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MILITARY HANDBOOK

GUIDANCE FOR THE DESIGN AND TEST OF SYSTEMS PROTECTED AGAINST THE EFFECTS OF ELECTROMAGNETIC ENERGY

FSC EMCS

DEPARTMENT OF DEFENSE
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Guidance for the Design and Test of Systems Protected Against the Effects of Electromagnetic Energy
28 July 1978

1 This Military Handbook is approved for use by all Departments and Agencies of the Department of Defense

2 Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to (Commander, Naval Electronic Systems Command, ATTN ELEX 50431, Washington, DC 20360) by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter

FOREWORD

Electromagnetic environments (EME) are becoming more complex and of higher intensi y Electronic circuits are constantly being developed to operate with or process smaller signals These technologies are in conflict in terms of susceptibility to electromagnetic interference (EMI) which could reduce operational capabilities A major objective of this handbook guide is to provide program managers with the available guidance for the design of these systems to operate and survive in expected tactical electromagnetic environments so that EMI reduction techniques can be incorporated as early as possible in the design.

Electronic hardware for system development begins with components and circuits Some components and circuits are inherently more susceptible to electromagnetic energy than are others. This handbook addresses items such as what the designer should be aware of, what methods of circuit protection are available, and how one determines what shielding is needed in any particular application either between circuit and circuit, black box and black box, or between the external environment and the inside electronic system.

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1 SCOPE

1.1 Purpose The purpose of this document is to provide program managers with guidance for the design and test of electronic systems which are to be immune to the detrimental effects of electromagnetic energy.

1 2 Applicability This handbook is applicable to any electronic system or equipment which may be exposed to electromagnetic energy during its life cycle, including the following

a Aerospace and weapons systems and associated subsystems
b Ordnance
c Support and checkout equipments for a and b

2 APPLICABLE DOCUMENTS

2 1 Issues of documents The following documents of the issue in effect or date of invitation for bids or request for proposal form a part of this handbook to the extent specified herein

SPECIFICATIONS

MILITARY

MIL-B-5087	Bonding, Electrical And Lightning Protection
MIL-E-6051	Electromagnetic Compatibility Requirements For Systems

STANDARDS

MILITARY

MIL-STD-220	Method Of Insertion Loss Measurement
MIL-STD-285	Attenuation Measurements For Enclosures, Electromagnetic Shielding For Electronic Test Purposes, Method Of
MIL-STD-461	Electromagnetic Interference Characteristics, Requirements For Equipment
MIL-STD-462	Electromagnetic Interference Characteristics, Measurement Of
MIL-STD-463	Definitions And Systems Of Units, Electromagnetic Interference Technology
MIL-STD-1310	Shipboard Bonding, Grounding And Other Techniques For EMC And Safety
MIL-STD-1377	Effectiveness Of Cable, Connector And Weapon Enclosure Shielding And Filters In Precluding Hazards Of Electromagnetic Radiation To Ordnance, Measurement Of
MIL-STD-1385	Preclusion Of Ordnance Hazards In Electromagnetic Fields, General Requirements For

HANDBOOKS

MILITARY

MIL-HDBK-235	Electromagnetic (Radiated) Environment Considerations For Design And Procurement Of Electrical And Electronic Equipment
MIL-HDBK-237	Electromagnetic Compatibility/Interference Program Requirements

PUBLICATIONS

AFSC DH 2-7	Air Force Systems Command Design Handbook, System Survivability
AFSC DH 1-4	Air Force Systems Command Design Handbook, EMC
NAVSEA OD 30393	Design Principles And Practices For Controlling Hazards Of Electromagnetic Radiation To Ordnance
AMC Pamphlet 706-235	Hardening Weapon Systems Against RF Energy

(Copies of specifications, standards, drawings, and publications required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

3 DEFINITIONS

3 1 The terms used herein are defined in MIL-STD-220, MIL-STD-285, MIL-STD-461, MIL-STD-463, MIL-STD-1310, MIL-STD-1377, MIL-STD-1385, MIL-B-5087, MIL-E-6051, and MIL-HDBK-235

4 GENERAL CONCEPTS

4 1 Electromagnetic environment (EME) The EME in which military electronics must operate and survive is extremely complex because of the higher powers of electromagnetic emitters and modulation techniques used To assure that a system is not affected by its intended EME, it is imperative that the EME be considered during all phases of the life cycle It is very difficult, if not an impossible, task to exactly describe the electromagnetic environment which any system is certain to encounter Thus, the approach to defining the electromagnetic environment should be to define a representative maximum electromagnetic environment to which the system can be subjected, that is, the maximum EME that can be encountered in each phase of a system's life cycle It may also be necessary to project, from the state-of-the-art, the potential for generating EM energy which could intentionally or unintentionally perturb electronics and couple this with the representative maximum environment to yield a description of the total potential threat Projections of system usage to different platforms may also be necessary Only after full awareness of the tactical electromagnetic environment can the development of detailed system specifications begin to be addressed

4 1 1 Parameters used to describe environment When evaluating the performance of a system it is necessary to determine whether the system is susceptible to electromagnetic energy To evaluate whether the system is vulnerable, one must determine whether the levels of susceptibility will be encountered in the system's operating environment These evaluations require a description of the electromagnetic energy, both friendly and hostile, which the system may encounter during its life cycle. The information required is as follows

a Frequency
b Power density
c Pulsewidth
d. Pulse repetition frequency
e Polarization of antenna
f Antenna gain
g Antenna scan rate and aperture type
h Emitter density
i Mission profile of system

Items a through g cover the characteristics which are required in order to determine the field strength as a function of time The emitter density details the locations and numbers of emitters that could be encountered This item is sometimes called electronic order of battle (EOB) information The detail in which any or all of this information is presented depends on the step in the acquisition process under which the system falls and the mission profile of the system

4 1.2 MIL-HDBK-235. Electromagnetic environmental data is currently available in MIL-HDBK-235 This document contains representative maximum values of electromagnetic environmental data (friendly and hostile) in terms of peak and average field strengths and power densities that could be encountered.

4.1.3 Other data sources. The DoD Electromagnetic Compatibility Analysis Center (ECAC) at Annapolis, Maryland, has developed a comprehensive, computerized data base of electromagnetic information for use in electromagnetic compatibility (EMC) analyses The data base includes environmental data, equipment characteristics data, organization and platform allowance data, spectrum allocation and use data, and topographic data Computer retrievals may be obtained from the data bases in numerous formats, some tailored for specific applications. ECAC also has computer programs capable of providing power density-vs-frequency data during a mission profile for any given scenario. Information may also be obtained from such sources as the Naval Surface Weapons Center/Dahlgren and other comparable activities in the DoD

4 1.4 Specifying the environment. It would be unrealistic to assume that the total, maximum energy in the intended environment should be the design basis for all components of a system. Metal compartments, enclosures, mounting chassis, and so forth, prevent a large part of the energy in the total energy from penetrating to the susceptible components. The energy which can be expected to enter specific electrical and electronic equipments should be determined or estimated by the system designer in each phase of the life cycle This baseline description of coupled energy will require analysis based on the physical and functional descriptions of the items. The degree and complexity of these definitions depends on the stage of development that the system is in. For example, when the system is in the concept stage, only very general definitions may be required. During hardware development and system certification, however, the environments must be described in much more detail. The description of energy coupled to critical items should be reviewed periodically by the program manager to assure that the threat estimates are realistic and to assess the adequacy of the design approaches However, regardless of how many definitions are made during system acquisition, there comes a time in that process when the environmental definition has to be frozen by contract It is mandatory, therefore, that the environments in each phase of systems acquisition be as realistic as possible

Where interfacing subcontractors are involved, the program manager should define or approve requirements which are to apply to each contractor's product to insure that the overall system contains no weak links, and that no product has unrealistic requirements. Specifying requirements for each link of a complex system must be approached with a clear understanding of the coupling mechanisms which transfer unwanted energy into items of the system, the possible consequences of coupled energy on system performance, and the technical and economic aspects of available protection techniques In order to assure this, proper management of the contract for system procurement and the environmental data dissemination must be maintained Additional guidance in these areas is contained in MIL-HDBK-235, MIL-HDBK-237, MIL-E-6051, AFSC DH 1-4 and AFSC DH 2-7.

4 2 System design. The trend toward employment of more complex microelectronic circuits is creating a progressively more difficult task for the system developer faced with designing a system to operate in a complex electromagnetic environment Given the intended environment, the system designer should determine the energy coupled to the equipments, subsystems, or system and the potential effects from this energy. From these determinations, the design can be established The design may include temporary protection measures if the threat at intermediate stages of the life cycle exceeds that which exists in the operational environment of the system. During the operational phase, maintenance activities and aging can result in the deterioration of the system and increase the threat The program manager must establish appropriate maintenance requirements and schedules to insure that the integrity of the design is maintained throughout the system's life cycle.

4.2.1 Layered protection. Electromagnetic energy can penetrate through various points-of-entry (POE) to the inside of enclosures of electrical or electronic equipments and systems and can couple to critical components. It is possible that these components can inadvertently respond to the coupled energy and cause mission failure. The effect can be in the form of circuit upset or circuit damage. The energy couples first to the exterior of outer enclosures and sets up skin currents and charge densities. These currents and charges excite penetrations such as antennas (real or virtual) and apertures. Thus, the energy penetrates to the inside of the system where it can couple to cables which are connected to sensitive, critical components. The layering approach attempts to interrupt these coupling paths, starting with exterior, to reduce the penetration of the outer enclosures and thus reduce internal fields. Next, cables are protected by various techniques, reducing coupling from the internal fields to cables. Finally the critical equipment, components, and circuits are protected. This approach represents a cost effective way to protect the system because it first takes advantage of the intrinsic shielding of the system exterior, then the subsystem enclosures, and finally equipment enclosures and component shielding. Improvement of isolation at each layer reduces the number of vulnerable points in successive layers.

4.2.2 Design approach. FIGURE 1 is a diagram of the approach that system designers may take to protect a system, subsystem, or equipment. The baseline inputs that are required from the program manager are indicated as blocks 1 and 2 in the diagram. These are definitions of the intended electromagnetic environment and the functional requirements of the system, subsystem, or equipment. Subsequently, the system designer should employ analysis and measurements to determine if the design item will suffer degradation of performance without additional protection (blocks 3 through 11). The emphasis is normally on measurements for items that are small and testable, but analysis may be used to define worst case threats for the small items. For large or distributed items, measurements will be limited in usefulness because the environment simulators will, of necessity, be low-intensity, imperfect-plane-wave sources. For large items, therefore, analysis (backed up by measurements of critical components) will play the major role. Additional protection will not normally be required for susceptibilities of less than 30 dB since at least that amount is obtained by enclosing the system. As indicated in block 11, the design is then submitted for approval (block 18). If the requirement for the design item is between 30 and 70 dB, additional techniques including network hardening, filtering, shielding, device hardening, functional hardening, and circumvention can be utilized (block 12). If a test prototype or model of the hardened item proves vulnerable, or if the requirement exceeds 70 dB, a design review is made, and the cycle of design is repeated (blocks 16, 17, and 19). Revised definition of the intended EME, or new functional descriptions, may be required for the new design cycle. The program manager reviews (block 13) indicate reviews of design, testing, trade-off analyses to assess the cost effectiveness of alternate protection approaches and, finally, design approval.

4.2.3 Trade-offs. In the design and development of complex systems, it is likely that conflicts will arise which will necessitate trade-offs between requirements for added protection and the functional requirements of the system. Also, trade-offs may be necessary to reduce the cost impact of additional protection. For example, the trend toward increased, discrete component sensitivity must be countered with better shielding or isolation techniques. After these sensitivities are determined, some approximation of the circuit sensitivity must be made. The estimated maximum system sensitivity threshold that produces unacceptable upsets or malfunctions is the starting place for protective design trade-off decisions by the system designer. Some elements of the design for trade-off studies are:

a. Selection of system operational signal levels as high as practical commensurate with the devices being employed.
b. Selection of the interconnect wiring and cabling techniques which provide the best rejection of normal mode and common mode energy transfer.
c. Rigid or flexible solid shielding versus single or double insulated metallic braid.
d. Employment of active or passive filtering or energy absorbing devices at electronic package cable interfaces.

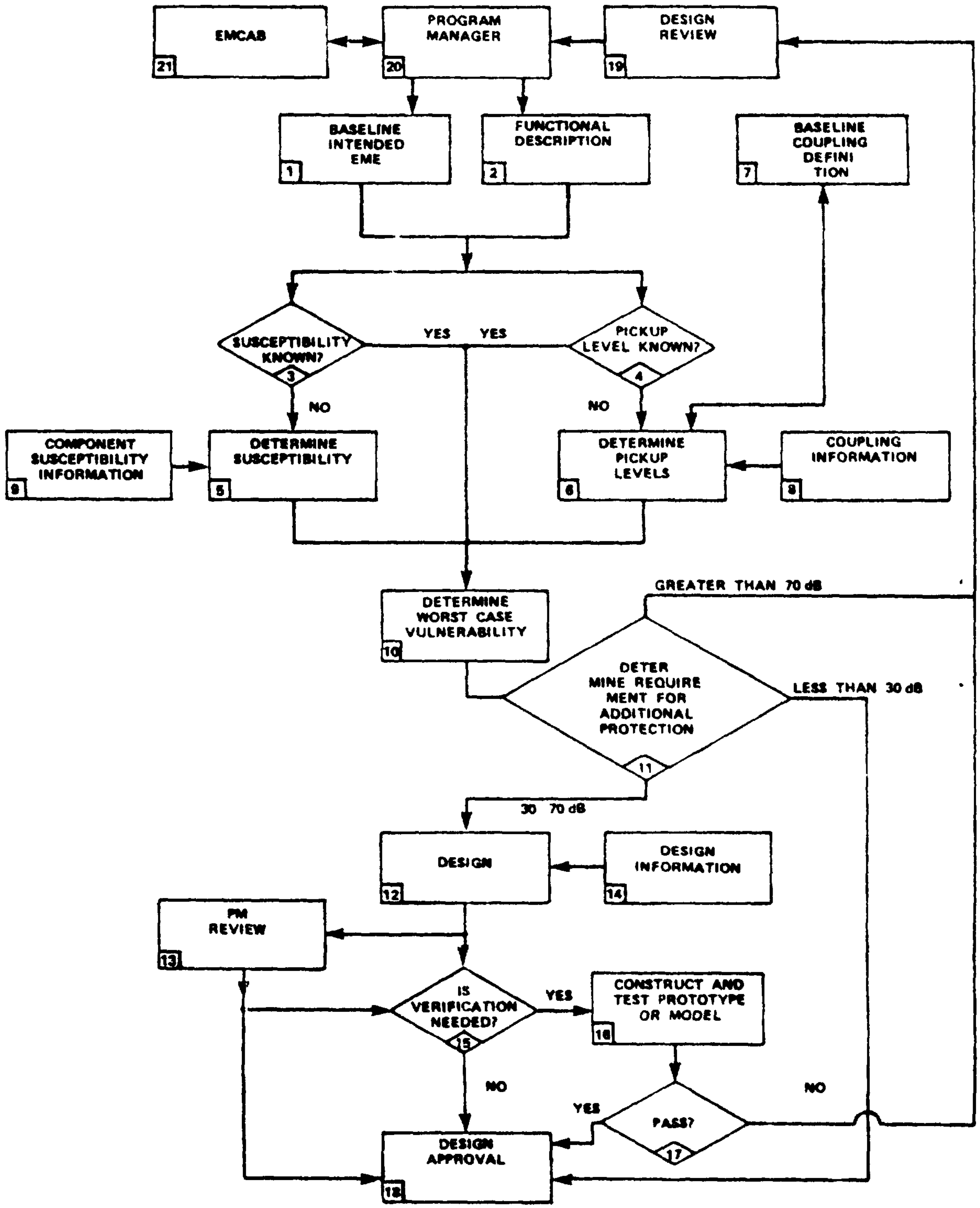

FIGURE 1 Design approach

e Proportional exclusion of energy by system structure, case, and cable electromagnetic shielding
f Multiple utilization of load bearing functional structures such as airframes, cable raceways, or conduits, so that considerable protection is provided at relatively little cost
g Utilization of specially related processes in the fabrication and assembly stages of system production
h. Employment of protected memory systems to periodically update unprotected signal circuits
i Use of sensors to update unprotected circuits from a protected memory
j Use of fiber optic guides versus conventional shielded cable

4.2.3 1 Generally, trade-offs involving a reduction in protection should be strongly discouraged However, where conflicts between these requirements and other system requirements arise, the program manager must resolve these conflicts and approve a course of action for the system designer based on

a The system designer's assessment of the impact of the trade-off on system vulnerability and system functional performance, and the rationale for this assessment
b. The criticality of affected equipments, subsystems, and systems relative to reliable performance
c The number of equipments, subsystems, and systems involved, and
d The impact on program cost and schedule

4 2 4 Analysis Analysis has its place in the integrated development effort, principally in arriving at predictions and requirements for design performance, so that the configuration submitted for survivability and vulnerability testing will require a minimal amount of modification before it is acceptable to the contracting agency The following analytical steps should be performed

a Determination of the worst case environment from the many possible cases of tactical exposure
b Predictions of major system elements response to the defined environment
c Employment of transfer impedance theory for shielding design
d Development of coupling transfer functions, which relate the incident energy to the desired electrical function, and
e Use of circuit models in cases where simple geometry, such as coaxial circuits or single pair lines, makes energy transfer calculations feasible

4 2 5 System testing After an item has been designed, a prototype may have to be developed and tested to verify the effectiveness of the design approach Tests may also be found to be necessary at various points during system development System tests can be divided into three general phases so that the tests appropriate for each phase of the system's procurement cycle can best be described with a sense of developmental continuity The testing phases are model tests, functional system tests, and proof tests.

4 2 5 1 Model tests The relative merit of design features or concepts can be readily determined on a simplified model of the proposed system The model should be as close to full scale as the economics of its construction, instrumentation, and the budget available for using environmental simulation facilities allow The numerical scaling applied to the system model requires that environmental simulation match any reduction in system dimensions so that the measured response of the scaled model can be converted to full-scale data

The model should duplicate the electrical characteristics of the system's metallic structures, including apertures deemed significant as points of entry The inclusion of cabling conduits, raceways, and simulated electrical/electronic subsystems should be to the degree of detail justified by the model scaling factor and the experimental objectives The model experiments should be designed to refine the accuracy of system transfer functions relating the test environment to the desired measurement of voltage or current effects at critical location or system interfaces under worst case orientation conditions The model should also be employed to determine the system worst case environmental orientations and to gather data on the various energy transfer mechanisms, such as structural surface currents, cable shield currents, or aperture coupling

The results of the model response measurements and transfer functions scaled to the threat environment can also be used to provide valid data for laboratory studies on functional mock-ups or prototype systems.

4.2.5.2 Functional tests. Functional system tests may be carried out in the laboratory with the simulation of effects on individual subsystems or on the complete, functional system as described above. The usual objective of these tests is to determine if the system will perform satisfactorily under conditions that are equivalent to the specification level If such is not the case, the weak link in the system is to be identified and corrective measures taken, such as improving shielding of the critical electronic package interfaces. A retest of design changes is in order, followed by tests of increased severity to demonstrate that an acceptable protection factor exists. The factor may be demonstrated either through increased environmental simulation levels or by degrading the shielding performance of individual cables or conduits. It is reasonable to assume one or more of the aforementioned iterations will be required on a newly developed system; therefore, it is strongly recommended that these steps take place in the developmental laboratory prior to subjecting the system to proof tests at specifications level.

4.2.5.3 Proof tests. Proof tests on a developed system are usually conducted at facilities which are capable of providing a specification level test environment. In practice, the systems are usually exposed to lower test levels for gathering useful calibration, mapping, and transfer function data prior to application of the threat level tests Instrumentation must be carefully designed and checked if it is left in place in the system, to ensure that it will not introduce spurious coupling to critical interfaces and become the direct cause of a failure of the system at threat level.

4.3 System management. There are numerous documents, including MIL-E-6051, MIL-HDBK-237 and AGSC DH 1-4, which address aspects of system management for the various electromagnetic disciplines as well as survivability and vulnerability. These documents define the tasks required during the various life-cycle phases to ensure compliance with specified electromagnetic requirements.

4.3.1 Management program. The EMC Program should be formulated early in the system project and should be applied during all phases of the system's life cycle, including concept, design, development, manufacture, deployment, operation, and maintenance Systems engineering and function analysis methodologies should be applied. Management actions for assessing and correcting degradation should be addressed so that the program produces consistent electromagnetic analyses and subsequent protection of all critical components, subsystems, and operational sequences associated with the overall system functions and mission profile The Program should include systematic and critical review throughout each phase of a system's development based on current, quantitative definitions of the intended EME and the system's performance as determined by design engineering, analysis, and test data. The Program should anticipate design, research and development, engineering, test, and evaluation problems that may be encountered and may need to be solved in order to satisfy the goals for the system and mission as determined by operational requirements, economics, or other considerations. In addition, the Program may require trade-offs which may be necessitated by engineering changes, by program milestone changes, economic factors, scheduling, or other constraints on the program. The program manager is responsible for the system concept phase. Protection measures may be incorporated at this point as the program manager begins to recognize the operational requirements of the systems, and the intended environment As the program moves into the contract definition phase, the program manager must ensure that applicable documents are specified in the statement of work and that the intended EME is as clearly delineated as possible. He should also see that system specifications are stated such that design requirements can be realized by the prospective contractors or developing agency. During the contract definition phase and as the program progresses, the applicable documents and environment definition can be redefined with greater precision This redefinition of the environment will generally lead to less stringent requirements and to changes which can be made to correct overdesign if they are economically justified. Effectiveness of control usually depends upon astute, flexible, knowledgeable management rather than upon strict adherence to general-purpose specifications and standards.

4.3.2 Advisory board. An advisory board, hereafter called the EMCAB, can be established by the program manager as a major resource for review, advice, technical consultation and other assistance. The EMCAB can also assist in identifying and resolving EM problems that may arise during the life cycle of the system or equipment and, in general, act in an advisory capacity in all EM aspects of a program.

The EMCAB should participate in the scheduled design reviews during the system development cycle and in the program's configuration control process, and generate recommendations for the solution or further definition of potential problem areas uncovered.

5. DETAILED GUIDANCE FOR COMPONENTS AND CIRCUITS

5.1 Introduction. The components of early electronic systems were predominantly vacuum tubes. By their very nature, these devices are rather insensitive to extraneous electromagnetic radiation such as might couple into a system from other emitters. The development of solid state semi-conductor devices with their low power requirements and small size made possible more compact and more sophisticated electronic systems. It also resulted in devices which could be strongly affected by electromagnetic energy, thus causing malfunctions in electronic systems. The effects of EM energy on solid state devices range from temporary interference through permanent degradation to catastrophic failure and are discussed in 5.2 through 5.4 of this document.

5.2 Interference. In the case of interference, the operational capability of the device is reduced in the presence of an undesired electromagnetic emission, with a return to normal operation when the signal is removed. One possible mechanism involved is rectification by a p-n junction when the signal is received on stray wiring or on other unintended antennas. A dc or video signal results which can propagate through the system as an undesired signal and overload a particular device, thus causing malfunctions such as misguidance or loss of track in a missile system. The resultant circuit response and the severity of interference in a given environment may be determined by using circuit analysis techniques and models. Because of the on-off nature of logic signals, a more sharply defined interference threshold is to be expected in digital circuitry. In general, it is found that high speed devices constructed for use with small signals are the most susceptible to EM energy.

5.3 Permanent degradation. In the case of degradation, some degree of physical or electrical damage may be suffered by a device as a result of energy, but the device can still function. The degradation may be such as to reduce the capability of life of the device after removal of the electromagnetic energy.

5.4 Catastrophic failure. In the case of catastrophic failure, physical damage or electrical damage or both is suffered by the device so as to render it nonfunctional. Three distinct failure modes have been observed in solid state transistors and integrated circuits.

a. Bondwire melt. Bondwire melt occurs when the currents generated achieve a sufficiently high density to melt the bondwire, which connects the internal semi-conductor device to the external circuitry thereby resulting in an electrical open circuit.
b. Metallization damage. Metallization damage occurs when the current densities on the surface of a chip are high enough to melt some portion of the metal conduction path.
c. Junction damage. Junction damage occurs when the device is driven into the second breakdown region by a signal and remains there sufficiently long to produce a permanent shorting channel.

6. ELECTROMAGNETIC COUPLING

6.1 Introduction. Electromagnetic interference problems may exist when external electromagnetic energy enters a system and is coupled into the components. One way to solve this problem is to remove the path or paths by which the energy enters.

6.2 Coupling phenomena. An incident electromagnetic field first produces current and charge distributions on the outside enclosure of an electronic system. The magnitude of these distributions at a particular point on the system enclosure depends upon the polarization and angle of incidence of the field as well as the system configuration. Depending upon the ratio of the incident wavelength to the primary system dimensions, resonant effects can produce standing waves along the device and thereby increase magnitudes of the current and charge distributions. Solid metallic enclosures with no surface discontinuities (holes, slots, seams, cable penetrations, and so forth) generally provide adequate shielding; however, some surface discontinuities are inherent in most systems. The coupling through a discontinuity depends upon the magnitude of the current and charge distributions at the location of the discontinuity. If the dimensions of the discontinuity are a multiple of the half wavelength of the incident radiation, coupling into the interior of the system will be greatly enhanced. Once inside an electronic system, the internal fields can exhibit additional resonant effects depending upon internal cavity dimensions. Loss mechanisms, however, such as the discontinuities themselves, internal circuit loads, or anechoic material can damp out these resonances and reduce their effect. The internal wiring, in addition to forming part of the internal cavity structure, also serves as the mechanism by which the electromagnetic energy is introduced into system components. Depending upon the wire or cable lengths, wiring resonances are also possible. The received power is then transmitted along the wire until it reaches a circuit element. The power absorbed by this circuit element depends on the degree of impedance match between the wire acting as a transmission line and the component impedance. Once the absorbed power has been determined, its effect on the circuit element can be determined. Knowing the effect on the circuit element, the circuit response can be predicted.

6.3 Use of coupling information at various system development stages.

6.3.1 Design stage. In this stage of system development, no hardware is available for testing, yet predictions are needed of both the shielding afforded by the system enclosure and the signal pick-up by internal circuits. Rigorous analytical techniques for predicting these quantities do not exist yet for actual systems, however, they may be approximated by assuming a free space field incident on a half-wave dipole, at the frequency of interest, matched to the circuit in question. The component and circuit responses may then be predicted.

6.3.2 Prototype hardware stage. At this stage of development, test measurements of the prototype hardware are the best way to determine coupling information. Tests can determine if a susceptibility problem exists, and if it does, they can be used to check the effectiveness of design. These tests can be carried out in a shielded room. However, an anechoic chamber may be required to simulate the free space condition of an aircraft or missile in flight.

6.3.3 Coupling measurements. The techniques currently published in such documents as MIL-STD's-1377, 285, and 462 cannot be applied directly to the free-space conditions associated with vulnerability and susceptibility testing because (a) the results are influenced by the particular test configuration and (b) there are no means by which the test results can be interpreted in terms of system performance in free space without some assumptions and computer simulation. However, these can indicate the existence of potential problem areas. Recent experimental work indicates that the more severe MIL-STD-1377 measurement results are the most realistic with respect to the free-space performance of the enclosure.

7. TESTING OF SYSTEMS

7.1 Introduction. Testing and evaluation of systems is required during the system acquisition life cycle prior to final acceptance. The methods that may be used to evaluate the potential effects from electromagnetic energy are outlined in this section. While many of the procedures described herein will not be used by contractors, but rather by a DoD test facility, their inclusion herein will make the contractors aware of the thoroughness and detail with which the system [illegible] be evaluated before final acceptance.

7.2 Information required from tests. To completely evaluate the performance of a system in an EM environment, it is necessary that it be tested for its dependency on and response to many factors. The major outputs derived from the testing will be those discussed in 7.2.1 through 7.2.9. External electromagnetic environments can couple into the system through ports of entry caused by surface discontinuities and into the electronics through circuit ports.

7.2.1 Power density. One of the most obvious factors that influence the behavior of any electronics is the power density to which it is subjected. Given enough power, interference could be experienced on any piece of electronics. Therefore the requirement is not to determine how much brute force power it takes to affect a system, but, within realistic limits, how much power is required to cause an effect and whether the system is more susceptible to peak power or average power.

7.2.2 Frequency. The effects that known and projected emitters will have on a system must be determined. Every effort must be made to evaluate the system at the exact frequencies it will or can encounter.

7.2.3 Modulation. As with frequency, there can be several aspects to addressing modulation. When simulating a known threat, it is important to duplicate as nearly as possible all characteristics of that threat, including its modulation. It is also necessary to look at the electronics and determine the modulations which, if induced into the system, would be processed or would disrupt the processing of intended signals. A system can normally be broken up into small relatively independent units. For example, modulations which would affect one function of a system may be different than those which would affect another, so each should be investigated independently. Modulations may have different formats including those which may give the system false information and those which might upset or blind a system. Among items to be investigated are the pulse repetition frequency, pulse width and complex format (that is, pulse dropping, amplitude, swept, and so forth).

7.2.4 Aspect angle. Since the system and its electronics respond as antennas, the coupling between the external field and those antennas will be a function of aspect angle. The maximum lobe, corresponding to the maximum gain of the antenna is related to the effective aperture and wavelength and is greatly influenced or altered by its surroundings. One should look at the entire system and monitor its response versus aspect angle for a few selected points in the system.

7.2.5 Polarization. With the exception of a so called point source, antennas will respond better to some polarizations than they will to others. Therefore, it is important to investigate the polarization of the system with respect to the field in order to evaluate susceptibility of the system.

7.2.6 Boresight (for missile systems). When the electrical (with respect to RF) and the mechanical (with respect to seeker angle) boresights are not aligned, erroneous test results may be obtained. Tests performed on a stationary system may not prove valid during flight testing.

7.2.7 Track rate (for missile systems). Track rate is defined as the angular rate of change of a missile seeker as a function of time. The effects of various track rates in terms of deg/sec on system performance should be investigated.

7.2.8 Target intensity (for missile systems). Like RF power, the ir-band power of the target is an important consideration in successfully completing certain missions and therefore must be determined.

7.2.9 Dwell time. Emissions causing interference may have amplitudes which vary with time, such as due to antenna scanning. If the energy directed at the system under test is of short duration, interference effects may be negligible. Dwell time is a measure of the minimum duration to cause a specified degree of interference.

7 3 Data dependency Data dependency is to be established for given power level and for a given circuit coupling port The dependency of each test parameter in 7 2 through 7 2 9 on the others is shown in TABLE I

TABLE I Data dependencies (variables)

Data Functions Dependent On Each Other	Independent Data Functions
Frequency	Modulation
Aspect Angle	Track Rate
Polarization	Target Intensity
Boresight	Dwell time
Power Density	

It should be noted that all of the dependent functions are related to system geometry If a system acts as an antenna, all functions in the left column are dependent on the geometry of that system However, modulation, track rate, and target intensity are functions only of one portion of the system (that is, a circuit port) For tests to determine the effects of any of the dependent items, the entire system must be present and the system must be tested in a free space environment. This is not the case for the independent data functions

7 4 Determining system susceptibility and vulnerability The types of tests required are described in 7.4 1 through 7.4.5.

7 4 1 Laboratory tests. The information which can be obtained from laboratory testing is listed in TABLE II, Column A As discussed in 7.2, this information can be obtained without using the entire system, and without regard to calibrated RF power Laboratory tests should result in the critical modulations, target track rate variations, and so forth, being defined Tests then normally move into a free space testing system (It may be necessary to bring a system back into the laboratory several more times during tests before the total test program is completed.)

7 4 2 Free space tests Tests whose outcome depends on system geometry must be performed in an essentially free-space environment Included are those items discussed in the left hand column of TABLE I Laboratory data provide the modulation and track rate inputs which are used for and verified in these evaluations Free space tests normally start with identification of a standard power response with which to compare data With a standard response established, aspect angle tests can be performed and the power response level vs aspect angle determined If response tests are performed correctly, tracking tests can then be done at one aspect angle and the effects of EM energy on tracking predicted at any aspect angle

7 4 3 Analysis/simulation The free space measurements described in 7 4 2 demand laboratory inputs Vulnerability analyses require the combined inputs of laboratory and free space tests The information from free space tests, along with the information required for vulnerability analysis are shown in Columns B and C of TABLE II The analyses and simulations are based primarily on the operational characteristics of the system with (a) measured data on the systems response to EM energy, (b) the tactical scenario for the system, and (c) the tactical electromagnetic environment in which the system must operate A system is termed vulnerable only if the energy which it could encounter in its mission will cause susceptibility sufficient to cause mission failure Otherwise, the system is not vulnerable, although it may respond adversely to many combinations of EM energy Mathematical simulations are normally required as a portion of the vulnerability analysis These simulations are particularly important when a system is interfered with by EM energy, but does not completely malfunction A simulation is needed to determine the signal level required to degrade system performance beyond a tolerable limit A simulation can

have another important role A properly designed simulation can provide inputs to initial testing as well as a quick analysis capability for laboratory testing. Having a simulation available at the beginning of a test program should reduce total test time and cost.

TABLE II. Approach to determine potential effects from electromagnetic energy.

A LAB MEASUREMENTS	B FREE SPACE MEASUREMENTS	C ANALYSIS/SIMULATION
Determine system sensitivity to: 1 Modulation A Pulse repetition frequency B Pulsewidth C Complex format 1. Pulse dropping 2. Amplitude 3 Sweot, and so forth 2. Relative RF power 3 Dwell time 4 Track rate 5 Target intensity Determine coupling mechanisms 1. Entry ports 2. Circuit ports Evaluate fixes	Determine system sensitivity (standard response) to: 1 Frequency 2 Aspect angles* 3 Polarization (all of above interdependent variables**) Determine system susceptibilities at parameters selected from laboratory and chamber measurements *Establish errors between electrical and mechanical boresight **Frequency may be a function of aspect angle, and so forth	Determine system vulnerability 1. Measured data 2. Scenarios 3. Tactical EM environment

7 4.4 Platform measurements Systems which require a platform interface in order to acquire a target are to be evaluated to insure that this interface is not vulnerable.

7 4 5 Field/flight tests The other aspect of Government certification is field or flight testing Such testing can be used to verify laboratory/free space tests or to determine the validity of simulations Field testing falls into two categories; (a) captive flights and (b) live firings. The present technology efforts are being developed with the goal of greatly reducing or eliminating the requirements for expensive field or flight tests.

8 INTRODUCTION TO SYSTEM PROTECTION The best method for reducing electromagnetic vulnerability in electronic systems is to preclude the inadvertent entry of EM energy in the first place There is rarely, if ever, an effective substitute for sound, EM tight design. This should be kept in mind constantly during design and redesign phases. Application of susceptibility reduction techniques should be considered early in the design stage and in each subsystem area so that the entire system hardness requirement does not need to be met by disproportionate efforts in one area only. The main emphasis is to (a) keep unwanted energy away from circuitry; (b) keep undesired signals which couple to wires away from intended signal paths and particularly

away from semiconductor devices, and (c) design circuitry such that undesired energy in the signal path does not severely disrupt circuit operation The major areas of endeavor in hardening circuits are shielding, bonding, filtering, grounding, and circuit design This section is intended to provide program managers with a general overview of these basic design approaches

8 1 Shielding

8.1.1 General. Shielding has two main purposes: (a) to keep radiated EM energy confined within a specific region, and (b) to prevent radiated EM energy from entering a specific region Thus, shielding is essentially a decoupling mechanism used to reduce radiated interactions between equipments, or between portions of a given equipment The shielding effectiveness of an equipment or subassembly enclosure is a complex function of a number of parameters, the most notable of these being the frequency and impedance of the impinging wave, intrinsic characteristics of the shield materials, and the numbers and shapes of shield discontinuities The equipment design process consists of establishing undesired signal levels on one side of a proposed shielding barrier, estimating tolerable signal levels on the other side, and trading off shield design options to achieve the necessary effectiveness level

8 1 2 Selected shielding considerations

8.1.2.1 Coatings and thin-film shielding. Thin shielding (that is, shield thickness less than one quarter wavelength at the propagation velocity dictated by the material) has been employed in a variety of ways, ranging from metallized component packaging for protection against RF fields during shipping and storing, to vacuum deposited shields for microelectronics applications

8 1.2 2 Cable shielding There are several methods for shielding cables as discussed in a through d·

a Braid, which consists of woven or perforated material, is used for cable shielding in applications where the shield cannot be made of solid material. Advantages are ease of handling in cable makeup and lightness in weight. However, it must be remembered that for radiated fields, the shielding effectiveness of woven or braided materials decreases with increasing frequency and the shielding effectiveness increases with the density of the weave The percentage covered by a braided shield has been a critical parameter in past designs

b Conduit, either solid or flexible, may also be used to shield weapon system cables and wiring from the EM environment The shielding effectiveness of solid conduit is the same as that of a solid sheet of the same thickness and material Linked armor or flexible conduit may provide effective shielding at lower frequencies, but at higher frequencies the openings between individual links can take on slot-antenna characteristics, seriously degrading the shielding effectiveness If linked armor conduit is required, all internal wiring should be individually shielded Degradation of shielding conduit is usually not because of insufficient shielding properties of the conduit material but rather the result of discontinuities in the cable shield These discontinuities usually result from splicing or improper termination of the shield

c Solenoids, or other devices associated with high inrush currents or incorporating switching devices that normally develop high-amplitude transients are of concern For protection against this type of energy, shielding materials with high permeability are desirable These materials cannot be drawn into tubing because they lose their shielding properties when cold worked, therefore, an adequate shield is often developed by wrapping a continuous layer of annealed metal tape around the cable A protective rubber coating is recommended

d The principal types of shielded cables that are available include shielded single wire, shielded multiconductor, shielded twisted pair, and coaxial. Cables are also available in both single and multiple shields in many different forms and with a variety of physical characteristics

8.1.2.3 Required visual openings. Often it is necessary to provide shielding over visual openings. The alternatives available are use of screening material, providing a shield for the assembly of concern within the system skin, and filtering all leads to the assembly; use of conducting glass, and minimize size of opening.

a. Use of screens over apertures has been employed for shielding purposes. A typical screen introduces a minimum of 15-20 percent optical loss. In some cases, screens can give good shielding at fairly low cost. Typical values may approach 20 dB at 10 GHz.
b. When utilizing internal shielding all leads entering the shielded assembly must be properly filtered. Selection of these filters must be such that the intended signal will not be altered. Filters may be installed at the input to the shielded assembly, or at any point on the external leads. However, if the latter approach is used, shielding integrity must be maintained between the installed filter and the assembly.
c. Glass coated with conducting material such as silver can provide shielding across viewing surfaces with some loss in light transmission. Conductive glass is commercially available from a number of glass manufacturers.

8.1.3 Summary of shielding practices. The following represent what might be considered the more salient points on shielding design considerations.

a. Good conductors such as copper, aluminum, and magnesium should be used for high-frequency electric-field shields to obtain the highest reflection loss.
b. Magnetic materials such as iron and Mu metal should be used for low frequency, magnetic-field shields to obtain the highest penetration loss.
c. Any shielding material strong enough to support itself will usually be thick enough for shielding electric fields.
d. In the case of thin-film shields, the effectiveness of the shield is fairly constant for material thicknesses below $\lambda/4$, as measured within the material, and increases markedly above that thickness.
e. Multiple shields (for both enclosures and cables) can provide both higher shield effectiveness and extended shielding frequency range.
f. All openings or discontinuities should be treated in the design process, to assure minimum reduction in shield effectiveness. Particular attention should be paid to selection of materials that are not only suitable for shielding, but from the electrochemical corrosion viewpoint as well.
g. When other aspects of system design will permit, continuous butt or lap weld seams are most desirable. It is important to get intimate contact between mating surfaces over as much of the seam surfaces as possible.
h. Surfaces to be mated must be clean and free from nonconducting finishes unless the bonding process positively and effectively cuts through the finish.
i. Conductive gaskets and spring fingers, waveguide attenuators, screens and louvres, and conducting glass are the major devices and mechanisms available for maintaining enclosure shield effectiveness. Many factors in addition to shielding capabilities per se, ranging from space availability to cost, and from air circulation requirements to visibility factors, will affect particular methods employed in particular situations.
j. Shielding represents only one method of reducing equipment EM interactions, and should not be considered without also considering tradeoffs of filtering, grounding and bonding techniques that simplify or eliminate requirements for shields.

8.2 Bonding.

8.2.1 General. Bonding is the establishment of a low impedance path between two metal surfaces. This path may be between two points on a system ground plane, or between ground reference and a component, a circuit or a structural element. The purpose of the bond is to make the structure homogenous with respect to the flow of RF currents, thus avoiding the development of electric potentials between metallic parts which can produce interference. The effectiveness of a bond depends on its application, frequency range, magnitude of current, and environmental conditions such as vibration, temperature, humidity, fungus, and salt content in the ambient environment. Many examples of techniques available for low impedance connections for bonds are described in MIL-STD-1310, AFCS DH 1-4 and AMC Pamphlet 706235. Generally there are two types of bonding: direct bonding, where there is metal-to-metal contact between the members to be bonded, and indirect bonding through the use of conductive jumpers.

8.2.2 Selected bonding considerations.

8.2.2.1 Surface treatment. Both direct and indirect bonding connections require metal-to-metal contact of bare surfaces with the area cleaned for bonding being slightly larger than the area to be bonded. Ridges of paint around the periphery of the bonding area can prevent good metal-to-metal contact. After bonding, the exposed areas should be refinished as soon as possible with the original finish. However, if the paint used is too thin, refinishing paint may seep under the edges of bonded components and impair the quality of the bond. A suitable conductive coating may be used when removable components must be provided with a protective finish. Where aluminum or its alloys are used, corrosion resistant finishes that offer low electrical resistance are available.

8.2.2.2 Corrosion. Corrosion occurs between two dissimilar metals in solution, since they form an electrochemical cell. The extent of corrosion depends on the metals comprising the electrochemical cell and the conditions under which the dissimilar metals come into contact with each other. By properly modifying these two factors, the extent of corrosion in the vicinity of a bond can be reduced.

8.2.2.3 Bonding resistance. Measurement of the DC resistance of a bond is often used as a guide to the anticipated performance of the bond. Depending on the purpose of the bond, some military documents specify the maximum DC resistance allowable for a good bond. For example, bonds that are installed to prevent shock hazards are required by both MIL-B-5087 and MIL-STD-1310 to have a resistance of less than 0.1 ohm. Bonds for RF purposes are required by MIL-B-5087 to have a resistance of less than 2.5 milliohm (mΩ). Additionally, in areas prone to explosion or fire hazards, maximum values of bond resistances are designated, these values are a function of anticipated maximum fault current in the event a power line to ground short occurs. A guideline as far as a good RF bond is concerned, is a DC resistance value of between 0.25 and 2.5 mΩ.

8.2.3 Summary of bonding design guidelines. The effectiveness of a bond depends on its application, frequency range, magnitude of current, and environmental conditions such as vibration, temperature, humidity fungus, and salt content in the ambient. Many examples of the variety of techniques available for low impedance connections for bonds are available in MIL-STD-1310 and MIL-B-5087. Some general guidelines for obtaining good bonds are provided in a through g.

a. The secret to good bonding is intimate contact between metal surfaces. Surfaces must be smooth and clean and not coated with a nonconductive finish. The fastening method must exert sufficient pressure to hold the surfaces in contact in the presence of deforming stresses, shock, and vibrations associated with the equipment and its environment.
b. Bonds are always best made by joining similar metals. If this is not possible, special attention must be paid to the possibility of bond corrosion through the choice of the materials to be bonded, the selection of supplementary components (such as washers) that will assure any corrosion will affect replaceable elements only, and the use of protective finishes.
c. Solder should not be used to provide mechanical strength to a bond.
d. Protection of the bond from moisture and other corrosion effects must be provided where necessary.

e Bonding jumpers are only a substitute for direct bonds If the jumpers are kept as short as possible, have a low resistance and low L/C, and are not lower in the electrochemical series than the bonded members, they can be considered a reasonable substitute A good rule to use is that the jumper should have a length-to-width ratio of less than 5

f Jumpers should be bonded directly to the basic structure, rather than through an adjacent part They should not be connected with self-tapping screws, or by any other means where screw threads are the primary means of bonding

g It is always important in the broadest types of bonding application that the bonding jumper or direct bond is sufficient to be able to carry the currents that may be required to flow through it

8 3 Filtering

8 3 1 General. Even when a system has been well designed and incorporates proper shielding and grounding considerations, undesired energy can still be conducted through the system to degrade performance or cause malfunction. Filters can reduce this unwanted conducted energy to levels at which the system can function satisfactorily by limiting the magnitude of extraneous currents or confining them to a small physical area The design of filters is an art as well as a science since much depends on the judgement and techniques used by the filter design engineer. The impetus to the establishment of equipment filtering requirements (or shielding or grounding requirements for that matter) are the formal and informal specifications imposed on the designer Thus, formal interference specifications based on MIL-STD-461 limits the amount of conducted emissions that may be introduced on a power line Tolerable interference levels on critical equipment leads must be defined during an early stage of design so that circuit designers know the conditions their subassemblies must meet The ability to comply with these specification limits can then be continuously assessed in the breadboard stage, and so forth. However, while filters may be necessary, care should be taken to avoid redundant filtering caused by uncoordinated efforts of separate design groups Redundancy usually occurs when each black box is required to meet an interference control specification regardless of final location. Although trade-offs must be made, there is no substitute for a well thought-out system control plan If formulated well ahead of the system design, filter duplication can be avoided

8 3 2 Selecter filtering considerations Certain guidelines are helpful in deciding what type of filter circuit to apply in any given instance For example, if it is known that the filter will connect to relatively low impedance in both directions, then a circuit containing more series filter elements is indicated (a T-circuit, for instance) Conversely, a high-impedance system calls for a π-filter If the filter is connected between two severely mismatched impedances, then an asymmetric filter circuit such as two L-section elements can be used. The series element faces the low-impedance side of the system

8 3 2 1 Insertion loss The basic characteristic used to describe filter performance is its insertion loss Insertion loss is defined in MIL-STD-220 and MIL-STD-463 It is represented as the ratio of input voltage required to obtain constant output voltage, with and without the filter in the system This ratio is expressed in decibels (dB) as follows

$$\text{Insertion loss} = 20 \log \frac{E_1}{E_2}$$

where E_1 = the output voltage of the signal source with the filter in the circuit

E_2 = the output voltage of the signal source with the filter not in the circuit

8 3 2 2 Lossy line filters While the input and output impedances of some filters can be expected to match their intended source and load impedances over a fairly broad frequency range, it is more often the case that such matches will not occur Because of such mismatch situations there have been many cases when the insertion of a filter into a line carrying interference has

actually resulted in more, rather than less, interference voltage appearing on the line beyond the point of its application This deficiency in all filters composed of low loss elements has lead to the development of dissipative filters that take advantage of the loss-versus-frequency characteristics of magnetic materials such as ferrites. One form of dissipative filter uses a short length of ferrite tube with conducting silver coatings deposited on the inner and outer surfaces to form the conductors of a coaxial transmission line The line becomes extremely lossy at radio frequencies, that is, it has high attenuation per unit length in the frequency range where either electric or magnetic losses, or both, become large Dissipative filters of this type are necessarily low-pass. One of the large uses of such filters is in general-purpose power-line filtering, in which the dissipative filter is combined with conventional low loss elements to obtain the necessary low cutoff frequency.

8 3.2.3 Ferrite beads. Another method of achievin a dissipative filter is by use of lossy beads. Tubular ferrite toroids offer a simple, economic l method for attenuating unwanted high frequency noise or oscillations. One bead slipped over a wire produces a single-turn RF choke tha* possesses low impedance at low frequencies, moderately high impedance over a wide high frequency band and small inductance. The presence of a ferrite bead on the wire causes a local increase of series impedance (largely resistive) presented to currents in the wire as a function of frequency. Adding more or longer beads provides additional units of series inductance and resistance in direct proportion. Extra turns of wire can be passed through the bead, increasing both resistance and inductance in proportion to the square of the number of turns. Because of distributed winding capacitance, this technique is less effective at the high frequencies High amplitude signals below 50 MHz may cause some reduction in the suppression effect due to ferrite saturation. However, as long as only one turn links the core, fairly high currents can be tolerated using representative materials before saturation is approached. At saturation, inductance and resistance will be low, but will return to normal values upon removal of the high field

8.3 2.4 Filter installation and mounting When filters are used, proper installation is absolutely necessary to achieve good results. Effective separation of input and output wiring is mandatory, particularly for good high-frequency performance, because the radiation from wires carrying interference signals can couple directly to output wiring, thus circumventing and nullifying the effects of shielding and filtering Input and output terminal isolation is most easily accomplished by the use of a filter that mounts through a bulkhead or chassis . This mounting can also minimize the bonding impedance between the filter case and the ground plane In all cases where this type isolation is not feasible, isolation by shielded wiring is advisable. When a filter must provide greater than 60 dB of rejection, double shielded cable should be considered

8 ? 5 Summary of filtering guidelines In designing or selecting a filter for a particular application, many paramet rs must be taken into account if the filter is to be effective Its insertion loss versus frequen y curve is obviously the primary characteristic that determines the suitability of the filter for a particular application However, other electrical and mechanical requirements must also be designated These include the following:

a IMPEDANCE MATCHING - For a reactive filter the elements of the filter must be chosen so that the impedance network matches the line into which it is inserted. This is especially true of transmission lines, so that the filter does not impair the normal function of the equipment at both ends of this line When a filter must be installed in a circuit where its source impedance or load impedance is either not known or may vary over a relatively wide range, it may be desirable to terminate the filter into fixed impedances to stabilize its performance b VOLTAGE RATING - Consider the voltage rating on the filter, particularly if used on power lines Under some conditions, the voltage may deviate by a large amount from its normal value In addition, short duration pulses whose amplitudes are well above rated line voltage may be on the power circuits, both AC and DC. The filter voltage ratings must be sufficient to provide reliable operation under the extreme conditions expected

c. VOLTAGE DROP - Determine the maximum allowable voltage drop through the filter and design accordingly

d CURRENT RATING - Current rating should be for the maximum allowable continuous operation of the filter Calculate the current rating for filter elements, such as capacitors, inductors, and resistors Whenever possible, the current rating of filters should be consistent with the current rating of the wire, circuit breakers, or fuse with which the filter will be used A filter with a higher current rating than the circuit in which it is installed will have poor reliability and may be a safety hazard. The safety factor used in rating filters should also be consistent with those used for other circuit components

e FREQUENCY - Consider both the operating frequencies of the circuit and the frequencies to be attenuated. In general, the cost of a filter rises rapidly as the required rate of skirt falloff goes up, therefore, care should be exercised in identifying insertion loss versus frequency needs. Also, the appropriate type of filter for your needs must be selected - a band-reject filter to reduce the level of a single close-in narrowband source may be better than a sharp falloff low-pass filter.

f INSULATION RESISTANCE - The insulation resistance of the filter may vary during the life of the filter. Determine the maximum allowable variation of this resistance for proper filter operation, and design accordingly

g. SIZE AND WEIGHT - Size and weight may be important in some filter applications When space is at a premium, adding or subtracting various filter elements may be traded against reduced size and weight of the filter. Filter manufacturers are fairly flexible in being able to provide a wide choice in shape of the filter unit, its method of mounting, and the methods of making connections

h TEMPERATURE - The filter must be able to withstand the environmental operating ranges of the equipment in which it will be used.

i RELIABILITY - Filter component reliability must be commensurate with the equipment reliability requirement, and should be high relative to other equipment components This is primarily dictated by the fact that faults in filters may be somewhat more difficult to locate than faults in other components

8 4 Grounding

8 4 1 General Grounding involves the establishment of an electrically conductive path between two points, with one point generally being an electrical/electronic element of a system and the other being a reference point When the system element of concern is a circuit within a missile, then the reference point can be the equipment case or a ground plane that may or may not be isolated from the case A good, basic ground plane or reference is the foundation for obtaining reliable, interference-free equipment operation. An ideal ground plane should be a zero-potential, zero-impedance body that can be used as a reference for all signals in the associated circuitry, and to which any undesirable signals in the associated circuitry, and to which any undesirable single can be transferred for its elimination. An ideal ground plane would provide equipment with a common potential reference point anywhere in the system, so that no voltage would exist between any two points However, because of the physical properties and characteristics of grounding materials, no ground plane is ideal, and some potential always exists between ground points in a system The extent to which potentials in the ground system can be minimized and ground currents can be reduced will determine the effectiveness of the ground system. A poor ground system, by enabling these spurious voltages and currents to couple into a circuit, subassembly, or equipment, can degrade the shielding effectiveness of well-shielded units, can essentially bypass the advantages of good filters, and can result in EMI problems that may be rather difficult to resolve after-the-fact It is important to note that the designer must consider grounding from both inter- and intra-system points of view

8 4 2 Cabling The problem of electromagnetic compatibility in a complex electrical or electronic system is in many cases dependent on the treatment of the shielding and the grounding of the shields of interconnecting leads Poor or incorrect application of a grounded shield to a wire may cause coupling problems that otherwise would not exist Grounding of the shield may be accomplished as single-point or multi-point grounding Factors that influence the selection of single-point or multi-point grounding include the interference signal frequencies involved, the length of the transmission line, and the relative sensitivity of the cirucit to high- or low-impedance fields These are detailed in the reference documents listed in 2 1

8 4 3 Summary of grounding design guidelines Although the specific grounding philosophy to be employed is dependent on the detailed design characteristics of the system, it is possible to establish general grounding guidelines to follow. These are stated in a through k, with the understanding that they should not be applied rigidly, but that alternate grounding methods should also be evaluated before selecting a final design

a Use single-point grounding when the dimensions of the circuit or component under consideration are small compared to the wavelength of concern (typically less than 0 15 λ) Use multiple-point grounding when circuit or component dimensions exceed 0.15 λ Whenever possible, ground large circuits or components at several locations, so that the separation between grounds is never greater than 0.15λ

b Transformers and other isolation techniques can be used to prevent ground loops

c Keep all ground leads as short and direct as possible Avoid pigtails when terminating cables

d Maintain separate ground systems for signal returns, signal shield returns, power system returns, and chassis or case ground They can be tied together at a single ground reference point

e Ground reference planes should be designed so that they have high electrical conductivity, and so that they can be easily maintained to retain good conductivity

f. Circuits that produce large, abrupt current variations should have a separate grounding system, or should be provided with a separate return lead to the single-point ground. This will reduce transient pickup in other circuits

g Grounds for low-level signals should be isolated from all other grounds

h Never run supply and return leads separately, or in separate shields A twisted pair is the best configuration for the supply bus and its return Also, avoid carrying signal and power leads in the same bundle or in close proximity to one another When signal and power leads must cross, make the crossing so that the wires are at right angles to each other

i Use of differential or balanced circuitry can significantly reduce the effects of ground circuit interference

j For circuits that operate below 1 MHz, tightly twisted pairs of wires (either shielded or unshielded, depending on application) that are single-point grounded offer the best approach to reduced equipment susceptibility

k When coaxial cable is necessary for signal transmission, signal return through the shield and single-point grounding at the generator end offers certain advantages at the lower frequencies However, other grounding arrangements should be considered At high frequencies, multiple-point grounding of each shield is recommended

8 5 Circuit design

8 5 1 General High sensitivity, low signal-level circuitry tends to be prone to interference problems In most cases, the interference signal produced is proportional to the amount of energy leaking into the circuit If the design signal levels are large, circuits are inherently more resistant to interference

8.5.2 Selected circuit considerations

8.5.2.1 Common mode cancellation. One technique which is useful in controlling interference is the use of common mode cancellation in a differential amplifier. The intended signal, which may be either differential or single-ended, is fed into a differential amplifier through an RF coupling device which insures that interfering signals appear in equal magnitudes and in phase on each amplifier input. The resulting interference is then rejected due to common mode cancellation. Such a technique may provide 10-20 dB of system hardness and may be used in addition to other hardening techniques.

8.5.2.2 Component selection. When leakage is unavoidable because of difficulty in applying shielding and filtering techniques, the designer may still exercise some freedom in choosing particular types of components that are known to be less susceptible to interference that other types. For example, high-speed devices are more susceptible than low-speed devices. The choice of one component type over another **that performs the same function can result in 10-30 dB of additional hardness in a system.**

8.5.3 Summary of circuit design guidelines. When RF leakage into a system cannot be avoided because system constraints prevent the application of sufficient shielding or filtering measures, the designer should choose components and circuit configurations which provide for some degree of hardening. If at all possible, high-sensitivity, low-signal-level circuitry should be isolated from probable points of entry of RF energy into the system or circuit. In addition, the guidelines of a through e may be employed.

a. Use low-speed devices which are less susceptible than high-speed devices and avoid circuit overdesign with respect to speed or frequency response.
b. Operate critical or potentially susceptible devices at low gain and high collector current levels if compatible with other requirements.
c. Give special consideration to the use of circuits which minimize the effects of amplitude variation of the desired signal. For example, frequency modulation (FM) should be used instead of amplitude modulation (AM) whenever possible.
d. Use field-effect transistors (FETs) instead of bipolar devices of comparable speed.
e. Employ the common-mode cancellation feature of differential amplifiers.

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