should consider the device static noise margin, where the width of the interfering pulse is large compared to the switching time of the device as well as the dynamic noise margin, where the width of the interfering pulse is short compared to the switching time of the device. Table 19 lists various logic families, rise times, bandwidth, logic swing, and static noise margin. Figures 119 and 120 shows a plot of static and dynamic noise margins for various logic families. For all logic families, the dynamic margin is always greater than the static margin.

Digital circuits are made-up of analog devices and therefore non-linear effects, such as DC rectification of high frequency signal, is also applicable. Figures 115 through 117 show the susceptibility and damage thresholds for some electronic devices. The same design precautions used for analog circuitry should be used for digital circuits. The following design configurations should be considered and are listed in order of decreasing susceptibility:

a. Level triggered signals

b. Edge triggered signals

c. Transition triggered signals

d. Sequence coded transition triggered signals.

5.4.2.3 Power Conversion, Conditioning and Distribution

Power conversion and conditioning devices such as AC to DC converters and DC to DC converters produce conducted and radiated interference. The nonlinearity of transformer materials leads to the production of harmonic noise. Large currents with high rates of change, can couple efficiently into nearby circuits, and parasitic reactance contributes to ringing to the noise spectrum. Modern high efficiency power supplies use DC/DC converters and switching regulators. Switching regulators generate noise well above 1 MHz. Most interference can be controlled by proper grounding shielding and filtering as described in previous sections. The following are some guidelines to minimize noise from these power supplies:

a. The shape of the switching waveform should be controlled to minimize the spectral components associated with switching.

b. Ringing due to parasitic capacitances and inductances in primary windings, should be reduced by shielding the primary from the secondary circuits and should be damped by placing RC elements across the windings.

c. Impulse noise due to changes in diode biasing in the transformer rectifier circuits should be minimized by using diodes with fast recovery times and inserting some resistance in series with the diode.

When an inductive load such as a relay coil is opened, a large reverse voltage (V) is produced [V=L(dI/dt), where L is the inductive load and I is the current]. In order to control this inductive transient the following protection networks should be considered as shown in Figure 121:

a. Resistive damping, can reduce inductive transients but increase power demand.

b. Capacitive suppression can cause the circuit to appear purely resistive and as the current is interrupted the capacitor behaves as a short circuit.

c. Diode suppression for DC circuits is the most efficient suppression. Zener diodes reverse biased knee should be 20% above the maximum DC voltage.

TABLE 16. Typical Characteristics of Various Logic Families

Logic Families	Output Voltage Swing	Rise/ Fall Time (ns)	Bandwidth (MHz)	Max Vcc Voltage Drop (V)	Power Supply Transition Current (mA)	PS Decoupling Capacitor* (pF)	PS Current*** Per Gate Drive (mA)	Input C (pF)	DC Noise ** Margin (mV)
Emitter Coupled Logic (ECL-10K)	0.8V	2/2	160	0.2	1	350	1.2	3	100
EMitter Coupled Logic (ECL-100K)		0.75	420						
Transistor-Transistor Logic (TTL)	3V	10	32	0.5	16	2350	1.5	5	400
Low Power TTL (LP-TTL)	3V	20/10	21		8	400	1.6	5	400
Schottky TTL Logic (STTL)	3V	3/2.5	120	0.5	30	1500	4	4	300
Low-Power Schottky TTL (LS-TTL)	3V	10/6	40	0.25	8	3700	2.1	6	300
Complementary Metal Oxide Logic (CMOS) 5V or (15V)	5V (15V)	90/100 (50)	3 (6)		1 (10)		0.2	5	1V (4. 5)
High Speed CMOS (5V)	5V	10	32	2	1	150	1	5	1V

$$* C = \frac{(I\ Gate\ \&\ I\ For\ 5\ Gates) \bullet Rise\ Time}{0.2 \bullet\ Max\ V_{cc}\ Drop}$$

0.2 x Max Vcc drop is to provide a -14dB safety margin for I/N ratio.

** DC noise margin = difference between V_{out} of driving gate and V_{in} required by driven gate to recognize a “1” or “0”.

*** Peak instantaneous current that the driving device has to feed into each driven gate.

Switch and relay contacts tend to bounce on closure and arc on opening. The contact transient should be suppressed as shown in Figure 122. The series resistor/capacitor combination is the most used. The resistor should be of the order of a few ohms and the capacitor between 0.01 and 1 mF. The resistor/capacitor/diode combination provides optimum protection. The capacitor and resistor are selected as described for the resistor/capacitor configuration. The diode should have a breakdown voltage greater than the supply voltage and possess an adequate surge current rating.

Common mode impedance coupling through the power bus should be minimized by providing separate power supplies for noisy circuits with high currents and more sensitive signal circuits. Further decoupling should be obtained by placing a resistor/capacitor or an inductance/capacitor across the load from source to ground as shown in Figure 123. The resistor/capacitor configuration is usually limited by the allowed voltage drop across the resistor. The inductor/capacitor configuration provides more filtering than the resistor-capacitor configuration. Care should be exercised such that the resonant frequency of the filter network is well below the passband of the circuit connected to the filter and enough resistance is included to ensure adequate dampening of this resonance.

5.4.2.4 Rotating Machines

In order to minimize harmonic content, AC machines should have symmetrical windings and the mechanical and electrical balance and tolerances should be maintained.

The most significant noise associated with DC machines is the brush noise which results from arcing along slip rings or commutators. In order to control brush noise the following should be included in the design:

a. Decreasing current density, surface friction and brush resistance

b. Increasing brush pressure.

Rotating machinery produces both conducted and radiated interference. Both can be reduced by placing a resistor-capacitor pair (in series) across each winding and bypassing the brushes with capacitors. Appropriate shielding should further reduce radiated interference.

5.4.2.5 Transmitters and Receivers

Transmitter and radar output stages produce a signal with a wide and high level harmonic content. Nonlinear elements can produce intermodulation products and other spurious signals. Usually proper shielding, grounding and filtering reduces spurious emissions to acceptable levels. In addition, the following guidelines for transmitter design should aid in achieving EMC:

a. Transmitters should be designed to use the least bandwidth and amplitude consistent with their function.

b. Use pulses with slow rise times.

c. The harmonics and spurious emissions should be filtered at the source or as close as possible to the source.

d. Antenna patterns and sidelobes should be managed to reduce sidelobes and transmission losses.

e. Shielding should be used to reduce radiated emissions from transmitter elements.

Receivers are often susceptible devices because they are intentionally sensitive to a portion of the EM environment. Good grounding and shielding will optimize the receiver's EMI mitigation features. Filtering and added shielding may be required to raise the receiver upset threshold above operating EM environment. Frequency management, antenna design, spatial and temporal isolation should be incorporated in the design to eliminate interference. The local oscillator associated with the receiver, unless shielded carefully, can be an important source of interference. Nonlinear devices tend to generate harmonic products that can combine with local oscillator frequencies and produce unwanted signals.

5.4.2.6 Printed Circuit Board Design (PCB)

Proper PCB design can reduce emissions and susceptibility to internal and external interference. The following factors should be considered during PCB design to ensure minimal circuitry radiation and susceptibility:

a. Loop areas between signal and return

b. Trace lengths

c. Component placement

d. Power distribution and decoupling

e. Ground distribution

f. Signal routing

Loop areas on PCB should be minimized to reduce radiated emissions and pick-up of external fields. This loop area should be minimized by routing the signal close to return. Routing a dedicated ground trace close to every signal trace may not be feasible because of the large number of signal traces. The alternative is to have ground grids or preferably multilayer boards with ground planes. If ground grids are used, care should be taken to ensure that the path taken by signal to get to the ground trace is short (see Figures 124 and 125). Multilayer boards with ground planes are the best technical alternative.

If a common impedance is shared by both the input signal return and the output signal return of an amplifier, unwanted feedback will take place. If the output is in phase with the input, positive feedback will occur and if the gain is greater than one, the amplifier will oscillate. However, if the loss through spurious ground paths exceeds the gain of the amplifier, the amplifier operating characteristics will be altered drastically, and the operating limits can be exceeded. Therefore PCB component placement is a major factor in minimizing emissions and susceptibilities. High speed components should be placed far away from the PCB I/O connector. They should also be placed to minimize the length of high speed traces. Interface circuitry including amplifiers, bus and line drivers/receivers of off-board loads, optical isolators, isolation transformers and filters should be placed as close as possible to he respective connector. Figure 126 shows a typical PCB functional layout. Digital and analog circuitry if present on the same board should be kept separate (see Figure 127).

Ideally, the power distribution layout should be the same as, and parallel to, the ground system. This reduces the impedance, on the power and grounds. This also provides a built-in decoupling capacitance between power and ground. In a multilayer board, adjacent power and ground planes are the best configuration.

The level of transient current on the power distribution can be reduced by placing a capacitor near the switching device (see Figure 128). Even if power planes are used, decoupling capacitors should still be used. Decoupling capacitors should be placed across each fast switching device. Decoupling capacitors should have low inductance. They should be placed as close as possible to the device. In addition, the capacitor leads connected to the power and ground should be as short as possible to ensure a low inductance. Figure 129 shows preferred placements for the capacitors. To ensure a higher capacitance self-resonance, the smallest value capacitor required should be used and it should be determined based on the allowed ripple voltage on the power and the current transient of the device. The use of distributed capacitor mounted under the device, socket mounted capacitor, surface mounted capacitor (on the non-component side of board) and lead-frame capacitor (molded into the device package) should be considered to ensure high self-resonance decoupling capacitors.

PCBs with a mixture of analog, digital and noisy circuits should keep grounds separate as shown in Figure 127. It is easier to connect grounds together, if required by equipment operation, than it is to separate them. Depending on the noise immunity of the input circuitry at the digital to analog interface, the ground connection between digital and analog circuits may not be required.

In high speed circuitry ground planes, microstrip and stripline designs may be required to provide constant impedance signal interconnections. In such cases, the use of ground planes and multilayer boards for EMC involves no additional cost.

Multilayer boards should have a layer organization similar to that shown in Figure 130. Each signal layer should be adjacent to a low impedance plane such as power, ground or shield. Clock traces and susceptible traces should be on the layer adjacent to the ground plane and their lengths should be as short as possible. Further protection of these signals can be provided by using zero potential traces (shields), one on each side of the signal. These shields should be connected to the respective signal ground. Long parallel traces should be avoided, especially for clock signals. If the use of long parallel traces is unavoidable, they should be arranged so they successively progress from low level to high level. Adjacent signal layers should have traces running perpendicular to each other to reduce crosstalk. Traces should not have right angles.

To prevent unintentional switching and noise generation, all unused pins should be connected to a low impedance reference and not left open. A floating input picking-up noise may cause devices to switch randomly. This is important for devices with high input impedance such as CMOS devices.

5.4.3 Software Design and Verification

The software design of a system may be implemented to increase the system immunity to Lightning/HIRF. The software architecture is driven by the hardware design. However, the software architecture may be augmented with the following techniques. for Lightning/HIRF hardening:

a. Data Link Communication

b. Interrupts

c. Timers

d. Multi-processor

e. Redundancy

f. Dissimilar Programs

g. Processing Sequencing

h. Fault Tolerance

The **Data Link Communication** software of the CPU with various input and display devices may use techniques for maintaining data integrity. 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. The data shared with a peripheral may be sampled over a period of time and integrated or compared to derive consolidated data. Re-send tactics may be used if interference is detected. Error correction algorithms may also be used. For internal computer digital buses and CPU control signals, data communication techniques can be used.

Computer Interrupts may be used for treating unexpected malfunctions like EMI bus errors and equipment malfunctions due to EMI. The computer interrupt along with the devices on the bus would be polled to locate and diagnose the failure.

Watch dogs or Time-outs are used frequently on communication links to detect unexpected malfunctions like bus errors or unused interrupts in order to allow the computer to reset after an event.

In a **Multi-Processor or Bi-Processor** architecture, one processor can monitor Critical software functions and software flow in order to detect anomalies of the other processor. It is important to implement programs devoid of loops and software with deterministic behavior must be implemented.

Another approach is to use **Dissimilar Software Programs** in redundant computers or dissimilar CPU types could host the software program resulting in unique processing environments for the Critical/Catastrophic functions. The techniques of fault tolerant software systems provide a means to harden the system to Lightning/HIRF upsets.

The **Sequence** in which the software executes its process may be structured in such a manner as to minimize the impact of HIRF/Lightning on Critical/Catastrophic functions. The process sequences may be real time, monitor, background, foreground, sequential, prioritized or interrupt driven.

Generally, all the above techniques may be applied at the equipment/system level to improve system immunity.

6.0 MAINTENANCE, REPAIR AND MODIFICATIONS

The information in this section should only be used to verify the protection adequacy of systems which perform Critical/Catastrophic functions.

This section provides guidelines on how to define maintenance procedures for design features required for EMI/HIRF/Lightning protection of aircraft structures and systems. Maintenance includes the actions required to restore or maintain an item in a serviceable condition including repair and modification.

The structures and systems Suppliers are required to review the guidelines of this section and provide de Havilland with maintenance procedures to ensure the continued AIRWORTHINESS of the aircraft and its systems during in-service operation.

EMI/HIRF/Lightning hardness degradation may be unintentionally introduced during normal maintenance and repair (paint overspray, errors in reassemble of connectors). Degradation may also occur due to corrosion, erosion, wear, damage or security of attachment.

Scheduled maintenance requirements for aircraft EMI/HIRF/Lightning protection should be defined as an integral part of the initial aircraft maintenance program and should be updated as the design evolves and in accordance with in-service experience. There are three primary design features used to ensure that the structure and systems operate satisfactorily in the EMI/HIRF/Lightning environment:

i. Aircraft primary and secondary structures

j. Electrical wiring installation protection (shields, connectors, cable trays)

k. Equipment protection (equipment case, I/O protection)

The maintenance program should identify the following:

a. EMI/HIRF/Lightning protection features

b. Degradation failure modes of these features and the resulting effect on system operation

c. Maintenance operations which are applicable to these features

The development of scheduled maintenance procedures requires an identification of the applicable task and a determination of the task interval.

In many cases, visual inspection may suffice to observe degradation of the protection design. In some cases, the protection feature must be verified by specific tests.

The maintenance task interval should take into consideration factors such as the relevant operating experience gained from similar designs, the exposure of the design to adverse operating environments such as humidity and marine climates, the susceptibility of the protection design to wear and damage, the criticality of each protective feature within the overall protection scheme as well as the Mean Time Between Failure (MTBF) of protective devices installed within equipment.

Table 20 provides some guidance as to the maintenance tasks which may apply to certain types of electromagnetic protection features.

Repairs and modifications to aircraft structure and system wiring installations may affect EMI/HIRF/Lightning protection. Changes or repairs to wiring type, connectors, bonding, shielding and equipment must be evaluated to ensure the electromagnetic protection design is maintained.

TABLE 17. Possible Maintenance Tasks

Protection Scheme	Example	Degradation or Failure Mode	Maintenance Operation
Cable Shield	Metal Braid	Corrosion, Damage	Visual Inspection, Measurement of cable, Shielding/Bonding
Cable Tray/Raceway	Metal Structure	Corrosion, Damage	Visual Inspection, Bonding Measurement
RF Gaskets	Removable Panels, Equipment	Corrosion, Damage, Deformation	Visual Inspectionq
Shield for Non-Conductive Structures	Conductive coating	Damage, Erosion	Visual Inspection, Measurement of Shielding Effectiveness
Structural Bonding	Contact Bonds, Rivet Joints, Bopnding Leads/ Straps, Pigtails	Corrosion, Damage, Security of Contact	Visual Inspection, Bonding Measurement
Connectors, Backshells	Termination Impedance	Corrosion, Security of Contact	Visual Inspection, Bonding Measurement, Transfer Impedance
I/O Protective Devices	Resistors, Zener Diodes, EMi Filters	Short Circuit, Open Circuit	Check at Equipment Return to Repair Facility

7.0 ANALYSIS/ DEVELOPMENT TEST

ESP 89 requires the system Suppliers to submit as part of their EMC Control Plan, a summary of development tests and/or analysis that will be carried out to substantiate design protection methodologies.

ESP 89 requires structures Suppliers to submit as part of their EMC Control Plan, a summary of the development tests and/or analysis to substantiate that design meets the shielding requirements specified in the DTRD. Shielding measurements can be conducted by following MIL-STD-285 or mode stirring techniques.

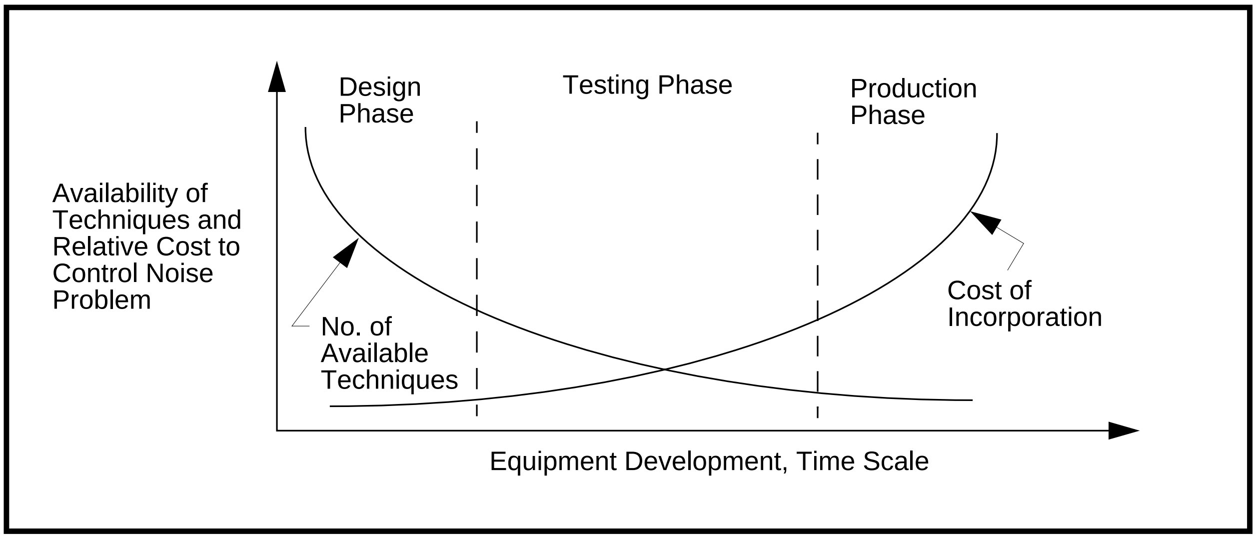


Figure 1. Cost and Availability of Interference Control Measures

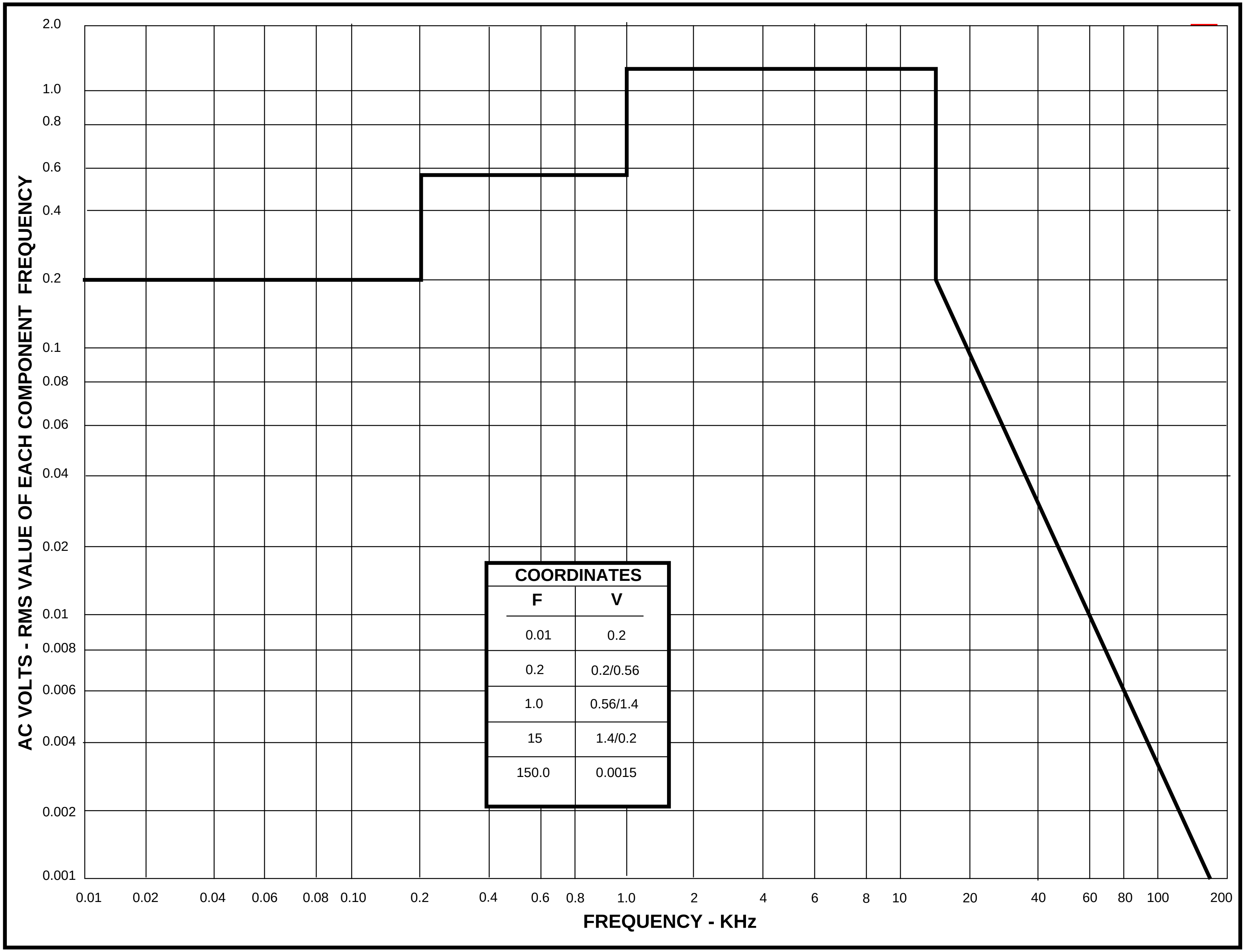


Figure 2. Frequency Characteristics of Ripple in 28 V DC Electric System - Categories A & Z

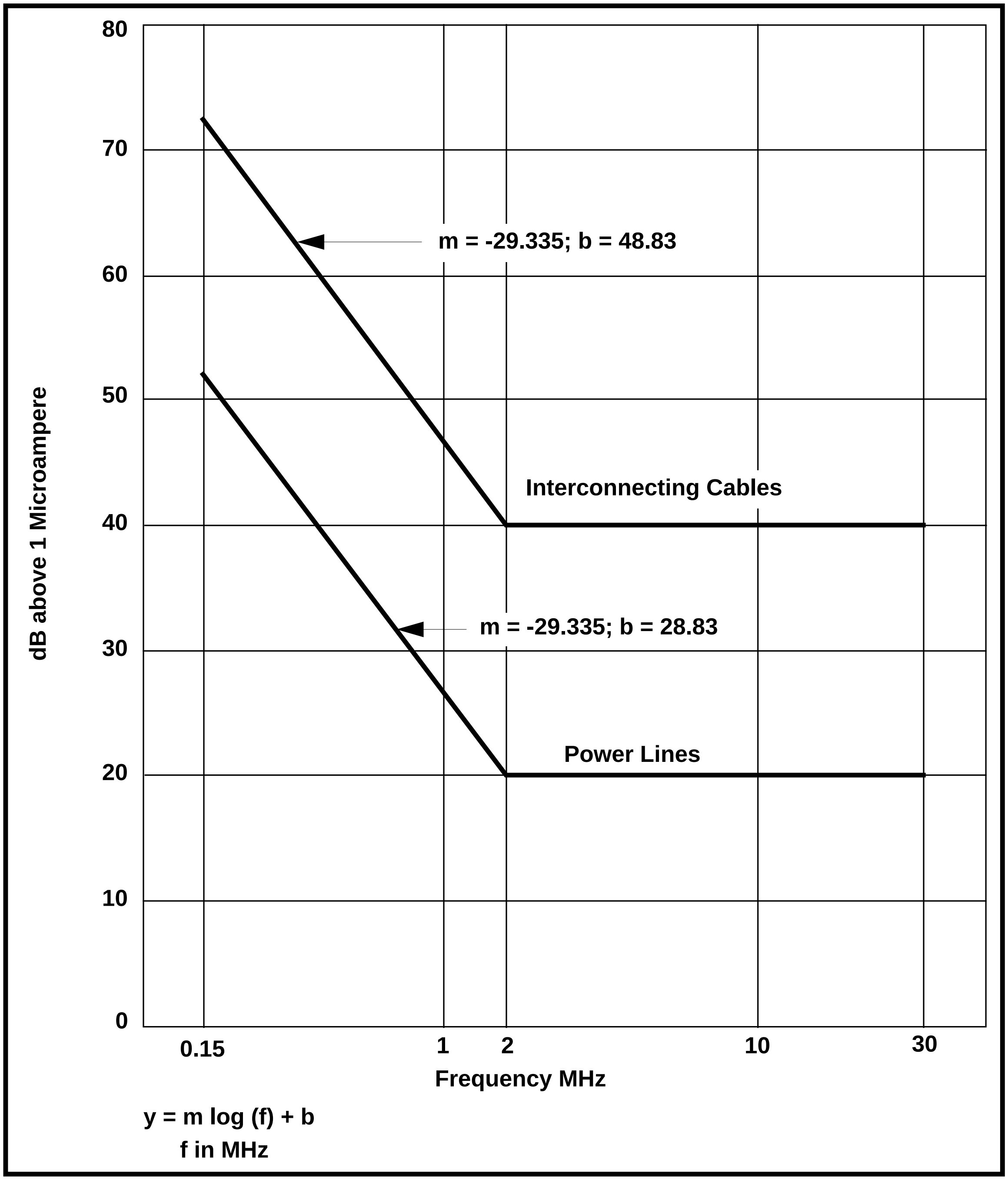


Figure 3. Conducted Narrowband Interference Limits Using Clamp-On Measuring Device - Categories A & Z

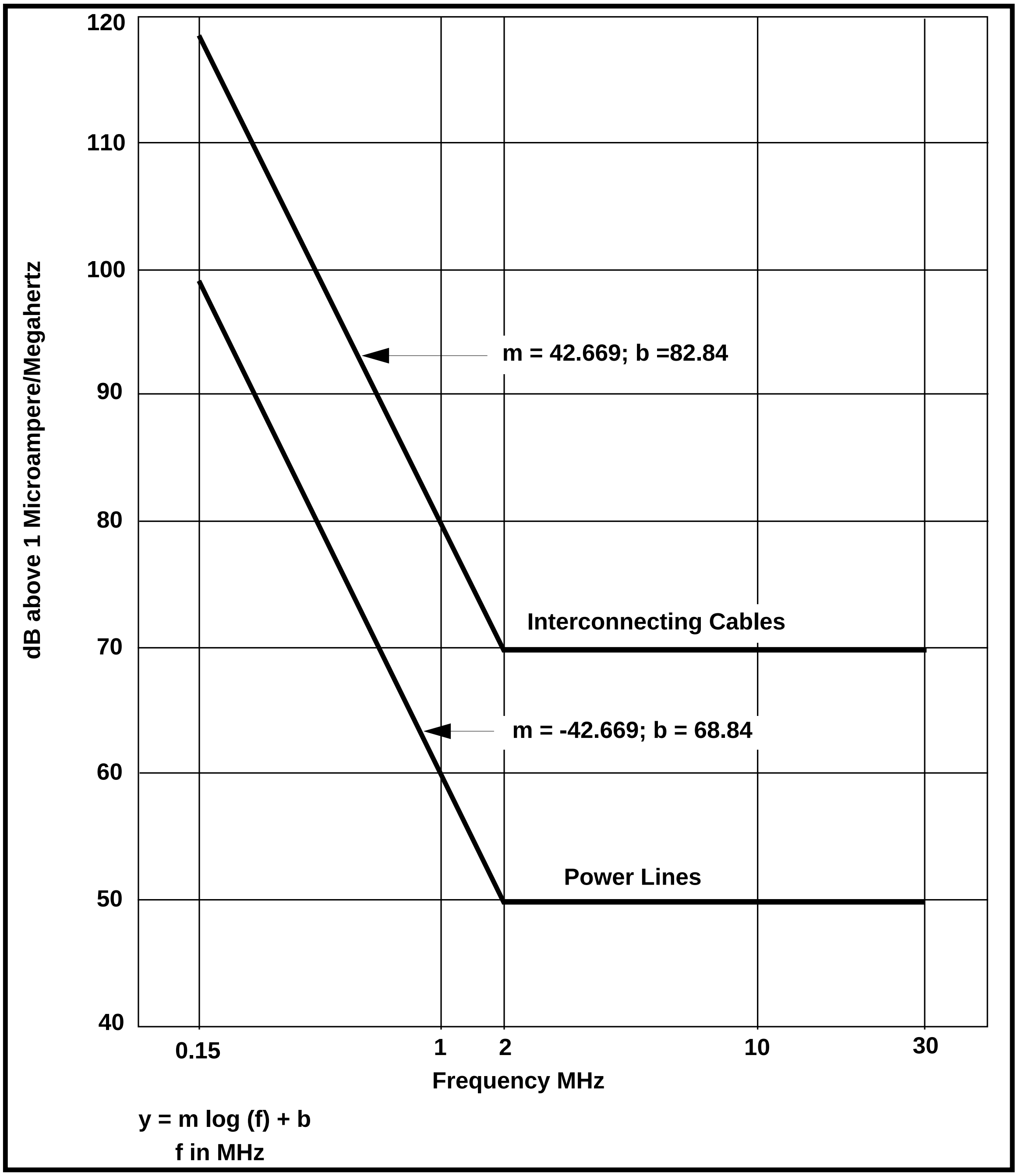


Figure 4. Conducted Broadband and Pulsed CW Interference Limits Using Clamp-On Measuring Device - Categories A & Z

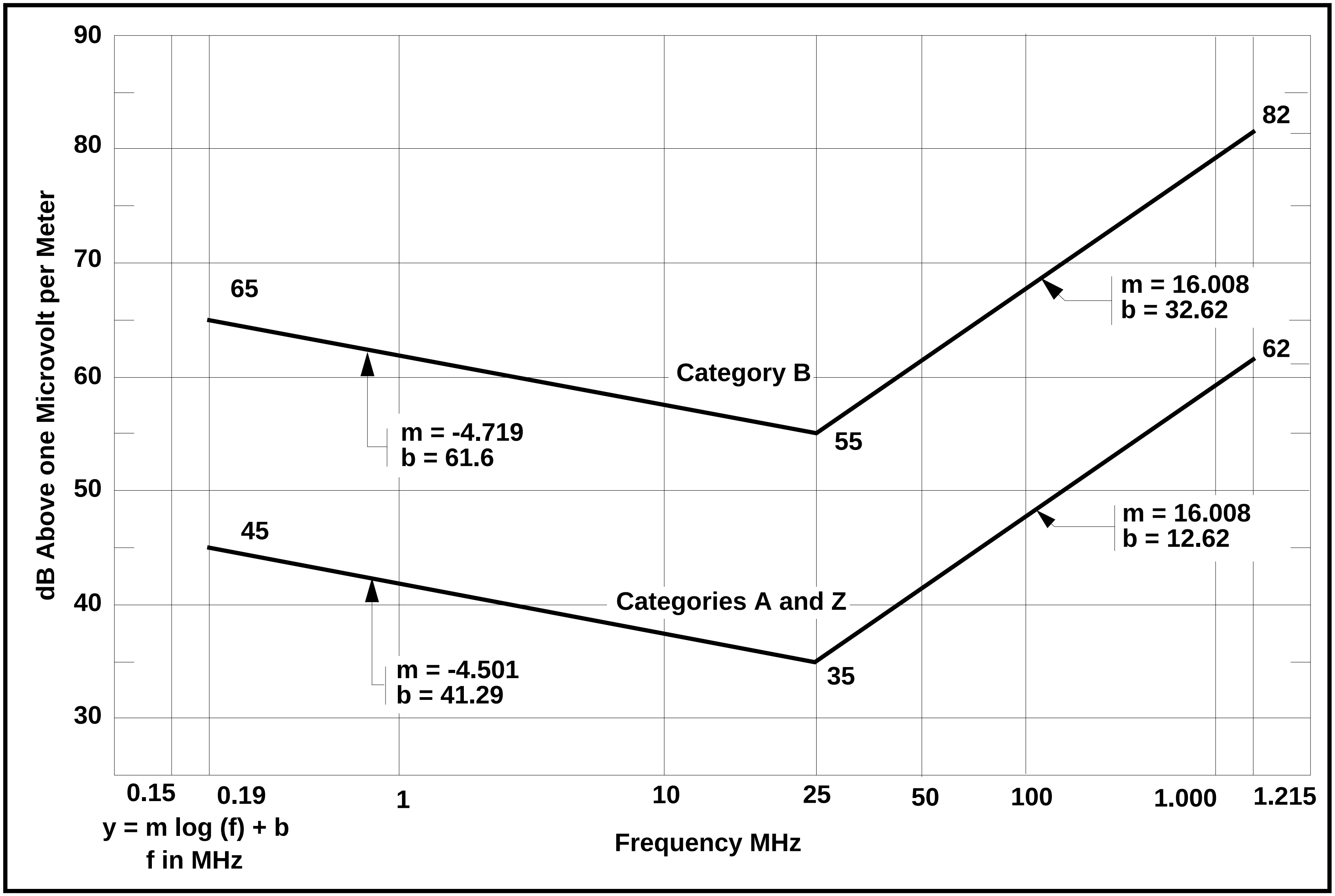


Figure 5. Maximum Level of Radiated CW Interference From Any One Equipment

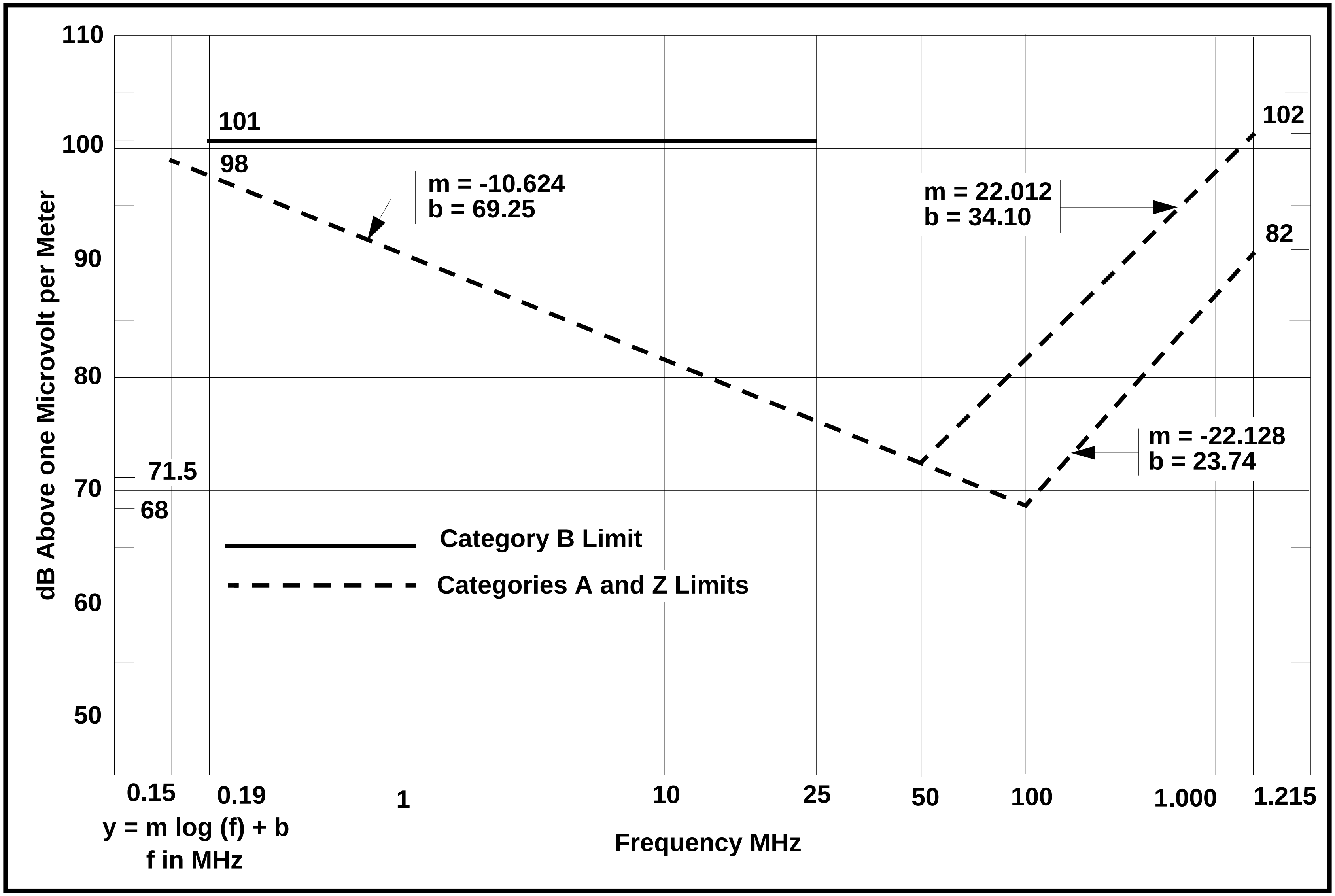


Figure 6. Maximum Level of Radiated Broadband and Pulsed CW From Any One Equipment

FREQUENCY (GHz)	CERTIFICATION TEST LEVELS (V/m)
0.4-0.7	400
0.7-1	700
1-2	650
2-4	900
4-6	850
6-8	250
8-12	900
12-18	450

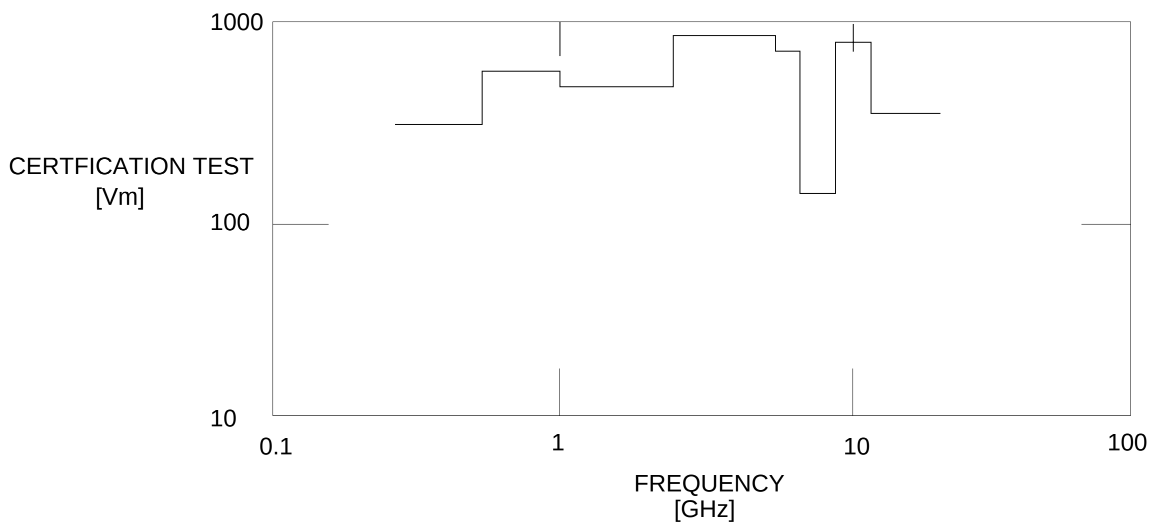


Figure 7. Level A, Certification Test Levels

FREQUENCY (GHz)	CERTIFICATION TEST LEVELS (V/m)
0.4-0.7	400
0.7-1	100
1-2	450
2-4	800
4-6	600
6-8	150

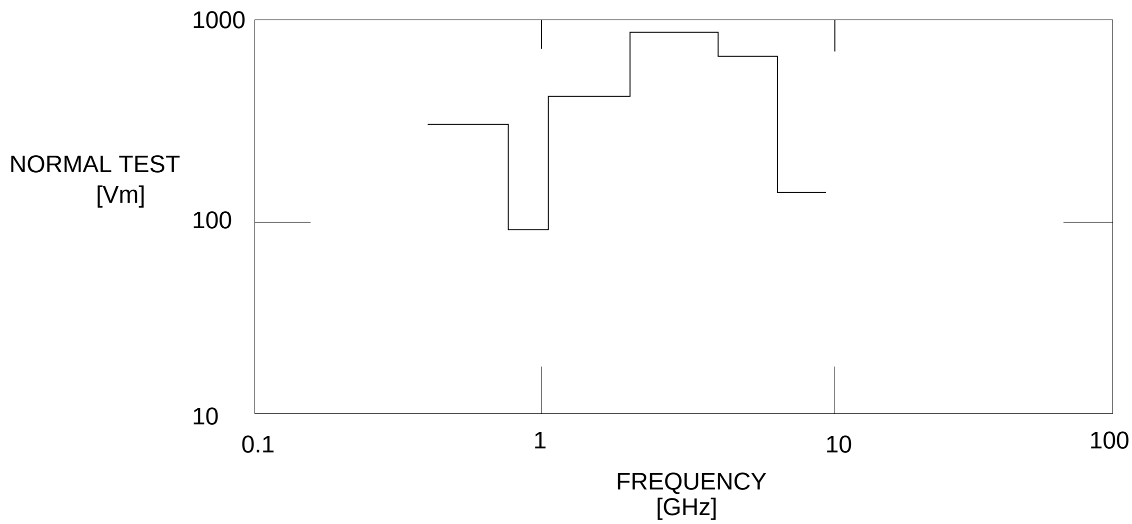


Figure 8. Level A, Normal Test Levels

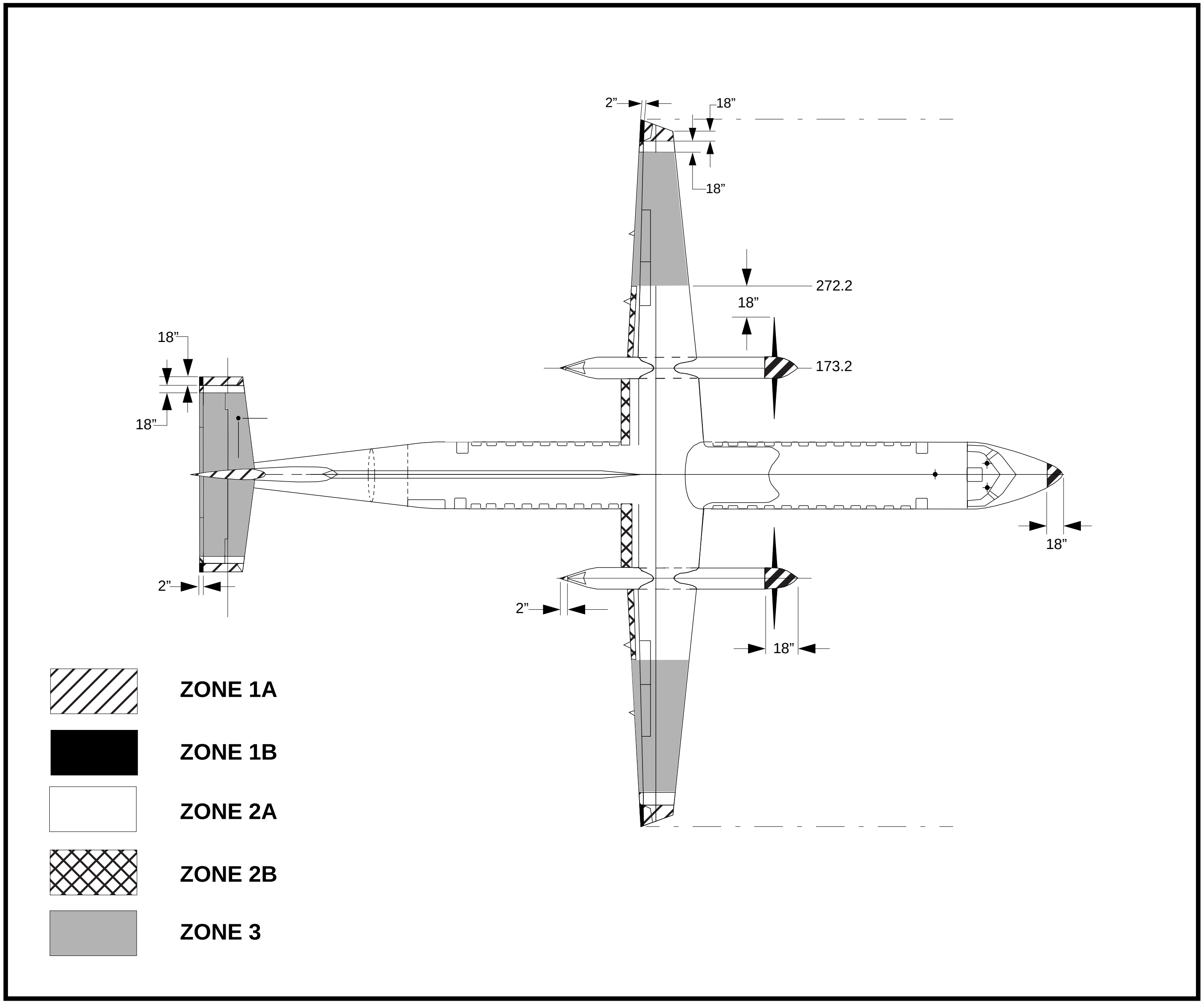


Figure 9. Lightning Strike Zones - Dash 8 Series 400 - Top View

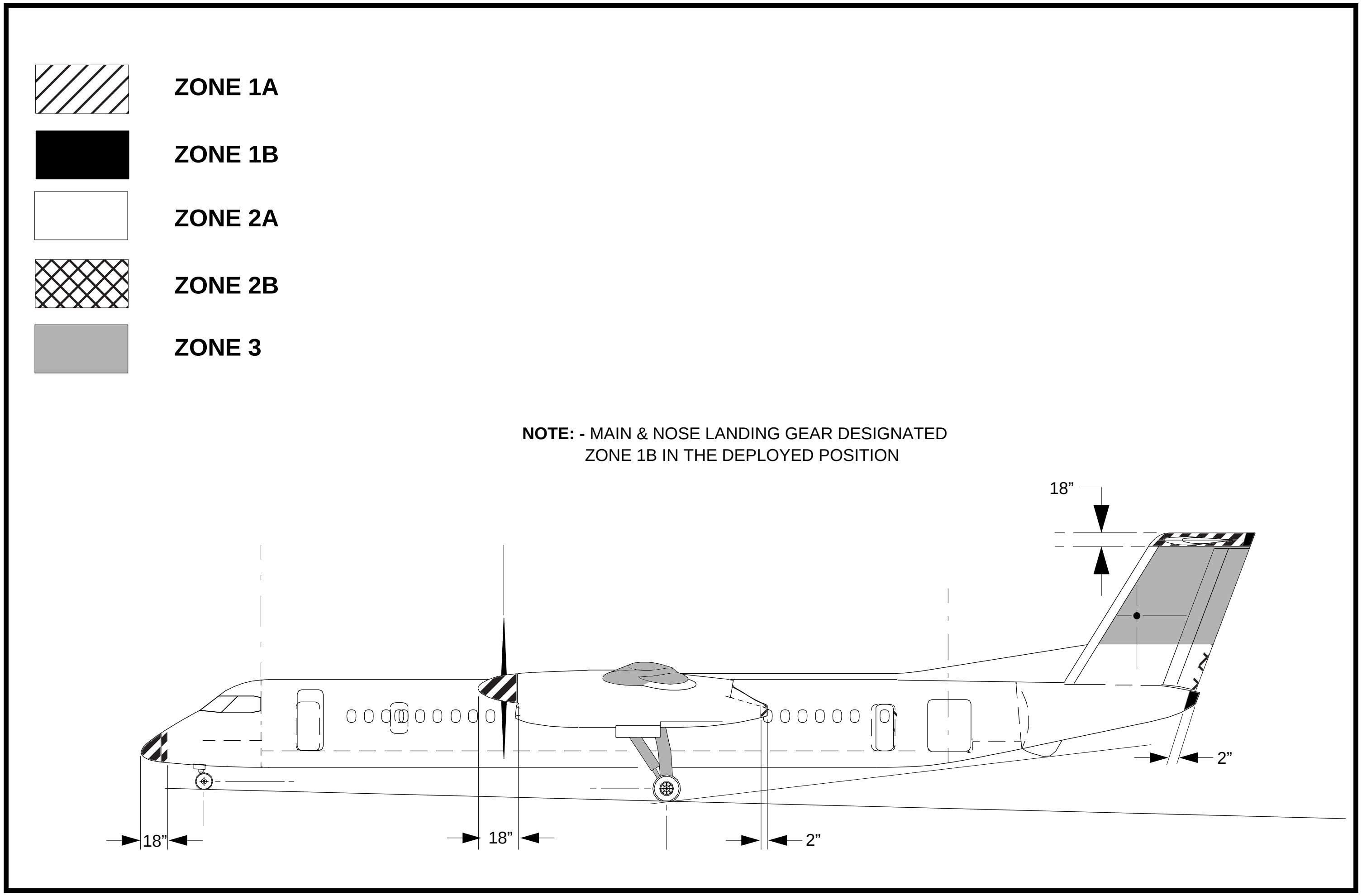


Figure 10. Ligntning Strike Zones - Dash 8 Series 400 - Side View

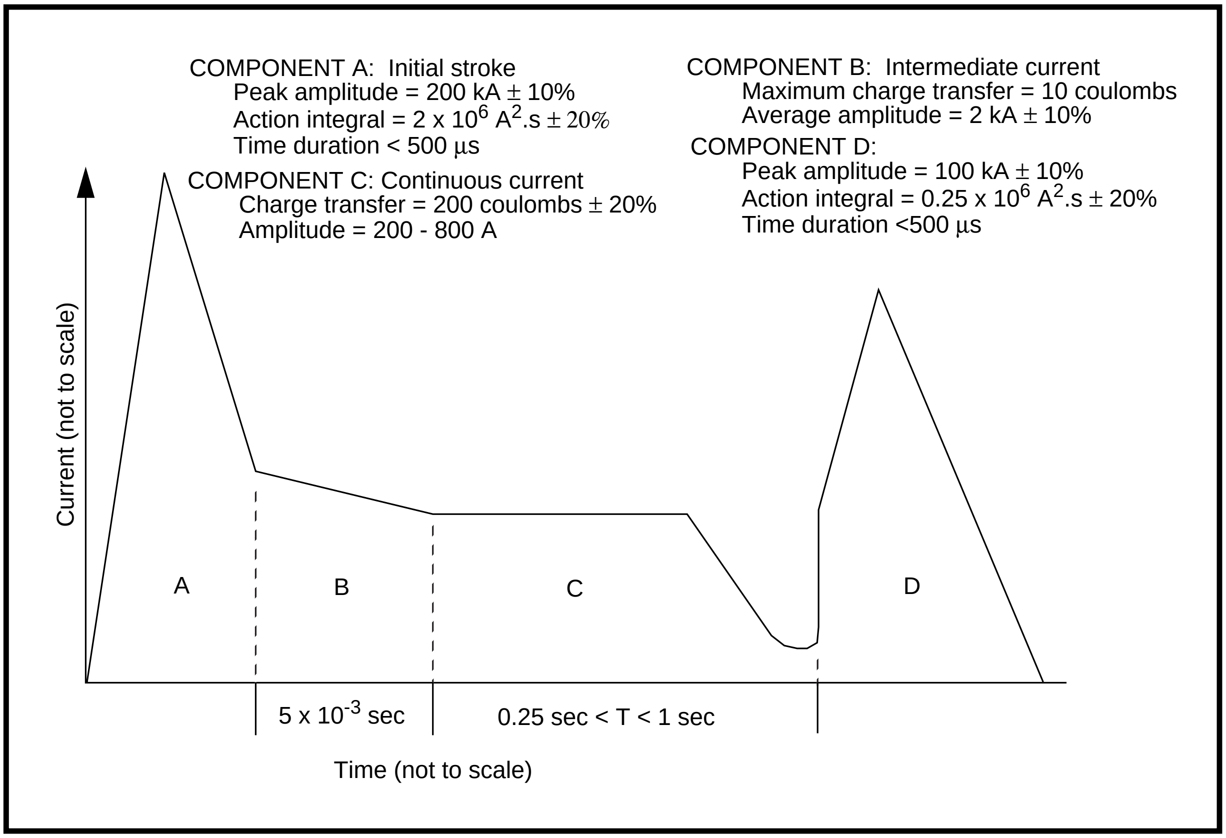


Figure 11. Lightning Flash Current Components

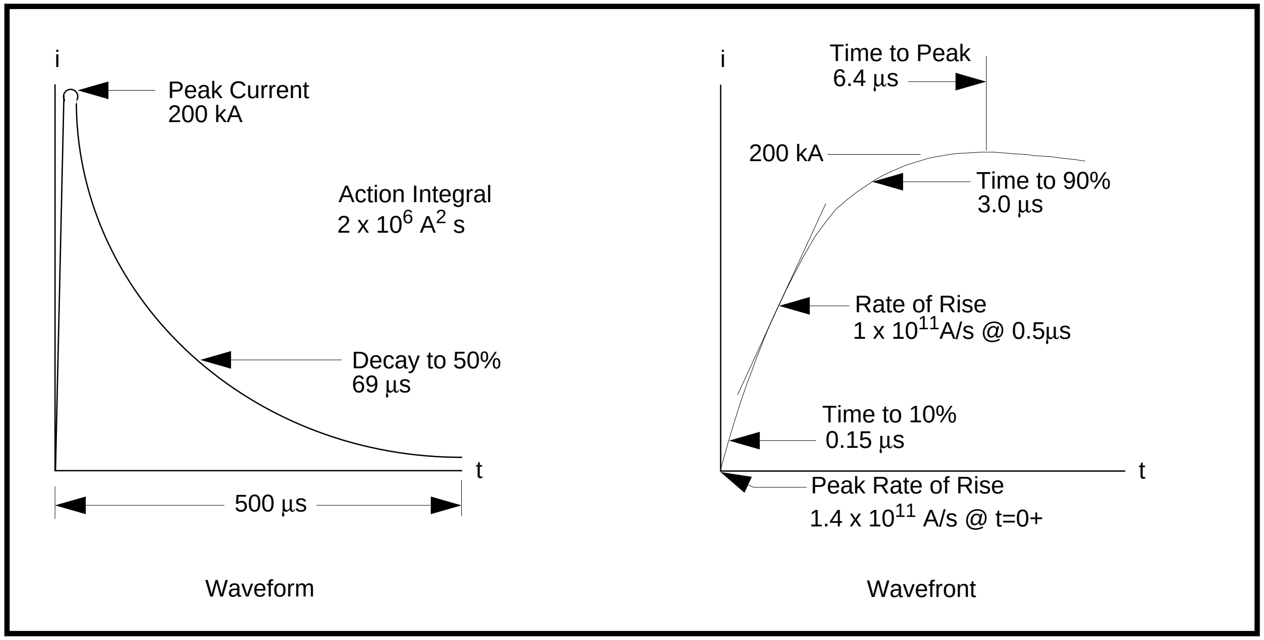


Figure 12. “A” Component

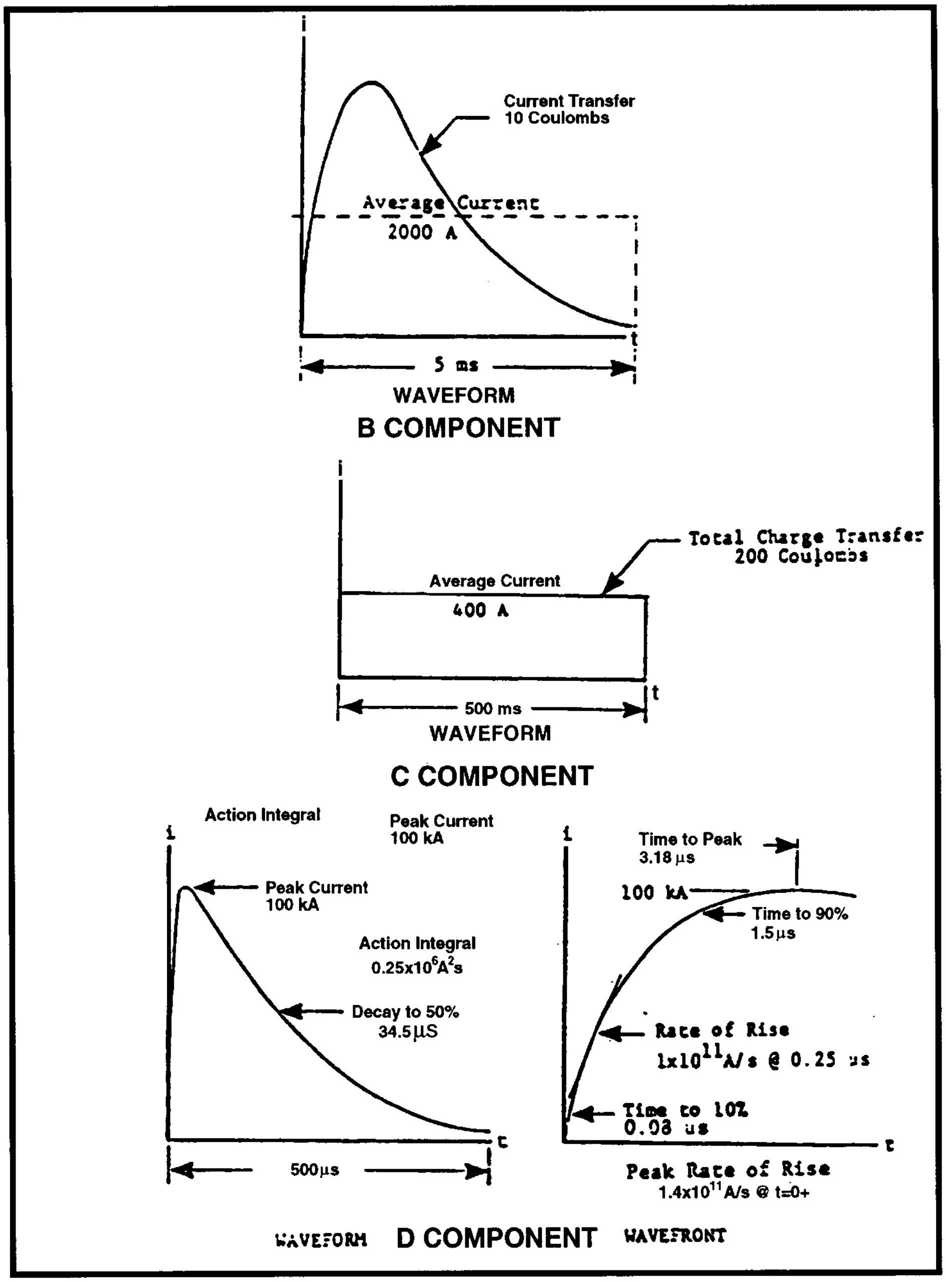


Figure 13. Lightning Current Waveforms

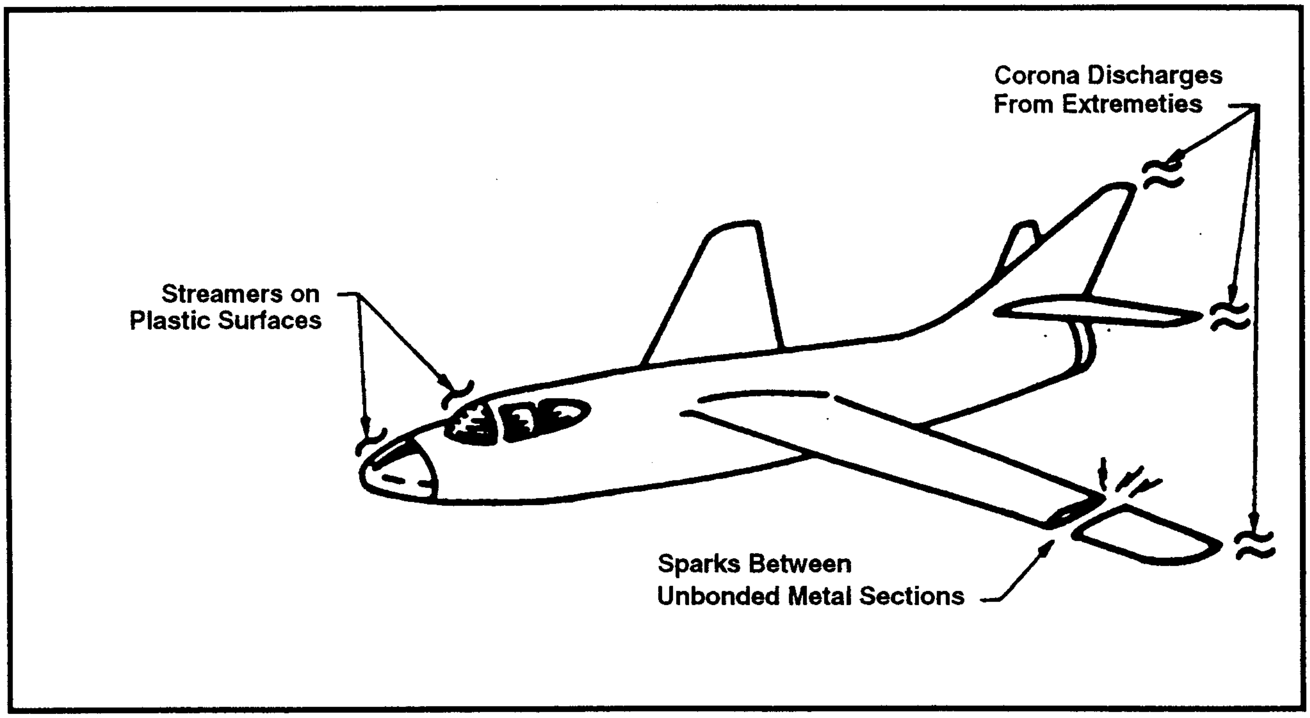


Figure 14. Sources of Precipitation State Induced Noise

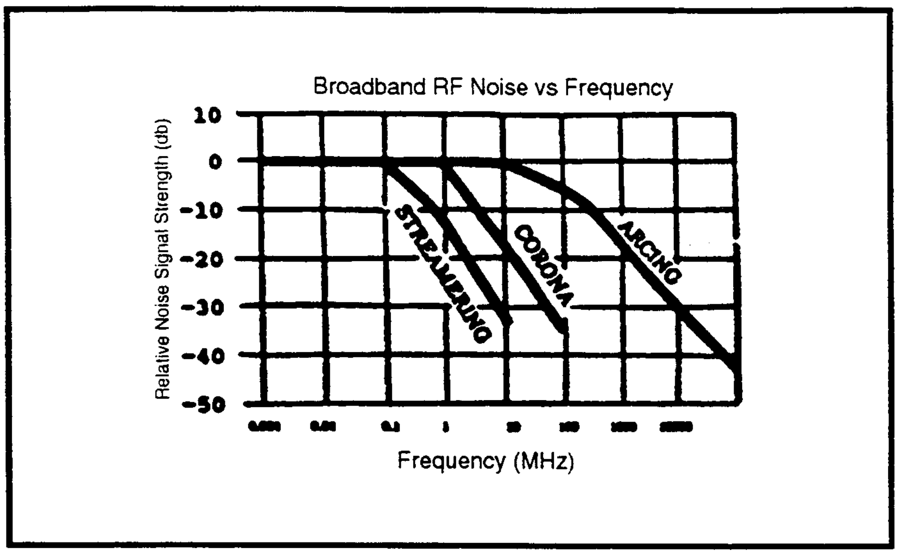


Figure 15. Noise/Signal Strength Graph

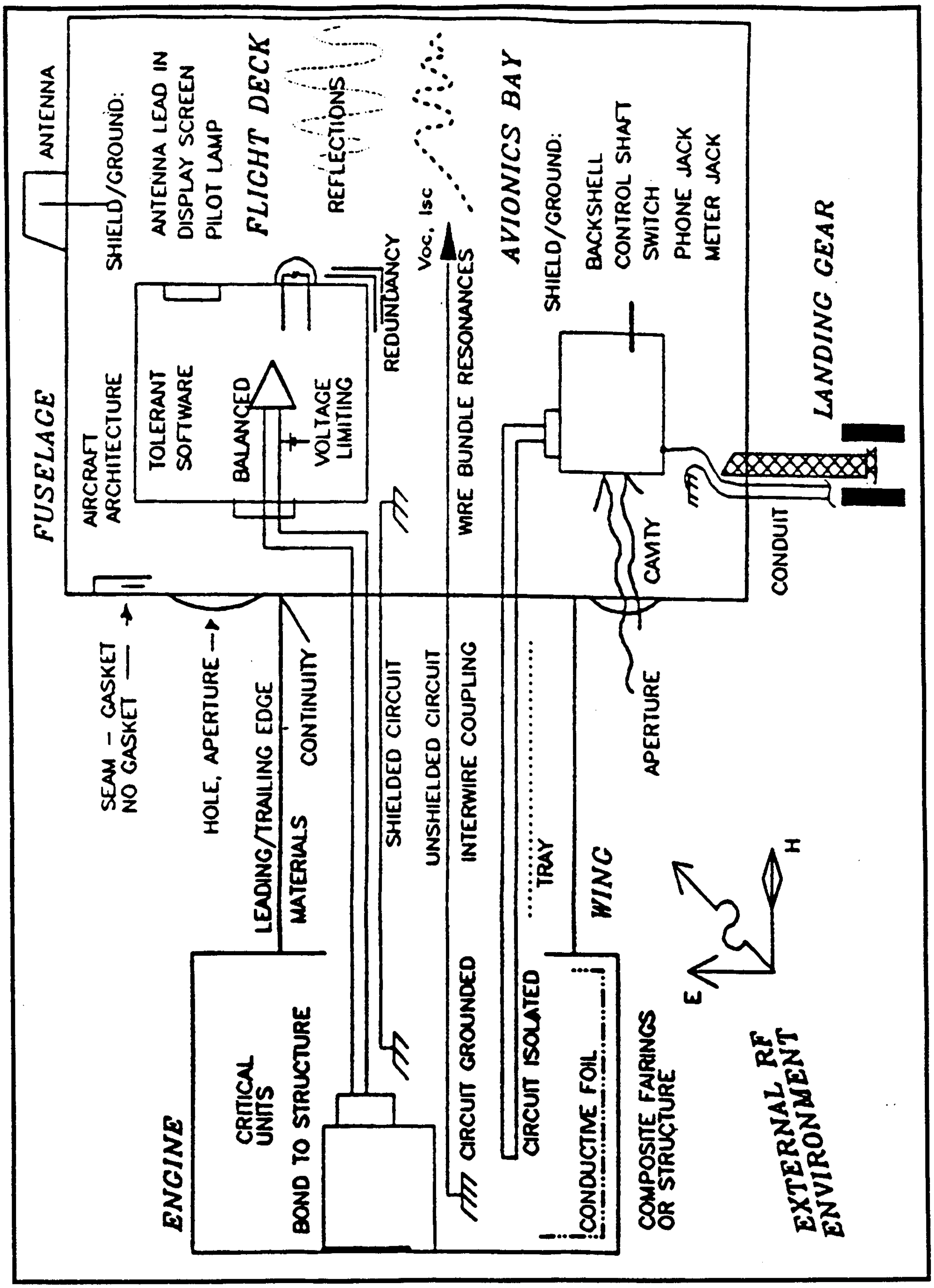


Figure 16. Aircraft Electromagnetic Architectural Topology Diagram

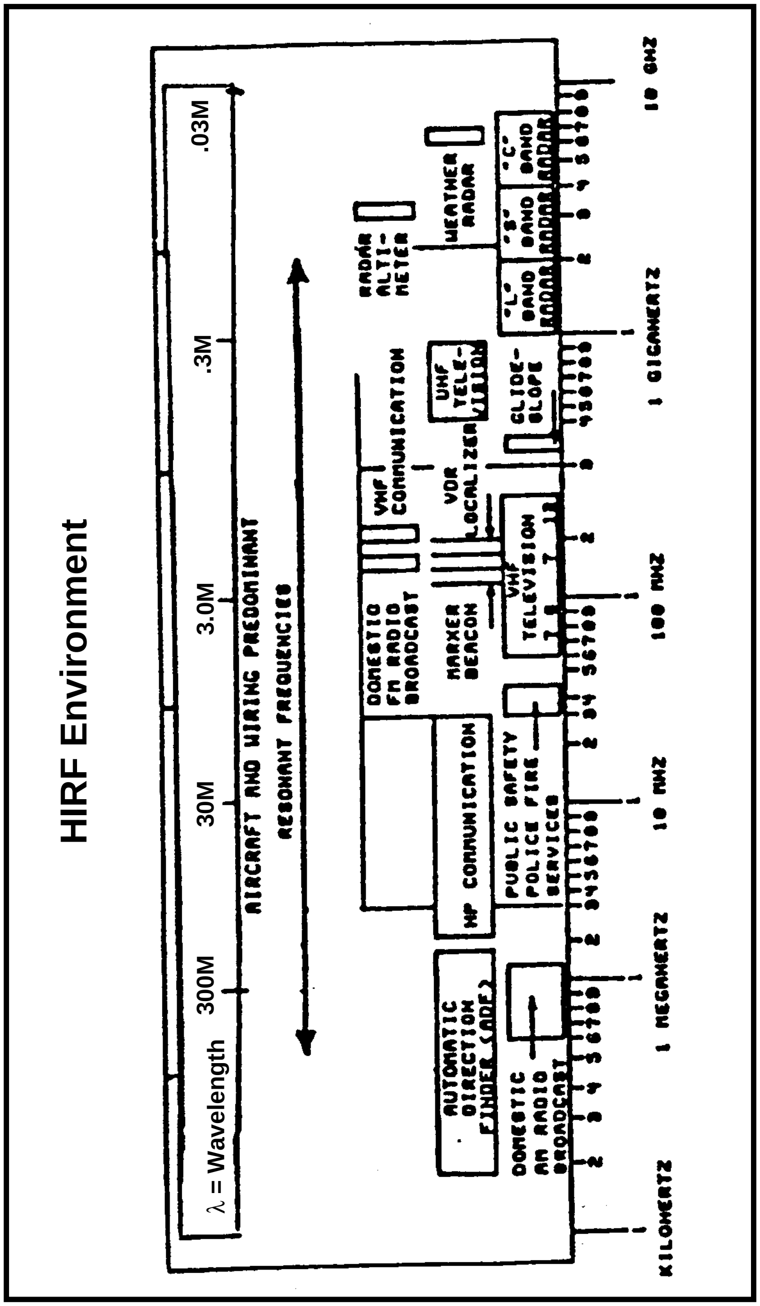


Figure 17. HIRF Environment

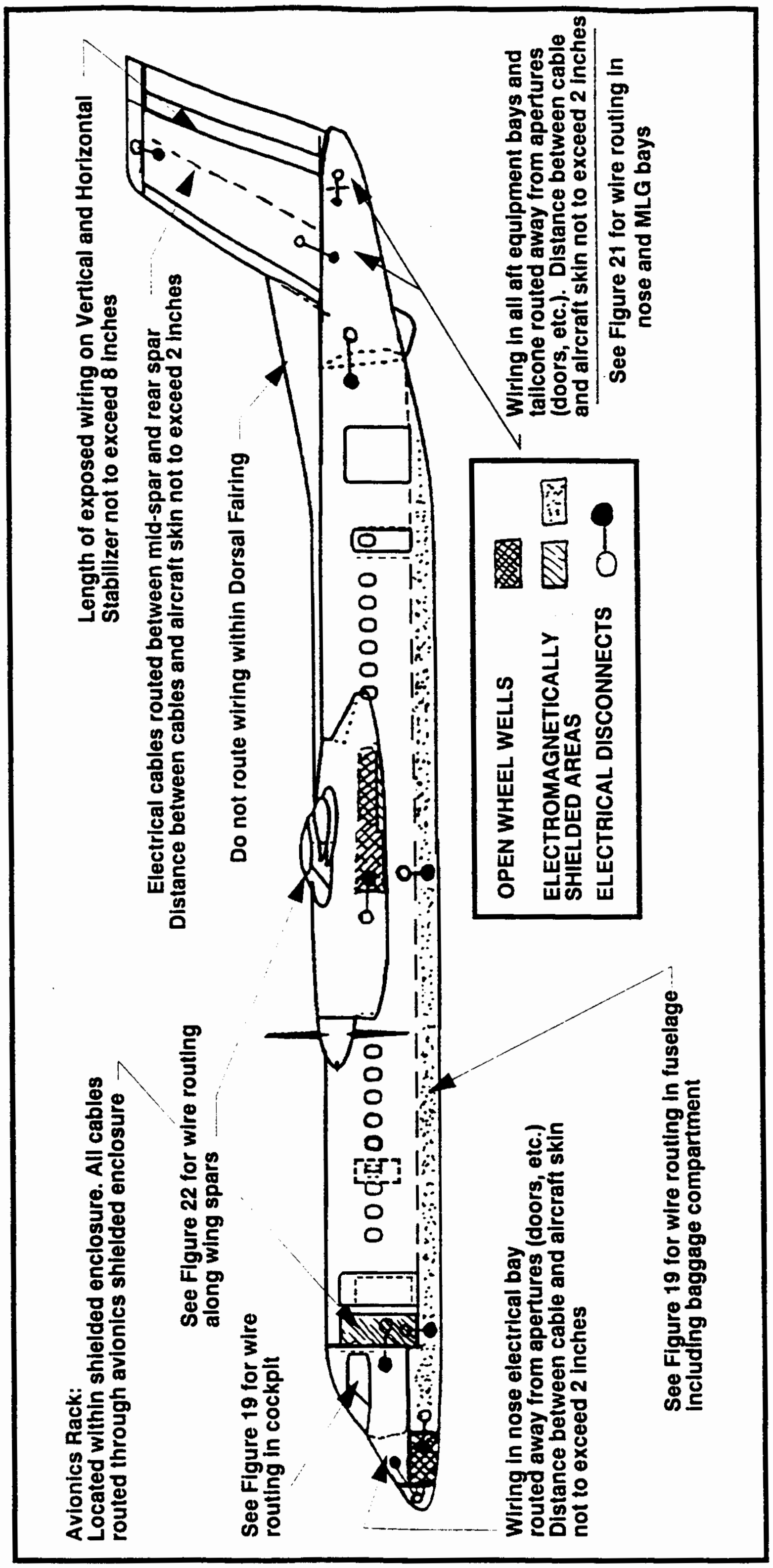


Figure 18. Wire Routing

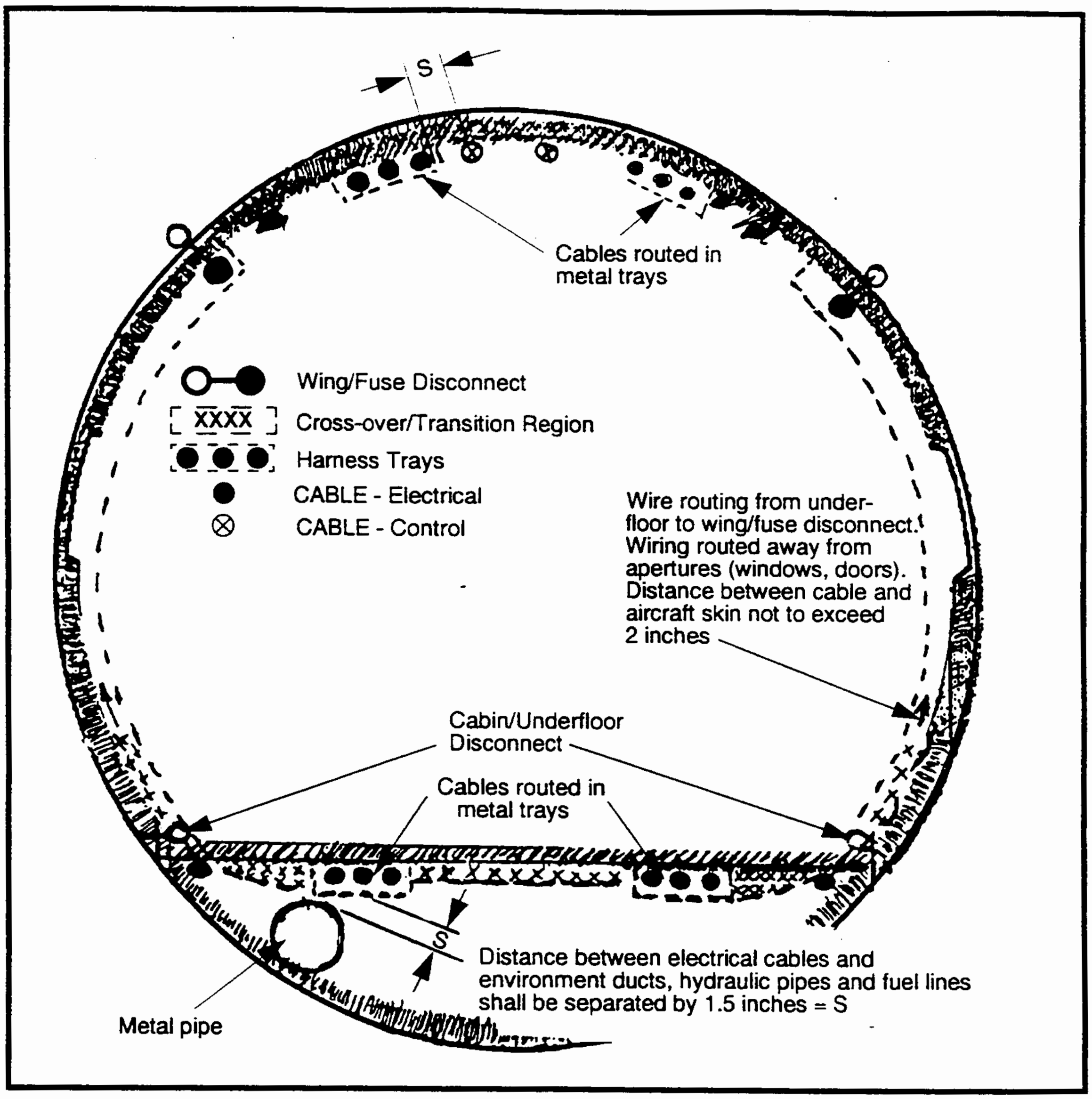


Figure 19. Section Through Fuselage Showing Wire Routing

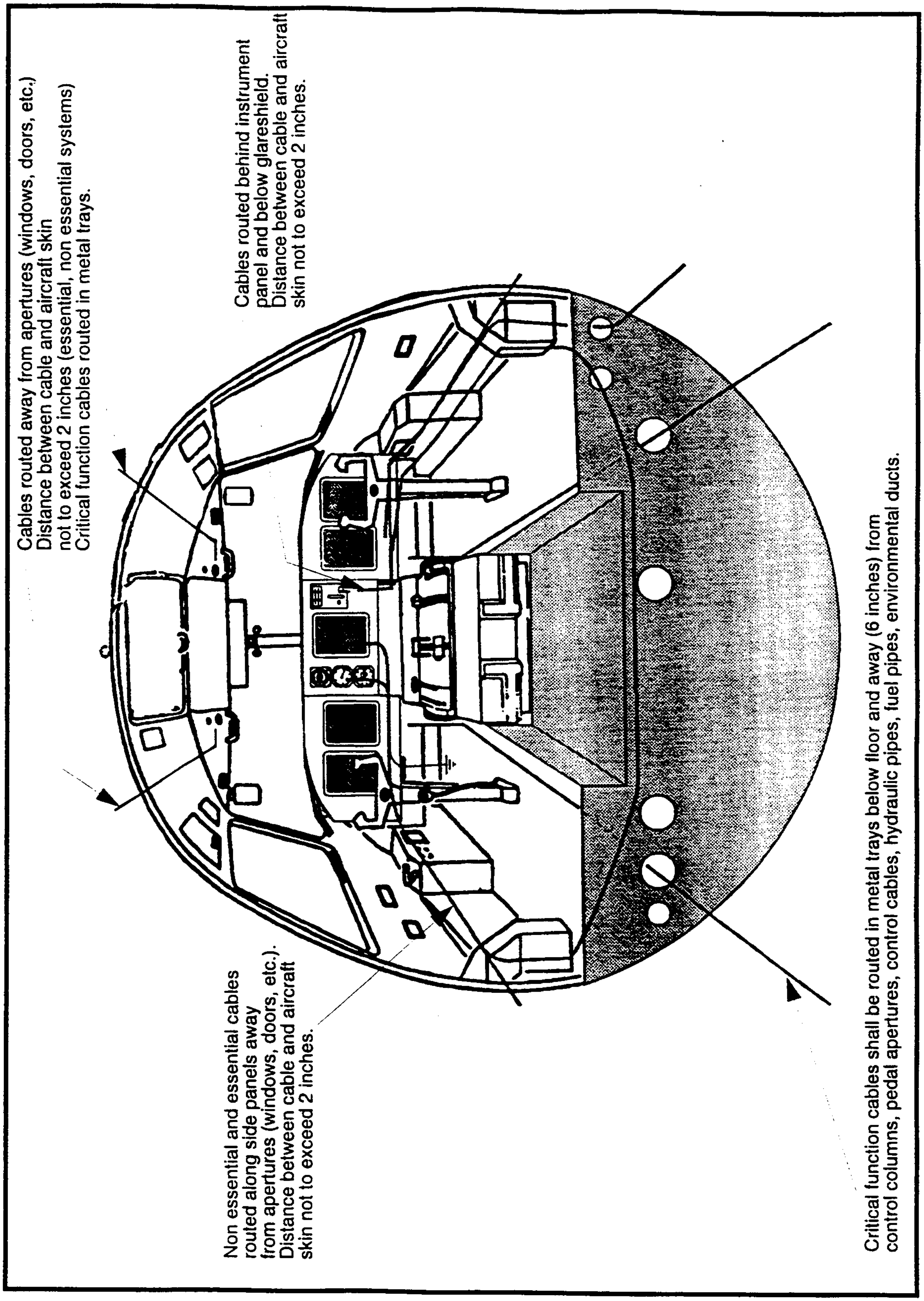


Figure 20. Cockpit Wire Layout

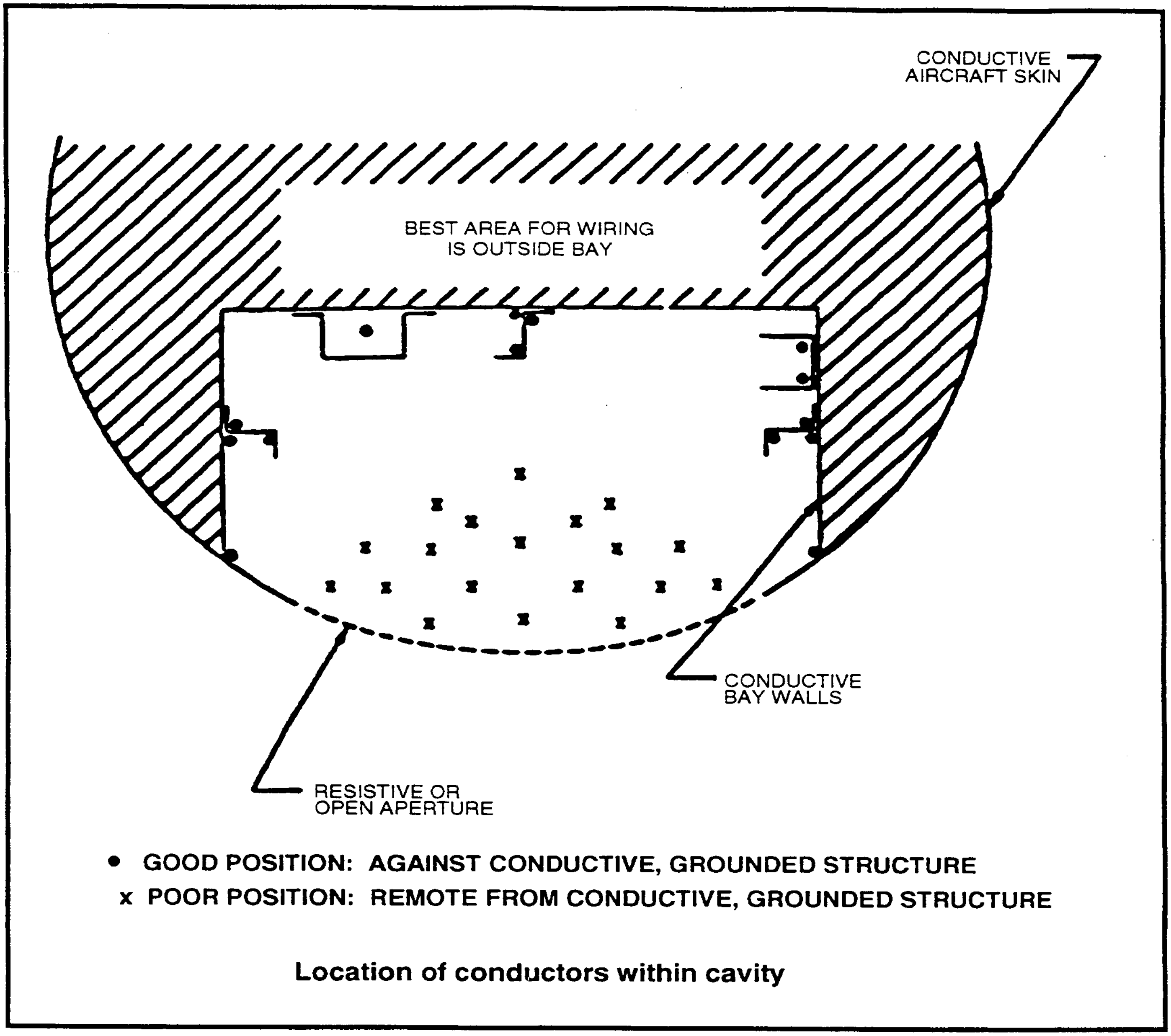
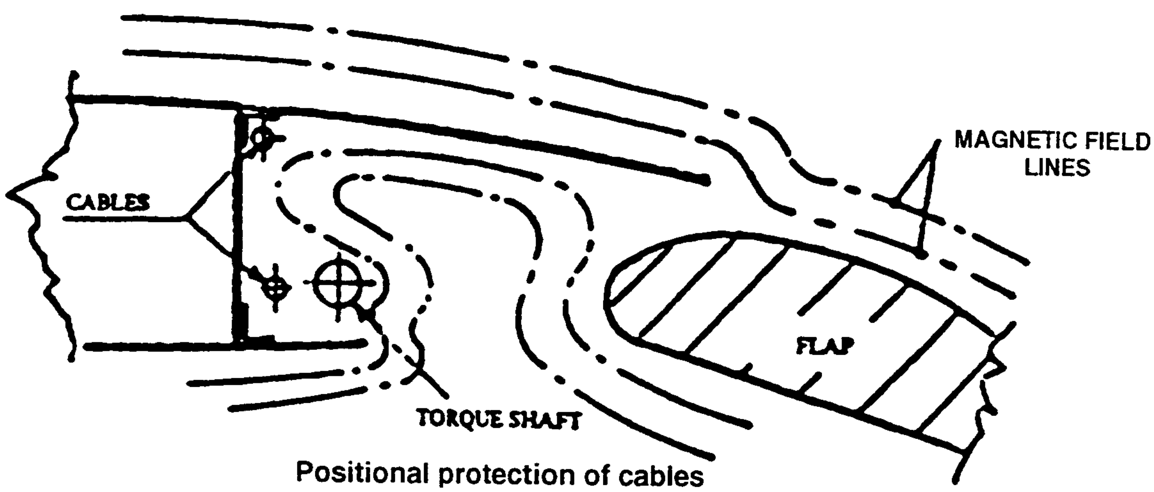


Figure 21. Cable Routing - Nose and Main Landing Gear Bays



Positional protection of cables

Position cables remotely from magnetic 'windows' and as close as possible to highly conductive structure. Section through Wing Trailing Edge.

Length of cable run on rear spar must be minimized. Where possible, route wiring down front spar.

Figure 22. Cable Routing Section Through Wing Trailing Edge

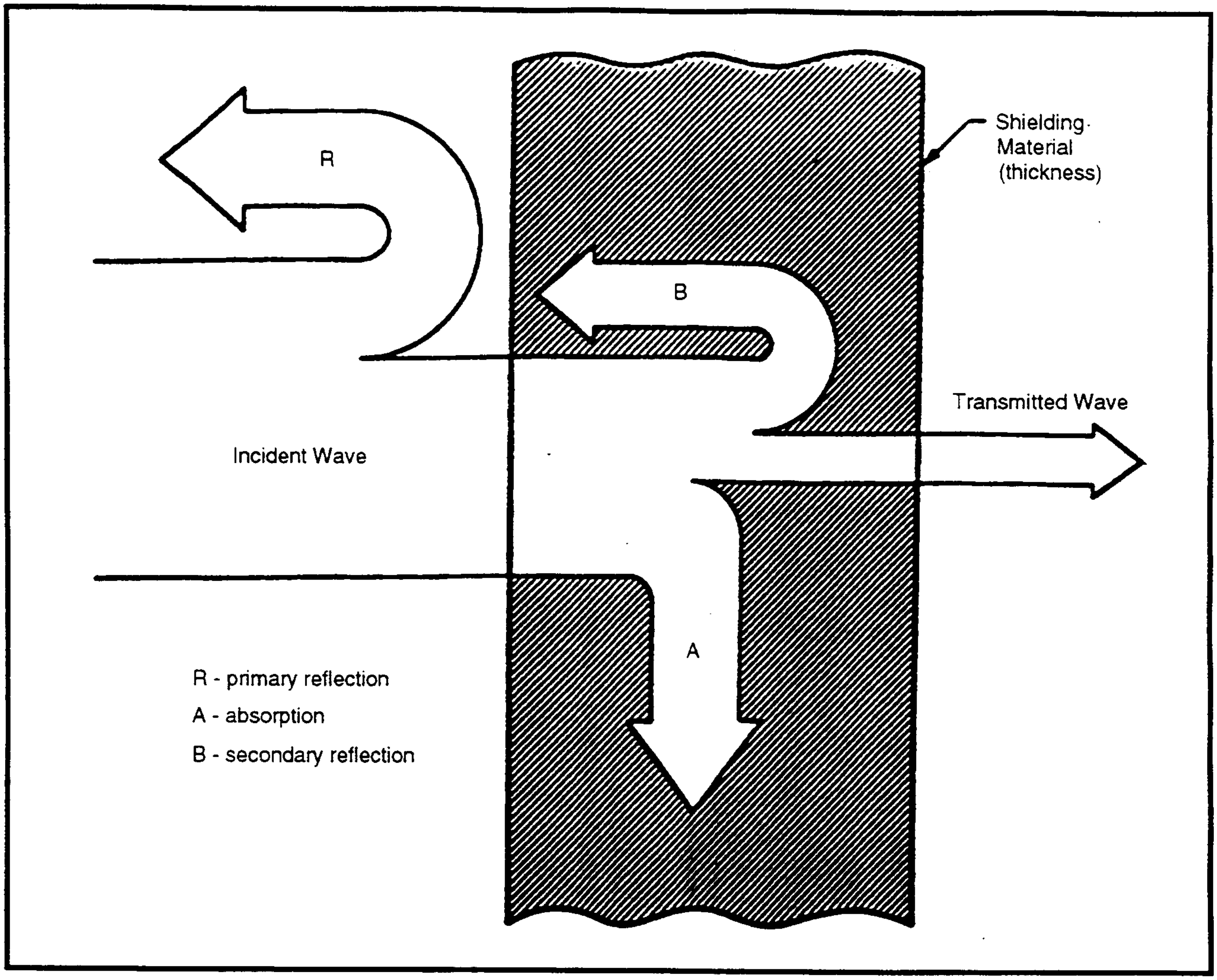


Figure 23. Shield Reflection and Absorption Losses

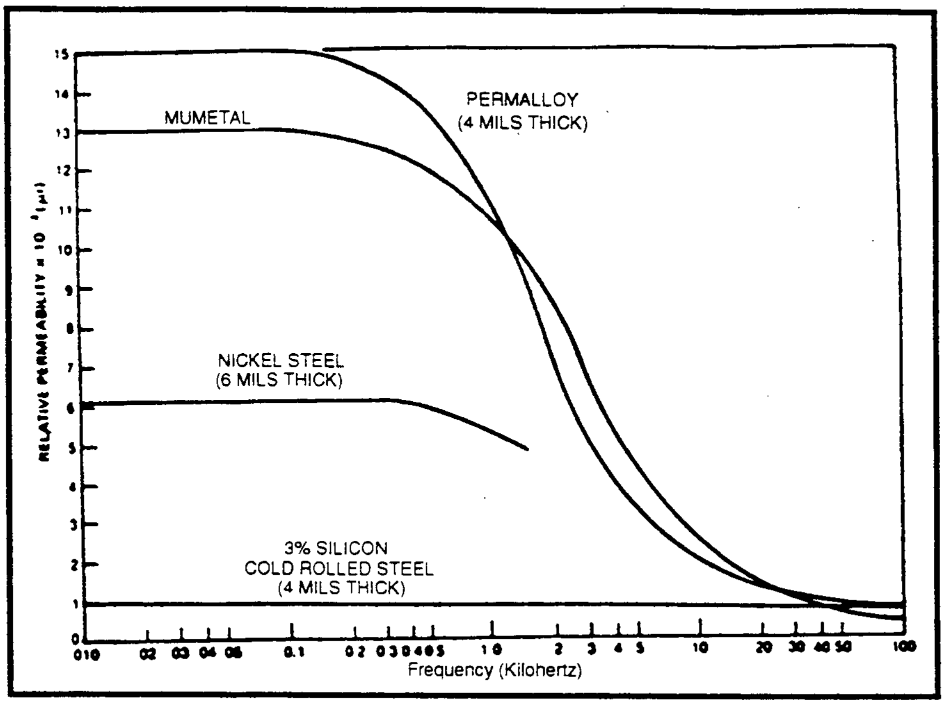


Figure 24. Relation between permeability and frequency for various magnetic materials

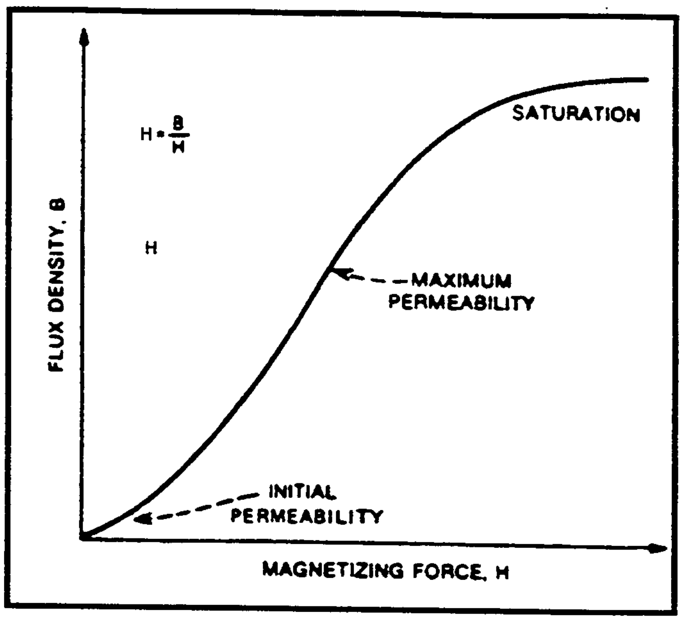


Figure 25. Typical magnetization curve. Permeability is equal to the slope of the curve.

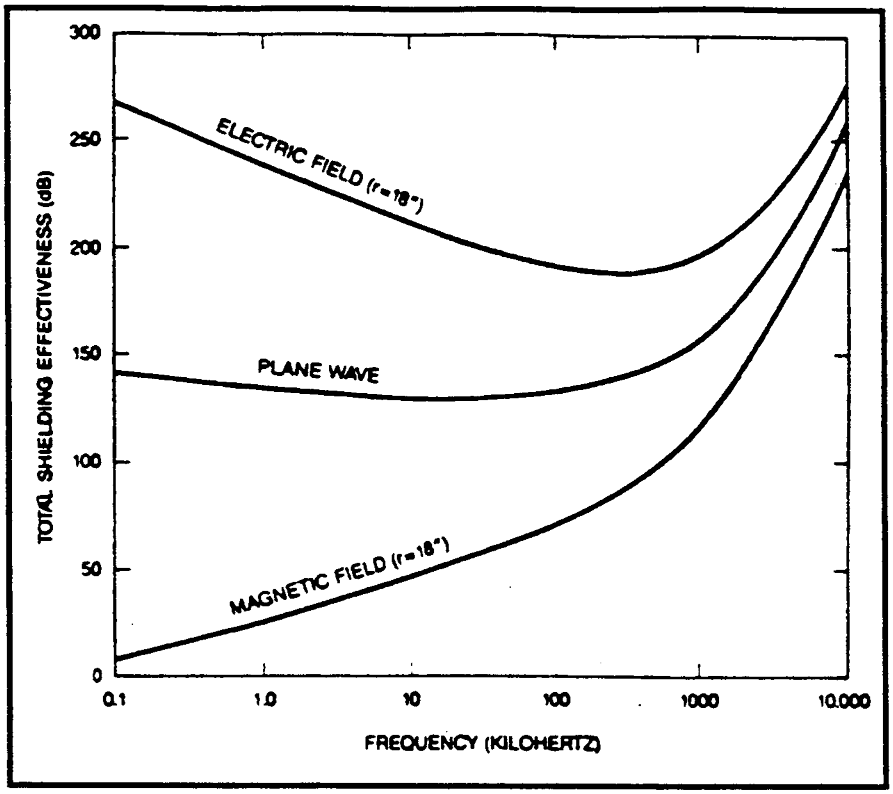


Figure 26. Electric field, plane wave, and magnetic field shielding effectiveness of a 0.02" thick solid aluminum shield.

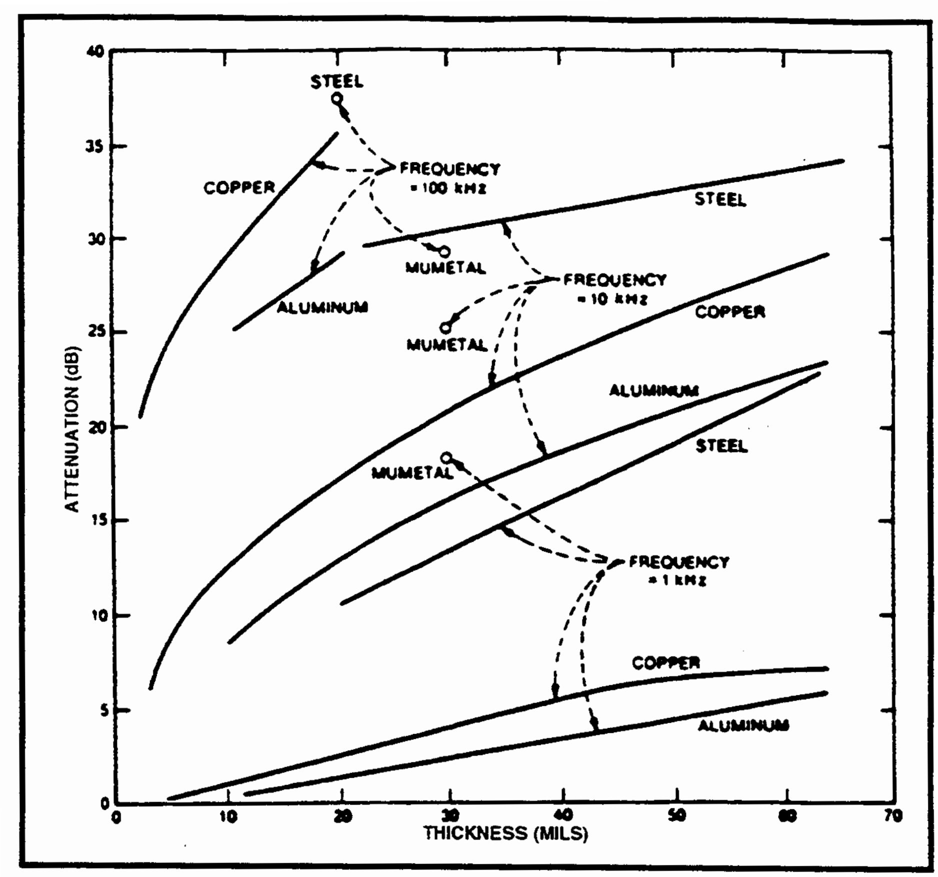
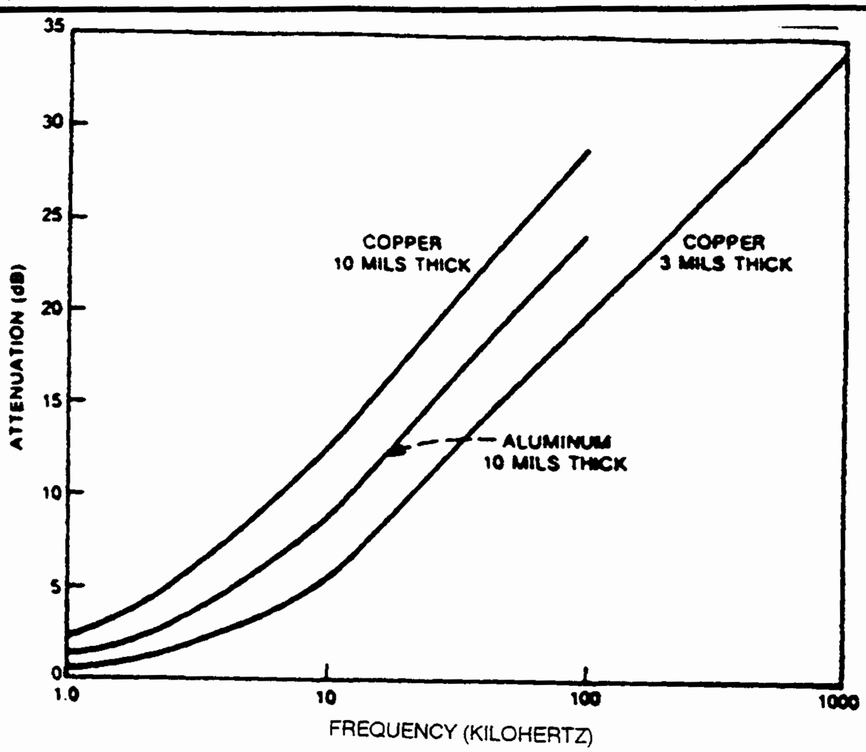
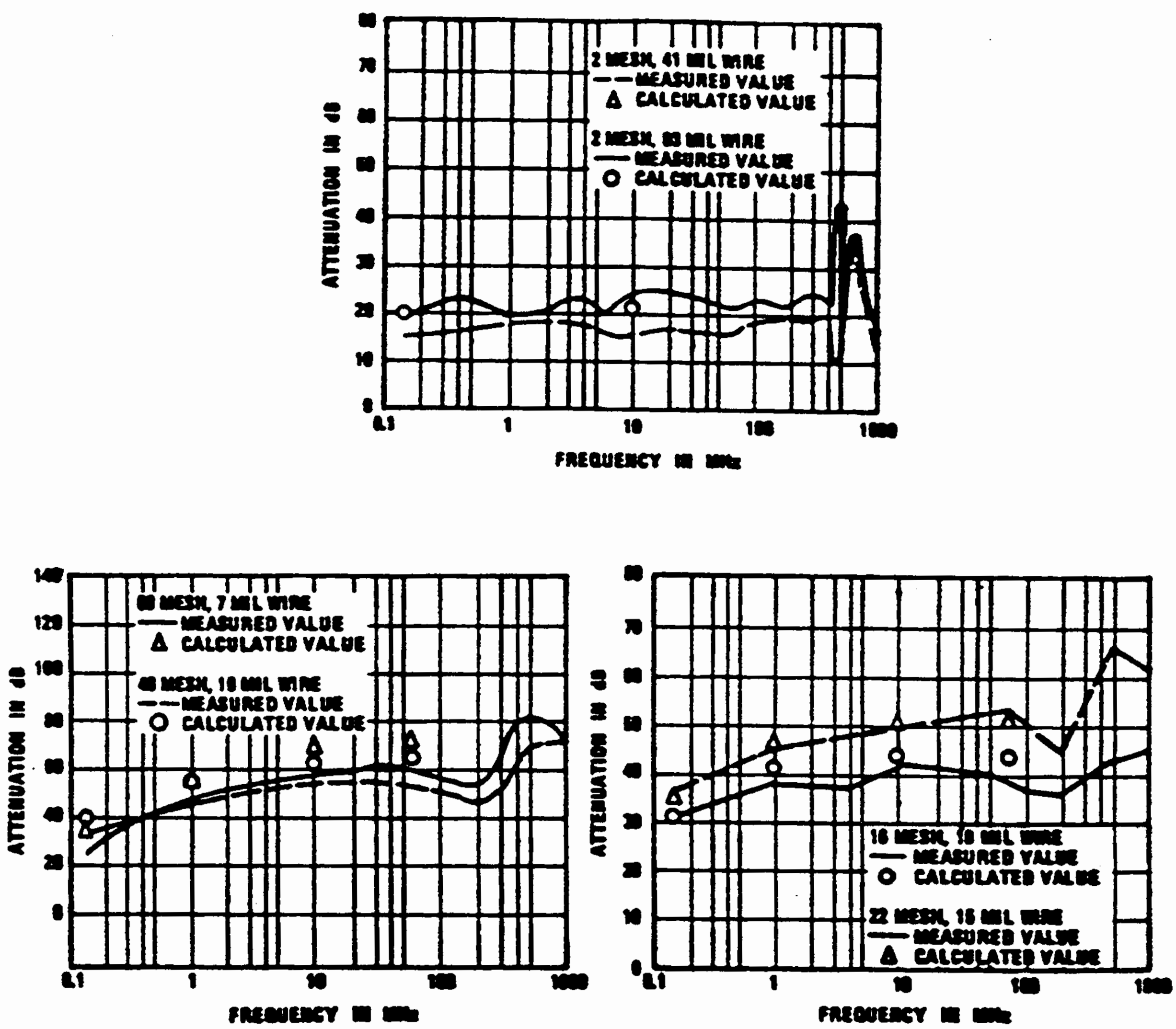


Figure 27. Experimental data on magnetic attenuation by metallic sheets in the near field.



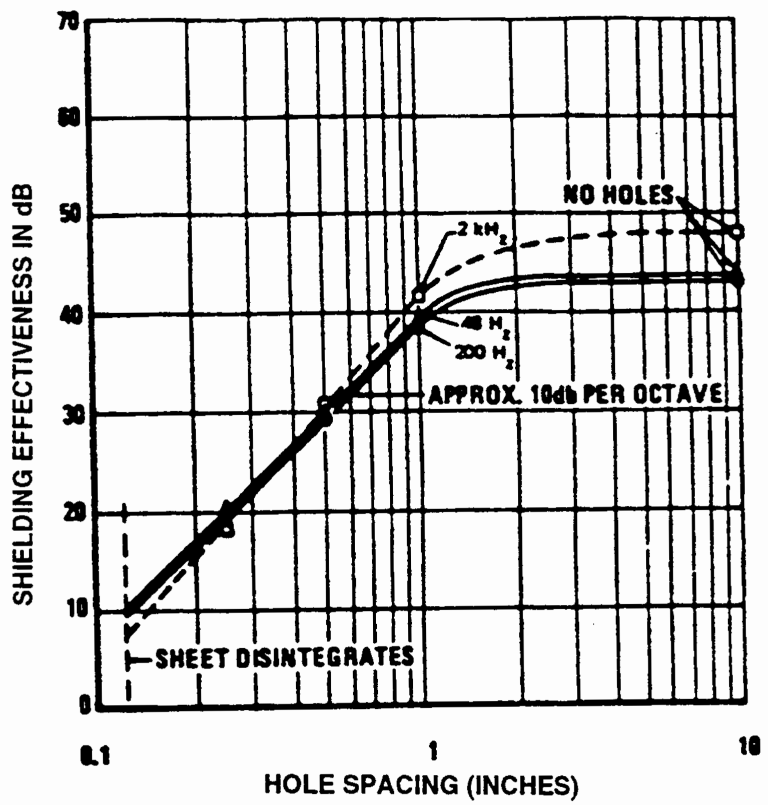
Experimental results of tests to determine magnetic field attenuation of conducting sheets in the near field.

Figure 28. Magnetic Field Attenuation of Conducting Sheets in Near Field



Measured and calculated shielding effectiveness of Copper Screens to low impedance fields

Figure 29. Shielding Effectiveness of Copper Screens to Low Impedance Fields



Shielding Effectiveness of a Perforated Metal Sheet as a Function of Hole Spacing

Figure 30. Shielding Effectiveness of a Perforated Metal Sheet

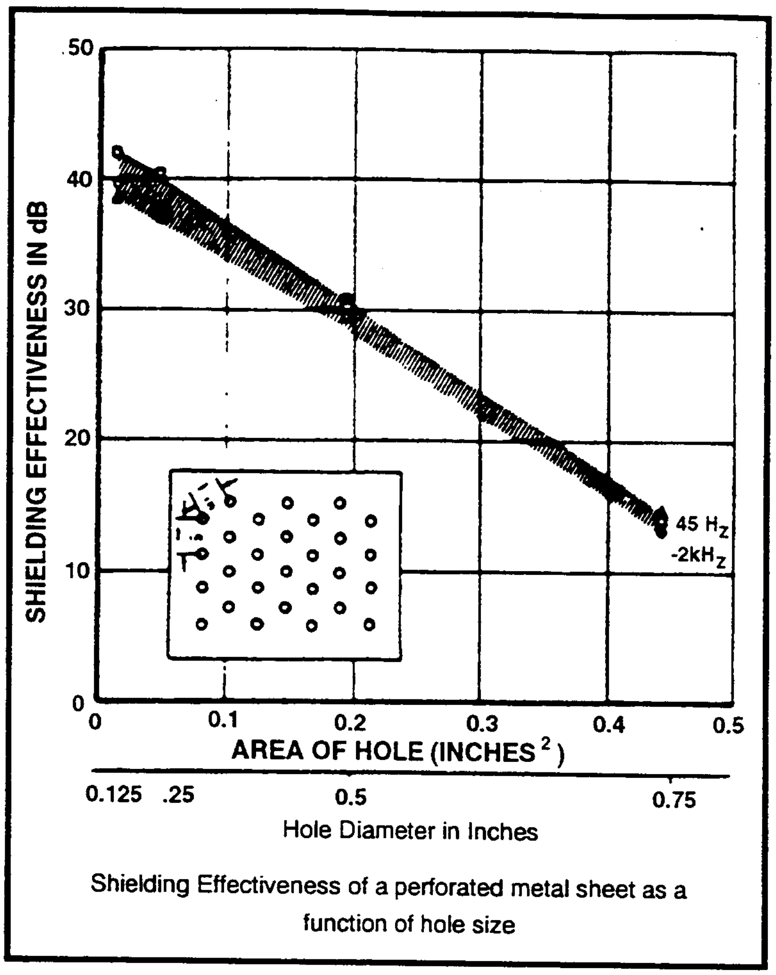


Figure 31. Shielding Effectiveness of a Perforated Metal Sheet

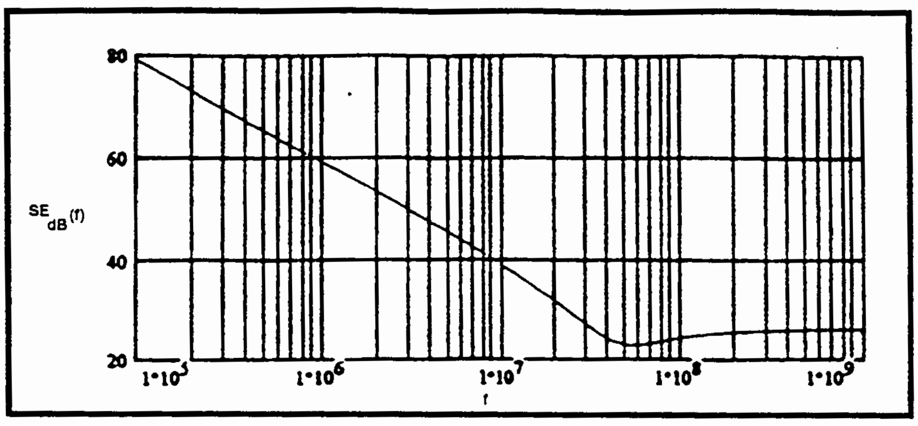


Figure 32. Shielding Effectiveness Conductive Glass High Impedance Waves 10 Ω/sq.

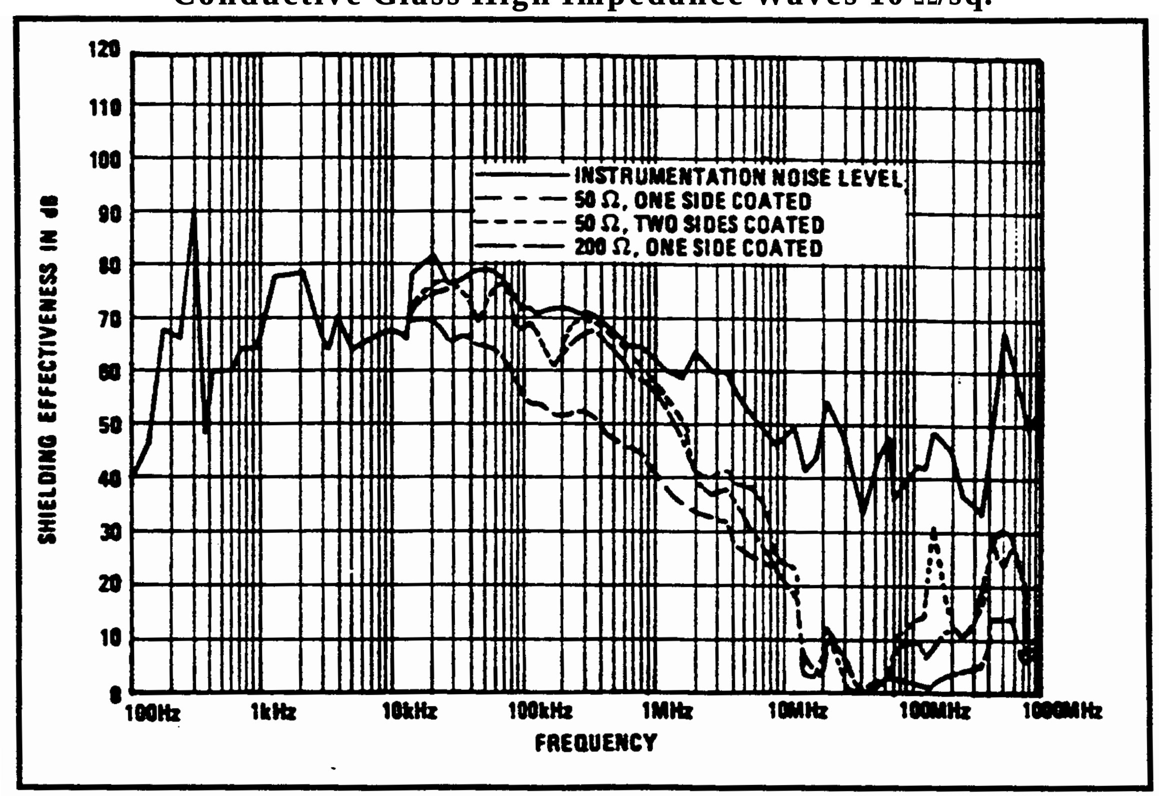


Figure 33. Shielding Effectiveness

Conductive Glass to High Impedance Waves

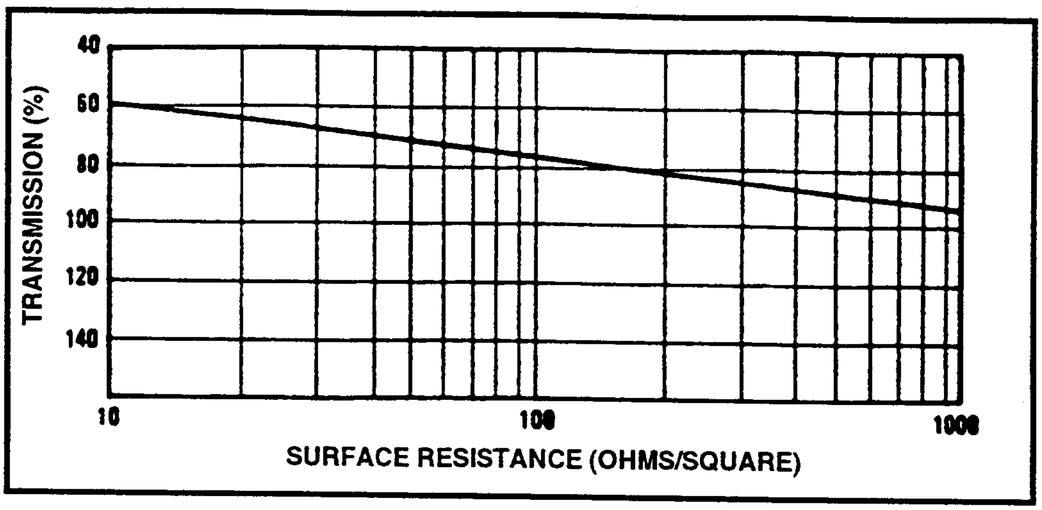


Figure 34. Light Transmission Versus Surface Resistance for Conductive Glass

Figure 35a illustrates amount of insertion loss typically achieved through open apertures ranging from 24” to 2” square (per MIL-STD-285). Typical insertion losses of various window materials (properly terminated) are shown in Figure 35b. To determine total shielding effectiveness attained for any size opening with any windows materials, add the appropriate curves in Figures 35a and 35b together.

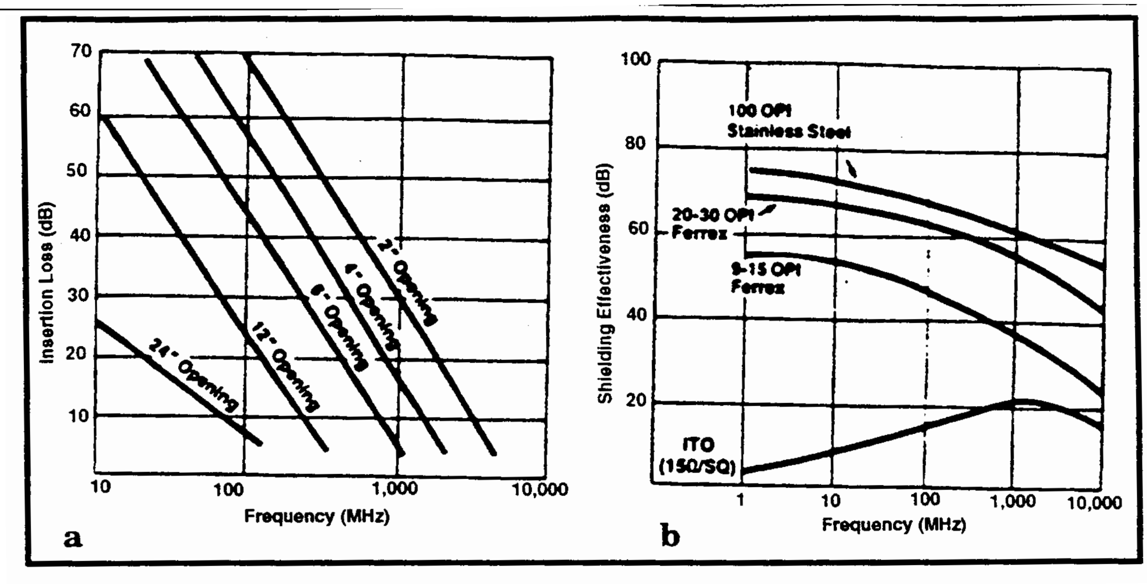


Figure 35. a & b: EMI Shielding Performance

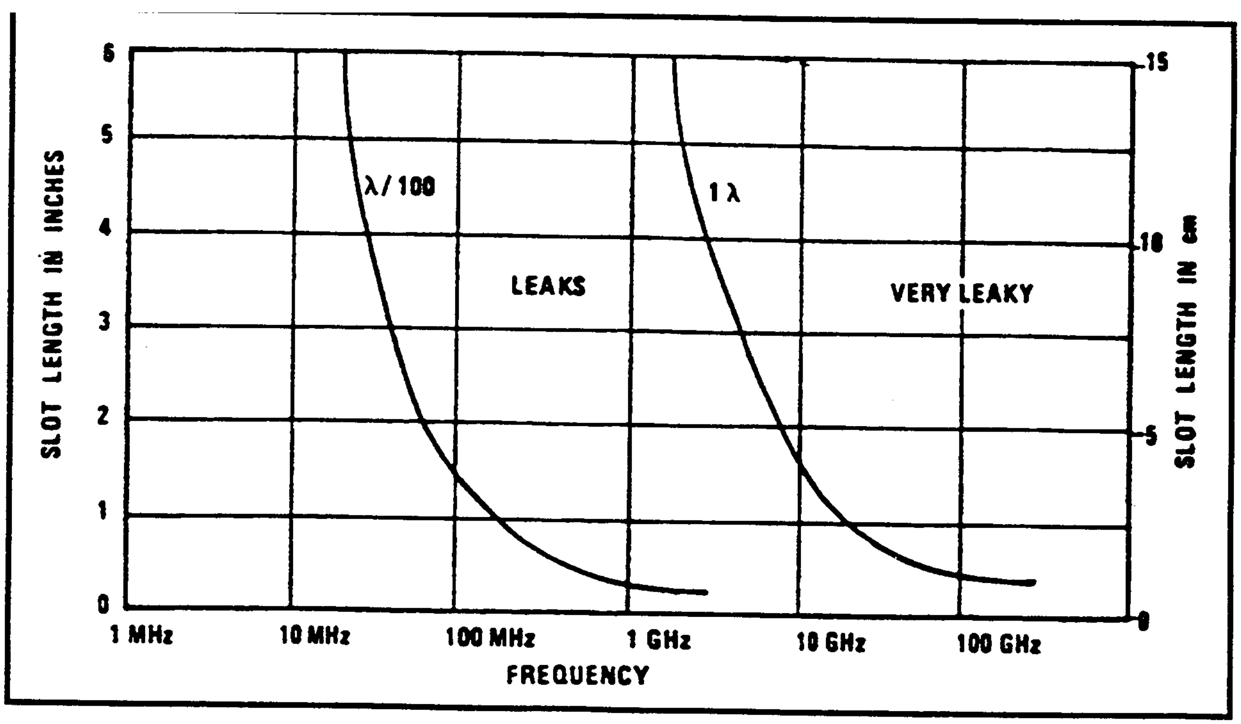
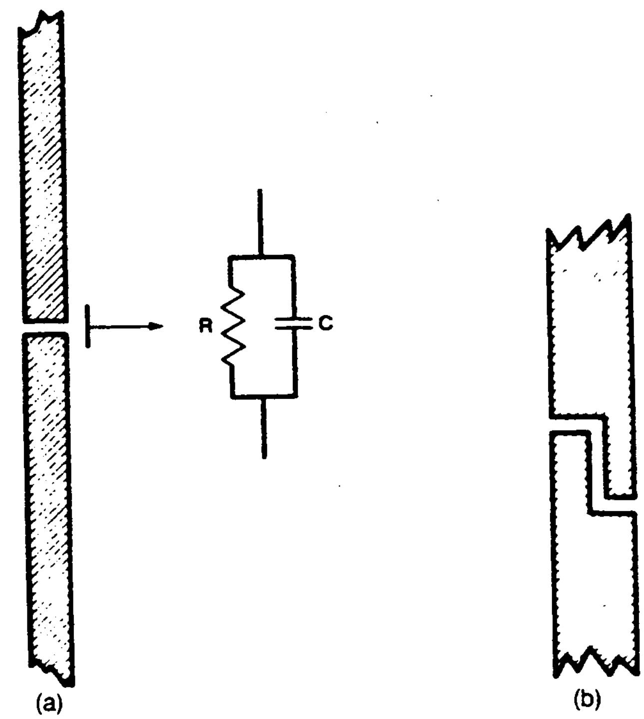


Figure 36. Slot Radiation (Leakage)



(a) The impedance of a seam consists of a resistive and capacitive component;
(b) Seam overlap increases the capacitance across the joint

Figure 37. Impedance Across a Seam

DHC-8 SERIES 400 EMI/HIRF/LIGHTNING CONTROL PLAN

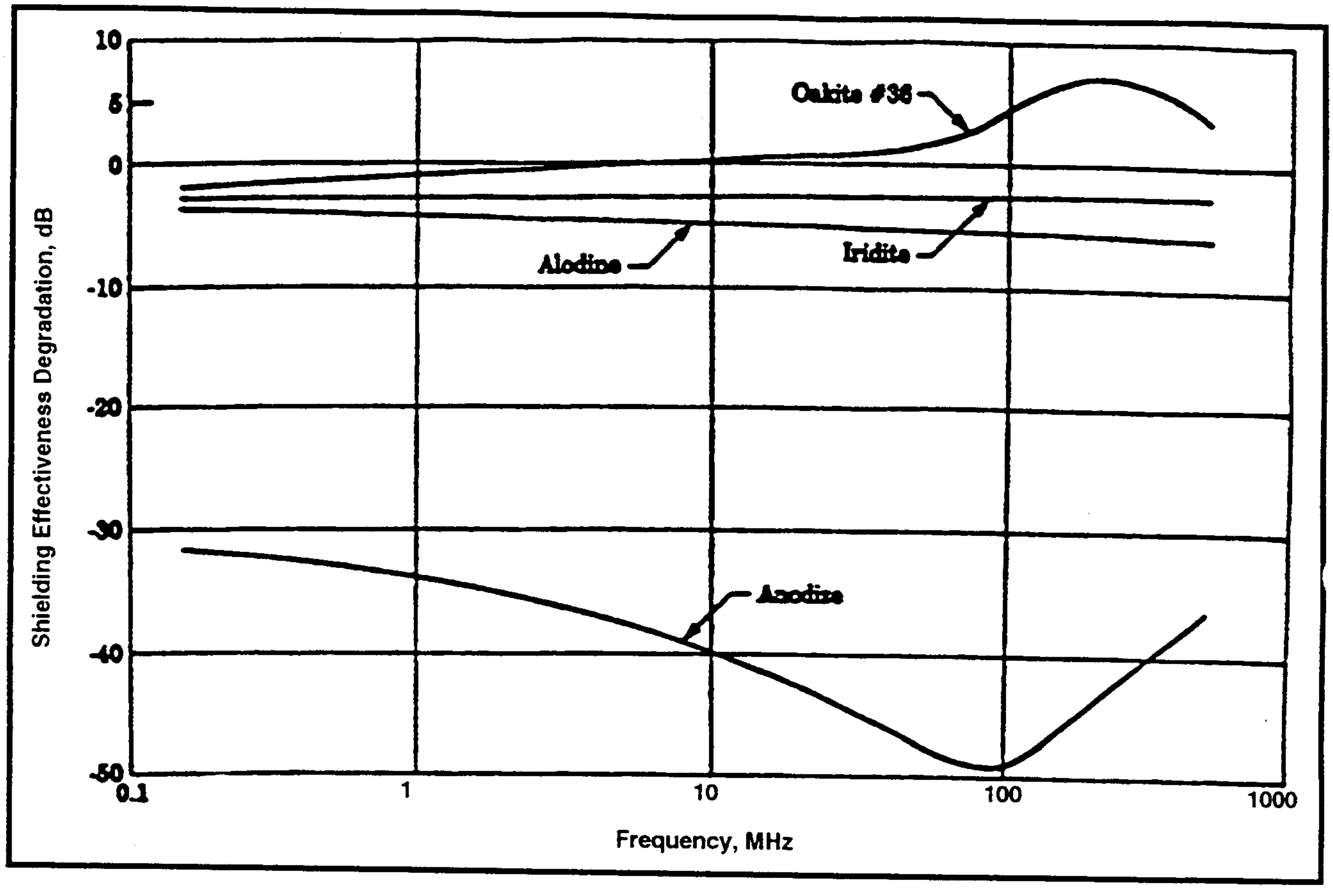


Figure 38. The Effect of Surface Treatment on Shielding Effectiveness

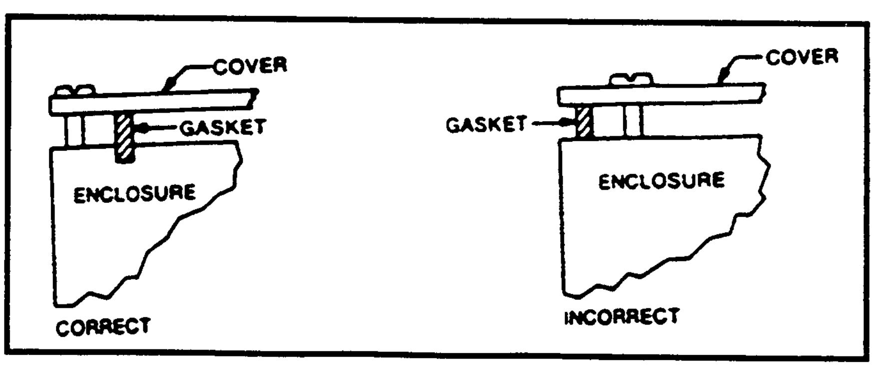


Figure 39. EMI Gaskets, correct and incorrect installations

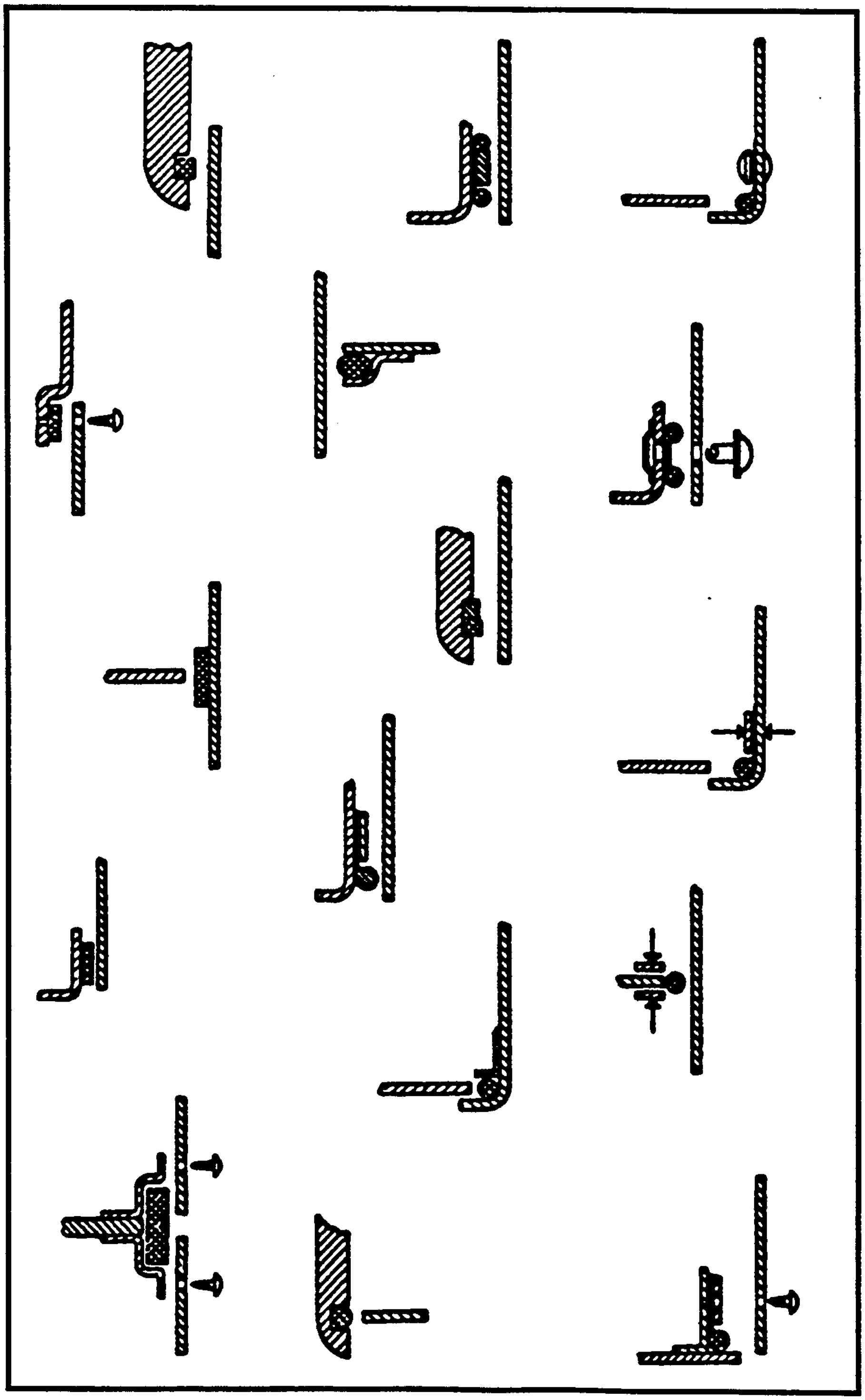


Figure 40. Typical Mounting Techniques for RF Gaskets

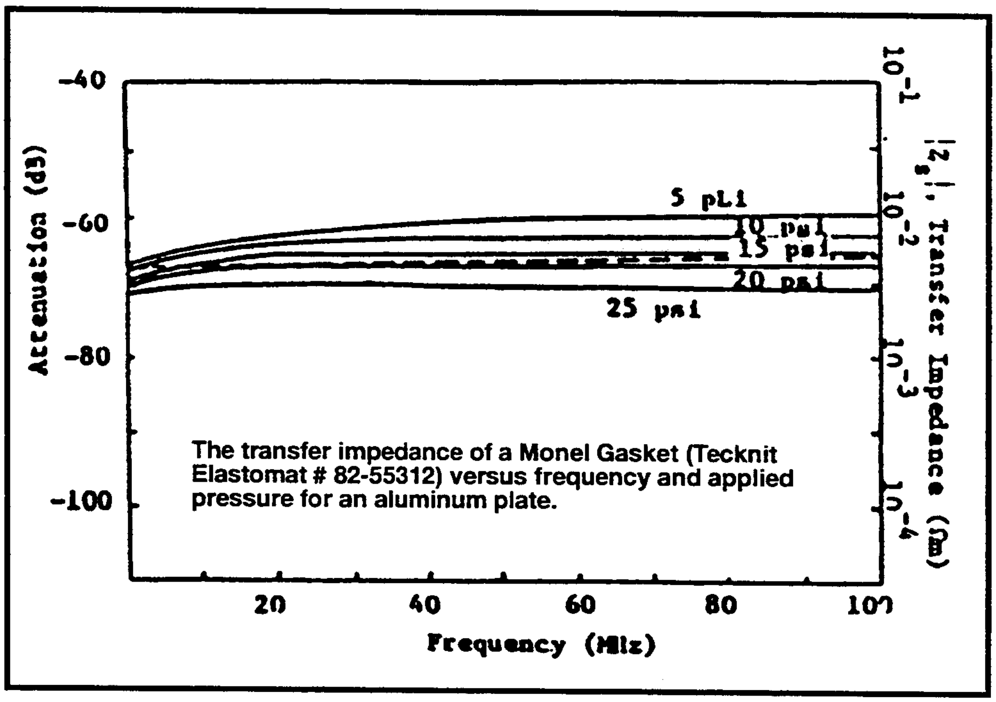


Figure 41. Transfer Impedance of Monel Gasket

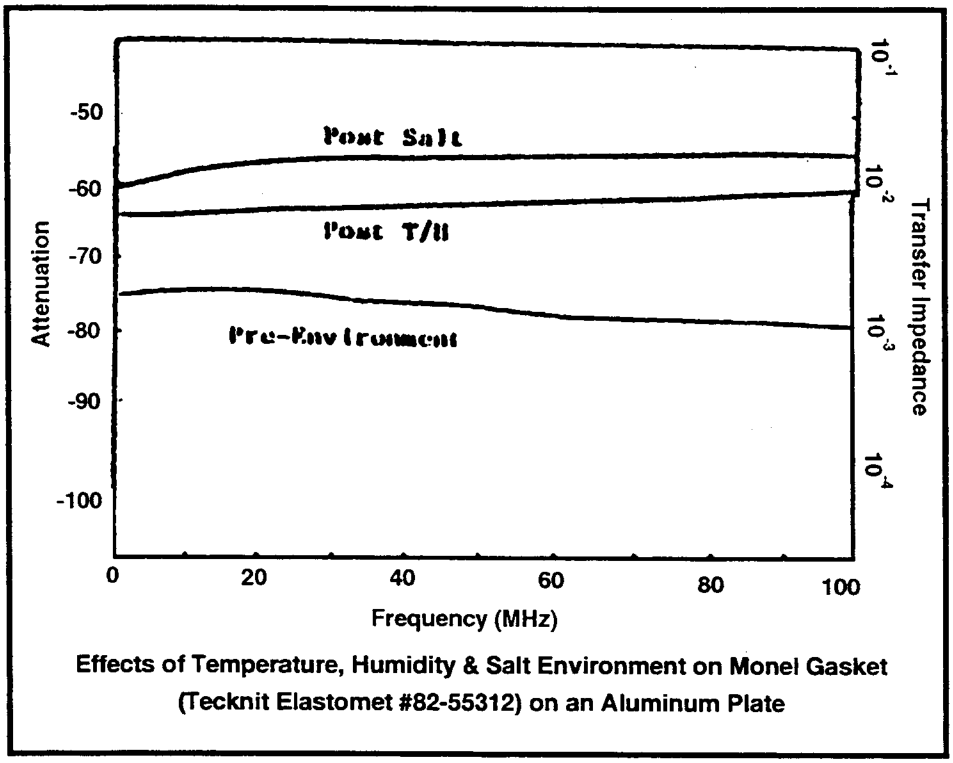
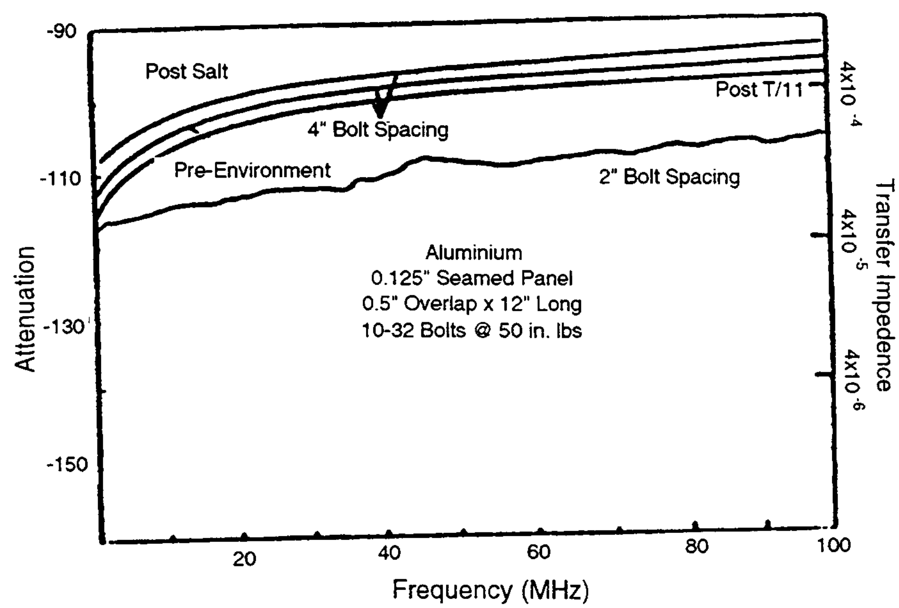


Figure 42. Environmental Effects Affecting Transfer Impedance of Monel Gasket



Effects of Bolt Spacing and Environment (Temperature/humidity and salt) on a 0.125" Aluminum-Aluminum Seamed Panel with a 0.5" Overlap

Figure 43. Transfer Impedance of Aluminum-Aluminum Seamed Panel

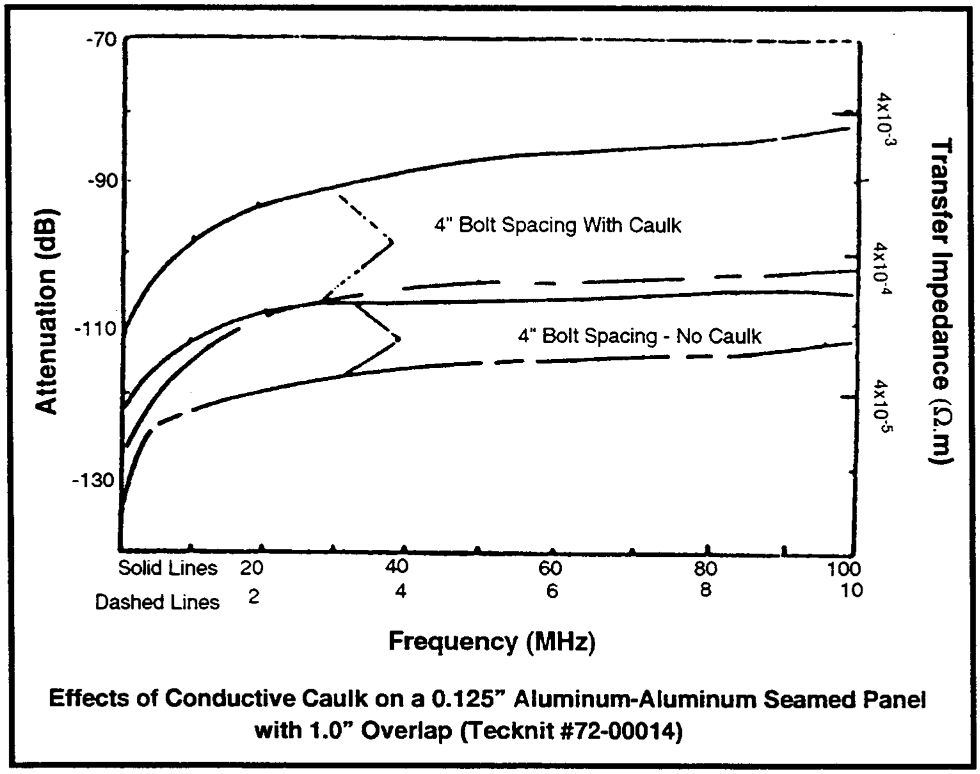
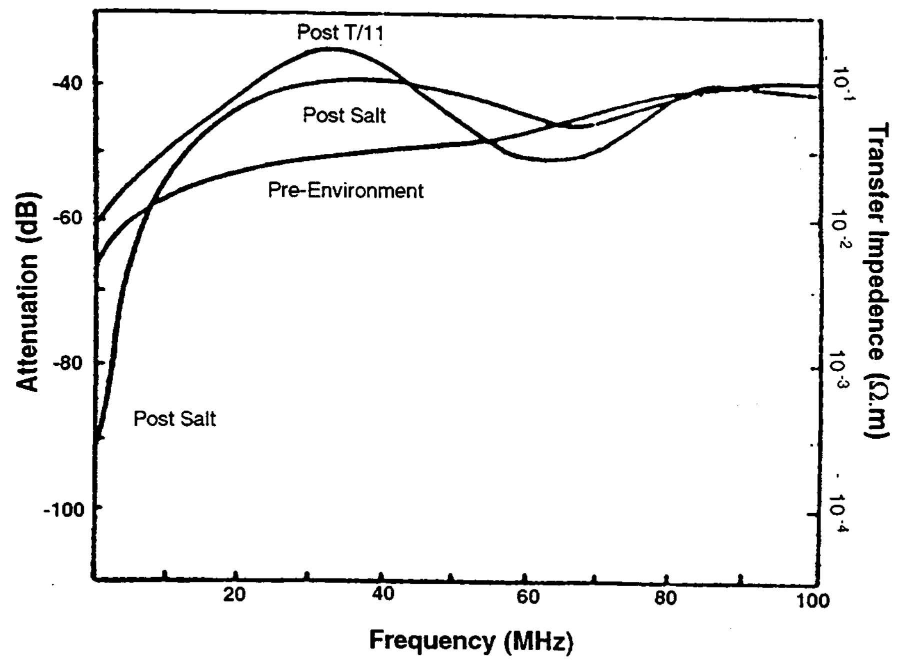


Figure 44. Transfer Impedance of Conductive Caulk



Effects of Temperature/Humidity and Salt Environments on a 1/8" x 1/4" Silver Consil-R Gasket (Tecnkit #85-10447) for an Aluminum Plate

Figure 45. Transfer Impedance of Silver Consil-R Gasket

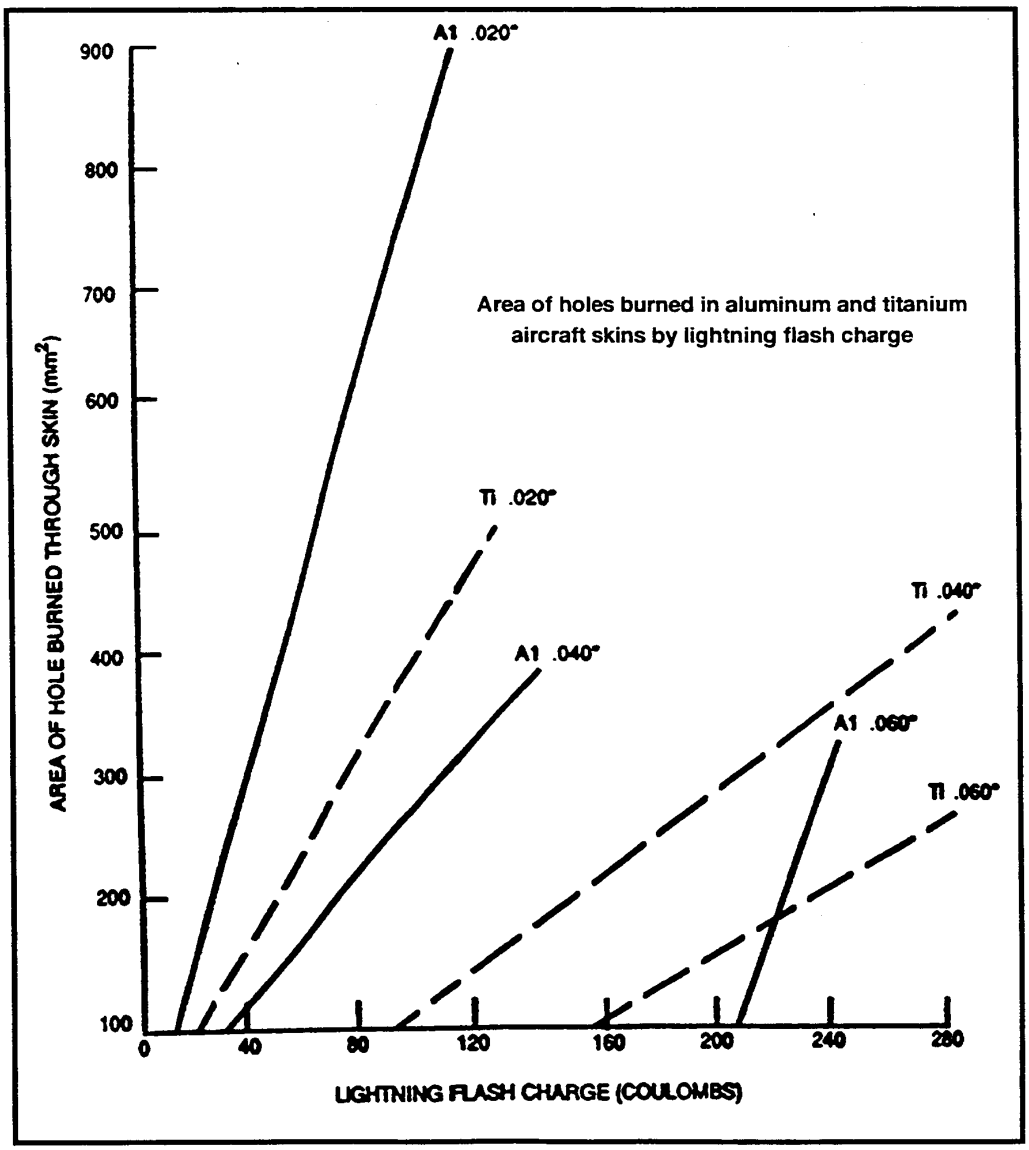


Figure 46. Melt-Through Data for Aluminum and Titanium Skins

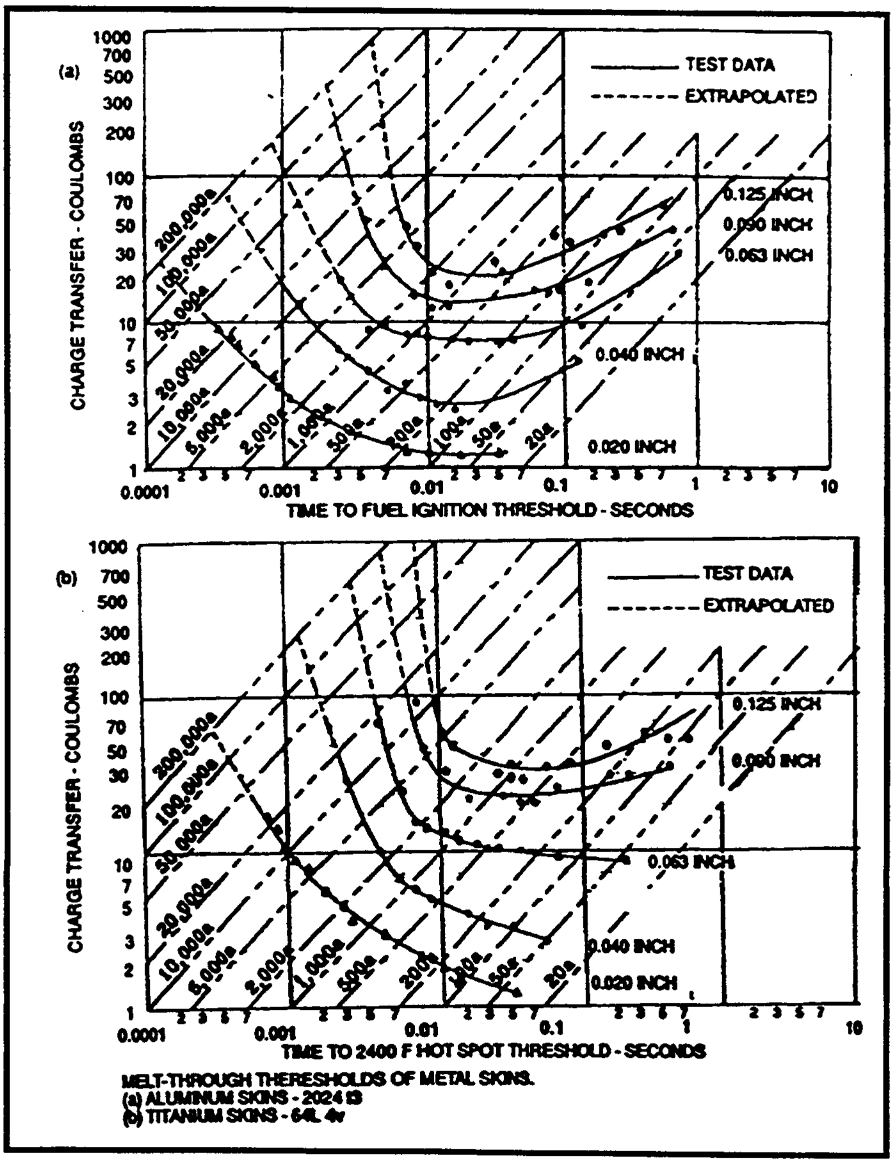


Figure 47. Melt-Through Thresholds of Metal Skins

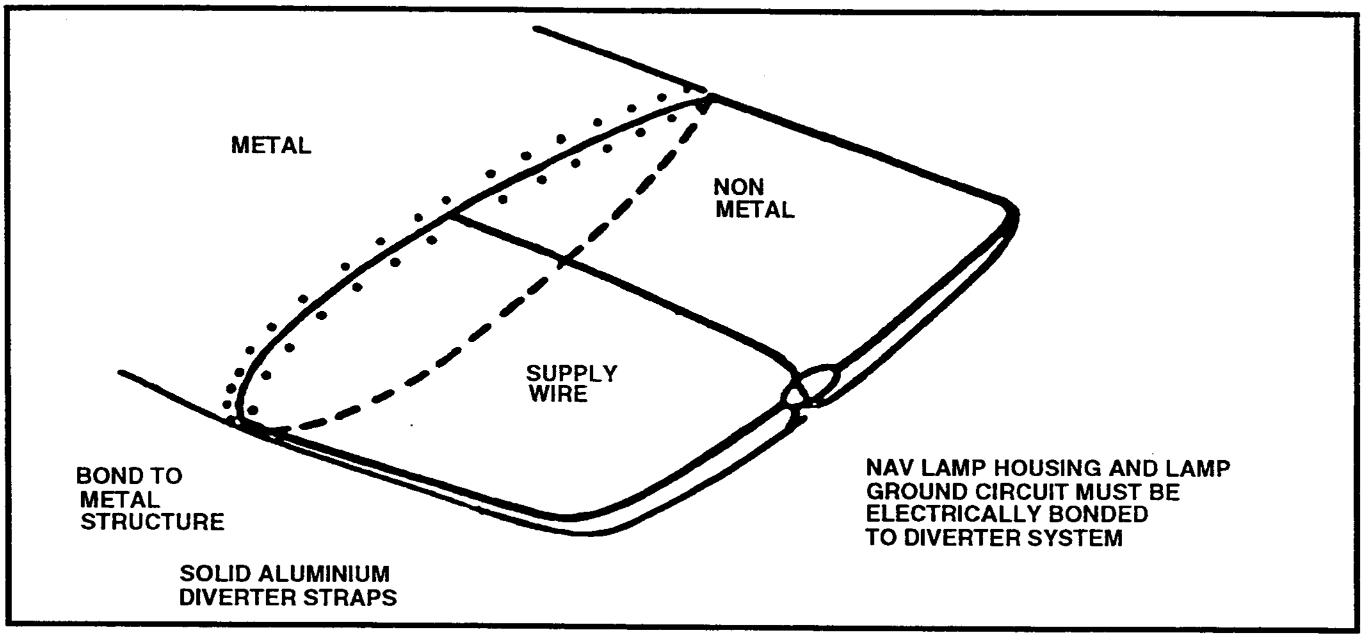


Figure 48. Diverter Strap Arrangement on Non-Metallic Components

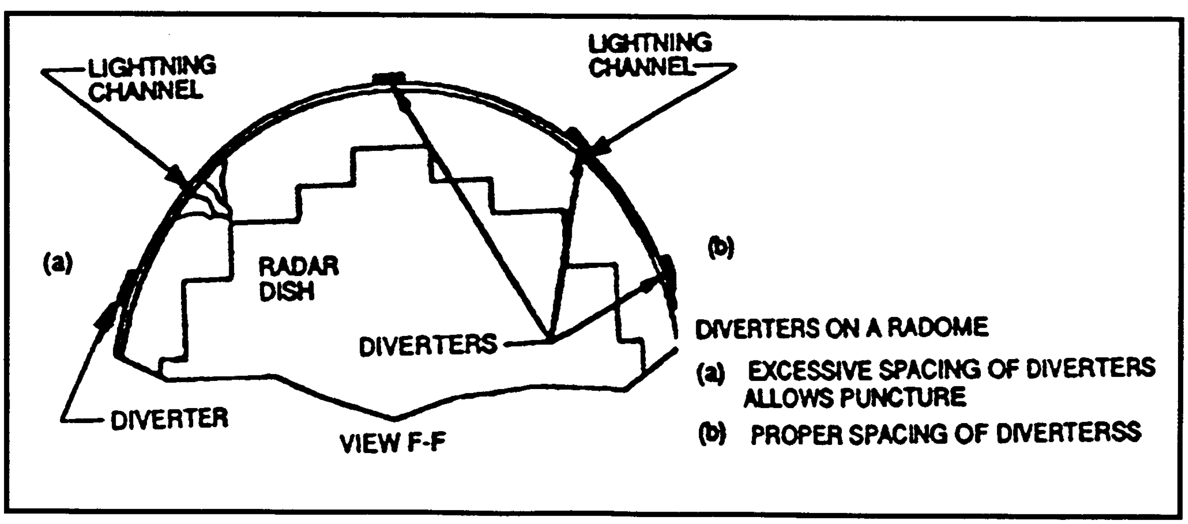


Figure 49. Diverter Spacing

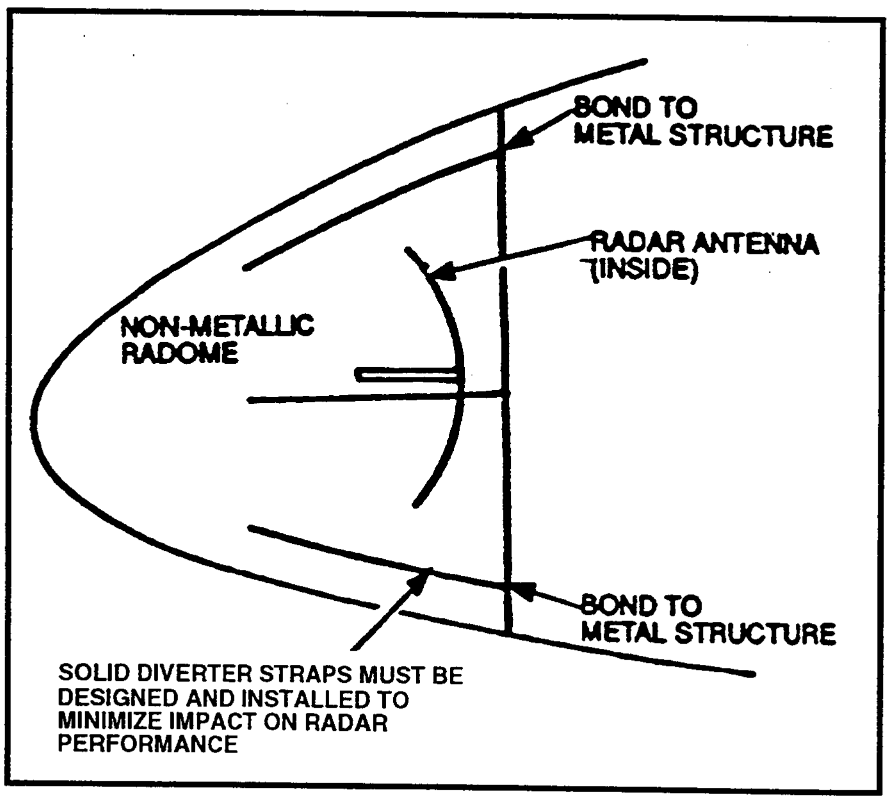


Figure 50. Arrangement of Diverter Straps to Protect Radome

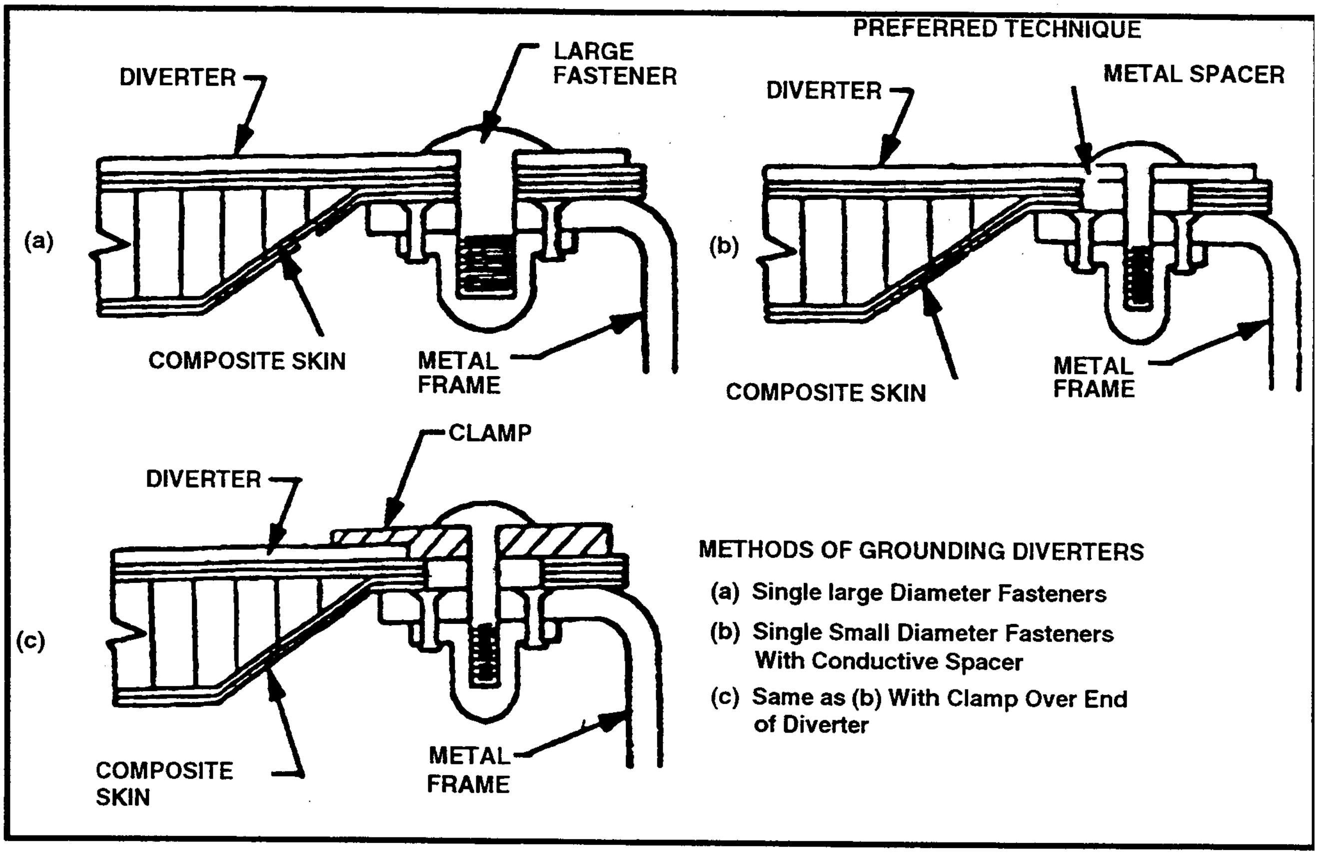


Figure 51. Methods of Grounding Diverters

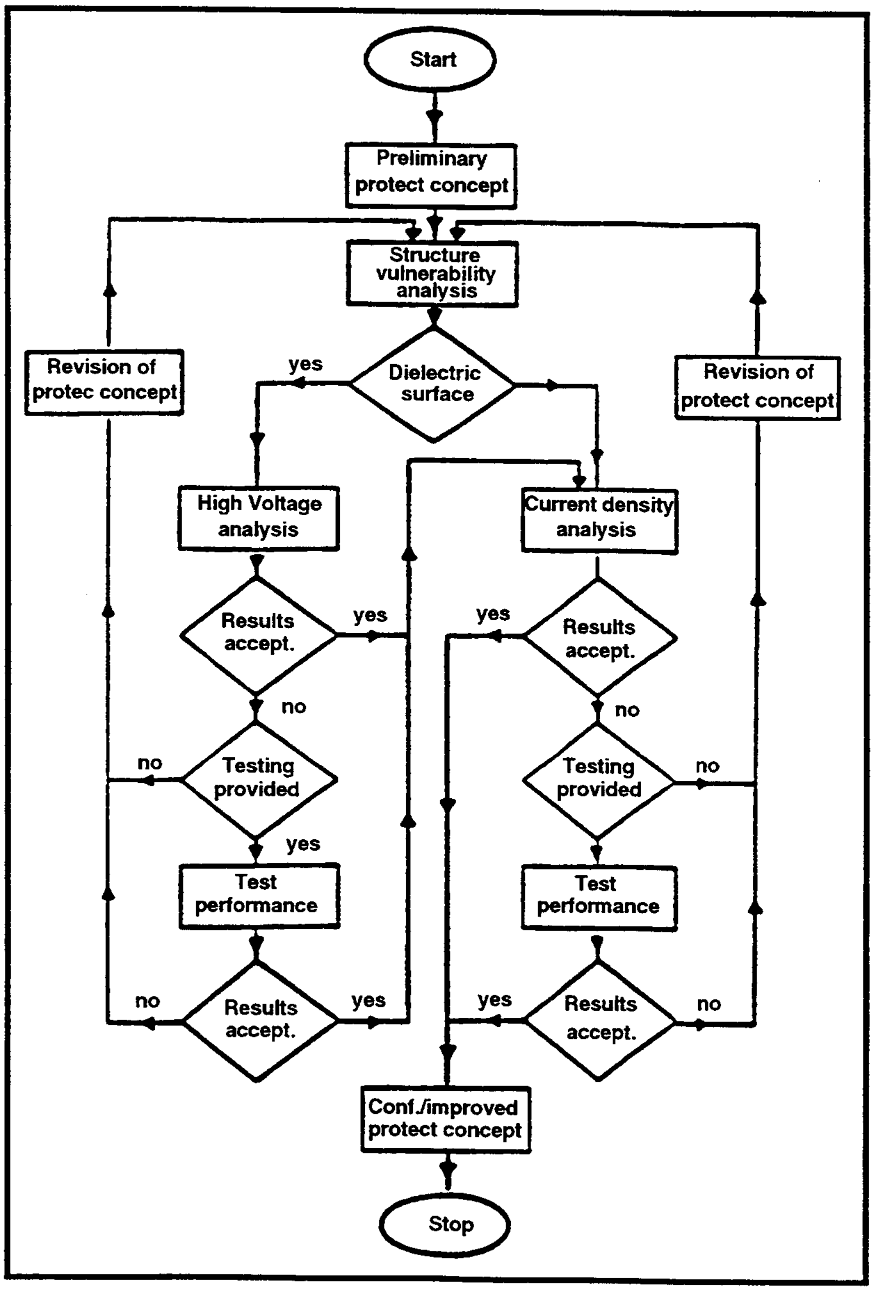
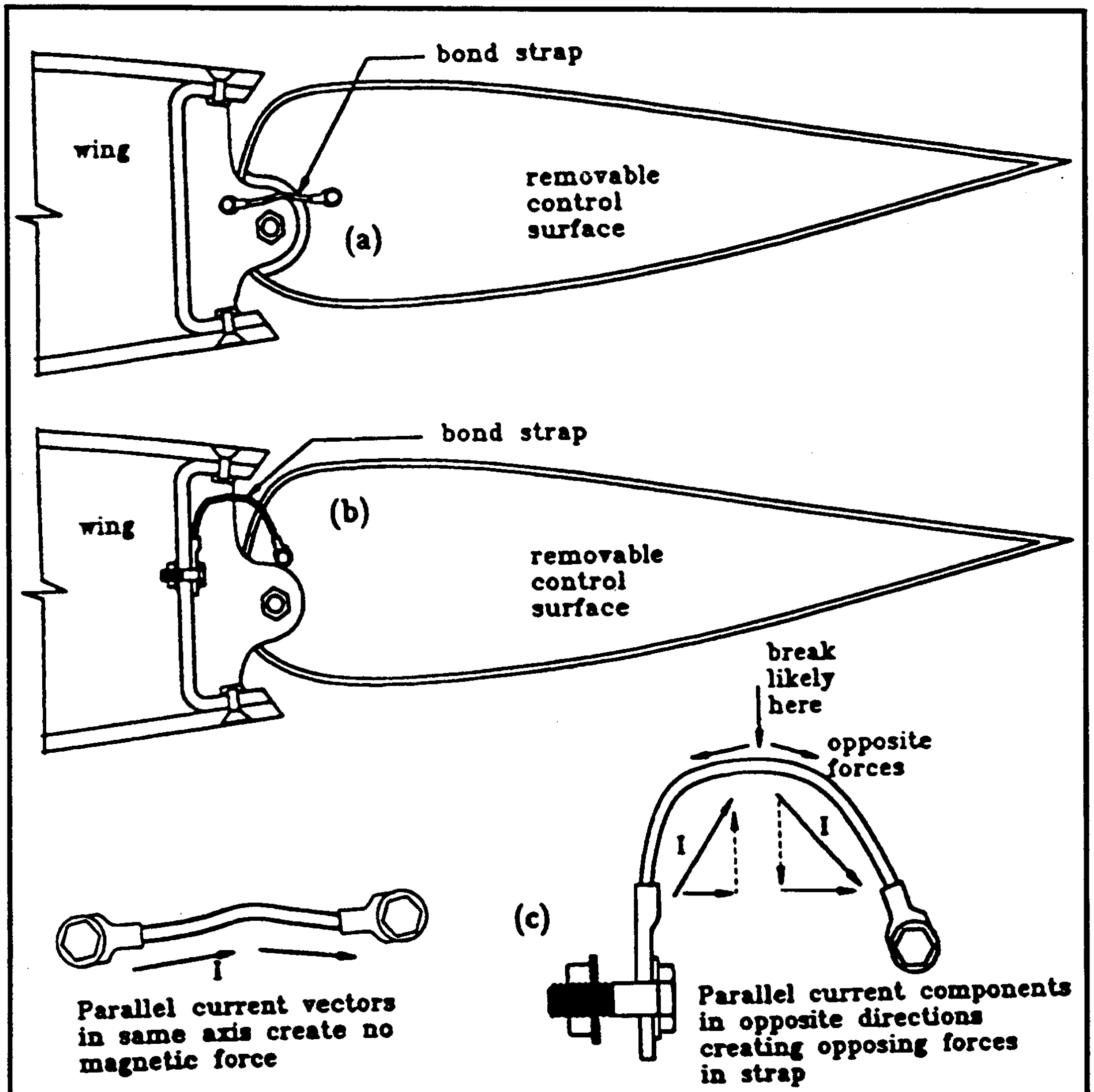


Figure 52. Pretest Analysis, Direct Effects



Magnetic force on a bond strap.
(a) Straight strap - good
(b) Sharply bent strap - bad
(c) Origin of forces

Figure 53. Bonding Straps

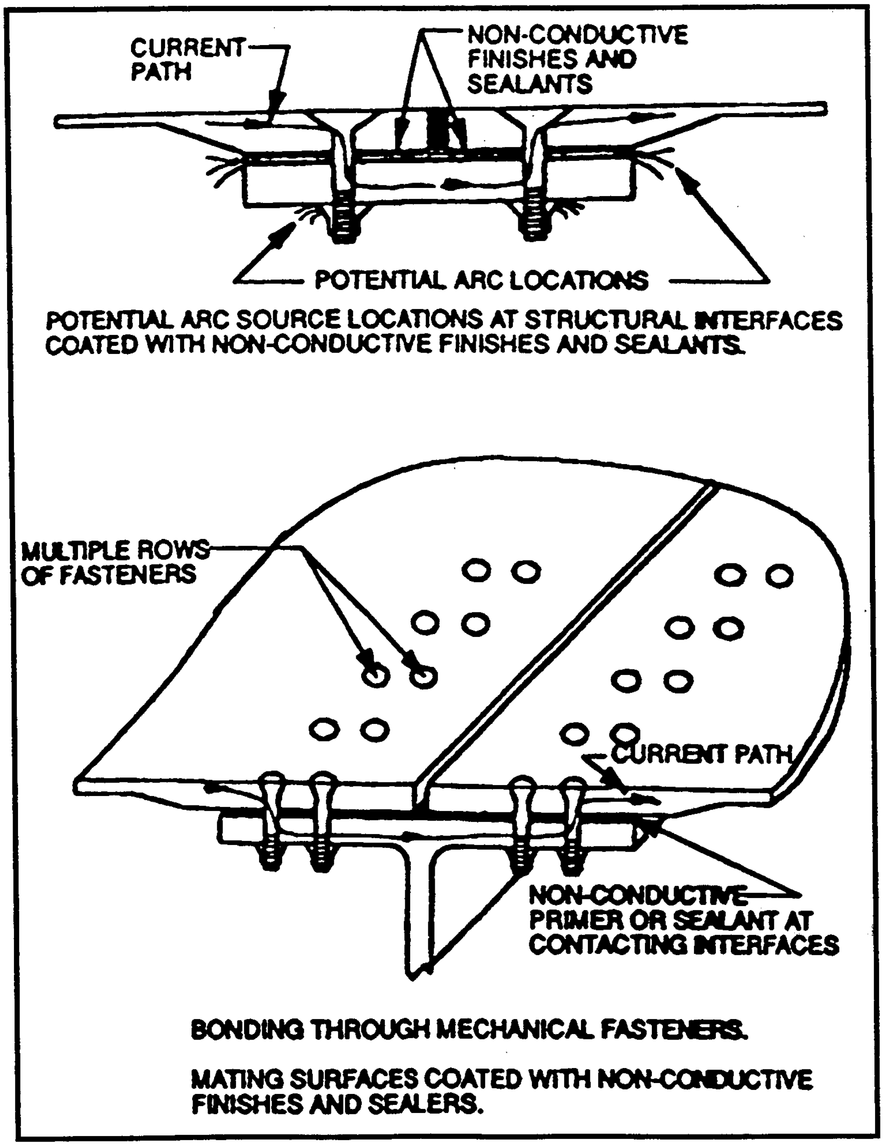


Figure 54. Current Reduction in Joints

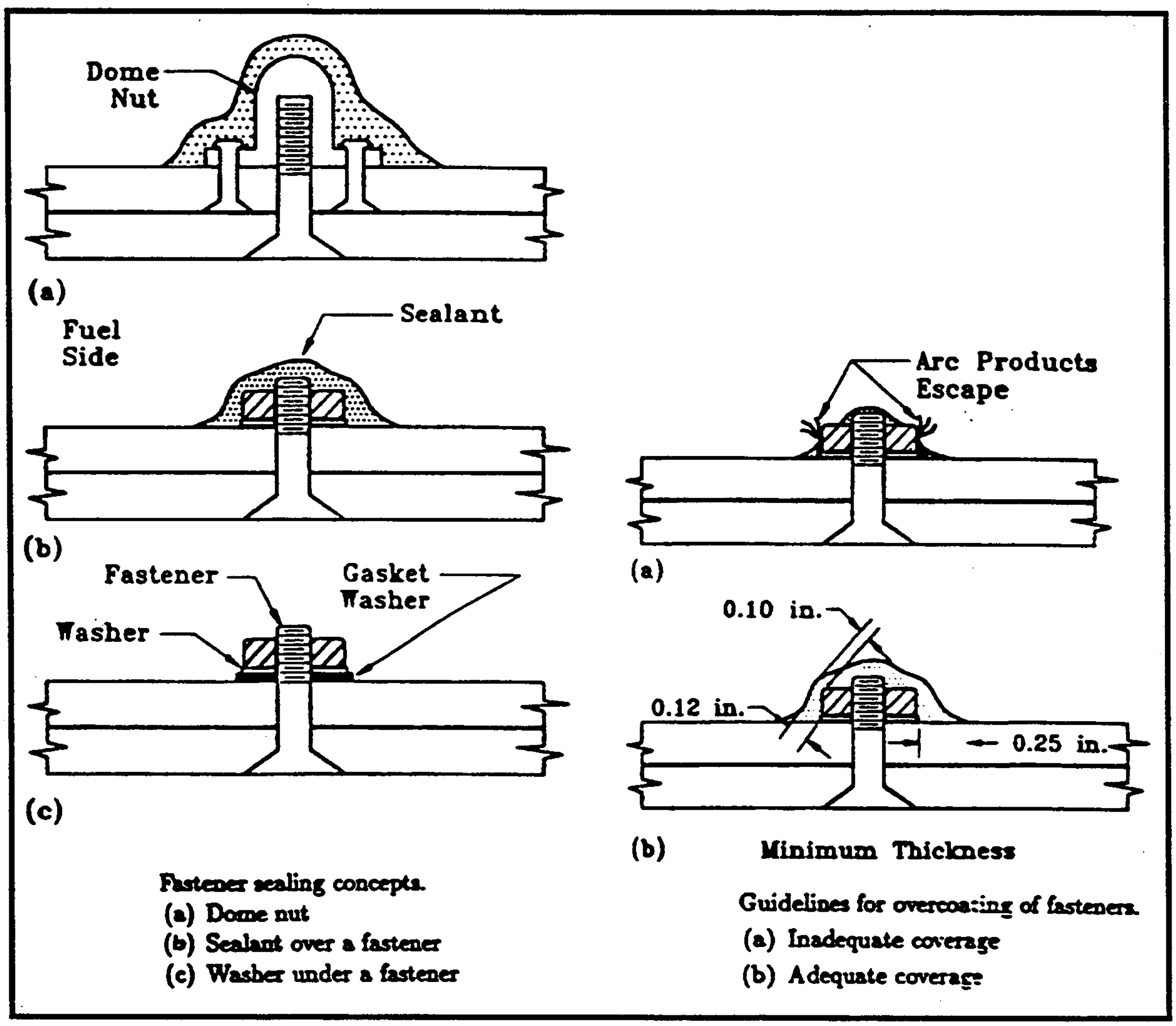


Figure 55. Fastener Sealing Concepts and Overcoating

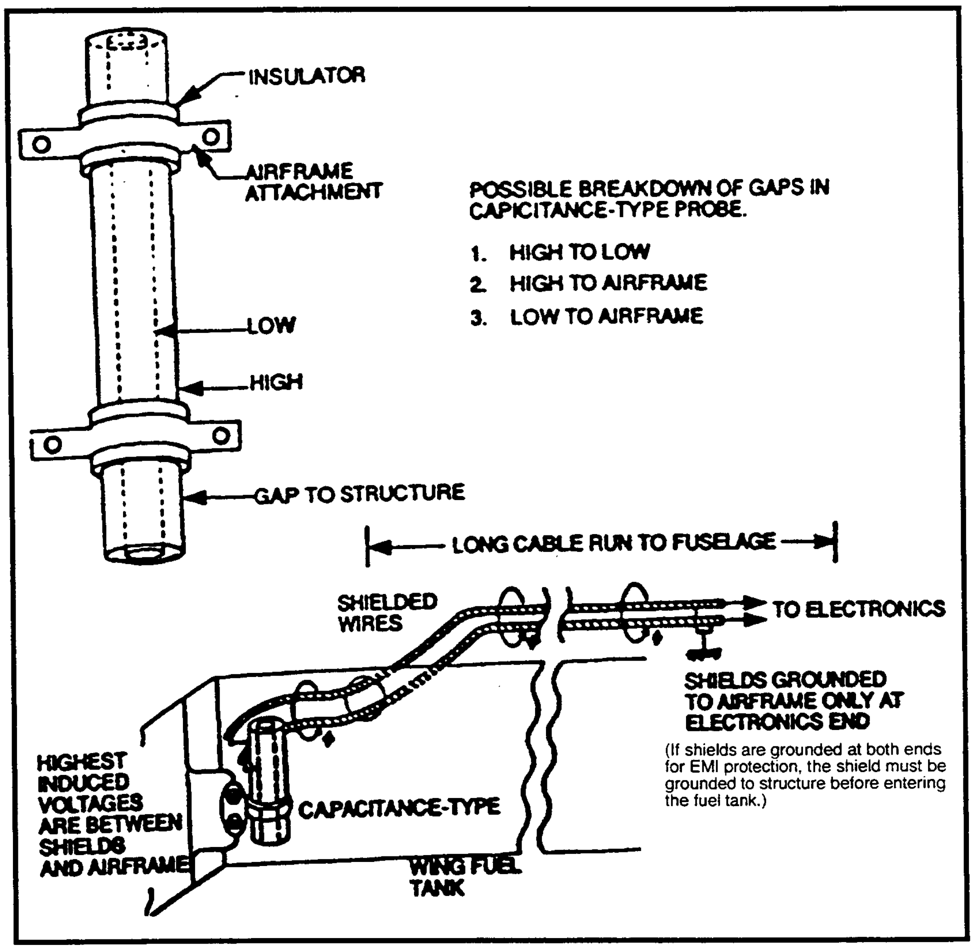


Figure 56. Fuel Probe Protection

Typical Fuel Probe Wiring

- Most magnetic flux and induced voltage appears between wire (or shield) and the airframe at probe end.
- Less flux and induced voltage exists between any two wires.
- Even less flux and voltage exists between a wire and its shield
- Other voltages can occur between probe and airframe because of structural IR potentials.

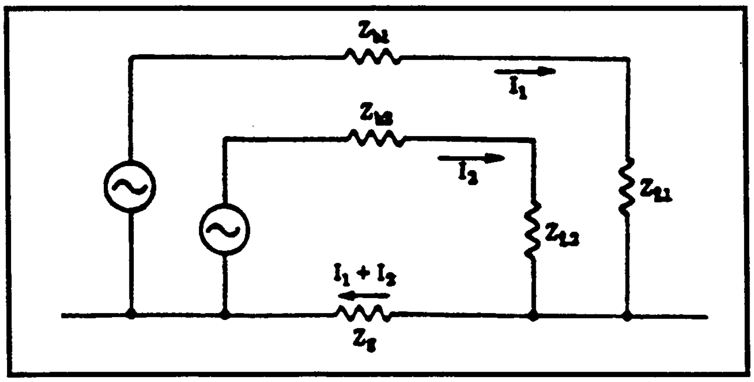


Figure 57. Common Ground Path (Zg)

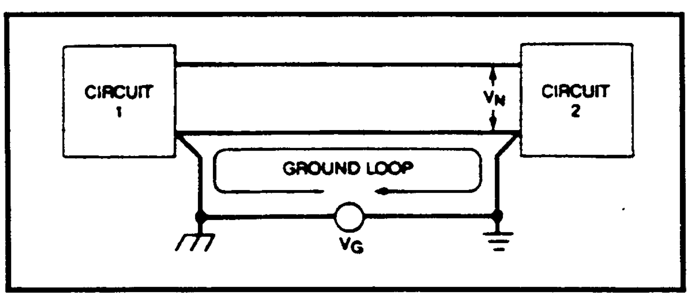


Figure 58. A Ground Loop Between Two Circuits

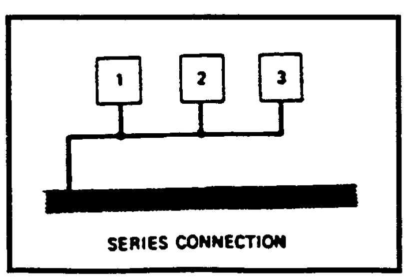


Figure 59. Series Connection

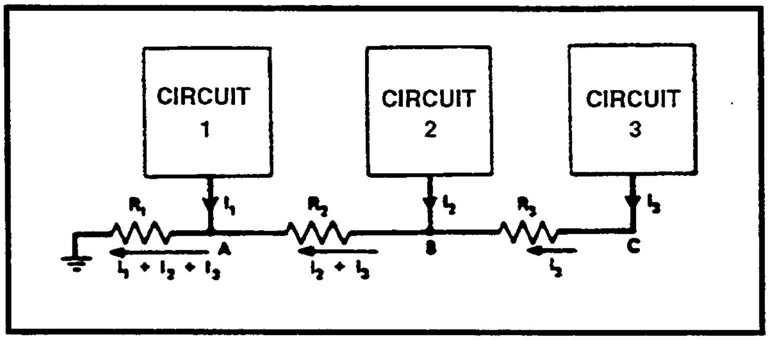


Figure 60. Common Ground System

A Series Ground Connection is undesirable from a noise standpoint, but has the advantage of simple wiring

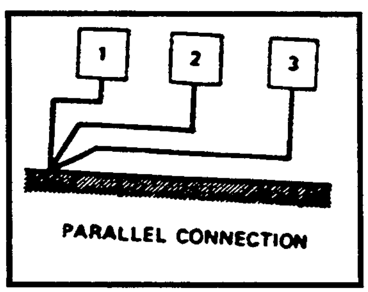


Figure 61. Parallel Connection

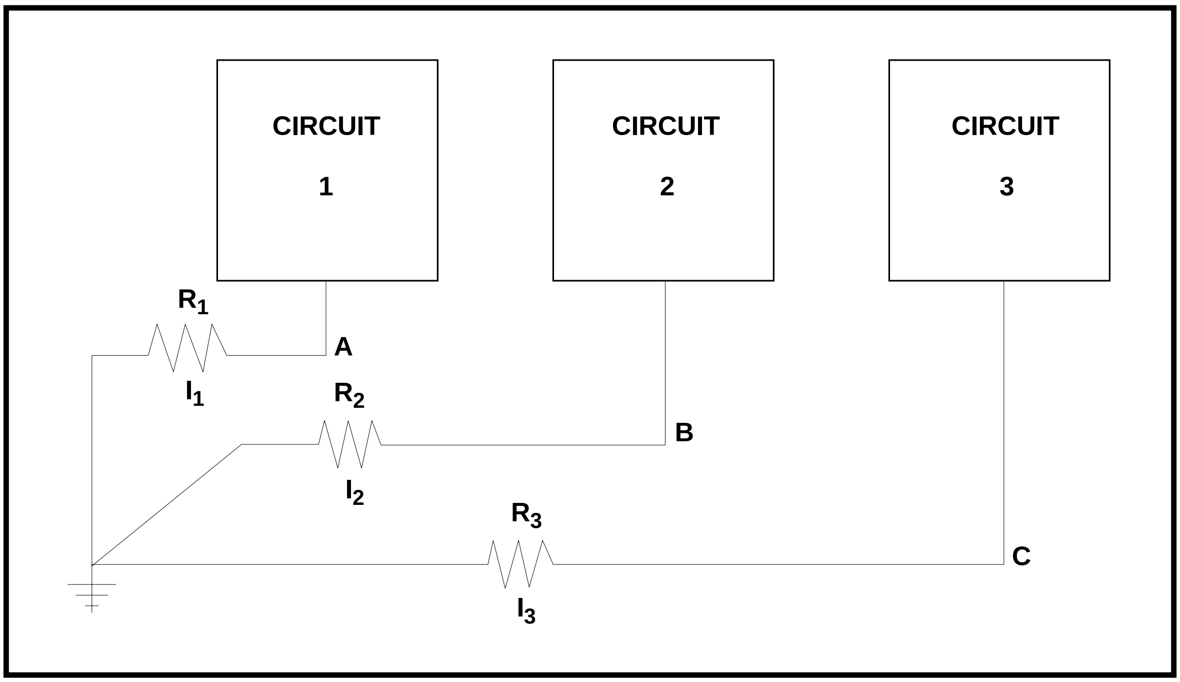


Figure 62. Separate//Parallel Ground System

This type of connection provides good low-frequency grounding, but is mechanically cumbersome.

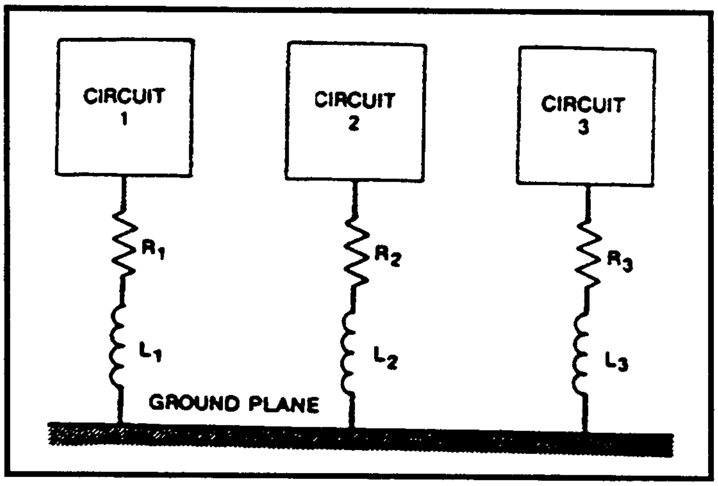


Figure 63. Multipoint Ground System
A good choice at frequencies above 10 MHz. Impedances R_1-R_3 and L_1-L_3 should be minimized.

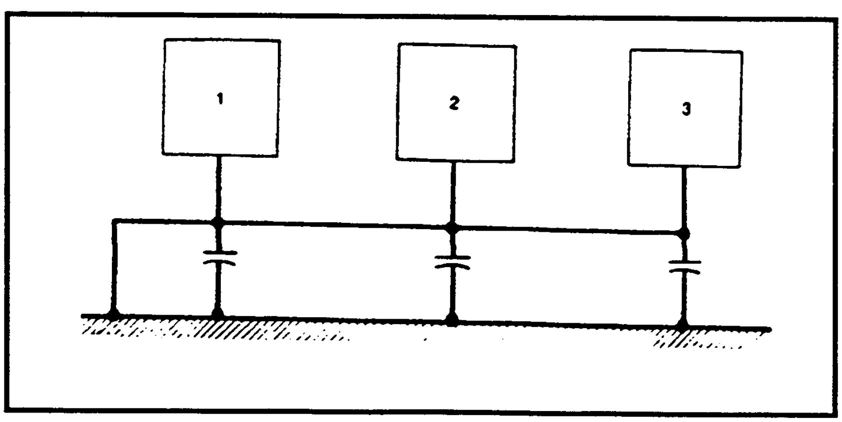


Figure 64. Hybrid Ground Connection
A hybrid ground connection that acts as a single-point ground at low frequencies and a multipoint ground at high frequencies.

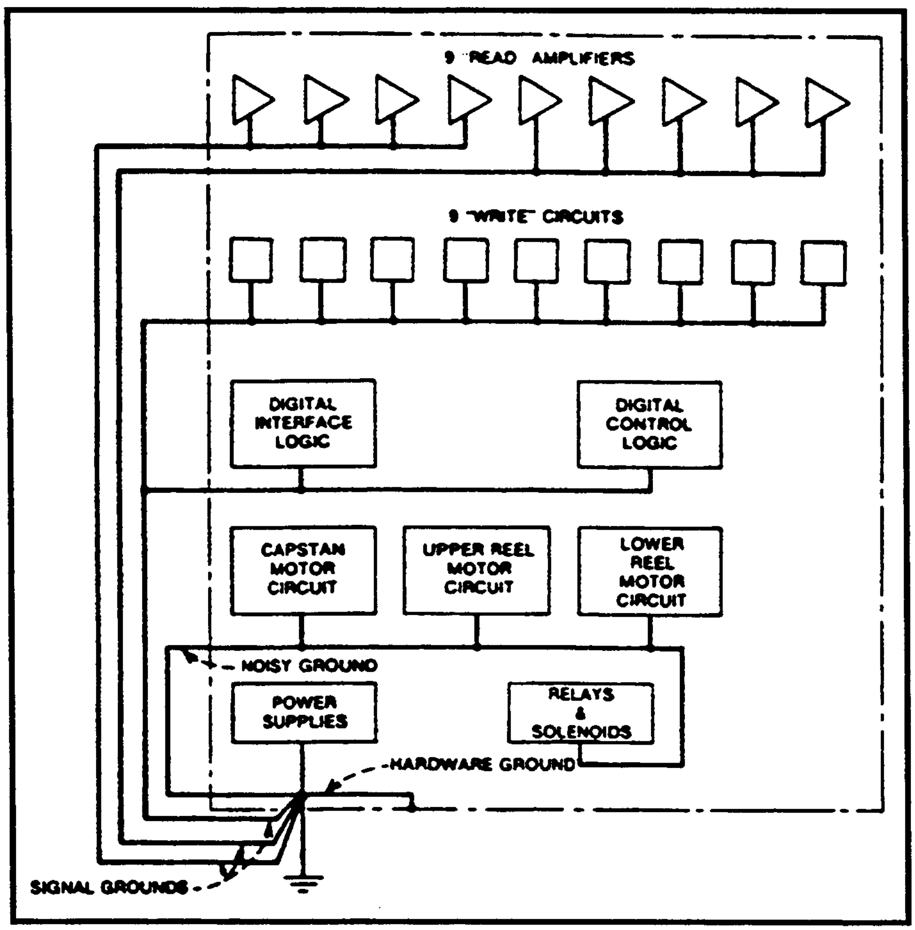


Figure 65. Grounding Diagram

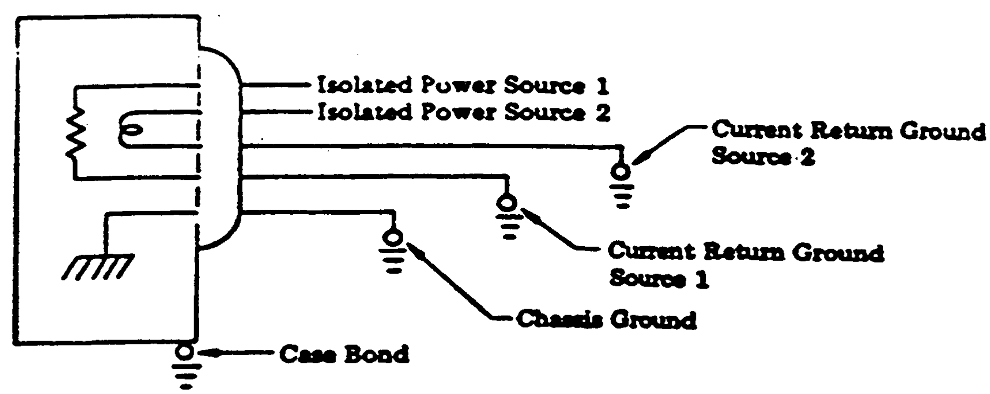


Figure 66. Preferred Equipment Grounding

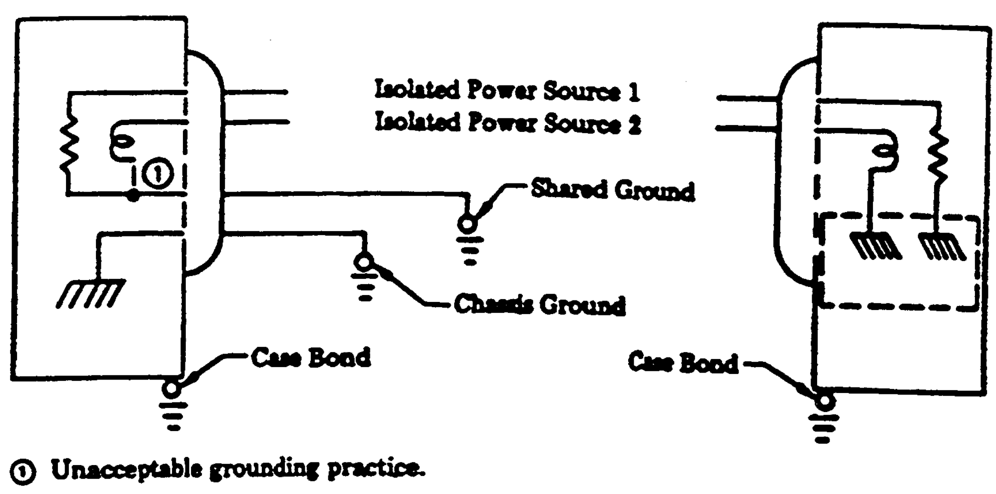


Figure 67. Unacceptable Equipment Grounding

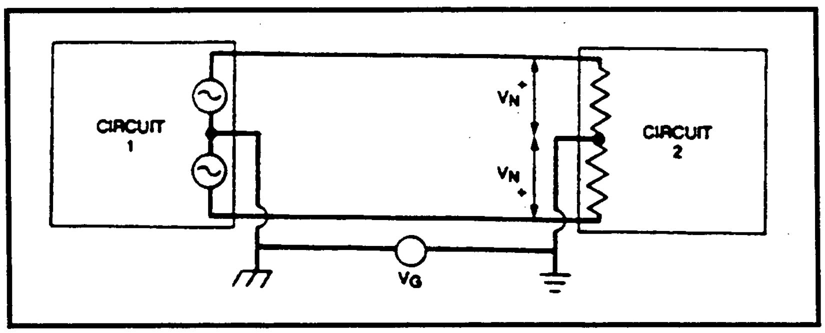
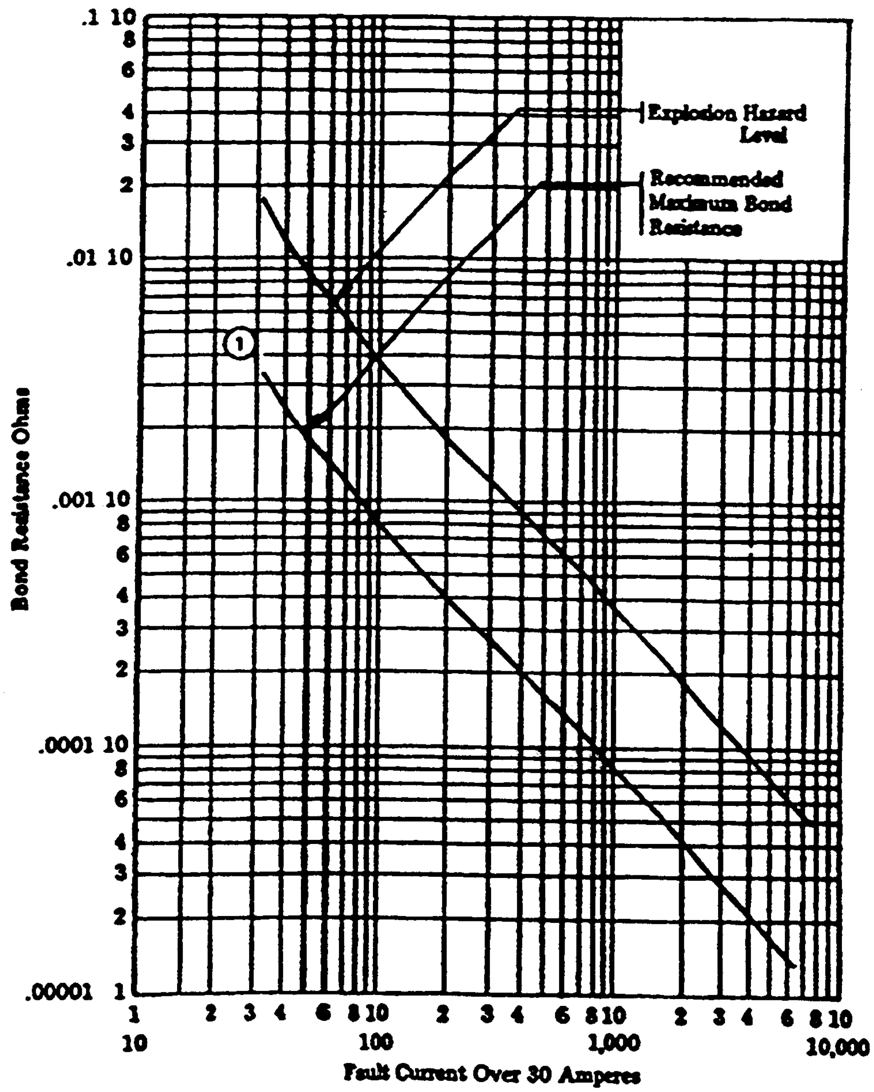


Figure 68. Balanced Circuit

A balanced circuit can be used to cancel out the effect of a ground loop between two circuits.



For fault current levels less than 30 amperes, the bond resistance value shall not exceed 0.008 ohms

Figure 69. Flammable Leakage Zone Bond Resistance Values

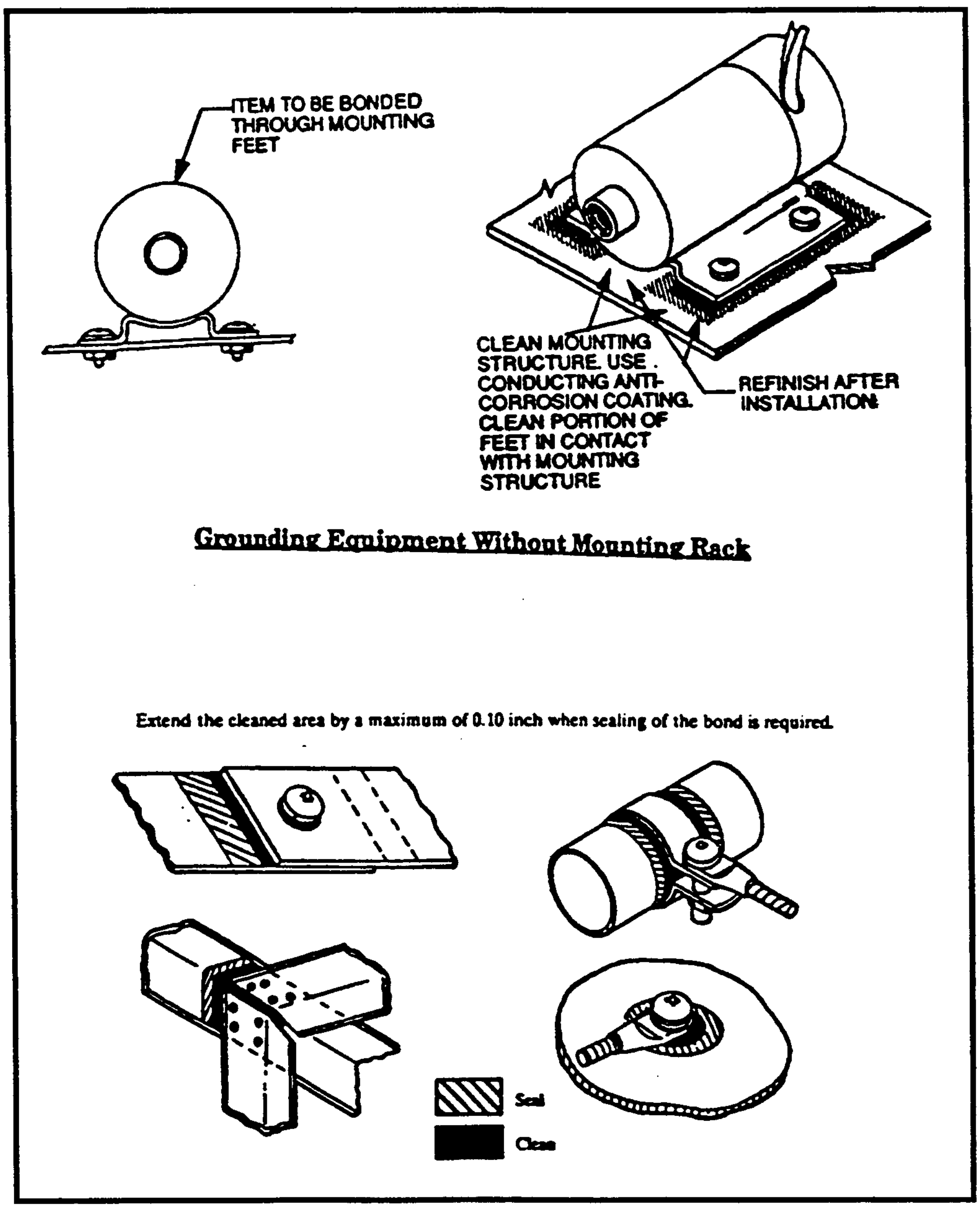


Figure 70. Bond Surface Contact Area

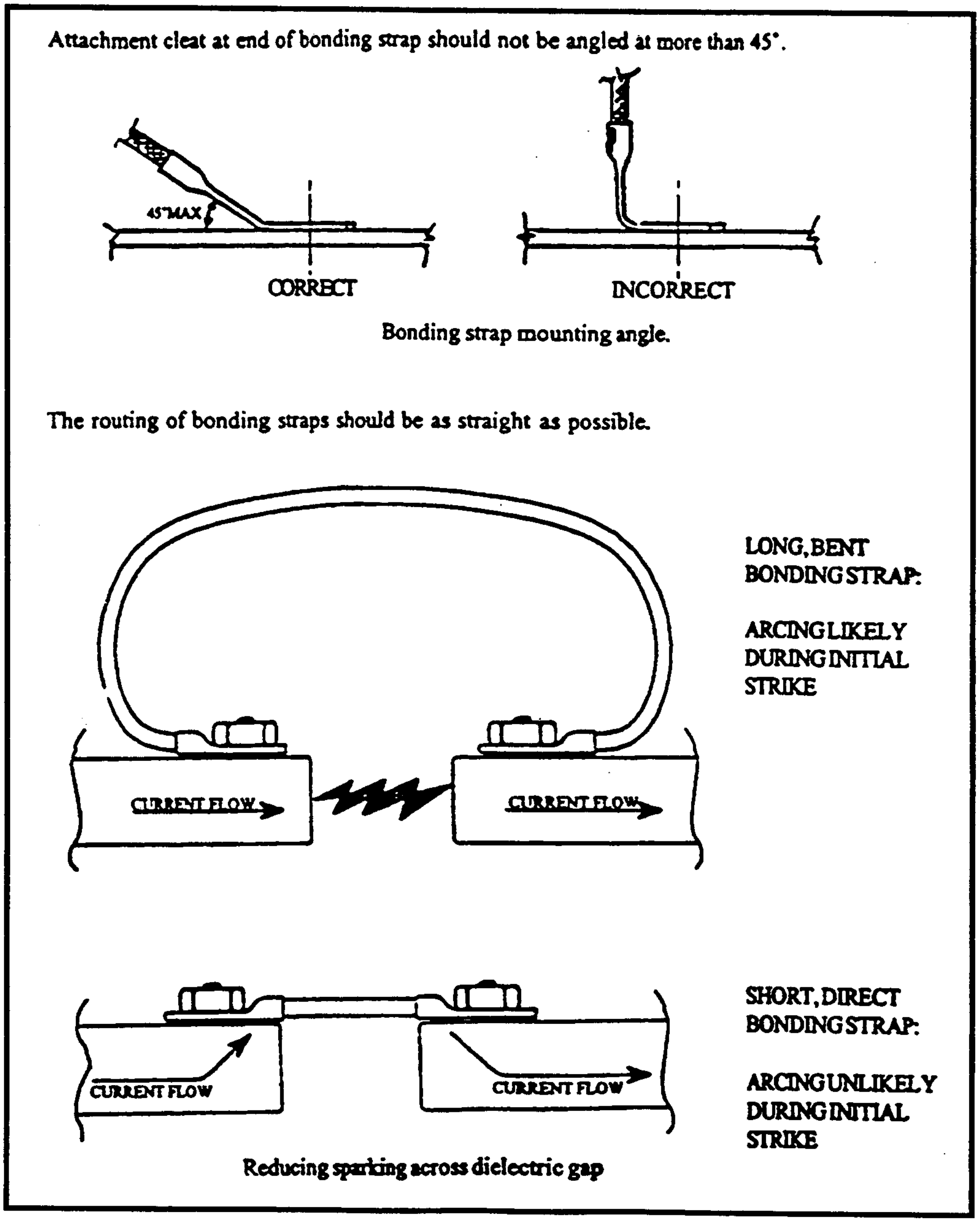


Figure 71. Cleat and Strap Attachment

Flange Mounted Electrical Connectors and Jam Nut Mounted Electrical Connectors must be electrically bonded at bulkhead penetrations by removing all protective finishes at locations shown. Apply alodine (MIL-C-5541,Class 3) to bare aluminum. After the connector is mounted, refinish with the original paint system.

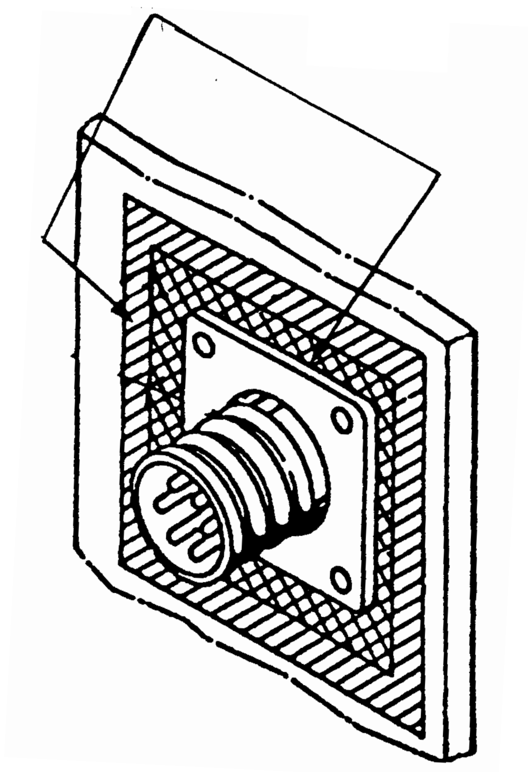


Figure 72. Electrical Bonding of Connector to Aluminum Bulkhead

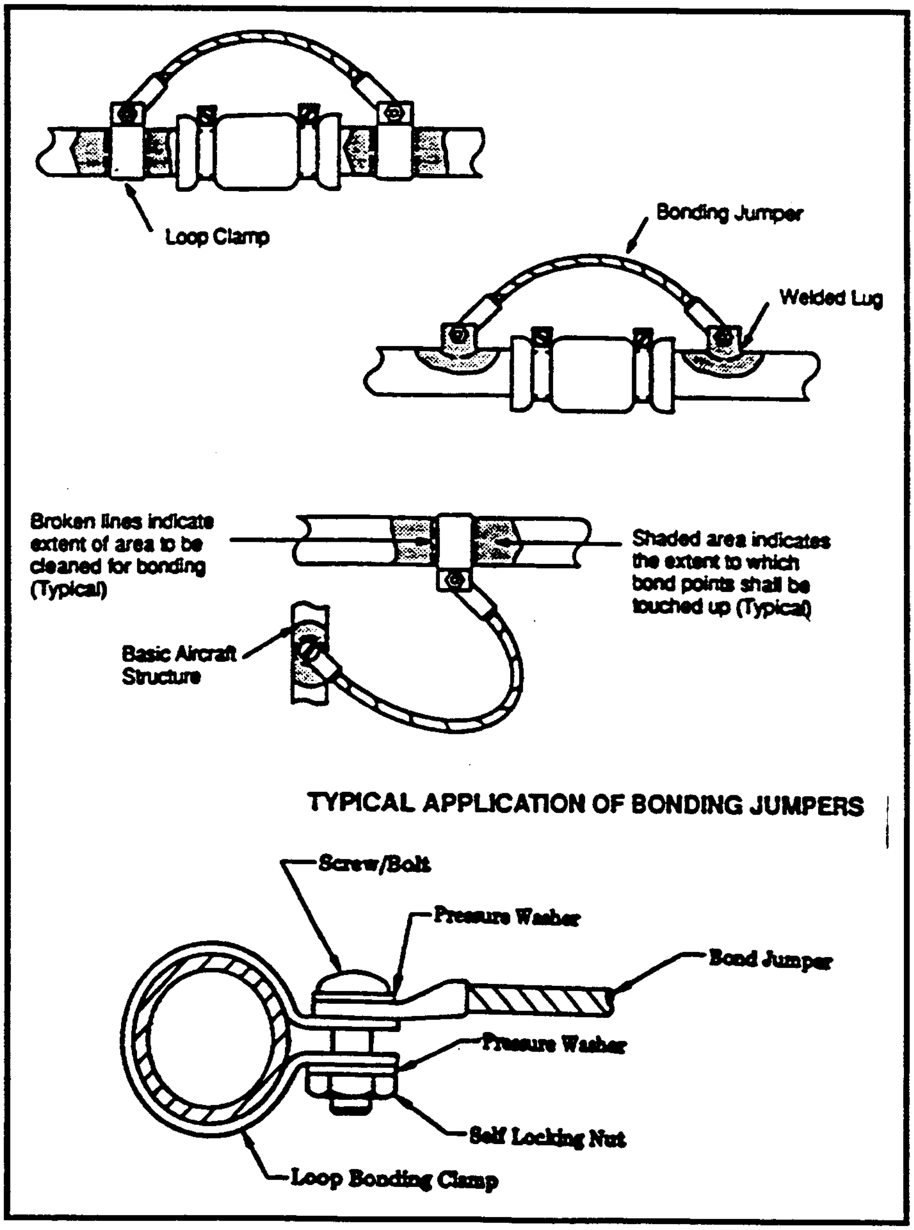


Figure 73. Typical Application of Bonding Jumpers

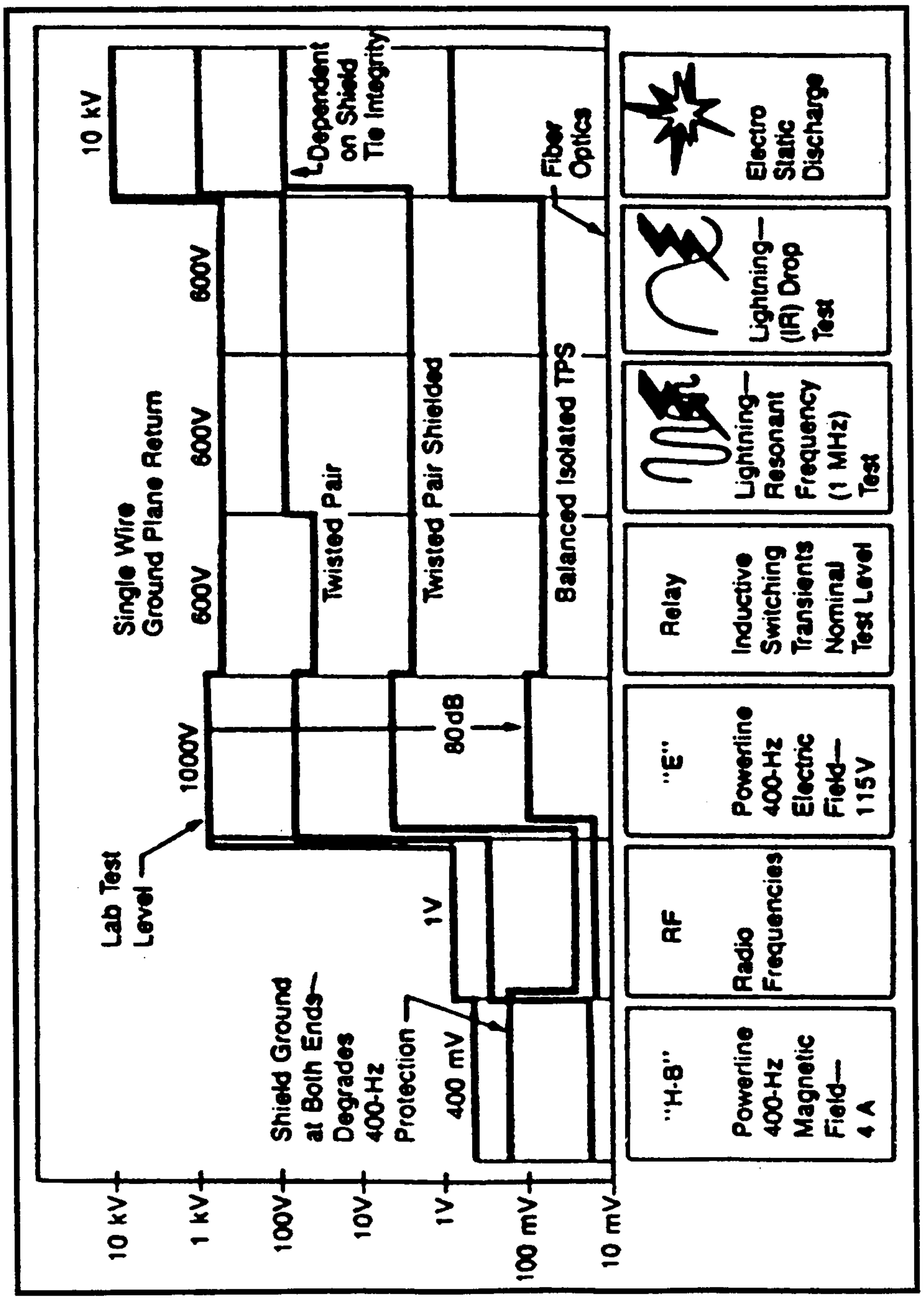
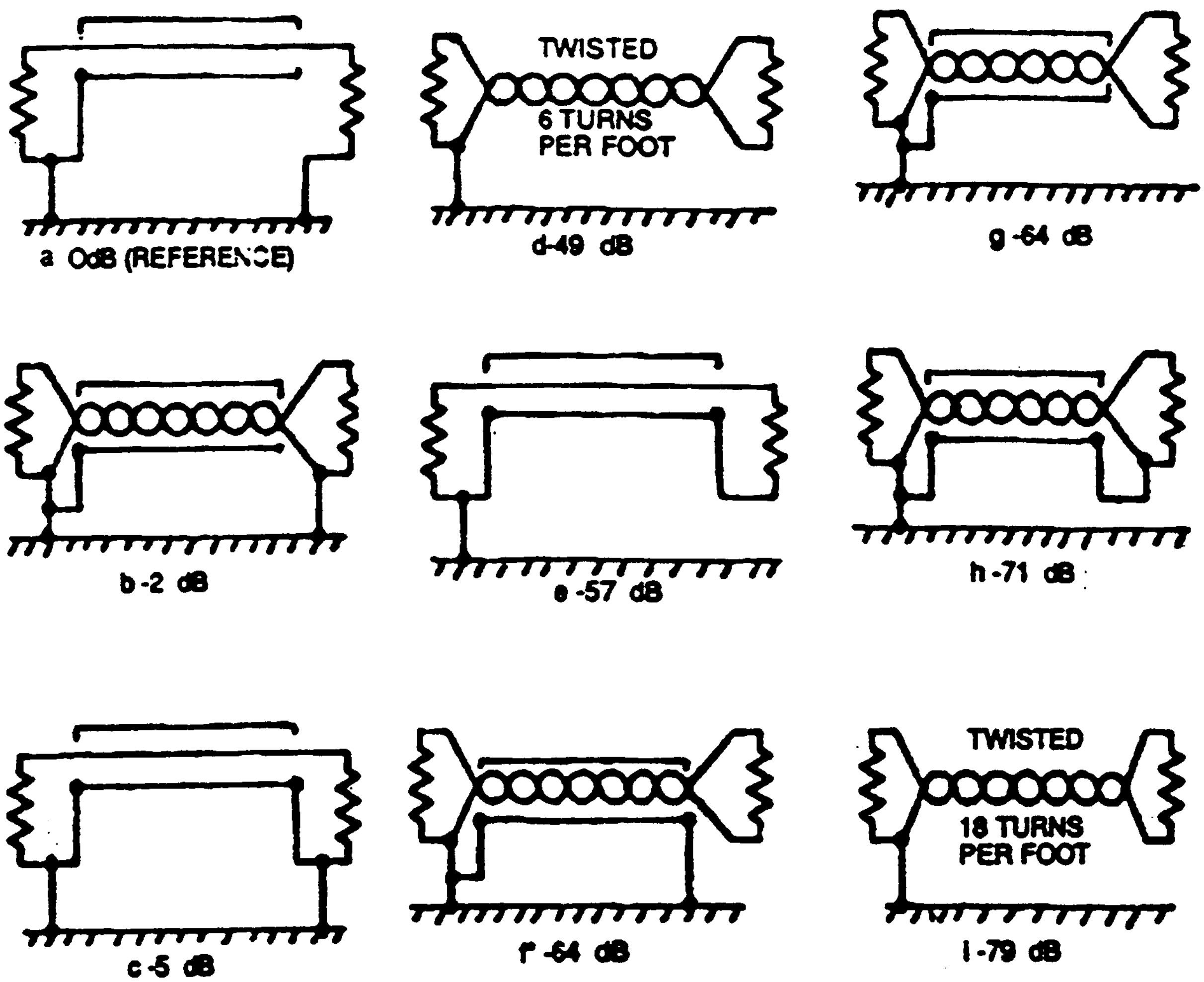


Figure 74. Circuit Response to EMI



*PREFERRED CIRCUIT FOR HIGH FREQUENCIES

VALUES GIVEN ARE FOR CIRCUITS 1 INCH ABOVE GROUND PLACE
BUT ARE ABOUT THE SAME FOR OTHER DISTANCES FROM GROUND PLANE.

Figure 75. Susceptibility of Circuit Configurations to Electric and Magnetic Fields

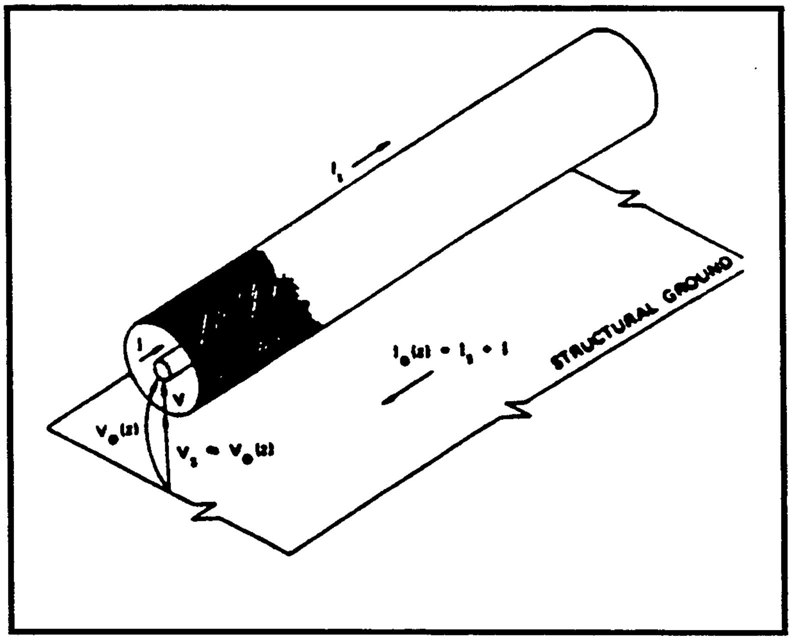


Figure 76. Illustration of Voltages and Currents Asociated with Shielded Cable Analysis

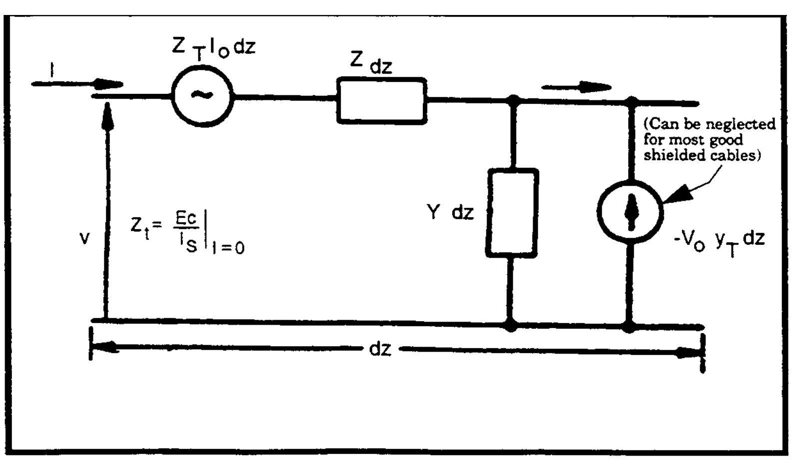


Figure 77. Equivalent Circuit for Internal Circuit

Equivalent circuit for the internal circuit when both the transfer impedance and the transfer admittance are included

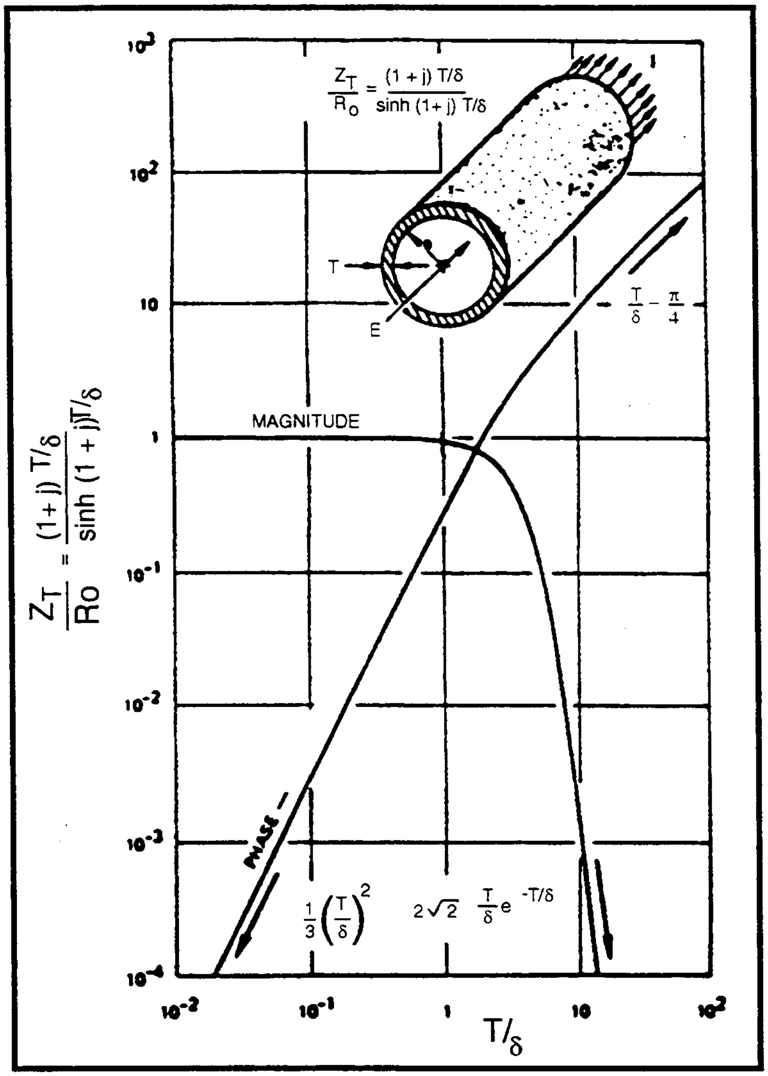


Figure 78. Normalized transfer impedance for thin-walled solid cylindrical shields

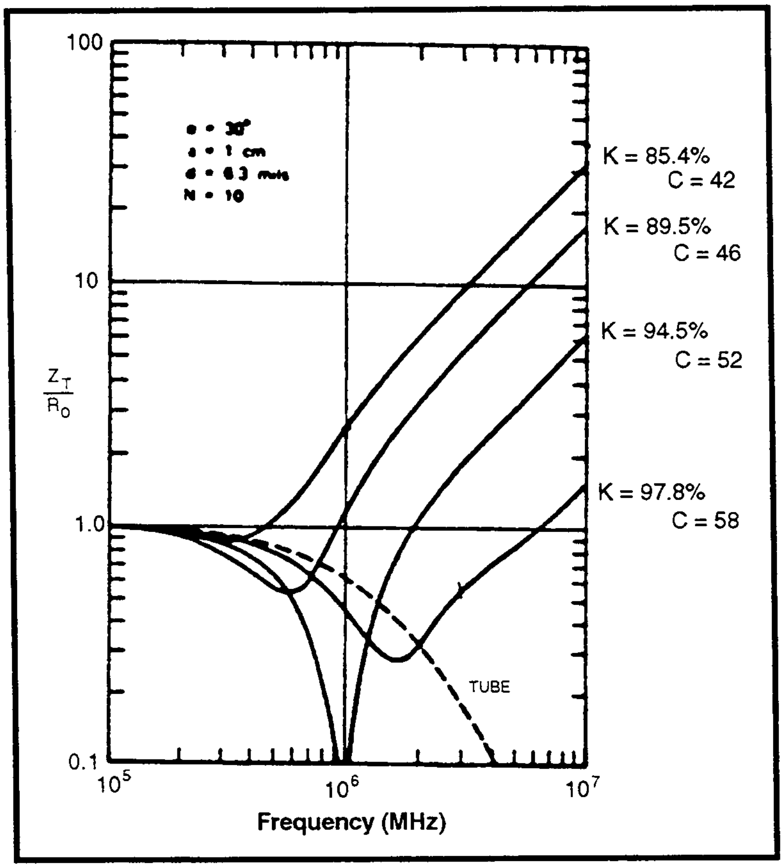


Figure 79. Transfer Impedance of a Braided-Wire Shield

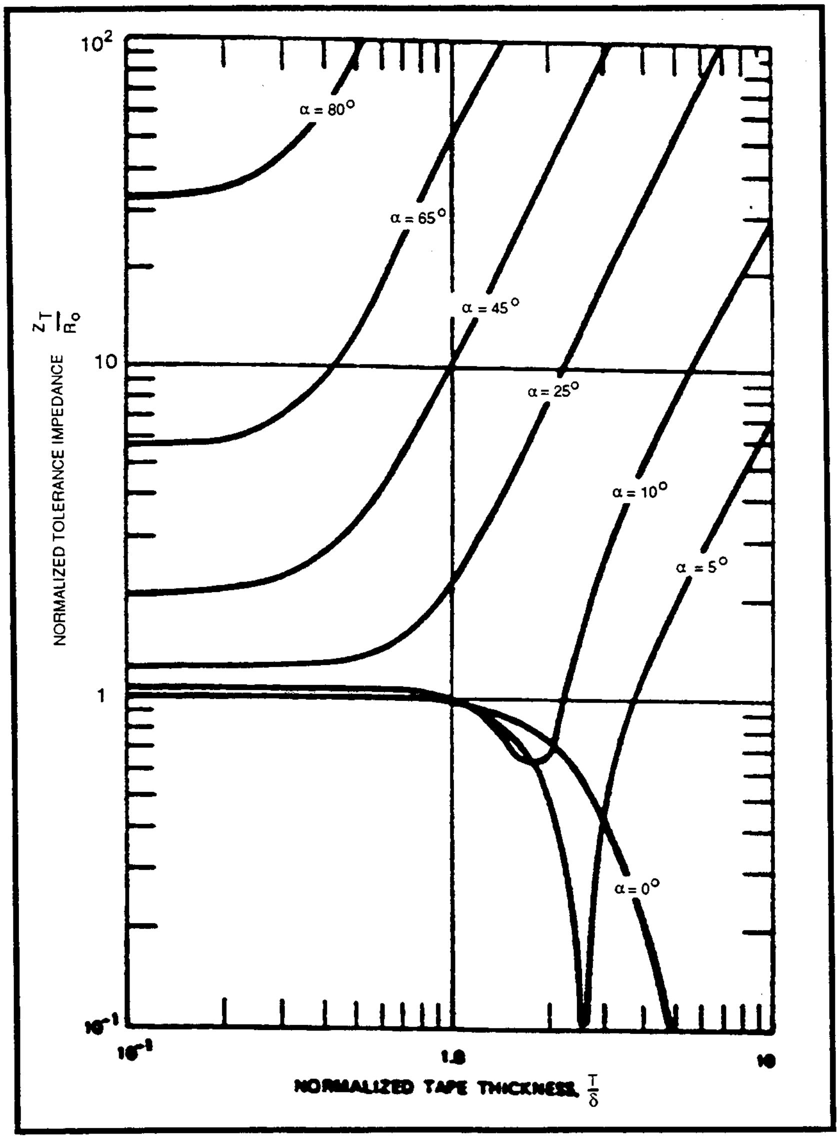


Figure 80. Magnitude of the Transfer Impedance Computed for a Tape-wound shield

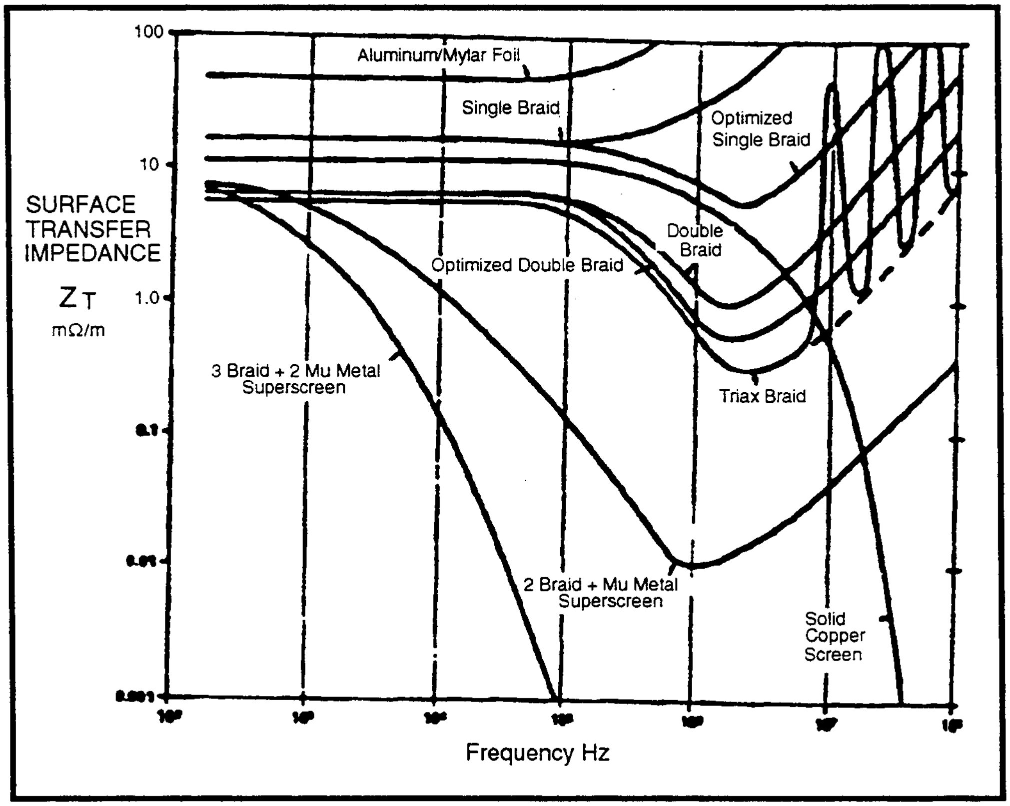


Figure 81. Variation of Z_T with frequency for different screen constructions

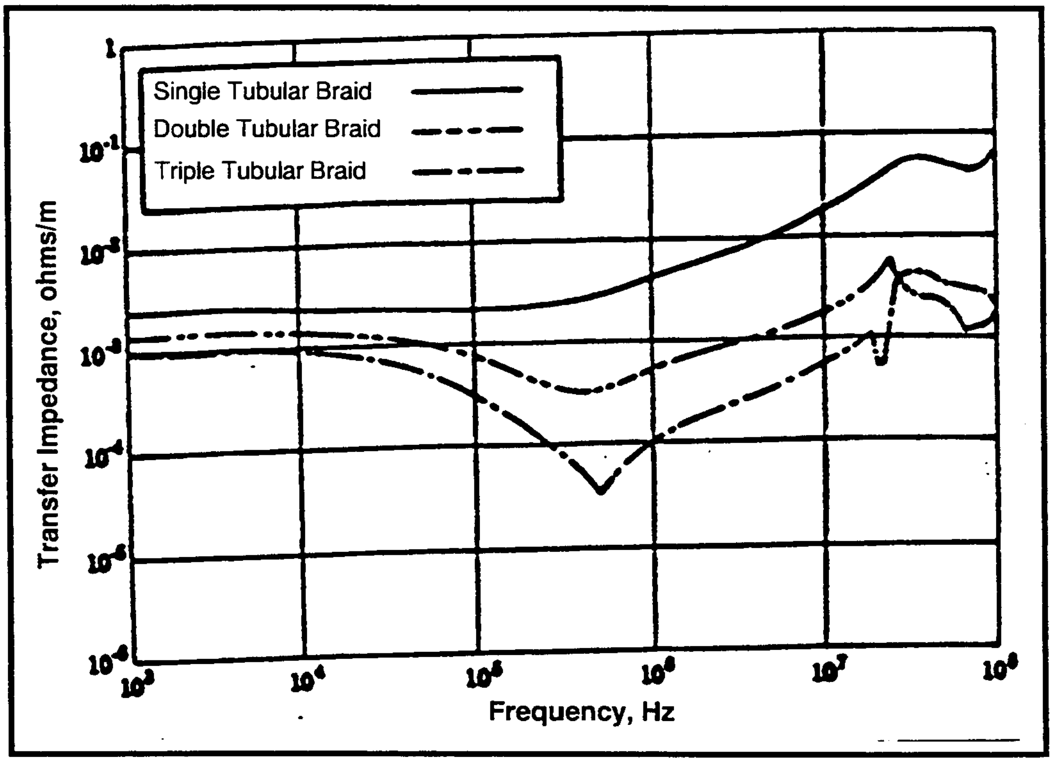


Figure 82. Transfer Impedance of Braided Shields

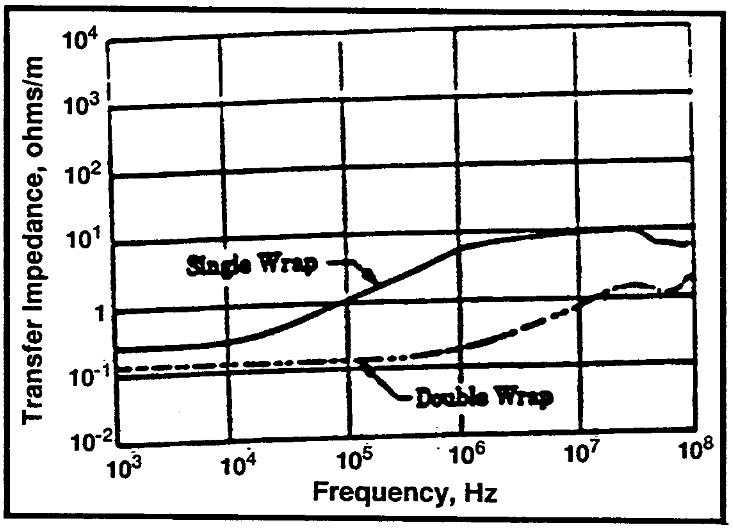


Figure 83. Transfer Impedance of Metallized Tape

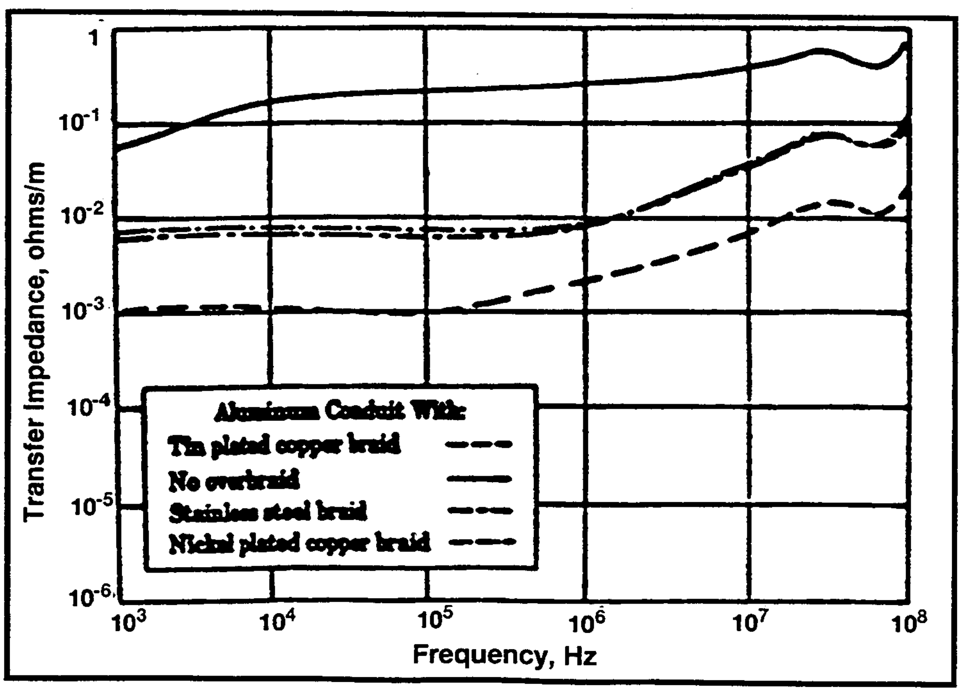


Figure 84. Transfer Impedance of Flexible Conduit

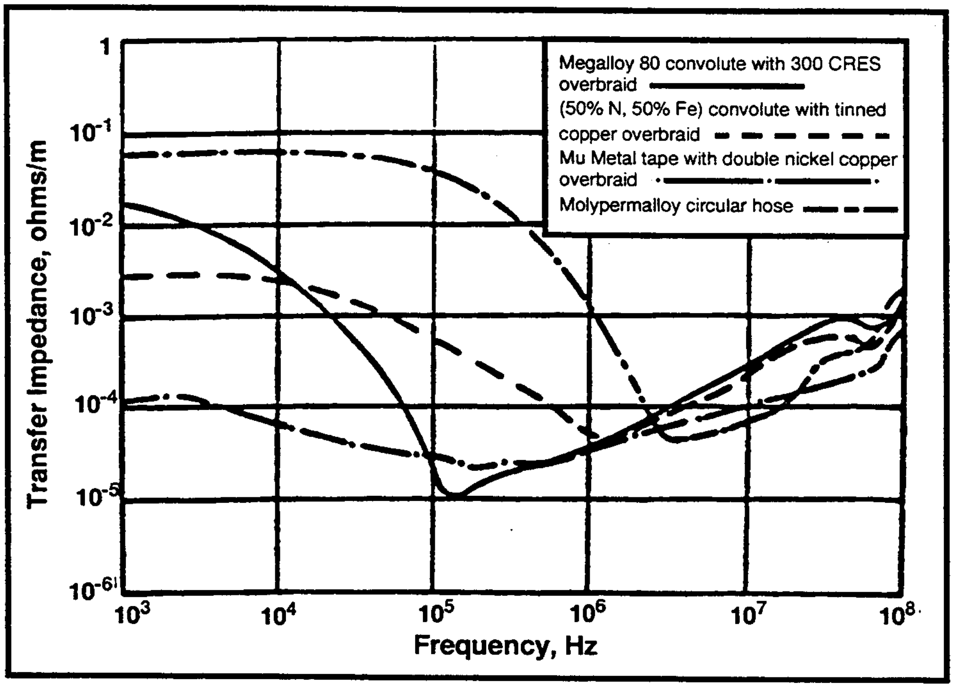


Figure 85. Transfer Impedance of Ferromagnetic Conduit

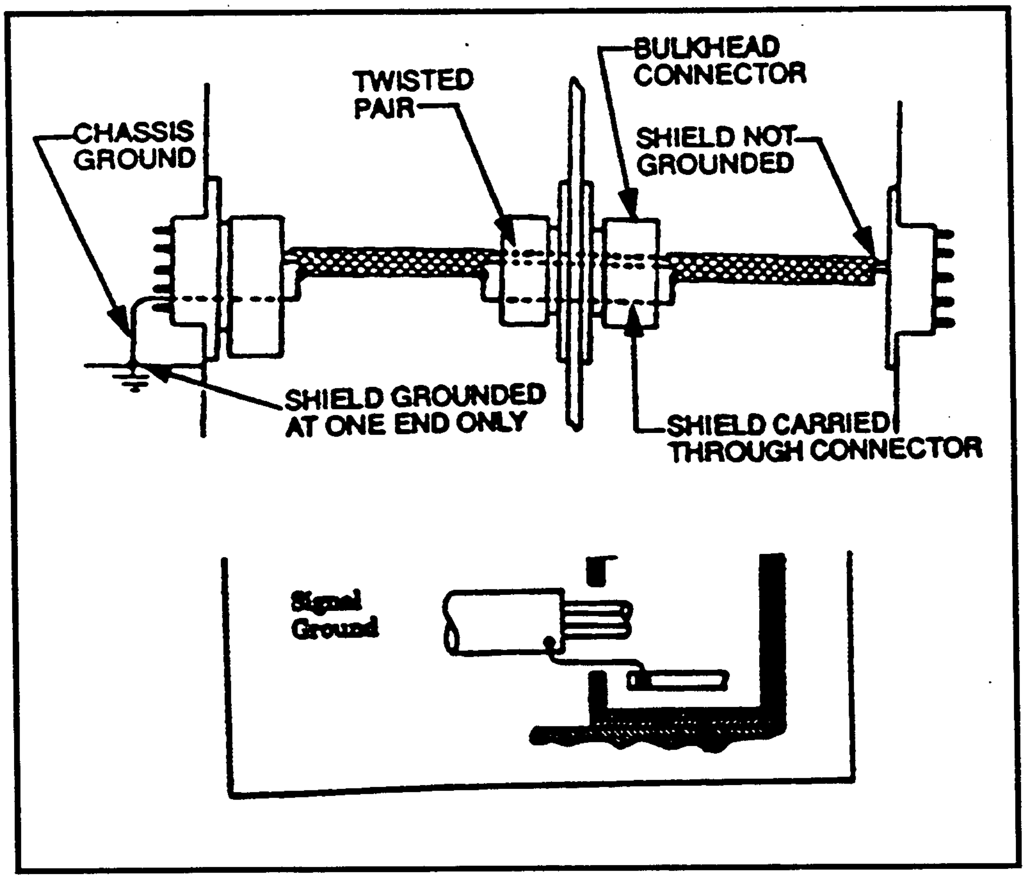


Figure 86. Internal Shield Termination for Audio Wires

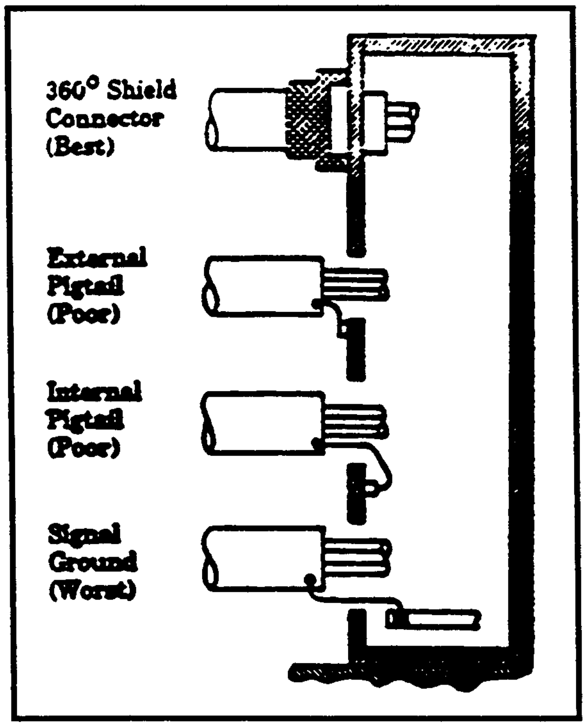


Figure 87. Shield Terminations - High Frequency/Transients

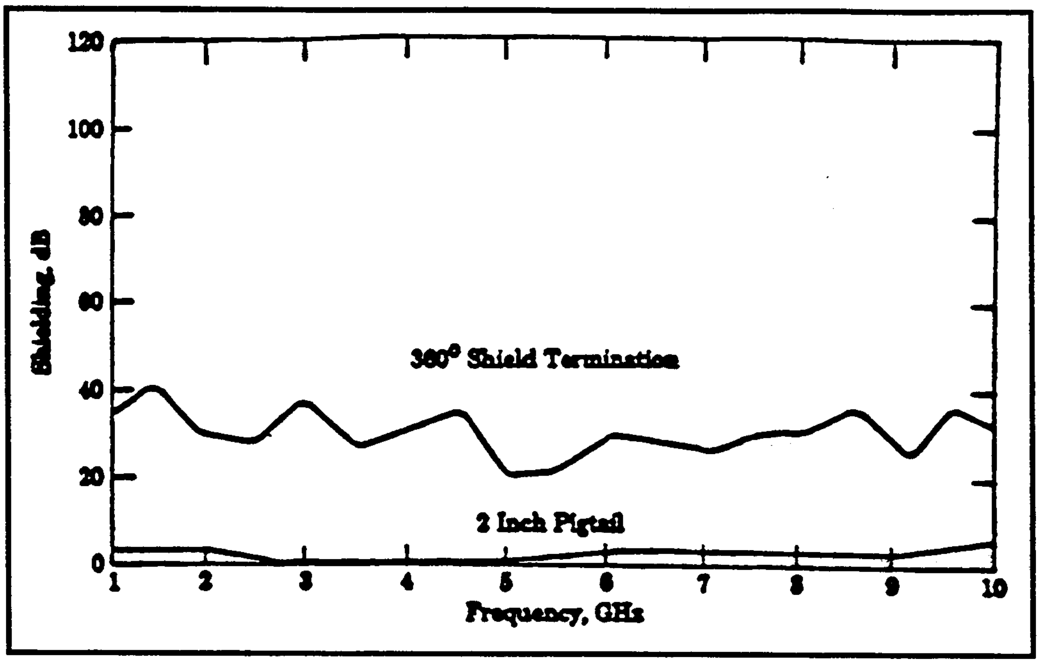
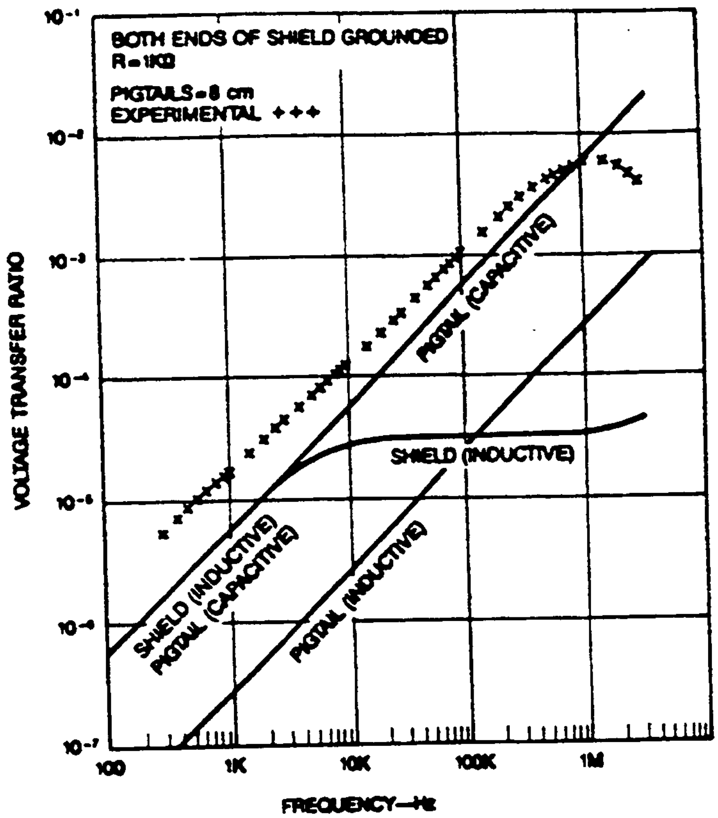
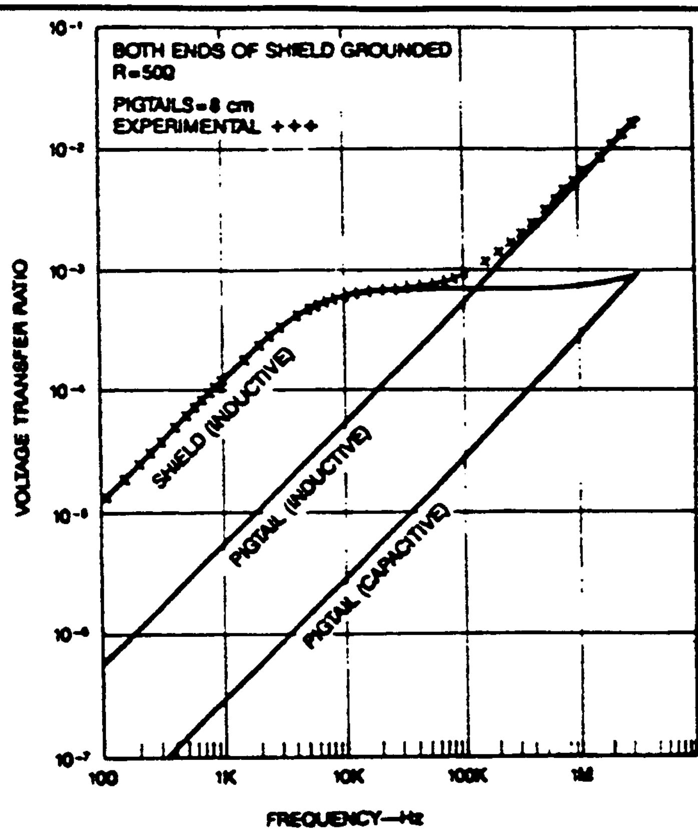


Figure 88. Effect of Pigtails on Shielding Effectiveness



Coupling to a 3.7m shielded cable with an 8cm pigtail termination.
Circuit termination equals 1000 Ω (from Paul, 1980, © IEEE).

Figure 89. Cable and Pigtail Coupling, 1000 Ω



Coupling to a 3.7m shielded cable with an 8cm pigtail termination.
Circuit termination equals 50 Ω (from Paul, 1980, © IEEE).

Figure 90. Cable and Pigtail Coupling, 50 Ω

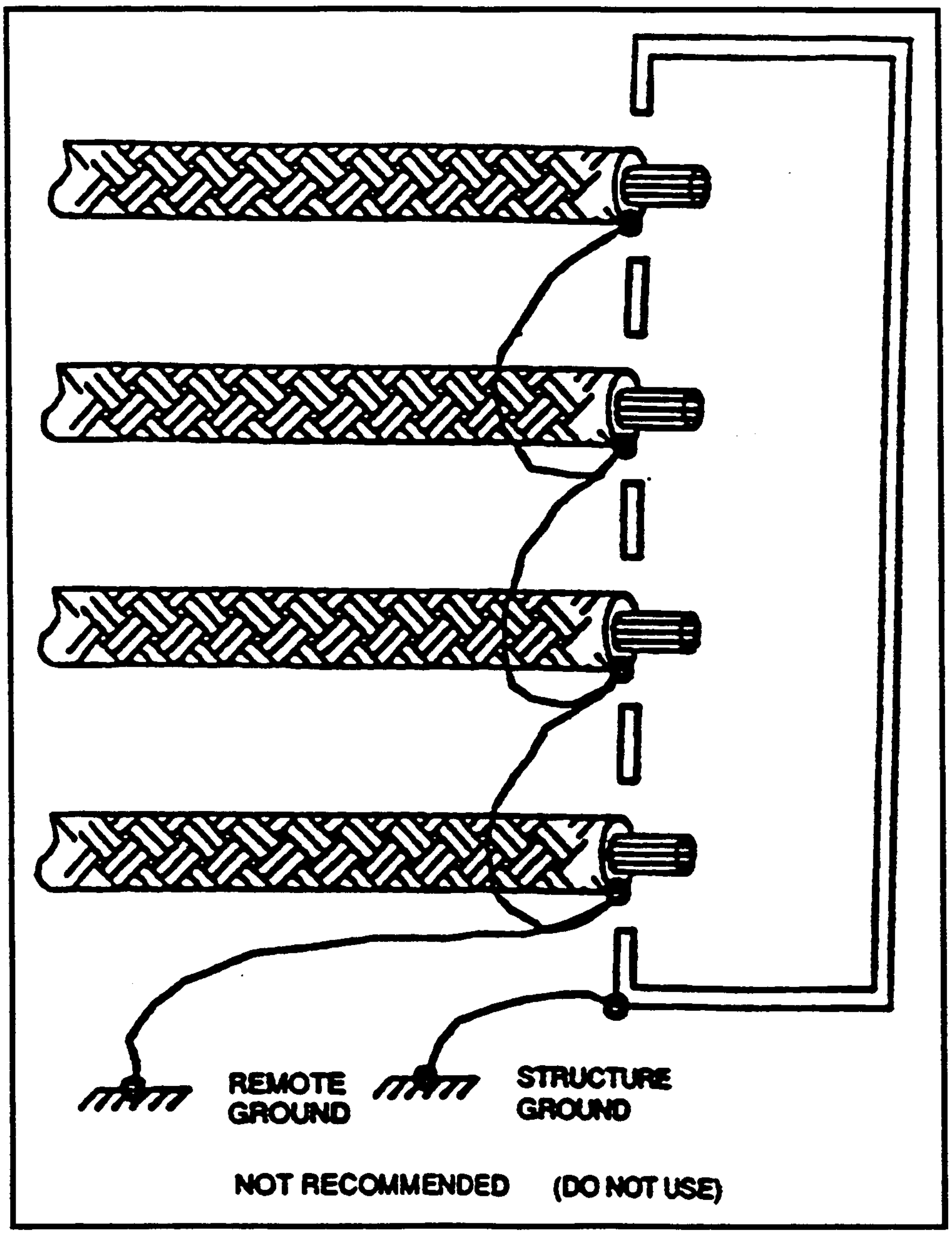


Figure 91. Daisy Chain Grounding

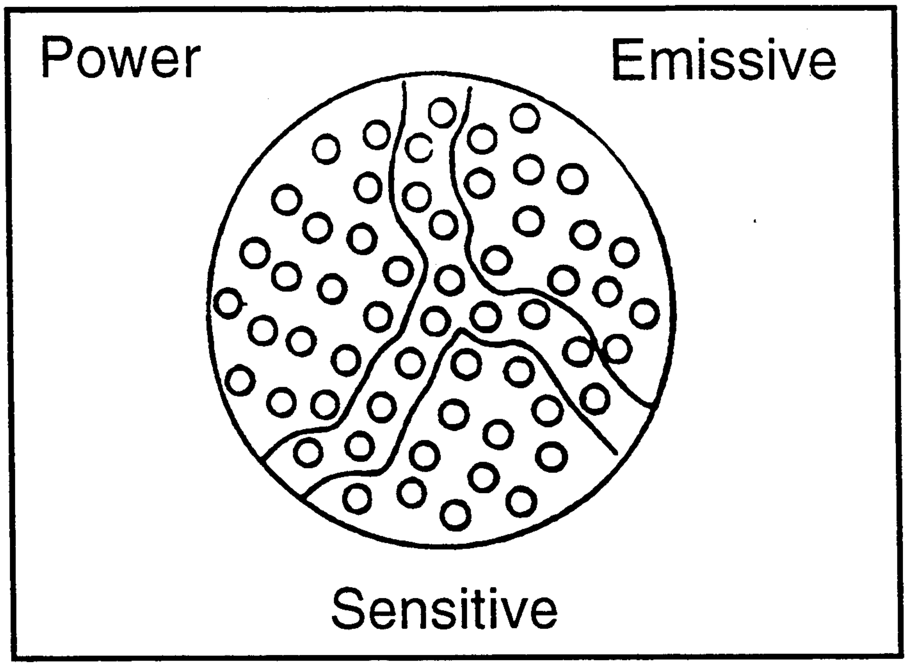


Figure 92. Example of Pin Allocation

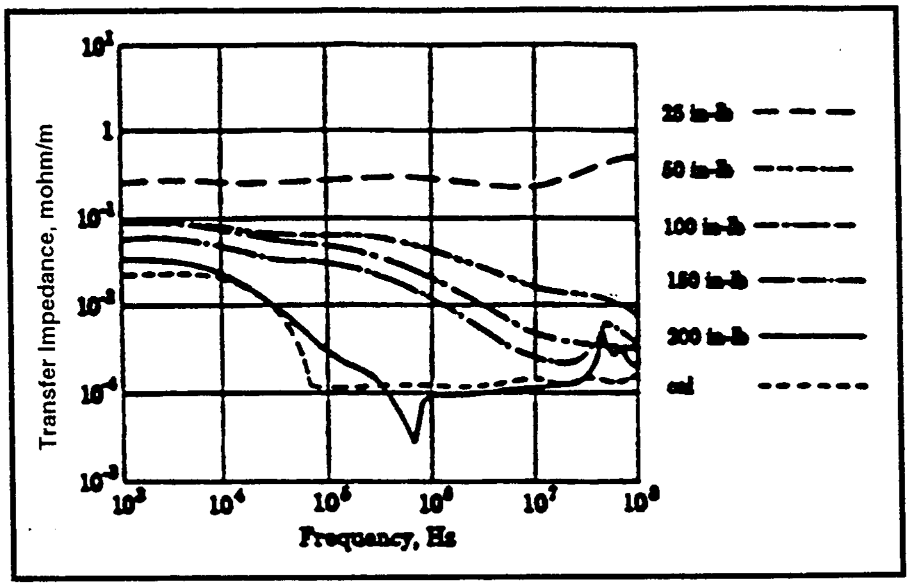


Figure 93. Effect of Connector Torque on Shielding Effectiveness

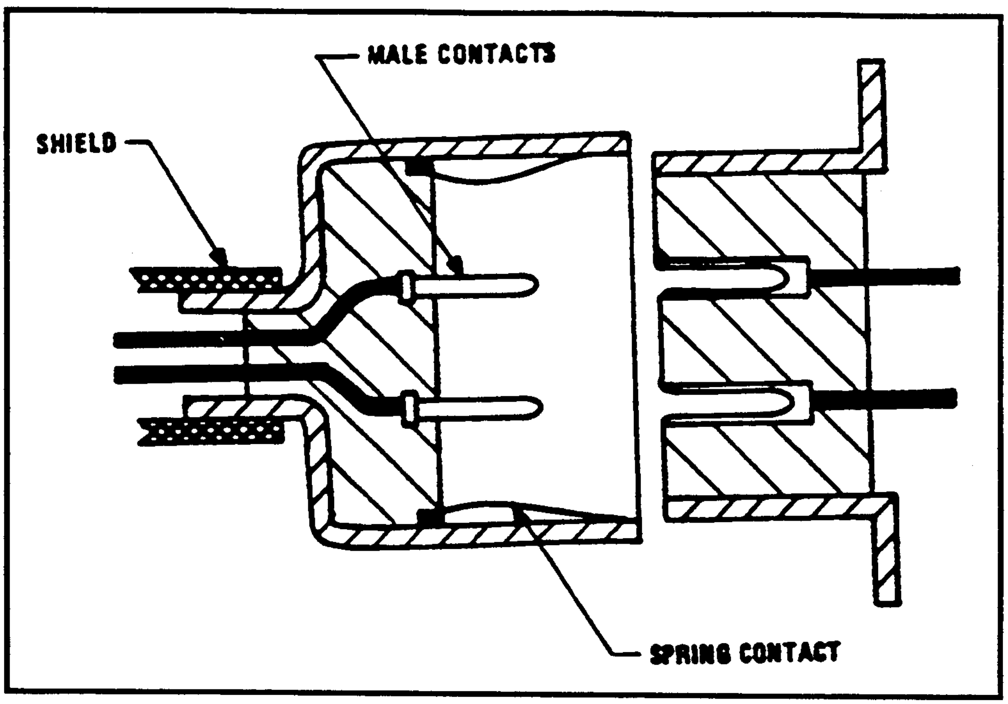
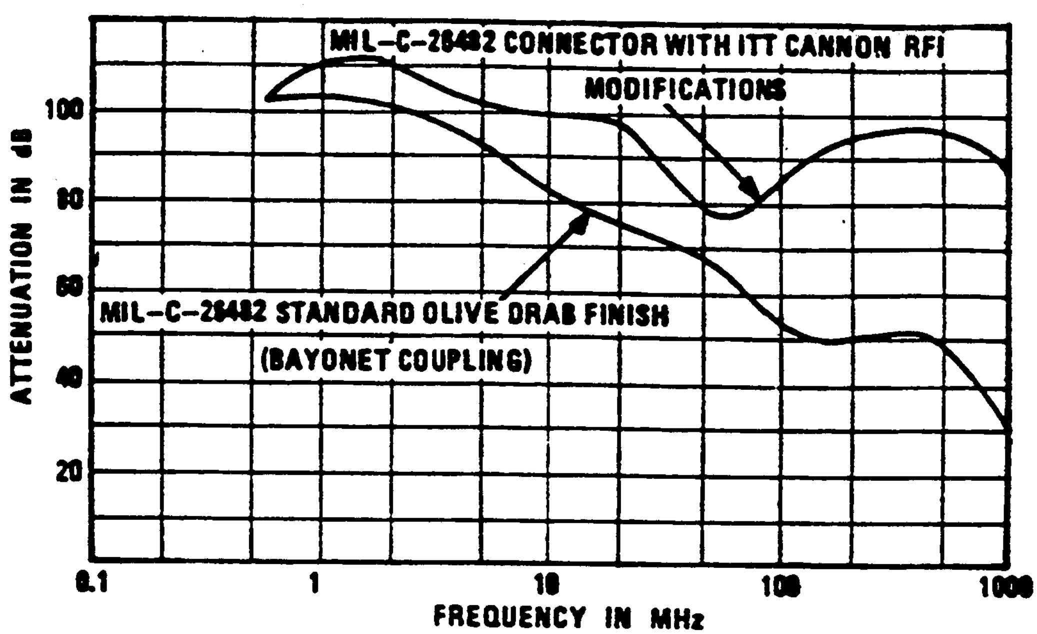


Figure 94. RF-Shielded Connector



Effectiveness of Circumferential Spring Fingers for Improving the Shielding of a Connector

Figure 95. Shielding Effectiveness of a Connector

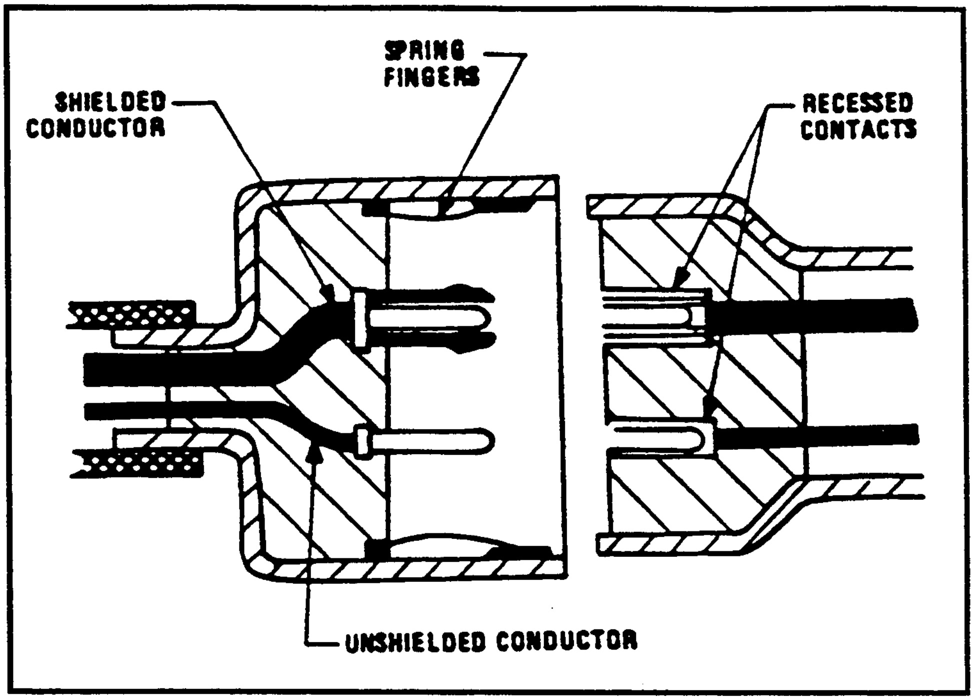
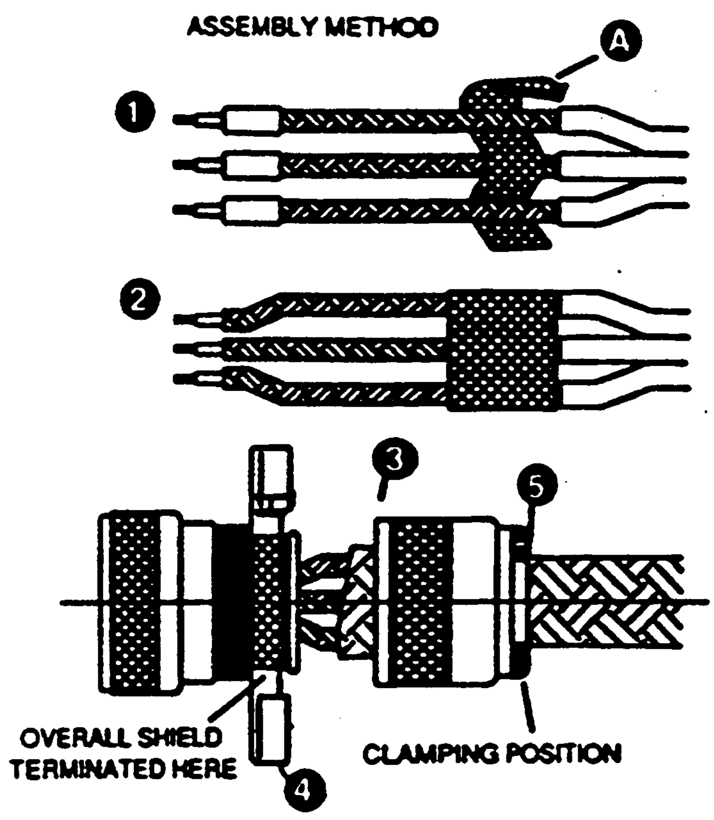


Figure 96. Connector for a Shield Within a Shield



1. Interwoven braid is passed between the exposed individual cable shields.
2. The cables are wrapped into a circular bundle with the mesh material.
3. The wrapped bundle area is positioned under the integral clamp arms of the adaptor, the rear nut is rotated until the shield termination is grounded inside the adaptor.
4. The overall shield is terminated to the adaptor using a banding clamp.
5. The strain relief clamp is attached to the adaptor with the clamping arms in contact with the overall sheild.

Figure 97. Assembly Procedure

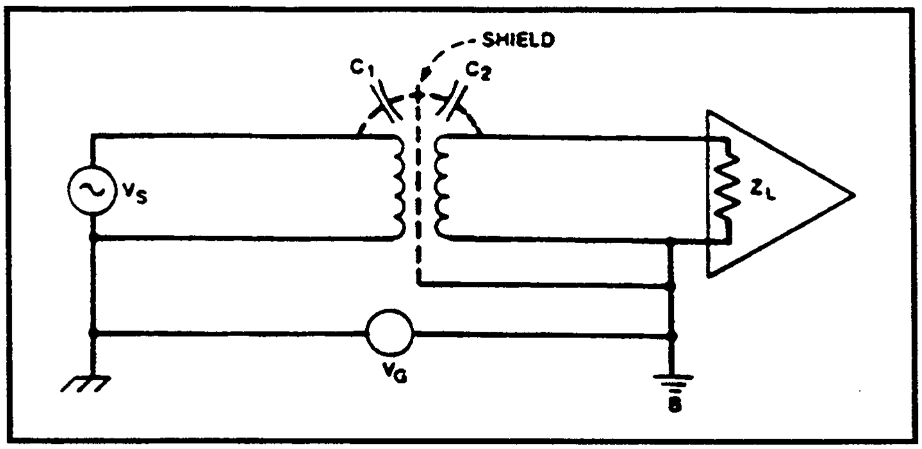


Figure 98. Grounded Electrostatic Shield Between Transformer Windings Breaks the Capacitive Coupling

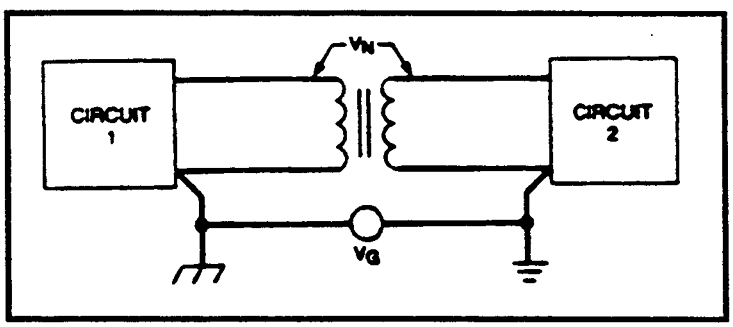


Figure 99. Ground Loop Between Two Circuits can be Broken by Inserting a Transformer

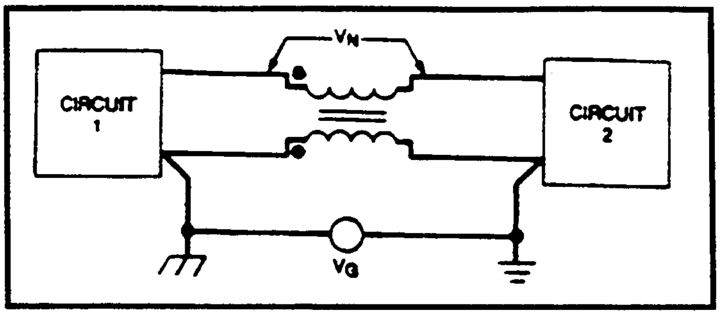


Figure 100. Ground Loop Between Two Circuits can be Broken by Inserting a Common-mode Choke

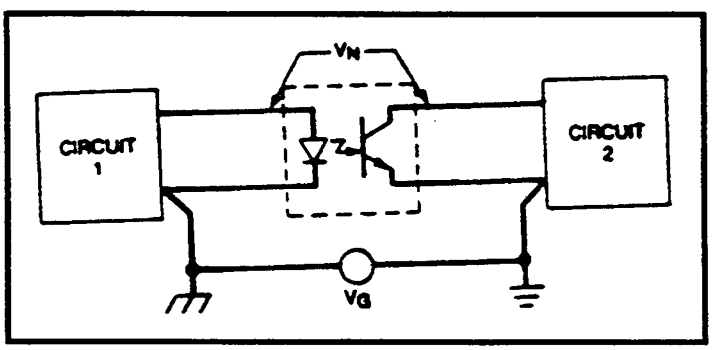


FIGURE 101. An Optical Coupler can be used to Break the Ground Loop Between Two Circui

t

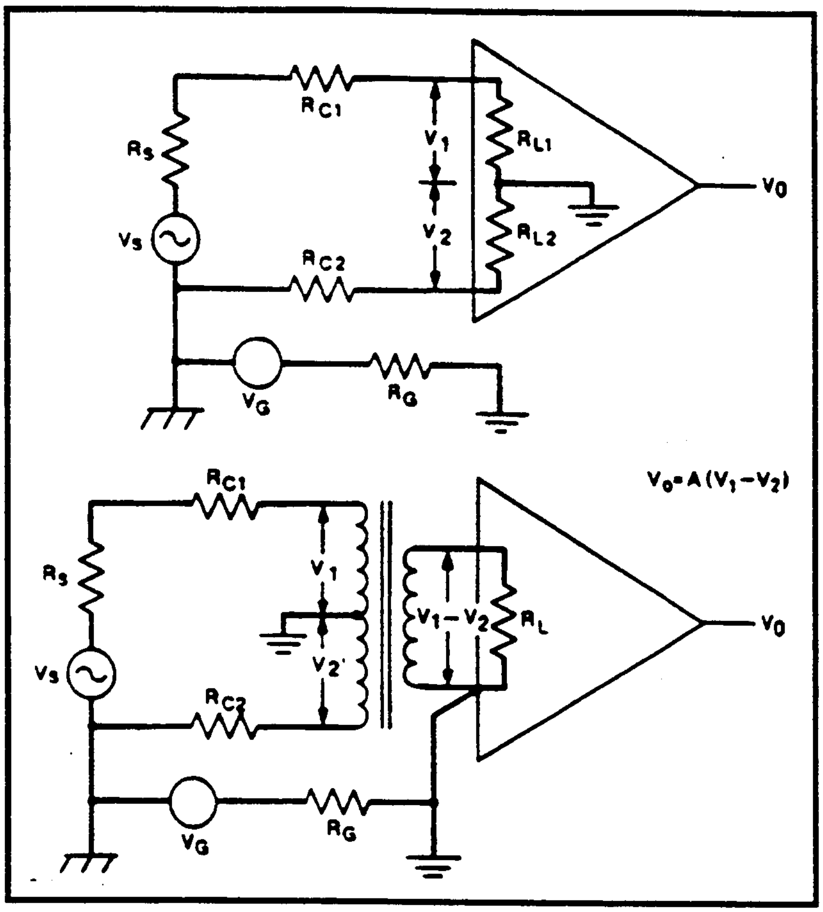


Figure 102. Differential Amplifier

A differential amplifier - or a single-ended amplifier with transformer can be used to reduce the effects of a common-mode noise voltage.

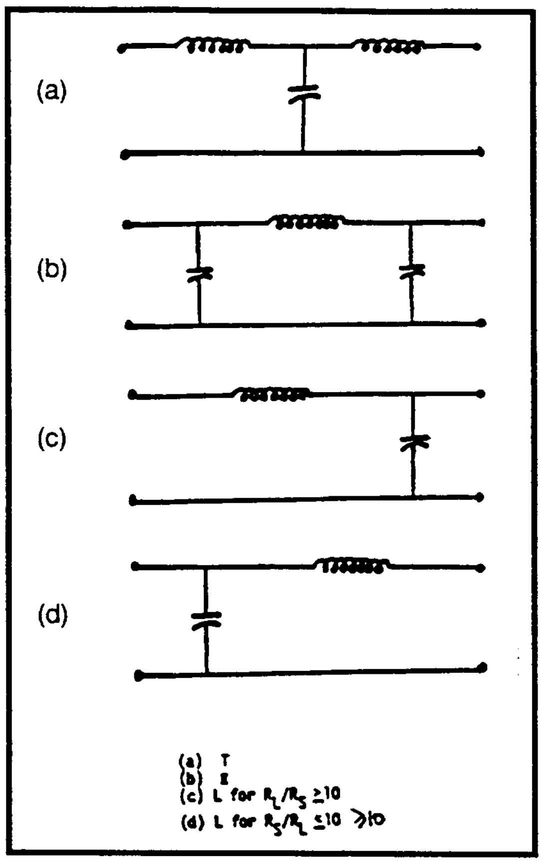


Figure 103. Filter Sections

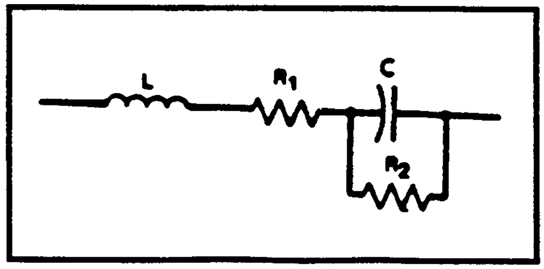


Figure 104. Equivalent Circuit for a Capacitor

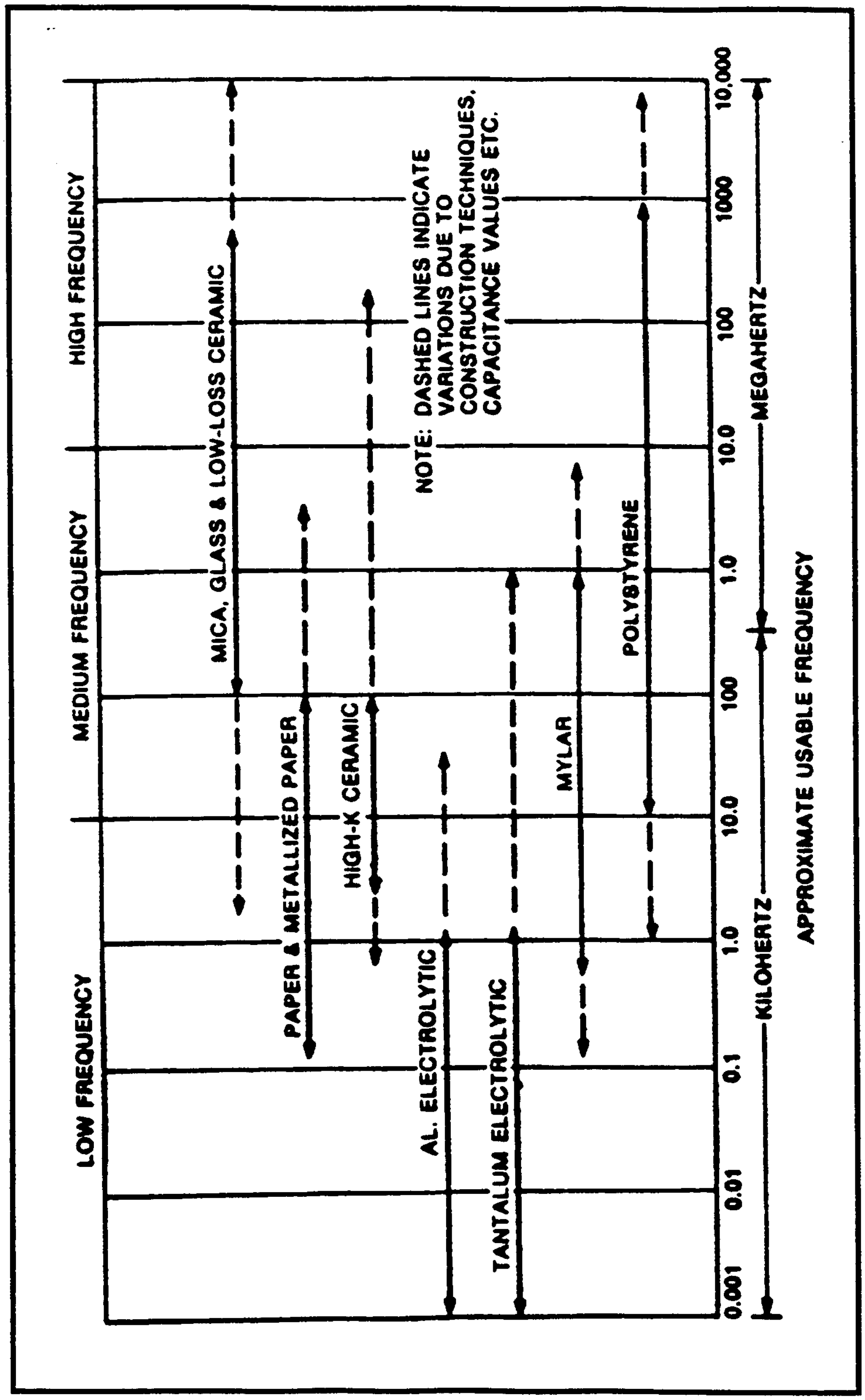

LOW FREQUENCY
MEDIUM FREQUENCY
HIGH FREQUENCY
MICA, GLASS & LOW-LOSS CERAMIC
PAPER & METALLIZED PAPER
HIGH-K CERAMIC
AL. ELECTROLYTIC
NOTE: DASHED LINES INDICATE VARIATIONS DUE TO CONSTRUCTION TECHNIQUES, CAPACITANCE VALUES ETC.
TANTALUM ELECTROLYTIC
MYLAR
POLYSTYRENE
0.001
0.01
0.1
1.0
10.0
100
1.0
10.0
100
1000
10,000
KILOHERTZ
MEGAHERTZ
APPROXIMATE USABLE FREQUENCY

Figure 105. Approximate Usaable Frequency Ranges for Various Types of Capacitors

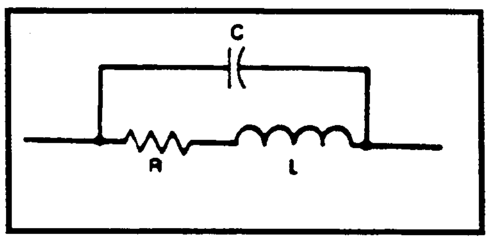


Figure 106. Equivalent Circuit for an Inductor

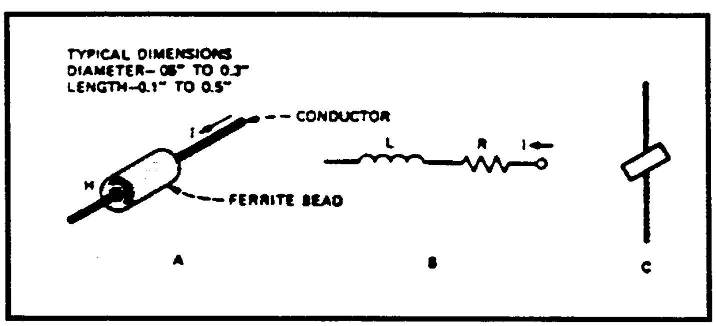


Figure 107. Ferrite Bead on Conductor; High-Frequency Equivalent Circuit; and Typical Schematic Symbol

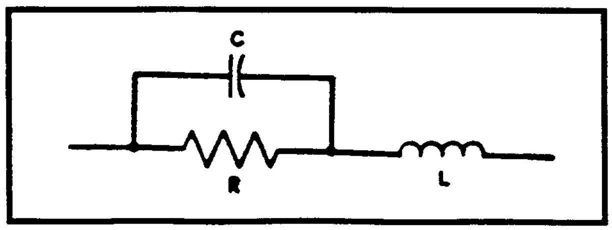


Figure 108. Equivalent Circuit for a Resistor

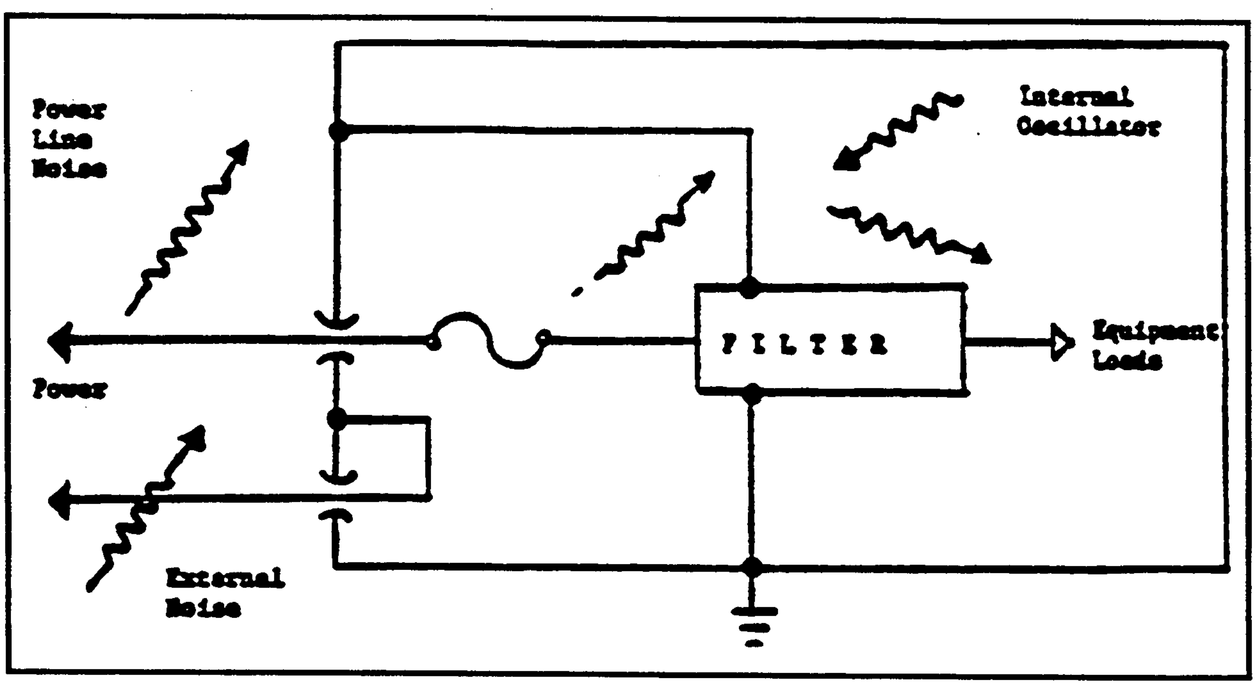


Figure 109. Good Filter Installation

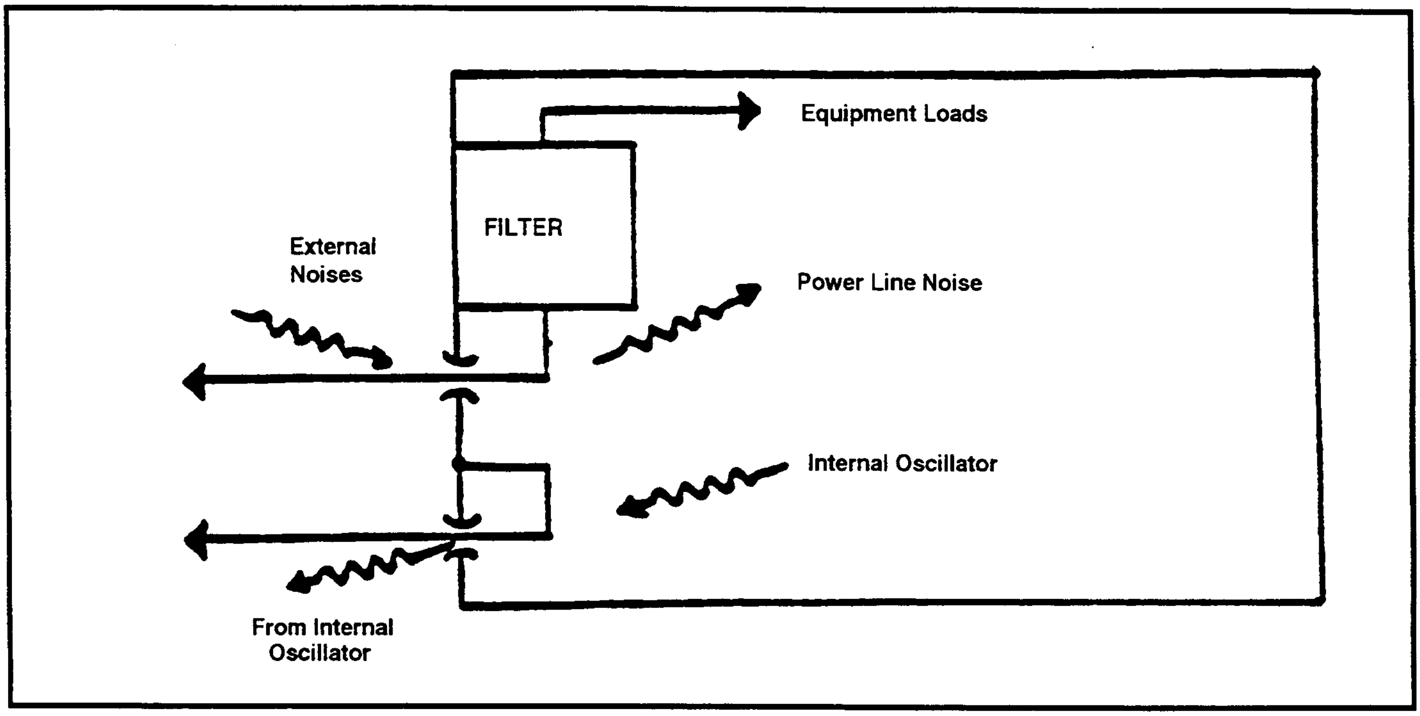


Figure 110. Poor Filter Installation

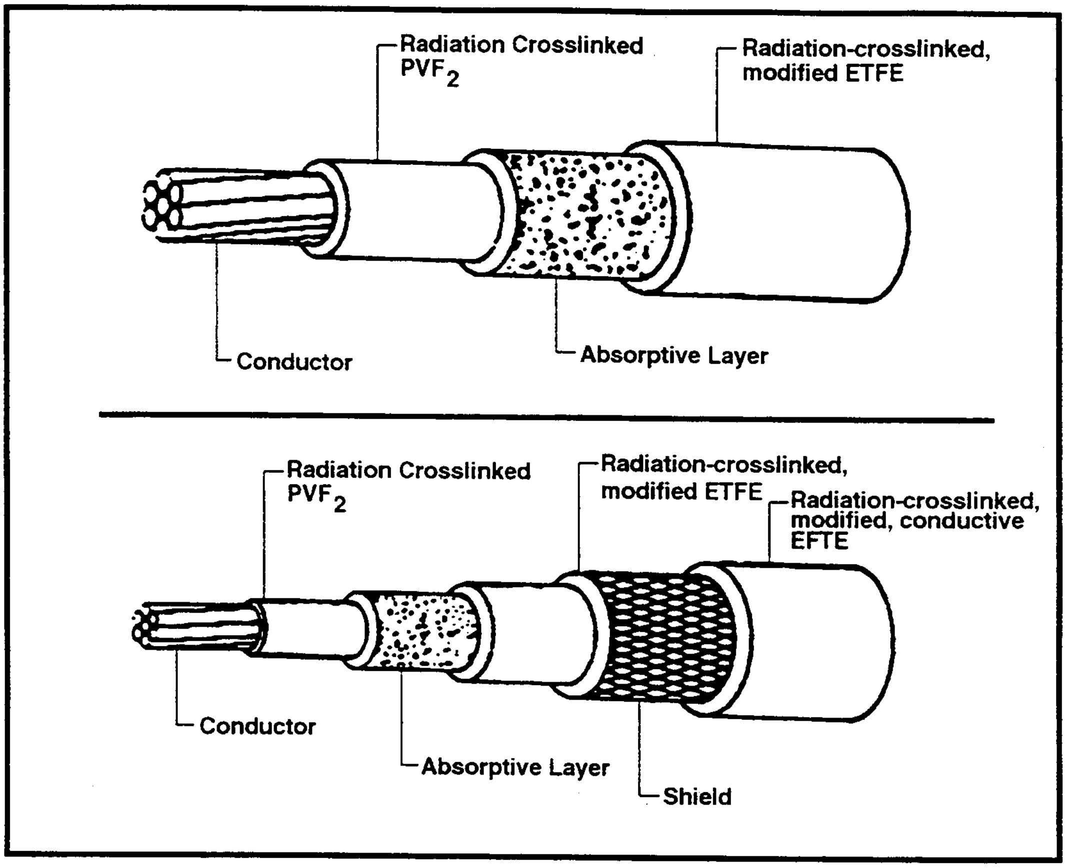


Figure 111. Lossy Line Wiring

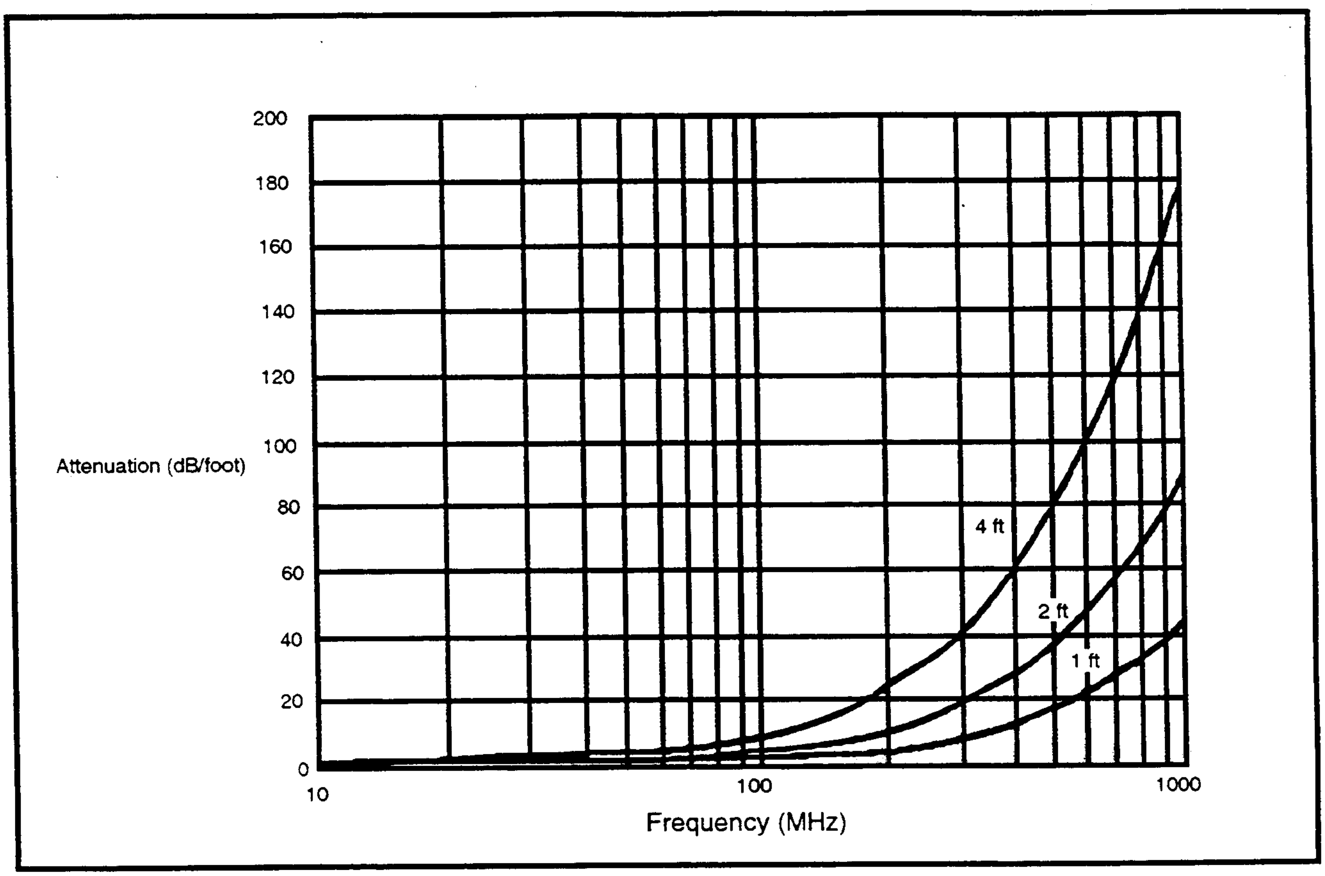


Figure 112. Typical Insertion of Lossy Line Wire

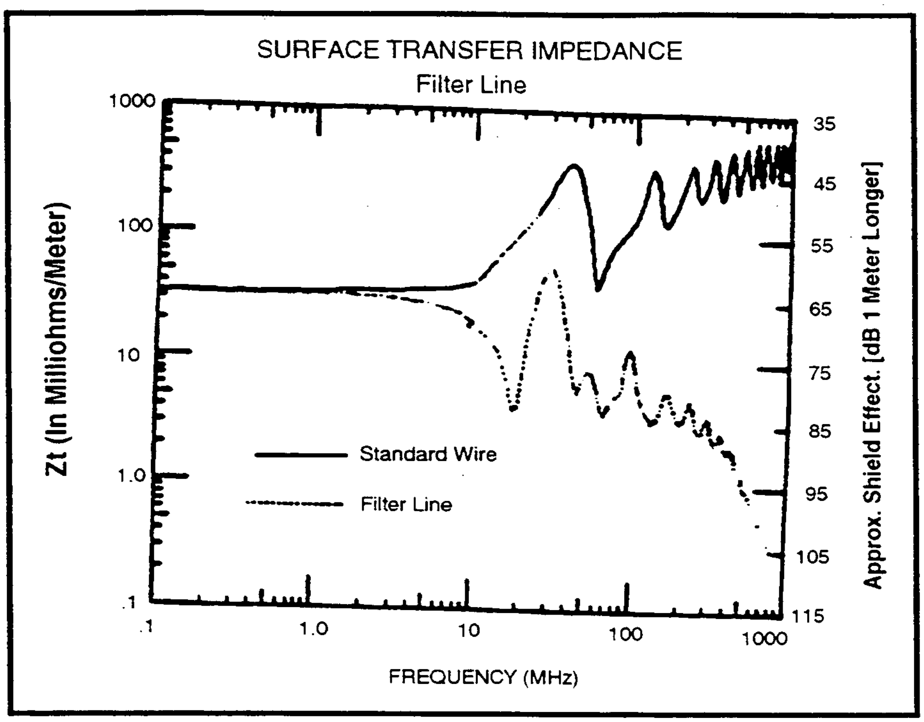


Figure 113. Surface Tansfer Impedance

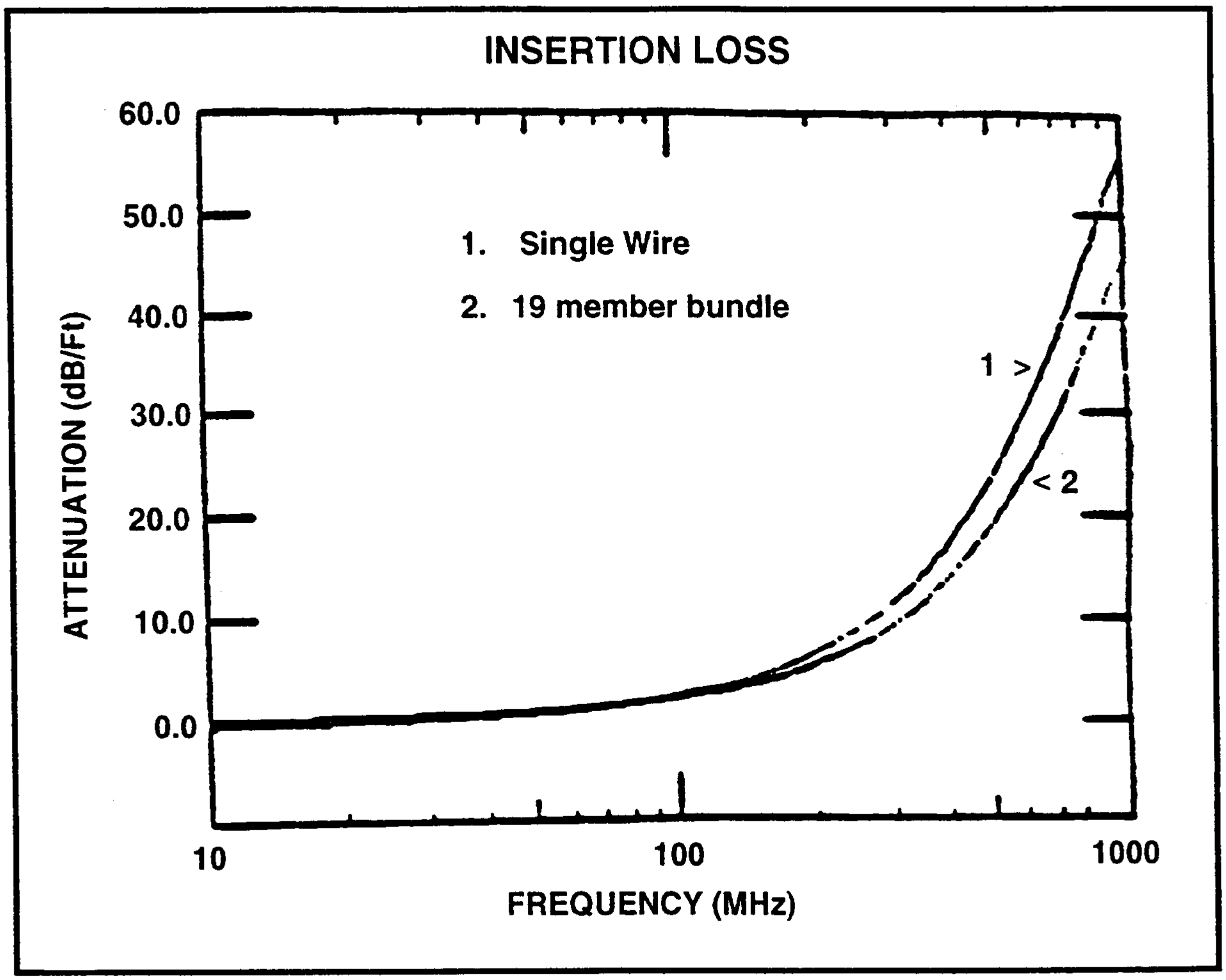


Figure 114. Attenuation Comparison

1: Single Shielded and Jacketed Filter Line Cable.
2: One of Nineteen Member Shielded Filter Line Bundle

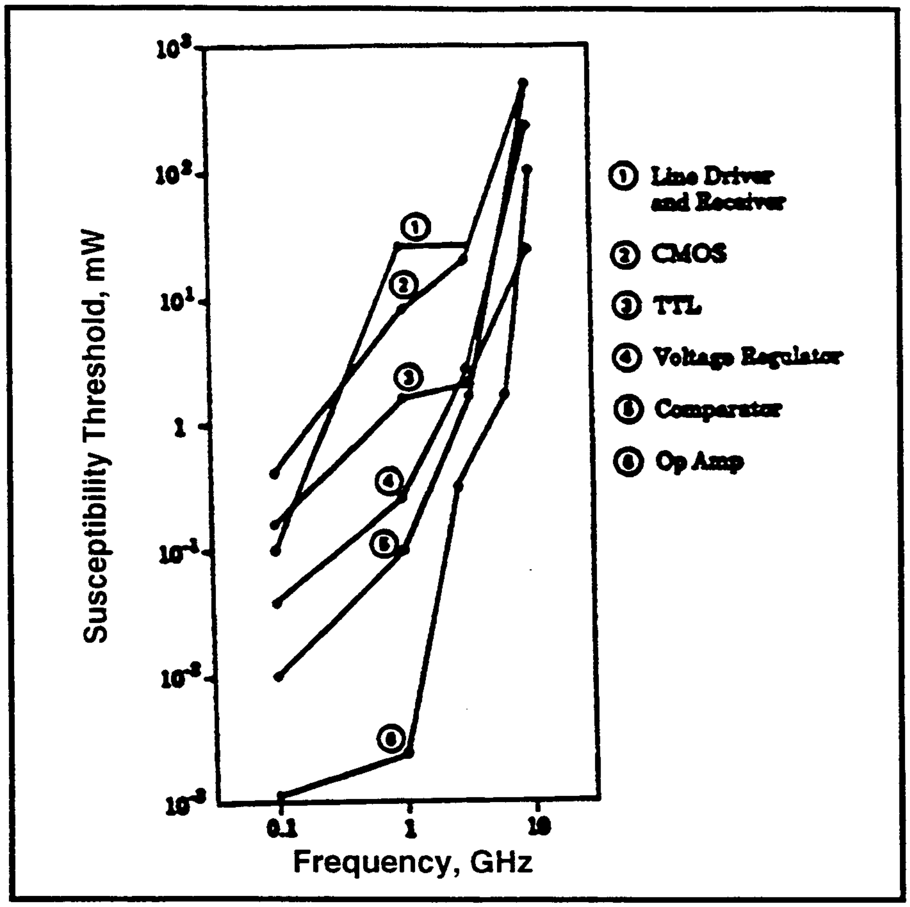


Figure 115. Susceptibility Thresholds of Semiconductor Devices

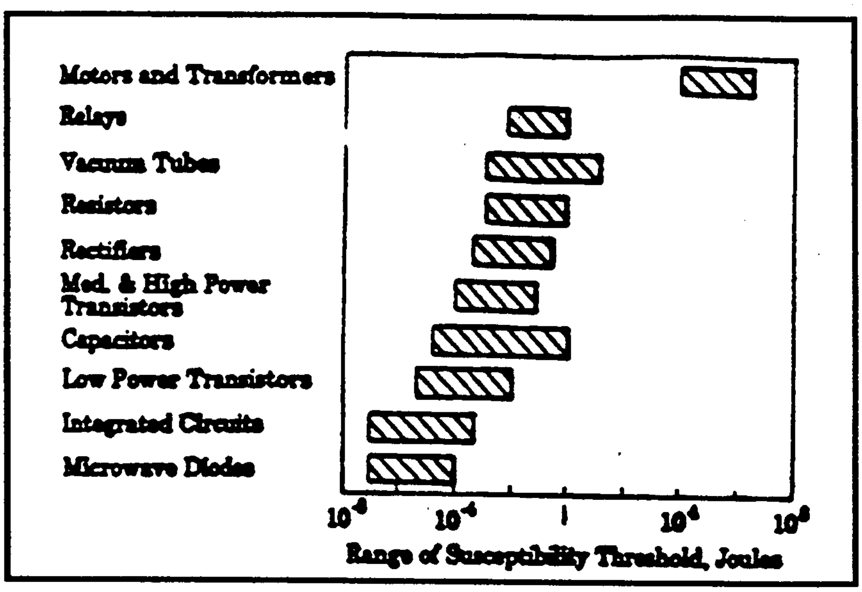


Figure 116. Susceptibility of Common Devices

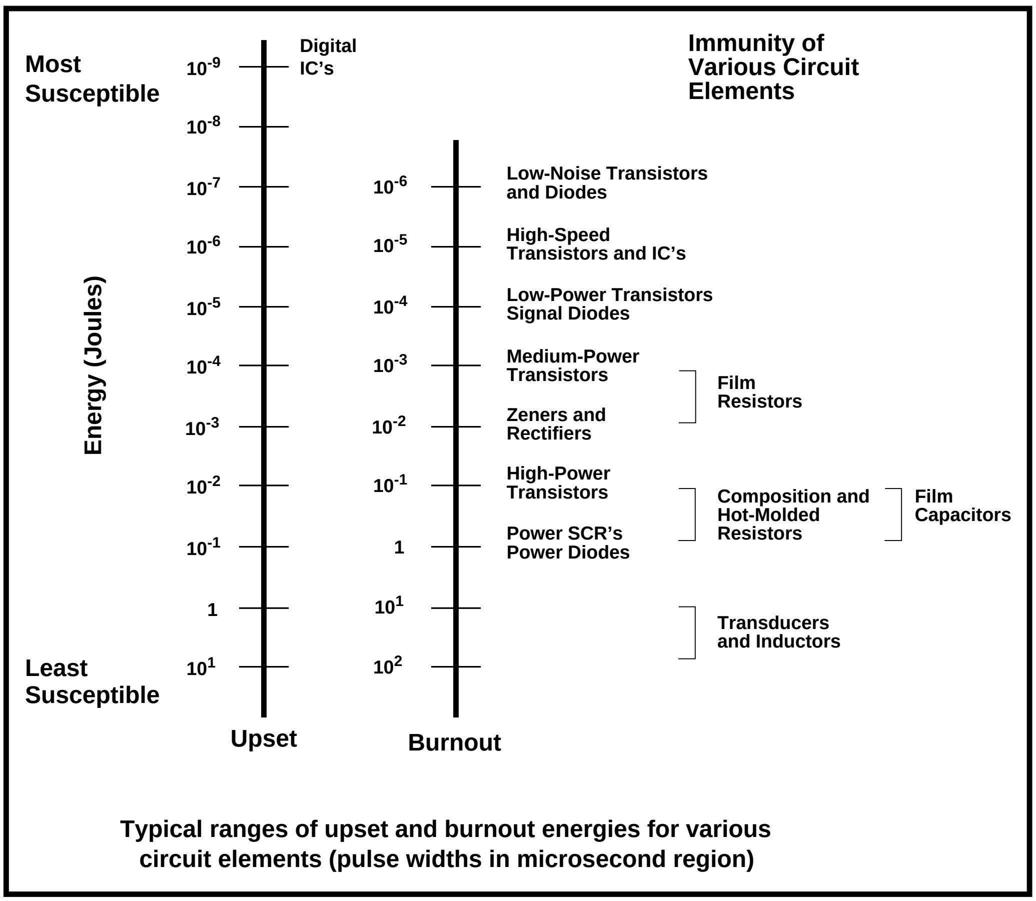


Figure 117. Upset and Damage Thresholds for Electronic Devices

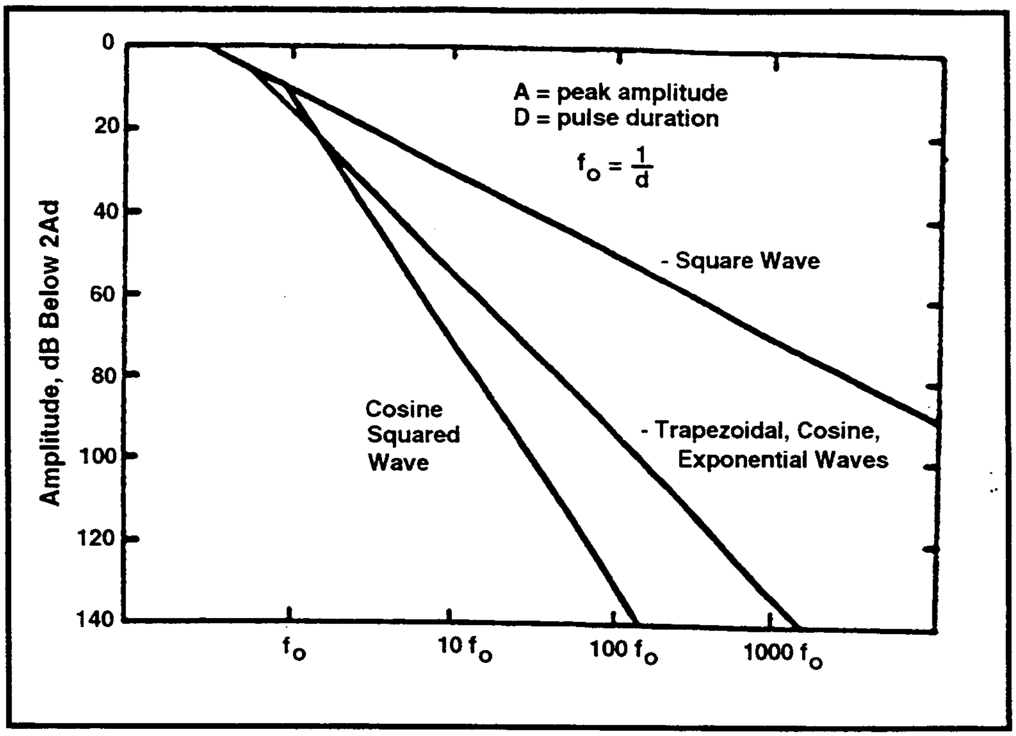


Figure 118. Spectra of Common Waveforms

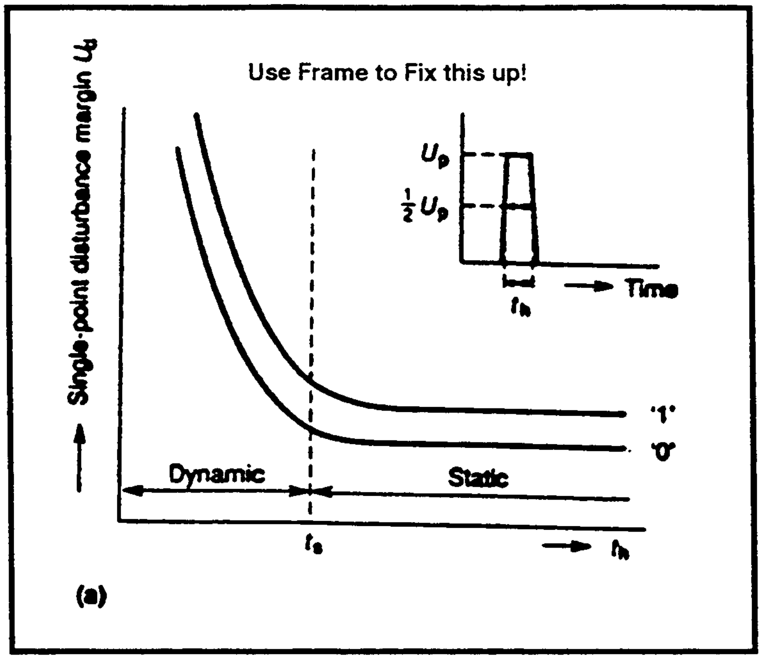


Figure 119. Dynamic and Static Disturbance Margin

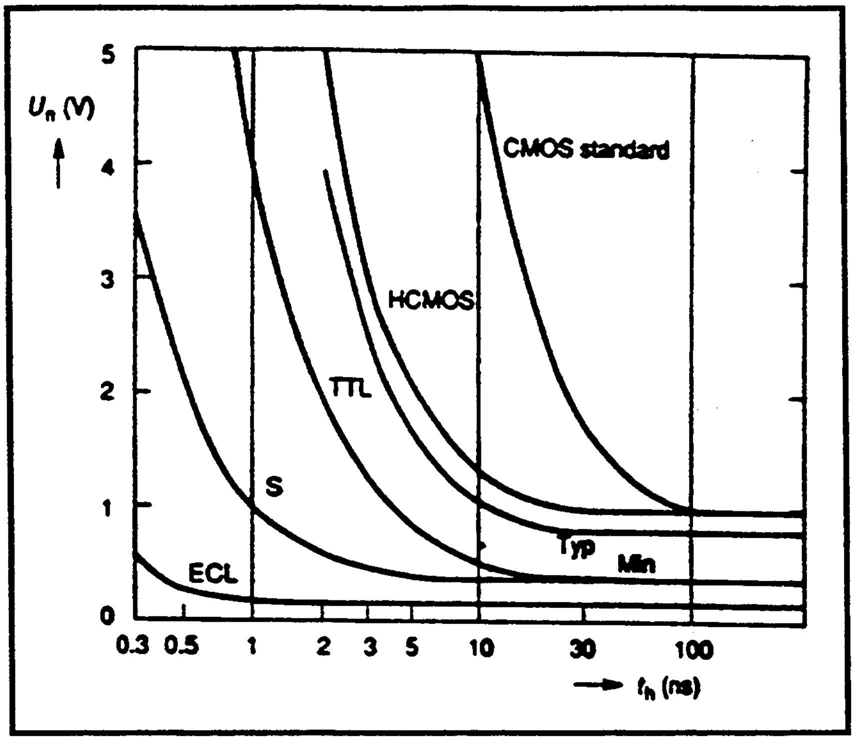


Figure 120. Disturbance Margins for Various Families of Logic Components

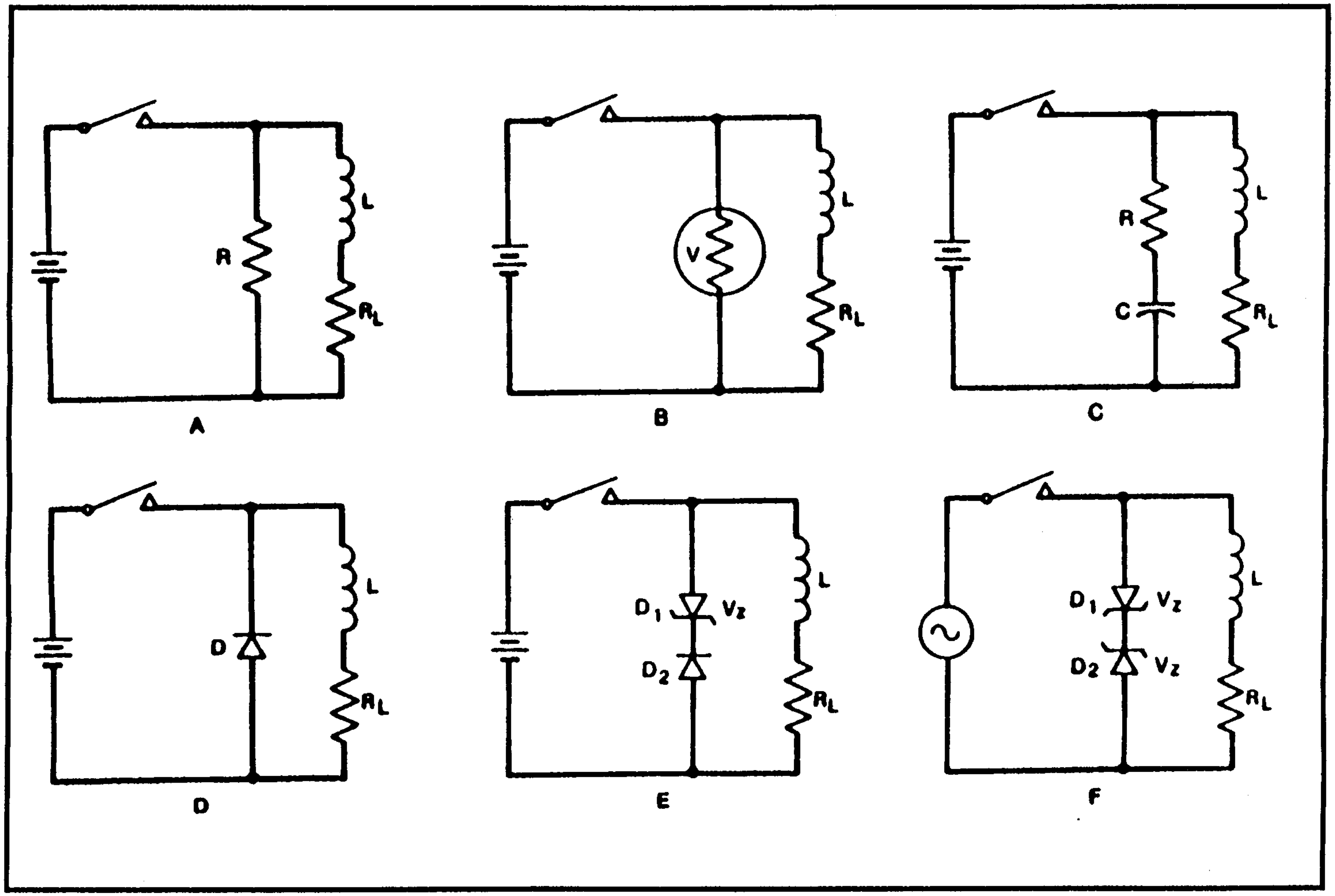


Figure 121. Networks Used Across Load to Minimize "Inductive Kick" Produced by an Inductor When the Current is Interrupted

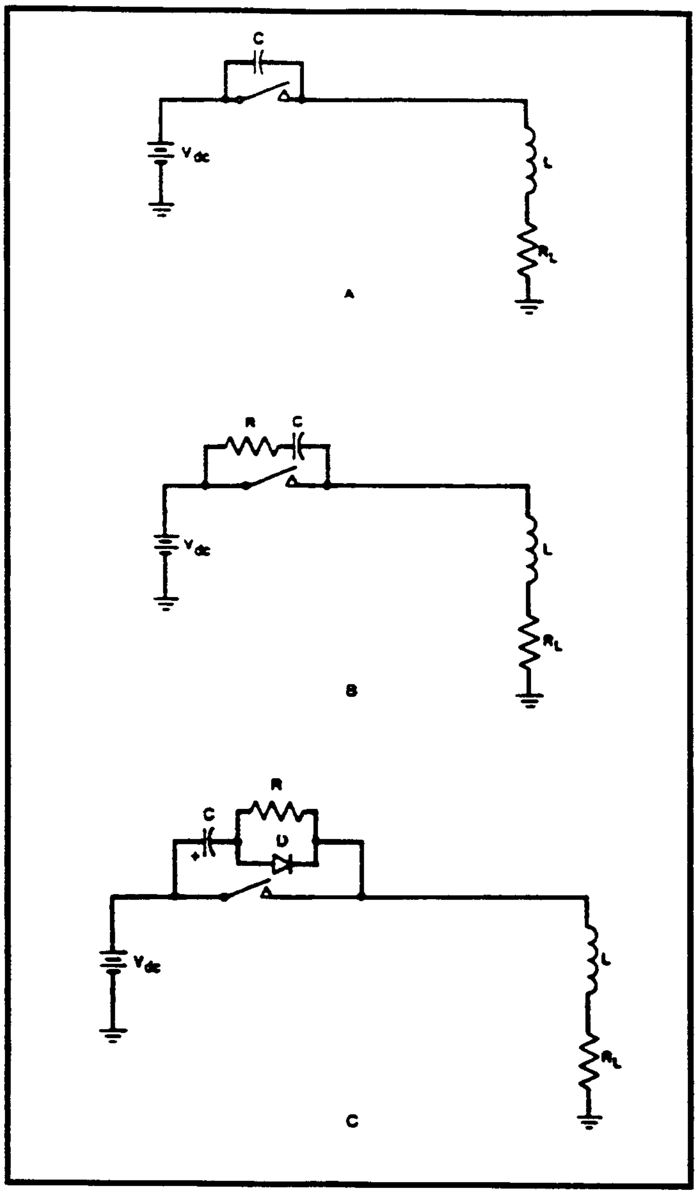


Figure 122. Contact Protection Networks Used Across switch Contact

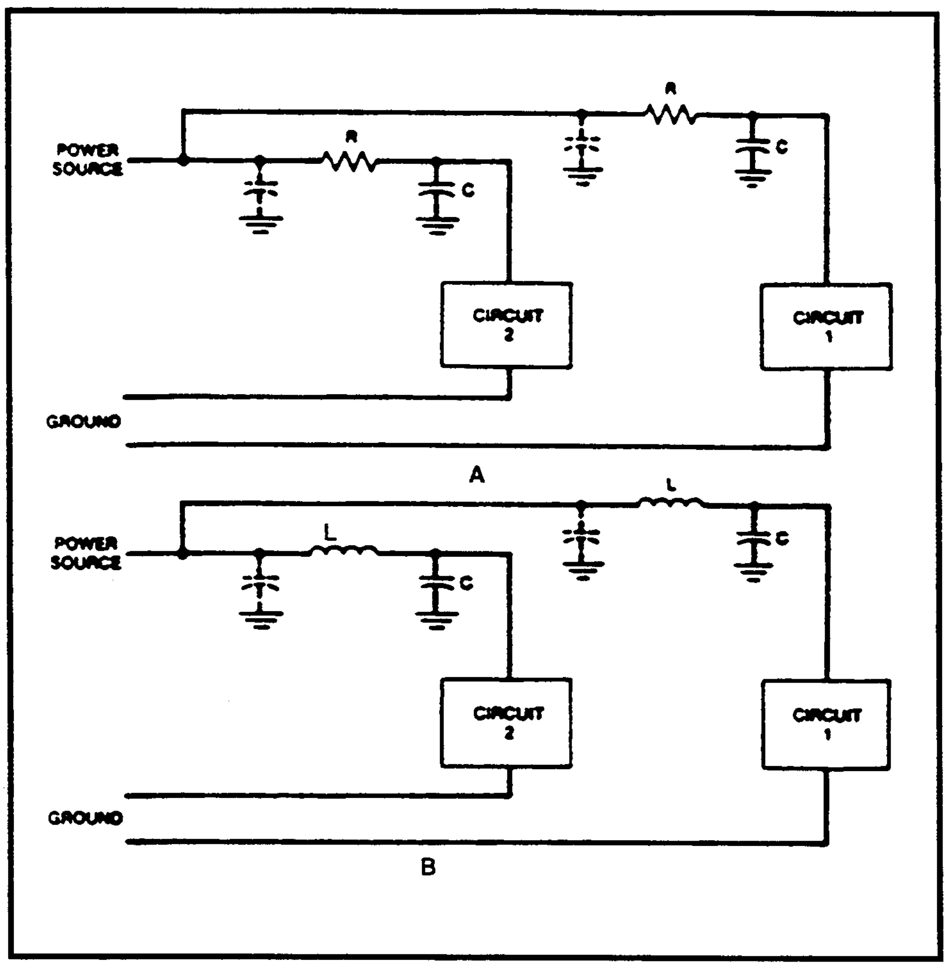
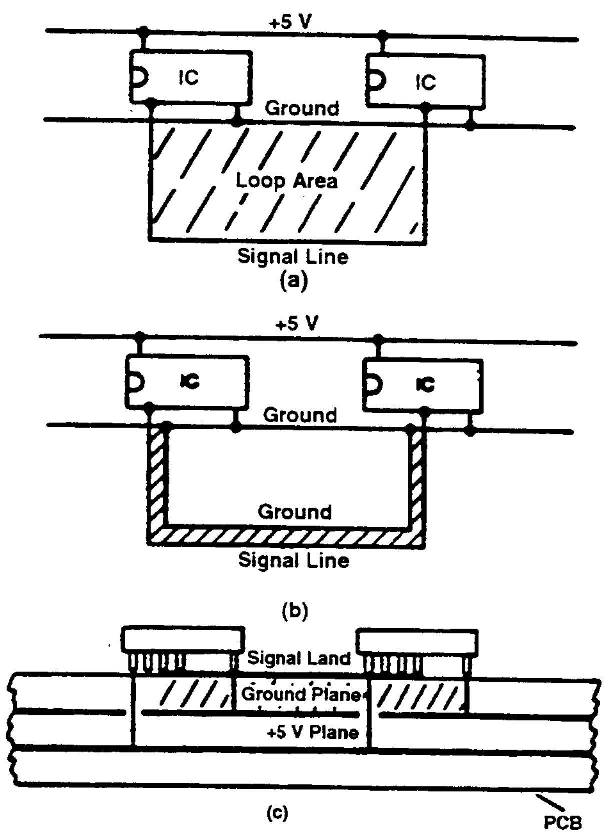
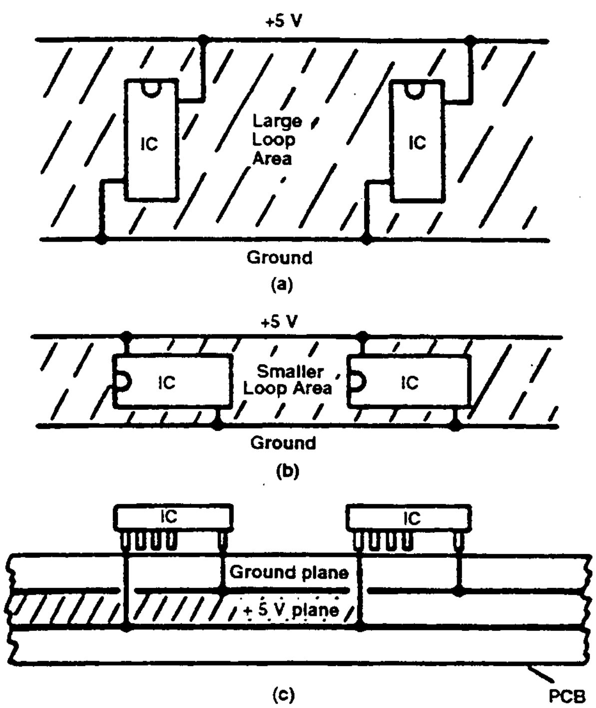


Figure 123. Circuit Decoupling with; (A) Resistance-Capacitance and (B) Inductance-Capacitance Decoupling Networks



Reduction of loop areas to reduce the pickup of signal lines:
(a) large signal-return area;
(b) smaller loop area using a dedicated return;
(c) use of an innerplane (multilayer) board to reduce the loop area of the signal-return path.

Figure 124. Methods of Loop Area Reduction



Reduction of loop area in power distribution circuits to reduce pickup of ESD field:

(a) large loop area;

(b) smaller loop area;

(c) use of an innerplane (multilayer) board to reduce the loop area and the characteristic impedance of the power distribution circuit.

Figure 125. Reduction of Loop Area in Power Distribution Circuits

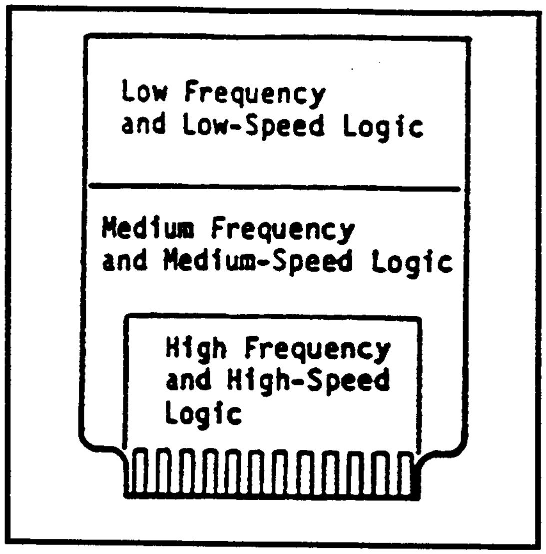


Figure 126. Functional Layout Guidelines

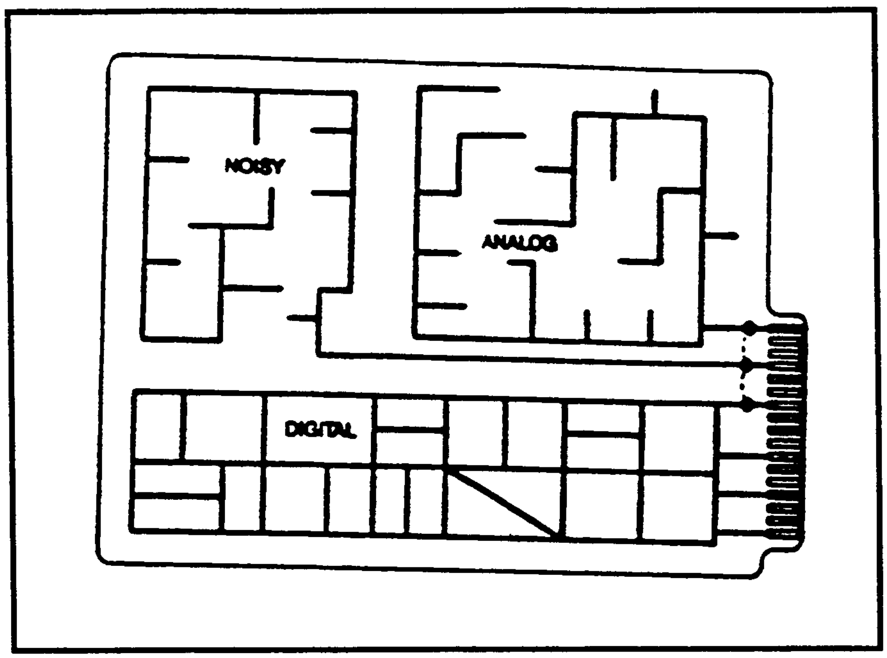


Figure 127. Printed Wiring Board With Three Separate Ground Systems: One for the digital logic, one for the low-level analog circuits and one for "noisy" circuits.

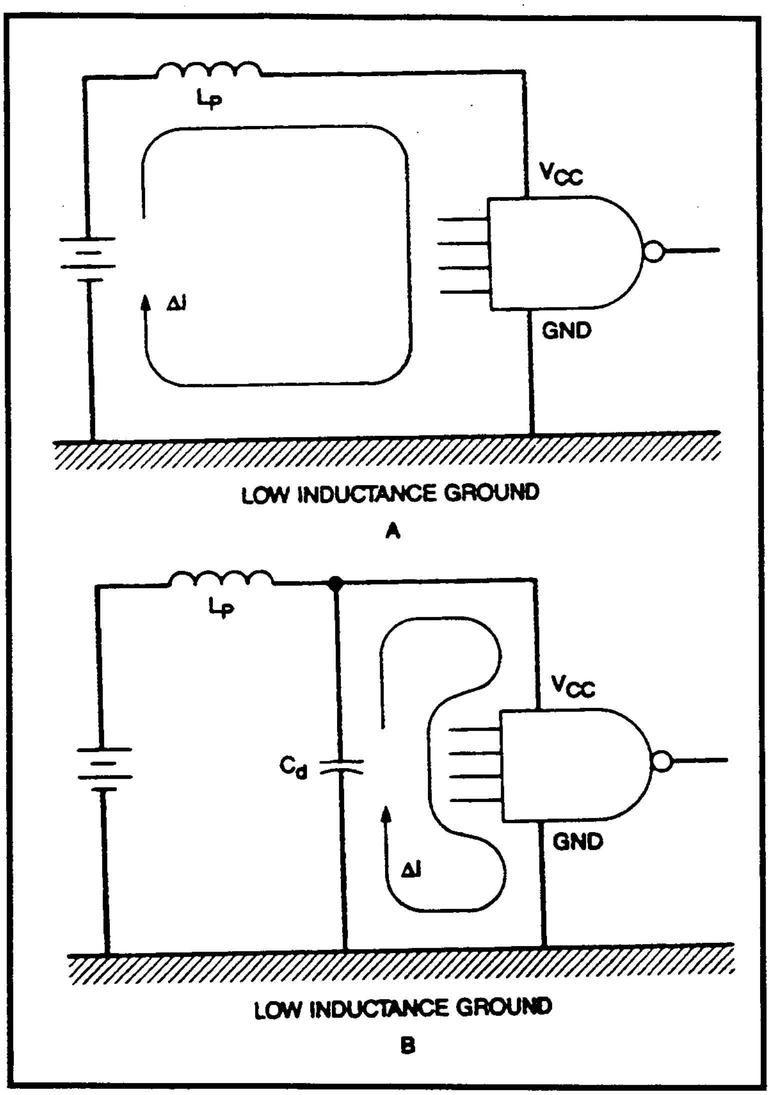


Figure 128. Transient Power Supply Current with (B) and Without (A) a Decoupling Capacitor

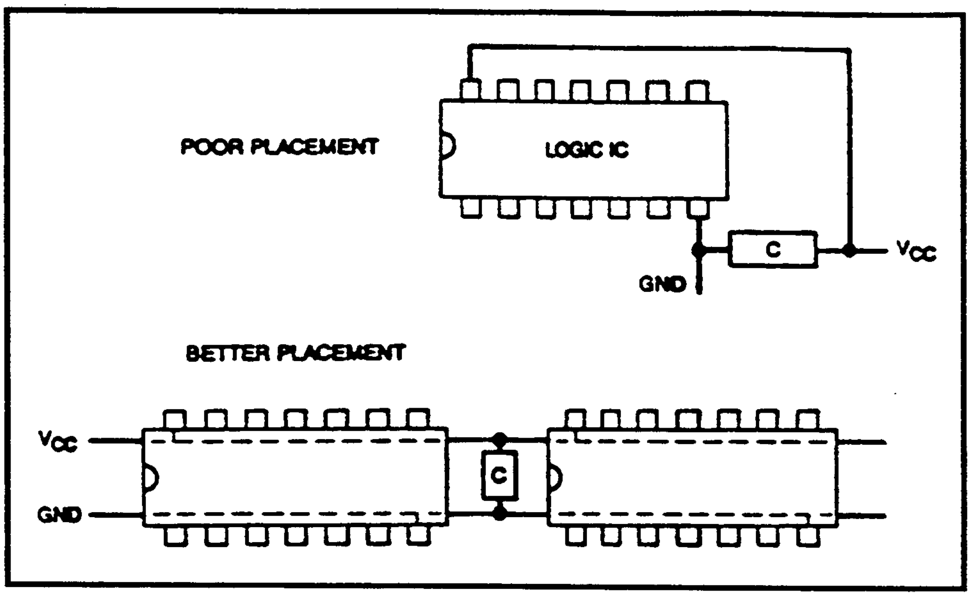


Figure 129. Decoupling Capacitor Placement
The loop area between the capacitor and the IC must be kept small to decrease the inductance.

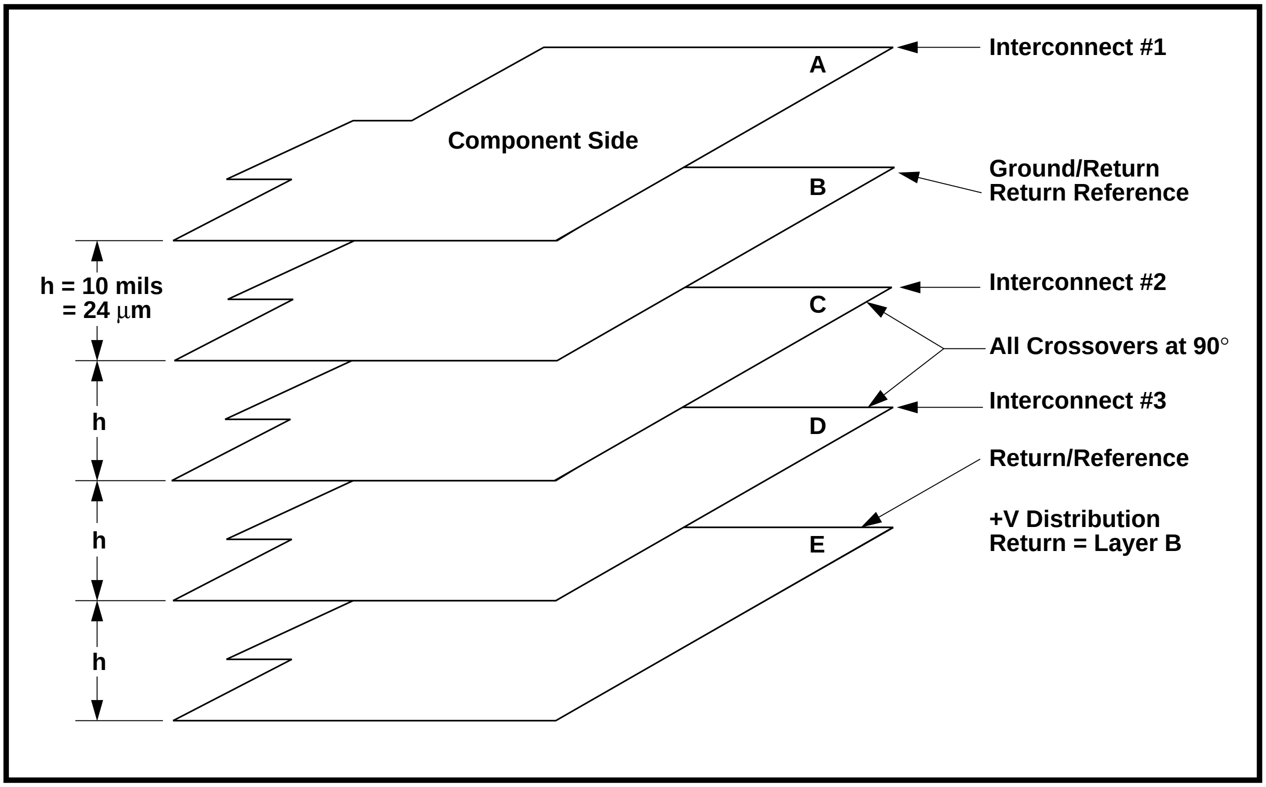


Figure 130. Digital Multi-layer Printed-Circuit Board for High-Speed Logic Impedance Control

Figure 131. Bonding Requirements for Plumbing Lines

Each section of metallic pipe, tubing and hose must be electrically bonded to the aircraft structure or the adjacent section of plumbing. If two or more plumbing lines are electrically bonded in series then the lines must be electrically bonded to structure to ensure that the loss of an intermediate bond does not result in an electrically isolated section. In addition, electrical bonding to structure shall not exceed 144 inches.