NASA Contractor Report 4759

System Guidelines for EMC Safety-Critical Circuits: Design, Selection, and Margin Demonstration

R.M. Lawton

Prepared for Marshall Space Flight Center
under Contract NAS8–40259 and sponsored by
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Foreword

This report describes work accomplished under contract NAS8-40259. This work was funded by NASA's Space Environments Effects Program through the Electromagnetics and Aerospace Environments Branch of the Marshall Space Flight Center.

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1. INTRODUCTION

1.1 Goal

Demonstration of safety margins for critical points (circuits) has traditionally been required since it first became a part of systems-level Electromagnetic Compatibility (EMC) requirements of MIL-E-6051C.[1-1] The goal of this document is to present cost-effective guidelines for ensuring adequate Electromagnetic Effects (EME) safety margins on spacecraft critical circuits. It is for the use of NASA and other government agencies and their contractors to prevent loss of life, loss of spacecraft, or unacceptable degradation. This document provides practical definition and treatment guidance to contain costs within affordable limits.

1.2 Statement of Problem

EMC critical circuit safety margin demonstration is essential for NASA program success. The process used for both critical circuit identification and margin demonstration is not clearly documented or widely understood. For major programs, multiple (sometimes thousands) of critical circuits are erroneously identified. If all of these circuits were actually critical the system design would be fundamentally unsafe. Instead, many of these circuits are identified because they support a critical function, although each circuit identified is not critical. For example, a keyboard may be identified as critical because it is used on a computer which controls a command which controls a critical circuit. Contractors have seen these lists of circuits and been overwhelmed with the magnitude of verifying an EMC safety margin for each circuit. Another common misconception is in the area of the safety margin demonstration process. Margin is sometimes added to the basic equipment level susceptibility requirements instead of identifying the system level environment-derived circuit specific margins. A clear process is needed to eliminate those circuits which are not critical for EMC safety margin verification and identify guidelines for the entire margin demonstration

process. Such processes have been successfully used on NASA programs in the past, but have not been documented for general use. This problem is not unique as there are also no known documented general EMC critical circuit process guidelines for military applications.

As referenced in this document, a critical circuit is a circuit whose improper function, as influenced by electromagnetic interference, would result in loss of life, serious crew injury, loss of vehicle, mission abort, or endangerment of mission. Traditionally, system-level EMC specifications have imposed requirements to demonstrate a safety margin between the interference malfunction threshold (susceptibility) and the actual electrical noise level present on the circuit, assembled into the system, under installed, operational conditions. See Figure 1-1., EMC Critical Circuit Safety Margins.

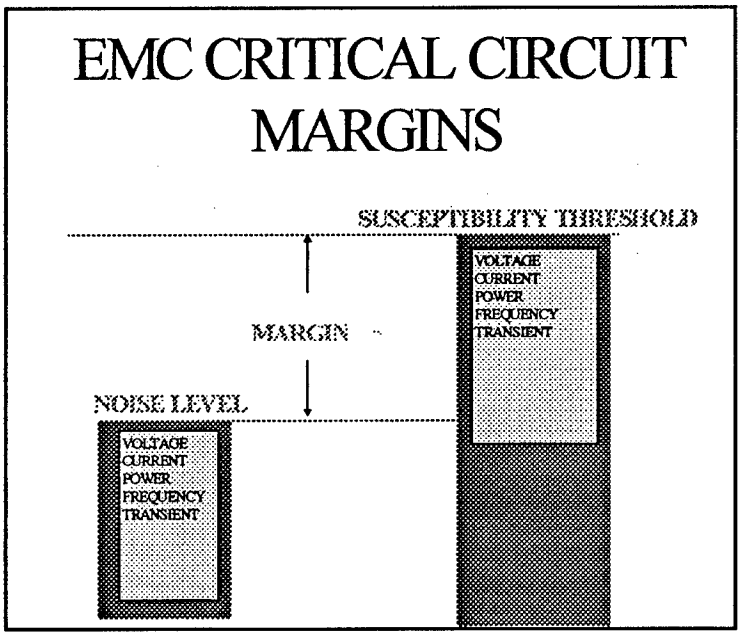


Figure 1-1. EMC Critical Circuit Safety Margins.

In practice, programs have limited the margin demonstration process to interference resulting from internal signal or power circuits and the external RF field environment. Other electromagnetic effects such as Electrostatic Discharge (ESD), lightning, strong magnetic sources, or other special noise

sources are treated as special cases and traditionally have not been part of the formal EMC margin demonstration program. Any program may elect however to treat these as a part of the EMC safety margin demonstration process and develop the special methodology required. This document will limit its treatment to the traditional intra- and inter- system noise coupling modes.

Generally, the demonstration requirement is 6 dB on signal, power, and control circuits and 20 dB on electroexplosive device firing circuits.

It is important to note that the EMC Critical Circuit process is an additional layer of safety practices over and above the normal requirements for good EMC engineering. It is assumed throughout this document that a high quality EMC engineering program to design and verify adequate performance of the system has been carried out.

REFERENCE

1-1. MIL-E-6051C, Military Specification, Electrical-Electronic System Compatibility and Interference Control Requirements of Aeronautical Weapon Systems, Associated Subsystems and Aircraft, 17 June 1960.

2. TECHNICAL MANAGEMENT OF CRITICAL CIRCUIT SELECTION PROCESS

2.1 Requirement for Safety Margins

The 6 dB margin (20 dB for electroexplosive devices) is well accepted. These margin values have been shown to be adequate for systems safety and performance and also technically achievable through experience with many systems over a long period of time. They should be applied.

2.2 EMC Critical Circuit Selection Management

The military specifications which define the criticality categories for margin demonstration requirements do not provide additional guidance criteria for critical circuit selection. Program management should require a dedicated, formalized process to be developed for critical EMC circuit selection. This process should be documented in the formal planning documents of the project with schedule milestones and progress reporting. The process should be tailored to fit the needs of individual programs. Systems Engineering, Electronic Subsystems Engineering, Safety, and Electromagnetic Compatibility functions must all participate in the process.

2.2.1 Assignment of Responsibilities

One difficulty in treatment of EMC-critical circuits is the confusion in organizations over responsibility assignments for the different tasks required in the process. Often the view is that, since the requirement is specified in an EMC standard, the EMC organization should be responsible for accomplishing all aspects of the process. However, this view fails to recognize that typically for large complex systems, EMC personnel have neither the training nor access to the information required to apply the selection criteria to identify those functions and circuits.

Proper assignment of responsibilities throughout this process is essential for success. Some relatively small programs may allow the EMC specialists to become sufficiently familiar with all the system functions to perform the entire selection process. However, for large complex systems, EMC expertise may not be useful during the critical function identification phase. Systems Engineering personnel should have primary lead with Safety oversight and support as needed from system designers. That phase requires assignment of personnel who must be knowledgeable of the overall system design as well as the planned operational scenarios. Evaluations are required of the credibility of many postulated modes of failure. Understanding of operations and caution and warning functions is necessary to determine credibility of failure recovery techniques. The flow chart of Figure 2-1., A through G, is applicable to this phase of the process.

2.2.2 Apply EMC Expertise

EMC expertise is required in steps H through K of the selection process of Figure 2-1. The documentation of candidate critical circuits prepared by Systems Engineering during the first phase is the starting point for the EMC engineer. First, the judgments of which circuits can reasonably be expected to have some susceptibility to Electromagnetic Interference must be made. Then EMC expertise is required to judge which circuits of redundant sets are most vulnerable if such a distinction can be made. Finally, the EMC engineer must document EMC critical circuits and plan the margin demonstration.

2.3 Detailed Selection Process

The following details an approach which leads to more effective cost control for the demonstration of safety margins for EMC-critical circuits. It is a logical method to eliminate from consideration circuits not having adequate justification for margin demonstration while ensuring that safety is not compromised. It discusses the flow of processes, decisions, and documentation illustrated in Figure 2-1. Activity Flow to Select and Document EMC Critical Circuits. Each block of the flow chart is described in the paragraphs following. Appendix A gives examples of the selection process applied to circuits.

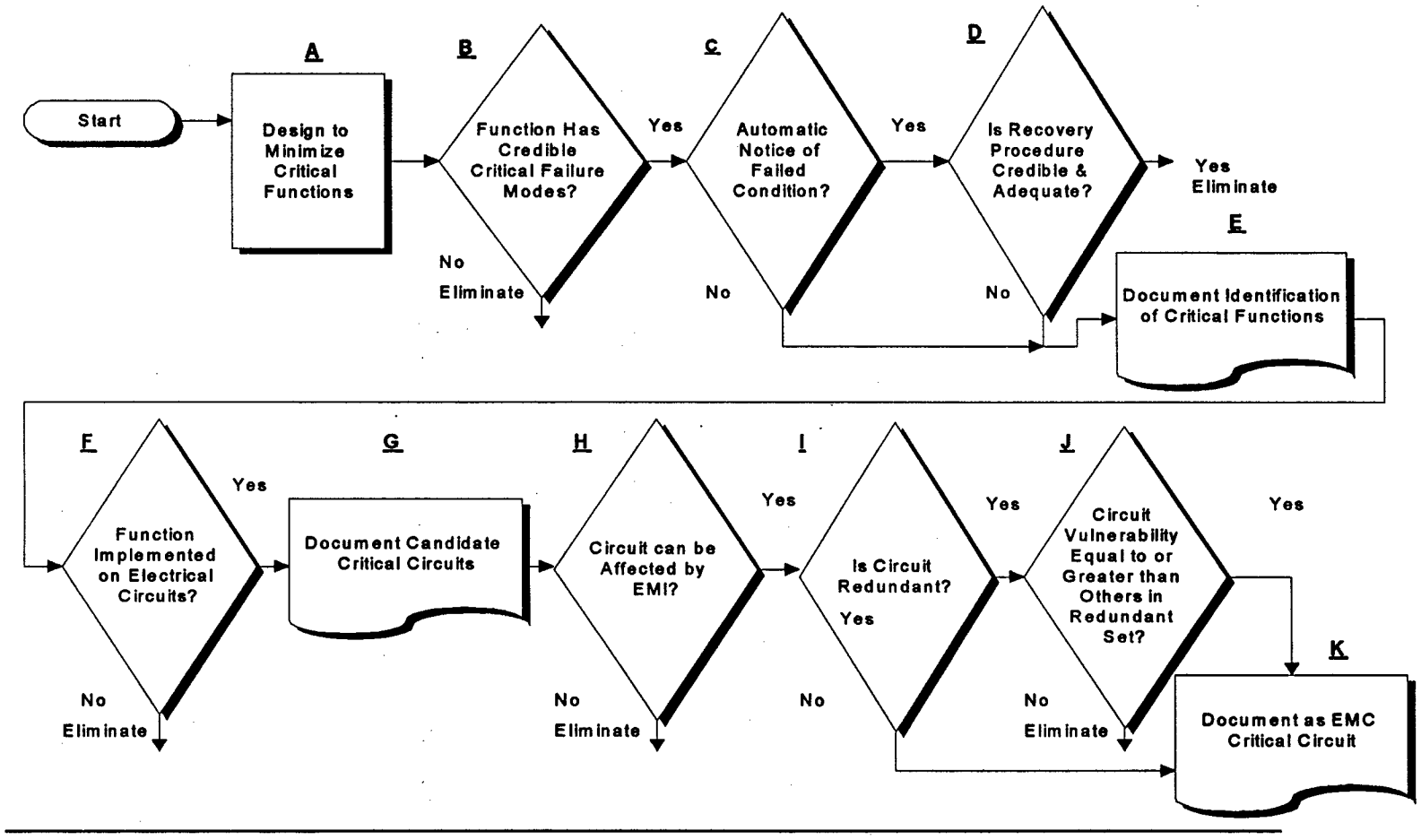


Figure 2-1. Activity Flow to Select and Document EMC Critical Circuits.

A Design to Minimize Critical Functions

As indicated in Figure 2-1, this step is a process, not a decision step. A significant consideration is the fundamental design practice which actively seeks to minimize the number of critical functions. A philosophy of designing failure tolerant systems underlies the safety, performance, and cost containment process. Limiting the number of critical functions necessarily limits the number of any subset such as EMC-critical circuits. While it may not be the purview of the EMC engineer, the success or failure of the designer in minimizing critical functions directly impacts program costs. Safety and cost control can be allies at the beginning of the project if a dedicated task is established to hold to a minimum the number of ways that functions can fail catastrophically. Control of EMC costs for critical circuit margin demonstration is directly affected by these early decisions since the EMC-critical circuits are a subset of the critical function list.

The Systems Engineering and Safety disciplines should share responsibility, with support from design groups, for performing this analysis and documenting the result for engineering management review. The task would consist of identifying critical function technical issues, performing interdiscipline coordination, issuing specific guidelines where required, analyzing failure effects, and documenting the results. Ground rules should be established at the beginning of this task.

B Function Has Credible Critical Failure Modes?

The test of function criticality is the effect on crew or craft of a credible failure of the function to perform its intended purpose at the intended time or inadvertent actuation of the function at an unintended time. If the result of such a credible failure is death or serious injury to the crew or destruction of the vehicle, then the function must be considered a candidate critical function.

Operational considerations should be taken into account. For example, if a potential critical function is active or vulnerable for a limited period of time and no threat of exposure is possible during that period, then it should be eliminated from further study. Consideration also should be given to potential changes in operational scenarios which would counter this logic.

Any number of highly unlikely failure events can always be postulated. Rigorous analysis is required of the operational conditions bounding a proposed failure mode. Engineering personnel expert in operations and effects should lead this decision step. Discipline is required to ensure that only those that are truly credible are identified as critical. Critical functions with non-credible failure modes must be eliminated from further consideration to control costs.

The system design knowledge required may be outside the domain of the EMC engineer. If the program is small enough that the EMC engineer can be in the mainstream of the functional design, then he or she may be in position to understand the mission consequences of any given functional failure and so may legitimately participate in the identification of the critical functions. However, some large programs may be so specialized and compartmentalized in their technical assignments that the EMC engineer does not have access to sufficient design information to make those determinations. Strong systems analytic skills are necessary to document an understanding of the failure effects. Good engineering judgment must be applied to ensure that failure modes so identified are credible. A common mistake is to "play it safe" and categorize many functions as critical to avoid the effort involved in making accurate determinations. This kind of overkill approach drives costs upward significantly. Another, and dangerous, approach is to "handwave" the requirements and jump to the conclusion that there are no or few such functions without doing the analytical work required.

Note that this process does not automatically result in all Electroexplosive Devices (EEDs) being classified as critical. If a credible rationale can be given that a particular EED cannot fail in a critical way, further testing and analysis might be wasteful and it may be excluded from the critical function category.

C Automatic Notice of Failed Condition?

If a failed condition is designed to provide automatic notice to the crew or operators of the system, there may be adequate time to take remedial action. If such a warning system exists, consideration of the function should be continued to the next decision step. If, however, no significant warning of the condition is given before the effects become catastrophic, the function is critical.

D Is Recovery Procedure Credible & Adequate?

This step presumes that the failure is obvious or a warning is automatically provided and that time is adequate to allow a recovery procedure. Any proposed recovery procedure should be evaluated to ensure that it is credible and reasonable. This procedure should be a documented part of the program. If such a documented procedure is found to be credible, the function may be eliminated from further consideration. However, if the recovery procedure is found to be inadequate, the function is critical.

E Document Identification of Critical Functions

At this point the list of critical functions should be documented along with the rationale supporting the selection. Descriptions of the rationale applied in the preceding steps are given in this phase of documentation. In practice, this may be a living document which may be modified as the design evolves and matures. It is the foundation for the selection process that follows.

F Function Implemented on Electrical Circuits?

This is a decision step which identifies those critical functions which are implemented through electrical circuits. It may or may not be a simple step, depending on the complexity of the system. The objective is to identify a list of circuits that can be considered as candidate EMC-critical circuits. Any function which is found to be implemented by purely mechanical means must be eliminated from further consideration. Those critical functions which are dependent on electrical circuitry to some degree must be analyzed to

determine if failure of the circuit can cause the function to fail critically. If the critical failure can be propagated through the circuit, the circuit is critical.

G Document Candidate Critical Circuits

The circuits identified by the preceding process should be listed at this point along with any supporting rationale used in making the decisions. This list constitutes the candidate critical circuits and will be used by the EMC specialists in the following steps.

H Circuit can be Affected by EMI?

The EMC specialists should study the candidate critical circuits list and evaluate the individual circuits for obvious immunity to Electromagnetic Interference. Circuits which, when examined by EMC personnel, are found to be obviously immune to EMI should be eliminated from further consideration. For example, a power circuit driving a simple DC motor is not likely to be influenced by stray electromagnetic energy. Or similarly, a high power relay is probably immune. Care must be exercised, however, to fully understand the circuit, since some apparently immune devices may have built-in sensitive circuit controls. Each of the candidate circuits must be documented as to the rationale for EMC-critical acceptance or rejection.

I Is Circuit Redundant?

Many critical circuits will be found to be redundant. At this point, if the circuit is not redundant it is identified as EMC Critical. If it is redundant it is subjected to the next decision step.

J Circuit Vulnerability Equal to or Greater than Others in Redundant Set?

If the circuit under consideration is one of a redundant set it must be examined relative to the other members of the set. It is cost-effective to test the worst-case circuit only. Normal design practices will dictate the routing of redundant circuit wiring through physically different paths, protecting against a common cause failing the set's function. A worst case may exist if

one circuit is physically routed so as to render it most vulnerable. Those shown to be less vulnerable than the others in the set may be taken as having margins greater than that demonstrated. Thus they may be eliminated from further consideration. If such a distinction cannot be made with confidence, then all members of the redundant set must be subjected to the test and analysis process for demonstration of margins.

K Document as EMC Critical Circuit

The final step in the process is to document those EMC critical circuits which require a safety margin demonstration. The rationale used in the selections made in steps H through J are given in this document. Those circuits which are firing circuits for EEDs are subject to requirements for demonstrating a 20 dB minimum margin and other circuits for only a 6 dB minimum margin.

3. ANALYSIS TECHNIQUES

3.1 Wire-to-Wire Coupling Analysis

At the system level, the primary entrance and exit points for extraneous electrical noise is through the exposed wire bundles which interconnect the electrical equipment. To minimize intra-system wire-to-wire noise cross-coupling, wire shielding and shield termination requirements, separation, and routing by EMC category are imposed. This isolates the sensitive circuits from the noisy circuits physically and by metallic shields and thus ensures that cross-coupling will be minimized. Strong enforcement of shield termination requirements must be a part of the systems EMC program. This is generally sufficient to achieve required safety margins for wire to wire coupled noise. However, circuits identified as EMC-critical should be analyzed for wire-to-wire coupling based on the actual physical routing of the circuit wires, frequency, and impedance characteristics of the commonly routed circuits. Particular attention should be paid to circuits sharing connectors. Typically, isolation from shielding and physical separation is diminished when circuits pass through connectors together. Several coupling algorithms are published. One of these is given below[3-1]. See Figure 3-1.

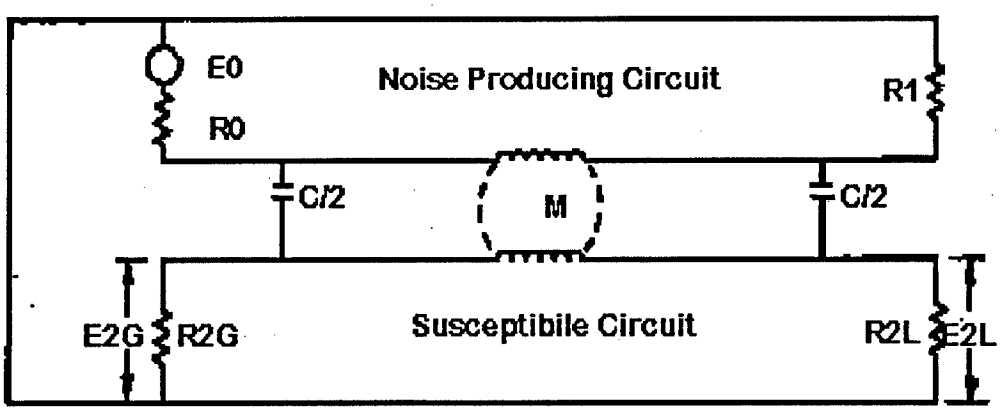


Figure 3-1. Wire to Wire Coupling.

For a system of two parallel wires as illustrated in Figure 3-1, the ratio of the voltage coupled into the generator side of the susceptible circuit to the noise voltage is given by the following:

$$E_{2G}/E_0=[R_1/(R_1+R_0)\cdot R_2/X_C]+[X_M/(R_1+R_0)\cdot R_{2G}/(R_{2G}+R_{2L})]=K_G\cdot f \qquad (1)$$

The fraction of the noise voltage appearing at the load end of the susceptible circuit is the following:

$$E_{2L}/E_0=[R_1/(R_1+R_0)\ R_2/X_C]-[X_M/(R_1+R_0)\cdot R_{2L}/(R_{2G}+R_{2L})]=K_L\cdot f \qquad (2)$$

where

E_0 = noise voltage in the interfering circuit,
E_{2G} = noise voltage coupled in the generator side of the susceptible circuit,
X_M = reactance component of the inductive coupling,
X_C = reactance component of the capacitive coupling,
E_{2L} = noise voltage coupled into the load side of the susceptible circuit,
K_G = coupling coefficient, generator side,
K_L = coupling coefficient, load side,
$R_2 = R_{2L}\cdot R_{2G}/(R_{2L}+R_{2G})$, (3)

f = frequency of interfering signal.

The following parameters and formulas must be known or calculated as inputs to the above equations.

$a_1 := 7.35\cdot 10^{-12}$ when l is in feet or $24\cdot 10^{-12}$ when l is in meters

$a_2 := 1.405\cdot 10^{-7}$ when using standard US units or $4.61\cdot 10^{-7}$ when using SI units

l = length of wires, millimeters (Inches)
D = separation of wires, millimeters (inches)
h = height above ground plane, millimeters (inches)
d = diameter of wire conductor, millimeters (inches)
d_1 = diameter of wire including the insulation, millimeters (inches)
K_0 = relative dielectric constant. For air, $K_0 = 1$
K_1 = relative dielectric constant of the wire insulation.

$S_{12} := \sqrt{(D^2 + 4\cdot h)}$

$$K_{eff} := K_0 + \frac{\left[\left(\frac{d_1}{d}\right)^2 - 1\right]}{\left[0.5\cdot\left(\frac{d_1}{d} + \frac{D}{d}\right)^2 - 1\right]}\cdot\left(K_1 - K_0\right)$$

C =Capacitance (in farads) between two wires above a ground plane.

$$C := \frac{a_1\cdot l\cdot\left(\log\left(\frac{S_{12}}{D}\right)\right)\cdot K_{eff}}{\left[\log\left[4\cdot\frac{h}{d}\cdot\frac{1}{\sqrt{2-\sqrt{\frac{d}{D}}}}\right]\right]^2 - \left(\log\left(\frac{S_{12}}{D}\right)\right)^2}$$

M = mutual inductance (in henries) between two wires above a ground plane.

$$M := a_2\cdot l\cdot\left(\log\left(\frac{S_{12}}{D}\right)\right)$$

$$X_M := 2\cdot\pi\cdot f\cdot M$$

$$X_c := \frac{1}{(2\cdot\pi\cdot f\cdot C)}$$

$$R_2 := R_{2L}\cdot\frac{R_{2G}}{R_{2L} + R_{2G}}$$

The coupling coefficients thus determined may be modified (reduced) by the common mode rejection of the victim circuit.

3.2 Susceptibility to External Fields

3.2.1 Introduction

The wire bundles also act as antennas and must be analyzed for field-to-wire coupling. The recommended process is generic and not limited in application to critical circuits and other approaches may be developed from the survey. However, a program might to apply the process to critical circuits and use that information to improve confidence in the overall system performance. The preliminary approach described herein is intended as a practical, conservative engineering process to be used as a general screening analysis to identify potential margin problems. The process is based on work funded by the Naval Surface Weapons Center in Dahlgren, Virginia. The basic work was performed by McDonnell Douglas, St. Louis. The approach builds on an assumption of normal EMC system-level design practices and wire routing. It is based on the disciplined application of the following three quantifiable factors:

1. RF environment at the circuit
2. Coupling to the circuit wiring
3. Generic susceptibility of integrated circuits

3.2.2 RF Environment at the Circuit

The RF environment must be determined from all relevant sources of information. The system communications and navigation specifications and installation drawings should specify the characteristics of transmitted signals such as average and peak power, antenna gain and pattern, directionality, and physical mounting geometry of antenna locations. Such characteristics of other RF systems that may be associated should be made available for analysis. Other RF emitters not associated but nonetheless causing RF field impingement on the subject circuit must also be evaluated. For example, spacecraft in Earth orbit are exposed to RF emanations from ground-based sources.

3.2.3 Coupling to Circuit Wiring

When the RF environment has been sufficiently described in terms of power density (watts/meter^2) at specified frequencies, the data can be applied to the following process to make a conservative prediction of the coupled noise power. It has been shown that a wire bundle can behave efficiently as a tuned dipole antenna. [3-2] Studies and experimental measurements on receiving patterns for spacecraft wire bundles have demonstrated this phenomenon. Measured patterns taken in an anechoic chamber in three dimensions yield a random directivity of radiation with the maximums lobes approaching the tuned dipole model as a limit. See Figure 3-2.

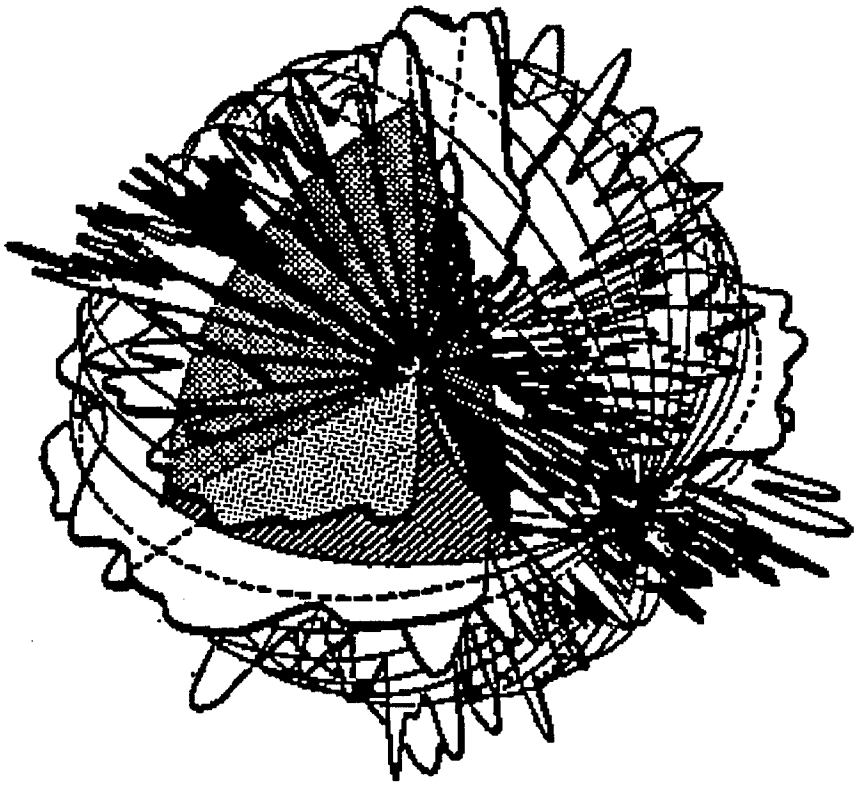


Figure 3-2. 3-D Antenna Pattern from Wire Bundles. [3-2]

Power received by an antenna is:[3-3]

$$P_r = P_d \cdot A_e \tag{4}$$

where: P_r = Received Power
P_d = Power Density
A_e = Effective aperture of the 1/2 wave dipole $= 1.64\lambda^2/4\pi$
$\lambda = c/f$; $c = 3x10^8$ m/sec, f = frequency of consideration

Or $$P_r = P_d \cdot 1.17x10^{16}/f^2 \tag{5}$$

For frequency stated in terms of megahertz:

$$P_r = P_d \cdot 11700/f^2 \tag{6}$$

Or: $$P_r = P_d \cdot K \tag{7}$$

where K is a calculated coupling factor.

This formula has been verified by test to approximate the limit of pickup on spacecraft wire bundles except at low frequencies. Below 300 MHz the predicted noise pickup becomes overly conservative, predicting unrealistically high levels. The recommended practice is to assume the 300 MHz value for frequencies below 300 MHz. Figure 3-3, Received Power Coupling Factor, shows the calculation of the coupling factor assuming - unshielded wiring.

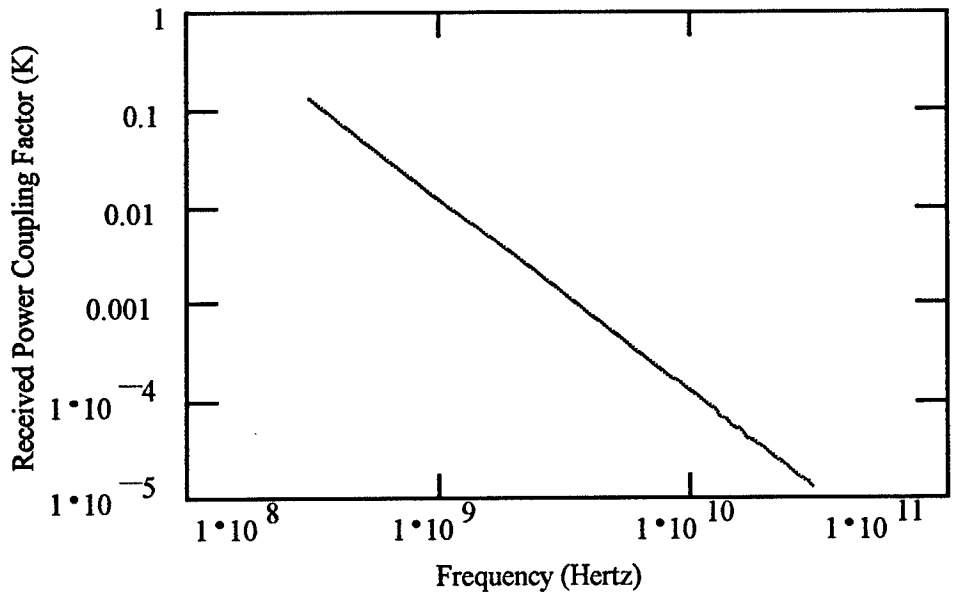


Figure 3-3. Received Power Coupling Factor.

An alternative, less conservative approach for calculating coupling at lower frequencies is given by Javor.[3-4] In terms of induced voltage, Vi, for a given electric field intensity, E, on a wire of length of l meters and a height above the ground plane of h meters:

$$Vi / E = (2\pi lh) / \lambda \qquad (8)$$

The power received on a circuit wire must also be modified by the effects of any wire shields and for the effects of any shielding enclosure in which the wiring may be installed. As shown in Figure 3-4, shielding effectiveness testing with the MIL-STD 1377 (Navy) test method in the range of 1 to 10 GHz, wire shielding with two inch pigtail termination is almost totally ineffective.[3-5] The two inch pigtail shield termination is considered a practical manufacturing limit on spacecraft wire bundle assemblies. One can usually expect the assembled bundle to be of less quality. By contrast, the same test method performed for wiring with 360° shield terminations was shown to have an effectiveness ranging from a minimum of 28 dB to a maximum of 43 dB over the same frequency range.

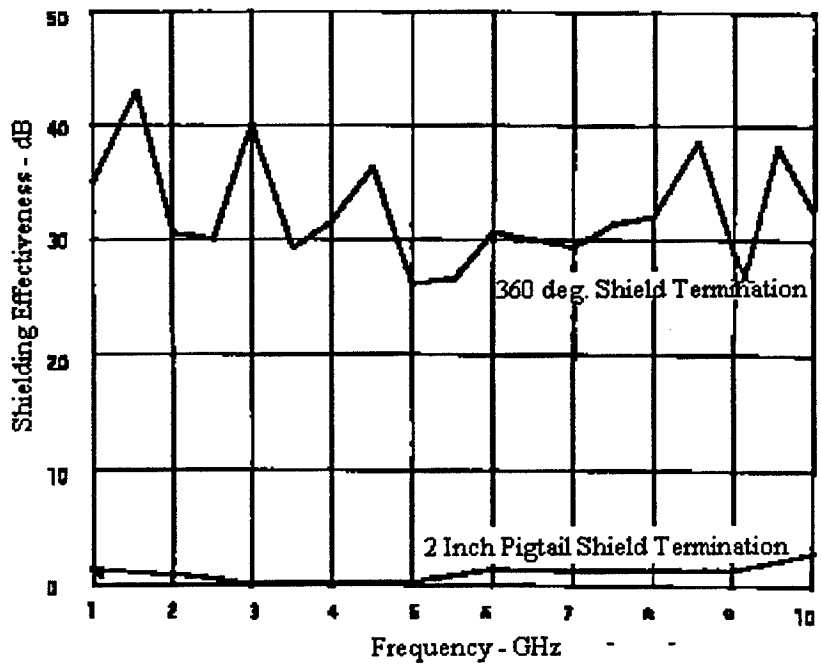


Figure 3-4. Cable Shielding Effectiveness per MIL-STD-1377.

For typical spacecraft wire bundles, it is recommended that a shielding effectiveness of 0 dB be assumed for the frequency range between 1 and 10 GHz For frequencies below that, it is recommended that an effectiveness of 20 dB be applied for up to 200 MHz, decreasing log-linearly to 0 dB at 1 GHz.

Figure 3-5, Power Coupling Factor with Shielding, shows the received power coupling factor with this shielding effectiveness taken into account. This approach is admittedly conservative and a specific project may have good justification for using greater shielding effectiveness. If justification such as test data on the specific manufacturing process for shielding installation exists, then it is prudent to use the less conservative values. The analysis should also include the shielding effectiveness of any metallic enclosure in which the wire bundle is contained.

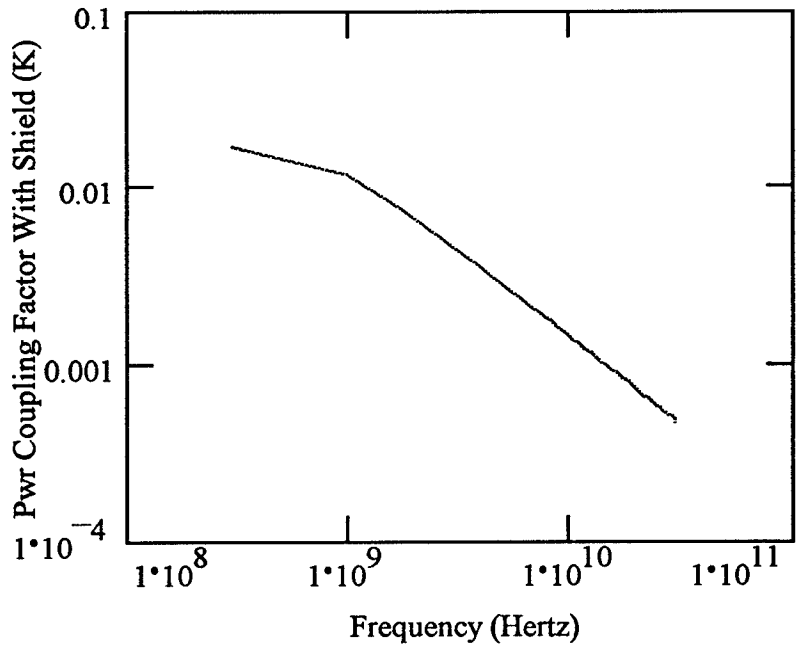


Figure 3-5. Power Coupling Factor with Shielding.

3.2.4 Integrated Circuit Susceptibility

3.2.4.1 Introduction

Integrated circuit RF susceptibility was determined in a generic way by the Navy and McDonnell Douglas.[3-6] Power was injected into many samples of a number of different device types. Thresholds were measured across a wide frequency range using impedance matching fixtures.

3.2.4.2 Digital Logic Device Susceptibility

Figure 3-6, Digital IC Susceptibility, gives the results of that effort for worst-case susceptibility for TTL and CMOS digital devices.

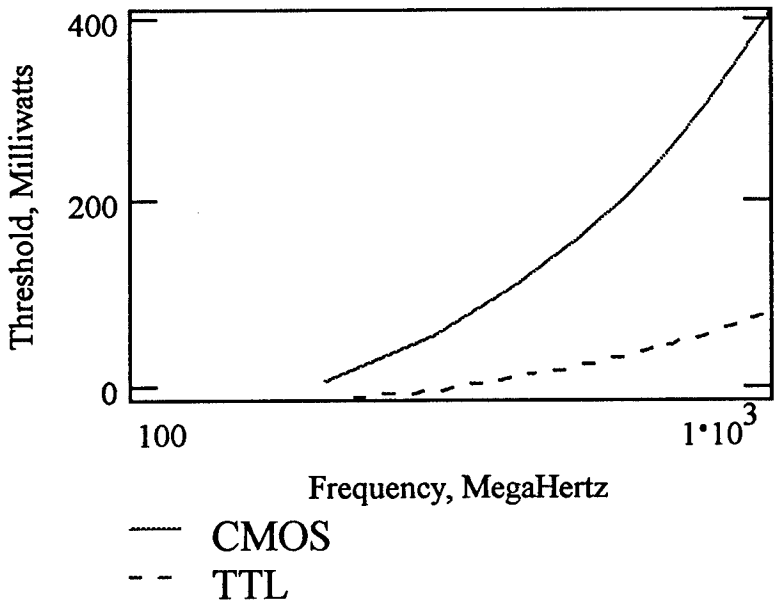


Figure 3-6. Digital IC Susceptibility.

The data shown in Figure 3-6 represents the mid-point of susceptibility taken by the study. Three levels of susceptibility were determined. The lowest level is the threshold of exceedance of manufacturer's tolerance. The highest level is that level that will ensure a digital upset. The level shown here is a point of ambiguous response where a digital upset may occur.

3.2.4.3 Line Driver and Receiver Susceptibility

Similar data were taken for line drivers and receivers. The receivers were found to be the most susceptible. Therefore the susceptibility data for receivers characterizes the set. Figure 3-7, Line Receiver Susceptibility, gives the threshold for receivers which caused a state change.

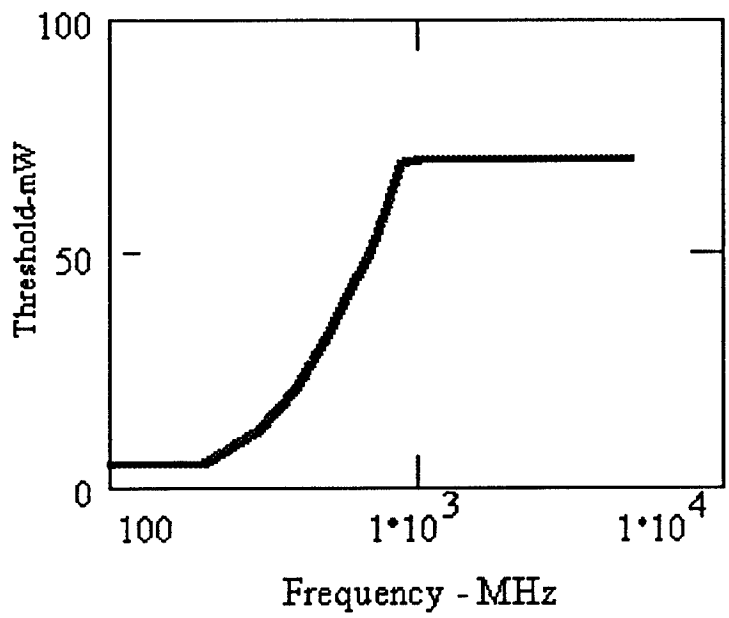


Figure 3-7. Line Receiver Susceptibility.

3.2.4.4 Analog Device Susceptibility

Figure 3-8, Operational Amplifier Susceptibility, shows the susceptibility of typical operational amplifiers. The data represent a level of susceptibility for a 50 millivolt offset of the operational amplifier output. A higher threshold can be used if greater offsets are allowed.

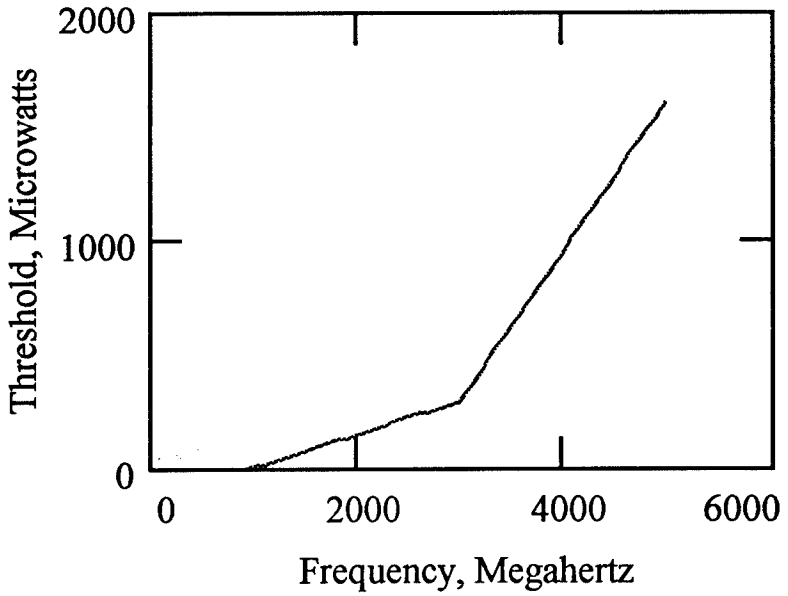


Figure 3-8. Operational Amplifier Susceptibility.

3.2.5 Summing the Effects

The EMC engineer applies the information of this section to get to a bottom line for critical circuits and overall system performance. The sum of the effects of the RF environment, the shielding effectiveness of the system and susceptibility of the components will yield a design margin. As can be seen from the coupling and susceptibility graphs, as frequency increases beyond 1 GHz, systems become less sensitive. The Integrated Circuit Electromagnetic Susceptibility Handbook[3-6] gives a more complete description of components tested.

REFERENCES

3-1. AFSC Design Handbook, DH 1-4, Electromagnetic Compatibility, Design Note 5B4

3-2. V. R. Ditton, Coupling to Aerospace Cables at Microwave Frequencies, IEEE International Electromagnetic Compatibility Symposium, 1975.

3-3. Reference Data for Radio Engineers, ITT.

3-4. Javor, Introduction to the Control of Electromagnetic Interference.

3-5. MIL-STD-1377 (NAVY), Military Standard, Effectiveness of Cables, Connectors, and Weapon Enclosure Shielding and Filters in Precluding Hazards of Electromagnetic Radiation to Ordnance, 20 August 1971.

3-6. Integrated Circuit Electromagnetic Susceptibility Handbook, Report MDC E1929, McDonnell Douglas Astronautics Company, St. Louis, 1 August 1978.

4. THE SAFETY MARGIN DEMONSTRATION PROCESS

4.1 Introduction

The process of demonstrating the required margins can vary considerably and should be developed in detail in the EMC Control Plan with close customer coordination. For very large systems, that must be assembled in space, such as International Space Station, a combination of analysis and test must be performed. A complete system-level test may not be possible before launch due to cost and logistics considerations. No one general process of analysis or test can be adequate for all situations. Therefore, the actual process must be defined for each system.

An additional consideration is the process to assure that margins are maintained over a long time period. There are instances of complex systems that are reused many times. They are also subjected to design modifications and can suffer damage (for example, damage to shielding terminations) from the manufacturing environment. For such systems a rigorous program of inspection and EMC test and analysis should be employed to verify that crew and mission safety is not compromised by design changes or performance degradation from damage.

The analytical methods of Section 3 can be applied when justified. Recommended test practices are included in the following section.

4.1.1 Conducted Noise Injection/Noise Measurement

4.1.1.1 Signal Circuits Susceptibility

4.1.1.1.1 CW Margins

Narrowband conducted interference is injected into the circuit by capacitive, inductive, or direct means. This is accomplished in the laboratory on engineering or qualification-type equipment. The interference level is increased until a threshold response is reached. In most cases these data are taken at discrete frequencies, i.e., four frequencies per decade. In some cases, a continuous frequency sweep is possible if the susceptibility threshold can be continuously tracked.

4.1.1.1.2 Transient Margins

Susceptibility thresholds are obtained in a manner similar to the CW method above except that the injected interference is in the form of pulses of varying widths. Data is taken for both positive and negative polarity pulses. Pulse amplitude is increased until the circuit response threshold is reached. These data are also taken in the laboratory on engineering or qualification - type equipment.

<u>Recommended Practice for CW and Transient Susceptibility Testing of Signal Lines</u>

Susceptibility testing for threshold determination is performed in the laboratory on non-flight units. CW (continuous wave) susceptibility is measured from 100 Hz to 20 MHz and to spikes of 1μs to 100μs duration. If the obtained data indicates the necessity of expanding the frequency range, additional frequencies and/or spike durations are evaluated. Since both ends of a circuit (source and load) can be susceptible, the failure criteria of the circuit is determined by the most susceptible end.

The methods for susceptibility testing are illustrated in Figure 4-1. Injection of interference by transformer coupling is illustrated in Figure 4-1a. This approach is typically used for low frequency (<200 kHz) CW injection. Figure 4-1b illustrates interference coupling obtained by capacitor coupling which typically is used for high frequency (≥200 kHz) CW injection. Spike injections can usually be performed using either transformer or capacitor coupling. In some instances, such as long duration spike injection, it may be necessary to connect the interference source into the circuit directly as shown in Figure 4-1c and 4-1d. When the interference source is directly connected in series (Figure 4-1c), care must be taken to keep the interference source isolated from ground. In all coupling methods, three parameters are measured during susceptibility testing.

For series coupling, the three parameters are:

(1) Interference voltage across circuit load;
(2) Interference voltage across the circuit source;
(3) Interference current, which is common to both the source and load;

For parallel coupling, the measured parameters are:

(1) Interference current to circuit load;
(2) Interference current to circuit source;
(3) Interference voltage, which was common to both the source and load;

By knowing the susceptibility of the circuit in terms of interference voltage and interference current, the system safety margin test is simplified in that either voltage or current, whichever was easiest to obtain, can be monitored for determination of the safety margins.

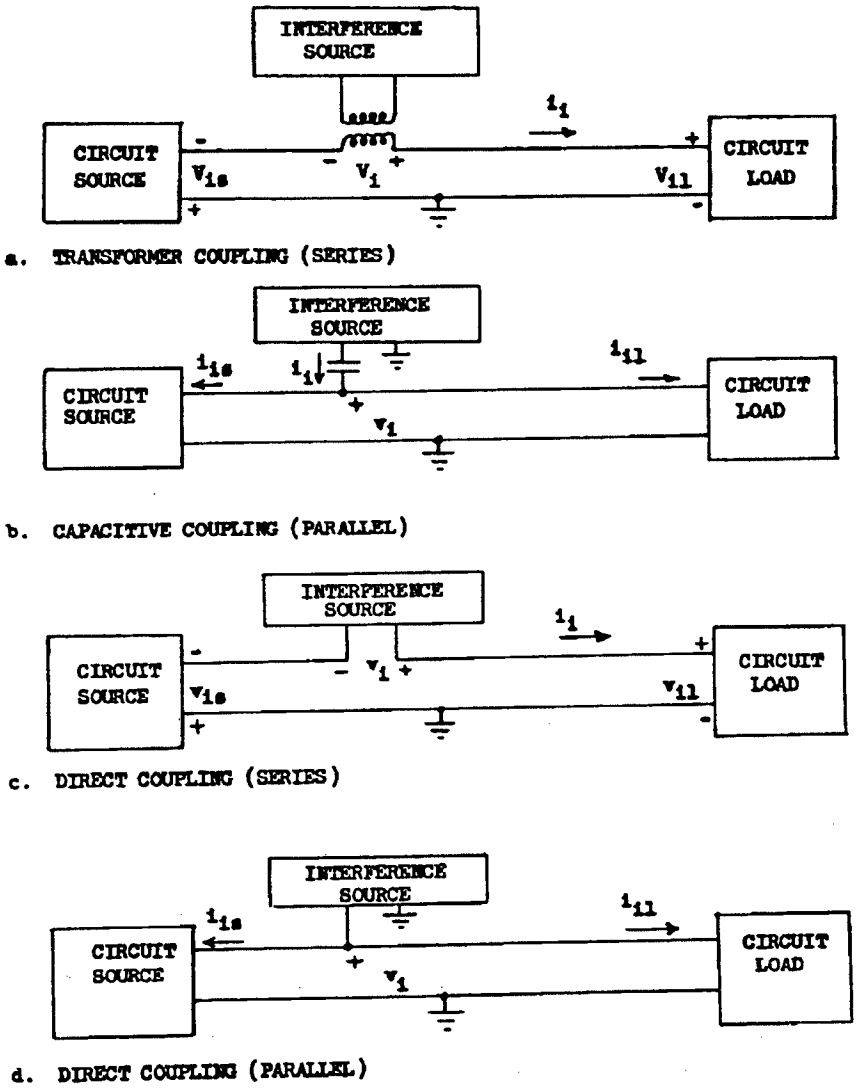


Figure 4-1. Susceptibility Test Methods.

CW susceptibility is determined at a minimum of four frequencies per decade (such as 100 Hz, 200 Hz, 400 Hz, 700 Hz, 1 kHz, 2 kHz, etc.) and spike susceptibility is determined for durations of 1μs, 10μs, and 100μs. The susceptibility data points are obtained by slowly increasing the interference amplitude or spike duration until a circuit malfunction occurs. To preclude circuit damage, the interference amplitude is not increased past 3 volts peak to peak for CW interference or 5 volts zero to peak for spike interference. If the circuit does not respond to these maximum levels, it is considered non-susceptible. If the calculated damage level of a circuit is less the 3 volts peak

to peak CW or 5 volt peak spikes, the interference amplitude is held below the calculated damage level. If the circuit does not respond to amplitudes below the calculated damage level, the susceptibility is considered equal to the damage level. If a preselected frequency causes a significantly greater susceptibility than other test frequencies, the frequency range near the troublesome frequency is tested in detail to find any susceptibility peaks.

All susceptibility testing is performed in the laboratory with the equipment under test connected in the configuration (including grounding) that is utilized in the flight vehicle. When susceptibility testing is completed, the data points are plotted to give continuous amplitude versus frequency or amplitude versus spike duration curves.

4.1.1.2 Power Circuits Susceptibility

Generally, CW and Pulse susceptibility of equipment power inputs is determined through testing to the equipment-level EMI requirements. MIL-STD-461 requires designing to meet specified injection levels.[4-1] These levels are, in general, sufficient to support the demonstration of the required safety margins on power circuits. However there is no assurance that the assembled system will not result in degradation of the margin. While power buses may or may not be defined as EMC critical, it is recommended that they be instrumented and tested for a 6 dB margin in any case. This practice is often helpful in demonstrating compliance with interface requirements of large systems which cannot be tested as an integrated assembly. Instrumenting the bus at the interface is a logical choice of location.

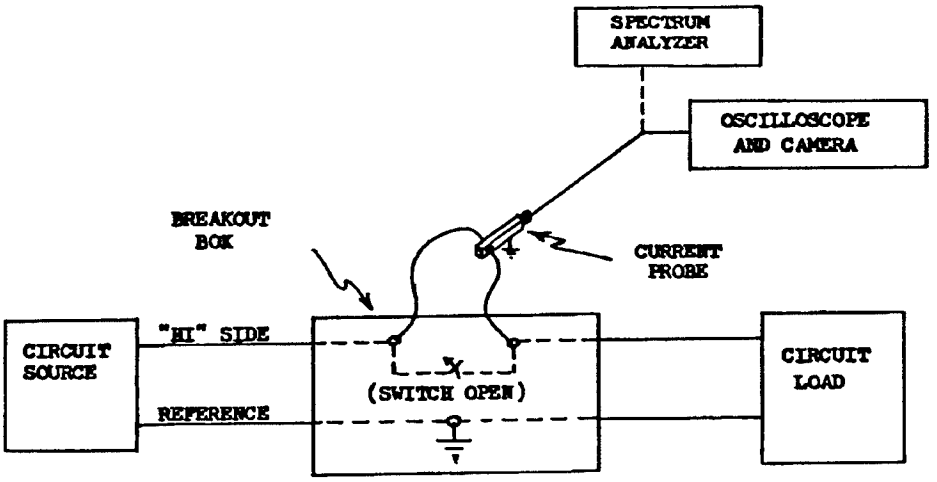
4.1.2 Signal and Power Circuit Interference

Measurements are made during system-level testing with all systems performing and sequenced as required during flight or mission. The same critical circuits examined for susceptibility earlier in the program are instrumented to measure the operating environment noise levels. These measured interference levels are then compared with the susceptibility levels for each circuit to derive the safety margin.

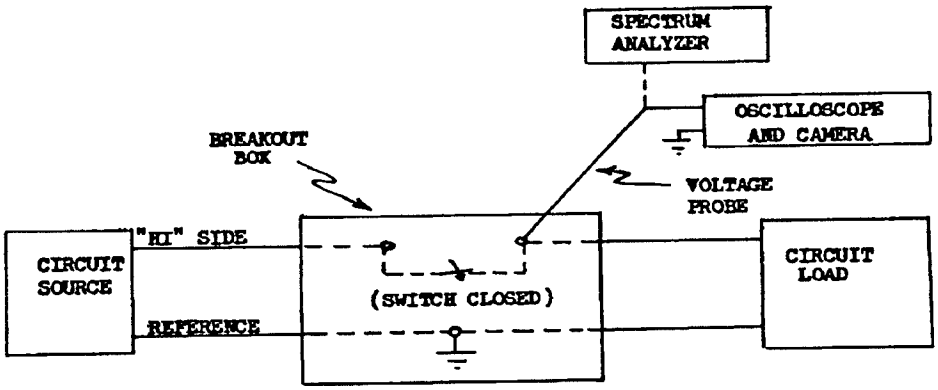
Recommended Practice for Conducted Interference Safety Margin Testing

The interference safety margins on the EMC-critical circuits are established by monitoring the interference on the circuits and comparing the observed levels of interference to the susceptibility thresholds of the circuits. CW interference is monitored while all systems are operating. Spike interference is continuously monitored while a simulated flight sequence is performed.

The EMC critical circuits are monitored by inserting a breakout box in the circuit, and connecting the necessary test equipment as shown in Figure 4-2. Interference waveforms with only one predominant frequency can be analyzed directly from the oscilloscope display. For complex interference waveforms, a spectrum analyzer is used to facilitate determination of the individual frequency amplitudes. In practice, oscilloscopes are used for these measurements until it becomes difficult to determine the frequency. At that point spectrum analyzers are inserted to measure the frequency content of the interference.



a. INTERFERENCE CURRENT MEASUREMENT



b. INTERFERENCE VOLTAGE MEASUREMENT

Figure 4-2. Interference Measurement Methods.

DC Power Buses

During a simulated flight sequence, transients on the buses are continuously monitored. The buses are monitored with a memory voltmeter, set up to measure spikes of 1 microsecond or greater duration, in conjunction with an analog recorder to give a permanent record of each bus. In addition, representative buses are monitored for voltage ripple with a wideband oscilloscope during a simulated flight sequence.

4.1.3 Radiated Testing Above Environment

The full-up system configuration is subjected to radiated RF electric field intensities a factor of 2 or 10 above the equipment radiated environment for the as-installed mission configuration. The specified noise environment will likely be an envelope which has been established with best available knowledge and is intended to include the effects of all RF radiated noise sources. If the critical component of the circuit has a known susceptibility vs frequency, the circuit may be monitored by a measuring device with equivalent impedance in place of the component and measurement of coupling be used to prove adequate margin. This type of test demonstrates safety margins only for the field-to-system coupling mode.

4.1.4 Increase Circuit Sensitivity

Still another technique that has been used is to insert overly sensitive (by the required margin) components in the critical circuit and demonstrate its performance in the system level environment. This technique is most appropriately applied when dealing with Electroexplosive Device (EED) firing circuits. Since the use of actual pyrotechnic devices could pose a hazard to the crew and system, dummy devices developed to indicate a power received 20 dB below the minimum fire level of normal devices may be inserted into the circuit instead of the EED. If a full simulated flight with realistic RF field exposures is performed and the device does not indicate power received greater than 20 dB below the flight device sensitivity, the safety margin has been demonstrated. Likewise, a measuring device of equivalent impedance may be used in place of the EED and the measured value of coupled noise can be used to show adequate margin.

REFERENCE

4-1 MIL-STD-461D, Military Standard, Requirements for the Control of Electromagnetic Interference Emissions and Susceptibility, 11 January 1993

APPENDIX A
EXAMPLES OF EMC CRITICAL CIRCUIT SELECTION AND ANALYSIS

A.1 Examples of Selection and Analysis

Examples of potential EMC-critical circuits are postulated and developed to demonstrate the selection and analysis process. A very brief discussion of selection is given as it relates to the process steps is Figure 2-1. It will be assumed that the system design is already fixed and the selection process will begin with the determination of credible critical failure modes.

A.1.1 Selection Examples

A.1.1.1 Example No. 1: A pyrotechnic firing circuit.

Function: Ignition of rocket booster motor for manned spacecraft.

Description: Inadvertent firing poses high safety risk for crew.

Operational requirements remove safing inhibitors 3 hours before launch. Inadvertent firing would have immediate catastrophic results without warning to crew. No recovery procedure is available. Function is implemented by a NASA Standard Initiator (NSI) with a 28V firing circuit. NSI susceptibility to RF interference is known. For this example, the minimum no-fire level is given as 1 watt or 1 amp pin-to-pin. Circuit is dual redundant. It cannot be demonstrated with confidence that either circuit is more exposed or vulnerable than the other.

Circuit wiring description: Twisted shielded pair, AWG 18, Kapton insulation, source and load impedance= 1 ohm, routed on dedicated path exposed to external launch environment under vehicle access panel, no other circuits in proximity. Shielding multipoint ground terminated. Length of firing circuit= 10 feet. Height above ground plane= 2 inches.

Selection Process:

A **Design to Minimize Critical Functions.**

In the example the system design has been completed and it is assumed that this critical function is necessary.

B **Function has Credible Critical Failure Modes? Yes**

After the safing devices are removed the firing functions are vulnerable to impinging RF energy. Inadvertent firing of the initiators yields catastrophic results. Unintended firings have occurred on other programs in the past. This failure mode is credible.

C **Automatic Notice of Failed Condition? Yes**

There is an indication of initiator firing by means of instrumentation. Automatic notice is given.

D **Is Recovery Procedure Credible & Adequate? No**

Due the almost instantaneous nature of the explosives involved, there is not sufficient time and no recovery procedure exists.

E **Document Identification of Critical Functions.**

The rationale for selection of this function as a critical function is documented for use in the completion of this process.

F **Function Implemented on Electrical Circuits? Yes**

The design uses NASA Standard Initiators which are activated by a 28 volt electrical signal.

G **Document Candidate Critical Circuits.**

The documentation is a simple selection of those functions identified in step **E** which are implemented on electrical circuits.

H **Circuits can be Affected by EMI? Yes**

The NSI has documented susceptibility to Electromagnetic Interference.

I Is Circuit Redundant? Yes

Circuit is described as dual redundant. That is, there are two circuits performing the same function.

J Circuit Vulnerability Equal to or Greater than Others in Redundant Set? Yes

Because there is uncertainty regarding the relative vulnerability of the redundant set, both of the circuits are taken as EMC critical.

K Document as EMC Critical Circuit.

This is the final documentation that describes in detail the rationale applied in selecting this circuit. It is add to the list of circuits for which safety margin demonstrations are required.

A.1.1.2 Example No. 2 Temperature sensing /control function

Function: Detection and correction of pressurized area over-temperature condition.

Description: Monitor and actively control temperature of habitable area.

Commercial grade components used. Over-temperature conditions result in a audible alarm and visual indication. Overall system has long time constant response. Operational reality is that flight crew would become aware of over-temperature since the catastrophic effect is not immediate, the crew will have adequate time to perform manual work-around. Work around operations are in place or planned.

Circuit and wiring description:

0 to 5 volt analog single ended, unshielded, high, and return sides routed on different paths. The analog circuit has a source impedance of 1000 ohms and a load impedance of 1000 ohms. Routed for 25 feet inside of pressurized volume adjacent to (average of 0.25 inch) 28 volt power bus, non-redundant. Height above the ground has been estimated at 2.5 inches. The bus has a predominant noise frequency of 3 kHz at 1 volt peak to peak. It's source impedance is 0.25 ohms and load impedance is 0.25 ohms. The wiring is AWG 20 gage and the insulation is Teflon. From wire tables it can

determined that the diameter of 20 gage wire is 0.032 inches. From engineering handbooks it can be found that the relative dielectric constant of Teflon is 2.1. It is given that the insulation thickness is equal to the radius of the wire conductor. Information resolution is 50 millivolts and the circuit bandwidth is 6 kHz. Therefore a noise level in excess of 50 millivolts will degrade the accuracy of the measurement.

Selection Process

A **Design to Minimize Critical Functions**

It is assumed that the design exists and that it has been determined that this function is necessary.

B **Function has Credible Critical Failure Modes? Yes**

Failure effects include potential electrical equipment failure from over-temperture and significant crew health hazard. Components used in the design which have reliability limitations and similar failures have occurred in other systems.

C **Automatic Notice of Failed Condition? Yes**

Alarm given when over-temperature occurs.

D **Is Recovery Procedure Credible & Adequate? Yes**

Sufficient time is available and recovery procedure exists. This eliminates the function from further consideration.

A.1.1.3 **Example No. 3** Experiment data bus.

Function: Provides experiment data to data relay system for transmission to ground station and use by experimenter. Effect of lost or corrupted data is of concern to experimenter but not a safety issue and does not catastrophically effect overall mission.

Description: 0 to 5 volt digital data stream, line driver/receiver routed on twisted shielded pair, shield multipoint grounded with 2 inch pigtail terminations. Device susceptibility is unstated. Routed away from other lines on external skin of vehicle. Vehicle flight attitude exposes the circuit to a 1 GHz radiated RF source that causes 80 volts/m to impinge on the wiring.

A **Design to minimize Critical Functions.**
It is assumed the design exists.

B **Function has Credible Critical Failure Modes. No.**
This function cannot be justified as critical.

A.1.2 Analysis Examples

This section is provided to give examples of how analysis may be applied to the margin evaluation of critical circuits. Since the primary entry of interference into the systems is through noise coupled from adjacent wiring or from RF fields propagated to the vicinity of the wire bundles, these sources of noise entry must be treated. This assumes that the basic EMC design job of electrical bonding, grounding, and the use of continuous metallic enclosures (elimination of RF apertures) has been accomplished. Methods of calculation of noise pick-up on system wiring are described. Then the technique of comparing the predicted noise to the generic susceptibility of integrated circuits is given.

A.1.2.1 Example No.1 Analysis

Taking example No. 1 again, it is observed that no other circuits are routed in proximity. Therefore, no calculation of wire-to-wire coupling is necessary. However, during launch the firing circuit is exposed to RF field intensities on the external vehicle of 60 volts/meter at 8.2 GHz.

At 60 volts/meter plane wave field intensity, the power density is $E^2/377$ or 9.6 watts/m^2. Applying the dipole model of equation (6) and making initial assumptions that the circuit is completely unprotected by shielding, the power received is:

$$P_r = (9.6)(11700)/(8200)^2 = 1.7 \text{ milliwatts}$$

This pyrotechnic device is assumed to have a worst case susceptibility higher than 1 amp or 1 watt differential (pin-to-pin). This noise pickup is common mode and the circuit is balanced. Therefore, an extreme worst case margin can be calculated assuming it is unprotected by shielding, and not accounting for the high common mode rejection. The worst case margin, even assuming that the noise is coupled differential mode, can be calculated as 10 log(1/.0017) or 28 dB. This margin is adequate and no evaluation of shielding effectiveness of the vehicle skin and wire bundle shielding is required. Should it have been necessary to include the effects of shielding, a very conservative assumption could be made, or it could have been determined by test or by comparison to similar installations with known shielding effectiveness. Some electroexplosive devices may have pin-to-case susceptibility and it could be lower than the pin-to-pin thresholds. In such cases the common mode noise would be compared to the pin-to-case susceptibility.

A.1.2.2 Example No. 2 Analysis

Circuit example No. 2 can be analyzed as follows. Even though it was determined that it is not an EMC critical circuit, normal design practice would dictate some analysis to assure its proper function.

Applying the calculation technique given in AFSC Design Handbook DH 1-4, Design Note 5B4, and inserting the parameters given in the circuit description yields the following[A-1]. Standard US units are used.

$a_1 = 7.35 \cdot 10^{-12}$ when l is in feet or $24 \cdot 10^{-12}$ when l is in meters

$a_2 = 1.405 \cdot 10^{-7}$ when using standard US units or $4.61 \cdot 10^{-7}$ when using SI units

l = length of wires, millimeters (Inches)

D = separation of wires, millimeters (inches)

h = height above ground plane, millimeters (inches)

d = diameter of wire conductor, millimeters (inches)

d_1 = diameter of wire including the insulation, millimeters (inches)

K_0 = relative dielectric constant. For air, $K_0 = 1$

K_1 = relative dielectric constant of the wire insulation.

For the given set of conditions for this specific circuit:

$l := 30$

$D := 0.2$

$h := 2.$

$d := 0.03$ For AWG 20 wire

$d_1 := 0.06$ Assumes insulation thickness = radius of conductor

$K_0 := 1$ For air

$K_1 := 2.1$ For Teflon

$f := 300$

$E_0 := 1.0$

$R_0 := 0.25$

$R_1 := 0.25$

$R_{2G} := 100$

$R_{2L} := 100$

$$S_{12} := \sqrt{(D^2 + 4 \cdot h)}$$

$$K_{eff} := K_0 + \frac{\left[\left(\frac{d_1}{d}\right)^2 - 1\right]}{\left[0.5 \cdot \left(\frac{d_1}{d} + \frac{D}{d}\right)^2 - 1\right]} \cdot (K_1 - K_0)$$

C = Capacitance (in farads) between two wires above a ground plane.

$$C := \frac{a_1 \cdot l \cdot \left(\log\left(\frac{S_{12}}{D}\right)\right) \cdot K_{eff}}{\left[\log\left[4 \cdot \frac{h}{d} \cdot \frac{1}{\sqrt{2 - \sqrt{\frac{d}{D}}}}\right]\right]^2 - \left(\log\left(\frac{S_{12}}{D}\right)\right)^2}$$

M = mutual inductance (in henries) between two wires above a ground plane.

$$M := a_2 \cdot l \cdot \left(\log\left(\frac{S_{12}}{D}\right)\right)$$

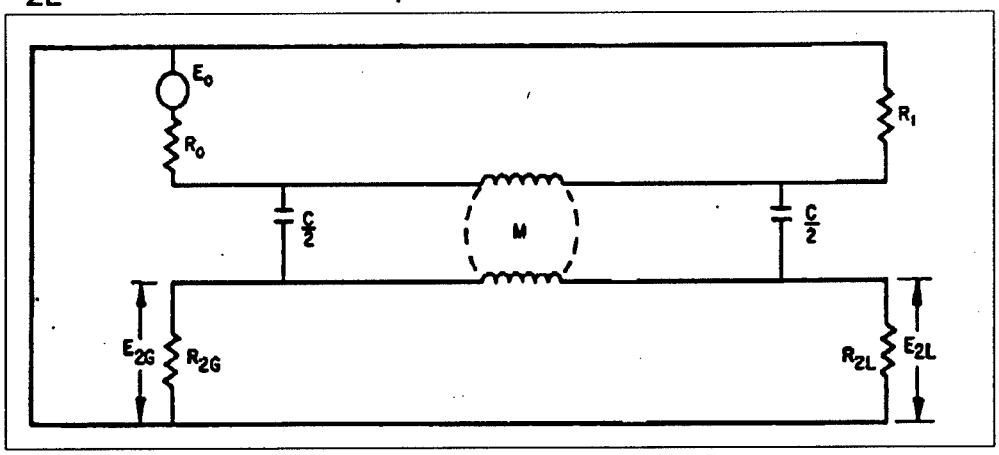
$$X_M := 2 \cdot \pi \cdot f \cdot M$$

$$X_c := \frac{1}{(2 \cdot \pi \cdot f \cdot C)}$$

$$R_2 := R_{2L} \cdot \frac{R_{2G}}{R_{2L} + R_{2G}}$$

The following equations yield the interference voltage at the generator end and the load end caused on a victim circuit by a culprit circuit.

E_0 = Culprit circuit Interference Source Magnitude
R_0 = Culprit circuit source impedance
R_1 = Culprit circuit load impedance
M = Mutual inductance between two wires
C = Capacitance between two wires
E_{2G} = Victim circuit noise voltage on generator end
E_{2L} = Victim circuit noise voltage on load end
R_{2G} = Victim circuit source impedance
R_{2L} = victim circuit load impedance



Model of wire-to-wire noise coupling

$$E_0 \cdot \left[\left[\left(\frac{R_1}{R_1 + R_0} \right) \cdot \frac{R_2}{X_c} \right] + \left[\left(\frac{X_M}{R_1 + R_0} \right) \cdot \frac{R_{2G}}{R_{2G} + R_{2L}} \right] \right] = 0.879 \quad = E_{2G}$$

$$E_0 \cdot \left[\left[\left(\frac{R_1}{R_1 + R_0} \right) \cdot \frac{R_2}{X_c} \right] - \left[\left(\frac{X_M}{R_1 + R_0} \right) \cdot \frac{R_{2L}}{R_{2G} + R_{2L}} \right] \right] = -0.874 \quad = E_{2L}$$

Thus, the coupled voltage for this circuit is approximately 0.88 volts. Clearly, it is well above the 50 millivolt allowable. At this point in the analysis the EMC engineer should have some good ideas of how to improve the system performance. Some combination of the following will provide acceptable performance:

- Route as balanced, twisted shielded pair with high common mode rejection instead of single ended, and unshielded.
- Separate further from the power bus.
- Use a bandwidth much more narrow if application allows it.

A.1.2.3 Example No. 3 Analysis

Circuit No. 3 is not exposed to wire-to-wire coupling but it is exposed to external radiated fields. 80 volts/m for free space impedance is $(80)^2/377$ or 17 watts/m^2. Using the dipole model of equation (6) yields:

$$P_r = (17)(11700)/(1000)^2 = 0.199 \text{ Watts} \quad \text{or say 200 Milliwatts.}$$

From Figure 3-4 it can be seen that wire shielding effectiveness for this type of circuit treatment (not 360 degree terminated) is negligible. Therefore it may be assumed that the 200 milliwatts can flow into the line receiver. Figure 3-7 gives the susceptibility threshold of line receivers at approximately 70 milliwatts for a frequency of 1 GHz. The indicated received RF noise is almost a factor of 3 above the threshold power. In a case like this 360 degree shielding terminations would be required.

REFERENCES

A-1 AFDC Design Handbook DH 1-4, Design Note 5B4

APPENDIX B
APPROACHES TO THE DEMONSTRATION OF EMC CRITICAL CIRCUIT SAFETY MARGINS

B.1 Approaches to the Demonstration Process

A discussion of approaches for demonstrating critical circuit safety margins taken by large man-rated systems is useful in understanding the range of acceptable possibilities. The following was taken from the EMC documentation of the Skylab Airlock Module (AM) Vehicle (includes all electrical/electronic systems) and the Solid Rocket Booster of the Space Shuttle Program.

B.2 SKYLAB

B.2.1 Requirements

The definition of Critical Circuits for this program is quoted from MDC Report H031, Electromagnetic Compatibility Control Plan for Airlock Module.[B-1]

"Those functions or circuits which if susceptible to EMI could cause a system response which would directly affect crew safety, to the extent of loss of life, or which would cause a mission abort, or failure to achieve a primary mission objective."

The Contractual requirement for safety margin demonstration on critical circuits is quoted from MDC Report H031.

"The AM, MDA, experiments, and assembled GSE will be subjected to EMC tests to comply with the intent of the Safety Margin requirements of MIL-E-6051C. These tests will determine if any undesirable interactions exist between the flight AM systems, MDA, experiments, and GSE. MDAC-East is required to demonstrate a Safety margin on all EMC critical circuits of the Airlock Module.

(1) To demonstrate the safety margin by test, susceptibility testing will be performed as laboratory development tests at St. Louis on AM subsystems (non-flight equipment). The critical circuits will be tested for susceptibility to CW from 100 Hz to 20 MHz and for susceptibility to transient pulse widths from one microsecond to 100 microseconds. These tests will establish the susceptibility thresholds of the critical circuits.
(2) Circuits which are discovered to have thresholds much higher than any expected noise level will be eliminated from further testing.
(3) Those remaining circuits will be monitored for CW and transient EMI during vehicle systems testing while the AM and MDA were operated in typical flight sequence.
(4) The interference data will be compared to the susceptibility threshold data to obtain the safety margin."

"The AM/MDA will be subjected to a radiated level which is six dB higher than the expected cluster radio frequency (RF) power level. This will require that all AM/MDA systems be monitored while the AM/MDA was simultaneously illuminated by the Skylab transmitters frequencies. If a malfunction occurs, the radiation will be reduced until the malfunction clears."

"The AM power buses will be monitored for transients during vehicle systems testing."

B.2.2 Skylab EMC Critical Circuits

The following was excerpted from MDC Report EO333, Airlock Module Electromagnetic Interference Test Plan.[B-2] The circuits identified in this plan were referred to as potential EMC-Critical Circuits. A list of these circuits follows.

a. Fire Sensor output for Fire Control Panel
b. Fire Control Panel output to C&W Unit
c. Rapid ΔP Sensor output to C&W Unit
d. CRDU (Command Relay Driver Unit) data input
e. CRDU ready input
f. VCG (Vector Cardiogram) Telemetry Parameters

g. Tape Recorder clock signal to Tape Recorder
h. Timing drive signal to Interface Box
i. Timing reset signal to Interface Box
j. Sample (3/4 word) signal to Interface Box
k. 5.12 kB clock signal to Interface Box
l. RZ timing signal to Interface Box
m. TRS clock signal to Interface Box
n. Bit signal to Interface Box
o. Bit rate signal to Interface Box
p. 12.8 kB signal to Interface Box
q. Digital insert signal to Programmer
r. Fine time insert signal to Programmer
s. HL data switch to Programmer
t. PSC Sync Signal to Programmer

B.2.3 Susceptibility Testing

Susceptibility testing for threshold determination was performed in the laboratory on circuits involving 9 pieces of equipment (non-flight units). CW (continuous wave) susceptibility was measured from 100 Hz to 20 MHz, and to spikes of 1μs to 100μs duration. If the obtained data indicated the necessity of expanding the frequency range, additional frequencies and/or spike durations were evaluated. Since both ends of a circuit (source and load) can be susceptible, the failure criteria of the circuit was determined by the most susceptible end.

The methods for susceptibility testing are illustrated in Figure B.2-1. Injection of interference by transformer coupling is illustrated in Figure B.2-1a. This approach was typically used for low frequency (<200 kHz) CW injection. Figure B.2-1b illustrates interference coupling obtained by capacitor coupling, which typically was used for high frequency (>200 kHz) CW injection. Spike injections can usually be performed using either transformer or capacitor coupling. In some instances, such as long duration spike injection, it may be necessary to connect the interference source into the circuit directly as shown in Figure B.2-1c and B.2-1d. When the interference source was directly connected in series (Figure B.2-1c), care must be taken to keep the interference source isolated from ground. In all coupling methods, three parameters were measured during susceptibility testing.

For series coupling, the three parameters were:

(1) Interference voltage across circuit load
(2) Interference voltage across the circuit source
(3) Interference current, which was common to both the source and load

For parallel coupling, the measured parameters were:

(1) Interference current to circuit load
(2) Interference current to circuit source
(3) Interference voltage, which was common to both the source and load

By knowing the susceptibility of the circuit in terms of interference voltage and interference current, the system safety margin test was simplified in that either voltage or current, whichever was easiest to obtain, could be monitored for determination of the safety margins.

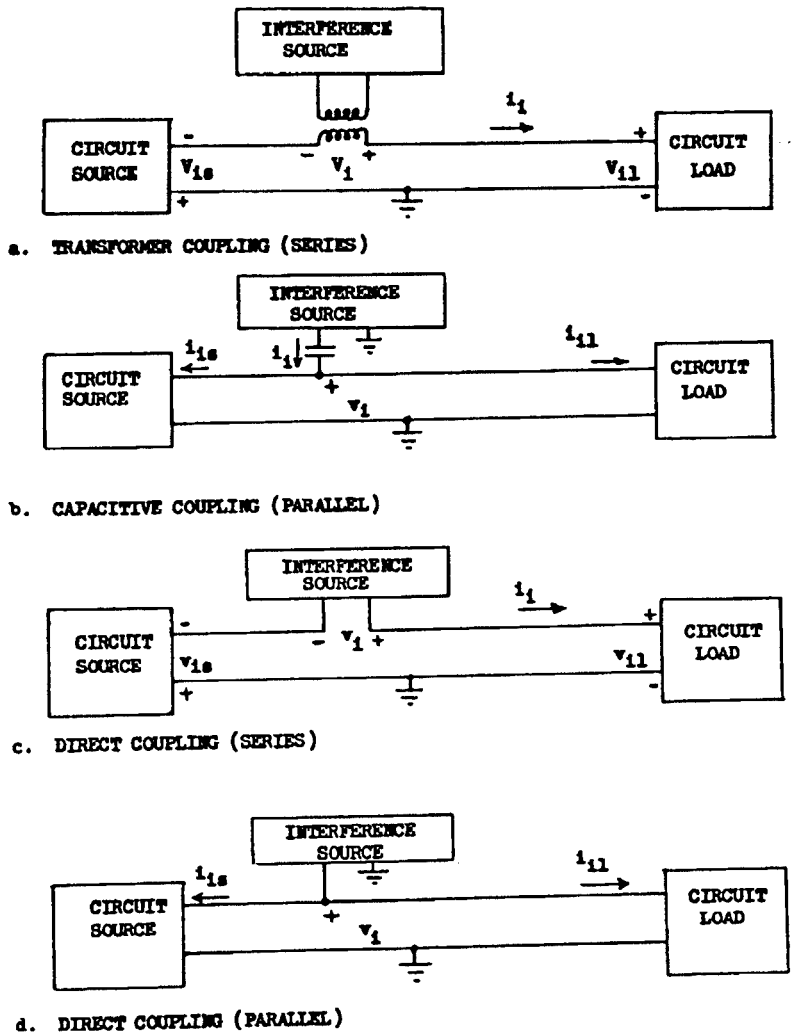


Figure B.2-1. Susceptibility Test Methods.

CW susceptibility was determined at a minimum of four frequencies per decade (such as 100 Hz, 200 Hz, 400 Hz, 700 Hz, 1 kHz, 2 kHz, etc.) and spike susceptibility was determined for durations of 1μs, 10μs, and 100μs. The susceptibility data points were obtained by slowly increasing the interference amplitude or spike duration until a circuit malfunction occurred. To preclude circuit damage, the interference amplitude was not increased past 3 volts peak to peak for CW interference or 5 volts zero to peak for spike interference. If the circuit did not respond to these maximum levels, it was considered non-susceptible. If the calculated damage level of a circuit was less the 3 volts peak to peak CW or 5 volt peak spikes, the interference amplitude was held below the calculated damage level. If the circuit did not respond to amplitudes below the calculated damage level, the susceptibility

was considered equal to the damage level. If a preselected frequency caused a significantly greater susceptibility than other test frequencies, the frequency range about the troublesome frequency was tested in detail to find any susceptibility peaks.

All susceptibility testing was performed in the electronics laboratory, with the equipment under test connected in the configuration (including grounding) that was utilized in the flight vehicle. When susceptibility testing was completed, the data points were plotted on graph paper and connected with straight lines to give continuous amplitude versus frequency or amplitude versus spike duration curves.

B.2.4 Safety Margin Testing for Conducted Interference

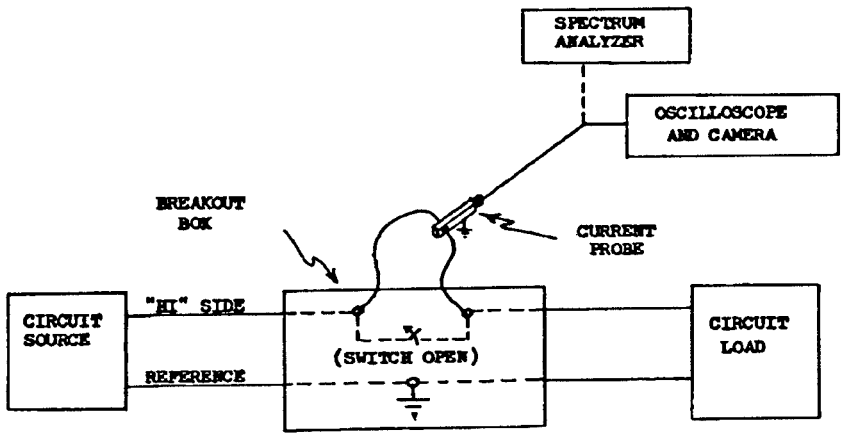
The interference safety margins on the EMC critical circuits were established by monitoring the interference on the circuits, and comparing the observed levels of interference to the susceptibility thresholds of the circuits. CW interference was monitored while all systems were operating. Spike interference was continuously monitored while a simulated flight sequence was performed.

Two safety margin tests were performed on the AM. The first test was performed during Airlock Systems Validation in which the interference on EMC critical circuits was monitored while all systems were operated in typical flight modes. Simulators for the Orbital Workshop (OWS)/Airlock Module and Airlock Module/MDA (CSM and ATM functions) interfaces were utilized to provide a realistic test configuration. EMC critical circuits that exhibit an interference safety margin of greater than 12 dB were exempt from further testing.

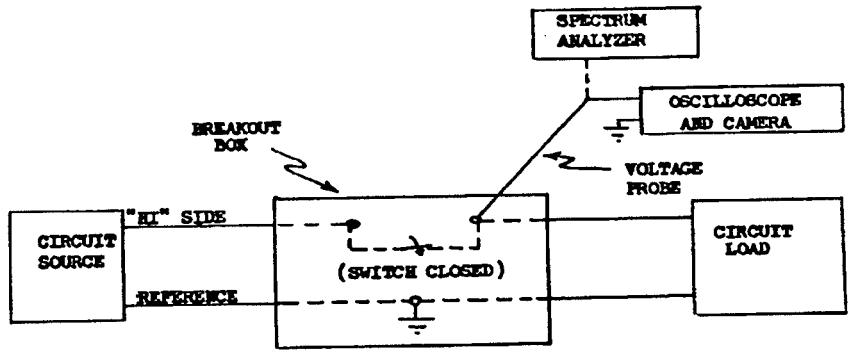
The second safety margin test was performed during AM/MDA simulated flight. EMC critical circuits not eliminated in the first safety margin test described above, were continuously monitored for spike interference during a simulated flight. The OWS/AM interface simulator and the AM/MDA interface simulators (for CSM and ATM functions) used in the first safety margin test were also used in this test. Due to the prohibitive amount of time required for a complete simulated flight, the EMC critical circuits were monitored during an abbreviated simulated flight. The

abbreviated flight includes nominal switching functions and the various combinations of equipment operation, but eliminates a large amount of "steady state" time between the different modes of operation.

All safety margin testing was performed with the AM and AM/MDA located in a Class 6 clean room. The EMC critical circuits were monitored by inserting a breakout box in the circuit, and connecting the necessary test equipment as shown in Figure B.2-2. Interference waveforms with only one predominate frequency can be analyzed directly from the oscilloscope display. For complex interference waveforms, a spectrum analyzer was used to facilitate determination of the predominate frequency amplitudes. In practice, oscilloscopes were used for these measurements until it became difficult to determine the frequency. At that point spectrum analyzers were inserted to measure the frequency content of the interference.



a. INTERFERENCE CURRENT MEASUREMENT



b. INTERFERENCE VOLTAGE MEASUREMENT

Figure B.2-2. Interference Measurement Methods.

During and AM/MDA simulated flight sequence, transients on the following 28 VDC buses were continuously monitored;

AM Bus 1	EPS Bus 1	Transfer Bus 1
AM Bus 2	EPS Bus 2	Transfer Bus 2
Regulated Bus 1	Sequential Bus 1	AM/CSM Bus A
Regulated Bus 2	Sequential Bus 2	AM/CSM Bus B
EREP Bus 1	Deploy Bus 1	AM/ATM Bus 1
EREP Bus 2	Deploy Bus 2	AM/ATM Bus 2

The buses were monitored with a memory voltmeter set up to measure spikes of 1 microsecond or greater duration in conjunction with an analog recorder to give a permanent record of each bus. In addition, representative buses were monitored for voltage ripple with a wideband oscilloscope during a simulated flight sequence.

B.2.5 Radiated Tests

During system level testing, both a radiated interference and radiated susceptibility testing were performed to verify RF compatibility.

B.2.5.1 Radiated Generation

With all AM frequencies being transmitted simultaneously during Airlock Validation, the interference levels in the cluster (entire on-orbit assembly) receiver's passbands were determined. The measurements were made using noise and field intensity meters and their associated antennas.

B.2.5.2 Radiated Susceptibility

A minimum 6 dB radiation margin of safety for the AM and MDA was demonstrated by simultaneously radiating power at the six primary Skylab orbital frequencies at the mated AM/MDA while monitoring all systems for proper operation. The 6 dB margin was assured by radiating levels that were 6 dB higher than the actual flight environment. The interference levels were

obtained with a special test unit supplied by the MSFC. Approval for these open field tests (outside shielded enclosure) was obtained in advance from the appropriate agencies.

B.2.6 Test Results

Continuous Wave (CW) margin measurements on signal circuits were found to range between 6 dB and greater than 29 dB. Therefore the CW margins met the 6 dB requirement.

Continuous Wave measurements on the power buses demonstrated wide safety margins except for a GFE High Intensity Light. This light produced 4 volts peak to peak ripple (repetitive ringing spikes) at 21 kHz. It was removed and returned to the government for modifications.

Transient measurements resulted in two instances of inadequate margins. Troubleshooting the source of these transients revealed that they were caused by an improper switching sequence of a Light Dimmer Control. This switching was performed by the flight crew during a phase of the mission when such activity would be impossible during the actual flight. A deviation request was submitted and approved by the customer.

Radiated Susceptibility testing resulted in discovery of susceptibility of the Rapid ΔP Sensor. The failure mode was a false alarm. It was demonstrated that the interference entry point to the equipment was through the cable. A redesigned cable incorporating a ferrite type filter was developed, tested and operated with the Rapid ΔP Sensor successfully demonstrating the required safety margin.

B.3 Solid Rocket Booster

The following contains excerpts from MSFC-RPT-694A, dated July 13, 1981.[B-3]

Six kinds of circuits were determined to be criticality category 1 or 2. They were as follows:

a) Ignition and Separation Firing Circuits (16 Circuits)

b) Rate Gyro Assembly (RGA) (12 Circuits)

c) DC Power Buses (4 Circuits)

d) Thrust Vector Controller Actuator Delta Pressure (16 Circuits)

e) Pyrotechnic Initiator Controller (PIC) (40 circuits)

f) Solid rocket Motor Chamber Pressure (6 Circuits)

g) Distribution Switching Circuits

h) Thrust Vector Controller Servo Bypass

i) Thrust Vector Controller Actuator Signal input to SRB Actuators

Margins for circuits in a) through f) (94 circuits) above were demonstrated by test. Demonstration of margins for circuits g) though i) was accomplished by analysis.

B.3.1 Safety Margin Demonstration

Electrical circuit compatibility was demonstrated during Shuttle Integrated Testing (SIT), Flight Readiness Firing (FRF), and actual launch.

used. The PIC capacitor charging voltage telemetry measurement shall be reviewed post test on all PIC's. This can be justified as a post-manufacturing test to verify no wiring or connection error applies voltage to the charging (ARM) circuits inadvertently.
Since the PIC Cap data is sampled at five times per second, two successive samples would represent approximately 200 to 600 milliseconds. The PIC could charge to a level that would fire an initiator between two samples (less than 200 ms), but two successive samples would be positive noncompliance. Seven volts for any two successive samples constitutes a no-go.

Thrust Vector Control System
Secondary Rock and Tilt Delta Pressure

The safety margin was defined in terms of the pressure measurement. This function was critical because the SRB separation depends on the pressure decreasing to low level after burnout. If interference on the pressure measuring circuit prevented the indicated pressure from showing accurate decrease to the proper level, the SRB separation could not occur. In this case, 6 dB was taken as equivalent to plus or minus 1100 PSID. This margin was derived from design parameters. The largest error pressure reading indicated during SIT, FRF and launch was +671 PSID, well within the limit.

B.3.1.2 Demonstration by Analysis

A typical circuit is used to demonstrate the approach used.

TVC Actuator Control

The servo valve delta pressure measurements are used in the Orbiter to determine satisfactory performance of the servo. When the pressure differential is excessive that servo channel is bypassed to neutralize the effect. All four measurements on each actuator on both SRBs were reviewed post test to verify that no interference approached a level that would cause a bypass judgment without a valid fault. In addition, these circuits were not considered susceptible to EMI because the system frequency response was less than 10 Hz by design. This approach, while not showing a quantitative 6 dB margin, showed a margin did exist.

Program constraints prohibited the use of normal EMC hardwire, continuous monitoring of critical circuits and interfaces. The EMC verification was performed using the on board telemetry measurement system. Specific limitations imposed by the use of the on-board telemetry measurement system included non-availability of some critical circuits for verification via telemetry, and for those available, sampling at relatively low rates, when compared to hardware monitoring. In terms of compliance verification, the parameter (critical circuit) may be monitored less that 1 per cent of the time at certain sample rates. While not verified 100% of the time, the sampled data presents evidence of compatibility, and there was no reason to doubt the validity of that data.

Critical circuits were divided into two classes, Ordnance and Mission. Ordnance circuits were required to demonstrate a 20 dB safety margin between undesired signals and signal levels required to activate ordnance. Mission critical circuits were required to demonstrate a 6 dB safety margin between undesired signals and signal levels required to activation. Two specific examples have been chosen of demonstration by test and one of demonstration by analysis.

B.3.1.1 Demonstration by Test

SRB and RSS PIC Capacitor Voltage

Plus or minus 1.5 volts was taken as the voltage limit which represented a 20 dB safety margin while the commands to arm and fire were not given. The report indicates that voltage measurements were within this limit during the SIT, FRF, and launch. Because it activates ordnance, the PIC is specifically designed to be immune to a severe interference environment. The arming circuit input must be applied long enough (150 ms) to charge a capacitor through a dc-to-dc converter. It is virtually impossible to couple enough energy onto the circuit inadvertently to operate the converter for the charging period. Additionally the PIC output required the "FIRE" circuit(s) be supplied with an activation signal of 28 volts for 1 millisecond. The combination of multiple inputs and time required on each make the PIC insensitive to coupled interference signals. But the effects of inadvertent operation of ordnance are catastrophic. As a result, cases could be made for both testing and not testing of PIC circuits. A reasonable compromise was

B.3.1.3 Additional Testing

After the SRB verification report was issued and the successful flight of STS-1, it was determined that some concern still existed in some areas. As a result, it is indicated that additional testing was performed. The SRB Rate Gyro signals were recommended for monitoring through telemetry during launch and simulated flight for STS-2, 3, or 4.

The Main Events Controller (MEC) to SRB Interface were recommended to be monitored during Orbiter checkout for the required 6 dB margin.

The SRB buses A and B were recommended for testing at KSC by monitoring equipment with frequency coverage to 150 kHz

B.4 Discussion of the Approaches

The different approaches to the process are discussed in the following sections.

B.4.1 Susceptibility measurement

Conducted susceptibility thresholds were determined for the Skylab program using breakout boxes on non-flight equipment for transient and CW interference both in band and out of band for each circuit. A limitation of this approach was that reliable measurements could not be obtained above 20 MHz. However no conducted noise was measured above this frequency. A different approach was used for the SRB program. No baseline for margin determination was developed from test for the actual circuit performance. It was assumed that the thresholds were defined by the specified minimum level for circuit response and that the interference effects were linear.

B.4.2 Interference Margin Measurements

The Skylab program measurements were made of actual voltage or current in the circuit over a wide frequency range using breakout boxes except during the 6 dB radiated susceptibility measurements when the

breakout boxes were removed. A negative effect of using breakout boxes during simulated flight is that extraneous interference could be introduced which would not normally be present. However the resulting tendency would be to err in the direction of conservatism and any safety margin demonstrated would be a minimum level.

The SRB program used some flight telemetry readouts which were related to the critical circuits. The advantage of this approach was that the parameters could be monitored during that actual Flight Readiness Firing Test and actual launch. This was definitely a more realistic condition than could be simulated. However, since test planning occurred after the vehicle was built, existing measurements and methods were not always adequate measure margins. There was no baseline susceptibility determined in terms of the voltage or current thresholds vs frequency of the circuits. Margin pass/fail criteria were established on terms of the physical parameter deviation from an assumed nominal as measured by the on-board telemetry system. Each critical circuit had to be assessed to determine how a margin could be verified by using existing measurements only. Since the telemetry readings were sampled, there is no assurance that transients exceeding the safety margin requirement did not occur between sampling periods in some cases. In addition, some critical circuits could not be monitored. Even though these methods produced less than perfect results in some cases, the process does show that safety margins can be proven by the use of existing measurements as long as a process has been defined to determine how these measurements indicate a safety margin. In addition, if any undesirable or unexplained effects were seen in the data, further evaluation would be required.

B.4.3 Conclusion

Two different approaches to safety margin demonstration have been presented. The differences were the result of different technical approaches and different funding priorities of the program management. The ultimate result is that both programs were successful. In the final analysis the method of margin demonstration must be determined from the judgment of the program management and technical advisors.

REFERENCES

B-1. MDC Report H031, Electromagnetic Compatibility Control Plan for Airlock Module, 10 January 1972.

B-2. MDC Report E0333, Airlock Module Electromagnetic Interference Test Plan, 30 March 1971.

B-3. MSFC-RPT-694A, July 13, 1981

APPENDIX C
EMC DESIGN GUIDELINES

C.1. EMC Design Guidelines - Background

MIL-STD 1818A requires that margins be included in the design process.[C-1] A number of EMC design approaches and variations could be applied to achieve protection of critical circuits. A general rule of thumb is, however, that successful system-level EMC design is at its foundation based on the proper equipment-level specifications, design, and verification. Equipment-level requirements are usually given as MIL-STD-461, Requirements for the Control of Electromagnetic Interference Emissions and Susceptibility, or a modified version of it.[C-2] This is where initial gains are made in the control of emissions and susceptibility. For the purposes of this document, it is assumed that this proper foundation has been successfully achieved.

System design for EMC applies design rules in the form of system-level requirements. The requirements are sometimes given as guidelines or design goals, but generally this approach is not effective. Key requirements stated in general terms follow.

C.2 Grounding

The term grounding is a holdover from the practice of making an electrical connection of one polarity of earth-based power, radio, or other signal systems to the earth. As applied to space vehicles, grounding simply means connecting one side of a circuit to the primary metal structure or ground plane of the spacecraft. An excellent discussion of grounding, the different variations of grounding configurations, and the relative advantages and disadvantages of specific practices is given in NASA Reference Publication 1368[C-3].

C.2.1 Power System Grounding

Grounding for power distribution systems have special requirements as described in the following sections.

C.2.1.1 Safety Grounds

One reason for grounding power circuits is for safety in case of a short circuit. By making a low resistance connection to one side of a power circuit to primary structure, accidental shorts to structure from the other side cause a current flow that is large enough to activate the circuit protection device, fuse, or circuit breaker. The generally accepted convention is to ground the negative side of the power bus. Power conditioning solid state devices have been developed for this convention.

C.2.1.2 Electrical Noise Control

Another benefit of grounding the power circuit is the shunting of conducted noise into the ground plane and away from electronic units connecting to the bus. It should be noted that the electrical noise is not only diverted from the negative side of the system but also, for frequencies up to several tens of megahertz, noise from the positive side. This is due to the low impedance of the power source and loads for those noise frequencies relative to the parasitic capacitive and inductive reactance of the wiring. This increases the effectiveness of the power circuit noise filters in the source and loads. Floating (ungrounded) power distribution circuits tend to be noisy.

C.2.1.3 Grounding - Single or Multipoint

Power systems can be single or multiple point grounded. In general a single-point ground should be specified. When applied with wire routing discipline this practice reduces the likelihood of unintentional coupling of power system noise into sensitive instrumentation or control circuits. When the high and return sides are on wires in close proximity (or twisted if possible) the resulting coupling field surrounding the power circuit is minimized due to the self-canceling tendency of the associated fields. This results because the high

and low side currents are always equal and opposite. Single-point grounding for power circuits is the lowest risk approach technically.

For certain systems a case may be made to use the vehicle structure as a power carrying conductor. For example, the Space Shuttle Orbiter uses the payload bay structure to carry the primary power return current between forward and aft sections of the vehicle saving hundreds of pounds of copper wire. Special design constraints were imposed which allow this practice. The payload bay structure is an electrically low impedance with specific requirements on the electrical bonding of the sections so that the power return current cannot develop significant voltages. Most of the sensitive electronic equipment of the Orbiter is located in the forward and aft avionics bays well removed from the payload bay. The power distribution in the volumes containing avionics bays is single-point grounded. The significant signal circuits routed through the payload bay are high-level data bus signals carried on twisted shielded pairs and enclosed in metallic wire trays. By applying such special considerations to the system design, the multiple-point grounded power distribution system is accommodated. Other cases may justify using the structure as a power carrying member. But each case should be considered on its own merit. It should be noted that relaxing the requirement for power circuit single-point grounding may be expedient and even proper for a given situation, but in so doing, the systems designer reduces the flexibility of design choices and may have to impose other special requirements.

C.2.2 Signal Grounding

Single-point grounding is recommended for each signal circuit. If a signal is connected to structure at more than one point, the signal becomes exposed to other power, signal, or noise currents that may be flowing through the structure. The structure becomes a part of the signal circuit. Multipoint grounding of signal circuits also makes the circuit more vulnerable to wire-to-wire and field-to-wire noise coupling. Likewise, if a group of signals share a return wire, they also share the noise voltage developed across the common impedance. When the high and return sides of the circuit are routed closely adjacent (and preferably twisted), any noise coupled will be equal on both high and low sides. That is, the coupled noise will be common mode and only that part that becomes differential will affect the signal. Now if the

return side is through structure or shared with structure, it is not possible to have equal coupling for both sides and a large amount of differential mode noise will appear on the signal. The reciprocal of that is also true. Signal circuits routed on twisted high and return side (or closely adjacent) wires will tend to self-cancel their generated noise. At any point, the signal current will tend to be equal and opposite. However, this balance is destroyed if multipoint grounding is used and the circuit becomes a noise source.

C.2.2.1 Control of System Grounding

The system EMC designer needs certain requirements placed at the equipment level to control the overall design of the system grounding. Equipment should be specified to have a high degree of mutual electrical isolation internally (typically 1 Megohm) between power circuit returns, signal circuit returns, and equipment chassis. This allows the system designer who must specify the interconnection configurations freedom to choose the physical locations of the ground reference points. Optimum locations can be chosen for the design and later if unplanned or uncontrolled situations develop revealing EMC problems in system test the system grounding configuration can be modified. If power or signal grounds are connected to chassis internal to the equipment enclosure, this freedom to design and modify is lost. Typically, a program may impose the use of Government Furnished Equipment (GFE) or Commercial Off-the-Shelf (COTS) equipment which may not meet the needed isolation requirements. Also, radio frequency (RF) equipment such as transmitters and receivers may, of necessity, have signal referenced to equipment chassis. By maintaining the general isolation requirements on equipment that can be specified, the designer's ability to deal with problems caused by the non-compliant equipment is improved.

C.2.3 Electrical Bonding

Sometimes the word bonding as used by the EMC community is a cause of misunderstanding and confusion. As used in this document, bonding means the electrical connection by special means of members that do not normally conduct intentional system electrical power or signal current. General bonding requirements are given in MIL-STD-5087B or MIL-STD-1541. This

document will not attempt to repeat all the requirements in those references. General rationale for certain practices will be described.

C.2.3.1 Class A Bonding (Antenna Installation)

This class of bond requires a ground plane with negligible impedance at the antenna operating frequency and a low impedance path for the RF return current.

C.2.3.2 Class C Bonding (Current Return)

The purpose of this requirement is to ensure that electrical hazards are minimized by providing a safe structural current return path for intentional currents and accidental faults (shorts to structure). For intentional structure current paths, voltage drop limits are specified as a function of the power system voltage levels. For fault current paths the resistance of the electrical bond must be low enough to allow sufficient fault current to activate the circuit protection device without overheating the connection point(s). Specific maximum resistance values are given in MIL-B-5087B for locations where hazardous fuels and gasses may be present.

C.2.3.3 Class H Bonding (Shock Hazard)

This category of bond provides personnel safety by ensuring low resistance to structure between electrical or electronic equipment and exposed conducting frames, as well as metallic conduit that carries electrical wiring. A maximum resistance of 0.1 ohm is specified.

C.2.3.4 Class L Bonding (Lightning Protection)

Most spacecraft are not required to comply with these requirements for direct lightning protection bonding since they do not operate exposed at the

earth's surface or in the atmosphere. However, some launch systems may require safe survival when exposed to specified secondary effects.

C.2.3.5 Class R Bonding (Radio Frequency)

This type of bond is of particular concern to the EMC specialist. The intent is to provide connections of very low impedance for RF noise to flow between elements such as equipment chassis to primary structure, conducting items near antennas, and interfaces between primary structural members. These low impedance connections provide a preferred path for RF noise and tend to divert it from sensitive signal circuits. It is important to keep the purpose in mind when considering specific implementation schemes.

C.2.3.5.1 Preferred Implementation

The preferred implementation method is direct electrical contact between the surfaces. Maximizing the area of contact reduces the impedance, thus improving the effectiveness of the bond. This requires the application of certain processes. The surfaces must be cleaned of all dirt, grease, and nonconducting finishes. When the surfaces are mated, appropriate sealing protection against corrosion should be applied. If bare metal surfaces are mounted in contact, care must be exercised to avoid using dissimilar metals to prevent corrosion problems.

C.2.3.5.2 Verification

The actual requirement is a maximum resistance of the Class R bond of 2.5 milliohms. However, this requirement can be met through a junction which has high impedance to the RF noise. The best assurance beyond the resistance measurement is review of the installation drawings for proper process specification call-outs and inspection of the actual installation.

C.2.3.5.3 Bond Straps

If surface-to-surface bonding cannot be accomplished, bond straps may be used to achieve the low impedance connection. Thin solid metallic conductors offer low inductive reactance. Skin depth of radio frequencies allows use of relatively thin conductors. A rule of thumb is to use straps with a maximum 5:1 length-to-width ratio.

C.2.3.5.4 Bonding Considerations for Shield Terminations

Proper termination of wire shields requires attention to minimize RF impedance. It is very important to the effectiveness of wire shields that low impedance terminations be used. For EED firing circuits with stringent safety margin requirements, the shields should be terminated continuously through 360 degrees of the periphery of the wire. This is best accomplished with special connector hardware. Other circuit shielding can be connected with very short "pigtails" to the backshell of RF connectors with tag-rings. The connectors must be designed for low impedance between the two halves of the shell and have a conductive shell surface to mount to the equipment chassis. The equipment must then have a high-quality RF bonding connection to its mounting surface.

C.2.3.6 Class S Bonding (Static Charge)

Electrostatic charge buildup between isolated conductive elements can result in electrical breakdown and arcs that cause electrical interference. Charge buildup can result from frictional action of materials or fluids. It can also occur on space systems as a result of energetic electrons found at geostationary altitudes and, in some cases, at low Earth orbit altitudes with high orbital inclinations. The MIL-STD-5087B requirement for prevention of electrostatic charge buildup is a connection resistance of 1 Ohm maximum. Experience has shown that this value is extremely conservative. However, in most cases it can be easily met. If concern about a specific electrical charging problem exists, the case should be analyzed and a design implementation that is adequate for protection and economically reasonable imposed. For example, if a spacecraft is predicted to be subject to auroral electrons from magnetic storms, the charging rate and the resistivity of

surface materials should be analyzed to determine if dedicated static bonding protection is needed. If it is needed then candidate bonding implementation methods should be quantified for effectiveness.

C.2.4 Wire Routing

One of the most important aspects of system-level EMC design is the treatment of wiring connections between equipment and subsystems. Wires which carry EMC-critical circuits need particular attention. Wire-to-wire coupling of electrical noise can seriously degrade system performance. Over the years, rules for circuit classification and separation have been developed and applied to various programs. The purpose of this practice is to ensure that sensitive circuit wires are placed at a safe distance from noisy circuits.

C.2.4.1 EMC Wire Classification

A system of classification is applied to identify and label the type of circuit for each wire. The following table has evolved from the Space Shuttle Program. It has been modified for the Space Station Freedom Program by testing and analysis performed by the Electromagnetics and Aerospace Environments Branch at NASA Marshall Space Flight Center. Further adaptations have been made for this document. Classifications are defined in terms of voltage or sensitivity, operating frequency, rise and fall times for pulses, and load and source impedance. While the classification is to some degree arbitrary, it reflects years of experience, improvement, and simplification.

Wire EMC Classification Guide

Frequency f: Rise, Fall Time (ms) tr, tf	Voltage or Sensitivity	Source Impedance (ohms)	Load Impedance (ohms)	Circuit Class	Wire Type	Shield Ground
Analog (ac,dc) f<=50 kHz tr,tf>10 μs	<=100mV	All	<600 k	ML	TWS	MPG
	<=100mV	All	=>600 k	ML	TWDS	MPG
	<6V	All	All	ML	TWS	MPG
	6-40V	All	All	HO	TW	None
	>40V	All	All	EO	TW	None
50kHz<f =<4MHz: tr,tf=<10 μs	<100mV	All	All	RF	TWDS	MPG
	=>100mV	All	All	RF	TWS	MPG
f>4MHz	All	All	All	RF	TWS	MPG

Acronyms and Abbreviations	ML, HO, EO	Arbitrary nomenclature to define circuit classification
	MPG	Multiple Point Ground
	RF	Radio Frequency
	TW	Twisted
	TWDS	Twisted Double Shielded
	TWS	Twisted Shielded

1. Shield Grounding shall be compatible with the circuit application.
2. The length of termination-to-ground lead for all circuits shall be the minimum length practical. The preferred method is to connect the shield peripherally to the backshell of the connector with continuous low impedance electrical bond path through both halves or the connector shell and the connector to mounting surface interface.
3. Digital signals shall be classified as RF.

C.2.4.2 Wire Separation

The system wire bundles are then fabricated and installed on the vehicle according to the separation rules for the classification. Each bundle must contain only wires of the same classification. Bundles may be routed together with no separation with bundles of the same classification for any distance. Bundles of different classifications may be routed in parallel with

no separation for distances equal to or less than 2 feet. Bundles with different classifications may be routed in parallel with a minimum of one inch separation for distances equal to or less than 8 feet. Bundles with different classifications may be routed in parallel with a minimum of two inches separation for distances greater than 8 feet. It is understood that in practical systems there will be some instances of noncompliance due to volume and access limitations. These instances should analyzed on a case-by-case basis and well documented.

C.2.4.3 Wire Treatment for Electroexplosive Device Circuitry.

Firing circuits for (EEDs) require special attention. MIL-STD-1576 provides explicit detail on all aspects of EEDs. The recommended treatment for firing circuit wiring is as follows;

- Label EED firing circuits separately and distinctly.
- All EED firing circuits shall be routed on twisted shielded pairs.
- Shields terminated at a connector shall provide 360° continuous shield continuity without gaps.
- Route the firing circuits a minimum of 2 inches from all other bundles.
- EED circuits may be routed within one bundle and share an overshield provided that current induced by one circuit within another is less than 20 dB below the no-fire current level of the EED.

REFERENCES

C-1. MIL-STD-1818A, Military Standard, Electromagnetic Effects Requirements for Systems, 4 October 1993.

C-2. MIL-STD-461D, Military Standard, Requirements for the Control of Electromagnetic Interference Emissions and Susceptibility, 11 January 1993.

C-3. NASA Reference Publication 1368, Marshall Space Flight Center Electromagnetic Compatibility Design and Interference Control MEDIC) Handbook, June 1995.

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Demonstration of required safety margins on critical electrical/electronic circuits in large complex systems has become an implementation and cost problem. These margins are the difference between the activation level of the circuit and the electrical noise on the circuit in the actual operating environment. This document discusses the origin of the requirement and gives a detailed process flow for the identification of the system electromagnetic compatibility (EMC) critical circuit list. The process flow discusses the roles of engineering disciplines such as systems engineering, safety, and EMC. Design and analysis guidelines are provided to assist the designer in assuring the system design has a high probability of meeting the margin requirements. Examples of approaches used on actual programs (Skylab and Space Shuttle Solid Rocket Booster) are provided to show how variations of the approach can be used successfully.

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