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Aircraft Generated Electromagnetic Interference on Future Electronic Systems

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Project Plan

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16. Abstract
A Federal Aviation Administration research project is presented to identify some of the electromagnetic compatibility (EMC) considerations associated with aircraft that incorporate advanced composite structures and high integrity digital avionics systems. This report suggests methodologies and resource requirements necessary to pinpoint equipment susceptibility, discusses the philosphy of system hardening inorder to minimize the effect of the threat, and recommends test methods and criteria.

The project is divided into the following elements: 1) aircraft generated electromagnetic interference environment - the instrumentation and measurement of several aircraft of various types to establish a database of typical EMI signatures, 2) experimental test plan to evaluate the performance of a series of recommended EMC testing procedures and criteria on a typical digital flight control system, and 3) a set of interim design guidelines showing the various hardening techniques and tradeoffs available in EMC control.

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AIRCRAFT-GENERATED ELECTROMAGNETIC INTERFERENCE IN FUTURE ELECTRONIC SYSTEMS

Chris Kendall* and Edward Black*

Federal Aviation Administration and Ames Research Center

SUMMARY

Until recently, avionic equipment was primarily analog, possessing limited bandwidths and utilizing time-averaged indicators. Such equipment was not responsive to transient disturbances unless they exceeded the analog-device damage level. Now digital electronics are becoming commonplace and their use, even in normally analog systems, will prevail in the future. However, unlike their analog predecessors, they are very susceptible to transient effects, as well as to discrete-frequency radiation from radio transmitters. Digital-device performance can be adversely affected before the device-damage transient level is reached. The operation of average digital devices is at least 10 times more susceptible to transients than that of their analog counterparts. Because of this significant difference in transient susceptibility, there is a definite need to review both the design and test requirements of digital equipment.

This program plan outlines just that type of study. The plan encompasses both analytical and experimental methods to insure a complete assessment. The major tasks include the following:

1. Development of the various transient failure mechanisms of digital equipment

2. Technical description of electromagnetic transients on typical digital electronics

3. Mathematical and experimental determination of the transient-interference coupling paths

4. Determination of the protection required to insure hardening of digital systems to the various transient sources, including lightning and electromagnetic-pulse-type (EMP) threats

5. Evaluation of the added protection required when composite fuselage materials are used instead of metal materials

6. Development of specific design guidelines to help digital equipment and airframe manufacturers to achieve better transient hardened designs

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7. Development of special test methods to insure that digital designs are properly tested to the required degrees of transient hardness

The needed analytical studies will use EMCad, a computer program specifically designed for the study of system and subsystem responses to external radiation and coupling sources. The actual stress on a piece of digital equipment may be determined by the use of EMCad and should be used for these analytical studies. EMCad is a computer program specifically designed to study system and subsystem responses to external radiation and coupling sources. An aircraft level computer assessment for both the lightning and EMP threat defines the transient field inside the airplane which is used as an input to the EMCad program. This approach will yield the specific data needed to determine the appropriate hardening techniques required to protect against the threat.

EXECUTIVE SUMMARY

Problem Statement

Until recently, avionics equipment was analog in nature, having limited bandwidths and utilizing time-averaged indicators. Such equipment was not responsive to transient disturbances unless they exceeded the analog-device damage level. Now digital electronics are becoming commonplace and their use, even in normally analog systems, will prevail in the future. However, unlike their analog predecessors, they are very susceptible to transient effects, as well as to discrete-frequency radiation from radio transmitters. Digital-device performance can be adversely affected before the device-damage transient level is reached. In normal operation, the average digital system is substantially more susceptible to transient phenomena than its analog counterpart. Because of this significant difference in transient susceptibility, there is a definite need to review both certification requirements and testing methods for digital systems. This plan outlines that type of study.

Background

This project plan is based on information and resources contained in the engineering and development program plan, "Atmospheric and Aircraft-Generated Electrical Hazards," DOT/FAA/CT-83/4, January 1983. It sets forth the engineering and technology viewpoints and reflects priorities and applications in technology for current and new-generation aircraft digital avionics electromagnetic compatibility (EMC). The goal of this project is to provide a data base and the information necessary to update and change existing FAA regulations and criteria, as required, to ensure the safe implementation of advanced electronic technology.

Historically, avionic equipment was primarily analog, with each system possessing limited bandwidths and utilizing time-averaged indicators. Similarly, the FAA standards addressing avionics certification and criteria have come from the viewpoint of separate engineering disciplines; however, these new-generation aircraft, which incorporate advanced integrated avionics and flight-control systems, are dependent, in a complex manner, on the total integrated system. For the FAA to meet its safety and certification responsibilities, a concentrated effort must be initiated and maintained in EMC technology with emphasis given to total system integration.

Program Objectives

In spite of the susceptibility to electromagnetic interference (EMI) of digital equipment, a proper systems approach to digital design can yield digital systems that are essentially immune to transient upset. This project encompasses both analytical and experimental methods to provide a complete systems-level assessment with the overall objectives of

1. Conducting thorough investigations and analyses, and providing data and information to support certification and regulatory activities

2. Be responsible for aircraft safety research needs identified as aviation-safety (AVS) associated

3. Establishing and maintaining an expertise in this extremely complex technology area

4. Coordinating and disseminating results and findings within the FAA and industry as appropriate.

Critical Issues

The source of the electromagnetic threat to the normal operation of the avionics system, whether digital or analog, are numerous. Although both digital and analog systems respond to the same threats, there are factors that make the threat response far more serious in digital systems than in analog. For example, the information bandwidth and, hence, the upper noise response cutoff frequency in analog devices is limited to at most a few megahertz, whereas in digital systems it is often in excess of 100 MHz. This bandwidth difference, which is at least 10 times more severe in digital systems, allows substantially more energy and types of signals to be coupled into the digital system.

Moreover, although a threat may cause disruption in both analog and digital systems, analog systems generally resume normal operation when the threat is removed. Digital systems, on the other hand, when once perturbed, require external intervention to resume normal operation. Unless substantial fault tolerance is built into it, the digital system is far more susceptible to system upset than its predecessor analog device.

A full understanding of the EMC of any avionics system requires a thorough understanding of the actual or potential noise-coupling paths and ultimate receptors inside the system, as well as knowing the actual source of the noise threat.

Program Technical Approach

This plan encompasses both analytical and experimental methods for providing a complete systems-level assessment of the EMC for digital avionics systems. The major phases of this plan include the following. First, a series of experiments to obtain an EMC signature of the actual worst-case expected aircraft conducted and radiated emissions signature across a series of commercial jet aircraft and then, by use of analytical techniques, develop a composite emission profile. Second, conduct a series of test procedures on the Reconfigurable Digital Flight Control System (RDFCS) at Ames to establish a data base and to specify limits for future digital avionics systems. And third, formulate a set of testing procedures that would apply across all avionics equipment and would complement the existing RTCA test procedures which are more applicable to analog equipment.

1. BACKGROUND

1.1 Introduction of Digital Avionics

One of the most profound recent advances in commercial jet transportation is the advent of digital avionics. Almost every function of jet transport operation is now involved or will be involved with digital monitoring and processing techniques. In many cases, highly successful and proven analog instrumentation has been improved upon by conversion to digital processing techniques. However, the susceptibility of these digital avionic systems to transient effects is significantly higher than that of their analog counterparts. Digital susceptibility has been highlighted by repeated cases of digital avionic "nuisance disconnects," "hardovers," "upsets," and "shutdowns" caused by aircraft-induced effects from the transport's electrical power, sensors, and other electrical/electronic systems.

1.2 Rapid Changes in Digital Techniques

For more than 20 years, documents such as DO-160 (Environmental Conditions and Test Procedures for Airborne Equipment) have imposed both transient and steady-state susceptibility requirements on avionic equipment. The methods used have been aimed with success at analog and early digital designs. However, the rapid changes in digital techniques, extensive use of microprocessors that use for example, the metal-oxide semiconductors (MOS's) to reduce power requirements and increase data rates for signal processing, raise new certification concerns.

The rapid changes in digital technology, employing greater operation bandwidths together with faster processing speeds, have caused greater incidents of unexpected digital "upsets." These incidents are the reason for developing this program plan. It is the objective of the program plan to research and investigate the possible failure mechanisms and coupling paths of digital avionics to insure that the certification process will achieve compatible operation between microelectronic digital avionics and the rest of the on-board aircraft system operations.

1.3 Appendixes

Appendix A contains a set of generalized EMC design principles that have been tailored to digital avionic systems. These design principles begin with considerations to be taken at the management level and become progressively more specific, concluding with detailed recommendations for avionics hardware design. This set of design guidelines does not cover the area of fault-tolerant software.

Appendix B is the test plan for conducting a set of recommended tests on an example digital flight-control system (RDFCS), which uses actual airborne equipment to establish a data base and confirm the appropriateness of this set of proposed EMC testing procedures and methods.

Appendix C is a proposed extension in bandwidth of paragraphs 17 and 19.5 of the electromagnetic tests specified in RTCA DO 160A. Several additional fast-rise-time narrow bandwidth tests not included in the RTCA document are also proposed. The table also provides the reader with a comparison of present test specifications and the bandwidth of response for typical digital avionics in use commercially today, and projects the requirements that will be necessary toward the end of the century.

2. PROBLEM DESCRIPTION

Jet air transports that utilize modern digital technology in their avionic systems are highly susceptible to transient and high-frequency transmitter field strengths. Because of the great number of digital equipment on board these aircraft, the probability of some operational disturbance is far higher than with earlier aircraft. The greater use of digital avionics coupled with the weight reduction measures (such as replacing the conductive aluminum fuselage sections with low or nonconductive composite materials) have created compatibility problems which indicate that present certifications standards have become outdated.

Digital avionics has progressed from discrete transistor devices (in which 10^{-5} J of transient energy were required to cause upset) to very large-scale integrated devices (thousands of transistors on one chip that can be upset at 10^{-9} J). This means that today's digital devices are four orders of magnitude more sensitive to transient amplitudes. In addition, digital integrated circuits (IC's) now can be upset by transients that last only 2 nsec; durations in the microseconds range were required to upset their predecessors.

The fast-rise-time, greater bandwidth characteristics of modern digital systems means that operational failures that have not been experienced before can occur. The causes of upset are noise sources that have always been present but never before caused problems. For example, metal-to-metal friction, and secondary arcing caused by lightning are fast-rise-time, short-duration effects that never bothered earlier systems. Now, because of the greater bandwidths and lower transient susceptibility voltage levels of MOS devices, logic errors can result.

It is anticipated that when the investigation program described herein is implemented, some changes will be recommended in the following areas:

1. EMI/EMC qualification testing (DO-160)

2. Types of avionic connectors used

3. Types and performances of shielded data cables

4. Signal filtering requirements of digital avionics

5. Shield and circuit ground reference requirements

6. Specific design guidelines for both avionic and airframe construction that utilize digital systems

2.1 Digital Systems Failure Mechanisms

Because of the safety threat imposed by potential malfunction of operating avionics equipment, it is important to understand what these failures are. The following is a list of potential avionics malfunctions ordered according to increasing severity:

1. Apparent normal operation, but with incorrect data

2. Aberrant or abnormal operation

3. System lock up or cessation of operation

4. System power down

Of the four failure types, the first (apparent normal operation with bad data) is extremely unlikely in digital avionics systems. Inasmuch as digital equipment operation consists of treating discrete data bits in a planned (programmed) manner, the only way to introduce a bias to the data resulting in incorrect, but apparently normal results, is through a programming error, or by having the bias introduced into the data stream before digitization.

Incorrectly designed or severely stressed digital equipment can and does fail in any of the last three modes mentioned above. The gross system failure mechanisms are obvious, but the underlying reason for the failure (i.e., what happened to the digital logic) is not so immediately apparent. Although in some rare circumstances it is possible to trace a system-failure indication to a specific digital fault, the complexity of the digital signal paths and component interactions does not easily allow the investigator to identify a specific logic failure mechanism. For this reason, it is most valid to deal with digital equipment malfunctions from a gross system operational description. Similarly, it is important to design into the digital equipment a substantial amount of fault-tolerant operation and operational threat survivability.

2.2 Threat Overview

The noise sources that are a threat to the normal operation of avionics systems, whether digital or analog, are numerous. Both digital and analog electronic systems respond to the same threats, but there are two factors that make the threat response far more serious in digital systems than in analog:

1. The information bandwidth, and hence the upper noise response cutoff frequency, in analog devices is limited to a few tens of kilohertz; in

digital systems it is often in excess of 100 MHz. This bandwidth difference, which is more than three orders of magnitude more severe in digital systems, allows substantially more energy and types of signals to be coupled into digital systems.

2. Although the noise threat may cause disruption of both analog and digital systems, upon cessation of the noise threat, analog systems will generally resume normal operation as if there had been no interruption. Digital systems, on the other hand, have a memory function which once perturbed requires external intervention to resume normal operations. In other words, without substantial fault tolerance built into them, digital systems of any nature can be made inoperative upon first application of the external noise threat. Resumption of normal operation then requires external (human) intervention.

Besides the actual sources of the noise threat to any electronic system, a full understanding of the electromagnetic compatibility of the system requires a thorough understanding of the actual or potential noise-coupling paths and,ultimately, that receptors be devised inside the system, if necessary. The operational response of an electronic system to a noise threat can often be traced to an entry point or coupling mechanism of noise into the system. Moreover, understanding the potential noise-coupling paths and the failure indications associated with them is invaluable in designing or retrofitting a system to survive potentially harmful electromagnetic noise.

2.2.1 Noise sources- Aircraft avionics systems are potentially exposed to electromagnetic noise from many sources. Some of the more important (and potentially damaging) ones, along with a discussion of the noise associated with them, are given below.

Power-distribution transients (normal mode): At any given time during flight, there is a more or less steady-state relationship between the aircraft-generated electrical power and the user loads. Any change of loads caused by either turning on or turning off any item of electrical equipment can cause a temporary disruption of the steady-state nature of the aircraft power distribution. A voltage spike or current surge, which may be caused by this change of load configuration, can cause a disruption to the normal operation of digital equipment unless the equipment is adequately protected.

Power-distribution transients (common mode): Besides the transients caused by power-load changes, the power-distribution network can be susceptible to externally generated transients. The various power cables distributing the electrical energy from the generating source to the using loads can act as receiving antennas for coupling radiant energy.

Instrumentation (incidental radiators): A potential serious source of noise coupling in digital electronics instrumentation is from the crosstalk between broadband noise envelopes of different digital subsystems operating in the same vicinity. The danger of this crosstalk is especially high when the systems have a hard-wired data link between them and when their power-distribution sources are widely separated.

On-board transmitters: Whereas the radiated energy from digital electronics is incidental to normal operation, communications transmitters intentionally radiate radio frequency (rf) energy which can couple in to the electronics and cause disruption. Of special concern are transmissions in the aircraft navigation and control band from 108 to 136 MHz, which is well within the bandwidth of most modern digital electronic systems.

Fixed local ambient: During aircraft operation close to the surface (i.e., takeoffs and landings) the power-density spectrum from ground ambient may be sufficient to couple into the digital electronics of aircraft that are not suitably protected.

Lightning: The distribution and power levels of lightning strikes (both air to air and air to ground) are only vaguely defined at this time, but it seems that the broadband nature of a lightning transient could readily couple into the broadband receivers represented by digital electronic systems.

2.2.2 Susceptors- Once the diversity and complex nature of noise sources is understood, the paths available for these noise signals to couple into the digital electronics must be examined for complete understanding of the noise threat. Ultimately, it is the digital electronics devices themselves that respond to these various noise threats, but it is useful to discuss the coupling paths by which the noise has access to the digital devices. In discussing noise-coupling paths, it is important to realize that every conductor can and does act as a receiving antenna. The efficiency of these antennas is what determines the amount of noise energy coupled into the conductor. Although most conductors associated with electronic systems have extremely low antenna efficiencies and hence are not important as noise coupling paths, those conductors that do have substantial antenna efficiencies can be important coupling paths and should be pointed out. The three most efficient noise-coupling paths (antennas) are power cables, signal cables, and case apertures.

Often, very little attention is paid to the common-mode noise threat found in power-distribution cables. It is assumed that either the common-mode energy is insubstantial or else that the input power filter can keep the electronic noise out of the system. Both of these assumptions can lead to design flaws giving rise to substantial power-susceptibility problems.

Not only can the noise picked up by signal cables directly interfere with the normal operation of the driving and receiving devices, but the signal cables themselves, once inside the system cabinet, can reradiate and bring external noise to any susceptible device internal to the system.

An aperture is the magnetic field equivalent to an electric-field dipole antenna. Case apertures, then, are substantial, often-overlooked paths for radiated energy coupling.

2.3 Aircraft Environment

Although not substantially different from the operating environment of any general digital electronic system, digital avionics have a combination of environmental and operational stresses imposed which require careful design attention and quality assurance provisions to insure safe, reliable system operation. In the aircraft, the three coupling paths discussed above (i.e., power lines, signal lines, and case apertures) will be immersed in the local ambient radiation noise environment, which will be the sum of all individual noise sources discussed. In addition to the radiated noise picked up by the system cabling and apertures, signal and power lines will each have their own characteristic noise signal. The noise in the signal lines will be a characteristic broadband digital noise, and that in the power lines will be related to the equipment power-supply noise. Finally, if care is not taken, the signal lines and power lines can have the undesirable noise from each other mixed in through a crosstalk mechanism.

2.3.1 Landing- The most critical need for equipment stability and at the same time the one having the highest intensity of noise interference signals is landing. When landing, an aircraft operates on the critical edge of the flight-safety envelope. Consequently, the need for flight-instrumentation stability and reliability is most pressing. On the other hand, the noise environment encountered by the aircraft is at a maximum: the power switching is greatest, the rf environment is highest, and the probability of lightning is highest.

2.3.2 Power switching- During landing, the drain on the aircraft electrical system is at maximum. Further, since the electrical generators are driven by the engines which require constant power adjustment, the source impedance is not constant. Following is a partial list of the systems requiring electrical power; they represent potentially harmful on/off switching transients: landing gear; flaps; intercom; transmitters; pressurization apparatus; and engines.

2.3.3 Worst-case rf environment- Not only is the power use most demanding during landing, but also the local rf environment is most severe. High power use, with its consequent more or less continual random switching transients, causes the power-distribution harness to become a relatively high-noise transmitting antenna. Transmissions from on-board aircraft transmitters are highest during landing, and field strengths generated by these transmissions are most intense in the vicinity of the aircraft avionics. Finally, landing brings the aircraft closest to any fixed rf transmissions, such as local broadcast stations, communications transmitters, and radar transmissions.

2.3.4 Lightning- During any phase of flight, should the aircraft be flying through clouds, cloud-to-cloud lightning strikes are possible. However, the closer the aircraft comes to the surface, the higher becomes the probability of cloud-to-Earth discharges in the vicinity of the aircraft. Furthermore, during any decent, there is the possibility of a charged airframe having a high enough potential difference between itself and the surface to induce a spark discharge (lightning strike) to equilibrate this potential difference. According to a study performed by the U. S. Navy, it was found that the great majority of the direct lightning strikes to aircraft occur within 2,500 ft of the surface.

2.4 Required Data

The above discussions of the electromagnetic environment in and around an aircraft in flight have been general in nature. No comprehensive study of the effects and requirements of digital avionics would be complete unless the conceptual problems were supported by hard experimental data. The goal of this section is to begin to determine exactly what data are required to gain a comprehensive understanding of the severity of the electromagnetic interference problem.

2.4.1 Aircraft power-distribution profile- The need for a comprehensive understanding of the interference potential requires that the relationship between actual noise levels on the power-distribution bus as seen by the noise-sensitive equipment (digital avionics) and the phase of flight during aircraft operations be established. The worst-case noise profile needs to be obtained in order to do the following:

1. Clean up the power-distribution noise as much as possible (i.e., decrease the efficiency of the power line in coupling and transmitting the noise)

2. Specify an acceptable worst-case power-distribution noise profile for guidance in subsequent aircraft power-distribution system design

3. Mandate a maximum worst-case power-distribution profile for design guidance in the development of all digital avionic systems

4. Set an airworthiness standard for aircraft power quality and digital avionics survivability

2.4.2 Aircraft-generated radiated environment- Just as important as the conducted noise profile, is the measurement of the radiated ambient aboard an aircraft in flight. This ambient will consist of radiated emissions from both power- and signal-distribution cables, the frequencies and power levels of all on-board transmitters, and the radiations from engines and other equipment. A correlation between the worst-case profile and the phase of flight for this aircraft ambient radiated profile should be determined.

2.4.3 Actual lightning problem- There is a good deal of discussion in the literature about the energy distribution contained in a lightning strike. A comprehensive study needs to be performed to obtain realistic waveform and amplitude data for lightning strikes. This study should contain information on the mixture and waveform differences between cloud-to-cloud strikes and cloud-to-ground lightning strikes. Further information should be obtained about the frequency of occurrence, altitude distribution of lightning strikes, geographical distribution, and seasonal variations in lightning. Finally, it is necessary to determine the probability of lightning strikes around aircraft operations. It is necessary to have data on the probability of direct-hit lightning and near strikes during all phases of flight. The justification for obtaining all of these data is that they would make it possible to determine whether it is realistic to specify survivability requirements under realistic worst-case lightning environments, or whether the proposed airworthiness standard should be based on a probability distribution curve, thus acknowledging that there are occasional severe occurrences that fall outside the scope of the survivability guidelines.

2.4.4 Fixed ambient radiation- It is likely that the threat to safe, reliable avionics operation imposed by ground-based electromagnetic interference fields is low compared with aircraft-based emissions or lightning strikes, but it would be desirable to have supporting data.

2.5 Digital Electronics Susceptibility

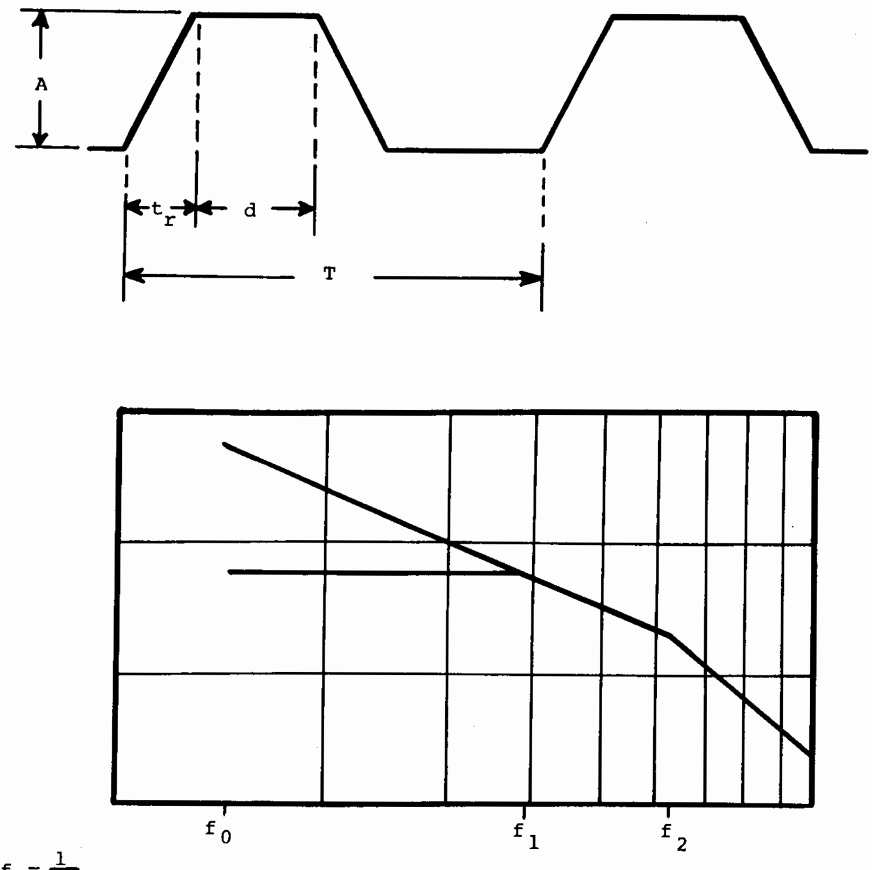
Figure 1 shows a typical digital signal with its associated frequency-domain transform. The most important parameter of this waveform for digital equipment compatibility is the logic signal rise-time denoted t_r. The digital signal bandwidth denoted f_2 in the frequency domain is related to the rise-time as follows:

$$BW = 1/\pi(t_r)$$

Inasmuch as even the slowest of modern digital electronic devices has a rise-time of the order of 15 to 20 nsec, the minimum frequency bandwidth of a digital system is about 20 MHz. This contrasts sharply with the 20 - 50-kHz bandwidths associated with analog electronics which have up until now been primarily used in avionics systems. This three-orders-of-magnitude increase in system bandwidth introduces new and different problems in terms of interference threats and the design principles needed to overcome these threats. Table 1 shows some typical digital logic families with their associated system bandwidth frequencies.

TABLE 1.- TYPICAL DIGITAL LOGIC FAMILIES: LOGIC BANDWIDTH $BW = 1/\pi t_r$

Family	Rise times, nsec	Bandwidth, MHz
7400	12 - 15	20 - 25
74LS	10 - 12	25 - 32
74S	3 - 8	40 - 110
74H	1 - 5	65 - 300
ECL	0.7 - 3	100 - 500



$$f_0 = \frac{1}{T}$$

$$f_1 = \frac{1}{\pi(t_r + d)}$$

$$f_2 = \frac{1}{\pi t_r}$$

Figure 1.- Typical digital signal waveform.

2.5.1 Digital failures mechanisms- The failures induced in digital devices can be classified as either hard or soft. A soft failure is one in which there is no permanent change induced in the physical circuitry; instead, there is a transient condition wherein a logic run is interpreted as a logic zero or vice versa. A hard failure, on the other hand, is one in which a physical change (damage) is inflicted on the digital device, and normal operations cannot be resumed until it is replaced.

2.5.1.1 Device upset: Device upset (soft failures) are incurred through three different physical mechanisms. Each of these mechanisms is related to the device logic bandwidth frequency. Although in most cases it is difficult to determine which of these three mechanisms are applicable in any given example of device upset, it is instructive to be aware of them and how they operate.

1. Induced logic-state transitions. This mechanism is a simple case of one logic state being altered by added electromagnetic noise such that it looks to the receiving device like a signal of the opposite polarity. These state transitions can only occur within the logic bandwidth frequency and are phase-related signal line noise as seen by the receiving device.

2. I/O level shift. At frequencies higher than the logic bandwidth, the noise-induced device-upset mechanism is a rectified ac offset of the signal value at either the driver or receiver gate of the digital logic. This is a power-related phenomenon which requires higher and higher power levels as the frequency increases beyond the logic bandwidth cutoff point.

3. Power distribution noise. Alternating-current noise induced upon the digital power-distribution network can cause a temporary failure in the power-supply regulation at the logic device. The power-distribution noise of all frequencies is phase-independent and related to the instantaneous power in the imposed noise signal.

Table 2 shows a sampling of the possible soft errors which could be induced upon digital logic devices and the undesirable failure response associated with the noise form. The various soft errors indicated are simply samples of the numerous types of failures possible in a digital system. A comprehensive list would be extremely difficult to compile; even then it would be of questionable use, because it is usually impossible to trace digital failures to exact mechanisms and devices. The sample does show, however, the desirability of designing digital systems to be as free from noise upset as is possible.

TABLE 2.- SAMPLING OF SOFT ERRORS: POSSIBLE DIGITAL NOISE RESPONSES

Signal device	Form of noise	Undesirable response
Clock line	Phase shift	Timing margins violated
		Operation trashed
Edge trigger	Spike	Data not valid
		"Garbage in garbage out"
Sense line	Spike	Mode alteration
		"Where are we?"
Memory device	Noise margins	Unreliable data
	Violated	"Which way did he go?"
I/O driver/receiver	Power bump	Communication scramble
		"Are you sure?"

2.5.1.2 Device damage: Hard failures causing a destruction of digital devices occur through one of two mechanisms: power or voltage overloads. Unlike soft failures, it is possible to determine the exact mechanism of device damage. However, from a functional standpoint, it is not really necessary.

A power overload is identical to the rectified ac soft error called the I/O level shift above. The difference between the hard and soft failures induced by the dc offset is a function of the total power seen by the digital device at the pin. When the total power at the pin exceeds ~0.5 W, the thermal dissipation ability of the IC is exceeded and three different thermal breakdowns can occur: junction wire failure, metallization pad fusing, and diode junction breakdown.

The voltage overload failure mechanism is a dc phenomenon whereby the digital device input diode junction is exposed to a voltage potential in excess of its breakdown limit. Failure of this mode is only at the IC diode junction itself and indicates a surge in excess of the withstand ability of the diode. For standard MOS-type devices, this voltage-withstand value is of the order of 2 kV.

2.5.2 Lightning- Figure 2 shows a typical waveform associated with a lightning strike. Various investigators report different values for the parameters of the waveform; however, they all agree on the basic waveform shape. It rises to peak value rather rapidly and then decays back to zero in a much

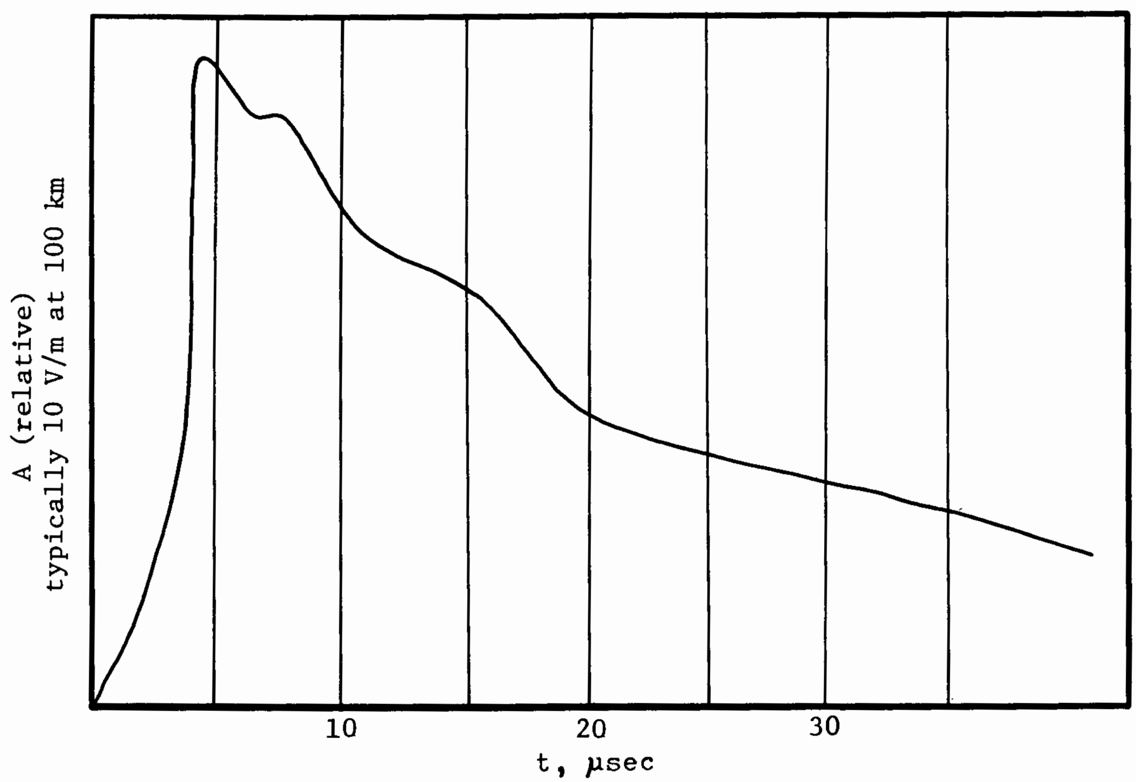


Figure 2.- Typical lightning flash waveform (cloud to ground).

slower, exponential-type curve. Figure 3 shows the frequency-domain transform of this waveform; the upper curve represents a rise-time of 200 nsec and the lower curve a rise-time of 2 μsec. Because of the complexity of the frequency transformation wave shape, the relationship between the amplitudes of the time-domain and frequency-domain waveforms is not simple; however, increasing the amplitude of one also increases the amplitude of the other. The frequency-domain waveform represents the power-density spectrum of the time-domain wave shape.

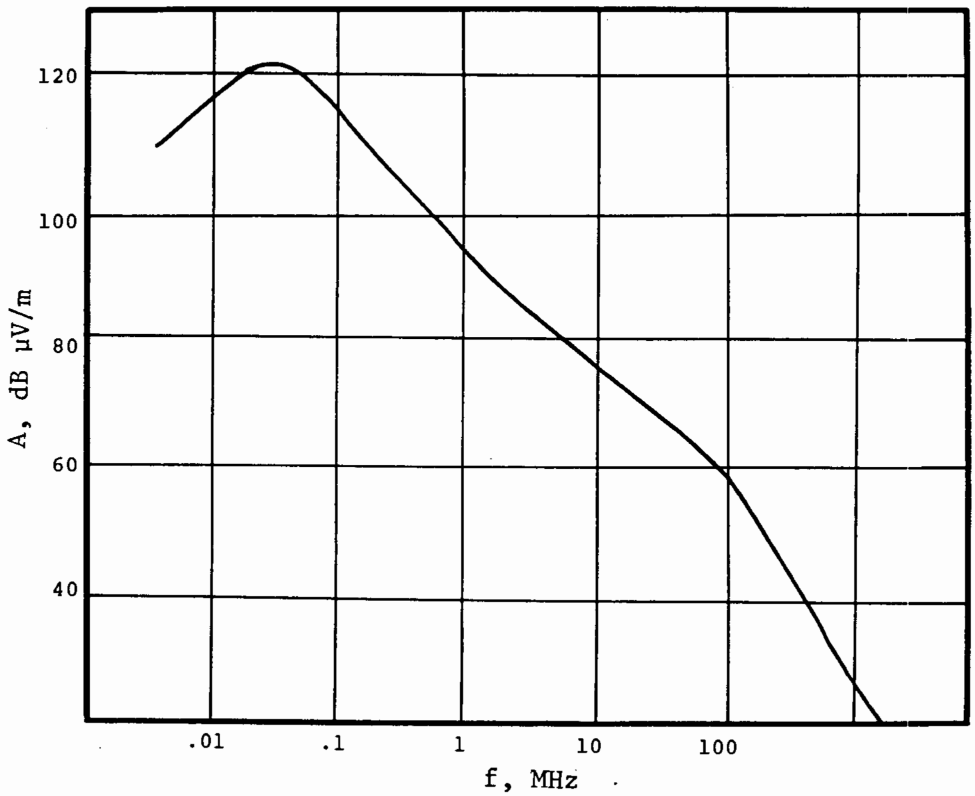


Figure 3.- Spectrum of total lightning flash. (Normalized to a bandwidth of 1 kHz and at a distance of 10 km. Uman and Krider, IEEE Transactions on EMC, EMC-24(2), 1982.)

2.5.3 ESD transients- The electrostatic discharge (ESD) phenomenon, although having different parameters in the time-domain wave shape, has the same waveform, hence the same shaped power-density spectrum as does the lightning transform. The ESD event has rise-times of the order of 1 to 10 nsec and, hence, a frequency bandwidth substantially wider than the lightning grid. However, the ESD event has an amplitude significantly lower than the lightning amplitude, which means that the power-density spectra of the lightning and ESD events are substantially similar beyond about 10 MHz. High probability of upset to a digital signal occurs when the power-density spectrum of the transient event overlaps the characteristic power-density spectrum of the digital signal itself. Figures 1 and 2 show a marked similarity between the broadband phenomenon associated with frequency transformations of both digital pulse and transient events. The phase information in both frequency-domain spectra has been left out so the comparison is not exact; however, it becomes easier to understand how a lightning or ESD transient can cause disruption to digital equipment when the two phenomena are viewed from their broadband, frequency-domain point of reference.

2.6 Specification Decisions

When all the data associated with digital avionics and aircraft threat environments are understood, it becomes possible to approach the problem of regulating the electromagnetic compatibility performance of digital avionic systems. This section is intended to illuminate some of the thinking that must go into specification decision making.

2.6.1 Know worst-case threat- Once all of the data called for in section 2.4 are in hand, it becomes possible to obtain a composite worst-case threat curve. This worst-case threat is obtained by adding together the amplitude-versus-frequency profiles of lightning, local transmitter, equipment/cable emissions, and fixed ambient noise sources. To obtain an operational survivability limitation curve, a safety margin (usually 6 dB, representing a factor of 2) is added to the worst-case composite threat, and this new curve becomes the minimum susceptibility limitation for the equipment. In actual practice, a radically simplified upper-limit survivability value is specified that may or may not be related to the actual threat imposed on the system. For power-line (conducted) susceptibility limitations, the realistic specification related to the actual worst-case threat would be obtained by adding a safety margin (suggested at 6 dB) to the actual measured power-line noise. Again, a simplified susceptibility curve is often used. It is strongly recommended that regardless of the amplitude-versus-frequency details for either the radiated or conducted susceptibility specifications that they be related to the environment found aboard the aircraft in order that the systems survivability specifications be meaningful.

2.6.2 Define acceptable system response- No system-survivability specification has any meaning unless there is first a definition of survivability for comparison with system response. Temporary (soft) upsets of system operation should be carefully discussed in the specification. For example, the following three items should be seriously considered in defining acceptable temporary upsets: (1) no operator intervention should be required for the system to resume normal operations; (2) the resumption of operations should be with the system in an identical state as it was before the upset; and (3) there should be no loss of critical data because of the temporary upset.

If a temporary disruption in normal operation of the equipment is to be allowed, the acceptable restart conditions must be carefully specified: (1) Must reset occur in the presence of noise similar to that causing the upset? (2) Is there a maximum acceptable time for the system to return to normal? and (3) Is there an acceptable time lag after the failure is diagnosed before the system begins the restart function?

Finally, a clear distinction should be made between acceptable interactions of systems based on the function to be performed by the system. Real-time data operations and time-critical operations should have more stringent operation requirements than operations that do not have a time-critical factor.

2.6.3 Set specification limits- Any comprehensive system EMC performance specification should include all of the following considerations: (1) emissions, both radiated and conducted; (2) susceptibility, both radiated and conducted; (3) crosstalk; and (4) failure indications.

2.7 Required System Tests

The specifications should require a specific testing protocol to probe system compliance with the specification limits. Care should be taken to insure that the tests are kept to a minimum, while at the same time comprehensively probing the entire range of required system performance. The test requirements should specifically and in detail discuss the exact test setup as follows: (1) site layout; (2) system configuration; (3) test equipment to be used; (4) actions to be performed by test personnel; (5) minimum acceptable performance limits; and (6) operational modes to include failure indications.

The ideal test specification should be an integral part of the document that lists the performance criteria for the avionics systems. Finally, the test specification should require a test plan to be written for each avionic system or subsystem to be tested; in the test plan, the generalized statements of the control document should be modified and adapted specifically to the device requiring certification.

3. SCOPE, SCHEDULE, MILESTONES

To this point we have attempted to discuss the nature of the problem and the direction to go in obtaining solutions. The discussion necessarily has been theoretical in nature and has, it is hoped, laid the groundwork for the actual process of obtaining airworthiness standards and certification guidelines for digital avionic systems for the future.

3.1 Aircraft EMC Signature

The first of a series of experiments and data-gathering efforts, in the process of obtaining ultimate qualification standards, is to understand the actual worst-case expected emissions from a commercial jet aircraft. Discussed below are the three efforts that will give a composite picture of these emissions.

3.1.1 Conducted emissions- The EMI noise on the power-distribution cables is varying and complex because of (1) the various and continually changing loads on an aircraft power supply, (2) the varying power-supply capabilities during different phases of flight, and (3) the effect of the loads back on the power supply. Furthermore, the actual power-line signature of one aircraft may differ substantially from that of another. To understand fully what is normal, and to have a statistically valid worst-case picture of the power-cable noise, an extensive test regimen is proposed. The most time-consuming portion of this procedure will consist of actually gathering power-line noise data from a number of different aircraft throughout the course of a normal commercial flight or a simulation of one. As envisioned, the effort will have the following elements:

1. Developing a comprehensive power-line noise data-gathering test program

2. Organizing test equipment, briefing test personnel, and scheduling aircraft for preliminary testing

3. Gathering emission data from one or two aircraft, both in ground tests and airborne tests

4. Analyzing data from (3), determining a minimum test plan for a large sample of different aircraft, and schedule testing

5. Conducting the large-sample emissions data-gathering procedures

6. Reducing the data gathered in (3) and (4) and compiling a generalized commercial jet aircraft power noise profile

3.1.2 Radiated emissions- The justification for gathering radiated emissions data from aircraft is partly to gain an understanding of what kind of susceptibility problems there will be with avionics devices mounted next to each other in the aircraft. Further justification for gathering these data lies in the need to ensure that these emissions are below some environmentally acceptable limit. The procedure for gathering the radiated emissions data will be somewhat different from that for the conducted emissions; however, the two efforts can be run in parallel. The approximate phases of radiated-emissions data-gathering procedure will be as follows:

1. Preparing and approving the test plan

2. Gathering test equipment and briefing personnel

3. Setting up radiation-monitoring stations for ground-based data gathering

4. Scheduling and installing equipment for airborne data gathering

5. Collecting the data

6. Reducing and correlating the data

3.1.3 EMC signature- Once the conducted and radiated emissions from aircraft in flight have been obtained, it is possible, using standard analytical techniques, to arrive at a realistic composite emissions profile for the aircraft. This phase is the combination of all of the emissions testing performed, and the final composite profile should be the baseline from which all future discussion of the EMC signature of digitally controlled transport jet aircraft are referenced. This analytical signature cannot be obtained until the completion of the tests described in subsections 3.1.1 and 3.1.2. The report issued at the end of this analysis should include as appendixes all of the data gathered in the above referenced tests.

3.2 Susceptibility

Along with the susceptibility of the instrumentation and the analytical expectation of shielding from the aircraft skins, a complete threat-hardening guideline requires data on the nature of real and potential threats from which the aircraft in flight will be exposed. These various threats each constitute a topic for an investigative study as set out below.

3.2.1 Electromagnetic pulse (EMP)- Whether commercial jet aircraft should be subject to EMP hardening criteria and if so, to what level, should be determined before any susceptibility-hardening criteria are issued for airworthiness qualification. The imposition of EMP standards and the level of required survivability are the responsibility of the FAA. The analysis performed during this task will, in part, develop transfer functions to translate EMP system-level effects (field strengths) into given threat levels observed at the avionics.

3.2.2 Lightning- The determination of the electromagnetic threat to aircraft posed by lightning strikes is a topic of considerable discussion and research. Gathering sufficient data for developing avionics-hardening criteria would not require much original research, but it would require substantial time to search through the existing literature and correlate and reconcile the experimental data from the various researchers in the field. The goal of the lightning-data search should be to determine the realistic electromagnetic energy that the digital avionics could be exposed to as a function of altitude, airspeed, and phase of flight. To be completely general, airworthiness criteria imposed upon digital avionic systems should be developed by taking into consideration the worst-case lightning threat that could be expected for aircraft in any portion of the world. Accordingly, the data used in this study will be taken from the area of the world having most severe lightning problems.

3.2.3 Ambient radiation- The primary danger that ambient radiation holds for the avionics of a digitally controlled commercial transport occurs mainly during approach and departure, when the aircraft is close to the ground. Potential sources of interference from the man-made ambient include radio, television, and other geographically fixed transmitter sources; mobile communications transmitters; citizens band (CB) transmitters; industrial noise; and automobile traffic noise.

The effects of these various interference sources may be mild relative to those of lightning or an EMP requirement; however, it is necessary to map the emissions profile of a worst-case approach path for a landing commercial transport to ensure that no radiation that is part of the ambient can seriously disrupt the approach of an aircraft during landing as a result of the electronic susceptibility of the digital flight-control instrumentation.

3.2.4 Electrostatic discharge- The ESD threat encountered by a commercial jet transport aircraft is similar in nature to the lightning and EMP problem inasmuch as both phenomena involve the generation of fast-rise-time, broad-bandwidth noise transients that can interfere with normal operation of digital guidance or control systems. The source of serious ESD interruptions to the digital avionics would be possible generation of high static potentials inside the aircraft in flight owing to triboelectric effect and outside the aircraft owing to precipitation effects (P-static). The present ESD-generation potential of commercial aircraft must be measured, and the ESD susceptibility of a characteristic digital avionics system (such as the Collins RDFCS) must be characterized so that ESD-hardening criteria of an appropriate level can be included in the system survivability specifications.

3.2.5 Expected aircraft shielding- Part of the susceptibility threat to aircraft systems is a function of how much shielding is provided by the outer aircraft skin. There is a significant reduction in the attenuation of the threat when composites, such as graphite-epoxy, are used in aircraft manufacture. A comprehensive shielding performance study needs to be performed on commonly used composite materials as opposed to previously used aluminum skin to determine the EMC-hardening requirements differences imposed by the use of composites. The analysis program will be as follows: (1) composite-material shielding effectiveness evaluation (existing data review, analysis and test); (2) evaluation of shielding provided by aluminum aircraft skins (performed on actual aircraft; and (3) analysis of differences in shielding of different materials as they affect avionic system survivability (signal cables, power lines, electronic's cases).

3.2.6 System-hardening criteria- Once all the data have been gathered from the above studies—EMP requirements, lightning threat, ambient noise threat, ESD-generation and threat, and aircraft skin shielding—it will be possible to develop a composite noise-threat curve. The requirements for hardening of digital avionics systems should insure survivability after exposure to the above compiled worst-case threat. The results of this effort (hardening criteria) will be a document that (1) shows the worst-case noise threat; (2) analytically determines transfer function between equipment survivability limit and the above transient and steady-state threats; (3) defines survivability; (4) outlines criteria for hardening systems as a function of system criticality; and (5) defines avionic systems shielding requirements differences for different aircraft skin material based on derived transfer functions.

3.3 Collins Redundant Digital Flight Control System

Installed at the NASA/FAA facility at Moffett Field Naval Station in Mountain View, California, is a working prototype of a relatively comprehensive digital avionics control system. This equipment, called the redundant digital flight-control system (RDFCS), was designed by Collins Avionics Division of Rockwell International. Without addressing the comprehensiveness of this particular digital flight-control system, its very existence is a valuable tool in characterizing the EMC posture of a fully integrated, state-of-the-art flight-control system. The emissions and susceptibility of the RDFCS can be measured at its current installation at Moffett Field. The step-by-step procedure for doing so would be as follows:

1. Prepare and approve a comprehensive test plan

2. Validate proposed test methods

3. Gather the necessary test equipment and schedule the RDFCS use for EMC test

4. Test RDFCS radiated and conducted emissions

5. Make comprehensive test susceptibility (these tests may require the installation of the RDFCS in a shielded room facility

6. Reduce and analyze data

3.4 Guidelines

As an aid to equipment manufacturers and purchasers, there is need of a series of guidelines to help evaluate potential and actual avionic designs. The compatibility of each system or subsystem should be predictable for both the provider of the equipment and the user.

3.4.1 Transfer functions- Each component or configuration of devices used in the manufacture of digital equipment is characterized in terms of emission, susceptibility, attenuation, or suppression. The total EMC of the completed system is a summation of the EMC of each component used therein plus the system interaction effects. These effects are predictable, and, given the design of any system, a "transfer function" can be developed that will translate the EMC of the system into a series of measures to be implemented to obtain fully reliable operation for the system. Given the nature, speed, complexity, and power use for a digital avionics logic design, it is possible to translate the expected EMC so attained into specific minimum requirements for shielding, filtering, and cable configurations to ensure that the system as designed will comply with the applicable performance requirements. Development of the transfer functions to accomplish these ad hoc design requirements will require a knowledge of the actual susceptibility environment of the aircraft coupled with the known EMI effects of digital electronics.

3.4.2 Design guidelines- A detailed guide to lead designers through the pitfalls and problems to be avoided would speed up EMC assurance for new designs. The guide would discuss grounding, shielding, filtering, circuit card layout, cabling protocols, software, and hardware design details. The document should present the design techniques that must be followed or avoided, but should also discuss the reasons behind the rules. There should be a design flowchart to track the design requirements and their interaction with each other.

3.5 Airworthiness Standards

The comprehensive airworthiness standard for both digital avionics subsystems and complete systems is the major goal of this program plan. The recommended airworthiness standards will identify maximum emission limits as a function of frequency for both radiated and conducted digital noise. Furthermore, they will identify a frequency-dependent threat noise level that the equipment should withstand without being susceptible. The airworthiness standards will describe recommended EMP and ESD threat levels that a digital system should be able to sustain and then resume normal operation. The susceptibility threat levels in the airworthiness standards should be independent of aircraft construction techniques and should only address actual threats to which the aircraft will be exposed. A final airworthiness standard should be able to make maximum use of the recommendations herein. The group responsible for developing the standards should have all the data gathered as a result of this study.

3.5.1 Preliminary standard development- Based on general principles of electromagnetic interference in digital systems, a preliminary hardening standard for digital avionics should be developed. This standard should include statistical estimates of the susceptibility threat to which functional avionic systems may be exposed. The preliminary standard should also provide a reasonably detailed description of hardening methods presently used on digital avionics equipment, with the aim of increasing their operational reliability. Accordingly, currently operational aircraft with their actually encountered reliability problems should be taken into consideration, and the preliminary standard should be developed specifically to reduce these problems. The final form of this preliminary standard should be a list of step-by-step changes to be made in the avionics and flight-control systems of functional aircraft that have already manifested problems related to digital equipment susceptibility. The changes suggested by this preliminary standard will relate to cabling, connectors, shielding, bonding, and grounding.

3.5.2 Shakedown testing- Once the preliminary standards have been fully developed and the implementation list completed, the suggested changes should be implemented in selected aircraft. These aircraft should then be returned to normal commercial transport duty. The operational reliability of these test aircraft should be carefully monitored and any problems encountered should be fully recorded. The data so developed should be compiled for final airworthiness standard development. To have any statistical validity, the shakedown test should include a representative number of different aircraft and should continue for a reasonable length of time (suggested minimum of 1 yr). The above described shakedown testing describes an idealized situation. Because of funding constraints, interagency coordination problems, industry corporation limitations, or liability restrictions, the ideal shakedown testing might not be possible. Acceptable alternatives should include implementing the provisions of the preliminary standard on at least one aircraft. The selected aircraft should have had unexplained avionics interruptions or be able to be put through a before-and-after test regimen to observe directly the operational upgrade provided by the preliminary standard.

3.6 Test Methods

Among the various EMI test methods presently in use, there are some that overlap others, some tests that conflict with others, and some tests that are irrelevant. Other test methods that have been developed and that could be used for valuable data gathering are not presently employed. A comprehensive study of all available EMI test methods for probing both the susceptibility of and the emissions from digital equipment should be undertaken. The goal of the study should be to identify a minimal set of test methods that will comprehensively probe the interference potential of digital electronic equipment.

3.6.1 Methods development- The testing developed herein should probe for two levels of compliance: black-box or individual avionics device, and system level. The avionics manufacturers would be responsible for insuring that their devices comply with the black-box level test; whichever agency assumes the role of system integrators would be responsible for compliance with the system-level tests. The test methods will make a clear distinction between component and system-level test procedures, with provision included for connecting components to actual or simulated system interfaces for black-box testing.

3.6.2 Qualification testing- After completing the recommended airworthiness standard and test-method development, a specific step-by-step qualification test standard will be developed. This test standard will delineate specific test setup configurations, test equipment, test procedures, and equipment acceptability criteria. This recommended qualification test standard could be the document from which all digital avionics equipment test plans are prepared. This also is most appropriately developed through government and industry corporation.

3.7 Schedule

Figure 4 shows each of the above discussed tasks laid out in an approximate time schedule for completion. The completion schedule for each task is approximate and the time schedule in figure 4 allows considerable "flow" beyond that indicated as necessary by the critical path analysis.

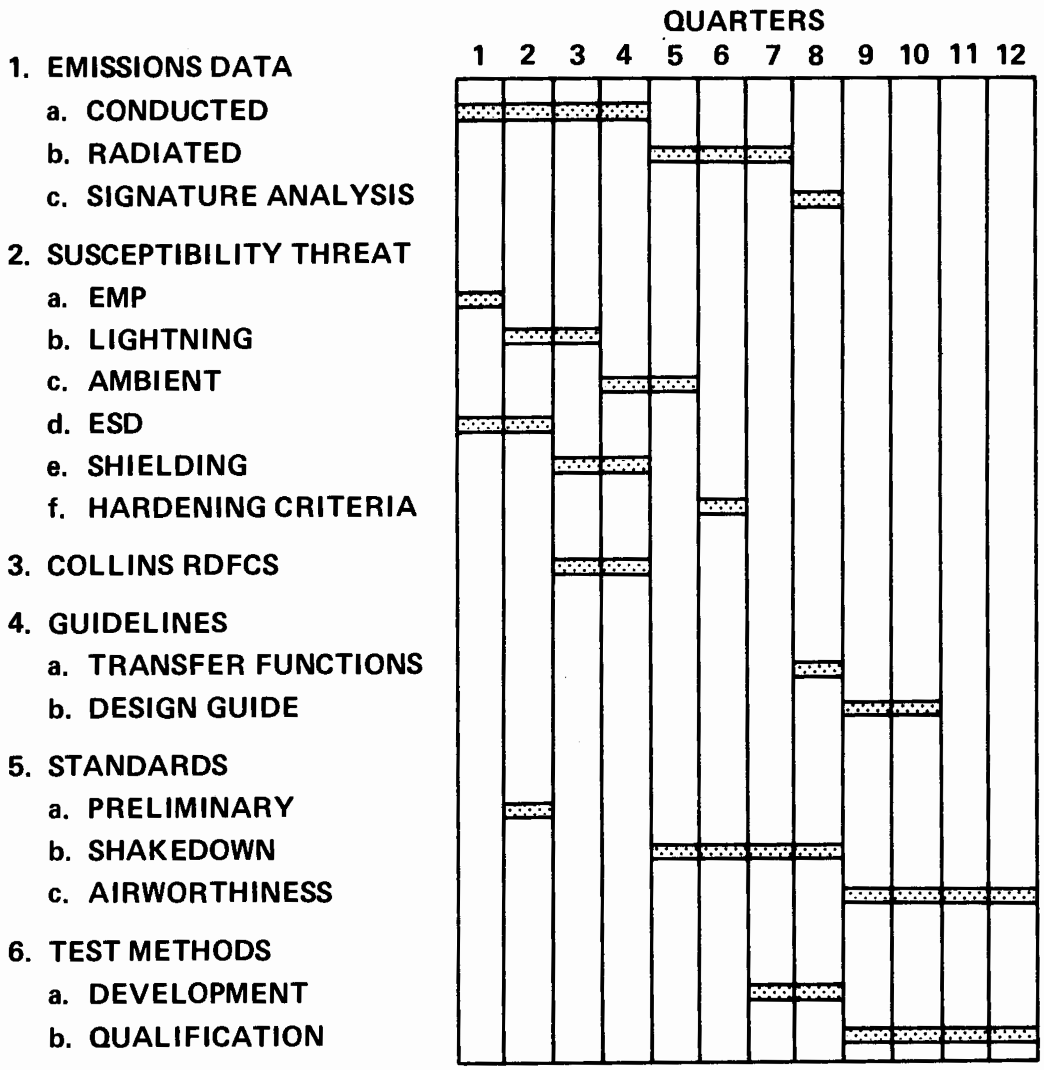


Figure 4.- Program schedule and approximate cost.

APPENDIX A

EMC DESIGN PRINCIPLES

A1. DESIGN GUIDELINES

In this section, an attempt is made to adapt generalized EMC design principles to digital avionics subsystems and systems. The section begins with management-type considerations and becomes more specific, finally ending with recommendations to be included in the design of digital avionics.

A2. IDEAL EMC DESIGN

Electromagnetic compatibility is a concern to most levels of management. The least expensive way of including EMC hardening into any system is to include it in the conceptual and early design stages. To do so, however, requires engineers who understand and can solve the problems, and, of course, requires that the necessary engineering time be budgeted. The problem gets more serious, however, by delaying the consideration of EMC concerns until later; the range of solutions radically diminishes, and the cost of implementing those solutions increases continually.

A2.1 Management Awareness

The best EMC design is done in a design environment wherein all levels of mangement are aware of the trade-offs and implications inherent in including EMC considerations. EMC-hardened designs affect the areas of engineering, marketing, manufacturing, quality assurance, and field service. Consequently, management has to be fully apprised and convinced of the positive side of factoring EMC concerns into their operations. There is of course the legal aspect of insuring that the design complies with the regulations, but there is also a substantial hidden benefit in that properly hardened systems perform more reliably in all situations, especially in the presence of potentially disruptive noise energy.

A2.2 Designer Awareness

The engineers actually doing the design should ideally have a working knowledge of the benefit of including EMC considerations in their design. Furthermore, their design skills should be complemented by a reasonable understanding of the solution options and the trade-offs inherent in each different EMC-control technique.

A2.3 Analysis

Very early in the design stage of a project, subsequent to the basic system logic definition, but before committing any design to hardware, a series of analyses should be performed to alert all personnel to the EMC implications inherent in following any design strategy. The analysis should point out the emissions, susceptibility, and crosstalk problems to be encountered in various circuit layout techniques, power-distribution schemes, and cabinet design philosophies. The analysis should flag the potential EMC-problem areas for immediate design attention with an indication of the cost effectiveness of the various solutions available.

A2.4 System-Level Coordination

Many EMC problems are electrical in nature (i.e., within the area of the electrical engineers understanding). Many solutions to EMC problems, however, are mechanical in nature and as such fail within the province of the mechanical designers. Accordingly, there is a need for the electronics and mechanical design teams to closely coordinate with one another. A system-level coordinator, schooled in EMC concerns, should be responsible for insuring that any designs or design changes that effect the EMC stature of a system are implemented in a way that does not negatively affect that stature. Ideally, this coordination function would fall within the duties of the project manager; however, if because of technical or time restraints this is not possible, the person performing the coordination should have sufficient authority to repidly resolve any technical problems that arise in attempting to optimize the individual performance of each design element.

A2.5 Fallback Positions

No EMC performance of any system can be guaranteed until that system has undergone a qualification test program. Accordingly, the conflicting requirements to produce the maximum EMC-hardened system with the minimum effect on time and budget will possibly give rise to design areas that are too close to predict in terms of their EMC performance. Accordingly, the system-level EMC coordinator should insure that fallback positions, including drawings, hardware, and suppliers be in place to rapidly retrofit any design application that the previous analysis has shown to be at or near the minimum acceptable design performance.

A3. LEVELS OF EMC CONTROL

In containing or controlling electromagnetic interference, there are numerous problems and equally numerous solutions. The solutions can be categorized into three different classes or levels of control techniques: device, system, and subsystem levels.

A3.1 Description

The following classification or description of different levels of EMC control is by no means a rigid one. In fact, the ordering of the descriptions is such that the third can be explained in terms of the first two.

A3.1.1 Device level- Individual components inside an electronic system can be lumped in the categories of emitters or susceptors or perhaps both. Controlling interference at the device level means to control the emissions or the susceptibility of equipment at a local level to either reduce the emissions at the source or to reduce the response of the susceptor to any imposed threat. Examples of device-level EMC control are careful impedance-control techniques used in the layout of printed circuit boards, waveform modification filtering of video signals at the driver, and on-board filtering components being added to switching power supplies.

A3.1.2 System level- Controlling emissions and susceptibility at the system level means to attenuate any unacceptable electromagnetic energy at the interface between the system and the external environment. System-level EMC control means to rely on the case and cable shielding to attenuate the undesirable energy to an acceptable level. The techniques of controlling EMC at this level consist of paying strict attention to aperture control and understanding the shielding effectiveness of materials.

A3.1.3 Subsystem (intermediate) level- Subsystem-level intermediate control means to address the noise-coupling problems internal to the system, but at a more complex level than at the individual susceptors and emitters. Examples of subsystem-level EMC control are the use of compartmentalization, shielded internal cables, or extensive use of internal ground planes.

A3.2 Trade-Offs

Table 3 is a chart of the trade-offs available in EMC control techniques. A choice of rework measures is basically dictated by the phase of the design in which EMC concerns are factored in. In the early design conceptualization stage, the simplest, most cost-effective method is a device-level control. However, once the hardware design is firm, both cost and lead-time considerations favor subsystem-level control as the method of choice.

A4. DESIGN MINIMUMS

There are a large number of design techniques that affect the EMC status of a system. Most of them are simply good design practices; however, some are of such importance to system operations that they should be specified explicitly in corporate design specifications. This section discusses several recommended design practices that should be strictly complied with in all digital avionic system designs.

TABLE 3.- EMC CONTROL TRADE-OFFS

	Design phase	Prototype	Final hardware
Advantages	Most elegant, best in design phase, lowest initial cost	Mechanical design does not affect bread boarding	Best retrofit solution, lowest redesign cost
Disadvantages	Not possible to retrofit easily; requires up-front attention; requires analysis	Total reliance can be costly; retooling is painful	Requires human engineering; limitation on effectiveness
Cost	Low initially, high later	Approximately same as on EMC	Moderate
Lead time	Short initially	Long	Moderate
Retrofit	Requires relayout	Possible in metal, not with plastic	Best approach after design is firm

A4.1 Things to Avoid

The design practices outlined in this section have been shown numerous times in practice to have such negative effect on the reliable operation of digital systems that they should be carefully avoided by conscientious designers: (1) remote latch triggers and reset lines; (2) cable shield terminations on printed circuit board (PCB) logic ground; and (3) PCB-mounted opto-isolators.

A4.2 Things to Include

The items contained in this subparagraph are included because over the years a substantial number of high susceptibility digital failures have been traced to violation of these design practices: (1) all I/O cables should be shielded or filtered, or both; (2) error checking and correction (ECC)/ (3) controlled PCB loop areas; and (4) well-filtered power distribution.

A5. GENERAL EMC DESIGN GUIDELINES

This next section will be devoted to the discussion and application of general best-practice EMC considerations in the design of digital electronic systems.

APPENDIX B

TEST PLAN FOR THE COLLINS REDUNDANT DIGITAL FLIGHT CONTROL SYSTEMS

B1. SCOPE

This document is a detailed description of the electromagnetic compatibility (EMC) test procedures to be used in characterizing the Collins redundant digital flight control system (RDFCS) presently installed and under evaluation at Ames Research Center, Moffett Field, California. The test procedures described herein are intended to characterize the EMC profile of the RDFCS. The data so obtained will be used as baseline comparison in testing and specifying limits for future digital avionics systems.

B2. APPLICABILITY

The procedures described herein are specifically written to obtain the EMC profile of the Collins RDFCS at the Ames facility at Moffett Field. However, the specific test procedures used are either direct copies of or carefully worked out derivations of standard EMC test procedures and could be used in the EMI characterization of general digital flight instrumentation.

B2.1 Applicable Documents

The test procedures contained herein are taken either directly from or have been carefully derived from the following EMI test standards:

1. MIL-STD-461, Electromagnetic Interference Characteristics, Requirements for Equipment

2. MIL-STD-462, Electromagnetic Interference Characteristics, Measurement of

3. IEEE Standard 472

4. AIR 1499

5. RTCA Document DO-160A, Environmental Conditions and Test Procedures for Airborne Equipment

Inasmuch as this document was derived specifically for the testing of the RDFCS installed at Moffett Field, conflicts which may exist between the above referenced documents and this test procedure will be resolved by giving priority to the details of this document.

B3. EMC TEST REQUIREMENTS

Table 4 contains a complete list of the EMC tests to be performed in characterizing the EMC profile of the Collins RDFCS. Because the purpose of this testing is to characterize the emissions and susceptibility profile of the RDFCS, no emissions or susceptibility limits will be imposed when performing the above discussed tests. However, the emissions tests will simply show the actual emissions profile of the system. Similarly, the susceptibility tests will be performed up to the indicated maximum signal strength levels. Actual failure thresholds that are below these limits will simply be recorded. Typical categories of interface limits are provided for convenience in figures 5 - 7. (All figures cited in this appendix are grouped at the end of the appendix.)

TABLE 4.- EMC TESTS

Subsection	Test	Frequency	Limit
B10.3.1	CE 03[a]	14 kHZ-50 MHz	Figure 5
B10.3.2	Maximum current	14 kHz-50 MHz	N/A
B10.4.1	RE-02 (modified)[a]	1 MHz-1 GHz	Fig. 6 NB Fig. 7 BB
B10.4.2	Maximum emissions	1 MHz-1 GHz	N/A
B10.5.1	CS 06	0.15 μsec pulse	200 V
B10.5.2	ESD cable induced[b]	ESD pulse	15 kV
B10.5.3	RF cable induced	20 kHz-30 MHz	100 mV
B10.6.1	RS-02 case plus cables	0.15 μsec pulse, 400 Hz	100 V, 20 A
B10.6.2	RS-02 (modified) ESD case[b]	ESD pulse	20 kV
B10.6.3	RS-03	20 MHz-16 Hz	20 V/m
B10.6.4	RS-03 (modified) loop probe	1 MHz-16 Hz	20 V/m
B10.6.5	ESD direct[b]	ESD pulse	12 kV
B10.6.6	ESD E field BB	ESD pulse	15 kV

[a]RTCA/DO-160 A Category A (for comparison only).
[b]Advisory limit, susceptibility signal increased until failure is noted.

Notes: BB = broadband; CE = conducted emissions; DO = document; ESD = electrostatic discharge; NB = narrow band; RE = radiated emissions; RF = radio frequency; RS = radiated susceptibility; RTCA = Radio Technical Commission of America.

B4. SYSTEM DESCRIPTION

The RDFCS is a multiple, rack-mounted series of digital equipment configured such that all the equipment necessary for control of flight operations along with simulation equipment is present. Figure 8 shows a block diagram of the entire system. Figure 9 shows the pallet configuration of the equipment in the rack mount and figure 10 is a photograph of the latest configuration of the RDFCS.

Simulation of the flight dynamics of the airplane resides in the PDP 11/60 computer which is located along with necessary information storage and hard-copy capability in the room containing the RDFCS equipment. The configuration of this simulation room is shown in figure 11. As the simulation dynamically calculates parameters, they are written to the memory-mapped I/O fiber-optic card internal to the PDP 11/60. This card formats the data and ultimately sends it out serially over a fiber-optic transmission line to a memory-mapped I/O fiber-optic card in the modular digital interface control unit (MDICU) portion of the RDFCS.

B4.1 Operational Modes

For purposes of the tests contained in this document, the RDFCS will be operated under normal control of the simulation computer. During all phases of the testing, the EMC profile of the flight-simulation computer and its associated peripherals will be carefully screened from the characteristics of the RDFCS by appropriate suppression techniques. This is necessary to insure that the data taken in the test represent only the RDFCS EMC profile and are not perturbed by responses of the simulation equipment.

B4.2 Functional Input and Output

As shown in figure 8, the I/O link between the PDP 11/60 simulation computer and the RDFCS is over a fiber-optic link. Although the fiber-optic link should have no effect on the EMC of the RDFCS, there are interfaces between the PDP 11/60 simulator computer and the PDP 11/04 flight-control computer and interfaces between the keyboard and printer to the flight-control computer that could have substantial negative effect. Decoupling the effects of the simulation and peripheral equipment from the RDFCS will require considerable attention to cable shielding and possibly case shielding of the untested equipment. This protective shielding will best be accomplished through liberal use of aluminum foil, taking care to insure that the foil shield is carefully grounded to the third wire everywhere and that no inadvertent shorts are made as a result of the foil. Should any question arise about the effectiveness of this decoupling between the EMC of the test equipment and the equipment under test, the simulator and peripheral equipment will be disconnected as much as possible and the PDP 1104 put into a loop self-test mode and the tests rerun, with the data from the two runs compared.

B5. TEST SAMPLE CONFIGURATION

The test configuration will consist of the RDFCS fully loaded and simulated by the PDP 11/60. The RDFCS rack will be rf-bonded to the safety ground network of the testing facility and each item of equipment in the test rack will be rf-bonded to the rack.

B5.1 Interface Cabling

The I/O interface between the RDFCS equipment and simulation and peripheral equipment will be that cabling presently in place without alteration unless the cabling is proved to have a significant effect on the EMC profile of the RDFCS. In the event that the interface cabling is shown to be a weak link, the cables will be upgraded by an add-on aluminum-foil shield and the test continued.

B5.2 PDP 11/60 Simulator Test Set

As for the I/O cables, the PDP 11/60 simulator will be left unmodified unless emissions or susceptibility testing show that this computer, with its peripherals, unacceptably degrades the profile of the RDFCS. Every effort will be made to perform the tests in the location where the equipment is normally installed without moving or reconfiguring any equipment. It should not be necessary to move the RDFCS into a shielded room, with the PDP 11/60 and associated peripherals outside the shielded room. However, extremely high emissions or low susceptibility of the PDP 11/60 and associated peripherals could force the use of a shielded room.

B5.3 Bonding and Grounding

Any flight-control system when mounted in an actual aircraft, will be well bonded to the aircraft skin ground reference potential. Inasmuch as the soundness of the ground reference potential of any digital equipment has a significant effect on the EMC profile of that equipment, every effort will be made to insure that all portions of the RDFCS equipment are well chassis-grounded. Each item of equipment will be well rf-bonded to the RDFCS mounting rack, and the rack itself will be carefully referenced to the safety ground grid network in the installation facility. If it is necessary to upgrade the grounding scheme of the system as presently installed to achieve this well-referenced configuration, the material used for the grounding upgrade will be solid strips of grounding material, such as copper or aluminum foil. This grounding upgrade or proof will be completed before any of the tests described herein are started.

B6. TEST SAMPLE OPERATION

Unless it is impossible to separate the EMC profiles of the RDFCS and the simulation and peripheral equipment, all testing of the RDFCS will be accomplished with a full interface configuration. Any degradation of the full configuration will be used only if an unacceptable interference situation exists using the full configuration.

B6.1 Full-Interface Mode

Full-interface test configuration shall be defined as having the PDP 11/60 simulation computer in normal operation with the simulation program for the RDFCS in normal operation. In this test mode, the interface cable shall be in normal operation with standard signal flow between the RDFCS and the simulation equipment.

B6.2 Degraded Configuration

In the event that full-interface configuration is not possible because of unacceptable emissions or susceptibility of the PDP 11/60 or the interface cable itself, the RDFCS shall be configured in a self-test or diagnostic mode, with the interface cables disconnected at the RDFCS end and all loop programming controlled by the PDP 11/04, which is part of the RDFCS.

B6.3 Susceptibility Failure Criteria

During all susceptibility testing, system failure shall be defined as the inability of the RDFCS or simulation equipment to continue in normal operation as a result of the susceptibility test signal. Failure shall further be defined as any situation that interrupts normal operation of the test system and produces an error report or system reset, requires operator intervention of any nature, or alters any critical data.

B6.4 Test Operational Software

The operational software used during the conduct of the test should be capable of not only performing all simulation routines in normal mode, but should also be able to recognize and identify system responses that are defined as failures during the test. It is not necessary for the software to shut down operation of the equipment when a fault has been monitored, as long as the failure is immediately reported in such a way that persons conducting the test will recognize that a fault has occurred.

B7. TEST CONDITIONS

The test facility used for the conduct of the tests will be the normally installed operational environment of the RDFCS at the Ames facility, if at all possible. The only condition causing the test facility to be moved from Moffett Field will be as described above (i.e., if the EDP 11/60 simulation computer and peripherals make unacceptable contribution to system profile).

B7.1 Test Facility

A complete description of the facility used to conduct the test will be included in the test report. This test facility description will include, but not be limited to, the following items:

1. A complete description of the power used

2. The condition of the system grounding and bonding protocol

3. A complete description of the ambient noise background, both radiated and conducted

4. Diagram showing configuration of the equipment tested, the simulation equipment, and the test instrumentation

5. A measurement of the input power voltage before the start of testing on each day that the test continues

B7.2 Announcement of Testing

All electromagnetic interference and susceptibility tests described herein will be announced at least 10 days before testing is started. Invitations to witness the testing will be issued to representatives of Ames, the FAA, and Rockwell/Collins.

B8. INSTRUMENTATION

Test instrumentation required for performing the tests discussed herein is described below.

B8.1 Required Test Equipment

The following items of test equipment, listed generically by type will be required to perform the testing discussed herein. The applicability of each type of equipment is discussed in the subparagraph describing the equipment.

B8.1.1 Frequency analyzer- A broadband multifrequency spectrum analyzer having a frequency range from 14 kHz - 1 GHz is the best equipment for measuring emissions, both radiated and conducted. The spectrum analyzer should have an adjustable sweep-frequency range with sufficient resolution to separate frequencies down to at least 1% resolution. Examples of acceptable instruments include, but are not limited to, the following: HP 8568A; ESA 1000, and Tektronics 7L12.

B8.1.2 Preamplifiers- When a spectrum analyzer is used as the measuring instrument of choice, it will be necessary to provide a broadband input signal preamplifier having amplification up to 30 dB across the entire frequency spectrum to be measured.

B8.1.3 Frequency synthesizer- One or more single-frequency, narrow-band synthesizers capable of covering the frequency range from 14 kHz to 1 GHz are required. The synthesizers used should have an output calibrated both in frequency and amplitude to within 1% accuracy. In the event that the frequency analyzers discussed above do not have an internal calibration, these calibrated frequency synthesizers can be used as an external standard in making emission measurements.

B8.1.4 Field intensity meters- As an alternative to using a frequency analyzer as a measurement device, a single, frequency-tuned receiver, having calibrated field-intensity input can be used. Any of a number of different tuned receivers can be used. The only important requirements for these receivers are that they must have a frequency range from 14 kHz to 1 GHz and must have a sensitivity of at least 10 dB above a 1 μV.

B8.1.5 Antennas- The following receiving and transmitting antennas will be required in the radiated testing.

Frequency	Description
015-30 MHz	41-in rod antenna
20-300 MHz	Biconical antenna
200-1000 MHz	Conical log spiral antenna
300-1000 MHz	Log periodic antenna
0.014-1000 MHz	Hand-held loop (S) antenna

B8.1.6 Auxiliary instrumentation- The following items will be used during the course of interference and susceptibility testing as support equipment required to implement specific test methods described herein.

1. Electrostatic discharge (ESD) generator, having a calibrated output from 0 to 20,000 V, and having an equivalent circuit with parameters C approximately 150 pF and R less than 1,500 ohms. The location of these discharge circuit components should be in the discharge head as close to the point of discharge as possible.

2. Impulse generator, built to comply with the testing requirements of test CS-06 of MIL-STD-461.

3. Ten-μF feedthrough capacitors; as many as required to perform the conducted emissions testing.

4. Current probe, calibrated for performing conducted emissions testing.

5. Isolation transformer.

6. Attenuator. Broadband signal attenuator having a value of 10 dB.

7. Field-strength meter. Sufficient to measure field strengths up to 20 V/m and down to 0.1 V/m.

8. Digital multimeter.

9. Oscilloscope, having at least 100-MHz bandwidth.

In addition to the above discussed equipment, the test engineer should have on hand a sufficient supply of wire, aluminum foil, and insulating material.

B8.2 Calibration Requirements

All instruments used in the performance of the tests described herein will be calibrated as recommended by the manufacturer. The EMI test engineer will verify that all instruments are in calibration before their use. The date of last calibration for each instrument will be recorded at the time of use and reported in the EMI test report.

B8.3 Instrument Operation

Interference measuring instruments operation and calibration will be in accordance with the manufacturer's specification and the test specification. Meters will be operated in the peak mode for all measurements.

B8.4 Measurement Instrument Grounding

The interference measuring instruments will be physically grounded with only one connection at all times. The antenna will be remote from the meter. The EMI receiving device will be grounded through the third wire safety ground for all tests.

B8.5 Frequency Selection

For steady-state operation, the EMI receiving device will be carefully tuned through each frequency band. Those frequencies at which maximum interference is detected will be measured and recorded. In the event that no peaks are detected, three evenly spaced frequencies per octave will be selected for measurement. If the emissions testing is performed with the frequency analyzer, the observe-frequency bandwidth of the device shall be set to observe no more than half of a frequency decade total bandwidth.

B8.6 Required Susceptibility Modulation

During the conduct of rf-susceptibility testing, the signal shall be modulated as follows:

1. A 400-Hz, 30% amplitude-modulated sine wave over the frequency range of 14 kHz to 1 MHz. Between 1 and 200 MHz, amplitude-modulate the rf sources with a pulsed signal having a 25% duty cycle and a frequency of 20 kHz. Above 200 MHz, amplitude-modulate the generator with a pulse signal having a duty cycle of 1% and a frequency of 20 kHz.

2. Sweep the required rf range with the applied signals modulated as specified in (1) above.

3. If no susceptibility effects are observed, the susceptibility requirement is considered to be met.

4. If susceptibility failures occur at one or more frequencies, steps (5) through (7) are to be followed.

5. Set the rf source to the frequency at which the test sample was found to be most susceptible.

6. Vary the modulation frequency from 400 Hz through 20 kHz at this rf and determine the modulation frequency that causes the most susceptible condition in the test sample.

7. Sweep the required rf range with the sources modulated by the worst-case modulation as determined in (6) above. Determine amplitude thresholds at each susceptible frequency and record as test data.

B9. TEST PROGRAM DEVIATION

Because of the nature of the tests described herein, namely, characterizing the RDFCS EMC, the tests can be considered neither comprehensive nor exhaustive. Every effort has been made to design a comprehensive test program, but some of the data required to understand fully the EMC of the RDFCS may not be completely understood at this point. Accordingly, in the conduct of this testing, enhancements to the tests may suggest themselves. Should a need for a change in the test procedure become apparent to the testing engineers during the conduct of the testing, such change shall be implemented after notification to and approval by FAA. Any changes to the herein-described test procedure shall be carefully recorded and reported in the test report.

B10. TEST PROCEDURES

This section describes the actual test to be performed in gathering the data on the RDFCS profile.

B10.1 RDFCS Verification Tests

Before the start of any EMC testing, a functional test will be performed on the RDFCS to verify proper operation. This test will consist of the RDFCS being exercised by the simulation equipment for at least 1 hr to insure that all systems are functioning properly and that no abnormal condition is present. Should this preliminary acceptance test prove the existence of any abnormal condition, the condition will be rectified and a clean 1-hr test of the system will be completed before the commencement of the EMC testing. With all test equipment and PDP 11/60-associated simulation equipment and peripherals operating normally, and with the RDFCS powered completely off, ambient data will be taken applicable to the test about to be performed. Any out-of-specification conditions observed will be carefully recorded and every effort made to correct the condition before the commencement of the test. Should unacceptably high ambient responses continue, the test will be run as outlined and the data recorded with the notation of the out-of-specification ambient condition. Upon completion of such compromise testing, a modified test of the same nature will be performed having the PDP 11/60 and associated simulation equipment shut off and the RDFCS running in loop mode. The data recorded during these modified tests shall also be reported in the test report.

B10.2 Conducted Emissions

<u>B10.2.1 Power-line conducted emissions (narrow-band and broadband) method CE-03</u>- Feedthrough capacitors will be placed in series with each of the power leads into the RDFCS equipment rack. The length of the power leads between the 10-μF capacitors and the RDFCS rack will not exceed 1 m. The minimum separation between cables, leads, and the ground plane will be 5 cm. The test setup is shown in figure 12. Measurements will be made over the frequency range of 15 kHz to 50 MHz for both broadband and narrow-band emissions. The data for both narrow-band and broadband emissions will be plotted on an amplitude-versus-frequency curve with all significant emission peaks plotted. Inasmuch as this is a characterization test rather than a qualification test, there is no pass or fail criterion; however, the data will be plotted along with the RTCA document DO 160A limits for comparison purposes.

B10.2.1.1 Required equipment for CE-03 tests: The following equipment is required to perform the CE-03 power-line conducted emission test:

1. Current probe

2. Spectrum analyzer, covering the frequency range 14 kHz - 50 MHz, or a narrow-band tuned receiver covering the same frequency range

3. Four 10-μF feedthrough capacitors

4. RDFCS system

5. PDP 11/60 simulator

B10.2.1.2 Selective band measurements:

1. Connect the current probe through a 50-ohm coaxial transmission line to the EMI receiver.

2. Turn on all equipment and place the test sample in the steady-state mode of operation as defined above.

3. Place the current probe around one of the power lines, as illustrated in figure 12. Probe along the power line to find the point of maximum emission.

4. Adjust the EMI receiver to an observe bandwidth of no greater than 2 octaves; the recommended frequency intervals are as given below:

20-60 kHz
60-200 kHz
200-600 kHz
0.6-2 MHz
2-6 MHz
6-20 MHz
20-50 MHz

5. Record both the frequency and intensity of each significant peak across the entire band being observed.

6. As a minimum, record at least two frequencies for each band under observation. If the EMI receiver in use is a spectrum analyzer, a photograph of the spectrum analyzer trace for each band will be sufficient, if there is no significant activity in the band.

7. Repeat steps (5) and (6) for each of the bands discussed in step (4).

8. Repeat steps (3) through (7) for each of the remaining power lines and the return lead.

B10.2.2 Maximum current locations- The data taken for method CE-03 will be used as a starting point for this test. The receive bandwidth of the EMI receiver will be set to 1 kHz (narrow band) throughout the conduct of the test. The data taken will be both tabulated and plotted graphically with maximum current locations shown on a simplified diagram of the RDFCS. The test configuration used will be identical to that for CE-03 above, as diagrammed in figure 12.

B10.2.2.1 Required equipment: The same equipment used in the CE-03 power-line emission test will be used for this test, with the exception that the current probe will be removed and replaced with a hand-held current "sniffing loop probe. The 50-ohm coaxial transmission line cable between the probe and the receiving instrument should be a minimum of 20 ft long for this test.

B10.2.2.2 Test procedure:

1. From the data taken for CE-03 test, extract the 10 to 15 most intense emission signals with their corresponding frequencies, regardless of the power line from which the signal was detected. Tabulate these most intense signals by increasing frequency with their corresponding amplitude.

2. If a spectrum analyzer is used as the detection equipment, adjust the observed frequency span to a bandwidth of no greater than 10% of the frequency that is being investigated.

3. Tune the receiving equipment to the center frequency of the emission signal to be observed.

4. Using the hand-held current probe, move the probe all around the RDFCS, covering the entire case, signal cables, and power cables, and locate the exact point of maximum current emission for the signal being observed.

5. On the table generated in step (1), record the relative amplitude of the observed signal at the position of maximum observed emissions along with a verbal description of the location of maximum emissions.

6. On a diagram of the RDFCS, locate the position of maximum current emissions for that frequency. The number from the table generated in step (1) will uniquely identify the frequency and its location.

7. Repeat steps (2) through (6) for all of the frequencies tabulated in step (1).

B10.3 Radiated Emissions

B10.3.1 Method RE-02 (modified)- This test is used for measuring radiated electromagnetic emissions from the RDFCS equipment. The system configuration for this test will be as illustrated in figure 13.

B10.3.1.1 Applicable frequency range: Narrow-band emissions taken with an EMI measuring equipment input bandwidth of no greater than 10 kHz, will be measured from 1 MHz to 1 GHz. Broadband emissions taken using an input bandwidth of 1 MHz shall be recorded between 20 MHz and 1 GHz. The input frequency scan of observation shall be adjusted to be no more than half of a frequency decade. The following observed bands are recommended.

1-3 MHz
3-10 MHz
10-30 MHz
30-100 MHz
100-300 MHz
300 MHz-1 GHz

B10.3.1.2 Required equipment for RE-02 (modified) tests: The following equipment is required for measurement of radiated emissions over the frequency range specified.

1. Antennas as specified in subsection B8.2.

2. Electromagnetic interference receivers having a tunable receive frequency range between 1 MHz and 1 GHz.

3. Ten-µF feedthrough capacitors as used for test method CE-03.

4. Complete RDFCS pallet.

5. PDP 11/60 simulation computer with associated peripheral equipment.

B10.3.1.3 Ambient scan:

1. Set up the test sample and associated equipment as shown in figure 13.

2. Energize all simulator and peripheral test equipment, but insure that no power is applied to the RDFCS pallet.

3. Scan through each of the frequency bands listed in subsection B10.3.1.1 above and record all significant emissions observed. Use an observe-bandwidth of 100 kHz.

4. If a frequency analyzer is used for this test, take a photograph of the analyzer screen set at each of the frequency bands.

5. Move the receive antenna to alternative position B as shown in figure 13 and repeat steps (3) and (4). Change the observe-antenna at the appropriate frequency for each applicable antenna.

6. For frequencies above 40 MHz, repeat steps (3)-(5) with the antenna polarized both horizontally and vertically.

B10.3.1.4 Test procedure:

1. Set up the test sample and associated equipment as shown in figure 13.

2. Energize the sample in the steady-state operational mode.

3. Position the rod antenna in location A as shown in figure 13.

4. Observe and record the emissions from the RDFCS and associated equipment in the observe-frequency band. Use an observe-bandwidth of 100 kHz.

5. If a spectrum analyzer is used as the measuring equipment, take a photograph of the analyzer display set on the frequency band limits appropriate.

6. Repeat steps (4) and (5) for the first three observe-bands.

7. Change the observe-antenna to the biconical oriented in a horizontal position and repeat steps (4) and (5) for the next two observe-bands (30 to 300 MHz).

8. Reorient the biconical antenna to the vertical position and reset the bands to 30 MHz and repeat steps (4) and (5) for the same two frequency bands.

9. Replace the biconical antenna with the log periodic antenna in a horizontal position and repeat the scan for the final frequency band.

10. Reorient the antenna to the vertical position and repeat steps (4) and (5).

11. Set the EMI receiving equipment at the broadband observe-bandwidth (1 MHz) and repeat steps (6) through (10).

12. Replace the antenna to position B as shown in figure 13 and repeat steps (3) through (10).

B10.3.1.5 Data comparison: Compare the data gathered in subsection B10.3.1.3 (ambient) with that taken in subsection B10.3.1.4 (RE-03). If there appears to be a significant masking of RDFCS emissions owing to the ambient, use aluminum foil and carefully wrap the data cable between the RDFCS and its associated simulation equipment; take care to chassis-ground the foil at both ends of the cable. In addition, shield appropriate portions of the simulation and peripheral equipment with aluminum foil as indicated, and repeat the test specified in subsection B10.3.1.4 for the appropriate affected frequency bands.

<u>B10.3.2 Maximum emission location</u>- As was done for the conducted emissions, the data taken for the radiated emissions in the above section will be used in performing this test.

B10.3.2.1 Test configuration: The configuration for this test will be the same as for test RE-02 (modified) with the exception that the rod, biconical, and log periodic receiving antennas will each be replaced by the hand-held "sniffer" probe. The length of the 50 ohm coaxial transmission line between the hand-held probe and the receiving equipment should be at least 6 m.

B10.3.2.2 Data selection: From the data taken in subsection 10.3.1.4 above, extract the 20 or 25 most intense emission peaks which from comparison to the ambient scan are uniquely identified as emanating from the RDFCS equipment. The peaks used from the data to identify the 20 or 25 highest emitting frequencies from the RDFCS equipment should be chosen regardless of antenna location or polarization. The frequencies chosen should be tabulated in ascending order with their associated maximum emission intensity in a table similar to that prepared for the conducted emissions above.

B10.3.2.3 Test procedure:

1. The receiving equipment should be set having an observation bandwidth no greater than 500 kHz and an IF bandwidth of approximately 10 kHz.

2. With the hand-held "sniffer" probe attached to the EMI receiving equipment through the 50-ohm coaxial transmission line, set the receiving equipment centered on the frequency to be observed and move the hand-held probe all over the surface of the RDFCS equipment, along the power cords down to the 10-μH feedthrough inductor, and along the RDFCS interface cable down to the point of connection with the simulation equipment. Using this technique, locate the exact point or closest area of maximum emissions from the equipment for each of the frequencies noted.

3. On the table generated in subsection B10.3.2.2, record the relative amplitude and description of the location of the highest emission point for the frequency observed.

4. On a diagram of the RDFCS system, locate the exact position of the highest emission location for the frequency observed using a number corresponding to the table generated in subsection B10.3.2.2 to identify uniquely the frequency on the chart.

5. Repeat steps (2) through (4) for each of the frequencies tabulated in subsection B10.3.2.2

B10.4 Conducted Susceptibility

<u>B10.4.1 Power-line conducted transient susceptibility method CS-06</u>-Power-line conducted transient susceptibility will be conducted on all power lines excluding the return. The spike generator will be precalibrated into a 5-ohm noninductive resistor for the proper voltage level, pulse width, and waveform characteristics, as shown in figure 14.

B10.4.1.1 Required equipment for CS-06 test:

1. Spike generator capable of supplying the voltage spikes shown in figure 14 into a 5-ohm noninductive resistor

2. Five-ohm noninductive resistor

3. Oscilloscope having 100-MHz bandwidth or greater

4. Ten-μF feedthrough capacitors, as used in method CE-03 above

5. RDFCS pallet system

6. PDP 11/60 simulation equipment and associated peripherals

B10.4.1.2 Equipment calibration:

1. Connect the 5-ohm noninductive calibration resistor across the spike generator output terminals

2. Connect the oscilloscope across the calibration load

3. Energize the spike generator

4. Adjust the generator to supply the pulse characteristics shown in figure 14 at a repetition rate of 10 pulses/sec

5. Turn off the spike generator and remove the calibration mode

B10.4.1.3 Test procedure:

1. Connect the spike-generator output in series with one of the power lines, as shown in figure 15.

2. Energize the system and operate as described in subsection B6.1.

3. Re-energize the spike generator and monitor for any susceptibility characteristics.

4. synchronize the spike-generator output with the power-line frequency and position the spike at each of the four 90° positions of the sine-wave power waveform. Operate the test sample for 5 min at each of these four positions while monitoring for susceptibility conditions.

5. Vary the pulse position gradually over the full 360° phase position of the power-frequency waveform while monitoring for susceptibility.

6. Invert the polarity of the pulse and repeat steps (2) through (5).

7. If no failure is observed, remove the spike generator from the power lead under test and connect to one of the remaining untested leads.

8. Repeat steps (2) through (7) for each of the power leads.

9. If a failure is noted at any point, reduce the spike amplitude until the system ceases to malfunction and record this voltage as the threshold, along with the details of the pulse position polarity and phasing. After recording the failure details, continue with the test until complete.

B10.4.2 Electrostatic-discharge-induced cable susceptibility- The cable-induced test imitates situations encountered in actual systems operations. It makes use of the fact that I/O cables and power cables act as significant noise-coupling paths because of the crosstalk efficiency between them. By taping a test wire directly to the cables to be tested, maximum intensity broadband noise voltages and currents will be generated. If the crosstalk (inductive and capacitive) is sufficiently high to cause it to be a significant noise-coupling path into and out of the system, this will be revealed by this test.

B10.4.2.1 Equipment needed: Equipment and materials needed for cable-induced testing are listed below.

1. EXP x ESD (electrostatic discharge) simulator, new HISH, or Schaffner handheld unit. Capacitor range of 150 - 250 pF, series discharge resistance 200 - 500 ohms, and voltage levels between 500 V and 15 kV with 25 kV being desirable.

2. Three- to 5-m length of 18 AWG insulated wire.

3. Masking tape.

4. EXP x dc probe rated for 25 kV or equivalent HISH or Schaffner probe.

B10.4.2.2 Test configuration: The equipment under test (EUT) shall be configured in a normal operation condition and monitored for any nonperformance operation. Remote monitoring equipment should not be used unless fully hardened to the same transient stresses described in this test procedure. The test wire shall be taped to each I/O cable, including the power cable, for a linear distance of 1 m starting 5 cm (2 in) from cabinet entry to EUT. The return loop of the test lead shall be routed 50 cm from the I/O cable under test and connected to the ESD simulator ground terminal. The opposite end shall also be discharged, as illustrated in figure 16. If the length of the cable to be tested is less than 1 m, the test wire should be taped along the whole length of the cable to be tested and not looped back and forth to bring 1 m of test wire in contact with the cable. If the cable to be tested is extremely long (4 m or longer), it is permissible to tape up to 2 m of test wire to the cable; however, the total length of test wire used should be recorded.

B10.4.2.3 Test procedure:

1. Connect the test cable as described in subsection B10.4.2.2 and figure 16.

2. Turn EUT on and start monitor for failure. Record software being used and describe CRT display or information being printed if applicable.

3. Set voltage level to 500 V and set EXP x mode selector to stop on count. Set thumb wheel to 50. If HISH or Schaffner units are used, set voltage to 500 V and ignore the other steps.

4. Discharge 50 times to the test lead. If no failures occur, set voltage level to 2 kV and repeat the steps in (3). If it fails, then record voltage settings. If no failure occurs then increase the test voltage again by 1 kV and repeat using 50 discharges until a 25-kV level is obtained or until a failure is reached.

5. Upon first identifying a failure induced by ESD, record the voltage level of the tester setting, then decrease the voltage in 1-kV steps and continue decreasing the voltage until the system again runs cleanly with no failure indications after 50 discharges.

6. On the ESD test record, record both the highest voltage at which the system ran cleanly after the initial failure and the lowest voltage at which the system failed.

7. Repeat steps (1) through (6) for all remaining external cables.

B10.4.3 Radiofrequency-induced cable susceptibility- This is an rf-conducted test with the rf energy introduced into the interconnecting leads over the frequency range of 20 kHz to 30 MHz. The test configuration used will be as illustrated in figure 17.

B10.4.3.1 Required equipment:

1. Signal generator having a 50-ohm output and a frequency range from 20-kHz to 30-MHz

2. EMI receiving equipment capable of covering the above discussed frequency range

3. Two current probes connected to both the signal generator and the rf receiver through 50-ohm coaxial transmission leads

4. Ten-microhenries feedthrough inductors as required for test CE-03 (subsection B10.2.1)

5. RDFCS pallet

6. PDP 11/60 simulator and associated peripheral equipment

B10.4.3.2 Signal modulation: The susceptibility test signal shall be a sine-wave rf current modulated as follows:

1. From 20 kHz to 100 kHz, the modulation signal shall be 400 Hz at 30% modulation.

2. From 100 kHz through 30 MHz, the modulation shall be 1,000 Hz at 80% modulation.

B10.4.3.3 Test procedure:

1. Configure the system as illustrated in figure 17.

2. Energize the system and establish a steady-state operational mode.

3. Tune both the frequency synthesizer and the rf receiving device to a center frequency of 20 kHz and adjust the output level of the signal generator until an input of 100 mV rms is monitored by the receiving equipment.

4. Slowly sweep the frequency-generator signal through the required frequency band at a rate no greater than 2 min/frequency decade, maintaining an output level of 100 mV rms throughout the sweep range as monitored by the rf receiving equipment.

5. Should a susceptibility condition be monitored at any time during the course of this testing, reduce the output level of the signal generator until the susceptibility condition just disappears. Record this level and the frequency of the susceptibility condition.

6. Return the output level to 100 mV rms and continue to sweep through the frequency range.

B10.5 Radiated Susceptibility

B10.5.1 Radiated magnetic induction field: Method RS-02- This test shall be performed on all interconnecting cables and the cases of the RDFCS system components. Do not perform this test on the power leads.

B10.5.1.1 Best configuration: Figure 18 shows the RS-02 cable testing configuration and Figure 19 shows the RS-02 case testing configuration.

B10.5.1.2 Required equipment for RS-02 test: The following equipment is required to perform the RS-02 radiated magnetic induction field test:

1. Spike generator used in CS-06 test previously

2. Five-ohm noninductive calibration resistor

3. Oscilloscope having a bandwidth of at least 100 MHz

4. Step-down transformer, 115 V ac 20-A rated (Variac)

5. Injection transformer

6. Ammeter, ac, having 20 to 30-A full-scale deflection

7. RDFCS pallet equipment

8. PDP 11/60 simulator and peripheral equipment

B10.5.1.3 Calibration procedures: The calibration of the spike generator for this test is very similar to that for the CS-06 test.

1. Set up the equipment as shown for figure 18 for the cable test

2. Connect the 5-ohm noninductive calibration resistor as indicated in figure 19

3. Connect an oscilloscope across the calibration load

4. Energize the spike generator

5. Adjust the spike generator, to obtain the pulse characteristics shown in figure 14 with a pulse repetition rate of 10 pulses/sec and a 100-V peak amplitude

6. With the settings left at the calibration position, de-energize the spike generator

B10.5.1.4 Test procedures:

1. Energize the test sample

2. Energize the spike generator and monitor the system for any malfunction occurring within at least 2 min of testing

3. De-energize the spike generator and connect a 20-A, 400-Hz source to the case susceptibility wires, as shown in figure 18

4. Re-energize the spike generator and apply 20-A to the cable susceptibility wires

5. Monitor the system for any malfunction during at least 2 min of operation

6. De-energize both the spike generator and the 20-A source and remove the wires from the cables

7. Wrap the current-carrying wire around one of the subsystem black boxes of the RDFCS system as illustrated in figure 19

8. Repeat steps (2) through (5) for each of the subsystem black boxes of the RDFCS system

9. If a failure occurs during any of the above testing, reduce the amplitude of the generating source until normal operation just returns. Record this level as the threshold of susceptibility and move on to the next step of the test

<u>B10.5.2 ESD excited magnetic field susceptibility: Method RS-02 (modified)</u>- This test is similar to the RS-02 test except that the exciting

function will be generated by an ESD generator instead of a spike generator. The test configuration will be as illustrated in figure 20.

B10.5.2.1 Required equipment:

1. ESD generator as specified in subsection B10.4.2

2. Five-meter length of insulated 20 AWG wire, single strand

3. RDFCS system

4. PDP 11/60 simulator and associated peripheral equipment

B10.5.2.2 Test procedure:

1. With the RDFCS system energized and running in steady-state mode, wrap the length of wire around one of the subsystem boxes of the RDFCS, as illustrated in figure 20.

2. Adjust the output of the ESD generator to 2,000 V and connect the return wire to the ESD generator to one end of the test wire.

3. Bring the discharge head of the ESD generator toward the bare end of the test wire until an ESD arc just occurs. Back the test head off slightly and repeat with a minimum of 30 discharges to the wire at that voltage setting for the generator.

4. If no susceptibility event is monitored, increase the voltage output of the ESD generator by 1,000 V and repeat step (3).

5. Repeat step (4) until a susceptibility event occurs.

6. Reduce the output level of the ESD generator by 500 V and repeat step (4).

7. If a susceptibility event occurs, continue repeating step (6) until no susceptibility event is monitored.

8. Record the lowest ESD generator output voltage at which a susceptibility event occurred, and the voltage setting immediately below that at which the system ran cleanly. This voltage pair will represent the threshold for that piece of equipment for the RS-02 (modified) test.

9. Move the test wire to a different subsystem box and repeat steps (3) through (8).

10. Repeat step (8) for each sybsystem box.

<u>B10.5.3 Electric field radiated susceptibility: Method RS-03</u>- This test will be run only if a shielded-room facility is made available for the RDFCS testing. The purpose of this test is to determine if the RDFCS is susceptible

to radiated electric fields over the frequency range of 20 MHz to 1 GHz. The field strength susceptibility levels generated will be 20 V/m across the entire frequency range.

B10.5.3.1 Test equipment required for Method RS-03:

1. Biconical and log periodic antennas as used above for test method RE-02

2. Signal generator capable of sweeping through the frequency range of 20 MHz to 1 GHz

3. Broadband power amplifier capable of amplifying the output from the signal generator to drive the antennas at a field intensity of 20 V/m

4. Field-strength meter capable of monitoring the field strength generated by the antennas

5. RDFCS pallet equipment

6. PDP 11/60 simulation equipment and associated peripherals

B10.5.3.2 Test procedure: With the equipment configured as illustrated in figure 21, maintain the output level at 20 V/m as monitored by the field-strength meter, and slowly sweep the signal through the appropriate frequency range. The test should be run with the antennas in both the horizontal and vertical polarization and changed at the appropriate frequency breakpoint. Sweep the frequency at a rate no greater than 2 min per frequency octave and monitor the equipment for a susceptibility indication. If a susceptibility indication occurs, reduce the power level at the frequency of susceptibility until the indication disappears. Record this frequency and susceptibility amplitude level and continue the test.

<u>B10.5.4 Discrete frequency electric-field radiated susceptibility</u>- This test checks the same susceptibility indications as the RS-03 test; however, it can be conducted in facilities not requiring a shielded room and gives a good indication of the susceptibility problem, an indication that is unobtainable from RS-03 testing. The frequency range of this testing will be from 1 MHz to 1 GHz and will be configured identically to the conducted emissions test procedure discussed in subsection B10.2.2. This test is the inverse of the emissions-locations monitoring conducted in the tests specified in subsections 10.2.2 and 10.3.2. The data sheets generated by the above referenced emissions testing will be required for the conduct of this test.

B10.5.4.1 Required equipment:

1. Signal generator capable of generating narrow-band frequencies between the range of 1 and 1,000 MHz

2. Power amplifier capable of boosting the output level from the signal generator to sufficient values for the conduct of the test

3. Hand-held loop probe to be connected to the power amplifier through a 50-ohm coaxial transmission line at least 6.0 m long

4. Field-intensity meter capable of monitoring the output level of the signal from the loop probe

5. RDFCS system

6. PDP 11/60 simulator and associated peripheral equipment

B10.5.4.2 Test procedutre:

1. Adjust the frequency level of the signal generator to the first frequency above 1 MHz found in testing specified in subsection B10.2.2

2. Using the field-strength meter as an indication, adjust the output from the power amplifier until the field strength is monitored to be 20 V/m at a distance 10 cm from the hand-held loop probe

3. Move the hand-held loop probe until the 10-cm distance (20-V/m field) is exactly at the location associated with the frequency set by the signal generator

4. If a susceptibility indication is monitored at this test frequency, reduce the amplitude of the signal until the susceptibility indication disappears, and measure the field strength at that output level

5. Record both the frequency and the susceptibility field strength level for all susceptibility conditions

6. Repeat steps (2) through (5) for all frequencies and locations above 1 MHz, recorded on the output data from tests, subsections 10.2.2 and B10.3.2

<u>B10.5.5 ESD direct discharge susceptibility</u>- A person or object that has developed an electrostatic potential different from that of the digital equipment can induce a spark to the equipment. The discharging arc equalizes the voltage difference. Any (conductive) point capable of accepting the energy from the direct arc discharge is susceptible.

B10.5.5.1 Equipment needed:

1. ESD simulator as described in subsection B8.1.6

2. Ground strap 1.5 m, 0.937 to 1.25-cm braid with spring clip

3. DC EXP x probe or equivalent (no ac probe)

4. Isolation transformer or line filter rated at 40 dB, at 120-kHz minimum common mode; suggest Voltestor, Pilgrim Electric Co., Plainview, N.Y., or LISN's per CISPR specifications

5. Two-square meter ground plane

B10.5.5.2 Test configuration: The configuration for the test should be as shown in figure 22. The ESD simulator should be plugged into the power-line filter or the isolation transformer. The ground strap should be attached between the ESD generator and the nearest chassis-ground metal in the vicinity of the power-line connect point for the unit. For this direct discharge test, it is preferable that the green/yellow wire safety ground on the ESD generator be isolated via the isolator transformer. However, if line filters are used, then the green/yellow lead must remain attached to the facilities earth ground.

B10.5.5.3 Test point selection: The points of maximum noise-coupling probability should be the points selected for ESD discharge testing. These points are typically key slots, on/off switches, I/O cable connections, and keyboards. Each black box should have five or more such points chosen for discharge testing. There should be a minimum of two points selected on the front and at least two on the rear of each box. The points chosen should be separated by 15 cm or more and should be those points most accessible to anyone working around the system. The test points chosen should be numbered and a diagram drawn locating their position on each box.

B10.5.5.4 Test procedures:

1. Configure the system as illustrated in figure 22, making certain that the unique system configuration with all peripherals and I/O cables attached is carefully recorded for future reproducibility.

2. Power up the equipment under test and have the diagnostic characterization software running normally with any printing or CRT display functions operating.

3. Turn power on the ESD tester and set the output voltage to 500 V. Discharge to the selected test point 50 times or until a failure is noted, whichever occurs first.

4. If a failure was noted during this 500-V-level testing, go to step (6) and continue.

5. Set the tester output voltage to 2,000 V and discharge to the selected test point 50 times. If no failure is noted, wait 1 min and monitor the system for any delayed failure indications. If none are noted, increase the voltage on the tester in 1-kV increments and continue testing until a failure is noted.

6. Upon first identifying a failure induced by ESD, record the voltage level of the tester setting, then decrease the voltage in 1-kV steps; continue the 50 discharges at each voltage level and continue decreasing the voltage until the system again runs cleanly with no failure indications after 50 discharges.

7. On the ESD test record, record both the highest voltage at which the system ran cleanly after the initial failure and the lowest voltage at which the system failed.

8. Go to the next point on the system to be tested, and repeat steps (3) through (7). Continue until the pass/fail threshold for each test point has been established and recorded.

B10.5.6 ESD-induced E-field broadband susceptibility- This test simulates the threat to which the EUT would be exposed when an adjacent unit experiences an ESD transient. The broadband E-field so generated by this near-field discharge could couple into the electronics of the system and cause unacceptable failure responses. Because of the proliferation of nonmetallic case packaging materials in the electronics industry with their associated reduction in case shielding effectiveness, this test is beginning to assume even greater importance than direct discharge testing.

B10.5.6.1 Equipment needed:

1. ESD simulator as described in subsection B8.1.6

2. Ground string, 1.5 m, 0.937- to 1.250-cm braid with spring clip

3. DC EXP x probe or equivalent (no ac probe)

4. Isolation for ESD simulator as described in subsection B10.5.5.2

5. A 0.5-m by 0.5-m aluminum sheet

B10.5.6.2 Test configuration: Set up the EUT and ESD simulator per figure 23, keeping the EUT a minimum of 1 m from all conducting materials, such as computer room raised floors, file cabinets, and shielded room walls and floors. Power to the ESD simulator shall be supplied from an isolated or filtered line with the safety ground supplied through the ac power cord. The ground strap shall be connected to one end of the aluminum sheet. The arc discharge shall be to the center of the plate. The aluminum plate shall be located 2.5 cm away from each test surface of the EUT. Low-density foam may be used to keep the position of the aluminum sheet 1 in from the surface of the EUT. For systems having a keyboard, the smaller plate should be cut to the approximate size of the keyboard and mounted resting directly on the keys of the keyboard. If the keyboard is in a separate package, this smaller plate could also be mounted directly underneath the keyboard to be tested. Initially, all surfaces of the equipment should be exposed to the plate mounted parallel to and within 1 in of the surface. Once the equipment threshold level has been determined for each of the orientations, the one (or possibly two, especially with an isolated keyboard) most susceptible surface should be chosen as the characterization location for future broadband susceptibility testing. The procedure to use in determining the most susceptible surface, as well as normal indirect testing, is described next.

B10.5.6.3 Test procedure:

1. Set up EUT and ESD simulator per figure 23.

2. Place test plate 2.5 cm away from first surface area of EUT.

3. Discharge to center of test plate 50 times starting at 500 V. Move up to 2.0 kV if first test passes. Test each 1-kV level between 2 kV and 25 kV.

4. Upon first identifying a failure induced by ESD, record the voltage level of the tester setting, then decrease the voltage in 1-kV steps; continue the discharge at each voltage level and continue decreasing the voltage until the system again runs cleanly with no failure indications after 50 discharges.

5. On the ESD record, record both the highest voltage at which the system ran cleanly after initial failure and the lowest voltage at which the system failed.

6. Repeat steps (1) through (4) for each additional surface of the EUT.

7. Repeat steps (1) through (5) for each test mode of operation.

8. Repeat steps (1) through (6) for each test configuration of the EUT.

9. Record data and stop testing.

APPENDIX C

COMPARISON OF PRESENT TRANSIENT BROADBAND REQUIREMENTS OF DO-160 AND CKC PROPOSAL METHODS

CKC proposed test method	Closest DO-160 method	DO-160 bandwidth of stress	CKC bandwidth of stress	Present[a] digital bandwidth of response
Fast-rise-time cable-induced transients; power lines 1-5-ns rise time	Paragraph 17, voltage spike conducted test, 2 ns rise-time	159 kHz	64-320 MHz	30-60 MHz
Fast-rise-time cable-induced transients; interconnect cables 1-5 ns rise-time voltage selectable	Paragraph 19.5, relay transients, go/no-go test only, 10 ns rise-time[b]	30 MHz	64-320 MHz	30-60 MHz
Fast-rise-time cable-induced transients; interconnect cables 1-5-ns	No equivalent	None	64-320 MHz	30-60 MHz
Direct ESD discharge to pilot or operator controls	No equivalent	None	64-320 MHz	30-60 MHz

[a]This is the bandwidth of response of typical digital avionics used on commercial aircraft today. The typical bandwidth should be 150 MHz by 1985, 300 MHz by 1988.

[b]Relay voltage most uncertain and varies from relay to relay.

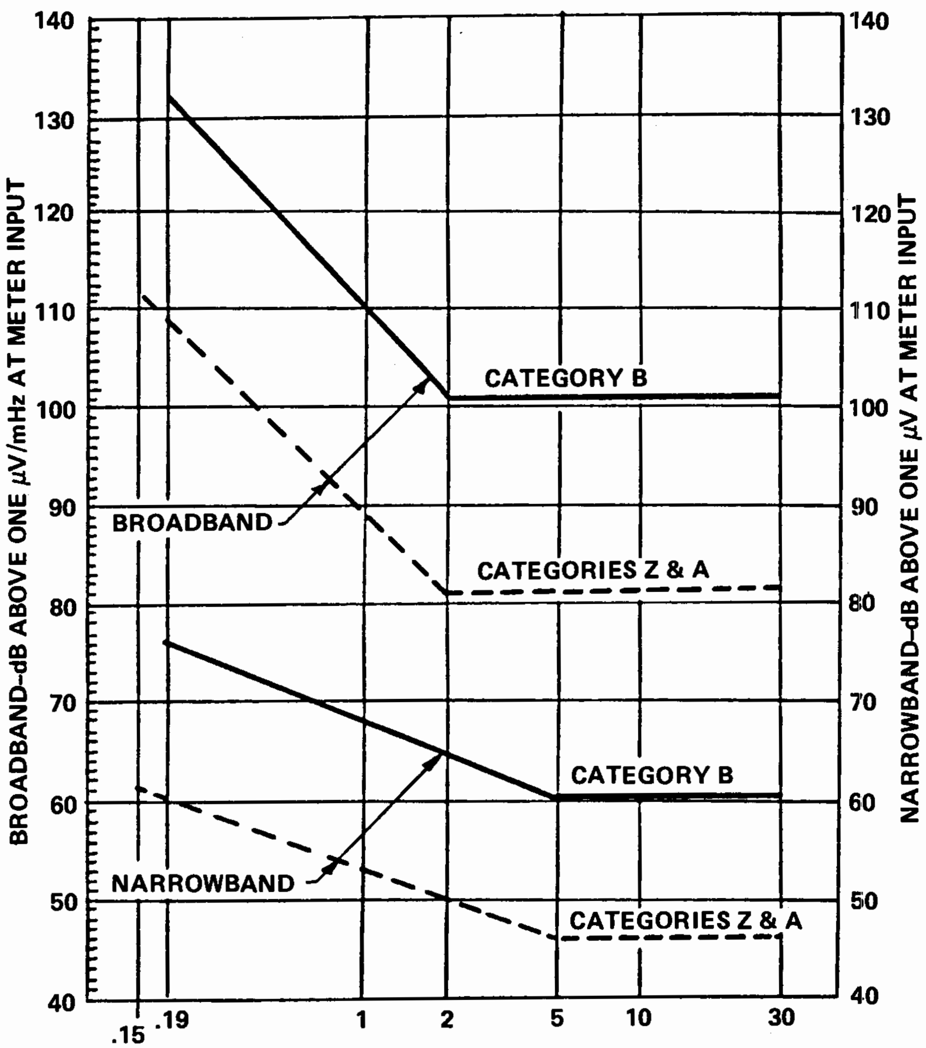


Figure 5.- Conducted interference limits power input using LISN.

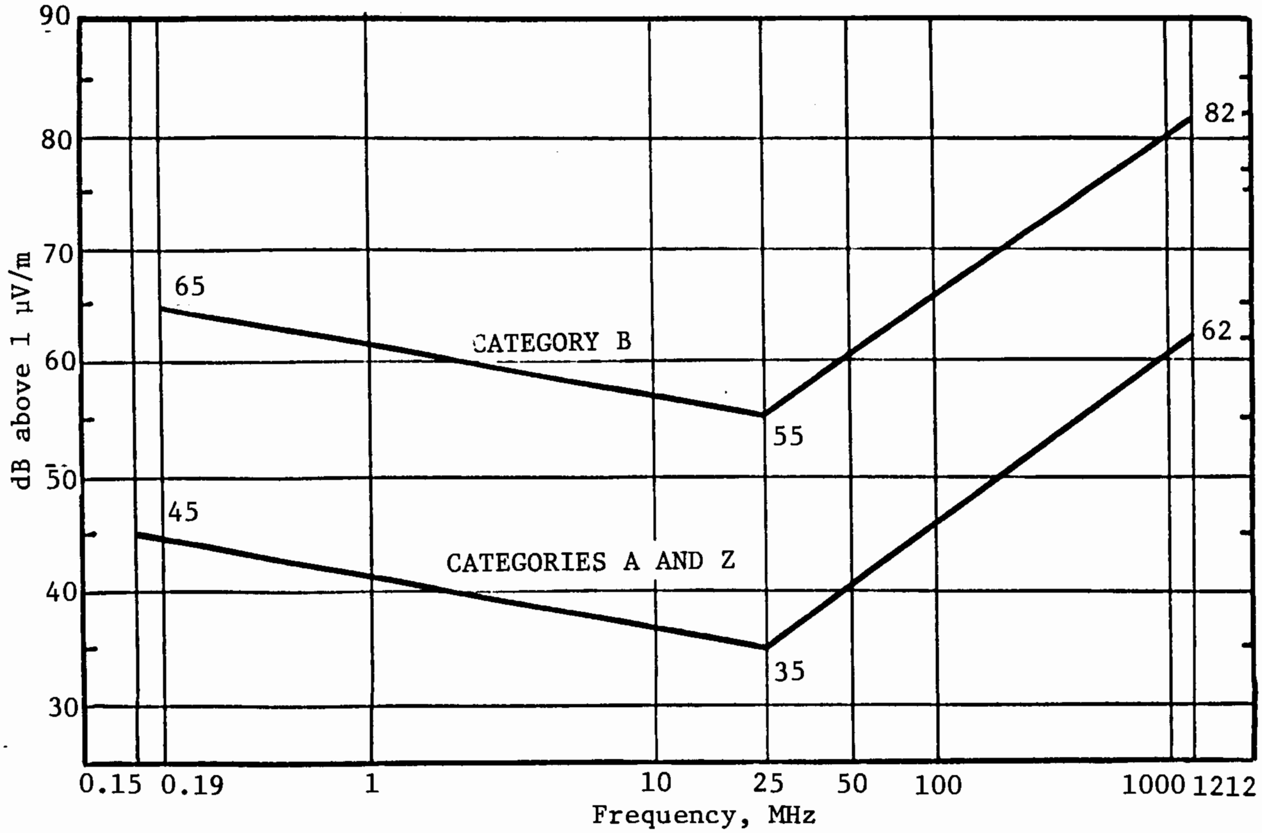


Figure 6.- Maximum level of radiated CW intereference from any one piece of equipment.

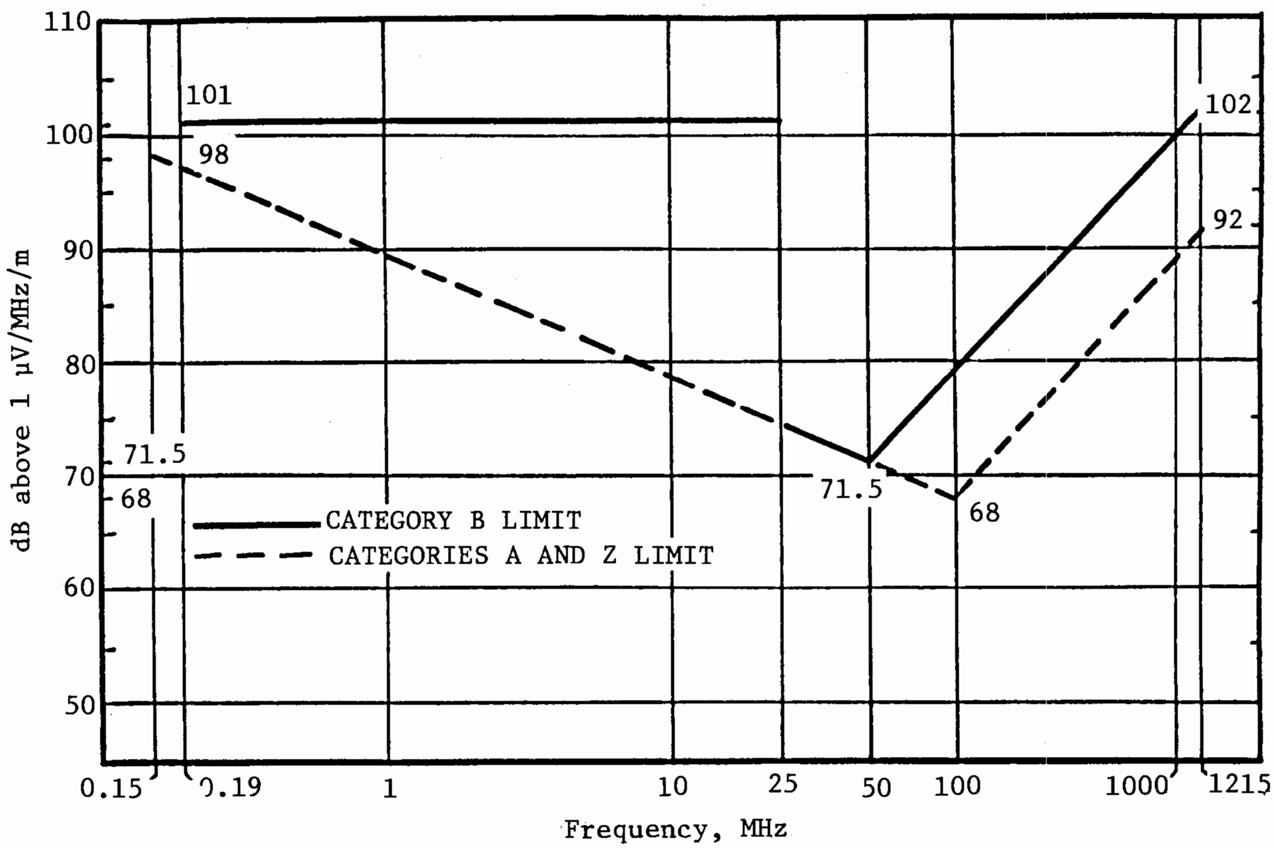


Figure 7.- Maximum level of radiated broadband and pulsed CW from any one piece of equipment.

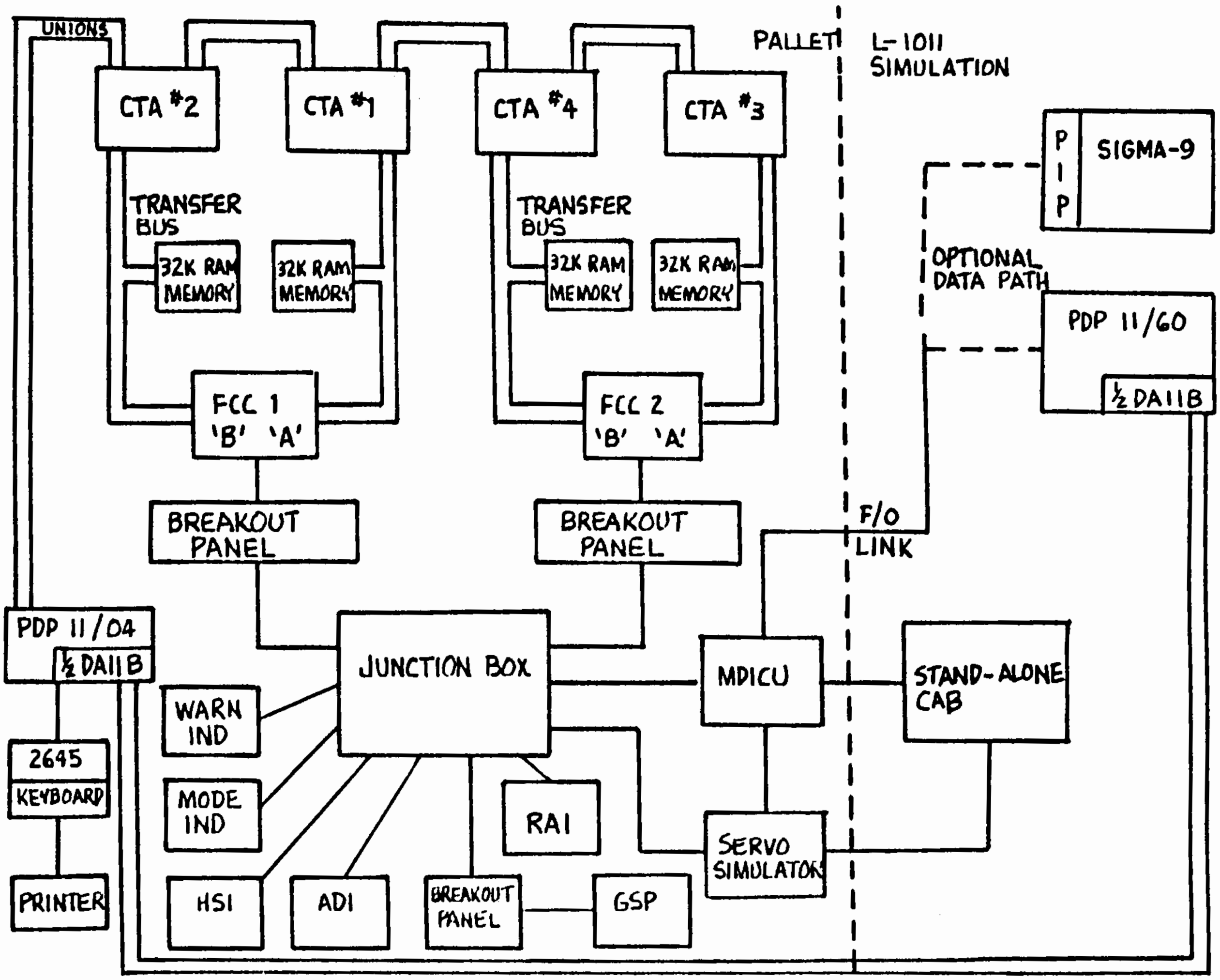


Figure 8.- Simulator configuration.

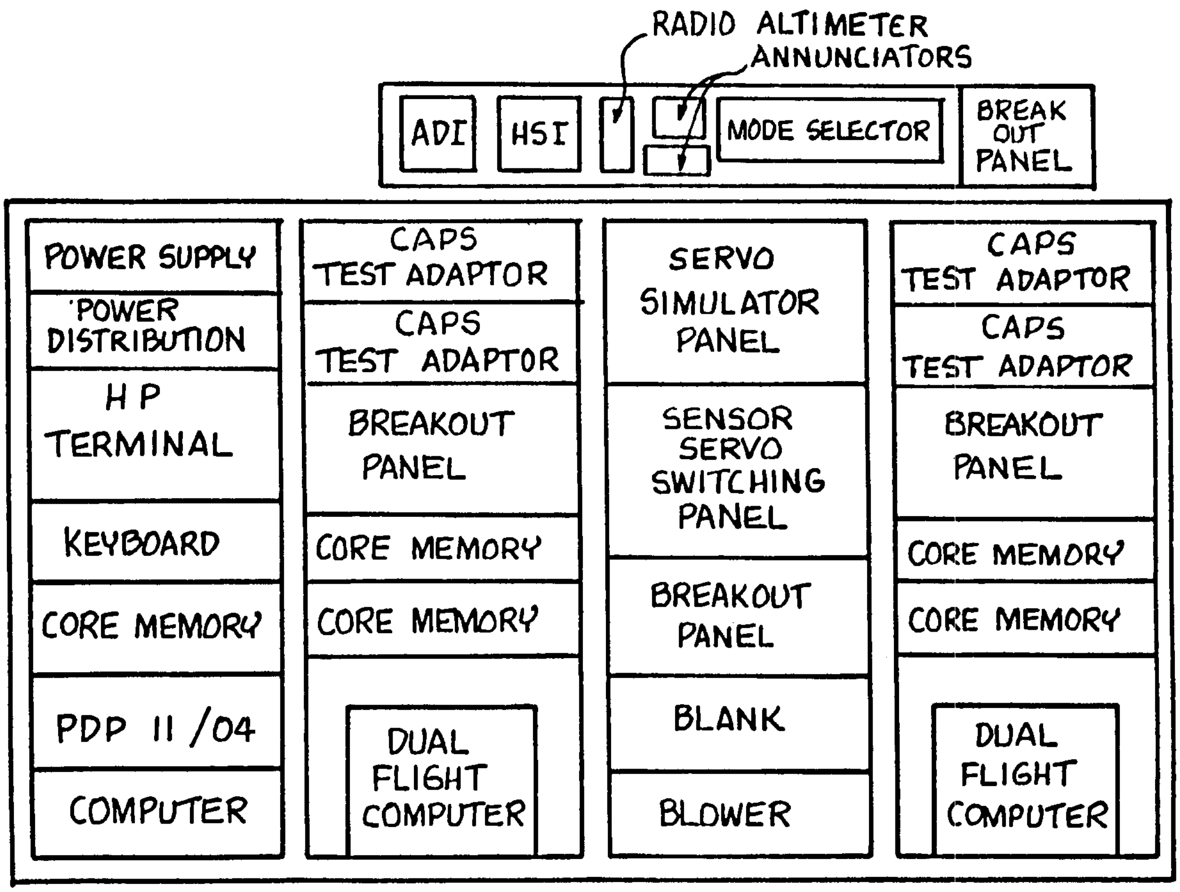


Figure 9.- Pallet configuration.

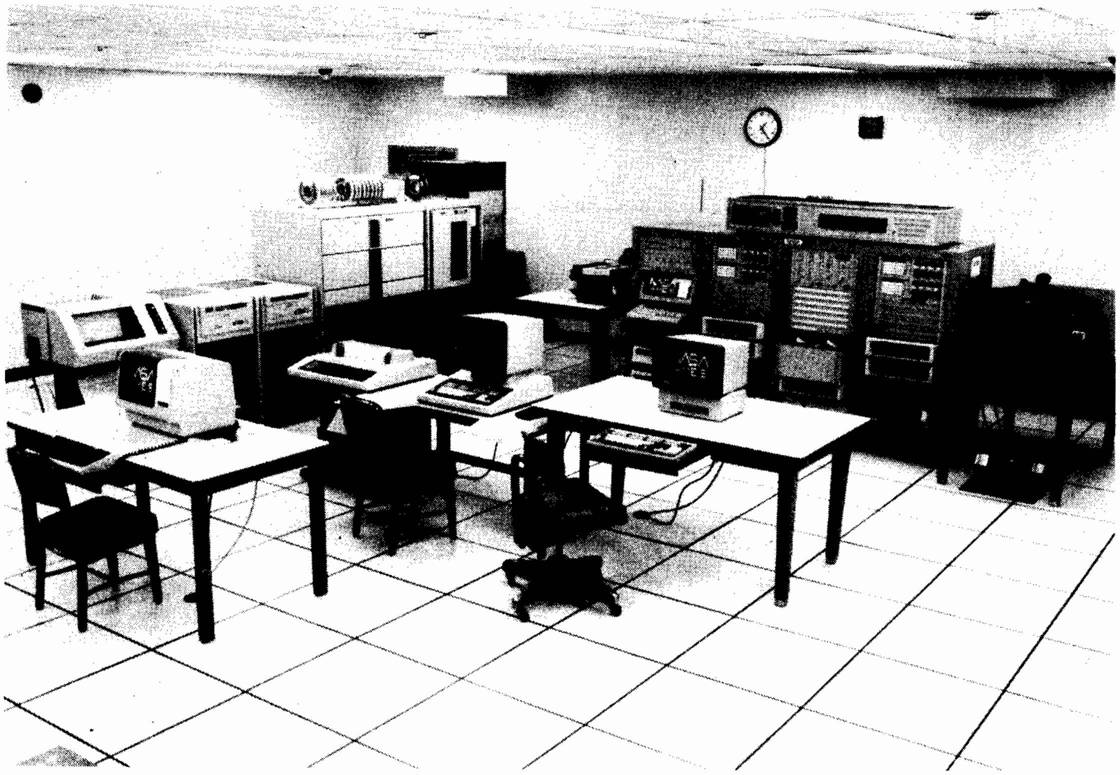


Figure 10.- Latest configuration of RDFCS.

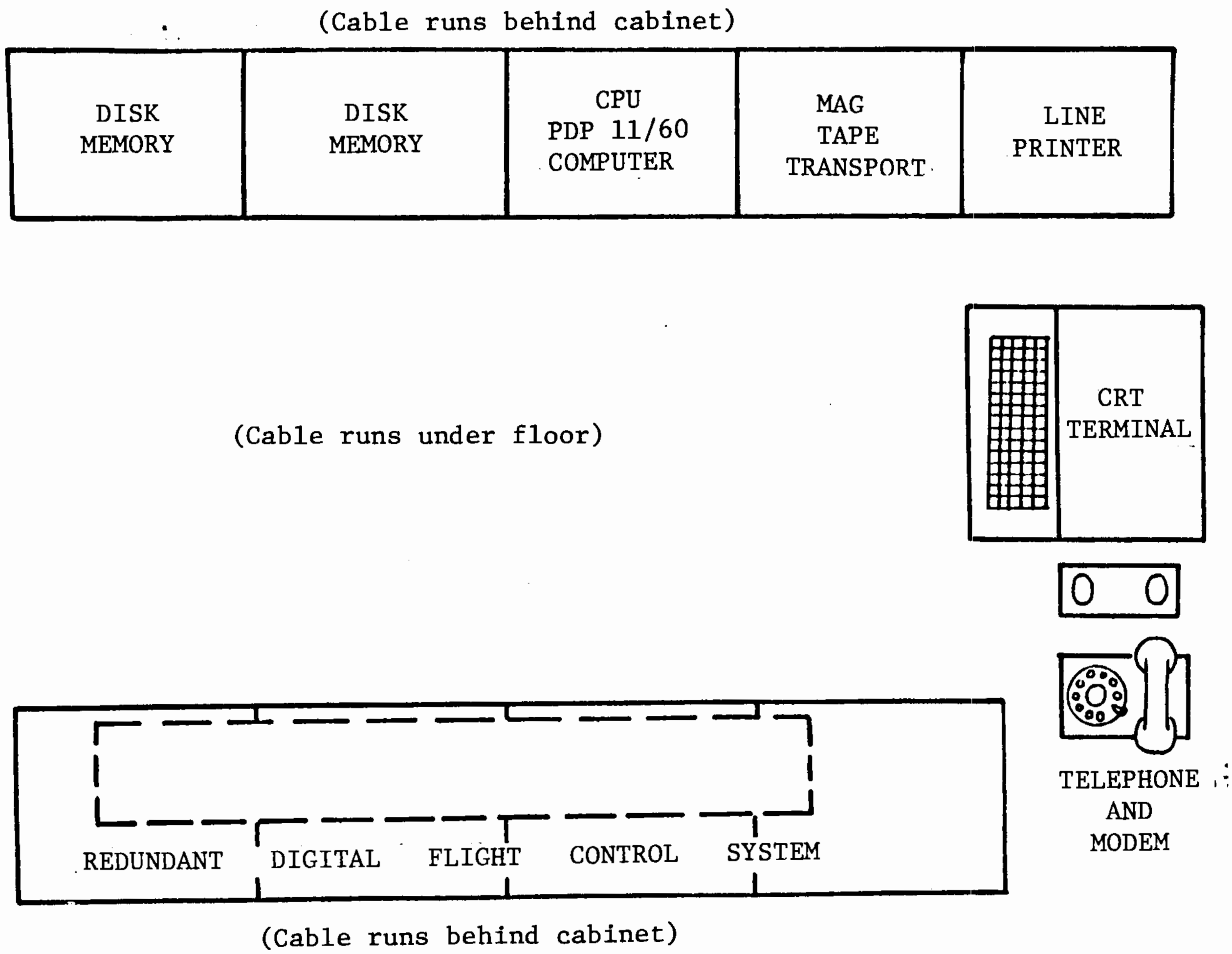


Figure 11.- Simulation room configuration.

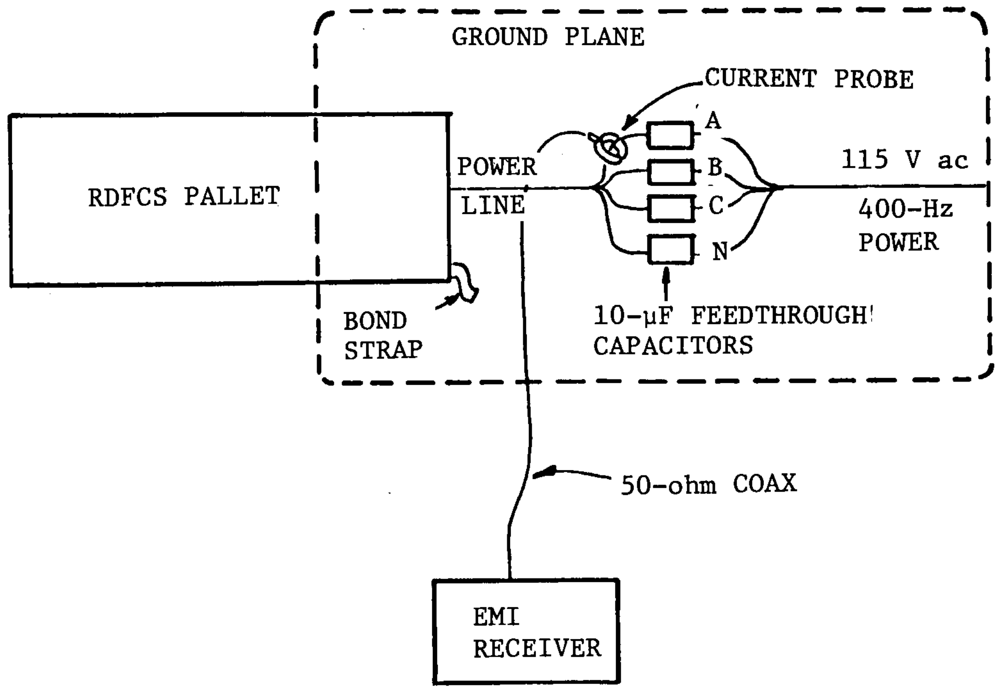


Figure 12.- CE03 test setup.

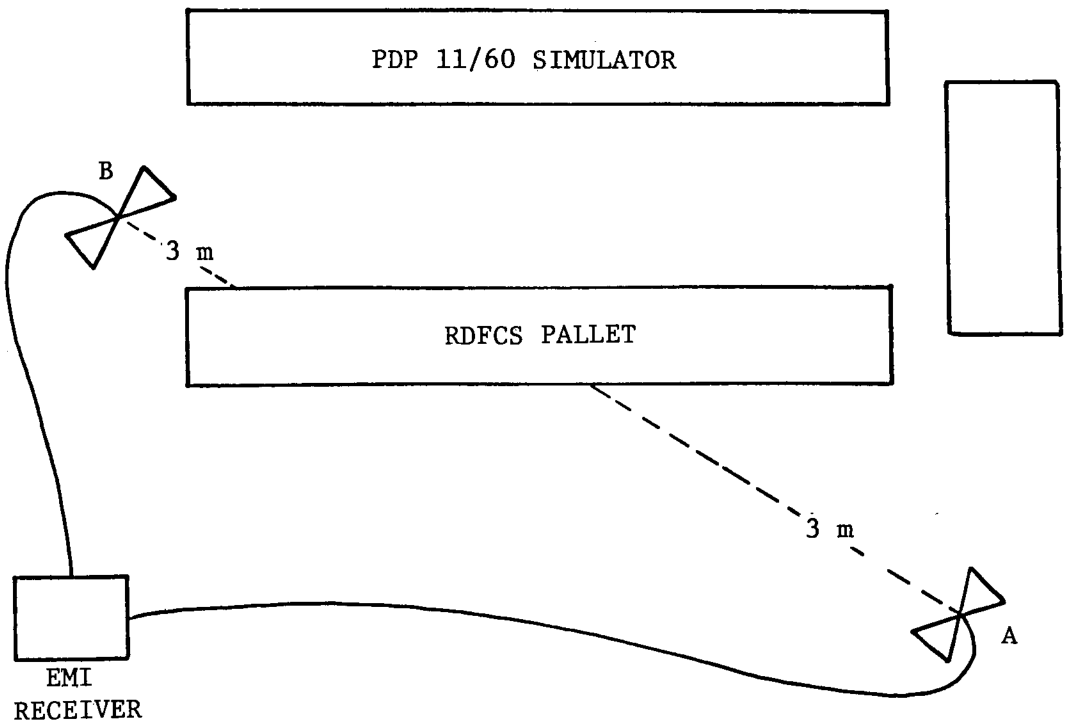


Figure 13.- RE02 (modified) test setup.

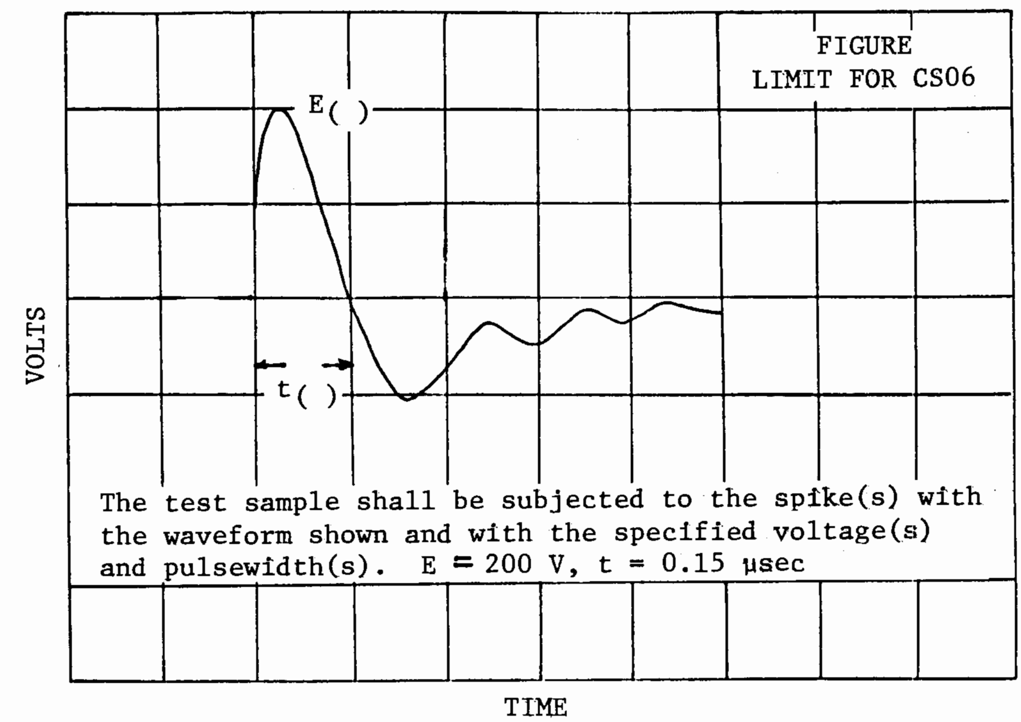


Figure 14.- Limit for CS06.

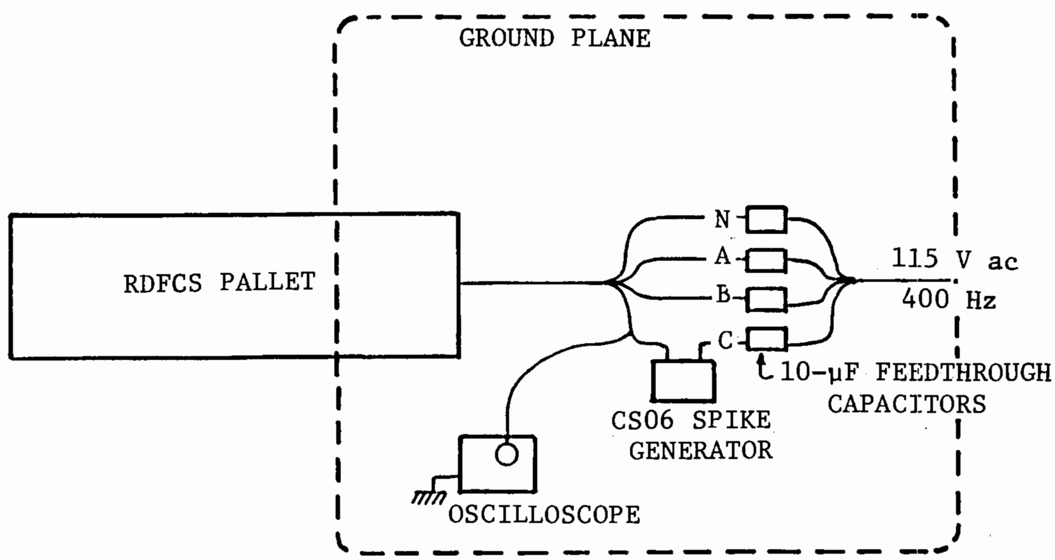
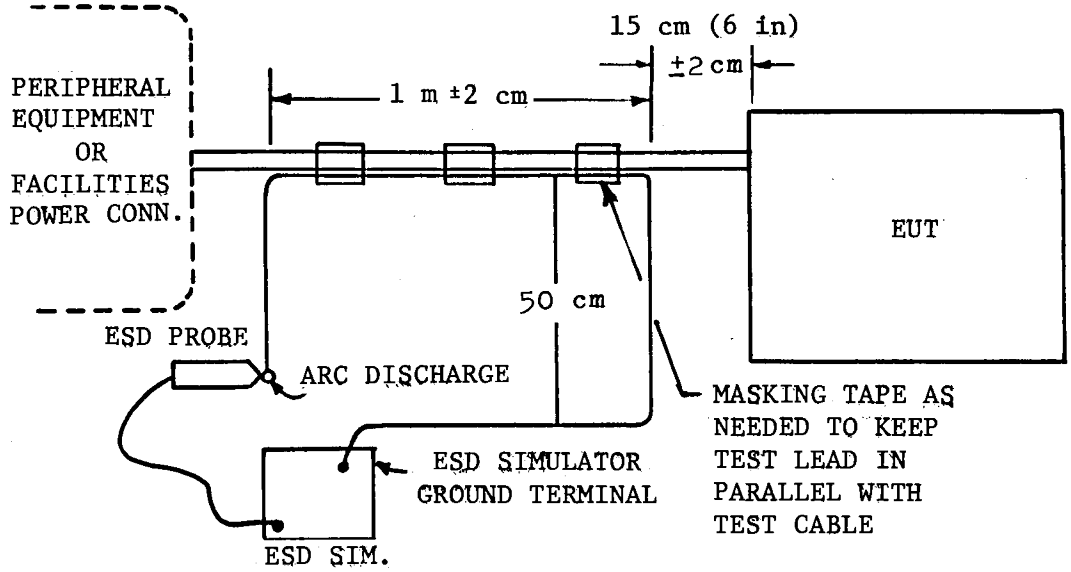


Figure 15.- CS06 test setup.



Notes: 1. Test lead plus loop should be 1 m away from any conducting surface, including cement floor. A wood table is an ideal test platform.

2. When test cable is less than 1.15 m in length, then test parallel shall be shorter and started a minimum of 5 cm (2 in) away from EUT connector.

Figure 16.- ESD test configuration (cable-induced).

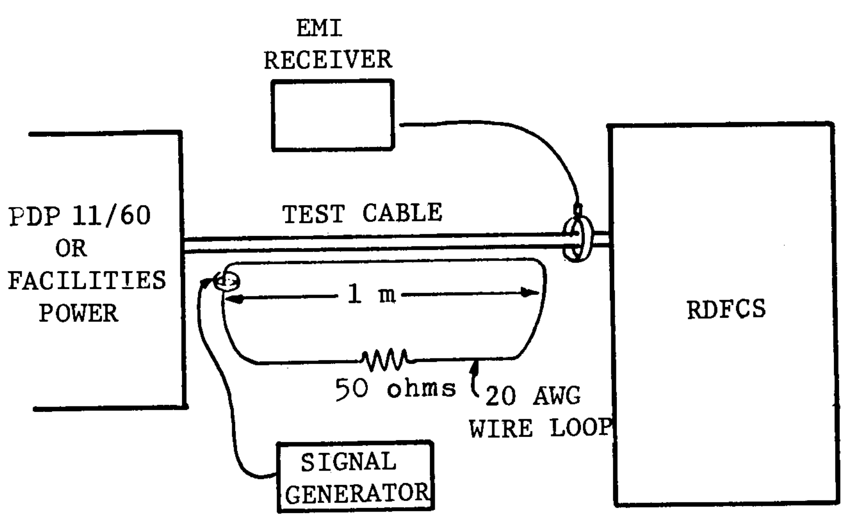


Figure 17.- RF-induced cable susceptibility test setup.

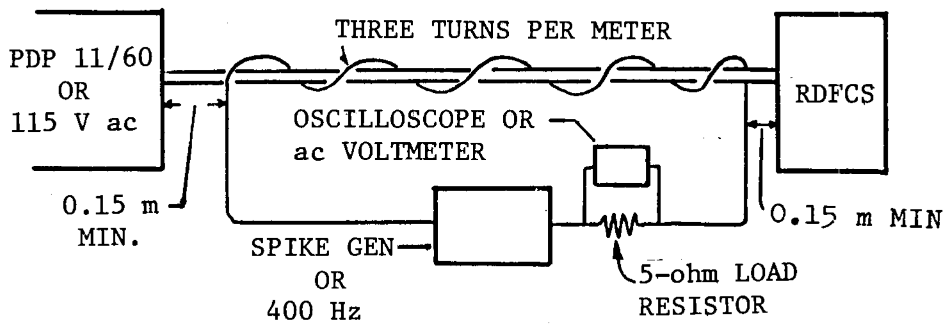


Figure 18.- RS02 cable test setup.

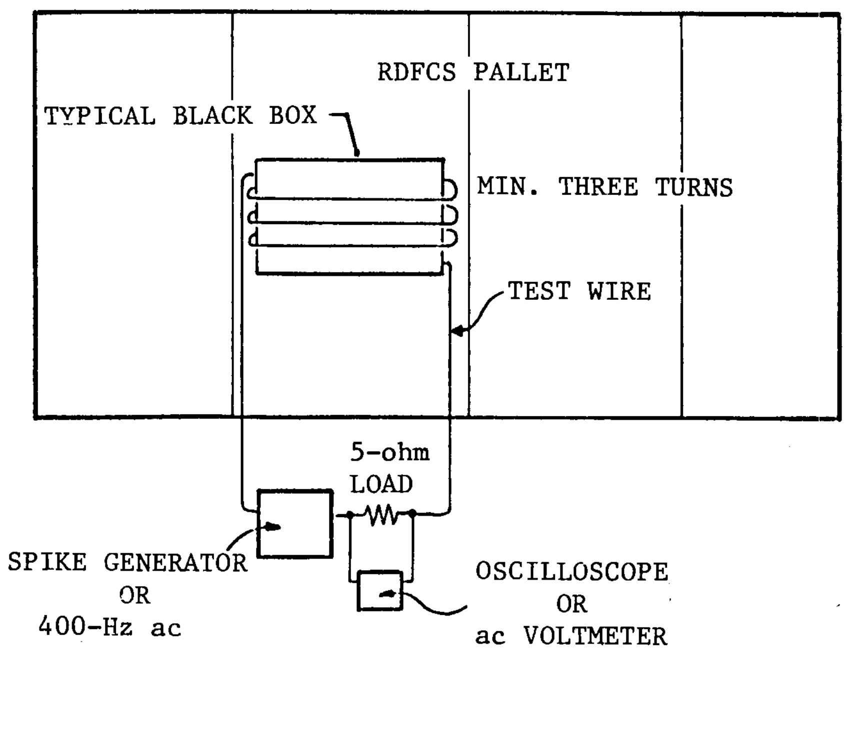


Figure 19.- RS02 case test setup.

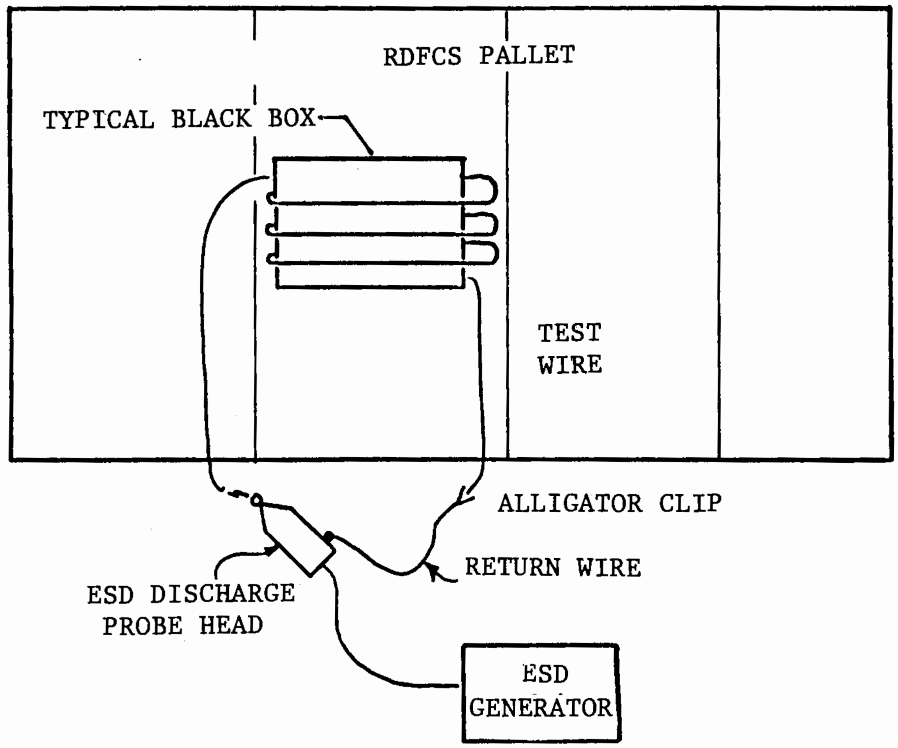


Figure 20.- RS02 (modified) ESD susceptibility test setup.

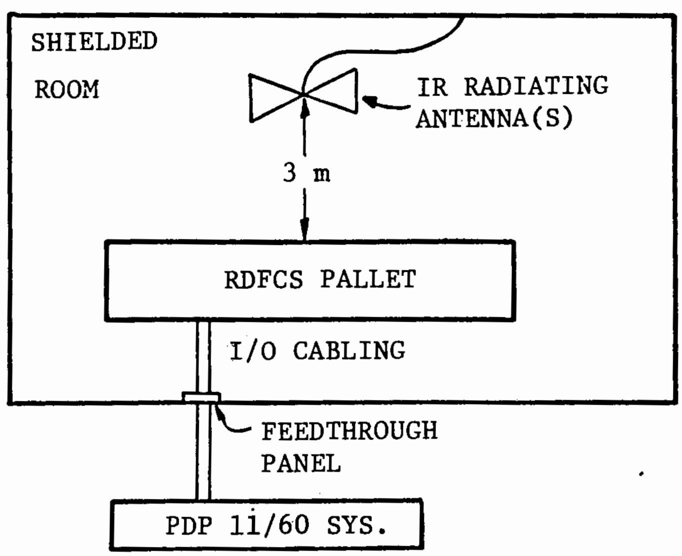


Figure 21.- RS03 test setup.

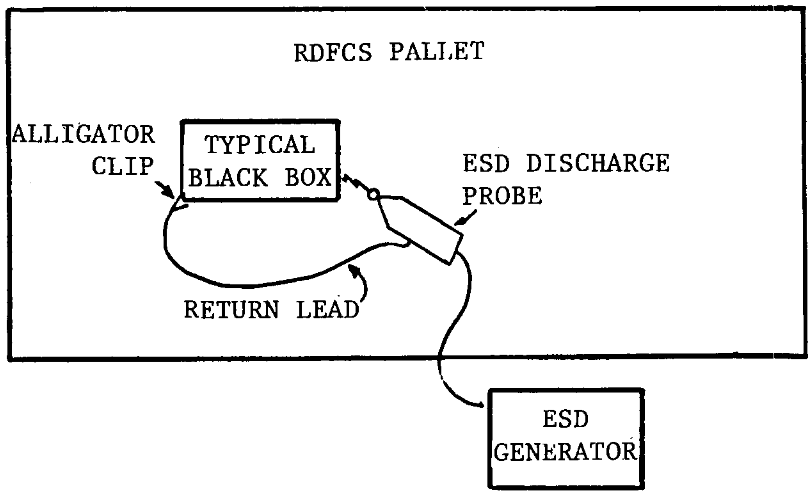


Figure 22.- ESD direct discharge test setup.

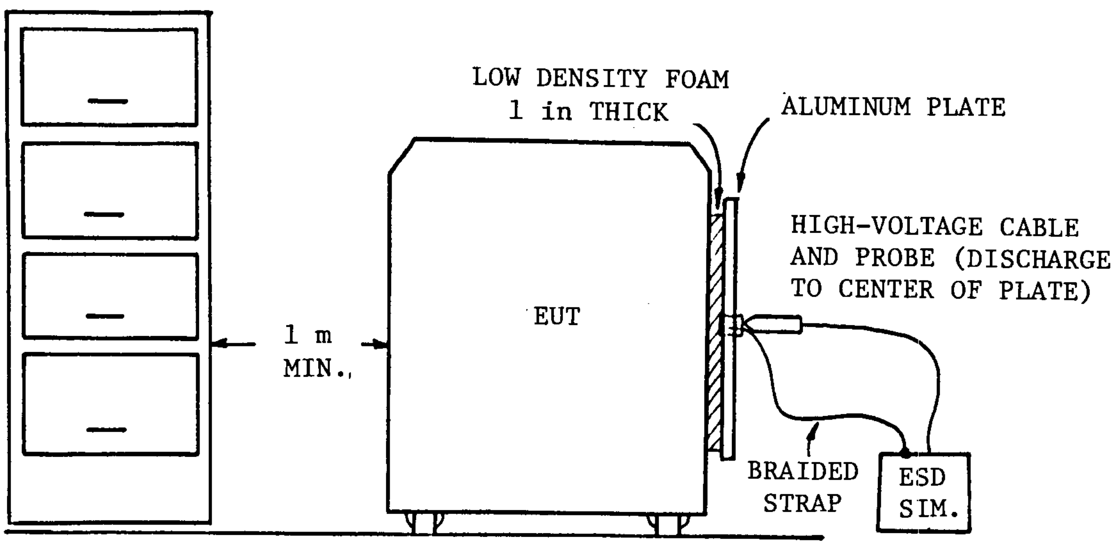


Figure 23.- Indirect ESD radiation test setup.