Interaction Notes

Note 420

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Unification of Electromagnetic Specifications and Standards Part I--Evaluation of Existing Practices*

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Abstract

To establish a basis for evaluating standards, specifications, and codes by which electronic equipment and systems are procured and installed, a review of electromagnetic interference control has been made. It is concluded that effective interference control is achieved by establishing an impervious barrier between the offending source and the circuit to be protected. This concept is developed and applied to practical control requirements for equipment and facilities. Over 70 standards, specifications, and codes have been reviewed to assess where they are incompatible with these principles. It is postulated that a set of documents compatible with each other and with requirements for electromagnetic pulse (EMP) hardening, interference control, and communications security can be developed. This report documents Phase I of this project which was limited to the development of a general interference control model and its application to the review of existing standards and practices. In Phase II alternatives to the incompatible requirements found during the review will be developed and demonstrated.

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SUMMARY

This report covers Phase I of Contract No. DNA 001-79-C-0206. The objective of this project is the development of a compatible set of shielding, bonding and grounding, and installation techniques for communications facilities to ensure that the COMSEC, EMI/EMC, NEC, as well as lightning and EMP requirements, can be met without mutual conflicts. In Phase I the pertinent existing standards, specifications, codes, etc., were collected and evaluated against a comprehensive interference control model to identify incompatibilities among these existing documents.

The scope of Phase I was limited to the development of a general interference control model and its application to the review of existing standards and practices. The topological model is applicable at any frequency and, therefore, any standard compatible with this general model would also be compatible with all other standards compatible with that model. This approach was chosen because it would be impossible to compare every electromagnetic requirement of one standard with every electromagnetic requirement of the other standards to check for compatibility. In Phase II alternatives to the incompatible requirements will be developed and demonstrated. However, only Phase I work is reported here.

Establishment of an impervious barrier between the circuit to be protected and the source of interference from which it is to be protected is the only method of interference control that does not require configuration control of either the source of interference or the circuit interfered with. This barrier is a topologically closed surface that is substantially impervious to electromagnetic waves propagating through space as well as those guided by conducting wires, cables, and pipes. Such a barrier may consist of filters, limiters, common-mode rejection devices, metal meshes, shields, and other components; no single one of these elements is totally adequate. Several partially impervious barriers (e.g., one at the building level and one at the equipment level) may be used to distribute the interference control so that no single barrier must be designed or maintained to provide a very high degree of imperviousness. A rational allocation of barrier effectiveness between a first level (e.g., building, room, or equipment rack) and a second level (e.g., equipment rack, equipment or circuit enclosure) is developed on the basis of practical thresholds found in communications facilities.

The allocation concept and the electromagnetic properties of barrier components and structures are used to evaluate the methods of specifying and testing packaged electronic

equipment. Within the spectrum below 100 MHz, it was concluded that the dominant excitation of equipment is produced by currents induced in interconnecting cables rather than by irradiation of the equipment enclosures. Therefore, it is important to simulate the proper cable and wire currents to perform a satisfactory test of the equipment-level barrier. A satisfactory test for the microwave frequency spectrum (100 MHz to 10 GHz) has not been developed.

The effectiveness required of the first-level barrier is examined. Based on the allocation concept, the first barrier should reduce external sources to a level that is small in comparison with internally generated interference. Several common sources of internally generated interference are examined to evaluate this level. Generally, transient voltages equal to the peak of the ac power voltage are common; when inductive components are present, the peak voltages may be several times the peak power voltage. Standard tests of building-level barriers do not exist. Standard tests should involve current injection on the power lines, communications cables, and other long conducting appendages in the spectrum below 100 MHz, since the current density produced on a facility by the conductors is usually larger than that induced by the plane wave incident on the facility. Without a well-defined barrier, any test of a facility is an extensive and difficult task, even in the spectrum below 100 MHz. As for the second-level barrier mentioned above, no practical test at the system level has been defined in the microwave spectrum (100 MHz to 10 GHz).

One of the apparent difficulties observed in reviewing standards and specifications is careless usage of the terms grounding, bonding, and shielding. In many cases, grounding is claimed to be a primary interference control technique, although it is not clear how grounding can be made a part of a barrier. Recommendations for grounding open shields are also frequently encountered; whereas it would be proper to close the barrier at the opening in the shield. These anomalies in usage and the proper roles of grounding, bonding, and shielding in interference control are discussed in a separate chapter.

Conclusions summarize the interference control approach presented in this report and briefly describe the problems inherent in the acceptance of new techniques.

Four appendices are included. Appendix A presents a list of 70 military and other electromagnetic standards and specifications reviewed under the terms of this contract. Appendix B gives more extensive reviews of four of the most widely used standards. Appendix C contains technical background information on the characteristics of balanced pair cabling and cable shield termination, followed by a report on the experiments conducted in the laboratory to demonstrate the compatibility of some of the concepts developed in this phase of the program. Appendix D provides a detailed discussion of system-generated transients.

PREFACE

The idea for a program for the unification of electromagnetic standards and specifications arose in connection with electromagnetic pulse (EMP) protection of ground-based facilities. In many cases, the cost of adding such protection to existing facilities was extremely high. However, analysis indicated that one reason costs associated with EMP protection measures are so high is that many current practices involving power distribution, electromagnetic compatibility, and other electromagnetic practices are not compatible with EMP protection practices. Thus, a large amount of the cost for EMP protection can be attributed to "reworking" an existing installation to make it compatible with EMP protection practices. There is no inherent reason why this should be the case. Electromagnetic interference may occur at any frequency from dc to light and, from a theoretical standpoint, EMP protection is no different than protection against some other source of interference.

This report is the result of Phase I of a program to unify electromagnetic standards, specifications, and design guidelines. During this phase of the program, we reviewed standards, specifications, and practices that affect EMP and other interference control measures and identified areas in which these procedures conflict with each other or with good EMP hardening techniques. Modifications to procedures identified as incompatible with a consistent interference control rationale will be proposed in Phase II of the program. A general approach to electromagnetic interference control was developed in order to identify incompatibilities and propose compatible techniques, and is discussed in some detail in this volume. Using this general approach to interference control, we reviewed more than 70 electromagnetic specifications and standards, evaluating the compatibility of interference control requirements. A condensed list of the incompatibilities found during the review is given, as well as a more extended review of four of the most widely used standards. Alternatives to the incompatible requirements will be developed and demonstrated during Phase II of the program. The results of Phase II will be presented in a subsequent report.

The review of existing standards and specifications was aimed only at identifying existing incompatibilities. In general, two types of incompatibilities were identified; those that result from adherence to explicit requirements set forth by the standards, and those that result from practices which are permitted by the standards, although not explicitly required. The reader is cautioned not to rate a standard according to the number of incompatibilities listed.

The motivation for this project came from experience with ground-based facilities. However, many of the standards reviewed here apply to aircraft and ships, as well as to ground-based facilities, although the techniques for applying them may differ. For example, ground in a ground-based facility may be interpreted as a good connection to earth, but it would not be so interpreted on an aircraft. Thus, although the interference control concepts developed here are very general, the evaluation of standards and specifications against these concepts is influenced by our experience with practices in ground-based communication facilities.

Finally, we need to mention a fundamental issue: new design versus retrofit. Many of the practices used today were originally developed as "field fixes," and, as such, were almost always solutions to specific problems rather than general ones. To the extent that an equipment unit works satisfactorily after a fix and does not interact adversely with other units, there is nothing wrong with this approach. However, it is clear that such an engineering approach will tend to treat symptoms rather than causes; therefore, in the long range this approach is less desirable than a more fundamental one. Furthermore, the cause of the problem has not been eliminated, and future equipment units manufactured in the same way will need the same kind of field fix. We have deemed it appropriate to examine first principles, deal with the fundamental causes of electromagnetic interference, and present solutions (where possible) which can be applied in new designs. Some of the suggested solutions may be readily applied in a retrofit situation; however, we recognize the possibility that in some cases retrofit would only be achieved at great expense. Nevertheless, it is desirable to know and understand what the ideal practices are and to apply them whenever possible. In the long range this will lead to more economical systems and, perhaps more importantly, to greater confidence that a system will survive and continue to function even in an adverse environment.

A draft of this report was reviewed by Mr. Frank Wimenitz (Kaman Tempo, Alexandria, Virginia), Dr. Jack Corbin and Mr. Chris Blake (Wright Patterson Air Force Base, Dayton, Ohio), and Mr. Art Whitson (SRI International, Menlo Park, California). We gratefully acknowledge the many suggestions received from these reviewers.

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Concluded)

I BASIS FOR EVALUATING STANDARDS

A. BACKGROUND.

The requirements for immunizing a system against the nuclear electromagnetic pulse (EMP) frequently conflict with standards and practices used in the design and construction of the system. This situation is particularly evident in the communications industry, where many practices that were developed when communications systems operated only in the audio frequency range have been retained or have evolved only slightly over the years. Since World War II, an electromagnetic compatibility (EMC) technology has emerged in response to the development of electronics in military systems and the interference control problems associated with the widespread dependence on these sophisticated and sensitive systems. Through this emergent technology, schemes have been developed specifically to control electronic intelligence-gathering activity and to protect against electronic countermeasures, but the basic problem of controlling electromagnetic signals entering or leaving a system is essentially the same for these areas as it is for EMC. In addition, the electric power industry recognized early in its development that certain grounding and wiring practices would enhance personnel safety, and these safety practices have been combined with interference control techniques; however, this has sometimes aggravated, rather than ameliorated, the interference control problem.

In general, the EMC practices that have evolved since World War II have tended to be responses to specific symptoms, rather than general solutions to universal electromagnetic interference problems. Thus, many of the EMC practices are inconsistent with those required to achieve system immunity to the EMP and other transient sources. Because of the diverse and specialized origins of much of the present interference control technology, these practices often conflict with each other as well as with good practice for developing immunity to broadband electromagnetic threats. Thus, when an existing system is to be hardened against the EMP, extensive changes are frequently necessary in the design of the system ground and penetration treatments. Sometimes it is cheaper to build a new facility than to harden an existing one, particularly if only part of the functions of the existing system need to survive the EMP. However, even the hardening of new systems is frequently more expensive than it need be because of the extensive effort required to ensure that some of the common practices do not subvert the hardening design.

Because EMP hardening concepts are applicable to any other electromagnetic interference control problem, it seems reasonable to consider developing compatible interference control standards and practices; peacetime interference control measures, then, would aid, rather than degrade, system performance in an EMP environment. Furthermore, including compatible techniques in new systems designs is cost-effective, since only minimal changes would be required if EMP hardening is specified at a later time. Finally, we believe that all interference control technology will be more effective if compatible techniques based on sound physical principles are used, since some marginally effective current practices will be replaced with effective techniques.

B. INTERFERENCE CONTROL PRINCIPLES.

In its most elementary form, the interference problem consists of a source of interference, a potential victim, and the intervening space and structure. The object of interference control is to prevent the source from interacting with the victim (in a detrimental way) through the intervening space and structure. The electromagnetic waves emanating from the source can be prevented from interacting with the victim if:

(1) The separation between the source and the victim is infinite [Figure 1(a)].

(2) The victim and/or its structure is orthogonalized (e.g., cross-polarized) to the source [Figure 1(b)].

(3) The source and the victim are separated by an impervious barrier [Figure 1(c)].

The use of an impervious barrier is probably the most common interference control method. In practice, the barrier is usually a sheet metal structure, with associated penetrating conductor and aperture treatments (e.g., an equipment housing and terminal protection compartments), that is easily identified and controlled although it is not quite impervious to electromagnetic waves. This sort of barrier is economical to apply, and it can be used whether or not the location and characteristics of the source are subject to control. These features make the barrier the primary EMP and other electromagnetic interference control tool, as well as a necessary adjunct to most orthogonalization methods. As implied in Figure 1(c), barriers can be used to confine sources as well as to protect victim circuits. (In this report "shield" is used to indicate a conducting surface, usually almost closed, and "barrier" is used to indicate an impediment to electromagnetic interaction; a closed barrier may contain a shield as one of its elements,but it also contains any aperture or penetrating conductor treatments necessary to make the barrier more impervious to electromagnetic waves.)

Large separation is preferred in some cabling practices, and it is one technique used to control electronic intelligence-gathering. Application of this technique requires either (1) control of both the source and the victim (or receptor) position, (2) control of

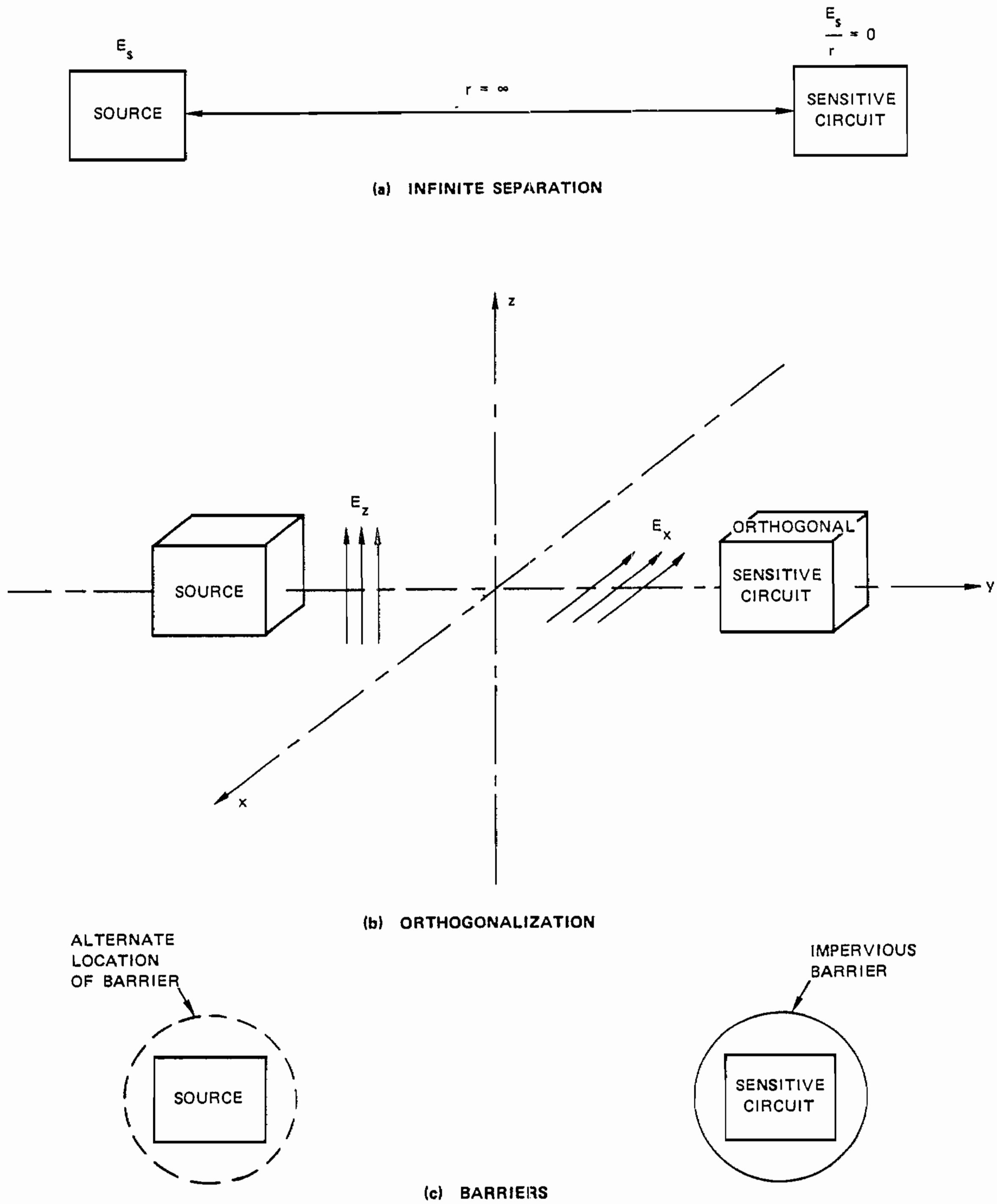


FIGURE 1 METHODS OF ELIMINATING THE INTERACTION OF AN INTERFERENCE SOURCE WITH A SENSITIVE CIRCUIT

either the source or the victim and a large space about it, or (3) that the position of one be permanently fixed and the position of the other be controlled. Large separation is most frequently used in controlling system-generated interference; it is not useful in EMP control because the location of the source is beyond influence.

Examples of orthogonalization are readily found in the field; for instance, the transposition of telephone and telegraph wires, as well as balanced twisted pairs, make use of this principle. Use of the technique usually requires predictable and unchanging source fields or control of the source fields against which the victim and its associated structures can be orthogonalized. In practice this technique frequently is used with a shield (e.g., twisted shielded pairs) so that the interference field geometry can be controlled even if the source cannot. Orthogonalization schemes that depend on discriminating against a common-mode interference while passing differential-mode signals are most effective at low frequencies (< 100 kHz); at high frequencies, small imbalances in stray capacitances and inductances cause poor common-mode rejection. Therefore, a shield may also be necessary to control the interference spectrum when these techniques are used.

In addition to interference control methods that operate on the interference after it has been generated, there are some source reduction or elimination techniques that can be applied to certain types of sources (but not EMP). For example, bonding is used to eliminate the arcing or intermodulaton that occurs when current must flow across insulating or semiconducting gaps between conductors. Such source control is a powerful and sometimes essential remedy; however, usually source control is merely an application of one of the three techniques described above to the source rather than to the victim.

Use of a finite barrier is the only method that does not require control of the source or its position relative to the victim, and therefore it is the only practical tool for developing a universal interference control rationale that can then be used to evaluate the compatibility of electromagnetic standards, specifications, and practices. The barrier concept can also be used to explain why some practices are effective and others are counterproductive.

C. BARRIER RATIONALE.

An ideal barrier is a closed, perfectly conducting shield between the system to be protected and the sources of interference. Such a shield completely isolates the source from the protected system. However, because the system must be supplied with energy and must communicate with elements outside the shield, openings to pass conductors must be made in the shield for these purposes. Additional openings in the shield surface typically are necessary to allow access for installation and maintenance of equipment, ventilation, etc.

The metal shield without such openings would be an adequate barrier even if the walls were constructed of fairly thin sheet metal, Table 1. The table shows the peak voltage induced in the largest loop that can be installed inside a 10 m radius sphere of various wall thicknesses and materials. The field incident on the shield is a 50 kV/m plane wave exponential pulse with a decay time constant of 250 ns. With only 0.2 mm (8 mils) of aluminum, the induced voltage is less than 1 V; therefore, the adequacy of the barrier is not limited by the shielding capability of finitely conducting metals of structural thicknesses -- it is limited by the openings made to accommodate the system.

Table 1 Shielding by Diffusion

Shield Thickness (mm)	Internal Voltage Induced in Loop*		
	Copper 5.8×10^7 mho/m	Aluminum 3.7×10^7 mho/m	Steel 6×10^6 mho/m ($\mu_r = 200$)
0.2	0.34 V	0.85 V	0.076 V
1.0	2.6 mV	6.4 mV	1.1 mV
5.0	21.0 μV	51.0 μV	15.0 μV

*Peak voltage induced in a loop of radius 10 m inside a spherical shield of radius 10 m illuminated by a high-altitude EMP (by diffusion through walls only).

The openings through which insulated conductors (such as power and signal wiring) pass almost completely defeat the barrier. Interference current can propagate through the shield virtually unattenuated along these conductors. Other openings or apertures are also important if (1) they are large, (2) there are many of them, (3) a strong source is near the opening, (4) a sensitive receptor is near the opening, or (5) the openings are of such size and arrangement that external fields efficiently excite the cavity inside the shield.

Thus, although a closed, continuous metal shield provides an adequate interference barrier, the typical practical shield structure that contains openings for many penetrating conductors, joints, doors, vents, etc. may be completely inadequate. Therefore, it is important to recognize that an effective barrier includes the aperture and penetrator treatments necessary to make the barrier a closed, substantially impervious surface. A metal shield with typical holes and penetrations does not form an adequate barrier. Because the openings required in shields defeat the barrier, the concept of shield topology[1,2] has been used to identify locations where the shield is compromised. The ideal barrier is a topologically closed, continuous, impervious surface between the source and the victim and, in practice, any deviation from this ideal must be examined closely to ascertain the effectiveness of the barrier.

The essence of interference control, then, is the definition of the topology of the barrier surface and the identification of weak spots in the barrier. When the barrier topology coincides with a conducting shield, the fortification of weak spots is analogous to closing the holes in the shield. That is, special treatment is given to apertures and to insulated conductors penetrating the shield to limit the interference that can pass through the shield at these openings.

Note that the barrier need not be a metal shield surface; it need only be a closed surface impervious to electromagnetic interference. However, the use of metal sheet or plate for the majority of the barrier has obvious advantages because metal shields are discrete and easily identified, controlled, and maintained. Furthermore, the barrier region of greatest concern in a metal shield is limited to the few easily identified openings in the shield; on the other hand, a barrier topology that does not coincide with a metal surface is apt to be less well defined, but it still must be controlled and maintained to be impervious to all forms of electromagnetic waves -- those propagating through space as well as those guided along wires or other waveguides. The physical shape of the barrier is not important, but the barrier must form a topologically closed surface surrounding the protected zone (or the source).

It is also important to recognize that the barrier can be located anywhere between the source and the circuit to be protected. It can be at the equipment level, where advantage can be taken of the metal equipment case, or it can be at the facility (building) level, if structural metal is available. Although the barrier topology is a simple closed surface, the actual shape may be very complicated because of construction and maintenance requirements, particularly if the facility barrier is formed along cable ducts and racks, as might be the case in an unshielded building.

D. BARRIER REQUIREMENTS.

The effectiveness of the barrier determines the electromagnetic stress that an external source is allowed to apply to components protected by the barrier. This stress is manifested as charge and current density induced on the component by the external source, and as voltages and currents induced on wires entering the component. If the system is to be immune to the external source (e.g., the EMP), this stress must be smaller than the threshold of the components protected by the barrier. The threshold of the component can be defined as the maximum level of stress that can be withstood without malfunction. However, what is considered a malfunction varies widely from a slight reduction in the mean-time-between-failures (usually associated with a stress slightly greater than ambient), to a high probability of immediate damage.

Nevertheless, the barrier must be at least effective enough so that system components in the protected zone will not be damaged by the external sources. Furthermore, if the barrier is such that the interference produced in the protected zone by the external sources is small compared to the internally generated interference (i.e., that produced by system components inside the protected zone), further improvement in the barrier does not provide a commensurate reduction in interference and, beyond a reasonable safety margin, we do not benefit from improving the barrier beyond this point. Thus, we have established upper and lower bounds on the effectiveness required of the barrier. (In general, the barrier is required to reduce the stress within the protected zone to a level that is smaller than the threshold of the equipment or circuits protected by the barrier, however this threshold is defined.)

The barrier may also be required to perform a signal-confining function if the internal circuits operate at large signal levels or if secure data processing or communications are required. Barriers to confine large signal sources must at least reduce the internally produced signal outside the barrier to below the damage stress of external equipment, but no benefit accrues from making this external signal much smaller than the ambient external environment. These are the same bounds that were stated for the source-excluding barrier since, topologically, the source-confining barrier is a source-excluding barrier. For secure data, however, the upper bound on barrier effectiveness must be applied, since it is necessary that the secure signals outside the barrier be masked by the ambient external noise.

In a system, the interference control measures can be allocated between a system-level barrier and an equipment-level barrier. The system-level barrier might be required to reduce the externally generated interference produced by the EMP, for example, to the internal ambient level (usually peak-voltage transients of a few hundred volts or peak-current transients of a few amperes associated with normal power switching and equipment operation and regulation). The equipment-level barrier, which is usually a part of the equipment as procured, would then have to reduce this ambient, fair-weather, peacetime environment inside the facility to a level below the threshold of circuits inside the equipment (typically a few volts). Because no single barrier is required to provide a very high degree of interference reduction, moderate-quality barriers are acceptable at both the equipment and system levels.

Some additional advantages are realized if the upper limit on barrier effectiveness is achieved for system-level barriers. First, the interference environment that equipment in the protected zone must tolerate is simply the ambient system-generated noise environment. Therefore, no special requirements need be imposed on the equipment to meet EMP hardening specifications. Second, internal components of systems hardened to the EMP will not be stressed by the EMP to levels greater than they normally are by the ambient environment, and system survival during an actual threat is more certain.

E. ALLOCATION.

A barrier that reduces the internal effects of external sources to a level that is small compared with the internally generated interference (or the other way around if the source is inside and the observer is outside) is <u>effectively impervious.</u> When interference protection is allocated so that each barrier is effectively impervious, the electromagnetic environment in each volume enclosed by barriers is independent of the sources in any other volume. Allocating protection between effectively impervious system-level and equipment-level barriers offers the following advantages:

(1) Equipment units are interchangeable because internal circuit environment is independent of the environment inside the facility but outside the equipment.

(2) Equipment units are inherently compatible because the interference generated by such units does not pollute the environment in the facility (therefore they do not affect each other's environment).

(3) No equipment-level specifications are required to accommodate exterior sources such as lightning and the EMP, since the environment inside the system level barrier is independent of exterior sources.

(4) Many communications security requirements are satisfied because spurious emissions are small compared to the noise level inside and outside the system-level barrier.

(5) Neither the system-level barrier nor the equipment-level barrier has to be of extremely high quality, since peak voltages of a few hundred volts at the facility level and a few volts at the circuit level are common.

However, there are many other feasible approaches. All of the protection could be placed at one level; for example, since the equipment cabinets or cases are normally used as a shield to protect the small signal circuits, one could improve the quality of these shields to the point that the equipment will tolerate the EMP or other external sources without additional (facility-level) protection. The equipment then becomes "inherently hard." However, this approach requires a very high integrity barrier because the protection is no longer distributed among two or more layers -- incident currents of tens of kiloamperes must be reduced to tens of milliamperes (120 dB of current reduction). While it is possible to design a single barrier of this quality, barrier performance is easily degraded by 40 dB or so by corrosion or oxidation of critical contact surfaces. Furthermore, because the barrier is never stressed to threat level during normal operation, there is no assurance that its integrity is maintained (unless it is periodically stressed to threat level). These considerations pose serious concerns for the use of this approach for complex systems, but it has been applied to ligntning protection of small units, such as power transmission system transformers, switches, etc., and remote cable and microwave repeaters in telephone systems.

Another approach is to harden the equipment to levels somewhat above the hardness required for peacetime fair-weather operations and reduce the currents on long cables and power lines to levels the system can tolerate. Thus, some kind of barrier at the facility level is assumed to be established, but it is usually vaguely defined and therefore neither easily identified nor easily controlled. In addition, the equipment threshold is unique to the facility configuration, and therefore the equipment is no longer interchangeable. This approach shares most of the limitations associated with "inherently hard" equipment and few of the advantages of the allocated hardening approach.

The allocated hardening approach using two or more well-defined barriers has a firm basis in electromagnetic theory,[3,4] and is the most easily specified and controlled approach; it has been used in this project as the norm for evaluating interference control concepts, standards, and practices. For this evaluation, the important consideration is not where the barrier is placed but whether the standards, specifications, and practices contribute to the formation of a topologically closed, impervious barrier surface.

F. OTHER INTERFERENCE CONTROL MEASURES.

In the EMC community, technologies using other than shielding or electromagnetic barrier methods are often credited with interference control properties. For example, bonding and grounding are commonly called interference control technologies. Bonding, to the extent that it is used to prevent arcing between otherwise insulated conductors or to prevent intermittent currents between intermittently contacting conductors, is a legitimate source prevention technique. More generally, however, bonding is simply the act of making good electrical connection between two or more conductors, and the arcing and intermittent current described above are the result of inadequate or ineffective bonding or electrical connection.

Similarly, interference control properties attributed to grounding are almost always the result of correcting illogical grounding schemes. Grounding is used to prevent electrostatic charge accumulation that might cause shock, explosion, or equipment damage, providing fault current paths so that protective devices such as fuses and circuit breakers can operate. Attempts to make grounding an interference control tool by implementing single-point grounding systems with power ground, safety ground, and signal common connected to a single grounding electrode inevitably result in poorer interference immunity. Correcting such designs does result in better system performance, but in this case grounding is the cause of the problem, rather than its cure. In fact, grounding can in no way be used as a part of the interference barrier. It can defeat the barrier, however, if insulated grounding conductors are allowed to penetrate the barrier. Therefore, we cannot emphasize too strongly that grounding conductors should not penetrate shield or other barrier surfaces; in this sense, control of grounding conductors is very important to effective interference control.

G. OTHER CONSIDERATIONS.

Specifications, standards, and practices for interference control should be consistent with a topological barrier concept and its corollaries controlling bonding and grounding. In addition, tests for evaluating the requirements of standards and specifications should also provide or confirm engineering data that can be used by the system designer to predict system performance (or at least bounds on system performance). This is not the case for many specifications currently used; too frequently, the tests are not conducted with the operational configuration, the equipment is not excited by anything approximating an operational stimulus, and the data produced by the test cannot be used to predict an operational response. Qualification tests of this sort are of little use to the system designer. Thus, one of the considerations in evaluating current standards and specifications is the utility of these qualification tests.

II THE SECOND-LEVEL BARRIER: EQUIPMENT SHIELDS

A. CONDITIONS ON SECOND-LEVEL BARRIER.

The second-level barrier is a topologically closed surface completely enclosing the protected small signal circuits and components. It is completely inside the first-level barrier. It must be sufficiently impervious to the electromagnetic waves inside the first barrier that the stress impressed on the circuits and components inside the second barrier is below the threshold. While the second-level barrier may be of any shape, it typically embodies the equipment case, rack, or cabinet, and it is usually provided by the equipment manufacturer, since this barrier is the primary means he uses to control the environment of the enclosed circuit and components. However, it is usually assumed that some first-level protection is provided — communications equipment is not usually expected to tolerate a direct lightning strike to its power or signal terminals.

The second-level barrier, usually composed of the equipment cases, interconnecting cable shields, and penetrating conductor treatments, must be sufficiently impervious to interference that:

(1) Interference penetrating the barrier from outside the equipment is small compared to circuit threshold levels.

(2) Interference penetrating the barrier from inside the equipment is small compared to the ambient level of interference outside the second-level barrier (but inside the first one).

The first condition implies a susceptibility criterion for interference penetrating the second-level barrier system, and the second condition implies an emission criterion.

Condition (1), illustrated by the second barrier in Figure 2, requires that the stress inside the second barrier is not increased by sources outside this barrier. This condition may apply to interconnecting cables, as well as to the equipment case; the shape of the second barrier is determined by the manner in which the closed barrier topology is achieved.

For example, if the interconnecting cables are shielded and the cable shield is continuous with the equipment shield through the cable connector (Figure 3), the cable shield and connector shield are a part of the second barrier. The interference penetrating the barrier is the important element in Condition 1 above, and the interference penetrating the cable shield and connector, and even other equipment cases, is as important as the

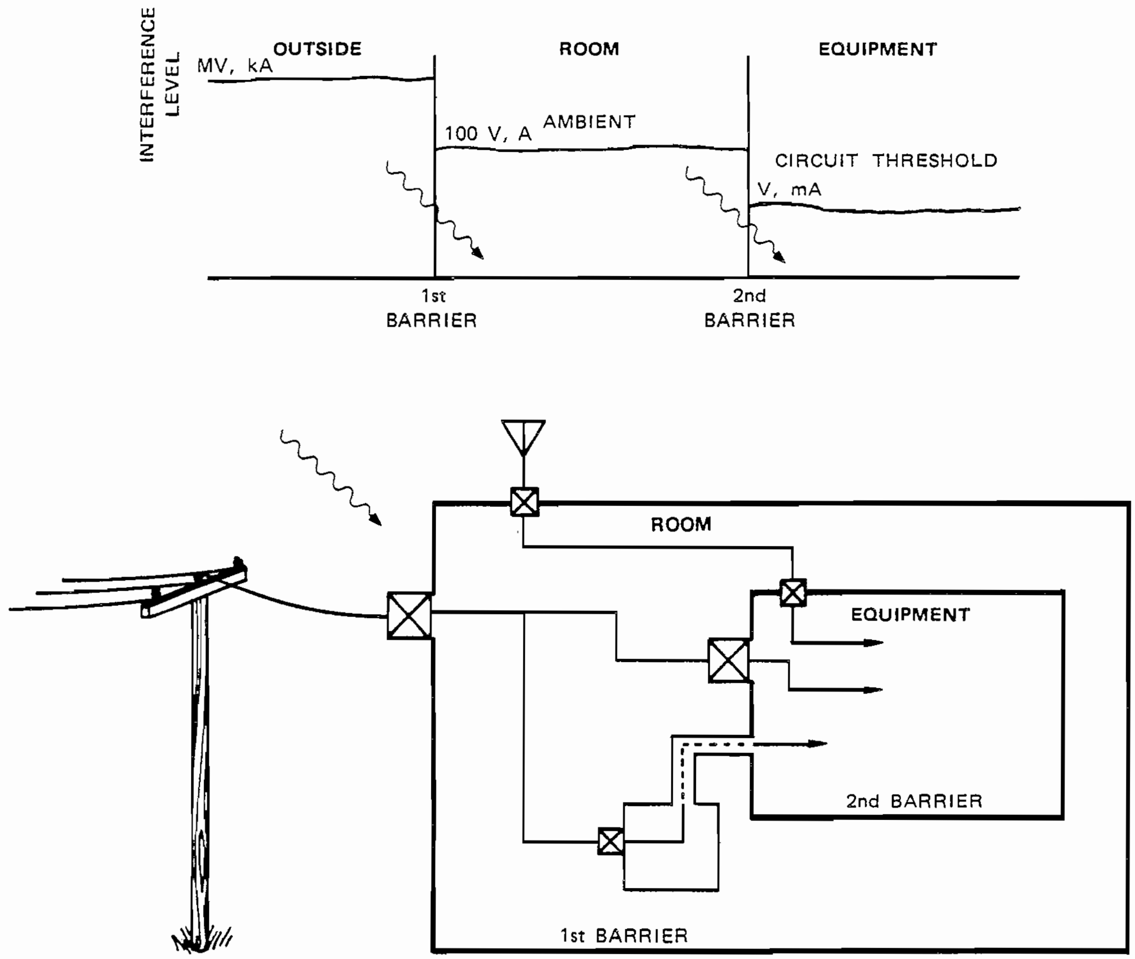


FIGURE 2 TWO-LEVEL BARRIER SYSTEM AND ASSOCIATED INTERFERENCE LEVELS

interference penetrating the primary equipment case. This observation has implications for equipment susceptibility, specification, and testing which will be discussed later.

If unshielded interconnecting cable is used, however, the barrier must be closed through "pin protection" devices such as the limiters, filters, etc., illustrated in Figure 4. In this case, each item has its own topologically closed barrier, since the connectors and cabling are outside the barrier (as indicated in Figure 4b). Thus, each item of equipment is fairly independent of the interconnecting cables and the other items of equipment, but this independence is achieved at the expense of adding "pin protection" devices to each item of equipment. The barrier test criteria may also be complicated because of the large number of excitation modes possible at the cable/equipment interface. Finally, system reliability may be affected by the added components.

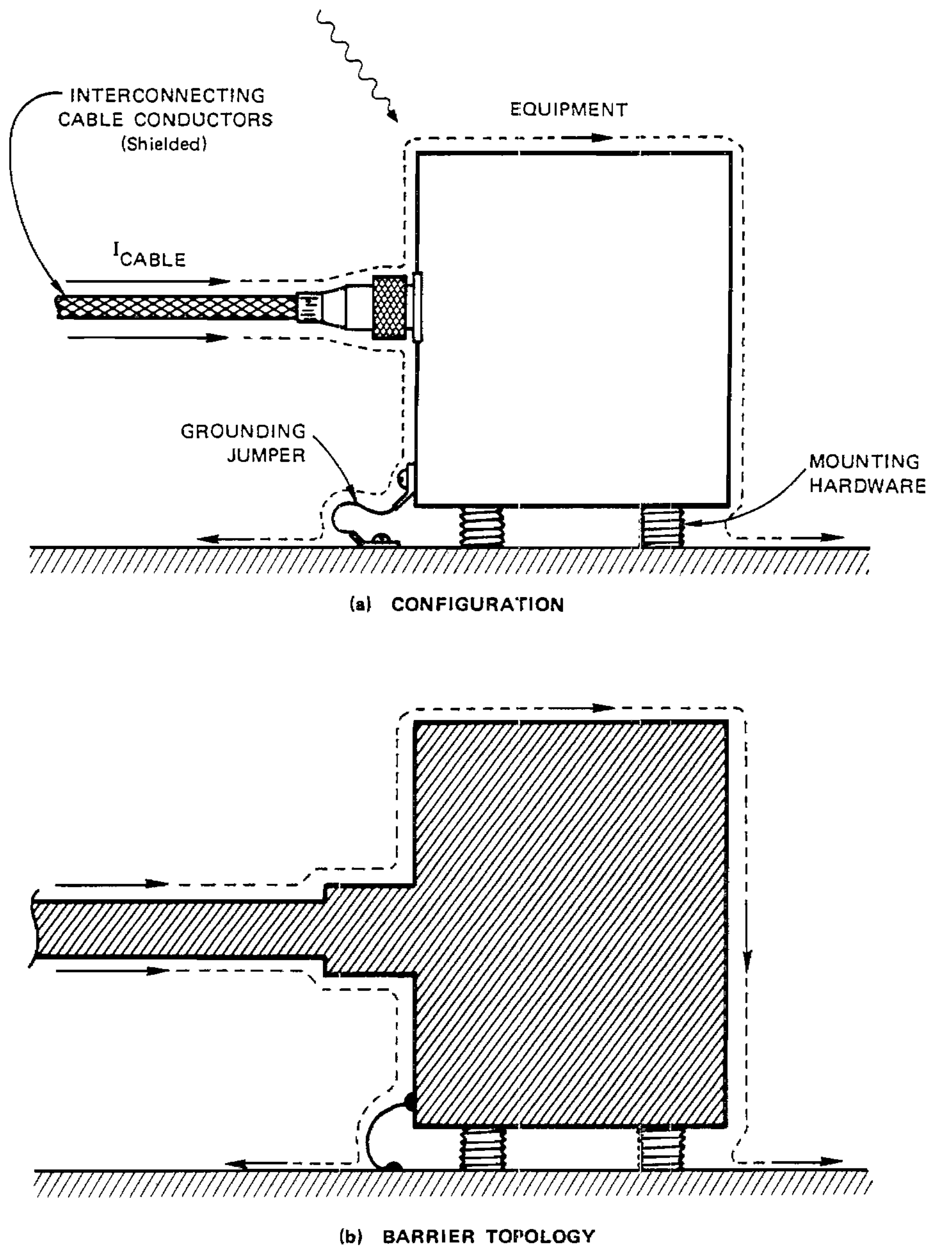


FIGURE 3 CONFIGURATION AND TOPOLOGY WITH SHIELDED INTERCONNECTING CABLE

Whether or not the cables are shielded, the cable current flowing onto and through the equipment case is a major source of excitation for the shield formed by the equipment container and its receptacles. Figures 3 and 4 also show a wave incident on the container, but because the second barrier is inside the first barrier, such a wave is significant only for wavelengths shorter than the dimensions of the first barrier. Therefore, for structures whose cross-sectional dimensions are of the order of a few meters, such waves may

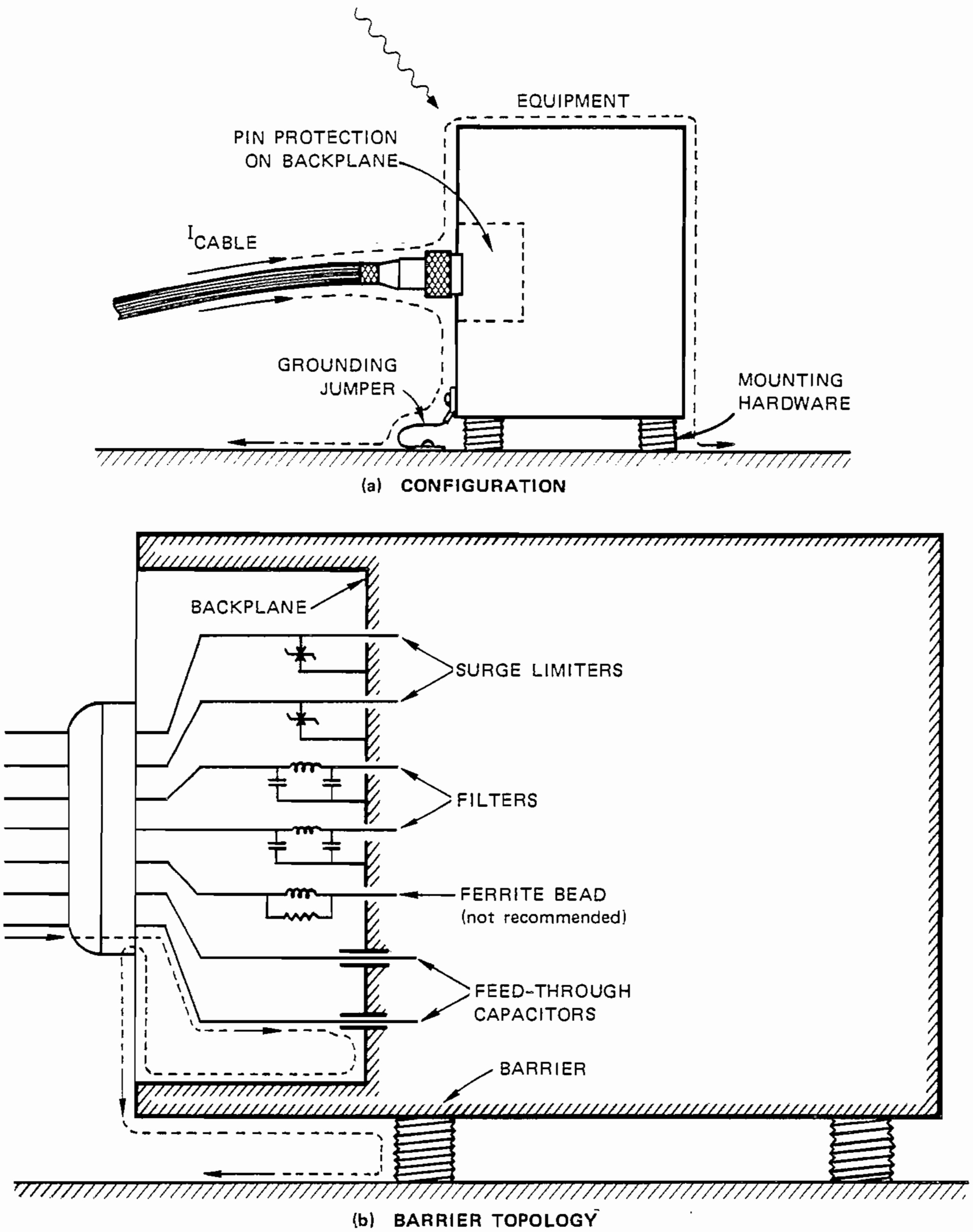


FIGURE 4 CONFIGURATION AND TOPOLOGY WITH UNSHIELDED CONNECTING CABLE

exist inside the first barrier (as propagating, approximate plane waves) only for frequencies above about 300 MHz. At lower frequencies, interior fields will be manifested as standing waves, quasistatic fields, or transmission line fields. The latter are associated with the cable currents that are often induced by standing waves or quasistatic fields.

The second interference condition stated at the beginning of this section requires that barriers enclosing interference-producing equipment be sufficiently impervious that the internally generated interference cannot penetrate the barrier and pollute the environment outside the barrier. This emission criterion implies (Figure 5) that the noisy equipment container and its penetration and aperture treatments must be such that the room environment is negligibly affected by the installation and operation of the equipment. If this criterion is met, the performance of the remainder of the equipment will be unaffected by the addition, removal, or alteration of the noisy equipment. That is, some future change in the noisy equipment will not require a change to, or reassessment of, all of the other equipment in the facility if the second condition is prescribed for equipment.

It is important to recognize that a given item of equipment may be both a "small signal" equipment and a "noisy" equipment. That is, it may contain circuits that are sensi-

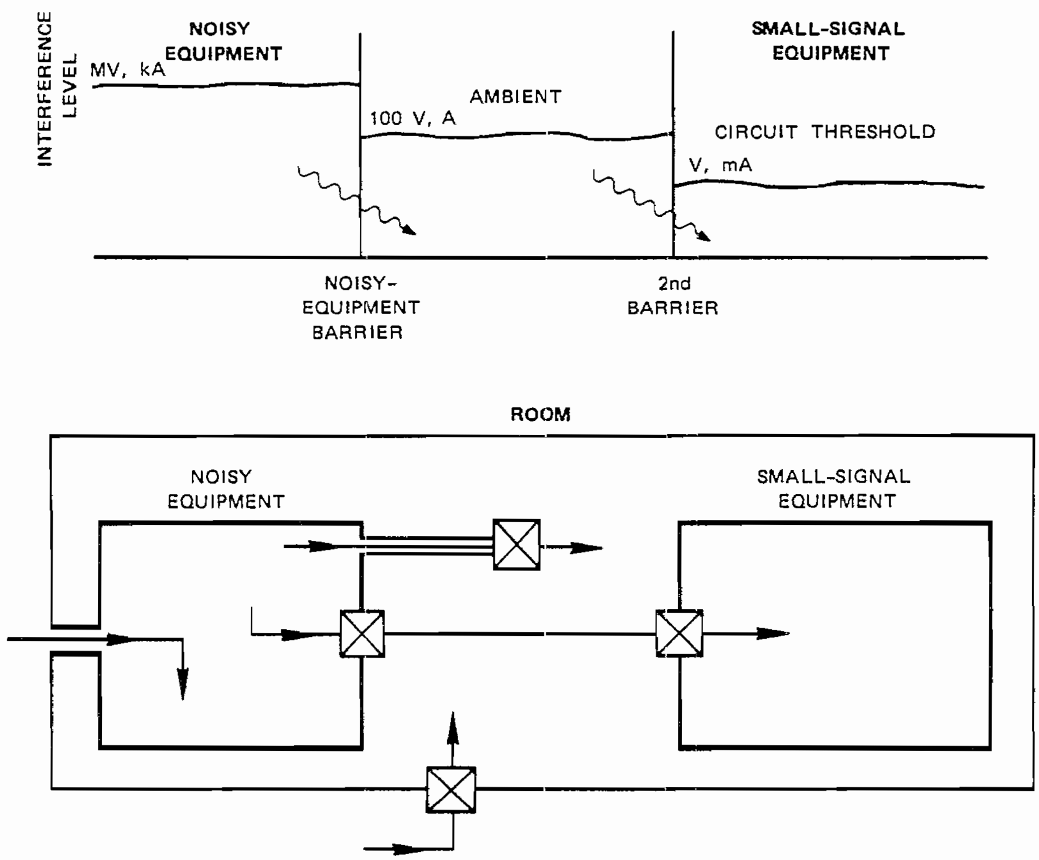


FIGURE 5 SECOND BARRIER TO CONFINE NOISY EQUIPMENT AND TO SHIELD SMALL-SIGNAL EQUIPMENT

tive to low-level interference of one type, yet produce high-level interference of another type. For example, it is common for digital electronics to operate in a moderate amount of self-generated noise if the interference is not coherent with the logic train (or is coherently excluded). Such noise, if it escapes the circuit container, may interfere with other equipment, while a lower level of interference occurring at a vulnerable moment may cause errors or upsets in the noise-generating equipment. It is appropriate, therefore, that packaged electronic equipment or subsystems be designed to meet both susceptibility and emission criteria.

B. INTERFERENCE IMMUNITY.

1. Achieving Immunity.

Interference immunity at the equipment level is achieved by meeting Condition 1 (see page 16): interference penetrating the barrier from outside the equipment should be small compared to internal circuit threshold levels. This condition is generally met by experienced equipment designers/manufacturers because an item of equipment is usually expected to tolerate a relatively uncontrolled facility environment. However, from time to time, notable exceptions to this norm are encountered, and no systematic method of meeting the susceptibility criterion has been available; Condition 1 is often met heuristically, by trial and error, or by treating specific symptoms.

The general philosophy for achieving second-level interference immunity is the same as it is for the first level. However, there are some significant differences:

(1) The volumes protected at the second level are usually much smaller than the first-level volumes.

(2) The open circuit voltages on penetrating conductors are much smaller at the second level; thus, current interruption (high impedance) techniques are acceptable.

(3) Because the field geometry can be controlled by a first shield, orthogonalization techniques, such as common mode rejection, can be used. (The field geometry can be controlled because the tangential component of the electric field at a metal surface -- e.g., inside a shielded cable -- is small and usually negligible.)

(4) Equipment items are frequently packaged in a metal container that is (or can be) adapted to perform shielding functions.

(5) There already exist commercial and military requirements for the electromagnetic compatibility of electrical and electronic equipment (although these are not always logically derived).

The generic interference control techniques are illustrated in Figure 6. They consist of providing a topologically closed barrier by:

(1) Using the metal equipment container as a shield.

(2) Limiting interference propagating through the shield on insulated conductors by closing the barrier about these conductors.

(3) Limiting the leakage through apertures by establishing a barrier in these openings.

At the second-level barrier, as at the first barrier, the insulated penetrating conductors constitute the most severe violations of the barrier. Therefore, techniques that reduce the number of penetrating conductors required will alleviate the interference control problem. The use of shielded interconnecting cables (or shielded cable trays) eliminates many barrier penetrations by extending the barrier from one equipment case to another along the cable shield. Thus, if there are many interconnecting conductors, using shielded interconnecting cables may be more economical than using pin protection in the equipment at both ends of the cable. For insulated conductors (such as power, signal, and control lines) that cannot be eliminated, it will be necessary to provide treatments that close the barrier about the cables or interrupt the current flowing on them. As indicated in Figure 6, the barrier may be partially closed with filters, limiters, or isolators. These devices restrict the spectrum of the interference propagating through the shield (filters), limit the voltage on the conductor (limiters), or interrupt the current on the conductor (isolators). Table 2 lists various devices of each class. Note that the limiters and filters close the barrier above some voltage threshold or outside some passband, while the isolators interrupt the interference current path with an insulating or high-impedance section at or near the shield.

To emphasize the fact that grounding systems frequently violate the closed barrier, Figure 6 also shows a topologically proper grounding system in which the external grounding conductor is connected to the outside of the shield and the internal grounding conductor is connected to the inside of the shield. Thus, neither grounding network violates the equipment shield. For frequencies such that the shield wall thickness T is small compared to the skin depth δ in the wall material [i.e., for $f < (\pi\mu\sigma T^2)^{-1}$ which usually includes power frequencies as well as dc], the two grounding networks are effectively continuous, and the separation shown in Figure 6 makes no difference. However, at higher frequencies, where $f > (\pi\mu\sigma T^2)^{-1}$, the two grounding systems become more independent electromagnetically. Thus, transients or RF interference induced on the external grounding system have little effect on the internal circuits (at least not through the internal grounding system). If it should be necessary (presumably not for interference control reasons) to connect the two grounding systems by means of an insulated conductor penetrating the shield, the penetra-

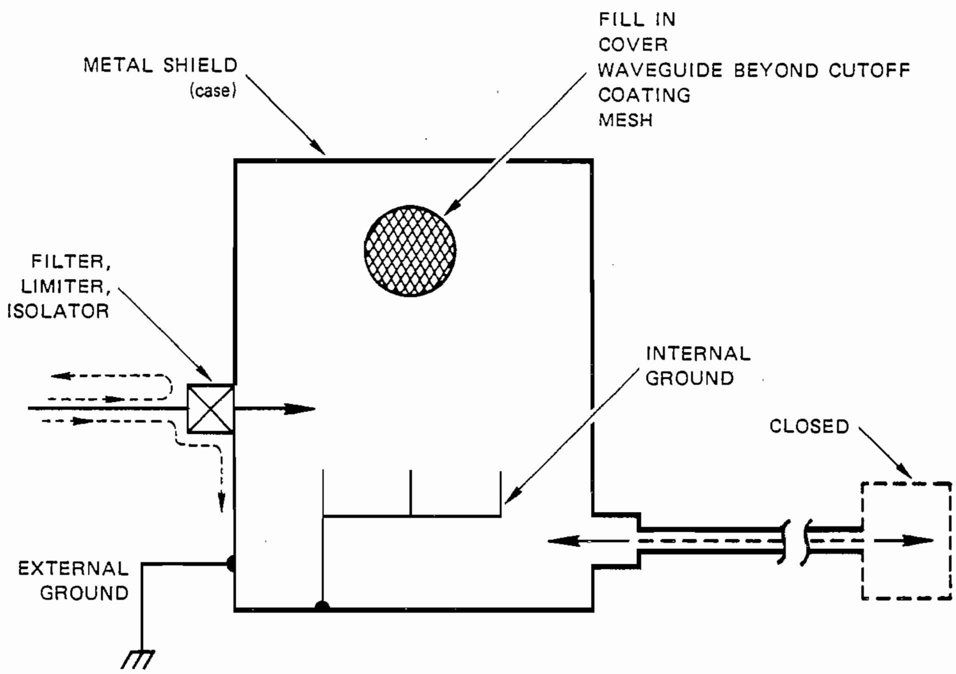


FIGURE 6 GENERIC INTERFERENCE CONTROL TECHNIQUES

TABLE 2 PENETRATION TREATMENT DEVICES

Filters	Limiters	Isolators
π - section	Avalanche diode	Optical coupler
T - section	Zener diode	Microwave link
L - section	Gas tube	Dielectric waveguide
Feedthrough capacitor	Metal-oxide varistor	Optical fiber link
Ferrite bead	Spark gap	Isolation transformer
Bifilar choke		Dielectric pipe or tube (for plumbing)
		Hydraulic or pneumatic links

ting grounding conductor would have to be treated with a limiter or filter in the same manner as any other insulated penetrating conductor.

A long, slender extension of the shield is also shown in Figure 6 on the right-hand side of the container. Such an extension of the shield might represent a shielded interconnecting cable or an electrical conduit. This protrusion is shown to emphasize the need to identify the complete barrier topology; the end of this protrusion must be closed (perhaps through the housing of another item of equipment) if a closed barrier surface is to be established. Failure to close the barrier at such protrusions may cause a severe compromise in the effectiveness of the barrier. Such would be the case if the protrusion were an electrical conduit with the power conductors exposed outside the barrier.

To complete the closing of the barrier, treatment of the apertures may be required. Open apertures, such as access ports, ventilators, etc., can be treated by several methods as suggested in Figure 6. Aperture treatments, in approximate order of effectiveness, are shown in the figure. Apertures that are not required for service or maintenance can be filled in by welding or soldering a plug in the hole. If future access is required, the cover may be bolted on (perhaps with an RF gasket) rather than welded. The other treatment methods shown in the figure are used where air flow or light transmission through the aperture are required.

2. Qualification Testing.

The systems designer who uses equipment components in his system needs specifications that set out the requirements and performance limits of the equipment. Specified performance limits, such as tolerance for interference, must usually be demonstrated by testing one or more samples of the equipment in the prescribed environment. However, frequently it has been impossible (or extremely difficult) to relate the "qualification test" results to the system requirements. The qualification test then has little significance to the designer; it becomes a "procurement" test.

This problem is usually caused by a failure to determine topologically appropriate parameters and, therefore, failure to specify and evaluate these topologically appropriate parameters. The shortcoming, then, is in the preparation of the specification. It is said that the function of a specification is to substitute rules for good judgment; if all buyers/designers/manufacturers displayed faultless judgment in all matters affecting the equipment, no specifications would be necessary. However, a specification that fails to provide the performance required by the system designer is not only ineffective; it is almost always detrimental to the extent that meeting the specification adds cost but no value. Therefore, it is extremely important that specifications for equipment interference tolerance and control be based on a rational, consistent view of interference control (i.e., that good judgment be used in preparing the specification).

The topologically closed barrier concept described in Section I is an appropriate basis for testing the requirements of specifications. Thus, if specification requirements and tests are consistent with the closed barrier concept described in Sections I and II-A, the interference-control goals can be met.

Since the fundamental precept of the topological barrier concept of interference immunity is that a closed barrier surface around the equipment be established, the specification of interference control for equipment in effect:

(1) Requires that the topologically closed barrier be formed.

(2) Requires that no significant violations of the barrier be permitted or accepted.

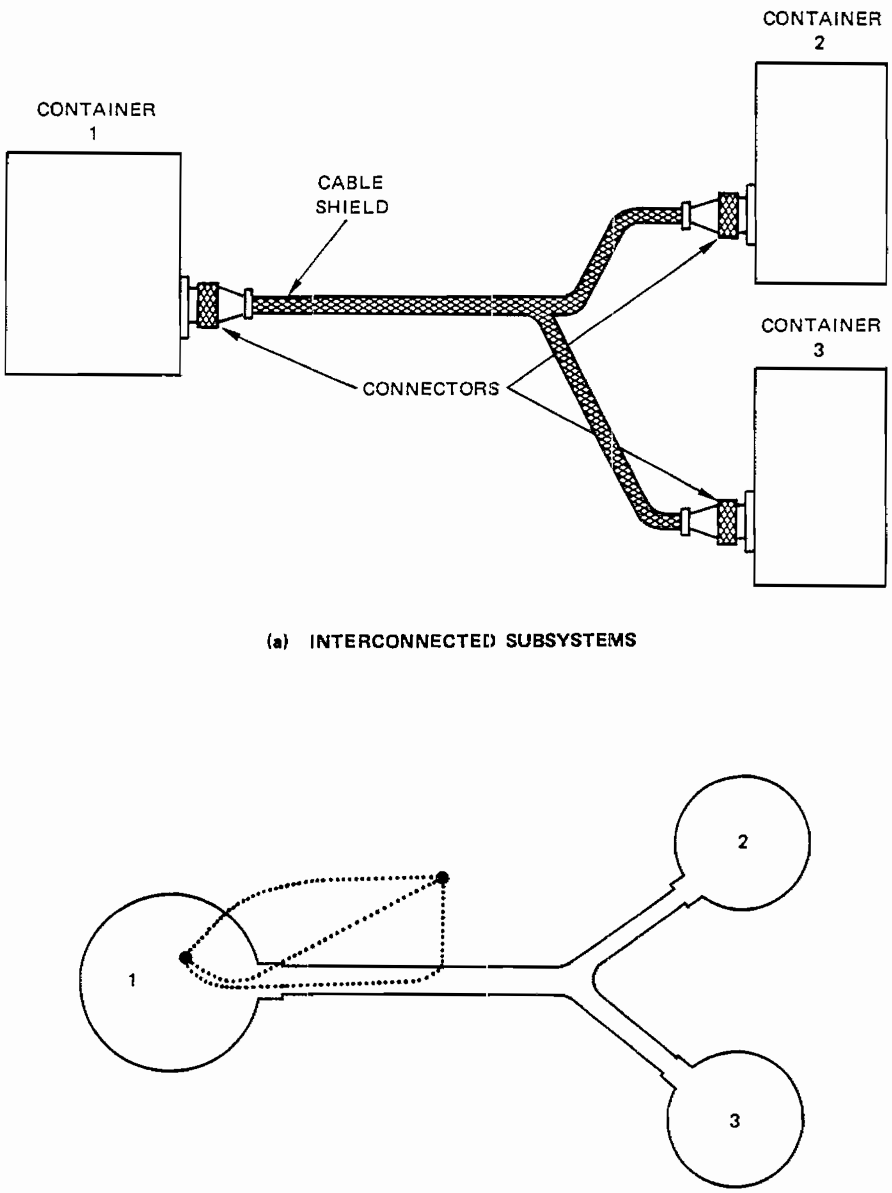
(3) Requires tests to measure the effectiveness of the barrier in a manner that can be related to the operational environments of the equipment.

Ways in which the first two requirements can be met have already been discussed; the primary task there is to adapt the barrier concept to the precise, yet general language of a specification.

Some of the considerations affecting equipment testing have been mentioned in Section II-A. Among the important considerations are the barrier topology, the mounting provisions, the external grounding provisions, and the number, size, and location of the interconnecting cable connectors. As suggested in Figures 3 and 4, the excitation current at frequencies below a few hundred megahertz will be derived primarily from the current, induced on the interconnecting cable, that flows through the cable shields, connectors, equipment case, mounting hardware, and grounding jumper. Therefore, the equipment qualification test in this frequency range should excite the equipment shield in the same way as does the operational interference, or it should provide more fundamental data from which the operational interference performance can be readily calculated.

Equally important, however, is the barrier topology to be specified and tested. As was noted in Section II-A, the equipment-level barrier includes the cable shields if shielded interconnecting cables are used (specified). In that case, the qualification test must test the cables also because, the cable shields are an important part of the shield system (Figure 7).

In fact, for the low frequencies, the leakage through braided wire shields on the interconnecting cables may represent the dominant interference penetrating the second-level barrier. For wavelengths greater than the dimensions of the container in Figure 7, very little current will be induced directly on the containers because they are small and are "open-circuit" structures. However, the interconnecting cables are long and their ends are



(a) INTERCONNECTED SUBSYSTEMS

(b) SHIELD TOPOLOGY AND INTERACTION PATHS

FIGURE 7 INTERIOR SHIELD SYSTEM AND SHIELD TOPOLOGY

short-circuited through the container mounting and grounding hardware. Therefore, much larger currents are induced and, because of the small cross section of the cable shield, the current densities in the cable shield are typically very much larger than in the equipment container. Failure to properly account for the leakage through the cable shields can invalidate the test.

Note again that the low frequency electromagnetic field at the second-level barrier is not typically a plane wave environment. Because the equipment is typically inside a structure such as a building, ship, rocket, or aircraft, propagating plane waves cannot exist for more than a few nanoseconds. The current induced on cables and equipment containers inside these structures is typically generated by gradients in the structural ground "plane," by the field about nearby current-carrying conductors, or by external fields penetrating an aperture in the first-level shield (Figure 8). Therefore, illumination tests in which the equipment is irradiated by a propagating wave from a transmitting antenna or transmission line are not appropriate for low frequency (below 100 MHz) tests of the second barrier.

If the complete second-level barrier is to be tested, an excitation method that produces the appropriate current density in the cable shields and equipment containers must be used. Some excitation methods for use in equipment tests are illustrated in Figure 9. In the first two examples, the test excitation is essentially the same as the system excitation modes shown in Figures 8(a) and (b). These test methods are somewhat inefficient, however, because a large source current (I_0) is required to produce a small cable current (I).

Figure 9(c) illustrates a method by which all of the source current is delivered to the system shield. To apply this method, it is necessary to isolate the equipment containers from the main ground plane and to mount them on a small plane that is used as one terminal of the driving source. Excitation current thus flows through the mounting hardware and container of this unit and arrives at the cable shield. For the simple two-unit system shown in Figure 9, this technique is simple and can produce a good direct simulation of the system excitation.

If the system contains more than two interconnected containers, the interpretation of the test data can be more complex, and it may be necessary to drive more than one container through its mounting hardware. A further complication arises if the interconnecting cabling is not manufactured (or provided) by the equipment manufacturers, or is not specified in the equipment specification. Similar difficulties surround systems in which several items of equipment of different manufacture are used; in these cases, it is convenient to test the equipment in its container without the interconnecting cabling and other associated equipment units. Such a single-unit test is also appropriate for equipment designed to have the barrier closed through pin protection devices rather than through the interconnecting cable shield.

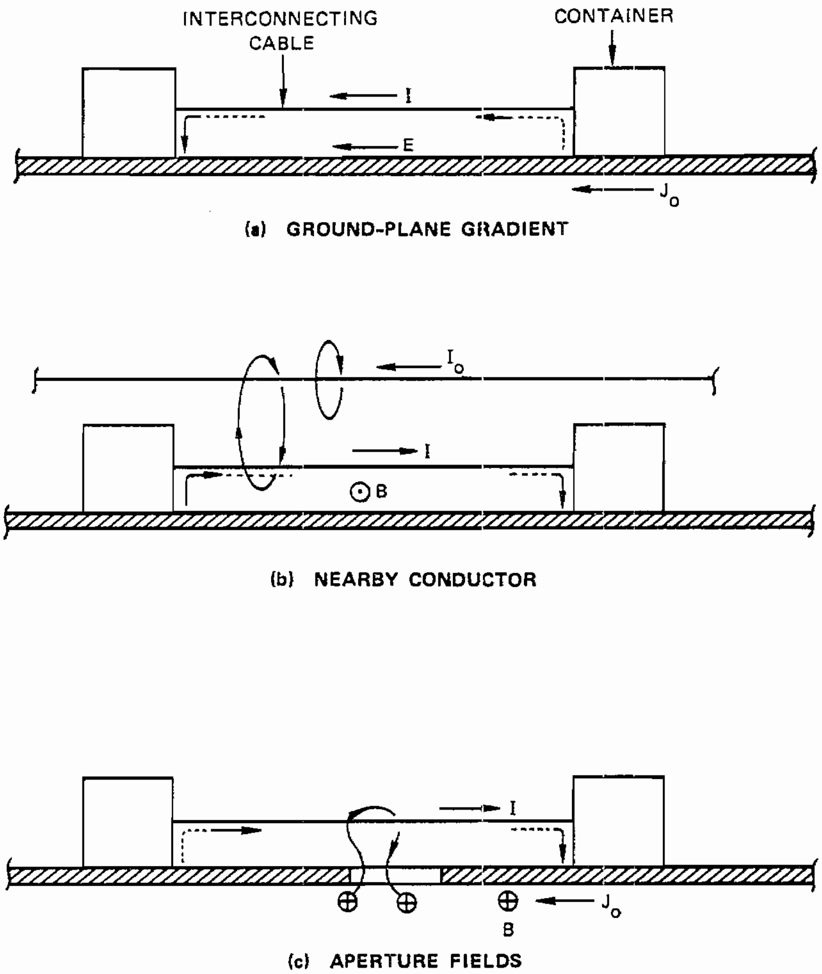
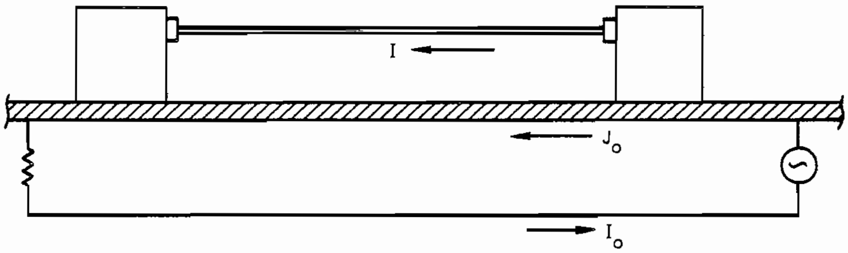


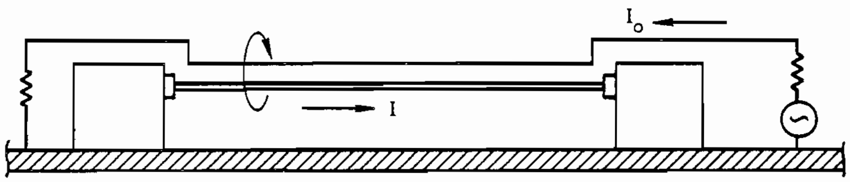
FIGURE 8 SYSTEM EXCITATION OF SECOND-LEVEL BARRIER

It should be emphasized, however, that although there are convincing arguments for performing qualification tests on individual items of equipment, such a test is much more complicated than the test of the interconnected system. The reason for the greater complication is illustrated in Figure 10 for the unshielded and the shielded interconnecting cable. For the equipment designed for unshielded interconnecting cable, the test must simulate the total cable current I and the wire currents I_1, I_2,...I_n. For this case, however, since the sum of the wire currents is the total current,

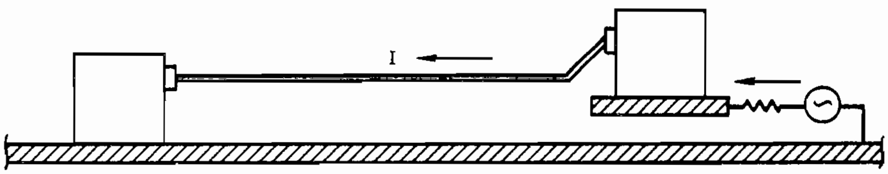
$$\sum_{i=1}^{n} I_i = I \quad ,$$



(a) GROUND-PLANE GRADIENT



(b) INDUCTION

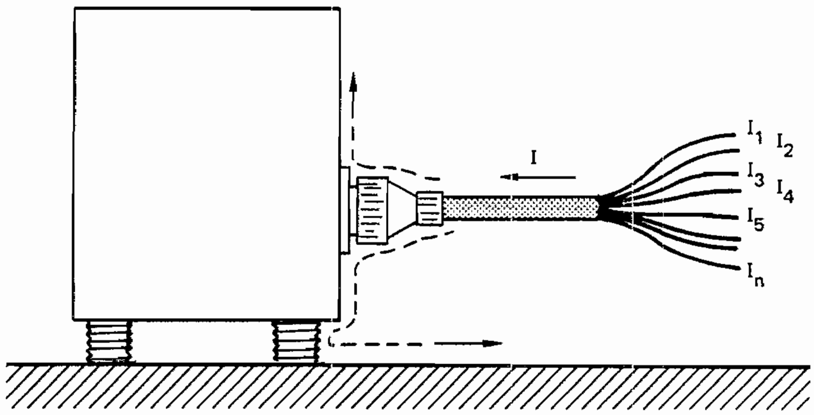


(c) CURRENT INJECTION

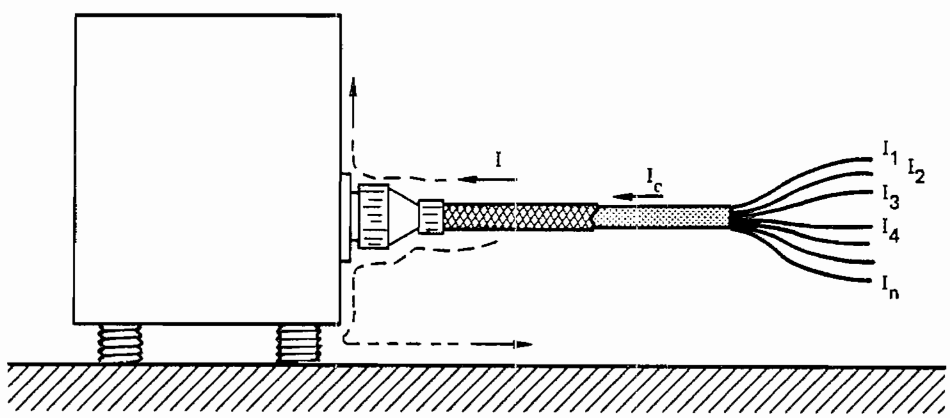
FIGURE 9 LOW FREQUENCY EXCITATION TECHNIQUES FOR SECOND-LEVEL BARRIER TEST

simulation of all wire currents simultaneously produces the total current. Thus, the individual wire currents (and their appropriate source impedances) must be simulated in the individual unit test, whereas only the total current needs to be simulated in the interconnected system tests illustrated in Figure 9; here, the cables are properly terminated and the individual wire currents will assume their operational values if the total current is correct.

The problem is slightly more complicated when testing individual items of equipment designed for use with shielded interconnecting cables. As illustrated in Figure 10(b), the test must properly simulate the shield current I, the total core current I_c, and the indi-



(a) UNSHIELDED CABLE



(b) SHIELDED CABLE

FIGURE 10 CURRENTS TO BE SIMULATED FOR TESTS OF INDIVIDUAL EQUIPMENT CONTAINERS

vidual wire currents I_1, I_2,...I_n. Again, the total core current is the sum of the individual wire currents,

$$\sum_{i=1}^{n} I_i = I_c \quad ,$$

so that accurate, simultaneous simulation of the wire currents automatically simulates the core current. This case is also different in that currents for two topologically separate regions must be produced; the shield current is outside the equipment shield, while the core wire and bundle currents are inside the equipment shield. Nevertheless, the interior currents I_i and I_c cannot be neglected because, in the operational system, they are generated in part by the leakage through the cable shield — a part of the equipment-level barrier.

For this discussion, we have deliberately chosen a simple unit with one multipin connector. Many practical units have several cables with multipin connectors. For a unit with k cables, the test problem is k-fold more complex, but as the individual wire currents sum to the core/bundle current, the individual cable currents sum to the total current flowing through the grounding hardware of the container mounting.

The added complication incurred by testing individual units rather than interconnected systems of units illustrates a maxim of system testing: the smaller the element of a system that is to be tested, the greater the understanding of the system required to determine the test conditions and interpret the test results.

One further comment regarding unit testing should be made. One of the strongest arguments for testing units rather than interconnected systems of units is that individual units may be used in several systems and with many different configurations of interconnecting cables. Therefore, one may argue that it is not possible to test the unit in all of its possible operational configurations. Yet the purpose of the qualification test should be to ensure that the unit will operate in all of the intended environments. Thus, a valid test must in fact simulate conditions equal to or worse than those that will be encountered by the unit in any of those environments. While it may not be practical to test the unit in all possible operational environments, it is necessary to understand the conditions that exist under these configurations and environments well enough to define valid test conditions. The burden of acquiring this understanding is the price of performing unit tests rather than tests of several interconnected system configurations. Failure to pay this price may result in an invalid test, which adds costs but not quality to the units tested.

C. INTERFERENCE CONFINEMENT: EMISSION CONTROL.

1. Interference Confinement Considerations.

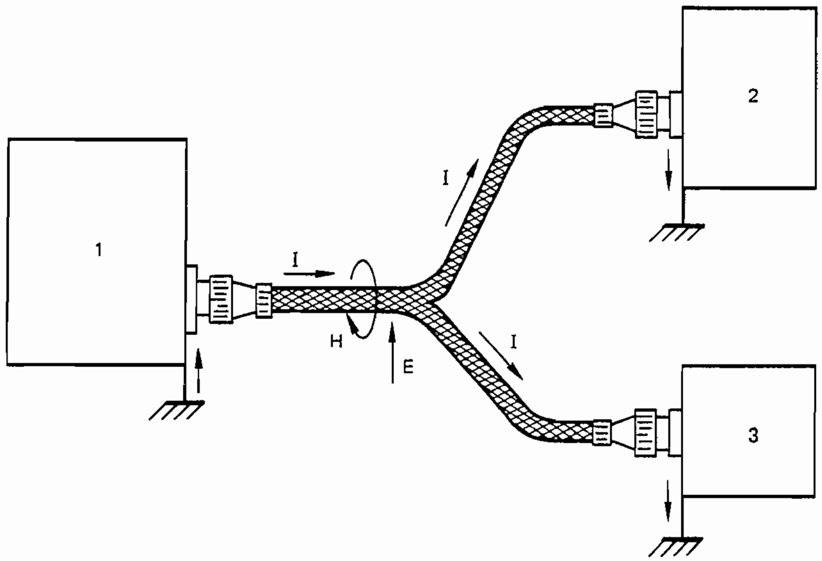
As stated in Section II-A, Condition (2) on the second-level barrier is that interference penetrating the barrier from the inside should be small compared to the ambient level of interference outside the second barrier (but inside the first barrier). That is, signals penetrating the shield from the inside should not significantly affect the environment outside the shield. As was discussed in Section II-A, the techniques for making an interference-confining barrier are identical to those for making an interference-excluding barrier if "inside" and "outside" are interchanged.

In fact, because the passive, linear barrier elements are often bilateral, most of the barrier that was designed to exclude interference will also serve to confine internally generated interference. The obvious exception is the class of conductor treatment devices that relies on nonlinear limiting. However, the nonlinear devices are chosen to limit the conductor voltages to values less than the voltage expected to exist outside the equipment shield (or else the devices would never function), and good design practice calls for a filter in addition to a limiter to suppress the frequency shifting and intermodulation effects of the nonlinear device. Thus, a well-designed barrier using a nonlinear limiter and filter will also function as either an exclusion or a confining barrier. In general, therefore, the problem of confining interference is identical to the problem of excluding interference (Section II-B-1).

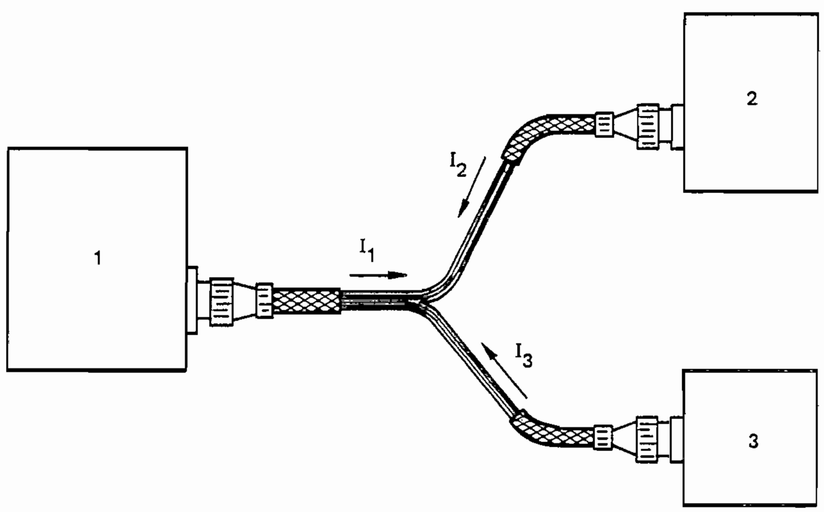
As illustrated in Figure 5, one goal of interference confinement is to prevent exceptionally noisy equipment from contaminating the system environment. Other goals include preventing electronic surveillance and providing secure communications circuits; however, the most common reason for concern about interference confinement is compatibility. It is important that none of the equipment units forming a system produce spurious signals that degrade the performance of other units in the system. Here an important distinction between desired signals and noise must be made. The signals produced or used by one unit are noise to any other unit that is not intended to receive and process those signals. Thus for a particular item of equipment, noise is any undesired signal (that is, any signal not required for input, control, or operating power), regardless of its origin.

The confinement role illustrated in Figure 5 relates to topologically separate units, each of which is surrounded by a closed barrier; interference produced by one unit must cross two barrier surfaces to reach sensitive circuits in the other. This topology is typical of items of equipment designed to be interconnected with unshielded cable, since each unit then contains its own closed barrier (Figure 4).

For units designed to be interconnected with shielded cable (or ducts), the confinement problem appears to affect two levels of environment. Figure 11 illustrates the interference penetrating the interconnected system shield. Although the shield has a more complicated shape when shielded interconnecting cables are used, the interference confinement



(a) PENETRATING NOISE



(b) PROPAGATING NOISE

FIGURE 11 PENETRATING AND PROPAGATING NOISE ideas and requirements are essentially the same as for the closed unit barrier case, that is, we wish to limit the interference that penetrates the barrier to a level that is insignificant compared to the ambient interference level outside the barrier.

As illustrated in Figure 11, however, there is also a concern regarding compatibility for signals that remain inside the equipment-level barrier, since the interconnecting cable conductors provide paths for signals (both desired and undesired) to propagate from one unit to another without penetrating the shield. However, this is not a system barrier problem in the sense of interference exclusion and confinement discussed previously. Topologically, this interference path along shielded interconnecting cable conductors is no different than paths within a unit along circuit board strips or between circuit boards on internal wiring, since the source coupling path and victim are all within the equipment-level barrier.

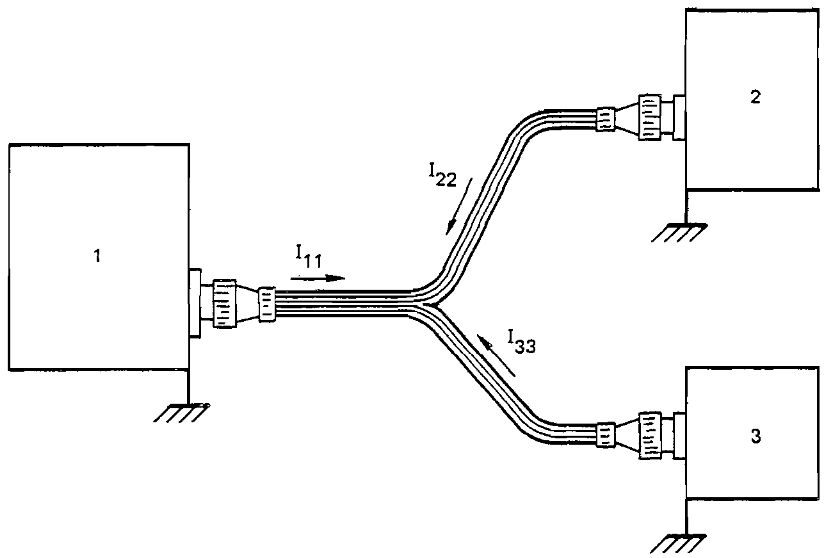
The control of interference propagating from unit to unit on shielded interconnecting cable conductors must therefore be regarded as a circuit design problem rather than a barrier problem (although, indeed, barrier concepts may be used within the equipment shield to control the circuit design). If units 1, 2, and 3 of Figure 11 are connected as shown, good design practice dictates that unit 1 should not produce spurious signals on the interconnecting conductors to degrade the performance of units 2 and 3. If all three units were produced by the same manufacturer, the manufacturer would certainly insist that the three units be compatible. Problems arising if the units are made by different manufacturers or are manufactured at different times should be handled by appropriate interface specifications. In the following discussions, therefore, only the penetrating interference will be considered.

2. Tests of Confinement.

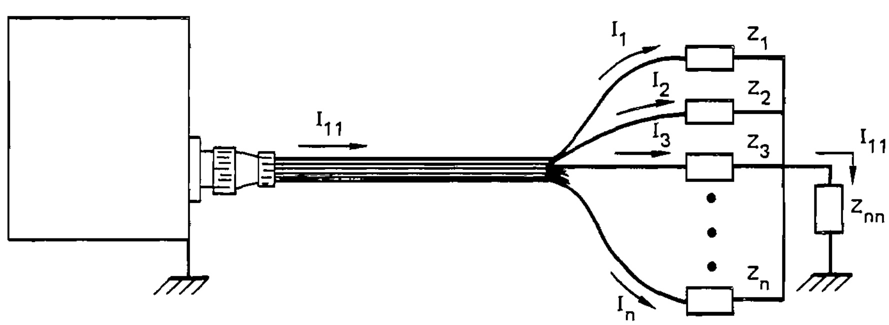
Testing the effectiveness of equipment-level barrier interference confinement is conceptually the reciprocal of that for interference exclusion effectiveness. The source of interference is inside the barrier and the controlled environment is outside the barrier. However, the source is the operating internal circuit in the confinement test, and the protected environment is the external cable and wire current at low frequencies and the ambient field strength at high frequencies. As was discussed earlier for the exclusion tests, the interference in the spectrum below about 100 MHz manifests itself as cable currents, while the spectrum well above 100 MHz may be manifested as propagating waves.

For units interconnected with shielded cable, the confinement test is quite simple if all of the interconnected units and cable are available. For the low frequency spectrum, the units are interconnected and energized, and the currents indicated in Figure 11 are measured. If only one unit — say unit 1 in Figure 11 — is available, units 2 and 3 must be simulated, both functionally and in impedance terminating the cable, to conduct the test. Still, only one current measurement per unit is required.

For units interconnected with unshielded cable, a much more extensive set of measurements is required because the individual wires (as well as the cable as a whole) are outside the barrier. Measurement of the cable currents illustrated in Figure 12 is essentially identical to that for shielded interconnecting cables. The individual wire currents



(a) CABLE CURRENTS



(b) WIRE AND CABLE CURRENTS

FIGURE 12 LOW FREQUENCY EMISSION TESTS FOR UNSHIELDED INTERCONNECTING CABLES are illustrated in Figure 12(b) for the case in which one unit is tested with a simulated cable termination. Since the wire currents I_1, I_2,...I_n depend on the terminating impedances Z_1, Z_2,...Z_n, and Z_{nn}, it is again important that the simulated termination have the same impedance as the cabling and units it replaces.

The measured cable and wire currents must ultimately be compared with the cable and wire currents that exist when the system is de-energized and exposed to the ambient operational environment. If the currents produced by the equipment are much smaller than the currents induced by the ambient environment, the equipment emissions are certainly acceptable. If they are not, better confinement, quieter circuits, or a more careful assessment of the Condition (2) emission criteria may be in order.

D. HIGH FREQUENCY CONSIDERATONS.

The specification and testing of meaningful high frequency interference immunity and confinement requirements has not been developed to the point that practical tests can be defined. If the system is viewed as an antenna (transmitting in the emission case and receiving in the susceptibility case), the logical measurement would be the antenna radiation pattern for reception (susceptibility) and the radiated power pattern when the system is energized. If one assumes that the system is installed on an infinite ground plane, the radiation patterns must be measured over the upper hemisphere illustrated in Figure 13.

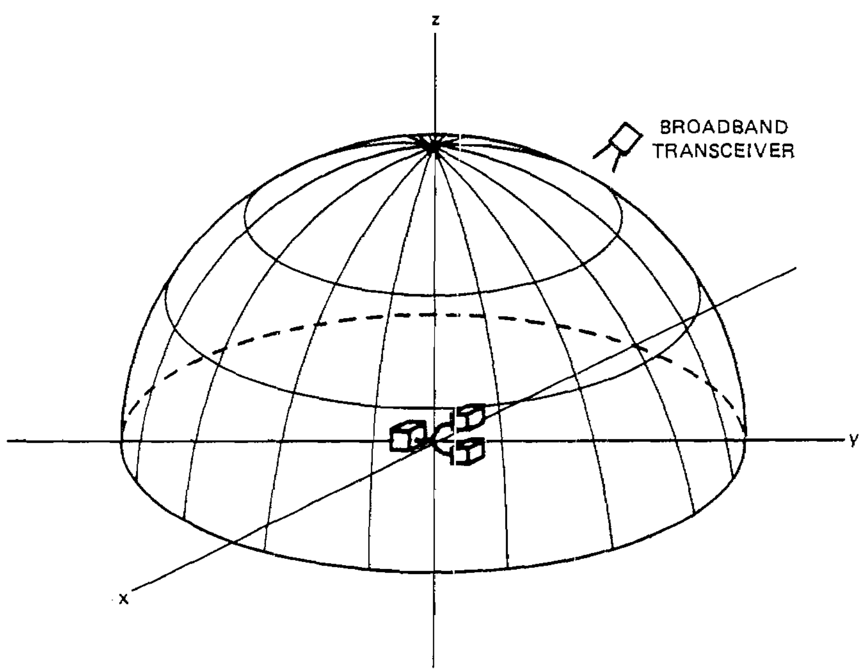


FIGURE 13 MEASURING SUSCEPTIBILITY OVER THE UPPER HEMISPHERE

The spatial grid over the hemisphere must be fine enough that no major lobes in the pattern are missed, and the frequency grid must be fine enough that no major resonances (poles or zeros) are missed. It is immediately apparent that performing such measurements for just one system configuration would be an enormous undertaking if the popular high-frequency range above 100 MHz to 10 GHz were covered.

Suppose for the moment that we can make these measurements. What can we do with them? If the measurements are made on individual units, as is often preferred, how can we combine the unit data to obtain system data? If we have data for the system mounted on an infinite plane, what can we say about the system installed inside an aircraft or rocket? At present, there are no practical answers to these questions. As a result, most of the specifications and tests for interference control at high frequencies do not provide data that can be used to predict system performance or guarantee interface compatibility.

III THE FIRST-LEVEL BARRIER

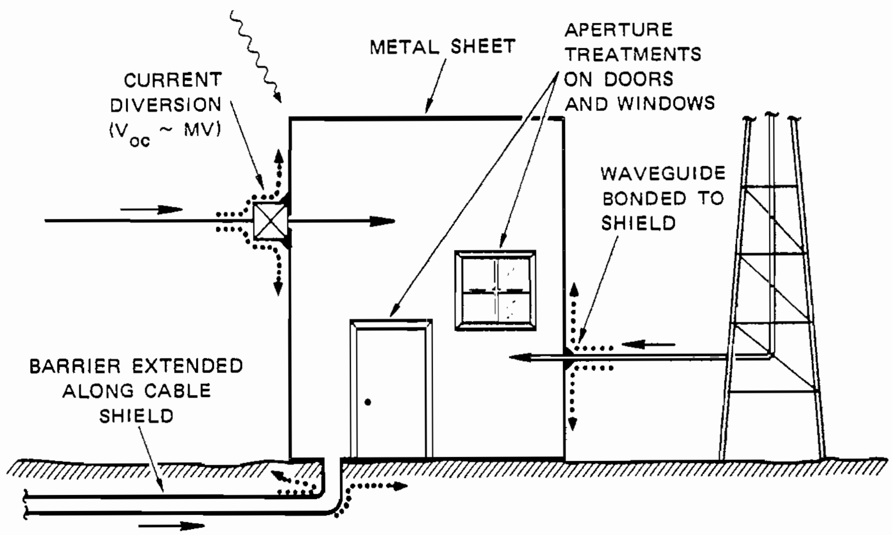
A. REQUIREMENT FOR BARRIER.

A first-level barrier is a topologically closed surface enveloping all of the protected equipment, its power supply, and its interconnecting cabling. The barrier must be sufficiently impervious to electromagnetic waves (space waves and guided waves) that the electromagnetic stress inside the first-level barrier is smaller than the threshold of the protected equipment (when the equipment is installed, cabled, and operating). The first-level barrier consists of the filters, surge limiters, aperture treatments, etc. as well as the intervening shield walls. The barrier may have any shape and it may be located at any position between the source and the protected equipment, so long as it is a topologically closed surface and sufficiently impervious to electromagnetic waves. Examples of first-level barriers are shown in Figure 14.

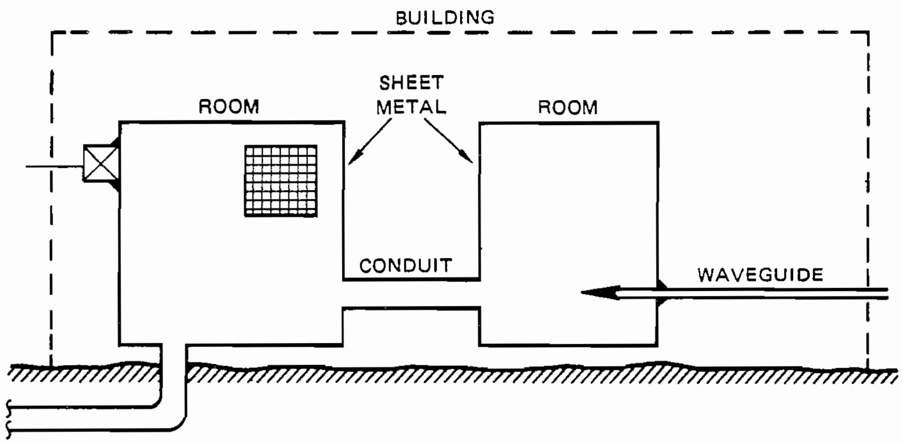
Although an immune system can be built without a first-level barrier, there are strong reasons for using a well-defined barrier if a facility contains moderately complex systems consisting of many interconnected equipment units. When a well-defined, effectively impervious facility barrier (which reduces the interference produced by external sources to a level that is negligible compared to the normal internal environment) is used, a detailed understanding of the response of the internal equipment and cabling to unusual sources such as lightning and the nuclear EMP, as modified by the facility, is not necessary.

Without the facility-level barrier to provide part of the protection, the equipment barriers must be designed to achieve a high degree of exclusion to cope with large external sources such as lightning and the EMP. Such high-performance barriers are difficult to maintain (or are easy to compromise). Furthermore, the amount of cabling and the number of insulated wire compromises inside the facility are usually much greater than at the facility level. This is because the external cables typically enter a distribution frame where they branch out to the many internal equipment units, and because there are many equipment interconnections within the facility. Thus, the number of treatments that must be installed and maintained is frequently much greater at the equipment level than at the facility level.

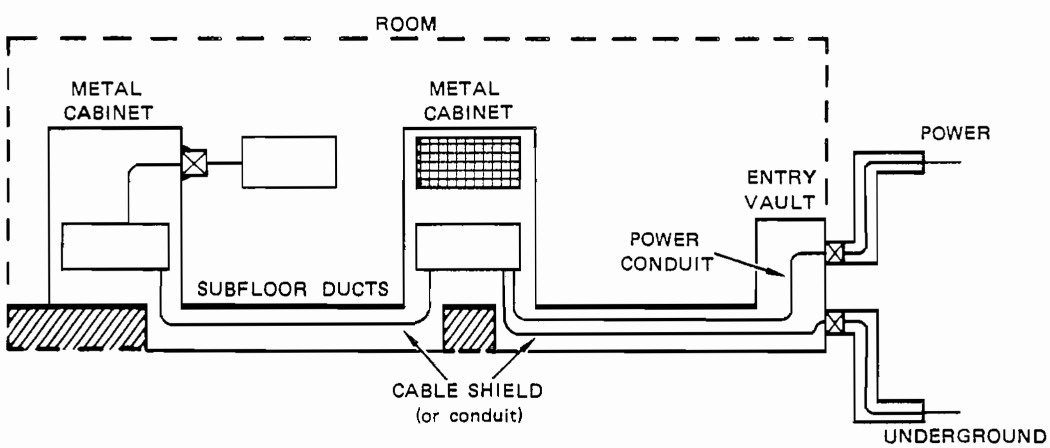
If shielded interconnecting cabling is used, many cables -- each up to tens of meters long -- and many multipin connector pairs must be maintained as high-performance shield components. These shield components may have to carry hundreds or thousands of amperes



(a) BARRIER AT FACILITY LEVEL



(b) BARRIER AT ROOM WALLS



(c) BARRIER AT CABINETS AND CABLE DUCTS

FIGURE 14 EXAMPLES OF FIRST-LEVEL BARRIERS without degradation of system performance. This implies that a thorough understanding of the detailed broadband electromagnetic behavior of this complex structure is possible, and that its behavior can be maintained during the expected life of the system.

The alternative of using pin protection at the equipment input/output terminals implies that many protective devices must be added to each unit. Without a facility barrier to reduce the large transients of external origin, these devices would probably have to be high performance, surge-limiter/filter combinations that can handle moderate energies and reduce kiloamperes of external current[5] to tens of milliamperes of internal current. Such devices are expensive, require additional space in the equipment housing, and add a nonlinear element to the already difficult problem of understanding the performance of the system.

Without a first-level barrier, an adequate susceptibility test of the system is very expensive and difficult to design. Because the system response is very complex and involves external lines (such as power lines and communications cables) as well as internal cabling, an adequate test requires simultaneous excitation with large-volume wave generators and current injection. Such a test must be conducted for each of the many angles of incidence that are to be simulated. Also, an adequate test requires sufficient wave and current injection to evaluate the important characteristics of each receptor, as well as requiring a thorough understanding of how the receptors interact with each other and the (nonlinear) system elements for all angles of incidence (over a broad bandwidth). Such a thorough understanding can rarely be developed unless the system configuration is very simple. For this reason, a facility-level shield is advantageous in that it makes the electromagnetic configuration of the system simple enough that its interactions can be understood with reasonable confidence.

There are other advantages to using a simple facility-level barrier to control external sources. For example, such a barrier will also confine system signals, making it easier to meet TEMPEST and other requirements that impose limits on intelligible signals detectable outside the facility. As has been noted earlier, future changes of equipment or layout can be accomplished without expensive reassessment and test of the protection system, since the internal equipment is only required to tolerate the moderately benign internal environment. (However, this ambient facility environment is much more severe than the small-signal environment required inside the equipment case; see Figures 2 and 5, and Section I-D.)

B. ENVIRONMENT INSIDE BARRIER.

In Section I, it was stated that the upper limit on protection provided by the facility-level barrier is the protection that causes internal interference of external origin to be small compared to internally generated interference. In Appendix D, some of the factors believed to be important in making a quantitative estimate of the internally generated interference level are discussed. This interference level is very important because:

(1) It is interference the equipment must tolerate routinely.

(2) It determines the maximum effectiveness required of the facility-level barrier.

This interference level lies between the very rough bounds of the circuit operating signal level and the external lightning- and EMP-induced signal levels.

Let us first identify the sources of the ambient interference to which the unprotected equipment will be exposed. The major sources of fair-weather, peacetime interference are believed to be:

(1) ac power switching and processing

(2) dc power switching and processing

(3) Circuit generated signals associated with digital electronics, transmitters, modulators, etc.

(4) Man-made noise generated in the near surroundings

(5) Atmospheric noise

(6) Thermal noise.

These sources are listed roughly in order of their importance, that is, ac power switching and processing is usually the source of the largest transients. There are, of course, many weak sources comparable to thermal and fair-weather atmospheric noise, but because these do not influence the facility barrier design they have not been included. Note also that sources (4) and (5) are produced externally and will be reduced by the facility barrier. Therefore, those classes of interference that are significant inside a facility with an effective barrier are (1), (2), and (3): the ac power, the dc power, and circuit-generated signals.

In Appendix D, it is shown that transient voltages having peak values comparable to the peak ac supply voltage will occur routinely inside a facility as a result of electric circuit switching and cyclic equipment regulation (air conditioners, water heater, etc.). Much larger transients, perhaps up to 10 times the peak supply voltage, may occur if untreated relays, solenoids, or other inductive loads in the facility are switched. Transient peak currents 1 to 10 times the steady-state load currents of the facility appliances may occur from routine operation of these appliances.

These currents and voltages are characterized by very fast risetimes; hence, they contain energy throughout the spectrum below 100 MHz, in which interference propagation along wires and cables is efficient. In the high-frequency portion of this spectrum, inductive coupling between power wiring and signal and control wiring is also efficient. Therefore, it is believed that this interference will be manifested primarily as currents and voltages on cabling inside the first-level barrier.

In addition to these transients that occur at least several times per day, there are lower level, but more or less continuous, sources of interference such as fluorescent lights and rectifiers. Interference from these sources affects the signal-to-noise ratio on the signal conductors, but it is not usually a factor in determining the barrier effectiveness required to control externally produced transients such as the EMP and lightning.

For typical digital electronics circuits, signal levels range from a fraction of a volt to about 10 V. Therefore, spurious interference of about this magnitude may be generated by these circuits. High-power transmitters for communications and radar systems may produce large signals over a limited band of the spectrum. However, these signals are usually produced inside the equipment barrier; due to the bilateral characteristics of the equipment barrier, the signal levels inside the facility barrier but outside the equipment barrier should be much smaller than these circuit-level signals.

C. INTERFERENCE IMMUNITY.

1. Achieving Immunity.

Interference immunity will be achieved when the first-level barrier is sufficiently impervious that the internal effects produced by external sources are less than the threshold of internal equipment. To achieve an impervious barrier, one must first define the topologically closed surface along which the barrier will be established, and then apply barrier components to this entire surface so that a closed barrier surface following the topologically closed surface defined in the first step is established.

While the barrier may be made up of various interference-reducing or interference-rejecting devices and techniques, ease of maintenance and testing are achieved if the bulk of the barrier surface is metal sheet or plate. Metal plate is so impervious to interference above a few kilohertz that leakage through those portions of the barrier made up of continuous plate is negligibly small compared with the leakage through essential weak areas such as cable penetrations, equipment and personnel access doors, ventilation windows, etc. Obviously, a metal surface is also easily identified; there is no uncertainty as to its location.

The essential (and weak) areas — the power and communications cable penetrations and openings for people, equipment, and air — can be treated at the first level in much the same way as has been described for the second-level barrier, except that high-impedance or current-interrupting treatments are not recommended for long insulated conductors penetrating the first barrier. Because open-circuit voltages of megavolts are possible on overhead power and communications lines, current interruption devices must be designed and maintained to hold off these voltages. High-voltage component design and maintenance is more expensive and usually less reliable than the short-circuit approaches to penetration treatment.

Some features of a first-level barrier are illustrated in Figure 14(a). Note the low-impedance current diversion on the overhead line, the use of metal sheet for the principal barrier surface, and the extension of the barrier along the shield of the underground cable. Also note that the waveguide should be bonded to the metal sheet barrier (i.e., made electrically continuous with the wall), not grounded (connected to earth through a cable).

It was noted in the discussion of the equipment-level barrier that currents induced on the long interconnecting cables were the primary source of low-frequency excitation of the equipment cabinets. Likewise, the currents propagating onto the facility walls from long external conductors (such as power lines, waveguides and cables from the radio towers, and buried communications cables) are the major sources of low-frequency excitation of the facility shield (except when the facility is subjected to a direct lightning strike).

Consider, for example, the current densities induced by a 50 kV/m exponential pulse similar to the high-altitude EMP. The incident magnetic field intensity is 133 A/m, and the current density induced in a large flat wall of metal is about 270 A/m. The current induced on an overhead power line by this incident field is as large as 10 kA. If this current is distributed uniformly over the girth of a building 3 m high and 10 m wide, the current density will be 385 A/m — not significantly larger than that induced directly by the incident wave. However, in the vicinity of the service entrance where the surge arrestors and filters are diverting this current to the wall, the current density can be as high as 50 kA/m (for 3-in. conduit). Thus, even when the cable current is most optimistically dispersed, the shield excitation is comparable to the direct wave excitation; however, since the current is always concentrated on the wall the cable penetrates, the excitation of that wall by the cable current is much greater than by the direct wave.

This observation is important in the design of a shield and in the method of testing the shield. Since the strongest excitation is in the vicinity of the cable penetrations, it is important that the barrier be as nearly flawless as possible in the region where the cables penetrate. That is, the wall and entry panel in this region should be conservatively designed, and apertures or other compromises should be excluded from the cable entry region. When possible, all cables and other external conductors should be concentrated in this conservatively designed region so that the large currents cannot flow across the entire barrier surface but rather must enter and leave in the same general region. This is the single entry panel concept often recommended for EMP hardening.

2. Immunity Tests.

The purpose of an immunity test of the first barrier is to determine if the barrier reduces the internal interference caused by external sources to a level smaller than the threshold of the equipment. Although equipment immunity tests of at least a type-qualification nature are commonly performed, such tests are not commonly specified for the facility-level barrier. Systems with an EMP hardness requirement are usually tested in some way, but this testing is frequently part of a research and development program rather then a qualification program. Aircraft and rockets are also tested with simulated direct lightning strikes, but traditionally this test is to ascertain mechanical integrity rather than electromagnetic interference immunity. Only recently has the interference immunity aspect of lightning testing been pursued.

Although it does not meet the requirements of an interference immunity test, MIL-STD-285, "Attenuation Measurements for Enclosures, EM Shielding for Electronic Test Purposes, Method," has been used to "evaluate" facility-level shields, airframes, and transportable shelters. The test is not performed with the operational configuration of the equipment, and the parameters measured are not easily related to the system response for a specific stimulus. As a result, the MIL-STD-285 tests are of limited value and are not recommended as an interference immunity qualification test.

The recent interest in lightning transient analysis and the maturing of EMP hardening studies as an engineering discipline have intensified interest in facility-level barrier tests of a type-qualification nature. However, at present there are no standard methods for performing these tests. Nevertheless, it is clear that the tests should provide solid evidence regarding whether or not the facility performance will be degraded by the external environment. Therefore, the test must either (1) simulate the external environment, (2) simulate the effects of the external environment on the barrier, or (3) provide fundamental data from which the system response can be readily, accurately, and confidently calculated.

Large area-of-coverage sources such as the high-altitude EMP cannot be economically simulated over all parts of the system that contribute to its responses due to the sheer volume and energy required to cover the facility and all power line and cable routes. In addition, the ability to accurately predict the system response from fundamental data is limited by the unknown broadband properties of 60 Hz equipment and of plumbing, mechanical, and structural equipment, as well as by uncertainties in nonlinear devices, unknown nonlinearities, nonuniform materials (soil and concrete), and many other factors. On the other hand, the number of possible coupling modes in a large, complex facility is so great that measuring all elements of the coupling matrix accurately and with proper accounting for nonlinearities is an extremely difficult task -- probably not a task whose results can be accepted with high confidence. Simulation of the effects of the external environment on the barrier can be done economically only if the barrier surface is well defined, as would be a metal shield with a few easily identified penetrating conductors and apertures. Currents on the long external conductors are the principal external excitation of a shielded facility; if these currents can be simulated, the response of the facility to the external environment can also be simulated. This approach is desirable because the current induced in the long conductors can be accurately predicted for most environments, and the excitation energy that must be provided is about equal to that delivered to the system by the environment. In contrast, much more energy is required if the energy density in the volume about the facility must be equal to that of the environment, since only a small fraction of the energy in this volume is actually delivered to the system.

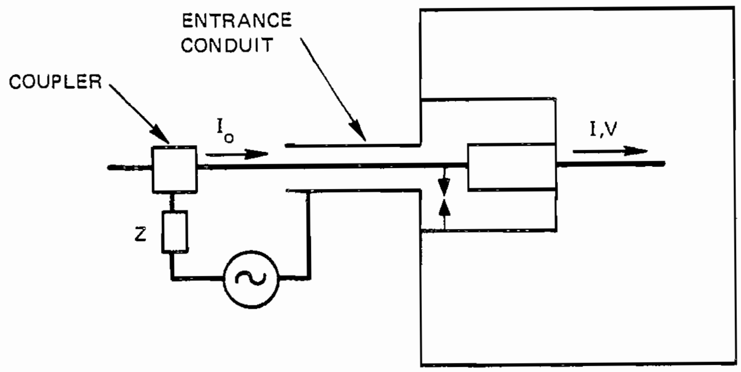
However, the validity of the current injection approach depends on the ability to produce proper excitation of the barrier by injecting current on the long appendages. Generally this requires that the barrier be substantially impervious everywhere except at the conductor penetrations and a few other openings. If the barrier is a metal shield everywhere except where necessary power and signal cables penetrate (and perhaps at a few essential apertures), the major weaknesses of the barrier will be the penetrating conductors themselves, and the largest interference of external origin inside the barrier will be the currents or voltages propagating inward on these conductors (that is, the conductor current and voltage that bypass the surge arrestors and filters used for the barrier).

Therefore, a low-frequency test of the facility-level barrier must test the effectiveness of the penetrating conductor treatments and any other barrier weaknesses in the vicinity of these or other long external appendages. This implies (1) that the external excitation should be the current and voltage on the exterior portions of the long external conductors, (2) the internal response should be the current and voltage on the interior portions of the penetrating conductors as well as the current and voltage on interior cables that have no direct connections to exterior conductors, and (3) the excitation should be large enough to activate any nonlinear devices that will be activated by the expected external environment. The test should also be performed with an excitation level that is just below the threshold of the nonlinear devices, since this level of excitation sometimes produces the largest response through the barrier.

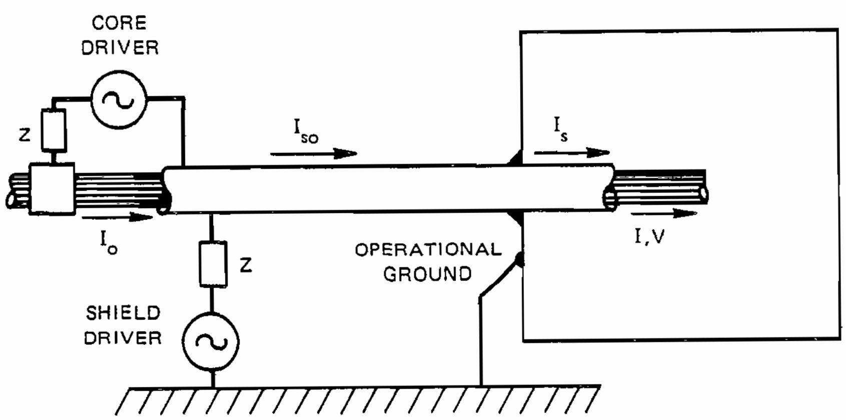
Typical current injection schemes are illustrated in Figure 15. The excitation source consists of a voltage source with its series source impedance Z, and a coupler to connect the source to the penetrating conductors. For excitation, power lines (and other unshielded external conductors) can be driven against the service entrance conduit or cable shield as illustrated in Figure 15(a). Since the power conductor and conduit are both external conductors, this test actually only excites the surge arrestor, filter, and the limited portion of the shield in the vicinity of these components that is most strongly excited by an external environment. A second test in which the conduit is driven against the soil or the facility grounding electrode is necessary to test the entry panel and wall outside the conduit. The effectiveness of the barrier can be quantified as ratios of the internal current I and voltage V produced by full-scale excitation to the internally generated currents and voltages at the same points.

For shielded cables, the two excitation modes are illustrated in Figure 15(b); the cable shield may be driven against the earth or the core conductors may be driven against the shield. If the cable shield is properly terminated in a facility shield at each end, the core conductors are topologically inside the first barrier, so that the core conductor excitation is not a proper external excitation. Nevertheless, this test may be desirable because long external cable shields, splices, and terminations may be weak barriers, and it is usually much easier to test the terminal protection on the cable conductors by driving them directly than by driving the cable shield. The effectiveness is again quantified as the ratios of the conductor voltage V and current I produced downstream of the protection to the internally generated current and voltage.

For external cables, the true barrier test would be one in which current is injected onto the cable shield (or conduit) and flows along the cable, through the splices and terminating junction, through the facility shield, and back through the soil to the source. For high energy tests that simulate lightning or the EMP, very large currents are required to excite the system to the environmental levels. Nevertheless, this excitation and test are required to qualify the system for operation in the lightning and EMP environments. The test may be conducted in a stepwise manner to alleviate some of the burden on the exciting source. Thus, the spliced cable shield and termination hardware may be tested separately and individually. The facility can then be tested with the "shield driver" current injection on a short segment of cable [Figure 15(b)].



(a) POWER ENTRY



(b) SHIELDED CABLE ENTRY

FIGURE 15 EXCITATION OF FIRST BARRIER WITH CURRENT INJECTED ON LONG CABLES

In all of the current injection tests, the impedance Z of the source (which, we may assume, includes the impedance of the coupling device between the source and the system conductors) must be large compared to the system impedance, if the source impedance is not to affect the system response. For simulating lightning and the EMP on high-impedance overhead lines, this requirement poses a serious problem. If the line impedance is of the order of 300 Ω, the source impedance should be of the order of 3 kΩ. Thus, to simulate an open-circuit voltage of 3 MV, a source voltage of 30 MV would be required. Obviously this constitutes a serious problem in simulator design and procurement.

However, if we examine the test requirements more carefully, we observe that these lines are usually provided with spark-gap surge arrestors that fire at a few kilovolts. After the surge arrestor fires, it behaves somewhat as a voltage regulator; the most important parameter, then, is the current delivered to the surge arrestor. Thus, as illustrated in Figure 16, it is necessary to simulate the proper impedance and voltage for these protected lines only until the surge arrestor fires; thereafter, only the current need be simulated.

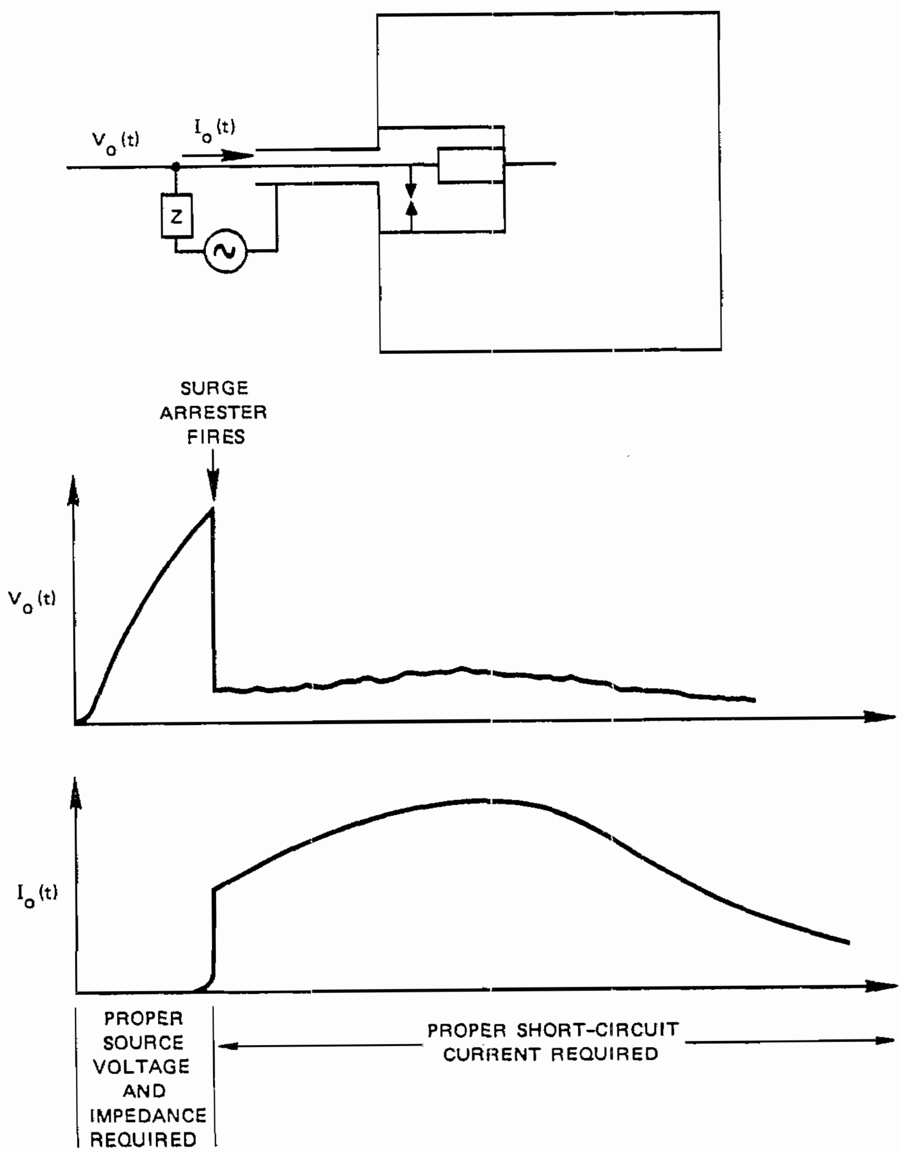


FIGURE 16 EXCITATION OF NONLINEAR PROTECTORS

D. SIGNAL CONFINEMENT.

At the facility level, the only interference confinement testing currently performed is intended to ascertain that the system will (1) prevent the compromise of secure communications, or (2) prevent the emission of electromagnetic signatures that can be used for locating the system. For either of these purposes, it is necessary that the barrier be sufficiently impervious that internally generated signals penetrating the barrier are small compared to the noise level outside the barrier.

Two important aspects of this problem are the noise level outside the facility and the means by which the internally generated signals penetrate the barrier. As is the case for interference penetrating the facility from the outside, the dominant path for signals escaping the barrier is along insulated conductors that penetrate the shield. Therefore, a measure of internally generated signals on the exterior conductor is an indication of the confinement capability of the barrier. Furthermore, because these exterior conductors usually carry large noise currents from natural and man-made sources in the vicinity, the signal-to-noise ratio on these conductors should be indicative of the detectability of the internally generated signal.

While one may argue that detection of the radiated wave far from the facility must also be prevented, such radiated fields for a well shielded facility are produced mainly by radiation from the external conductors. Thus, the signal-to-noise ratio on the conductors (for a given narrow bandwidth) should be equal to or less than the signal-to-noise ratio in the radiated field, and measurement of the signal on the conductors outside the facility should be equivalent to measurement of the distant radiated field.

An appropriate test for signal confinement is thus a measurement of the current on the external appendages to the facility barrier. This test should be performed with operational external conductors (power lines, communications cables, grounding conductors, metal piping, etc.) and with an operational system energized and performing its normal functions (Figure 17).

The criterion for acceptance should be the inability to detect specified internally generated signals outside a specified physical security area. The detectability of the signals may be specified as a maximum signal-to-noise ratio in a specified bandwidth. The physical security area may be congruent with the barrier, or its borders may be outside the barrier.

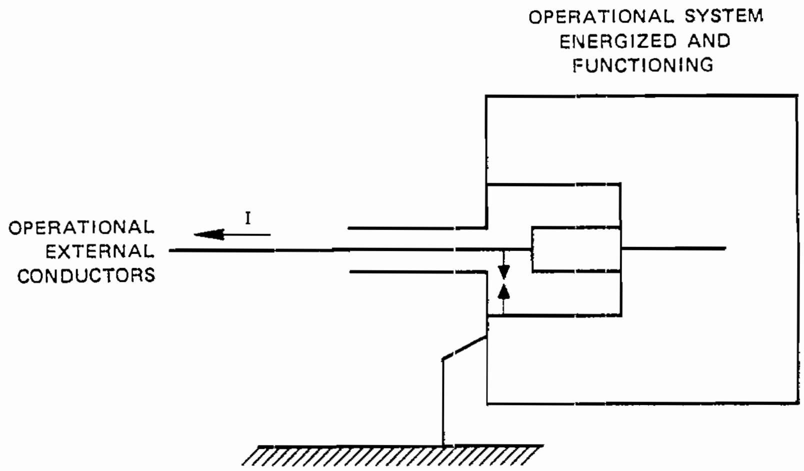


FIGURE 17 SIGNAL CONFINEMENT TEST

E. HIGH-FREQUENCY TESTS OF THE FIRST-LEVEL BARRIER.

As was pointed out in Section II-D, specification and testing of meaningful high-frequency interference immunity and signal confinement requirements have not been developed to the point that practical tests can be defined. The difficulty is that unique properties of the system that can be measured and used to predict system performance in a variety of environments have not been identified. Radiation patterns for emission and reception of high frequencies satisfy the uniqueness criterion, but it would be impractical to obtain sufficient radiation patterns of a system throughout the high-frequency spectrum between a few hundred megahertz to 10 GHz in order to define its performance. Several thousand radiation patterns would be required to define each system and, because the patterns for a system are affected by the external conductors, the patterns for one system would not necessarily be applicable to another, supposedly similar system installed in slightly different surroundings. For these reasons, no basis for evaluating the high-frequency characteristics of the first-level barrier has been identified.

IV GROUNDING, BONDING, SHIELDING (GBS)

A. INTRODUCTION.

Review of the specifications and standards revealed one widespread problem: the definition of the terms grounding, bonding, and shielding were almost always blurred; in fact, sometimes one term was substituted for the other. While the three terms are intimately related, each has a distinct meaning. We consider this point to be of great importance, especially since the misuse of the three terms is so widespread.

Accepted definitions of grounding, bonding, and shielding are presented below, as are some of the practical aspects of the function each term describes. To implement the rational approach to interference control discussed in previous sections, a clear concept of each function is vital. We cannot emphasize enough that strict adherence to definitions is mandatory to achieve effective and compatible interference control.

1. Grounding.

The National Electric Code (NEC) definition of grounding is as follows:

> "Grounding: A conducting connection, whether intentional or accidental, between an electric circuit or equipment and the earth, or to some conducting body that serves in place of the earth."

From studying the NEC and other documents such as IEEE-STD-142, it becomes clear that the primary goal of good grounding practices is safety for personnel, equipment, and buildings. Note that grounding is not necessarily a connection to earth.

2. Bonding.

Good grounding and shielding practices depend on good bonding. Of the three terms, bonding is perhaps the easiest to define and understand. The NEC defines bonding as follows:

> "Bonding: The permanent joining of metallic parts to form an electrically conductive path which will assure electrical continuity and the capacity to conduct safely any current likely to be imposed."

Thus, bonding means nothing more than making a good connection. The last qualification stated in the definition is especially important where the conductive joint provides a path for fault currents to flow. If the bond disintegrates in the event of a fault before the circuit breaker can be tripped, the fault-clearing circuit cannot perform its function. In addition, if the bond of a waveguide corrodes, it may then provide a path for RF to leak into a region from which it was to be excluded.

Therefore, good bonding practices are essential in interference control. We have not found any incompatibilities directly related to poor or misapplied bonding. However, we have found numerous instances in which the term was incorrectly used; e.g., bonding was specified where grounding was meant. Such misuse is not beneficial for good interference control practices.

3. Shielding.

To define a shield, we present the definition given by the IEEE in 1955:

> "A shield is material used to suppress the effect of an electric or magnetic field within or beyond definite regions."[8]

Inside a closed, perfectly conducting shield there is no evidence of an external electromagnetic event. Shielding is a valuable interference control technique, as was discussed in Sections II and III. However, as discussed earlier, for a barrier containing a metallic shield to be effective, it is important that the barrier be closed.

In summary, grounding is an electrical safety procedure used to prevent hazards associated with electrical faults, equalize potentials of nearby objects, prevent static charge buildup, and thereby provide safety for equipment and personnel. Bonding is the means of establishing a good electrical (and mechanical) connection. A closed shield can separate electromagnetic environments and serve as part of an electromagnetic barrier. A distinction between the three terms must be made, especially since they are so intimately related. Interference control problems can be solved in an effective manner when compatible techniques are used, and when grounding, bonding, and shielding are applied where they are needed.

B. PRINCIPLES OF GROUNDING.

With the development of the first National Electric Code in 1897 (it has been sponsored by the National Fire Protection Association [NFPA] since 1911), the importance of proper grounding was recognized in connection with the growing usage of electrical power. A particularly clear discussion of proper grounding practices is given in IEEE-STD-142, "Recommended Practice for Grounding of Industrial and Commercial Power Systems" (now adopted as an American National Standard ANSI-C114.1), and also in IEEE-STD-141, "Recommended Practice for Electric Power Distribution for Industrial Plants." Personnel working in and around an electric power distribution station must be protected from the high voltages and currents involved. Proper grounding does enhance personnel safety because a fault current path is provided by the connection to ground. Grounding can equalize potentials of nearby objects, prevent static charge buildup, and provide a path for fault or lightning currents.

1. Fault Current Paths.

The earth is a poor conductor, but it plays an important role in providing a path for fault currents in the distribution system. Beginning at the power station and proceeding to the individual service entrances, it is now established practice to connect the neutral to earth ground. The advantage of this scheme is that when a phase conductor becomes shorted to ground, a large current will flow in the phase conductor. If the system is designed properly, the fault current will be large enough to trip a circuit breaker, remove power from the faulty circuit, and thereby prevent the hazards associated with faults at distribution voltages (5 to 30 kV).

Connecting the consumer's neutral to earth ground is intended to prevent hazards in the event the distribution voltage is applied to the low voltage circuit (e.g., through a faulty transformer). If an earth electrode resistance to earth is to be specified, it should be related to the distribution voltage and the distribution circuit trip-current, neither of which is related to the consumer. The NEC states (Section 250-84): "A single electrode...which does not have a resistance to ground of 25 Ω or less shall be augmented by one additional electrode..." The resistance to ground of the pair of electrodes is not specified.

In providing a path for the consumer fault current in the low voltage wiring, the resistance of the ground rod is unimportant. What is important is that any grounding conductor (i.e., the green wire) have a low resistance between any exposed metal of electrical appliances and the neutral ground point. In this case, we can specify how low that resistance has to be. Assume, for the sake of illustration, that an electric motor is some distance away from the service entrance, and that the case of the motor is (ultimately) connected to the point where the neutral is grounded at the service entrance. If the full voltage normally supplied to the motor is applied to the case, the resistance of the fault-clearing circuit must be low enough that the increase in current is sufficient to trip the circuit breaker providing power to the motor. This will promptly clear the fault (de-energizing the potentially hazardous circuit). Thus, the earth electrode resistance does not enter into safety considerations inside a facility.

2. Lightning.

Lightning, one of nature's most powerful phenomena, involves potential differences of the order of megavolts; peak currents of many kiloamperes result during the lightning strike. Grounding provides a current path to earth in order to safely conduct the high currents involved. We therefore should have a conductor from the lightning rod(s) to earth of sufficient size, as well as a low-resistance connection to earth. However, because of the transient nature of lightning it is not the resistance, but rather the inductance, of the connection to ground that will dictate to what potential the ground point will rise. In practice, this impedance cannot be made low enough to avoid dangerously high potentials during a direct strike. A lower impedance is always better than a higher one, but even a so-called 1 Ω ground rod will have a potential of thousands of volts during a direct lightning strike (typical peak currents are 20 kA). This dilemma is recognized by the Lightning Protection Code (NFPA-78). Appendix B of this code states, "...low resistance is desirable, but not essential..." and goes on to discuss two examples; one example concerns a building resting on moist clay soil where the achievable ground rod resistance might be from 15 to 200 Ω ("...two such connections have been found to be sufficient..."), and the other example is of a building resting on bare solid rock. In this case, no good connection to earth can be made, yet safety can still be provided by other means.

There is the question of the safety of personnel working near the earth ground connection, especially personnel working outside during a thunderstorm. It would appear attractive to lower the ground rod resistance, by whatever means, to a very low value, say to 1 Ω or less. Would this not result in a lower potential rise of the ground point during a lightning strike? Indeed it would; however, because peak currents are frequently 40 kA and more, the potential of the ground rod would still rise to many thousands of volts, which could hardly be called a safe potential. There is currently no practical way to achieve a sufficiently low earth electrode impedance to keep the potential rise during a lightning strike within safe limits.

To summarize, a good low-impedance connection to earth is desirable where lightning protection is important, but it is not meaningful to require (as many of the standards do) a 1 Ω or even a 10 Ω ground-rod resistance. These requirements, which are difficult to meet, add nothing to the safety of personnel and equipment, but they do add to the cost of a facility. Good grounding practices to protect against the effects of lightning are discussed in the references mentioned. The impedance to earth of the earth electrode system is only one aspect of the protection system; another important one concerns step and touch potentials, especially near high-voltage distribution systems. However, this is rarely discussed in electromagnetic specifications and standards. An exception are the IEEE standards mentioned above, and a good discussion on this subject can be found in IEEE-STD-142.

3. Interference Control.

It is apparent that grounding cannot reduce interference, provide an infinite current sink, or prevent the potential rise of an earth electrode due to a lightning strike. However, it is popularly believed that one can "ground out" interference; therefore, a shield will be "grounded" when, in fact, it should be "closed." While poor grounding practices may aggravate an interference problem, grounding per se is not a tool for interference control. We need only recall the basic concept of interference control: the impervious barrier between the source and the protected circuit. It is difficult to imagine how grounding can be used as an element of the barrier. However, it is easy to violate a barrier by passing an insulated grounding conductor through it.

One of the incompatibilities found most frequently in the standards and specifications reviewed (Appendix A) is the penetration of a shield by a ground conductor. The NEC does not require a ground conductor to penetrate a cabinet or a shield. All that is required is a low-impedance connection to the ground point at the service entrance. It makes little difference whether the ground is connected inside or outside the cabinet for dc or low frequencies, but for high frequencies and transients, the location of the ground connection is significant (Figures 18 and 19). At high frequencies, the skin effect forces currents to flow on the surface of conductors, and the connection made inside the cabinet will also introduce all the undesirable high-frequency noise. For safety reasons, it is clearly unnecessary to carry the ground conductor through the cabinet (if the cabinet is not metal it need not be grounded); a better approach is shown in Figure 20. This approach is compatible with all electromagnetic interference control disciplines, and with safety considerations as well. We cannot emphasize enough that grounding conductors should never penetrate barrier surfaces.

Since an electromagnetically compatible grounding scheme such as the one illustrated in Figure 20 can be used, the requirements for a particular grounding electrode impedance for interference control purposes are baseless. Furthermore, making the system performance independent of the earth electrode impedance is strongly desirable inasmuch as the available soil conditions range from mountain granite to salt marsh and from permafrost to desert sand. Requiring a controlled electrode impedance under a wide range of conditions that are not under the control of the designer is as illogical as it is unnecessary, since the cost is significant but the benefit is nil.

Of course, if one insists on violating the system's interference control barriers with grounding conductors that connect signal common to the earth electrode, then control of the grounding conductor impedance is necessary. The required value is 0 Ω; however, achieving even a 1 Ω approximation to this impedance is not possible with the range of "earth" types noted above. Again, the cost of making this connection is significant because of the added

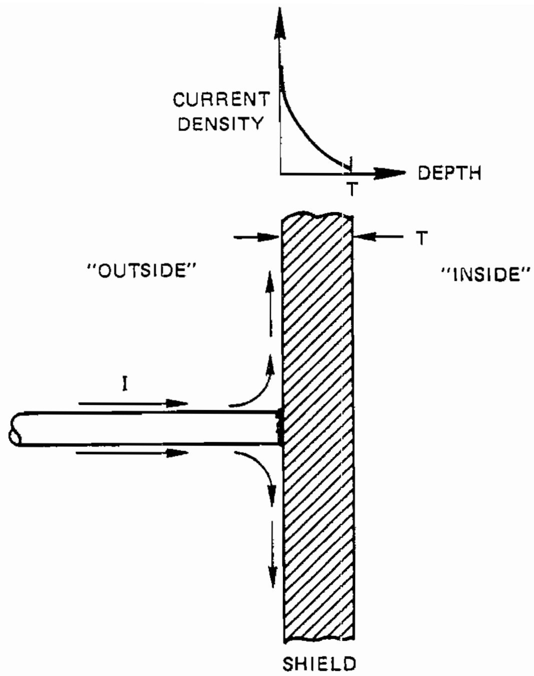


FIGURE 18 CONFINEMENT OF CONDUCTOR CURRENT TO "OUTSIDE" SURFACE BY SKIN EFFECT

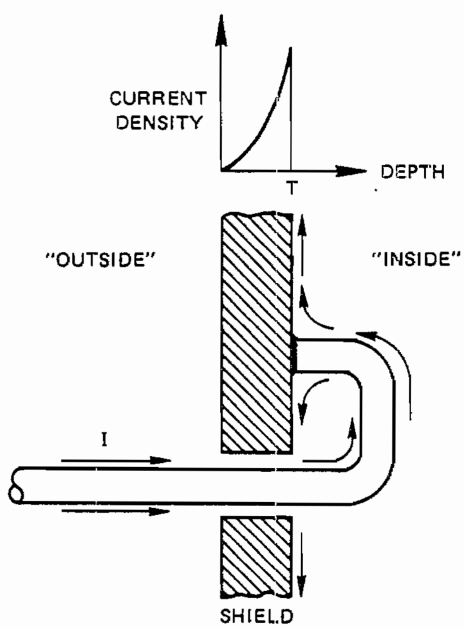


FIGURE 19 CONDUCTOR CURRENT INJECTED ON THE "INSIDE" OF A SHIELD

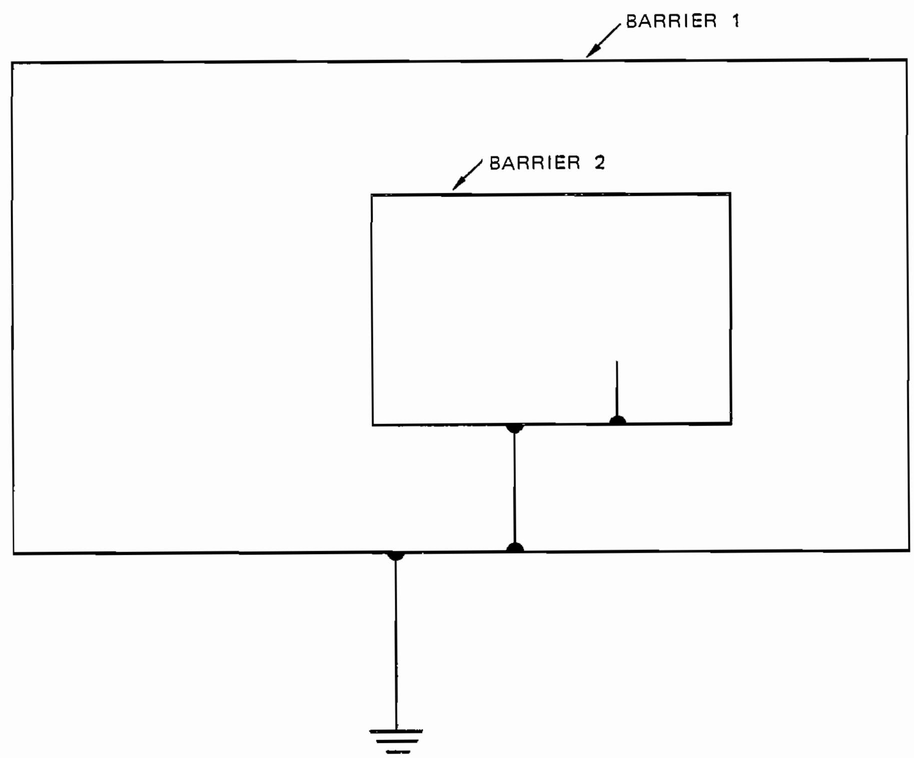


FIGURE 20 A COMPATIBLE GROUNDING TECHNIQUE

effort in installing and maintaining this grounding system and because of the extra burden on the equipment designer to make his circuit performance independent of a conductor that is not under his control. The benefits received for this cost are negative; the system performance is degraded, rather than improved. Complex electronic and communications systems can operate without the connection to earth -- aircraft such as the AWACS and AABNCP do quite well without a ground tether.

C. SHIELDING CONSIDERATIONS.

As noted above and in Section I, a closed conducting shield provides an excellent barrier between the enclosed volume and the external volume. However, if the shield is not closed, it may not be an effective barrier; in particular, if the shield contains openings through which insulated conductors pass, the barrier may be almost totally circumvented by the penetrating conductor. In practice, then, shields are violated by apertures and penetrating conductors and are not necessarily good barriers. Nevertheless, they may be elements of a good barrier composed of metal walls with aperture treatments and penetrating conductor treatments. The effectiveness of the practical barrier is almost always limited by the aperture and conductor treatments rather than by the penetration of fields through the walls.

An important exception to the last observation is the long, slender shield of a cable. Because it is long and has a small cross section, and because the internal conductors are aligned for maximum interaction with the shield current, significant penetration of the cable shield can occur. Even this penetration is small compared to that induced on internal conductors at open cable ends or open splices by the shield currents and voltages. Thus, a cable shield, like any other shield, must be closed to be an effective barrier. This was recognized long ago in high-frequency applications and many different panel connectors have been developed to circumferentially connect a cable shield to an equipment cabinet, thus closing the cabinet shield.

In spite of these considerations, it is still common practice for low-frequency applications to "ground" the cable shield at one end only and to leave up to 20 mm of wire exposed at both ends. These exposed wires are insulated conductors penetrating the shield; hence, they provide a path for interference to enter a system.

A practical shield containing the openings necessary to accommodate useful systems is a rather ineffective barrier due to the holes in the walls rather than due to limitations in the metal walls themselves. Therefore, the most effective barriers contain metal shields as a component, but the greatest effort in barrier design is devoted to identifying the holes and providing barrier-preserving devices at these locations. One current limitation facing the interference control engineer is that he has little information on the absolute or relative effectiveness of many aperture treatment techniques. For example, when is an aperture too small to be of concern? How many apertures can be tolerated? Some mesh "shields" are, in essence, simply a large collection of apertures; if such a "shield" is adequate, need we be concerned about windows, doors, and air vents? Further work (probably experimental) is required to provide quantitative data in this area.

V CONCLUSIONS

We have presented a systematic approach to interference control that is conceptually simple and therefore easy to implement. The approach is derived from electromagnetic theory, and it applies equally well to problems in electromagnetic compatibility, EMP and lightning, and safety. In today's communications facilities, many different requirements have to be met simultaneously. A unified approach to these various requirements is important for the maintenance of a cost-effective facility. Since the techniques described in Sections II and III are compatible with all electromagnetic disciplines, little extra cost will be involved if, for instance, a facility meets only EMC requirements but, at a later time, EMP requirements are imposed. At present, some of the EMC requirements and practices conflict with each other as well as with EMP requirements; thus, if EMP hardness is imposed on a facility that did not have to meet such requirements initially, it can be implemented only at great cost.

We have examined the different methods used to treat first- and second-level barrier penetrations. The techniques differ because, for EMP and lightning protection, the first barrier is required to reduce hundreds of kilovolts to the order of hundreds of volts, while the second barrier is only expected to reduce interference of the order of hundreds of volts to volts. We have also described a system for interference allocation that will simplify EMC requirements.

During our review of the large number of documents relating to electromagnetic specifications, standards, and testing, it became clear that the terms grounding, bonding, and shielding are often used interchangeably; although these terms are related, they are by no means synonymous. Many of the incompatibilities discovered in the standards and specifications listed in Appendix A arise from a poor understanding of these terms. We have offered appropriate definitions in Section IV.

We felt that four of the documents reviewed deserved a more extensive discussion because of their widespread use; MIL-STD-285, IEEE-PRP-299, MIL-STD-461/462, and MIL-STD-188-124. These discussions are presented in Appendix B. (A more condensed version of these reviews is given in Appendix A.)

We conclude that serious incompatibilities exist in presently used electromagnetic specifications and standards. We have presented one approach to meeting requirements in a unified manner; however, adoption of new techniques and methods will be a slow process because some of the present practices are firmly established (even though it is known that some of these practices do not work). The techniques proposed must be demonstrated to be workable prior to their acceptance; however, with their basis in fundamental electromagnetic theory, such a demonstration of effectiveness should be readily accomplished.

The goal of this phase of the program was to identify incompatibilities in currently used specifications and standards. In Appendix A we have listed those incompatibilities that are explicitly required by the standards, and those that result from practices permitted (although not required) by the standards. It should be recognized that the number of incompatibilities listed does not represent a rating of the standards in question. In Phase II of this program, alternatives to the incompatibilities identified in this report will be developed and demonstrated. The results of Phase II will be presented in a subsequent report.

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7. H. W. Ott, Noise Reduction Techniques for Electronic Systems (John Wiley and Sons, New York, 1976), UNCLASSIFIED.

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Appendix A

INCOMPATIBILITIES IN EXISTING STANDARDS

The following pages present reviews of 70 military and industrial standards or specifications related to electromagnetic requirements such as EMC, EMP and lightning, and safety. Each document is identified in the upper left-hand corner of the listing by its abbreviated name or identification number; for instance, MIL-STD-285. (The list is presented with the identification codes in alphabetical [not numerical] order.) This is followed, on the left, by keywords (the file is computerized and can be searched by keyword). On the upper right of the listing is the full title as it appears on the document, followed by the year of publication and the publisher (in parentheses). Beneath the title, authors are identified, if known, followed by remarks (in parentheses). Incompatibilities are listed by section. (Reference to a different document under this heading means that the incompatibilities of the referenced document are implied to the extent the referenced document applies.)

The selection of documents was initially based on their frequency of use, but we found that many less-known references were often quoted in these documents. If these quoted references had substantial impact on electromagnetic practices, we included them in the review. No ranking in order of importance has been attempted.

The list presented in this appendix is for reference only; the principal purpose of the data base was to provide on-line cross-reference capabilities during Phase I of the project. To reduce the cost of data storage requirements, many comments given under the heading "Incompatibilities" are terse. This in itself should not pose any difficulties in interpretation; none of the remarks made is intended to explain why a given practice is incompatible, since this subject has been dealt with at length in the main body of the report. Abreviations have been avoided, with the exception of the most common ones like EMP, EMC, DoD, USAF, etc., which are assumed to be familiar to the reader.

In this phase of the program, the incompatibilities between the reviewed documents and the general principles of interference control (as outlined in this report) are identified. Proposed revisions to make the documents compatible with these general principles will be generated and demonstrated in Phase II of the program.

AFAPL-TR-69-89

RFI Attenuating Materials and Structures (1969 USAF)

Attenuation
Shielding Effectiveness
Enclosure Design

Prepared by R.B. Cowdell/R.A. Hupp/J.N. O'Leary

(Report Produced for WP-AFB)

INCOMPATIBILITIES
None identified

AFSC-DH-1-4

Electromagnetic Compatibility (1979 USAF)

(An AFSC Design Handbook)

EMC
Lightning
EMI
Grounding
Bonding
Shielding

SECTION	**INCOMPATIBILITIES**
3A2-2.2.1	Shield grounded at one end. Recommends carrying shield through a connector pin and then bonding internally to equipment enclosure
5B5-3.1	Penetrating ground conductors. Poor grounding scheme for shielded cables

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AIR-1189

Airborne Internal Interface Standards for Moderate Bit Rate Digital Time Division-Multiplex Systems (1972 SAE)

Interface Standards
Multiplex Systems
Airborne

(Aerospace Information Report)

INCOMPATIBILITIES
None identified

AIR-1394

Cabling Guidelines for Electromagnetic Compatibility (1978 SAE)

Cabling Guidelines
EMC

(Aerospace Information Report)

SECTION	**INCOMPATIBILITIES**
1.6	Definition of ground as infinite current sink
2.2	Penetrating ground conductor
2.8.3	Permits ungrounded (open?) shield

AMCP-706-235 — **Hardening Weapon Systems Against RF Energy (1972 AMC)**

Lightning
Shielding Effectiveness — (An Engineering Design Handbook)
EMP
Grounding
EMI
EMC

INCOMPATIBILITIES
None identified

AMRC-R-17 — **Engineering Design Guidelines for EMP Hardening of Naval Missiles and Airplanes (1973 NAVY)**

EMP
NAVY — (Prepared by MRC)
Aircraft

SECTION	INCOMPATIBILITIES
4.1.1, 4.1.2	Penetrating ground conductor

ARP-1308A — **Preferred Electrical Connectors for Aerospace Vehicles and Associated Equipment (1977 SAE)**

Connectors
Aerospace Vehicles — (Aerospace Recommended Practice)

INCOMPATIBILITIES
None identified

BELL-1975 — **EMP Engineering and Design Principles (1975 Bell Laboratories)**

EMP
Theory
Design Guidelines
Coupling
Shielding
Susceptibility

SECTION	INCOMPATIBILITIES
ch. 7	Filter mounting not discussed
4.5	Claims rebar is effective shield without considering penetrations
5.3	Neglects untreated penetration as violation of shield

C114.1/IEEE-STD-142 — **Grounding of Industrial and Commercial Power Systems (1972 IEEE)**

Grounding
Power Systems

(IEEE Green Book)

INCOMPATIBILITIES
None identified

C37.13/IEEE-STD-20 — **Low-Voltage AC Power Circuit Breakers Used in Enclosures (1973 ANSI)**

Low Voltage
Power Circuit Breaker

INCOMPATIBILITIES
None identified

C37.90a/IEEE-STD-472 — **Guide for Surge Withstand Capability (SWC) Tests (1974 ANSI)**

Surge Withstand
Capability

(Supplement to C37.90-1971)

INCOMPATIBILITIES
None identified

C62.1/IEEE-STD-28 — **Surge Arresters for Alternating-Current Power Circuits (1975 ANSI)**

Surge Arresters
Power Circuits

(Supercedes IEEE-STD 28-1972)

INCOMPATIBILITIES
None identified

DA-36-039 — **Interference Reduction Guide (1964 ARMY)**

(Prepared by Filtron Company (2 Volumes))

Interference
EMC
EMI
Grounding
Bonding
Shielding

SECTION	**INCOMPATIBILITIES**
p. 2-8	Penetrating ground conductor (in text, also in Figure 2-3)
p. 2-17	Penetrating ground conductor
p. 2-182	Shield grounded at one end only
p. 2-186	Shield carried through connector pin

DACA73-67-C-0016	**Design Instructions for NEMP Protection of SENTINEL System Ground Facilities (1969 ARMY)**

EMP Protection
Ground Facilities

INCOMPATIBILITIES
None identified

DARCOM-P-706-410	**Electromagnetic Compatibility (1977 DARCOM)**

(Engineering Design Handbook)

EMC
EMI
Grounding
Coupling
Susceptibility
Filter
Shielding Effectiveness
Bonding
Measurements

SECTION	INCOMPATIBILITIES
4-4.9	Shield grounded at one end only
4-5.5.2	Figure 4-68 shows two undesirable methods for mounting filters
4.7.1	Penetrating ground conductor

DCAN-310-70-1	**Grounding, Bonding, and Shielding (1976 DCA)**

(To be replaced by MIL-HDBK-419)

Grounding
Bonding
Shielding
Earth Electrode
Ground Rods
Lightning Protection
Power Protection
Interference Coupling
Inspection

INCOMPATIBILITIES
This document contains many of the incompatibilities found in MIL-STD-188-124.

DOD-E-8983C — **Electronic Equipment, Aerospace, Extended Space Environment, General Specification For (1977 DOD)**

Electronic Equipment
EMC
Aerospace

(Replaces draft MIL-E-8983C)

SECTION	INCOMPATIBILITIES
3.5.4.2	Refers to DOD-W-83575 for shielding and grounding criteria
3.3.4	Requires aperture and seam treatment but implicitly permits penetrations
3.3.6.4	With no EMP requirement, shield may be connected through connector pin

---

DOD-W-83575A — **Wiring Harness, Space Vehicle, Design and Testing, General Specification For (1977 USAF)**

Wiring
Space Vehicle
Test Requirements
Cables
EMC
Shielding
Grounding
EMP

(Replaces MIL-W-83575A draft)

SECTION	INCOMPATIBILITIES
3.4.3	Shield grounded at one end only
3.4.3.3	Permits open shield when no EMP specified, with up to 20 mm exposed wire

---

IEEE-PRP-299 — **Measurement of Shielding Effectiveness of High-Performance Shielding Enclosures (1969 IEEE)**

Shielding Effectiveness
Measurement
Shielding Enclosures

(Published for Trial Use)

SECTION	INCOMPATIBILITIES
4.2, 4.4, 5	Test results not relatable to operating environment/response
4.2.5, 4.4.5, 5.5	Test results probably not unique: different testing labs may get different results for same enclosure

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IEEE-RP-135

Aircraft, Missile, and Space Equipment Electrical Insulation Tests (1969 IEEE)

Aircraft
Missile
Space Equipment
Insulation Test

INCOMPATIBILITIES
None identified

IEEE-STD-141

Electric Power Distribution for Industrial Plants (1976 IEEE)

Safety
Power Distribution
Industrial Plants

(IEEE Red Book)

INCOMPATIBILITIES
None identified

IEEE-STD-241

Electric Power Systems in Commercial Buildings (1974 IEEE)

Power Systems
Commercial Buildings

(IEEE Gray Book)

INCOMPATIBILITIES
None identified

IEEE-STD-32

Requirements, Terminology, and Test Procedure for Neutral Grounding Devices (1978 IEEE)

Neutral Grounding
Devices
Test Procedure

INCOMPATIBILITIES
None identified

IEEE-STD-404

Power Cable Joints (1977 IEEE)

Power Cable Joints
Splice

INCOMPATIBILITIES
None identified

IEEE-STD-80 — **Safety in Substation Grounding (1976 IEEE)**

Safety in Substation
Grounding
Guidelines
Earth Electrodes
Ground Grid
Ship Potential
Touch Potential
Power Lines

INCOMPATIBILITIES
None identified

IEEE-STD-82 — **Impulse Voltage Tests on Insulated Conductors (1971 IEEE)**

Impulse Voltage Test
Insulated Conductors

INCOMPATIBILITIES
None identified

IEEE-STD-94 — **IEEE Standard Definitions of Terms for Automatic Generation Control on Electric Power Systems** (1970 IEEE)

Power Systems
Generation Control
Definitions

INCOMPATIBILITIES
None identified

ISA-RP-12.2 — **Intrinsically Safe and Non-Incendive (sic) Electrical Instruments (1965 ISA)**

Safe Instruments
Ignition
Hazards

INCOMPATIBILITIES
None identified

MIL-B-5087B — **Bonding, Electrical, and Lightning Protection, for Aerospace Systems (1968 USAF)**

Bonding
Grounding
Aerospace Systems
Lightning Protection

SECTION	INCOMPATIBILITIES
3.4.2.b	None required, but grounding conductors permitted to penetrate shield surfaces

---

MIL-C-172C — **Cases/ Bases, Mounting/ and Mounts, Vibration (For use with Electronic Equipment in Aircraft)** (1977 USAF)

Enclosures
Bases
Aircraft Equipment

(Specifications for enclosures only)

SECTION	INCOMPATIBILITIES
3.5.1.4	Requires aperture and seam treatment but implicitly permits penetrations

---

MIL-C-38999G — **Connector, Electrical, Circular, Miniature, High Density Quick Disconnect (Bayonet, Threaded and** Breech Coupling), Environment Resistant, Removable Crimp and Hermetic Solder Contacts, General Specification For (1979 DOD)

Connector Specifications

SECTION	INCOMPATIBILITIES
3.31	Measurement method not applicable above 1 GHz, corrected by amendment 3

MIL-E-6051D — **Electromagnetic Compatibility Requirements, System (1968 USAF)**

EMC
System Requirements

INCOMPATIBILITIES
None identified

MIL-E-8983C — **Electronic Equipment, Aerospace, Extended Space Environment, General Specification for (1977** DOD)

Space Vehicles
General Specifications

(Now issued as DOD-E-8983C)

INCOMPATIBILITIES
See DOD-E-8983

MIL-HDBK-216 — **R.F. Transmission lines and fittings (1977 DOD)**

Transmission Lines
Filters

(Does not deal with penetrations or filter locations)

INCOMPATIBILITIES
None identified

MIL-HDBK-412 — **Facility Handbook for Satellite Earth Station (1979 DOD)**

Satellite Earth Station
Grounding
Earth Electrodes
Noise Reduction

(Draft only - not approved yet)

SECTION	INCOMPATIBILITIES
4.4.5.3c	Voltage divider is actually low-pass filter (will not pass transients above 10 kHz)
4.9.3	Separate ground system recommended for lightning and EMP protection
4.9.9.5	Grounding requirements are not clear
4.9.16	Signal ground conductor is also protective ground conductor (fault currents flow on signal ground network)
4.10	Ground system supposed to maintain equal potential throughout facility (not possible and not necessary)
4.10.1.2	Implies that an earth ground is a current sink. Design objective: < 1 ohm ground rod resistance
4.10.2.3	Gas tubes may not tolerate lightning surges on exterior wiring
4.10.4	Signal reference subsystem supposed to CONTROL noise currents
4.10.4.1	Penetrating ground conductor
4.10.4.2	Requires signal ground to earth electrode, conflicts with section 4.9.9.5
4.10.4.3	Conflicting requirements for signal reference and ac power ground connections
4.10.4.4	Conflicting requirements: shield isolated from chassis etc., yet connected to signal (and hence ac power) ground

---

MIL-P-24014 — **Preclusion of Hazards from Electromagnetic Radiation to Ordnance, General Requirements for** (1965 NAVY)

Weapon Systems
EMC
Radiation
EED

SECTION	INCOMPATIBILITIES
3.8.6	None identified, but refers to MIL-B-5087 for GROUNDING the weapon (and hence permits ground conductor penetrations)

MIL-STD-108E	**Definitions of and Basic Requirements for Enclosures for Electric and Electronic Equipment** (1966 DOD)
Enclosures	(Deals only with mechanical properties of enclosures)

INCOMPATIBILITIES
None identified

MIL-STD-1310D	**Shipboard Bonding, Grounding, and Other Techniques for Electromagnetic Compatibility and** Safety (1979 DOD)
Bonding Grounding EMC Safety Ship NAVY	(Contains idea of grounding out interference)

SECTION	**INCOMPATIBILITIES**
3.9, 3.11	Poor definition of grounding -- implies penetrating ground conductors
5.2	Recommends tree ground
5.2.3	Requirement: No ground loops
5.3.5.1, 5.4.7.2.b	No termination of conduit specified

MIL-STD-1377	**Effectiveness of Cable, Connector, and Weapon Enclosure Shielding and Filters in Precluding** Hazards of Electromagnetic Radiation to Ordnance, Measurement of (1971 NAVY)
Shielding Cabling Connectors Weapon Enclosure Shielding Effectiveness Filters	(Refers to MIL-P-24014)

INCOMPATIBILITIES
None identified

MIL-STD-1395A	**Filters and Networks, Selection and Use of (1979 DOD)**
Filters Networks	

SECTION	**INCOMPATIBILITIES**
2.1	Restriction: reference to MIL-STD-220 means all insertion loss specifications are for 50 ohm circuits

---

MIL-STD-1512 — **Electroexplosive Subsystems, Electrically Initiated, Design Requirements and Test Methods** (1976 USAF)

EED
Test Methods
EMC
Subsystems

SECTION	INCOMPATIBILITIES
5.3	Requires twisted shielded pairs used in unbalanced configuration
5.10.1	Firing circuit return grounded at one end only
5.10.2	Implies normally floating circuits but, if grounded, at one end only

---

MIL-STD-1540A — **Test Requirements for Space Vehicles (1974 DOD)**

USAF
Space Vehicles
Test Requirements
EMC

(Refers to MIL-STD-1541 for EMC tests)

INCOMPATIBILITIES
See MIL-STD-1541

MIL-STD-1541 — **Electromagnetic Compatibility Requirements for Space Systems (1973 USAF)**

EMC
Space Systems
EMI

(Will be superceded by MIL-STD-1541A)

SECTION	INCOMPATIBILITIES
4.6.2	Requires aperture treatment but does not mention treatment of penetrations
4.7.1.3	Twisted shielded pair grounded at one end only
4.7.1.5	Shield grounded at one end only
4.7.1.11	Permits shield termination inside equipment

MIL-STD-1541A — **Electromagnetic Compatibility Requirements for Space Systems (1977 USAF)**

Space Systems
EMC
Grounding

(Draft - not approved yet. Revision of MIL-STD-1541 (USAF))

SECTION	INCOMPATIBILITIES
3.10	Single point ground (SPG) is also signal reference
4.10.9	Implies that ground network may be used for power return

---

MIL-STD-1542 — **Electromagnetic Compatibility (EMC) and Grounding Requirements for Space System Facilities** (1974 USAF)

EMC
Grounding
Space System Facilities

SECTION	INCOMPATIBILITIES
3.1.1	Requires single point ground
4.2	Illustration contains ground loop, and implies penetrating ground conductor
4.3.2	Requires ground rod resistance to be less than 1 ohm
4.4	Ill-conceived relation of lightning and ground rod
4.5	Requires penetrating ground conductor (in text, and in Figure 1)
5.1.1.7	No penetration treatment
5.1.1.10	Specifies filters for some conductors but permits unfiltered penetrations by others
5.1.1.13	Requires shielding without penetration treatment
5.1.2.6	Requires single point ground
5.2.1	Emphasizes ground loop problems, without proper recommendations
5.2.2.2	Shield termination unclear
5.2.2.3	Poor wording. Requires low frequency (<100 kHz) ground at one end only, high frequency (> 100 kHz) multipoint ground
5.2.3.1	Emphasizes ground loop problems, recommends isolation of ground from building structural steel
5.2.5	Interference limit not relatable to operating environment
5.2.8	Shielded twisted pair carried through connector and junction box

---

MIL-STD-1553B — **Aircraft Internal Time Division (1978 DOD)**

EMC — (Refers to MIL-E-6051 for EMC)
Data Bus
Computer

SECTION	INCOMPATIBILITIES
4.5.1	Conductors penetrate shield (Figure 9 and 10)

MIL-STD-1605 — **Procedures for Conducting a Shipboard Electromagnetic Interference (EMI) Survey** (Surface Ships) (1973 NAVY)

Test methods
Interference Limits
EMC
EMI Survey

SECTION	INCOMPATIBILITIES
5.1.2	Interference limits specified appear to be arbitrary
5.2.1	Refers to MIL-STD-1310 for EMC, does not mention shielding, only bonding and grounding

---

MIL-STD-188-120 — **Military Communication System Standards Terms and Definitions (1976 DOD)**

Definitions
Communication Systems

SECTION	INCOMPATIBILITIES
p. 43	Definition of Ground Potential and Ground-Return Circuit are restrictive compared to definition of Ground

---

MIL-STD-188-124 — **Grounding, Bonding and Shielding (1978 DOD)**

Grounding
Bonding
Shielding
Signal Grounds

(For Common Long Haul/Tactical Communication Systems)

SECTION	INCOMPATIBILITIES
5.1.1.1.1	Signal circuits connected to earth electrode system (implied)
5.1.1.1.5	Signal reference subsystem connected to external earth electrode subsystem (implied)
5.1.1.2.4	Implies relation between low-frequency signal reference network and the fault protection subsystem
5.1.1.2.4.4	Cable shield system is required to be connected to ground, not continuous with facility shield
5.1.1.2.5.5	dc power ground (a zone 1 ground) required to be connected to the earth electrode system (a zone 0 ground)
5.1.1.3.10.1	Implies that shield system can be opened by the condoned use of non-metallic manholes
5.1.1.4.2	Signal ground plane connected to building structure and earth electrode
5.1.1.4.3	Signal ground connected to earth electrode system
5.1.1.4.7	Signal and interior grounds connected to exterior grounds (penetrating ground conductors), implies signal ground comingled with facility and exterior grounds
5.1.2.1.1.1	Signal common isolated from interior of cabinet (floating)
5.1.2.1.1.2	Signal reference isolated from interior of cabinet (floating)
5.1.2.1.1.4	Shields required to be grounded, rather than closed. (a) Furthermore, shield is to be grounded to signal reference network
5.1.2.1.1.5	Shields required to be grounded, not closed
5.1.2.1.1.6	(a) and (b) Signal reference subsystem (zone 2) connected to facility ground system (zone 1)
5.3.1.2	Implies that shields to be used only if failure is demonstrated
5.3.2.7	Cable shields must be bonded together but they are to be open (not closed with facility shield system)

MIL-STD-188C — **Military Communication System Technical Standards (1976 ARMY)**

Communication
Technical Standards
Hardware

(Standardization of operating features of end instruments in communication systems, does not deal with detailed designs)

INCOMPATIBILITIES
None identified

MIL-STD-189 — **Racks, Electrical Equipment, 19-Inch and Associated Panels (1961 DOD)**

Equipment Rack

SECTION	INCOMPATIBILITIES
3.1	Base is bolted to rack, no specifications for conductivity

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MIL-STD-202C — **Test Methods for Electronic and Electrical Component Parts (1965 DOD)**

Electronic Components
Test Methods

INCOMPATIBILITIES
None identified

MIL-STD-220A — **Method of Insertion-Loss Measurement (1959 DOD)**

Insertion Loss
Measurement

(Foreword: "...little correlation between .... test and performance of filter in particular application...")

SECTION	INCOMPATIBILITIES
1.1	Method applies to 50 ohm circuits only

MIL-STD-285

Attenuation Measurements for Enclosures, Electromagnetic Shielding, for Electronic Test Purposes, Method of (1956 DOD)

Attenuation Measurements
Electromagnetic
Shielding Effectiveness

SECTION	**INCOMPATIBILITIES**
4.1.3	Test method not valid for all required frequencies
4.1	Test results not relatable to operating environment/response
4.1.1.4.2, 4.1.2.5.2, 4.1.3.4.2	Test results not unique: different labs will get different test results for same enclosure

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MIL-STD-454E

Standard General Requirements for Electronic Equipment (1977 DOD)

Electronic Equipment
General Requirements

SECTION	**INCOMPATIBILITIES**
69-3	Requires insulated conductor penetrations through shields
1-3	Definition of single point ground unclear

MIL-STD-461A

Electromagnetic Interference Characteristics Requirements for Equipment (1973 DOD)

EMI
EMC
Equipment Requirements

(Replaced by MIL-STD-461B)

INCOMPATIBILITIES
See MIL-STD-461B

MIL-STD-461B

Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference (1980 DOD)

EMI
EMC
Test Requirements

INCOMPATIBILITIES
See Appendix B

MIL-STD-462		**Electromagnetic Interference Characteristics, Measurement of (1971 DOD)**
EMI EMC Measurements		
	INCOMPATIBILITIES See Appendix B	

MIL-STD-463A		**Definitions and System of Units, Electromagnetic Interference and Electromagnetic Compatibility** Technology (1977 DOD)
EMI EMC Definitions Units		
SECTION	**INCOMPATIBILITIES**	
4.25	Poor wording	
4.171	Refers to MIL-STD-285 for standard military shelters	
4.86	Good definition of Grounding (NATO and NEC)	
4.165	Claim: Dielectric shield is a barrier for EM energy	

MIL-STD-826A		**Electromagnetic Interference Test Requirements and Test Methods (1970 USAF)**
EMI Test		(For new procurements use MIL-STD-461/462)
	INCOMPATIBILITIES None identified	

MIL-W-83575A		**Wiring Harness, Space Vehicle, Design and Testing (1977 USAF)**
Space Vehicle Shielding Cabling Grounding		(Now issued as DOD-W-83575A)
	INCOMPATIBILITIES See DOD-W-83575A	

NASA-SP-3067 — **Radio Interference Handbook (1971 NASA)**
Prepared by Ralph E. Taylor

RFI Handbook
EMC
Lighting Protection

INCOMPATIBILITIES
None identified

NAVAIR-AD-1115 — **Electromagnetic Compatibility Design Guide for Avionics and Related Ground Support Equipment** (1974 Navy)

EMC
Shielding
Bonding
Grounding
Filters
Test

SECTION	INCOMPATIBILITIES
5.4.2	Shield grounded rather than closed
p. 7-8	Figure 7.7 does not include balanced circuits

NAVFAC-DM-4 — **Electrical Engineering (1969 NAVY)**

EMI — (Design Manual)
Lightning

INCOMPATIBILITIES
None identified

NFPA-70 — **National Electric Code (1978 NFPA)**

NEC — (Primary goal is safety)
National Electric Code

SECTION	INCOMPATIBILITIES
250	None identified. Penetrating ground conductor often implied, and certainly permitted (but not necessary for safety)

NFPA-75 — **Electronic Computer/Data Processing Equipment (1976 NFPA)**

Computer
Fire — (Primary concern is fire hazards)

INCOMPATIBILITIES
None identified

NFPA-78 | **Lightning Protection Code (1977 NFPA)**

Lightning Protection

SECTION	INCOMPATIBILITIES
3-22	Permits ground conductor penetrations
3-25	Requires interconnection of ALL grounds
3-32	If steel structure only in center of building, possible EMI problem

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NSWC-75-193 | **Emp Design Guidelines for Naval Ship Systems (1975 NSWC)**

Prepared by IITRI

Navy Handbook
HEMP
Hardening Guidelines
Ship Hardening
Coupling
Antennas
Apertures
Cables
Protection Devices
Installation Practices
Retrofit

SECTION	INCOMPATIBILITIES
5.4	Refers to MIL-STD-1310 for ground system
5.4, 3.3.3	Stresses importance of penetration treatment of ALL cables and pipes etc., but never mentions ground conductors. Shows penetrating ground conductors in Figure 5.20

TIB-78-1 | **EMP, Lightning and Power Transients: Their Threat and Relevance to Emp Protection Standards** for Telecommunication Facilities (1978 NCS)

(Prepared by DCEC)

EMP
Lightning
Transients
Standards
Communication Facilities

INCOMPATIBILITIES
None. Contains EMP and lightning data only

Appendix B

REVIEW OF FOUR COMMONLY USED STANDARDS

Four of the standards were particularly important due to their widespread use. Therefore, we have prepared a more extensive review of the four standards: MIL-STD-285, IEEE-PRP-299, MIL-STD-461/462, and MIL-STD-188-124.

1. Review of MIL-STD-285 dated 25 June 1956

ATTENUATION MEASUREMENTS FOR ENCLOSURES, ELECTROMAGNETIC SHIELDING, FOR ELECTRONIC TEST PURPOSES, METHOD OF

Paragraph 1.1 of this standard states its scope: "This standard covers a method of measuring the attenuation characteristics of electromagnetic shielding enclosures used for electronic test purposes over the frequency range 100 kilocycles to 10,000 megacycles."

The test is basically a substitution method to measure the amount of attenuation required to produce the same change in transmission between a transmitting antenna and a receiving antenna as the shielded enclosure produces when it is placed over the receiving antenna system.

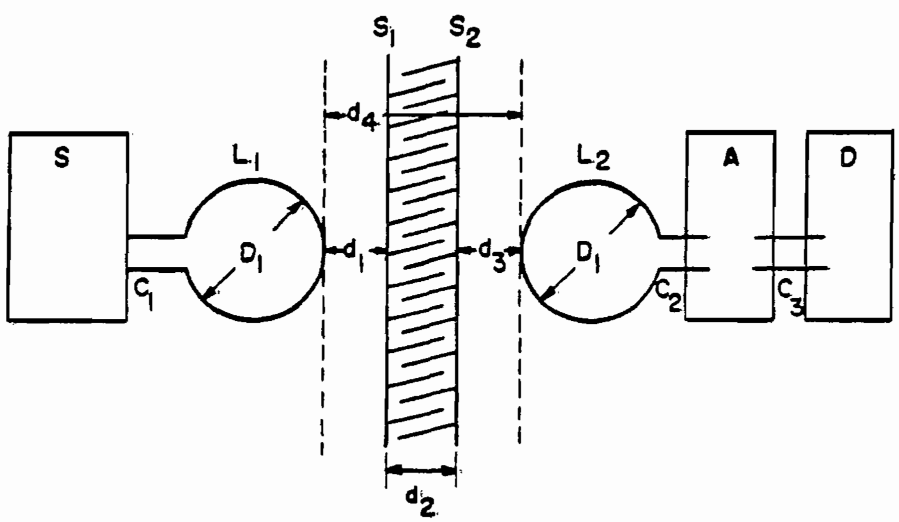
Three types of antennas are used: a loop 1 ft. in diameter, a monopole 41 in. long, and a dipole tuned to 400 MHz. An array of excitation sources, including ignition coils from Model-T Fords, is recommended. According to the standard, the sources may be continuous wave (CW), modulated CW, pulsed CW, or the pulses from one of the electromechanically switched sources.

Although the standard is meant to cover frequencies from 100 kHz to 10 GHz, the loop and monopole antennas do not appear to be suitable for measurements above about 100 MHz, and the CW plane wave source is implied to be a fixed-frequency 400 MHz source. Therefore, the validity of the standard's recommended test methods is questionable above a few hundred megahertz.

Although the distance between the transmitting antennas and the shield wall and the distance between the wall and the receiving antenna are specified, the location and orientation of these antennas are not fixed. The transmitting antenna can be "...anywhere around the enclosure and in any orientation to the section seams and access panel seams." We assume that the intent is to find the orientation and location that produce the largest leakage, but the standard does not state this; it merely states that "several readings" (plane wave), or "A reading...on all four sides..." (low-impedance fields), or "A reading...at each side..." (high-impedance fields) should be taken and the lowest of these recorded (Figures B-1 through B-3). Thus, it seems likely that different laboratories could test the same enclosure and obtain quite different results.

Another serious problem with the standard is the "substitution" method used to measure the attenuation. Because the loop and monopole antennas are only 25 in. apart, they are inductively coupled when the shield is not present. When the shield is present, it is in

4.1.1.4.2 The position of L_1 with respect to the enclosure shall be anywhere around the enclosure and in any orientation to the section seams and access panel seams. A reading shall be taken on all four sides of the enclosure, and the minimum attenuation recorded. This shall be a minimum of 70 db.

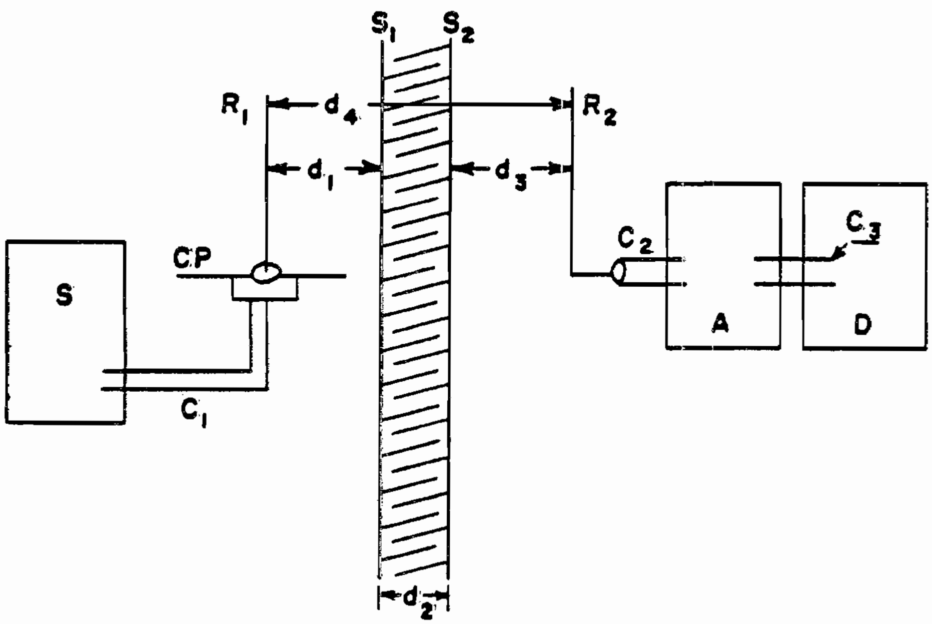


d_1 = 12 inches.
d_2 = separation between inner and outer shields.
d_3 = 12 inches.
d_4 = 25 inches—($d_1 + d_2 + d_3 = d_4$).
S_1 = Outer screen.
S_2 = Inner screen.
S = Low impedance signal source to obtain adequate output at the frequency of test.
D_1 = 12 inches.
Frequency of test = One frequency in the 150 to 200 kc. range.
L_1 = Transmitting loop radiator; low impedance. One turn of No. 6 AWG copper wire. Oriented at any angle in a plane perpendicular to the shielding enclosure wall.
D = Detector of adequate sensitivity tuned to frequency of test. Used only as a reference level indicator.
L_2 = Receiving loop antenna, positioned in the same plane as L_1.
A = DB attenuator of low impedance input, calibrated at the frequency of test.
C_1, C_2, C_3 = Shielded transmission line cables. As short as possible and used only if necessary.

Note.—The code letters used on this figure should not be confused with electrical and electronic reference designations (see MIL-STD-16).

FIGURE B-1 ATTENUATION MEASUREMENT LOW-IMPEDANCE MAGNETIC FIELD

4.1.2.5.2 The positioning of R_1 with respect to the shielding enclosure walls shall be anywhere around the enclosure, in any orientation to the section seams and access-panel seams. A reading shall be taken at each side of the shielding enclosure and the minimum attenuation recorded. This minimum shall be over 100 db.



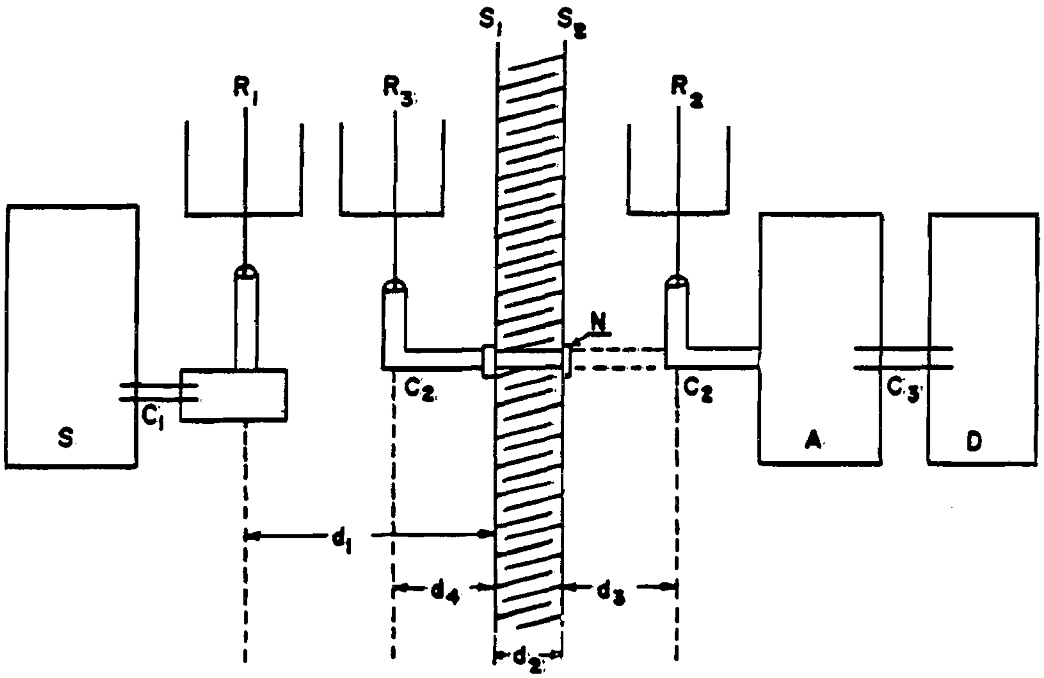
d_1 = 12 inches.
d_2 = Separation between inner and outer shields.
S_1 = Outer screen.
S_2 = Inner screen.
S = High impedance signal source to obtain adequate output at the frequency of test.
Frequencies of test = 200 kc., 1.0 mc. and 18.0 mc.
R_1 = Transmitting rod radiator, 41 inches long. High impedance oriented in any position parallel to the shielding enclosure wall.
C_1, C_2 and C_3 = Shielded transmission line cables. As short as possible and used only if necessary.
A = Capacity type db attenuator. High input impedance.
CP = Counterpoise.
R_2 = Receiving rod antenna, 41 inches long. High impedance, positioned parallel to R_1 and in the same plane.
D = Detector of adequate sensitivity. Tuned to frequency of test. Used only as an equal reference level indicator.

d_3 = 12 inches.
d_4 = 25 inches = ($d_1 + d_2 + d_3 = d_4$).

Note.—The code letters used on this figure should not be confused with electrical and electronic reference designations (see MIL-STD-16).

FIGURE B-2 ATTENUATION MEASUREMENT HIGH-IMPEDANCE ELECTRIC FIELD

4.1.3.4.2 The position of R_1 with respect to the shielding enclosure walls shall be anywhere around the enclosure in any orientation with respect to the section seams and access-panel seams. Several readings shall be taken, and the minimum attenuation recorded. This minimum shall be over 100 db.



d_1 = 72 inches minimum. Distance shall be as great as possible and limited only by the output of S. However, always hold more than two times the wave length from S_1, S_2.

d_2 = Distance between shields.

d_3 = 2 inches. Two inches is the minimum value. R_2 is positioned anywhere inside the enclosure and oriented for maximum indication on detector D, in order to minimize the effect of reflections.

d_4 = Not less than 2 inches, and not more than 24 inches—R_3 is positioned anywhere outside the enclosure and oriented for maximum indication on detector D, in order to minimize the effect of reflections. The entire region, from 2 to 8 inches shall be explored for maximum indication. R_3 shall never be closer than 2 inches to S_1 or S_2, in order to prevent capacity coupling.

S_1, S_2 = Outer and inner shields, respectively.

N = Transmission line connector.

S = Signal source, to obtain adequate output at the test frequency.

Frequency of test = 400 megacycles.

R_1 = Transmitting radiator. Dipole, tuned to 400 mc. If a tuned dipole is used with a single coaxial line, it shall be a balanced dipole, similar to the Antenna AT-275/URM-28. Other suitable antenna types are: Antenna AT-141A/ARC, used with the Radio Set AN/ARC-27, Antenna AT-292/URM-29 used with Radio Interference Measurement Equipment AN/URM-29, and Antenna AT-90/AP used with Radar Set AN/APT-5. The radiator shall be positioned to obtain maximum field intensity at the shielding enclosure.

R_2 = R_3 = Receiving antenna. May be similar to R_1.

C_1, C_2, C_3 = Shielded transmission line cables. As short as possible, and used only if necessary.

A = Attenuator, calibrated at the frequency of test.

D = Detector of adequate sensitivity, tuned to the frequency of test. Used only as an equal reference level indicator.

Note.—The code letters used on this figure should not be confused with electrical and electronic reference designations (see MIL–STD–16).

FIGURE B-3 ATTENUATION TEST FOR PLANE WAVE the induction zone of the antennas, and antenna characteristics are quite different in the presence and the absence of a shield. These characteristics also change with orientation and position of the antenna relative to the enclosure. These anomalies are extremely difficult to evaluate, and it is very difficult (if not impossible) to use the attenuation value derived from the test to make an accurate statement concerning the performance of the shield enclosure in a known environment (other than the test environment).

The results of the test are, at best, qualitative at frequencies up to 400 MHz and highly questionable above that frequency. The standard test produces no design information, and test results cannot be used in an accurate system analysis.

Since the standard is meant for shielding enclosures to be used for test purposes, the standard is not in conflict with other standards, practices, or specifications used for procurement of system components. On the other hand, the standard is of questionable value for its intended purpose of measuring the attenuation characteristics of screen rooms to be used for testing. At present, there is no specification or standard that prescribes a satisfactory method for measuring the shielding effectiveness of an enclosure. This subject will be discussed further in Phase II of this program.

2. Review of IEEE No. 299 dated June 1969

Proposed Recommended Practice for

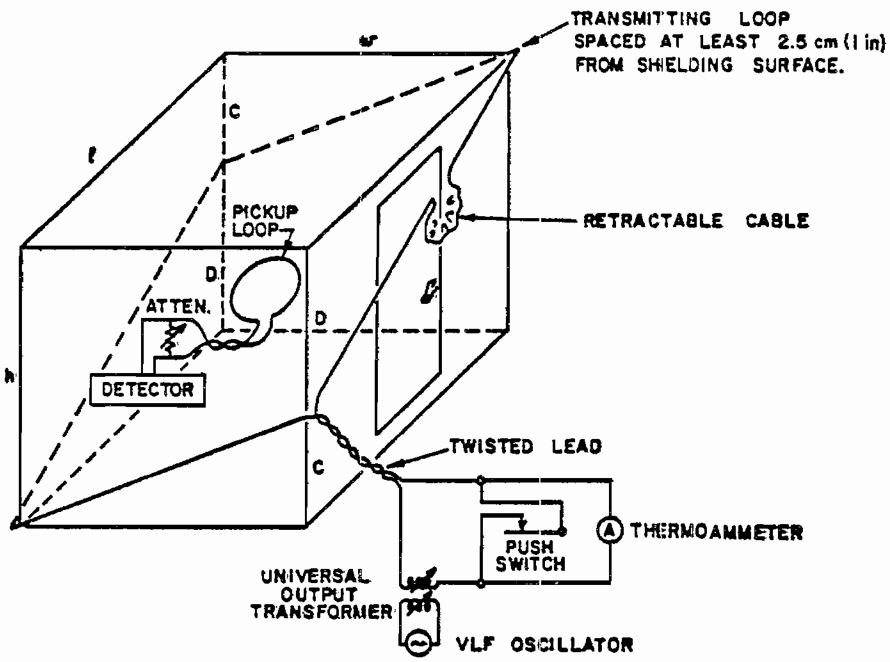
MEASUREMENT OF SHIELDING EFFECTIVENESS OF HIGH PERFORMANCE SHIELDING ENCLOSURES

The stated objective of this IEEE Recommended Practice "...is to provide uniform test procedures and estimation techniques to determine the relative effectiveness of room-size high-performance shielding enclosures." Tests to determine shielding effectiveness in three frequency ranges (0.1 to 20 MHz, 300 to 1000 MHz, and 1.7 to 12.4 GHz) are recommended. These ranges are called the low frequency, ultrahigh frequency, and microwave ranges, respectively.

During the tests, the response of a sensor inside the shielding enclosure to excitation outside the enclosure is measured. The results are compared to sensor response to the same excitation in the absence of the shielding enclosure (or to an excitation that simulates the absence of the shield). Although not explicitly stated, the substitution method required in MIL-STD-285 (in which the attenuation that produces the same effect as the shielding enclosures is measured) seems to be implied. The tests are to be performed with "...all radio-frequency cables, power lines, and other utilities normally entering the shielding enclosure...in place..." (Paragraph 3). However, "...metallic equipment...such as tables, chairs, and cabinets, should be removed prior to conducting the tests." (Paragraph 4.2.4). The standard also advises that "...special care should be taken to make measurements in the vicinity of utility entrances, doors, access panels, and panel-to-panel seams." (Paragraph 3).

Two tests are described for the low-frequency range: a large-loop test (see Figure B-4) and a small-loop test. The large-loop test uses a loop about the enclosure (see illustration) to excite the outside of the structure, and a multiturn loop 30 in. in diameter inside to sense the internal response. CW excitation is used.

The small-loop test is similar to the MIL-STD-285 low-impedance test in that two 12-in. diameter single-turn loops, a transmitter outside the enclosure, and a receiver inside the enclosure are used. The test differs from MIL-STD-285 in that these loops are positioned at specific points near seams, doors, power lines, and air inlets to measure the leakage in these areas, and the upper frequency for these tests is 20 MHz (rather than 10 GHz as in MIL-STD-285). Shielding effectiveness is determined from the implied reduction in magnetic field strength by the shield.



NOTES: $C = \frac{w}{l+w} h$ PICKUP LOOP IN PLANE OF LARGE LOOP OR CENTER OF ENCLOSURE

$D = \frac{l}{l+w} h$

ALSO $C = h - D$

$D = h - C$

FIGURE B-4 LARGE-LOOP TEST SETUP (from IEEE No. 299)

The ultrahigh frequency tests use a folded dipole transmitting antenna 1.3 m or 1.3 wavelengths (whichever is greater) from the wall of the enclosure, and a one-eighth-wavelength dipole antenna 1 ft (0.3 m) from the inside wall as the sensor. Probing to find the hot spots near seams, vents, or cables is recommended as a preliminary procedure. Shielding effectiveness is determined from the implied electric field reduction produced by the shield.

The microwave tests use a horn antenna inside to sense the internal response. The internal horn is on the center line of the structure; the external horn is 2 m from the wall of the structure. Shielding effectiveness is determined from the reduction in power density (as received by the internal horn) due to the shield.

The IEEE tests appear to be considerably better conceived than the MIL-STD-285 tests in that the IEEE microwave tests are to be conducted with microwave instrumentation, whereas those of MIL-STD-285 are conducted using 1-ft. diameter loops or 41-in. long monopoles that cannot be considered microwave components.

The IEEE method shares some of the problems of MIL-STD-285 in that the antenna characteristics are undoubtedly altered by the presence of the shield; the measurement in the absence of the shield effectively is made with a sensor of different characteristics than the one used with the shield present. In addition, three different shielding effectiveness ratios are used — one for each frequency range. Thus, for the lower frequency range, loop antennas are used and:

$$S = 20 \log H_1/H_2 \quad ;$$

for the ultrahigh frequencies, dipoles are used and:

$$S = 20 \log E_1/E_2 \quad ,$$

while for microwave frequencies, horns are used and:

$$S = 10 \log P_1/P_2 \quad .$$

The comparability of the three shielding effectiveness numbers is questionable. Although the tests are not intended for obtaining quantitative data (and the standard does contain a disclaimer to that effect), the results of the tests (which are given in a numerical form) are indeed quantitative.

The most serious limitation of the IEEE standard may be its lack of concern with those frequencies about the fundamental cavity resonances and external resonances of the enclosure. These are not measured because they "...often give rise to uncorrelatable results." Nevertheless, leakage in this frequency range (20 to 300 MHz) may be very significant to system compatibility, particularly if aperture coupling to the cavity approaches the characteristics of a matching transformer.

The tests are formulated primarily for shielding enclosures for test and R&D work rather than for system housing, and so they do not really conflict with other standards, practices, or specifications. However, the low-frequency tests are not representative of the usual environment of such a shield because the external conductors, which are usually the principal low-frequency exciters of the shield, are only incidentally excited by the loop tests. Therefore, if the standard were to be used to procure system shielding enclosures, a modification of the low-frequency test would be in order.

3. Review of MIL-STD-461B/462

MIL-STD-461B dated 1 April 1980

ELECTROMAGNETIC EMISSION AND SUSCEPTIBILITY REQUIREMENTS
FOR THE CONTROL OF ELECTROMAGNETIC INTERFERENCE

MIL-STD-462 dated February 1971

ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS, MEASUREMENTS OF

MIL-STD-462 defines test procedures, while MIL-STD-461 defines the allowable emanations of equipment and the environments the equipment must tolerate. These standards were developed primarily for procuring aerospace systems, although the use is much broader.

The current version of MIL-STD-461 seems to be a higher-quality document than the previous version in that many of the meaningless requirements on "Interference Control Plan," "Management Controls," and "Antenna Measurements" have been eliminated, and more precise statements of test criteria for the nine classes of equipment have been substituted. The "A" version of the standard contained four classes of equipment; two of these had four subclasses, one had three subclasses, and none was well defined. In the current version, a separate mini-standard has been written for each of the nine equipment classes. The spike test levels have been expanded to cover two waveforms and peak voltages up to 400 V.

While MIL-STD-461B is a statement of the required maximum emission and minimum test levels for determining the tolerance of the equipment, MIL-STD-462 is still the standard that dictates the measurement methods; these measurement methods are questionable to the extent that they cannot be related to any operating environmental conditions, and they do not appear to be based on a rational theory of interference control. Without a logical interference control scheme, it is not possible to evaluate the specified emission and susceptibility levels in MIL-STD-461B.

MIL-STD-462 contains a number of logical inaccuracies and misinterpretations of electromagnetic theory. The latter relate to the recommendation of several poorly conceived test methods. For example, CS06, the "spike" injection test, may be conducted with a shunt capacitance across the power leads for ac lines, or a series inductor for dc lines. The source impedance of the "spike generator" and the reactance seen by the test item are radically different in the two cases, but either test is deemed adequate. (Among the logical inaccuracies is the fact that the "spike" is injected in the differential mode, while the environment is more likely to induce common-mode transients.)

Another problem is illustrated by Figure RS02-1, which is meant to illustrate a radiated susceptibility test. What is illustrated, however, is a wire tightly wrapped around all but the last 6 in. of an interconnecting cable between two items of equipment. A current from a "spike generator" is passed through this wrapped wire. Because the coupling element is the coil of wire, the test is entitled "Radiated Susceptibility, Magnetic Induction Field Spike," although the magnetic induction may be smaller than the electric induction in some circuits. The electric induction is apparently not measured or controlled. Other examples are:

- The RS01 radiated susceptibility test is conducted with a loop of 12 cm diameter 5 cm from the surface of the test sample. (Neither the test field nor its relation to an operating environment can be defined.)
- A "longwire antenna" is defined for conducting radiated susceptibility tests; it consists of a wire strung across the interior of a screen room and driven by an RF source. (The relation between the excitation and any environment is unknown.)
- In the Army Notice 3, a "parallel strip" line for plane wave excitation of the test sample is specified in Figure RS03-7. However, the test specifies the orientation and height of cables for the test (not the operating characteristics), and it requires that the equipment be insulated from the bottom plate (even if the operational equipment is grounded). Therefore, the test cannot be related to an operational environment.

4. Review of MIL-STD-188-124 dated 14 June 1978

GROUNDING, BONDING, SHIELDING

Section I of this standard states the following objectives: "This standard establishes the minimum basic requirements and goals for grounding, bonding and shielding of ground-based telecommunications C-E equipment installations..." (Paragraph 1.1); "...the requirements of this standard are intended to reduce noise and electromagnetic interference caused by inadequate grounding, bonding and shielding..." (Paragraph 1.4).

In its present form, the standard cannot achieve these objectives. Many of the required practices degrade rather than improve the interference environment. A detailed discussion of the general interference problem has been given in the main part of the report; this review will only point out the incompatibilities and conflicting requirements.

The beginning paragraph in Section 4 (General Requirements) presents the idea that a low impedance connection to earth assures that "...no voltage differentials exist on the ground plane...that will produce noise or interference to communication circuits." (4.1). In practice, the ground connection is never perfect and, therefore, a ground conductor potential does exist. The suggestion (as in 4.2.1.d) that the signal reference be connected to the same point as the lightning and the equipment fault protection subsystem is not a good one because this is about the noisest point in a facility. Finally, a zero-impedance ground plane will prevent voltage differentials on the ground plane itself, but even such a perfect plane cannot prevent interference to the communications circuits.

Bonding does not prevent the development of electrical potentials between metal surfaces as stated in Paragraph 4.3.1 (see Section IV in this report). Paragraph 4.4.1 states that "shielding is required...to prevent the equipment from propagating interference..." The meaning of this statement is not clear.

Individual sections follow on grounding (5.1), bonding (5.2), and shielding (5.3).

The first grounding requirement (5.1) states that the four grounding systems (which include the lightning and power grounds, and the signal reference) are to be interconnected. However, without a zero-impedance ground electrode, some of the direct-strike lightning current will flow to the signal reference subsystem, which can lead to potential differences inside an equipment cabinet (the fault current path and the signal reference path generally do not have the same impedance to the ground electrode). Paragraph 5.1.1.1 states that the earth electrode system will "...ensure that hazardous voltages do not occur between the facility and earth." However, on the next page of the standard, a 10 Ω earth resistance is allowed (5.1.1.1.3.1); with an average lightning stroke current of 20 kA, the electrical potential between facility and earth will be 200 kV, which is hazardous. In the same paragraph (5.1.1.1), it is also required that "...the earth electrode subsystem shall not degrade the quality of signals in the signal circuits connected to it." One cannot connect the signal circuits to the earth electrode without degrading their performance.

"The resistance to earth of the electrode system should not exceed 10 ohms." (5.1.1.1.3.1). The use of the word "should" instead of "shall" means that this statement is a recommendation and not a requirement; no justification for this recommendation is given. If safety is the concern, why not follow the National Electric Code? The NEC recognizes both the difficulty and the needlessness of requiring an arbitrarily low ground rod resistance. It states that if a single electrode exceeds 25 Ω resistance to earth, such an electrode should be augmented by a second electrode. However, the NEC does not specify the resistance of the combined system. The Lightning Protection Code mentions (Appendix B) that a ground-rod resistance up to 200 Ω has been found quite safe when proper procedures are followed. While paragraph 5.1.1.1.3.1 recommends that the resistance to earth should not exceed 10 Ω, this recommendation takes the character of a requirement in the next paragraph (5.1.1.1.3.2), which states "...where 10 ohms are not obtained...alternate methods for reducing the resistance to earth shall be considered."

"Special efforts shall be made to assure the integrity of the low-frequency signal reference network." (5.1.1.2.4). What does this mean? It is not clear what the special efforts are to be, nor what the integrity of the low-frequency signal reference network entails. Another unclear statement is made in 5.1.1.2.4.3: "All electric and electronic wiring and distribution equipment enclosures...shall be grounded." This statement could be interpreted to mean that all electrical and electronic wiring must be grounded. In 5.1.1.2.5.1 it is suggested that dc isolation of the power neutral will prevent ac return current from flowing on the fault protection subsystem or the signal reference network. (The original intent of this paragraph was probably that the fault protection system, i.e., the green wire, should not carry any ac current except during a fault condition; see section 250-21 of the National Electric Code.)

For grounding dc power sources, "...one leg of each dc power system shall be grounded with a single connection directly to the earth electrode subsystem." (5.1.1.2.5.5). This implies a separate, single long grounding lead from dc supply to the earth electrode system, which contributes nothing to safety and will lead to penetrating ground conductors.

In secure facilities, "...all areas required to maintain communications security equipment and associated power systems shall be grounded..." (5.1.1.2.6). The meaning of this requirement is not clear.

After dealing with the fault protection subsystem, the standard then turns to the lightning protection subsystem (5.1.1.3) requiring that, in general, the practices of the Lightning Protection Code (NFPA 78) be followed.

A question is raised by a reading of Paragraph 5.1.1.3.8.4.d, which states that "...waveguides shall be properly bonded to the panel..."; the panel is neither defined nor described. The paragraph also blurs the distinction between grounding and bonding: at the antenna, whether the waveguide is grounded is immaterial, but it must be bonded to the antenna structure.

Conduit is used to "...completely enclose susceptible wiring...to shield against lightning..." (5.1.1.3.10.1), but the same paragraph permits nonmetallic manholes where the shield is opened (although it is made electrically continuous for dc by a "bridge" [bonding jumper?]). Paragraph 5.1.1.3.12 requires lightning arrestors on power lines, but lightning arrestors alone are insufficient for interference control; filters are also required.

Requirements for the signal reference subsystem are given in Section 5.1.1.4. This section begins with the statement that "...signal circuits are grounded to control...noise..." (5.1.1.4.1). However, signal circuits are not grounded to control noise; we have elaborated on this point throughout the main part of this report, and especially in Section IV. Also, the same paragraph (5.1.1.4.1) uses the terms "lower" and "higher frequency" without defining them there. The next paragraph (5.1.1.4.2) continues to discuss the "higher" frequency network, still without defining how high the frequency really is. The standard requires that the equipotential plane be connected to the building structure and earth electrode subsystem "at many points" (how many?). "Lower" frequency networks are considered next (5.1.1.4.3), and here a range is given: dc to 30 kHz "...and in some cases to 300 kHz." By implication, then, the "higher" frequency network would embrace the range from infinitely high (e.g., 100 GHz) down to 300 kHz, and in some cases to 30 kHz. Most C-E facility will contain equipment that operates above 30 kHz; therefore, an equipotential ground plane appears to be required in all those facilities (Paragraph 5.1.1.4.1.c), and the low-frequency considerations would not seem to apply. Furthermore, it is stated that the low-frequency signal ground network "...prevents stray currents...from developing voltage potentials (sic)...on the ground network" (5.1.1.4.3), which is not true. It is also required that the signal reference network be connected to the earth electrode system (by implication and illustration) with a long ground wire, penetrating shields if necessary. Such a connection transforms the ground network to an interference distributor, thereby degrading the interference environment.

The reason for requiring that the main ground plate be mounted on "...phenolic or other nonconducting spacers" (5.1.1.4.4) is not clear. If the floor of the facility is metal, potential differences can then exist between the ground plate and the floor. Isolation is also required (5.1.1.4.5) between signal ground and the structure, except for one connection via a very long and tenuous path (namely, the connection to the ground electrode subsystem). The required isolation is specifically mentioned to be dc resistance, yet most signals in a C-E facility are likely to be ac. The rationale for specifying a No. 1/0 AWG (or larger) cable (5.1.1.4.7) for the connection of the signal ground plate to the earth electrode system is also not clear.

Paragraph 5.1.1.4.10 presents the same requirements for the feeder ground plates as for the main ground plate (discussed above), and Paragraph 5.1.1.4.11 suggests that (unshielded) signal reference ground cables up to 150 ft long are acceptable. It is not clear why a ground plate is labeled "CAUTION — SIGNAL GROUND" (5.1.1.4.13).

An alternate method for the low-frequency ground network with ground plates is described in Paragraph 5.1.1.4.14; namely, the use of the ground bus. However, this information, together with that in Paragraph 5.2.10.2, leads us to believe that the racks or cabinets are connected directly to the (signal) ground bus. This ground bus "shall not form a closed loop"; however, by implication, Paragraph 5.1.1.2.4.2 requires such loops. In 5.1.2.1.1 ground loops are permitted (for the signal reference subsystem in C-E equipment) if they are small:"... minimal ground loop paths shall be used..."

Paragraphs 5.1.2.1.1.1 and 5.1.2.1.1.2 deal with the isolation of the signal reference from the equipment case. Both paragraphs contain only recommendations. Not only is it recommended that chassis and signal reference be isolated from the equipment case, but the signal reference conductor is then to penetrate (without treatment) the equipment case and connect to the signal reference subsystem. This connection is achieved by a long (yellow) wire that, because of its length, is a highly inductive and antenna-like conductor. The connection to the external signal reference system also requires that this yellow wire be directly connected to the power and lightning ground point, which is usually the noisiest point in a facility. Furthermore, since the equipment case is grounded (as required elsewhere in the standard), a large ground loop is formed (certainly for ac, although not for dc if the recommended isolation is achieved).

Shielded signal lines are discussed in Paragraph 5.1.2.1.1.4, but it is required that the shields be grounded rather than closed; this is very likely a consequence of the idea that one can "drain" interference away, or "ground" it out. The subparagraphs emphasize these ideas: in (a), a shield is required to be grounded at one end only, which implies that the other end of the shield is open; (b) implies that the shield, instead of being closed, is connected to the equipment with a minimum length of grounding lead; (c) requires an open shield system; (d) requires that the shield current be delivered to the signal circuit with a shield grounding conductor (i.e., that the shield be "extended" with a wire through the equipment case); (e) reaffirms the open but grounded shield idea, and explicitly permits penetrating ground conductors. The next paragraph (5.1.2.1.1.5) extends these ideas to overall shields, which again must be grounded rather than closed. Paragraph 5.1.2.1.1.6 details requirements concerning the connections of the signal ground network to the main facility ground plate. It requires that the signal reference be connected to the facility ground, which is also the point to which lightning and power ground conductors are connected. This connection is required regardless of whether the signal ground is connected to the equipment case or not. Furthermore, (a) suggests that a long insulated wire (an inductive antenna) is better than a direct connection to the structure of the facility (or the equipment rack), and (c) amplifies the idea of an insulated grounding conductor for the equipment external signal ground.

For the higher frequency signal reference network, a ground plane is required, but minimal dc resistance (< 1 mΩ required) between any two points cannot guarantee the avoidance of RF potential differences (5.1.2.1.2). Again, the shields are said to be "grounded" to the equipment case (5.1.2.1.2.3) when what is really meant is "bonded." Also, "peripherally grounding (sic) the shield to the equipment case" is not consistent with the requirements of Paragraph 5.1.2.1.1.4. This conflict also arises in 5.1.2.1.4, where it is stated: "...if the lower frequency and higher frequency circuits share a common signal reference, both circuits shall be grounded in accordance with 5.1.2.1. and 5.1.2.1.2."

No incompatibilities were found in section 5.1.2.2 on the fault protection subsystem. Also, none were found in the section on bonding (5.2), except that pararaph 5.2.1.f credits bonding with the prevention of static buildup when, in fact, this is one of the few things grounding can accomplish.

In the general requirements for shielding (5.3.1) it is stated that "...radiated energy may...be coupled...through a shield of inadequate thickness, through holes penetrated (sic) for ventilation and other purposes, and through imperfectly joined shielded sections." While this is all true, the most important coupling mechanism, penetrating conductors, has not been mentioned.

Paragraph 5.3.2.3 requires the filter case to be grounded; they should be bonded to the shield.

The requirement for waveguide-beyond-cutoff sleeve for small control shaft holes is inconsistent with the requirements for a noise distributing ground system or requirements for open shields on twisted shielded pairs.

Paragraphs 5.3.2.5 and 5.3.2.6 have nothing to do with shielding, and they should be moved to Section 4 (General Requirements).

The last paragraph (5.3.2.7) reiterates the idea that shields should be grounded rather than closed. It also states that "...it is important that electrical continuity of all cable shields is maintained..." which conflicts with ideas on low-frequency signal reference networks (where shields are "grounded" at one end only, the other end is open and not connected).

Appendix B of this standard contains a brief discussion of different signal ground systems. The ideas expressed here are understandable when viewed against the background of historical developments after World War II. However, electromagnetic theory is better understood today (from a practical standpoint), and many of these old ideas are now seen to be incompatible with physical laws. In some cases, causes and effects are blurred; for instance, it is true that improper grounding can aggravate interference problems, but it does not follow from this that proper grounding reduces interference.

This military standard would be vastly improved if all incompatible and inconsistent information was corrected. It is an important standard and, after suitable revision, will lead to better and more cost-effective practices for grounding, bonding, and shielding.

Appendix C

TECHNICAL CONSIDERATIONS

This appendix contains three Research Memoranda entitled "Characteristics of Balanced Pair and Associated Shielding and Grounding for EMP Hardening," "Termination of Cable Shields at Low Frequencies," and "Shield Degradation by Penetrations and Apertures."

The first two Memoranda were prepared early in the contract period; the third discusses laboratory experiments that were performed under this contract.

1. CHARACTERISTICS OF BALANCED PAIR AND ASSOCIATED SHIELDING AND GROUNDING FOR EMP HARDENING

I INTRODUCTION

This memorandum discusses the interaction of balanced twisted pairs and their termination and grounding conductors with the EMP. Although these parts of the system are difficult to analyze exactly, some trends and tendencies can be established. For the balanced, twisted pair, the induced interference is predominantly in the common mode, while the signal is in the differential mode. Conversion of the common-mode interference to differential mode is very small (-60 dB) below 20 kHz, but it increases with frequency so that at 20 MHz the conversion approaches 0 dB (100%). Similar conversion properties are characteristic of small unbalances in isolation transformers used to discriminate against the common-mode interference. That is, small unbalances produce small (-60 dB) conversion below 20 kHz, but the conversion increases with frequency so that at 20 MHz the conversion is -10 dB to -20 dB. Thus, with optimum shielding and grounding, the twisted pair and isolation transformer provide excellent discrimination against the common-mode interference in the spectrum below 20 kHz. The property of some single-point grounding systems that permits interference generated in one part of the system to be distributed to other parts of the system on the grounding conductors is reviewed in Section IV. It is concluded that grounding should probably not be considered a high-frequency interference control technique.

An important characteristic of nonlinear surge arresters, namely, that they regenerate high-frequency energy that is excluded by the shield system, is also discussed in Section IV. Generally, it is recommended that these devices not be used inside the first level of shielding because the characteristics of the surge arrester conflict with the goals of the shield design — particularly when orthogonalization concepts, such as a balanced pair with common-mode rejection, are used.

II COUPLING TO TWISTED PAIR

A twisted pair can be represented by filamentary conductors spiraled about a circular cylinder as illustrated in Figure 1. The radius of the cylindrical form is h_0 and the axial distance required for one complete turn about the cylinder is the lay length L. An electromagnetic wave with its magnetic vector perpendicular to the plane of the figure can interact with the loops formed by the projection of the spiraled conductors onto the

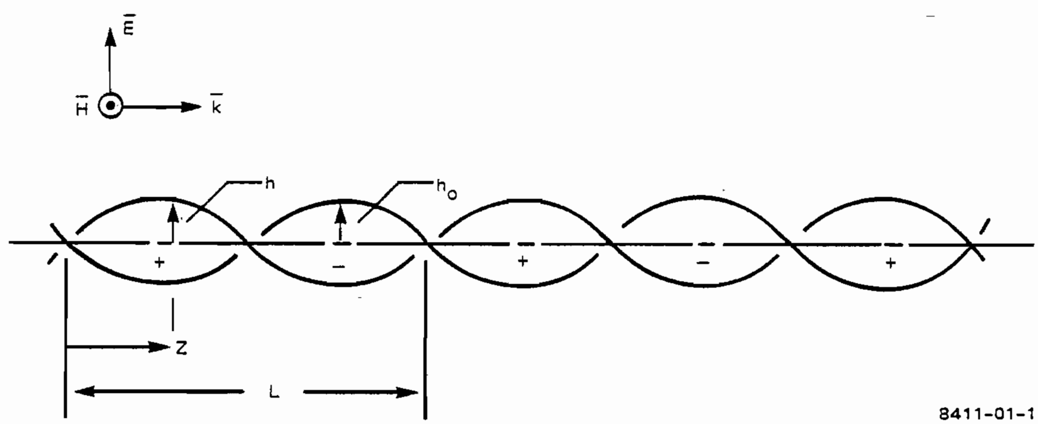


FIGURE C-1 PROJECTION OF TWISTED (spiraled) FILAMENTARY PAIR ON A PLANE

plane.[1*] Electric field interaction can induce charge on the conductors. In this note, only the magnetic field interaction is considered.

A. "Odd Loop" Model

Because the wires cross at points L/2 apart along the line, the voltage induced in one loop is the opposite polarity of the voltage induced in the loop on either side. Thus in the quasistatic approximation these induced voltages of alternating polarities cancel each other. In a long piece of twisted pair, the induced differential voltage is zero if the number of loops is even and equal to the voltage induced in one loop if the number is odd. In fact, the propagation time between the loops may preclude exact cancellation of the voltages induced in two adjacent loops.

For the case in which h_o is small compared to a wavelength, the voltage induced in a loop is

$$\Delta V = j\omega\mu_o H_o h_o 2 \int_0^{L/2} \sin\left(\frac{2\pi z}{L}\right) e^{-jkz} dz \tag{1}$$

where H_o is the magnetic field strength incident on the loop, the wave convention is $e^{j(\omega t-kz)}$, and the wire projection shown in Figure 1 is defined by

* References are given at the end of this paper.

$$h(z) = h_o \sin \frac{2\pi z}{L} \quad . \tag{2}$$

The voltage induced in one loop of length L/2 centered at z = L/4 is then

$$\Delta V = j\omega\mu_o H_o \frac{2L}{\pi} \cos(kL/4)\, e^{-jkL/4} \tag{3}$$

where the term $e^{-jkL/4}$ is the average phase of the voltage if the phase of the incident field is zero at z = 0 and the $j\omega t$ dependence is suppressed. Equation (3) gives the differential voltage that would be induced between the wires in the "odd loop" model. For this model, however, it is usually assumed that kL << 1, so that both the cosine and exponential functions are approximately 1.0.

B. Wave Model--Magnetic Coupling

From Figure 1 and Equation (1), the induced voltage per unit length is[2]

$$\frac{dV}{dz} = j\omega\mu_o h_o H(z)\; 2\sin \frac{2\pi z}{L} \quad . \tag{4}$$

From the solution for a transmission line of finite length terminated in its characteristic impedance at one end, the open-circuit voltage at the other end is

$$V_{oc}(0) = \int_{-\ell}^{0} \frac{dV}{dz} e^{jk_p z} dz \tag{5}$$

where k_p is the differential-mode propagation factor for the twisted pair. If $H(z) = H_o\, e^{-jk_c z}$, where k_c is the common-mode propagation factor for the cable core,

$$V_{oc}(0) = -\frac{j\omega\mu_o H_o 2h_o}{k_L^2 - (k_p - k_c)^2}\; k_L \left\{ 1 - e^{-j(k_p - k_c)\ell} \left[\cos k_L\ell + j\,\frac{k_p - k_c}{k_L} \sin k_L\ell \right] \right\} \tag{6}$$

where $k_L = 2\pi/L$. For a lay length $L < 10$ cm, $k_L < 60\ m^{-1}$, and for $f < 10^8$ Hz and $v \simeq 10^8$ m/s, $k_p \simeq k_c < 2\pi\ m^{-1}$. Therefore, for all practical values of interest, $k_L >> k_p - k_c$, and

$$V_{oc}(0) = -\frac{j\omega\mu_o H_o 2h_o}{k_L}\left[1 - e^{-j(k_p-k_c)\ell}\cos k_L\ell\right] \tag{7}$$

or the maximum magnitude of the voltage is

$$V_{oc}(0) \simeq \omega\mu_o H_o h_o \frac{2L}{\pi}\quad , \tag{8}$$

which is the same as the magnitude of the voltage given by Equation (3) for the "odd loop" model. To examine the effect of the induced voltage, consider the shielded cable in Figure 2 which carries a core current of 1 A and has a common mode characteristic impedance of 10 Ω. A pair in the outer layer at a radius a will interact with the magnetic field associated with the core current as illustrated in Figure 2(b). Thus $H_o = I_o/2\pi a$ and, for a 100 Ω pair made from 1.0 mm diameter wires insulated with polyethylene, $h_o \simeq 1.0$ mm. For a lay length $L = 5$ cm, the induced voltage at 1 MHz is

$$\left|V_{oc}\right| = 5 \times 10^{-3}\ V \tag{9}$$

for $a = 8h_o$, compared with a nominal value of 10 V for the common-mode voltage on the core (and on each pair). Thus the differential voltage at 1 MHz is about 66 dB smaller than the common-mode voltage. If perfectly balanced terminations are used, the differential voltage across the termination will also be 66 dB smaller than the common-mode voltage.

Because of the $j\omega$ dependence of the induced differential-mode voltage in the frequency domain, the open-circuit voltage in the time domain is proportional to the derivative of the magnetic field, or common-mode current, and the common-mode rejection of the twisted pair cable is about 60 dB at 1 MHz, and it decreases at about 20 dB per decade as frequency increases.

Since a tubular cable shield, when properly closed at all splices and building entry points, does not permit frequencies above about 10 kHz to penetrate to the core conductors, the common-mode rejection for a perfectly-formed twisted pair should be over 100 dB for the

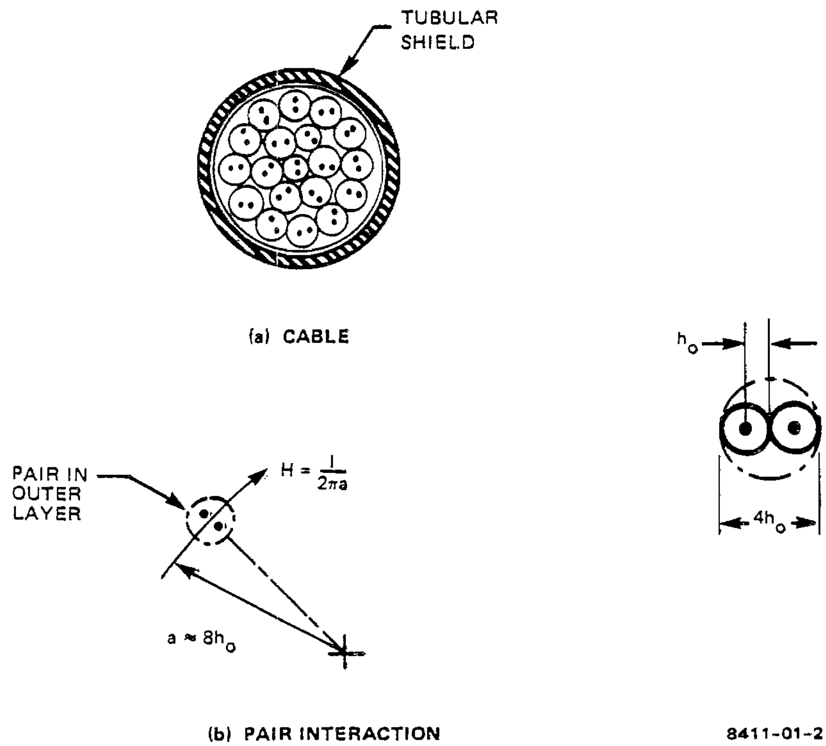


FIGURE C-2 INTERACTION OF A PAIR IN THE OUTER LAYER OF CABLE WITH THE CORE COMMON-MODE CURRENT

frequencies passing through the shield. While it is probable that minor imperfections in form can also cause common-mode conversion into differential-mode voltage, the differential-mode voltage induced on the twisted pair is probably not a major source of differential-mode interference at the frequencies passed by the shield.

It may be of interest to note that because the common-mode rejection of the twisted pair or twisted quad is so good, it is very difficult to measure. In particular, accurate measurement of the common-mode rejection ratio is extremely difficult on short samples of cable because irregularities at the ends or terminations and "odd loop" effects tend to dominate in the common-mode conversion.

III SURGE ARRESTERS AND ISOLATION TRANSFORMERS

Assume each pair from the external cable passes through a surge arrester and isolation transformer as illustrated in Figure 3(a). The common-mode characteristic impedance of the wires is represented by Z_o in Figure 3(a), and a common-mode voltge source V_c is assumed to represent the open-circuit voltage induced on the cable conductors by the EMP. The

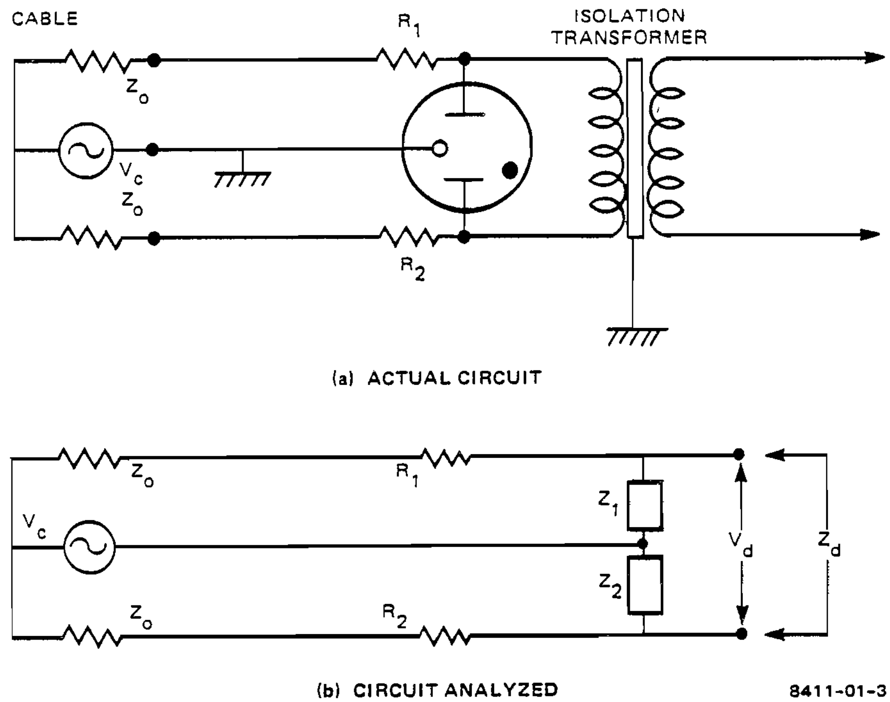


FIGURE C-3 SURGE PROTECTION DEVICES AND EQUIVALENT CIRCUIT ANALYZED

protection unit consists of a dual anode gas tube, with series 3.33 Ω resistors R_1 and R_2 to limit the current through the tube, and an isolation transformer. The resistors R_1 and R_2 may not be exactly equal; thus, some unbalance may occur from this source.

Although the circuit of Figure 3(a) is difficult to analyze accurately over a broad bandwidth and wide dynamic range because of the nonlinear gas tube and undefined properties of the transformer and ground leads, we can examine some effects on a simplified circuit such as that shown in Figure 3(b). Here we replace the gas tube, the transformer, and everything beyond the transformer by the impedances Z_1 and Z_2 between each conductor and "ground." The open-circuit voltage V_d between the two conductors (or across $Z_1 + Z_2$) is the differential voltage developed by conversion of the common-mode source V_c induced on the pair. This conversion may result from unbalance in R_1 and R_2 or in the load represented by Z_1 and Z_2. We can also compute a source impedance Z_d across the terminals to completely define the equivalent differential source.

The differential voltage V_d in Figure 3(a) is given by

$$V_d = \left[\frac{Z_1}{Z_o+R_1+Z_1} - \frac{Z_2}{Z_o+R_2+Z_2} \right] V_c \qquad (10)$$

Note that if $Z_1 = Z_2$ and $R_1 = R_2$, the circuit is perfectly balanced and no common-mode voltage is converted to differential-mode voltage.

Consider first the case in which $Z_1 = Z_2$, and the only unbalance is in the tolerance in R_1 and R_2. Then, assuming 10% resistors with maximum deviation,

$$\frac{V_d}{V_c} = \frac{Z_1}{Z_o+Z_1+R_o(1+0.1)} - \frac{Z_1}{Z_o+Z_1+R_o(1-0.1)} \tag{11}$$

and for nominal values of $Z_o \approx 100\ \Omega$, $Z_1 \approx 300\ \Omega$, and $R_1 \approx 3\ \Omega$,

$$\frac{V_d}{V_c} \approx 1.1 \times 10^{-3} \tag{12}$$

(i.e., for each volt of common mode we get about 1 mV of differential mode).

If the load impedances Z_1 and Z_2 are 1 Ω instead of 300 Ω, the conversion ratio is

$$\frac{V_d}{V_c} \approx 5.5 \times 10^{-5} \quad . \tag{13}$$

Thus a fairly large imbalance in the 3 Ω current-limiting resistors (or wire resistance) does not cause much common-mode conversion because of the large source impedance.

Now consider large imbalances in Z_1 and Z_2. If $Z_1 = 0$ and $Z_2 = \infty$ (i.e., one wire grounded and the other open-circuited),

$$\frac{V_d}{V_c} \approx -1$$

or complete conversion of the common-mode voltage into differential voltage occurs. For $Z_1 = 1$ and $Z_2 = 300$, $V_d/V_c \approx 0.73$. It is apparent, therefore, that any application in which one conductor of the twisted pair is grounded should be avoided.

The isolation transformer is intended to block the common-mode voltage and current and to pass the differential-mode signal. If the input winding were perfectly balanced and shielded from the output winding, no common-mode interference would reach the output winding. Such properties can be approached at audio frequencies, but at high frequencies minor differences in stray capacitances between the winding and ground can cause significant unbalances. The variation with frequency of the conversion ratio is shown in Figure 4 for a circuit in which the stray capacitance to ground is 100 pF on one side but only 50 pF on the other side. It is apparent that for frequencies below 20 kHz, the common-mode rejection ratio is less than 10^{-3} but at 20 MHz the rejection ratio is only 0.3; one common-mode volt produces a 0.3 differential-mode volt.

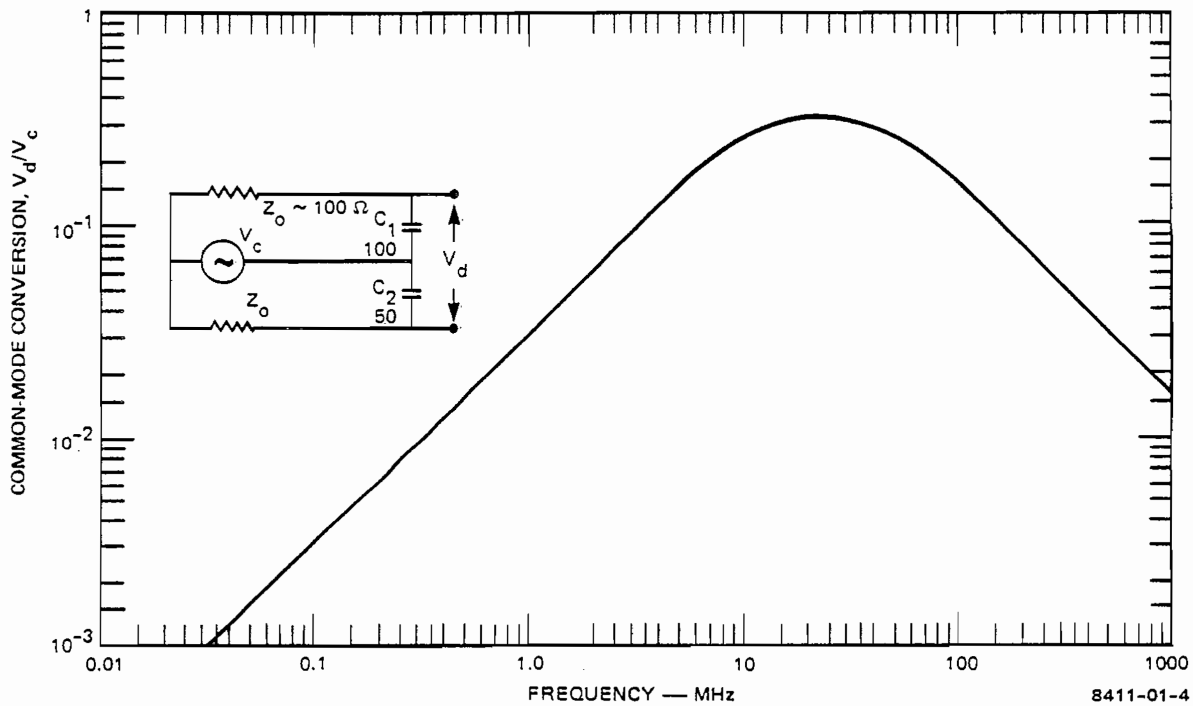


FIGURE C-4 EFFECT OF WINDING-TO-GROUND CAPACITANCE ON ISOLATION TRANSFORMER

For a final example, consider the circuit shown in Figure 5(a) in which the isolation transformer is used as a balun to couple the balanced pair to the unbalanced 600 Ω load. Here we neglect the small effects of the 3 Ω resistors and the gas tube, but consider the possibility of a 20 pF capacitance between the primary and secondary windings of the transformer. The common-mode conversion ratio is then

$$\frac{V_d}{V_c} = \frac{Z_1}{Z_o + Z_1 + 1/\omega C_1}$$

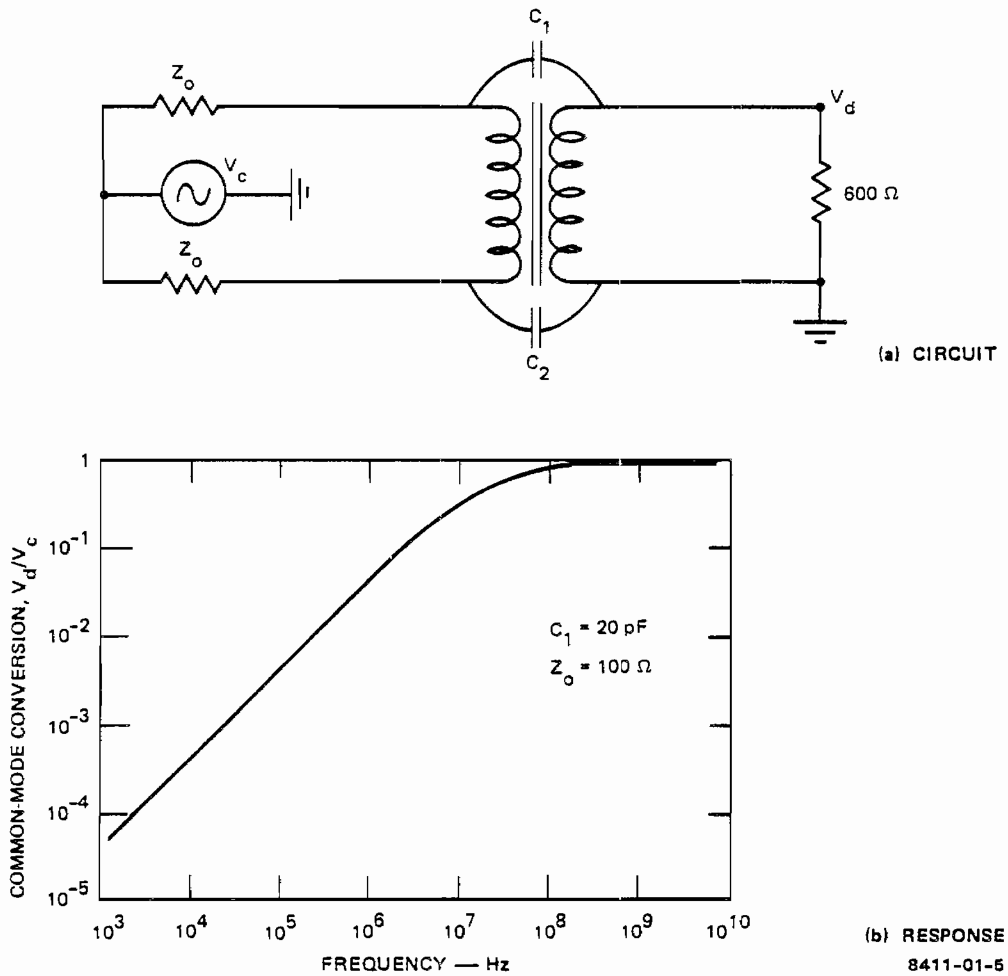


FIGURE C-5 EFFECT OF INTERWINDING CAPACITANCE ON BALUN TRANSFORMER

and, as illustrated in Figure 5(b), this ratio is less than 10^{-3} for frequencies below 20 kHz. Above 10 MHz, however, the small stray capacitance combined with the unbalanced secondary circuit causes a conversion ratio of 0.3 or larger. Note that the common-mode conversion does not depend on the value of C_2 in Figure 5(a), but only on C_1.

IV SHIELDING AND GROUNDING CONSIDERATIONS

In the analysis above, it was assumed that the cable shields were closed with the building shield and that the surge-limiter ground leads were short so that their inductance was negligible.

Because of the inductance of these cables, however, large surge currents may cause large Ldi/dt potential differences between parts of the system. If, for example, a large transient current is produced on the high-current ground cable (e.g., several surge arresters fire), then the outer end of the high-current ground cable in Figure 6 will be at a different potential than, say, the frame.

Furthermore, because of the impedance of the earth connection (which includes cable inductance as well as earth electrode impedance), the ground current in the high-current ground cable will produce a voltage $R_g i + L_g di/dt$ across the common ground impedance.[3] This voltage will drive all of the other grounding conductors at the junction in Figure 6. In particular, it will drive the TECHNICAL and SYSTEM ELECTRONICS ground cables, so that large currents from cable shields and surge arresters may flow into small-signal circuits.

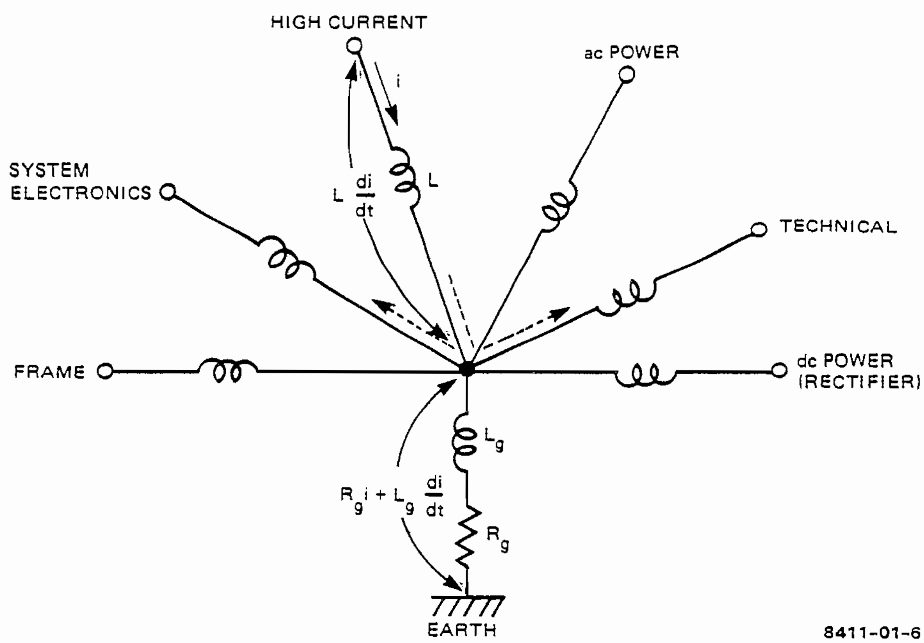


FIGURE C-6 GROUND SYSTEM COUPLING AND POTENTIAL DIFFERENCES

To examine these effects, consider first a surge on a cable shield that is connected to the frame ground. The rate of change of the EMP-induced current may be 10^9 A/s and if the inductance of the ground cable is 20 μH, the end of the cable will have a potential of 20 kV with respect to the other parts of the system. This voltage may pose insulation breakdown problems, but also of concern is the fact that the junction point in Figure 6 is raised to 10 to 20 kV (if the lead inductance of the grounding conductor is 10 to 20 μH). Thus, even if the current shown by the dotted lines in Figure 6 is small, the SYSTEM ELECTRONICS and TECHNICAL grounds are suddenly raised to potentials of 10 to 20 kV with respect to the ambient potential of the soil. Since these are parts of the small-signal electronic circuits, this coupling would be of concern if only a small fraction of the 10 to 20 kV actually appeared inside the equipment cabinet.

Because zero-inductance ground cables and zero-resistance ground electrodes are not feasible, a grounding system such as that of Figure 6 cannot prevent large fluctuations in potential and intrasystem coupling when transients such as lightning and EMP are impressed on the system. In fact, "grounding" is an electrostatic concept, designed to prevent electrostatic potential differences between components of the system. Because wavelengths at power frequencies (50 to 400 Hz) are usually much larger than the dimensions of facilities, electrostatic principles are also valid for many power safety and protection applications.

Electrostatic grounding techniques are not effective for controlling high-frequency or transient interference, however. To control such dynamic interference, the propagation of electromagnetic waves and their interaction with conductors must be controlled (these conductors may be signal conductors or grounding conductors). We must either exclude the electromagnetic waves with shields or orthogonalize the system so that it does not interact with the electromagnetic fields (e.g., use balanced twisted pair with the signal in differential mode and interference in common mode). Shielding is almost always required because complete orthogonalization is not possible in practice. Over 100 dB of interference rejection is required to reduce the EMP-induced currents to the mA levels tolerable by the small-signal electronic circuits, but only 50 dB (or less) may be achieved from conventional orthogonalization techniques. Furthermore, orthogonalization is usually effective only if the fields are controlled by shields (as inside a shielded cable). For transient interference control, therefore, it is more fruitful to think in terms of shielding or excluding electromagnetic fields and waves than in terms of equalizing electrostatic potentials (grounding).

The use of shields to control interference is illustrated in Figure 7. The first shield (Shield 1) separates the internal environment (Zone 1) from the external environment (Zone 0). The external interference environment may consist of lightning, the EMP, and other large transient and high-frequency sources of electromagnetic waves. Note that the cable shield is a part of Shield 1 and, for the shield to perform properly, the cable shield must be electromagnetically continuous with the facility shield so that current on the cable shield flows onto the outside of the facility shield (see dotted path in Figure 7) rather than into Zone 1. Also note that the only cable connection to earth is from the outside of Shield 1. No grounding conductors should be allowed to penetrate a shield because such a penetration provides a path for interference to propagate from a lower zone to a higher, more protected zone.

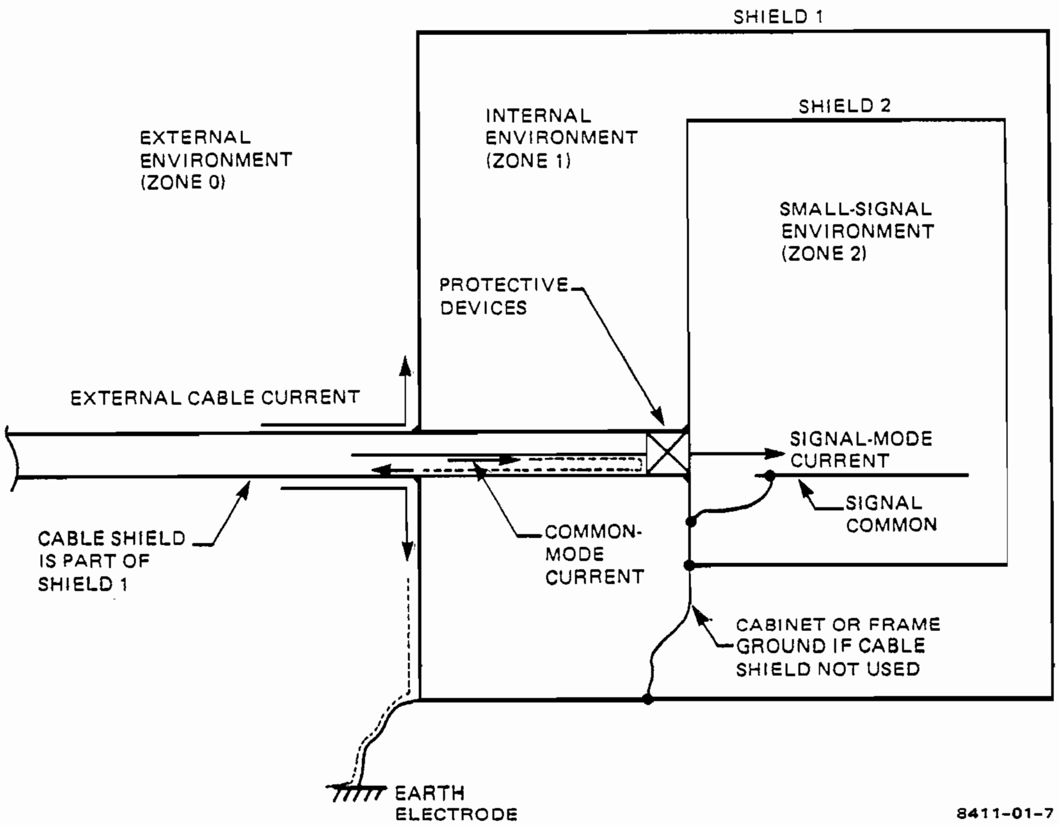


FIGURE C-7 CONCEPT OF SHIELDING FOR INTERFERENCE CONTROL

Interruption of the external cable current might also be considered as an alternative to the accommodation shown in Figure 7. However, interruption must be achieved without opening the shield, since opening the shield simply lets the external current flow onto the signal conductors in the cable core. One may consider such schemes as ferrite cores about the cable to increase its inductance. However, it must be remembered that the open-circuit voltages developed on such cables are very large (100 kV to 10 MV), so that any current-interruption scheme must be designed, fabricated and maintained to withstand such voltages. It is almost always more economical and more reliable to simply accommodate the short-circuit current on the shield as illustrated in Figure 7.

At the second shield, we may use orthogonalization to separate the differential-mode signal current from the common-mode interference induced on the cable core conductor pairs. The isolation transformers may be effective for this provided: (1) the interference spectrum does not contain high frequencies, (2) the insulation strength of the transformers is not exceeded by the common-mode interference, and (3) the transformer shields are connected by a low-impedance path to the common-mode current return (i.e., the cable shield). If the cable shield continues inside the first shield and serves as the common-mode current path for the protective devices as illustrated in Figure 7, the third condition can be met. To meet the second condition, high-quality transformer insulation or filtering may be used. The first condition will be met if the cable shield is continuous with the facility shield so that the high-frequency spectrum, is excluded.

It should also be observed that nonlinear surge limiters such as gas tubes have two characteristics that are usually undesirable. The first is that because of their nonlinear behavior, they regenerate much of the high-frequency spectrum that the shield system is carefully designed to exclude. Thus, the use of these devices in Zone 1 or Zone 2 is usually undesirable because of their tendency to shock-excite the otherwise protected internal circuitry.

The second undesirable characteristic of these devices is that they are active devices in the sense that, to function, they must change state (e.g., ionize a gas). Failure or inability to change state thus causes loss of protection, but because the device functions only under abnormal conditions, its inoperability may easily go undetected. Passive devices that produce some observable effect generally are more desirable when life-cycle maintenance and hardness assurance costs are considered. Some passive alternatives are illustrated in Figure 8.

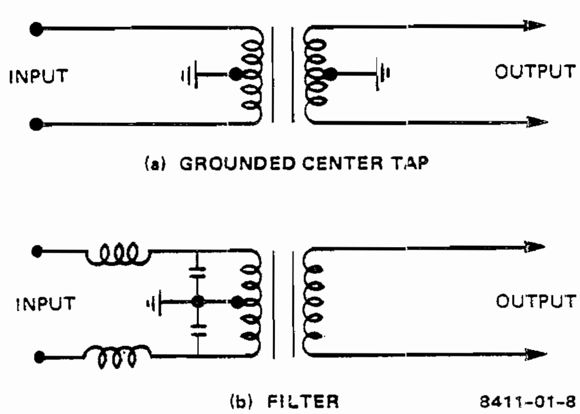


FIGURE C-8 PASSIVE ALTERNATIVES TO THE LOW-VOLTAGE GAS TUBE SURGE LIMITER

REFERENCES

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2. TERMINATION OF CABLE SHIELDS AT LOW FREQUENCIES

I INTRODUCTION AND BACKGROUND

Much has been written in the EMC literature on the problem of "grounding" the shields on shielded twisted pair or shielded single-wire circuits.[1,2] The problem is illustrated in Figure 9. It is well understood that if the shield is grounded at both ends as illustrated in Figure 9(a), the magnetic flux B from an interference source (e.g., a nearby conductor carrying a large ac current at the power frequency) will induce a current I in the shield. The current I is limited only by the impedance of the loop formed by the shield, the ground plane, and the grounding leads:

$$I \approx \frac{j\omega BA}{R + j\omega L} \qquad (1)$$

where A is the area of the loop, R is the total resistance of the loop, and L is the total inductance of the loop. It is assumed that most of the resistance and inductance will be contributed by the cable shield.

For a typical twisted shielded pair routed near a ground plane, the resistance per unit length, R', is about 10^{-2} Ω/m and the inductance per unit length L' is about 0.3 μH/m. Thus, the corner frequency at which $R' = \omega L'$ is

$$f_1 = \frac{R'}{2\pi L'} \approx 5 \text{ kHz} \qquad (2)$$

if all of the impedance is attributed to the cable shield. Since the loop area A is the product of the cable length ℓ and its height, h, above the ground plane, the shield current at ac power frequencies ($R' >> \omega L'$) can be written

$$I \approx \frac{j\omega Bh}{R'} \quad . \qquad (3)$$

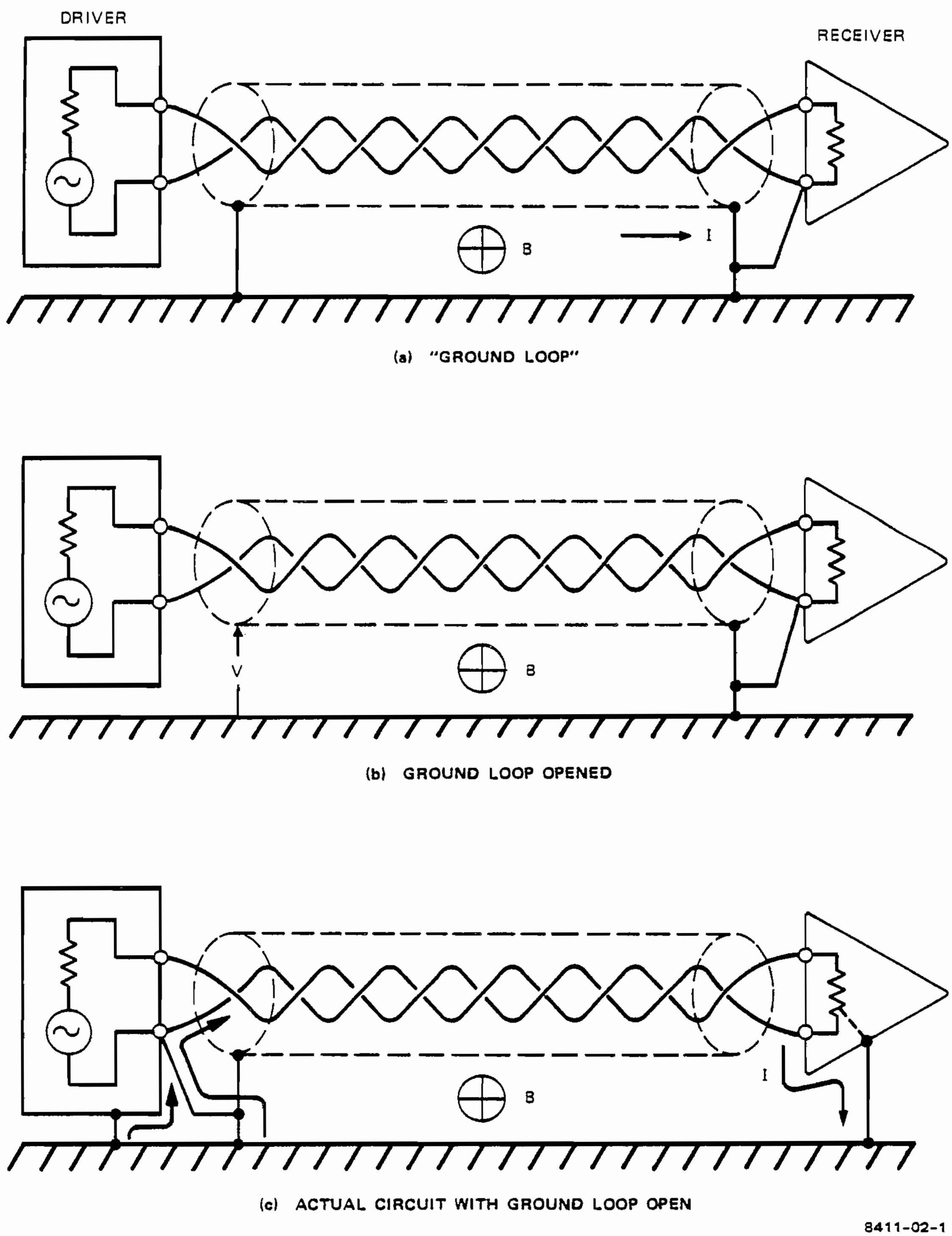

FIGURE C-9 ILLUSTRATION OF CONVENTIONAL SHIELD "GROUNDING" PROBLEMS WITH TWISTED SHIELDED PAIRS

If B is the magnetic flux produced by a conductor, 1 cm above the shield, carrying 10 A at 400 Hz as in Figure 10, the current I will be about 0.25 A in the shield, and the open-circuit voltage

$$V = R'\ell I \approx j\omega Bh\ell \tag{4}$$

will be about 0.025 V for a cable 10 m long. This 0.025 V is the maximum 400 Hz voltage that can appear between the pair of conductors and the shield. At 400 Hz the loop current is limited by the shield resistance rather than by the loop inductance. Therefore, it can be deduced that the shorted-turn effect is small and that the voltage induced in the shield is also induced as a common-mode voltage on the pair. However, in Figure 9(b) the wire-to-shield voltage is nil throughout the length of the cable (at 400 Hz) because the same voltage is induced in both the shield and the wires in Figure 9(a). On the other hand, grounding the shield at both ends causes a part of the open-circuit voltage to appear between the wires and shield at the left end. Only for a perfectly conducting ground plane

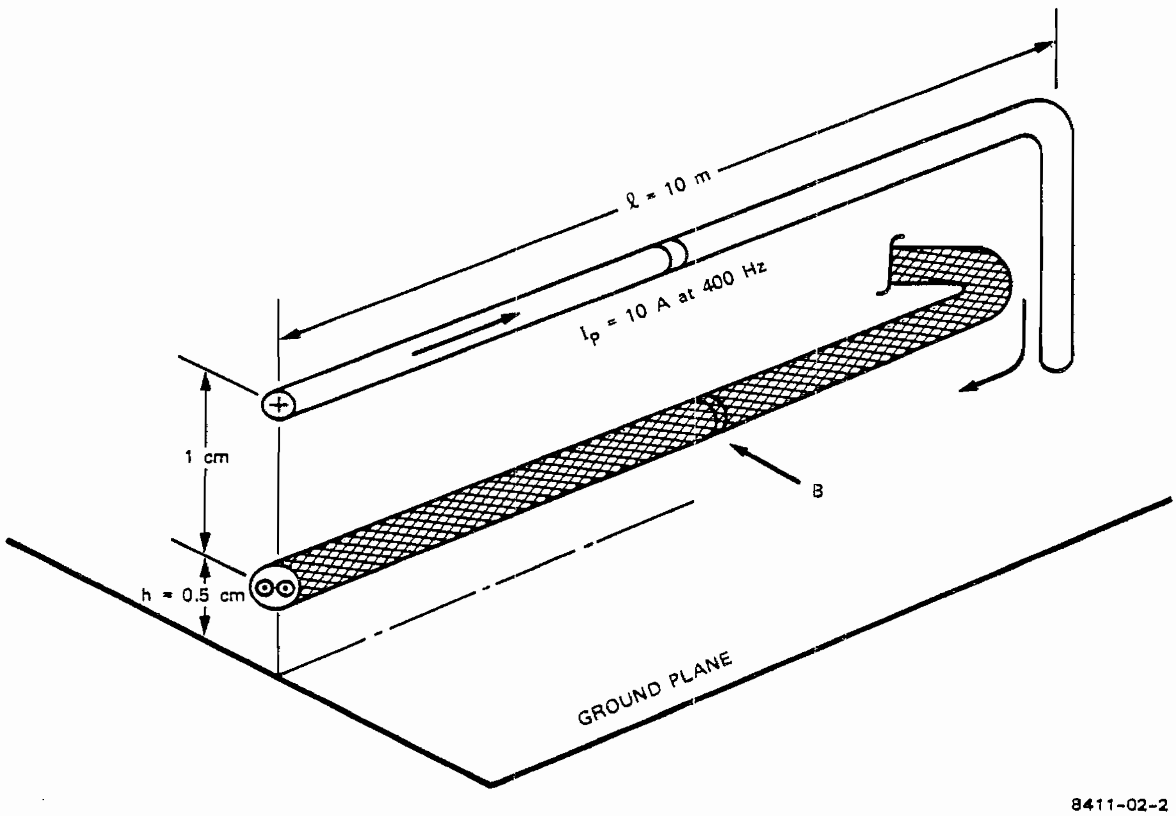

FIGURE C-10 CONFIGURATION ASSUMED FOR ac POWER CONDUCTOR AND TWISTED SHIELDED PAIR and zero-impedance grounding conductors will all of the open-circuit voltage V appear between the wires and the shield.

The examples of Figure 9(a) and (b) are simplifications that probably do not exist in complex facilities. The case shown in Figure 9(c) may be more representative of a practical circuit in which cabinet grounds and stray capacitances between circuits and cabinets are present. The shield may be inadvertently grounded at both ends, and one wire of the twisted pair may be grounded at both ends. Note that if the shield is not grounded at both ends, the induced current is forced to flow on the signal conductors.

If balanced, twisted pairs with balanced terminal circuits are used, the common-mode interference can be very effectively rejected from the signal circuits.[3] In all of the circuits illustrated in Figure 9, however, the signal circuit has been deliberately unbalanced by grounding one of the wires at one end. Thus the 60 dB or more of 400 Hz interference reduction potentially available from common-mode rejection in a balanced circuit has been wasted in these examples. The interference reduction that can be achieved at 400 Hz from common-mode rejection in a balanced circuit is much greater than can be achieved with any manipulation of cable shield ground connections.

II TOPOLOGICAL APPROACH

Let us now examine the shielded cable problem in the light of shield topology.[4-7] Topologically, none of the shields shown in Figure 9 are closed. All of these shields are open at both ends, and all have the most serious of compromises — insulated conductors crossing the shield surface. Therefore, the cable shield does not constitute an electromagnetic shield in the topological sense.

To be an electromagnetic shield in the topological sense, the shield must be closed at the ends. This can be accomplished by enclosing the driver and receiver in shields (e.g., closed metal cabinets) and joining the cable shield to these terminal-circuit shields as illustrated in Figure 11. For electrical safety, one or both of the circuit shields may be grounded (i.e., connected) to other metal structures in the facility and to earth. Also, note that in Figure 11 the balanced receiving circuit inside the shield is grounded inside the shield through its neutral point, so that its common-mode rejection capabilities can be utilized.

Because isolating metal equipment cabinets from structural ground requires unorthodox practices (e.g., the installation of insulating mounting hardware),* the shield would normally be grounded through the cabinet at both ends. That is, the dashed ground connection

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*However, Bell Telephone purports to do this in their switching centers.

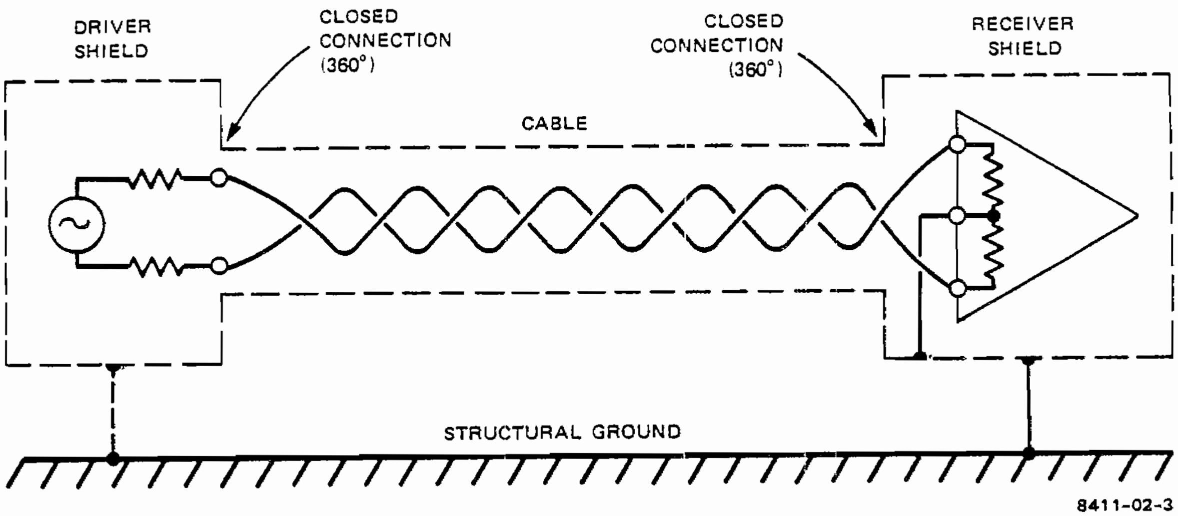

FIGURE C-11 TOPOLOGICALLY CLOSED ELECTROMAGNETIC SHIELD OVER BALANCED TWISTED SHIELDED PAIR

between driver shield and the structural ground in Figure 11 would normally exist, and a "ground loop" consisting of the cable shield, circuit shields, and structure would be formed. Any spurious magnetic field linking this loop will induce a current in the cable shield. Although it is desirable to minimize this current so that the excitation of flaws in the shield can be minimized, it should be emphasized that the proper approach is to open the shield circuit by eliminating the dashed ground connection, rather than to open the shield by disconnecting the cable shield from the driver shield (cabinet).[4,5]

Quantitatively, the voltage given in Equation (4) will be induced between the driver shield and ground if the dashed ground connection in Figure 11 is removed. Then the current flowing in the shield system is nil, and only electric field shielding is required of the shield system. (In fact, the current will not be zero; assume, instead, that it is the current through a 200 pF capacitance between the driver shield and structural ground. At 400 Hz the capacitive reactance is 2 M Ω, and the current induced by the 10 m long, 10 A source cable would be 18 nA. This current would produce no more than 1.8 nV common-mode voltage between the twisted pair and the shield!)

If the dashed ground connection is not removed, and it is assumed that the impedances of the driver and receiver shields and the structural ground are small compared to the cable shield resistance, the current in the cable shield will be given by Equation (3) and the maximum voltage (common-mode) that could be developed between the pair and the shield, given by Equation (4), is, again, 0.025 V for the 10 m long, 10 A example. Well-balanced circuits should reduce the differential-mode voltage to at least 25 μV. Further reduction in the induced interference voltage can be achieved by:

(1) Using a separate additional driver shield that is "floating" inside grounded driver cabinet

(2) Using twisted pair for power as well as for small signals

(3) Segregating power (or other noisy cables) from small signal cables.

In applying the first method, we are topologically removing the dashed ground connection in Figure 11 and building a grounded cabinet around the driver shield as illustrated in Figure 12. This is a very effective method since it eliminates the current flowing through the shield. The driver shield, when arranged as in Figure 12, is often called a guard shield.

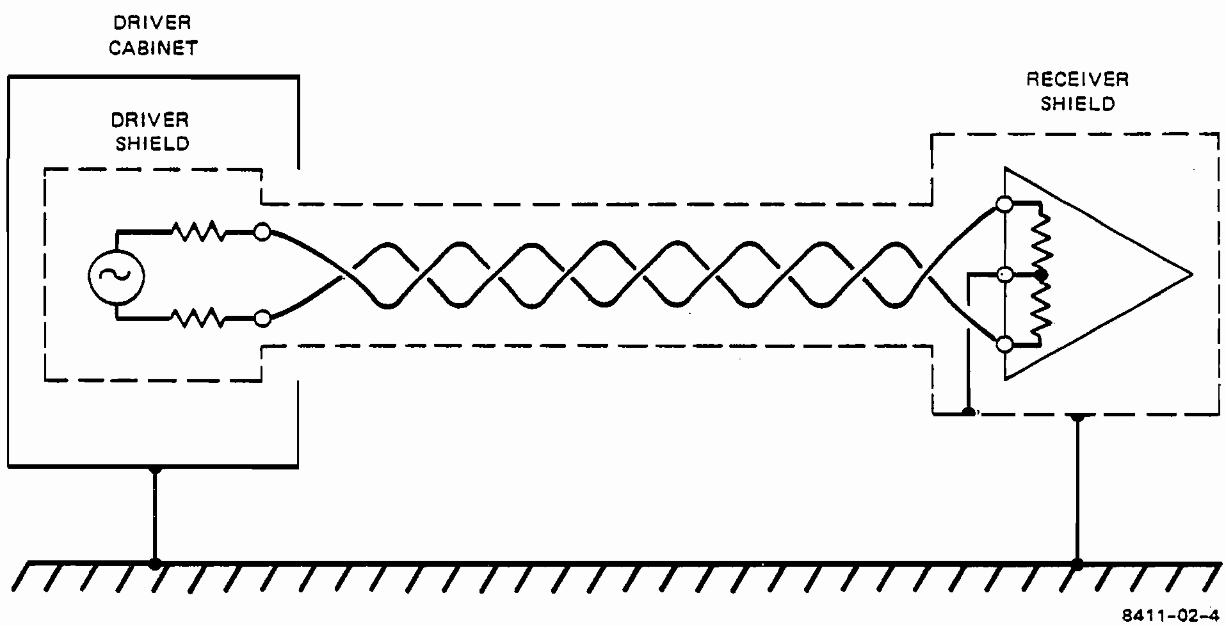

FIGURE C-12 TECHNIQUE FOR MINIMIZING SHIELD CURRENT WITHOUT COMPROMISING SAFETY GROUND ON DRIVER CABINET

The second method is an attempt to control the source of the interference. Since the use of twisted pair for ac power will greatly reduce excitation of the form illustrated in Figure 10, this method can also provide a large reduction in power frequency interference

(40 to 60 dB). However, some building wiring cannot be treated in this manner; hence, the maximum benefit of this approach may not always be realizable.

The benefit that can be realized from segregating power and signal wiring varies widely according to the techniques used. If the height of the power conductor in Figure 10 is increased, the excitation is reduced as the logarithm of the separation, and the improvement is barely detectable even when large separations are used. Greater improvement is observed if power and signal wiring are separated laterally rather than vertically, as in Figure 10. Placing power and signal conductors in separate, closed steel conduits or cable trays is also effective. This method is most effective, however, if two-wire power wiring is used so that the ac power return current does not flow on the structural ground.

It is important to note that when the arrangement of Figure 11 (without the dashed ground) or Figure 12 is used, one need not be concerned about the voltages induced in the shield grounding leads, since these are not a part of the signal circuit. Such voltages are worrisome in circuits such as those in Figure 9(a). In the circuits of Figures 11 and 12, it is also immaterial how the voltage across the cable shield is developed — it can be induced by a magnetic field as illustrated in Figure 10, or by an IR drop across a poor bond in the ground plane, or by any other mechanism. Thus, although the analysis has been performed assuming a magnetic field linking the loop, any other source of voltage would have a similar overall effect.

III CONCLUSIONS

Application of topological shields to low-frequency shielding problems will provide more effective protection against ac power frequency interference than the best present shield grounding techniques. The topological approach has the further advantages that the rules for its application are simpler and the same shield system is effective for high frequencies and transients as well as low frequencies. In addition, great improvements in the performance of circuits using shielded twisted pair could be realized with either current practices or the topological approach if the common-mode rejection capability of shielded twisted pair were more widely utilized. The common practice of grounding one wire of the twisted pair allows all of the common-mode interference to be converted into differential-mode interference.

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3. SHIELD DEGRADATION BY PENETRATIONS AND APERTURES

I INTRODUCTION

The effectiveness of an electromagnetic barrier is not limited by the material used as the barrier, but rather by the openings and penetrations necessary for access and communications. To support theoretical calculations we have carried out some simple experiments in the laboratory. This memorandum describes the setup used, and some of the results obtained. Despite the difficulties which arose mostly due to resonances which could not be eliminated, the results support the theory that any untreated penetrating conductor (and this includes grounding conductors) is a far more serious violation of shield integrity than apertures, cracks, and the like.

II BASIC SETUP

A chamber made of mild sheet steel of 0.8 mm thickness was used to simulate an arbitrary but well-defined electromagnetic barrier. The chamber is 2.13 m high, 2.74 m wide, and 2.42 m deep. The seams are bolted together with an equivalent overlap of about 2 cm. The chamber was set up 13 cm above a ground plane of aluminum sheets riveted together. The wall thickness of the chamber is approximately five times the skin depth at 1 MHz. The average shielding effectiveness as measured by the amplitude reduction of a double exponential driving pulse was about 60 dB. While this is not a high-performance shield it is a perfectly adequate electromagnetic barrier for the experiments described below.

The chamber was driven near the center of one side wall, with the return conductor connected to the center of the opposite wall and the ground plane. The driving pulse was produced by a FRP 50 high-voltage pulse generator; the pulse had a rise time of about 40 ns, and a decay time of about 2 μs. While this pulse shape resembles a high-altitude EMP, the purpose of the pulse was merely to obtain a reasonably wide band in the frequency domain. Figure 13 schematically illustrates the basic setup. The Appendix lists all of the instruments used in the experiments.

Many different sensors could have been used to measure the response on the inside of the chamber. We decided to use the largest loop which could be fitted inside the chamber. Ideally, we would like to measure the responses of a set of system conductors to the shield excitation. However, frequently such conductors are not installed, or are not available at the time a measurement of the effectiveness of the shield is required. We must then simulate a system conductor, or devise a conductor that will have a response at

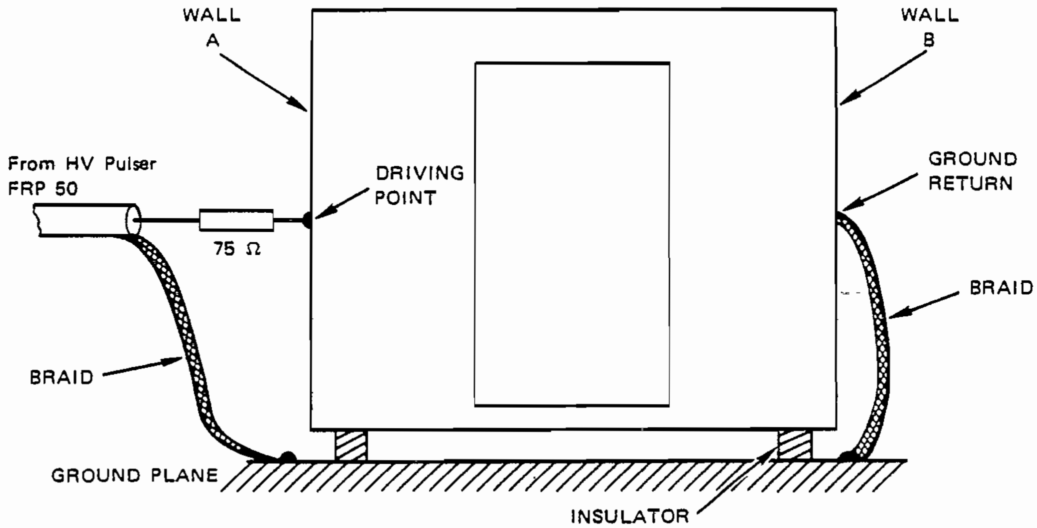


FIGURE C-13 BASIC SETUP FOR EXPERIMENTS

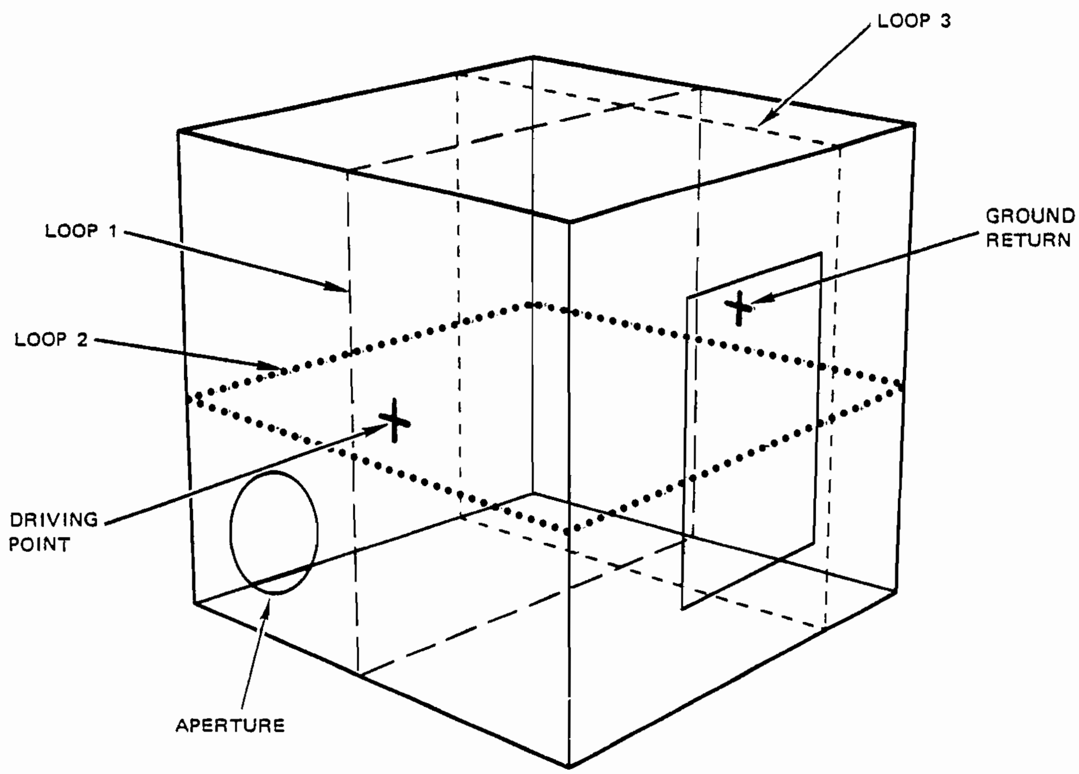


FIGURE C-14 SCHEMATIC REPRESENTATION OF PICK-UP LOOP LOCATIONS. The aperture shown is normally closed. Compare this illustration with Figure 1. The loops were mounted 2.5 cm from the inside walls.

least as large as the system conductor. It was postualted that the largest loop that could be installed inside the shield would provide such a response. To obtain measurements in three orthogonal planes we actually used three loops, each spaced 2.5 cm from the inside walls. These loops are indicated in Figure 14, together with the identification number assigned to each loop. We measured open-circuit voltage and short-circuit current for each configuration (only peak values were measured). This sensor arrangement assures that the results represent an integrated response.

The shielding effectiveness of the chamber itself in the basic configuration was not measured because all barrier violations (described below) were compared to the pulse amplitude measured inside the chamber in the basic configuration, that is, without any penetrations or apertures. (We have estimated that the walls will attenuate signals by about 60 dB over the frequency range of interest: 0.1 to 100 MHz).

III BARRIER VIOLATIONS

A. Penetrating Conductors

To simulate a penetrating ground conductor, the return lead was connected to the inside of the wall by a small pigtail with a radius of 5 cm. The peak value of the short-circuit current in this configuration was 25 mA for loop 1, whereas in the basic configuration it was only 5 mA. The open-circuit voltage increased only by a factor of 2, but a large amount of ringing (presumably due to direct coupling between the pigtail and loop 1) make an exact reading impossible. Loop 2 also showed a factor of 2 increase in signal, and loop 3 showed no increase. However, in all three cases a resonance around 25 MHz is evident, which indicates a substantial loss of shielding effectiveness. The resonance could not be excited when the return conductor was connected to the outside of the chamber, that is, when the barrier was closed.

To investigate the dependency of signal strength on the length of the pigtail, the return conductor was also connected to the back wall (equivalent to a pigtail 1 m in length), to the wall which was driven by the pulse generator (2 m pigtail), and to the same point but with the return conductor following the walls and floor (4 m pigtail). The results of the measurements for these five configurations with loop 1 are presented in Table 1.

The results shown in Table 1 should be interpreted with caution; the numbers represent typical losses in performance, but they are of course dependent on the geometry of the entire experiment. However, in the cases where we were able to obtain data for loop 2 and 3 we found that the results obtained with loop 1 are confirmed, at least in a qualitative sense. The measurement of the peak of a double exponential pulse does not characterize the loss in shielding effectiveness in a unique manner, but to obtain complete information on the performance loss, CW measurements covering the entire band of interest have to be taken, preferably with a network analyzer. However, such measurements are time-consuming and did not fit into the simple test plan used at this time.

B. Filter Location

Filters used to harden a facility or an individual item of equipment against EMP are usually installed at the proper location — at the shield interface, with the input terminal "outside" and the output terminal "inside" — and the filter case is circumferentially bonded to the equipment case. In other EM disciplines the filter (or a combination of surge arrestor and filter) is not always mounted properly, and we conducted an experiment to show the loss in performance that might be expected. We used a combination of a surge arrestor and a filter because the latter component would have been destroyed by the 15 kV pulse produced by the FRP 50. With the filter properly mounted at the interface and the surge arrestor outside (see Figure 15) we obtained an open-circuit voltage of 80 mV in loop 1, the same value obtained with no penetrations. With both the filters and surge arrestor mounted inside the chamber, we measured 15 V peak-to-peak ringing, even though the penetrating lead was kept very short (about 3 cm).

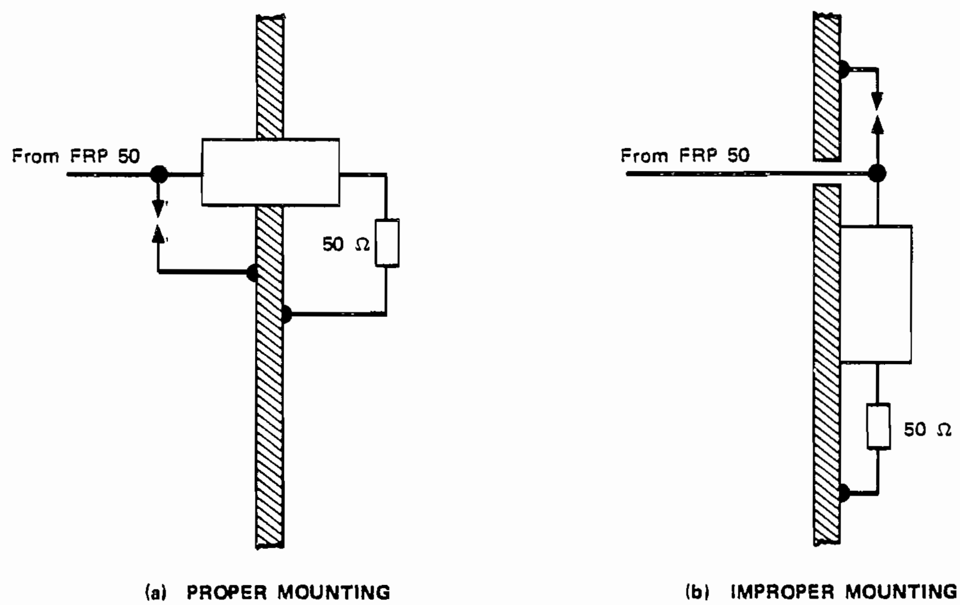
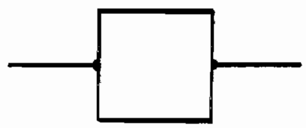
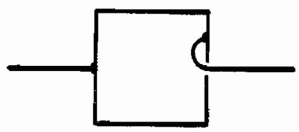
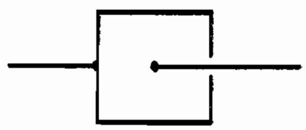
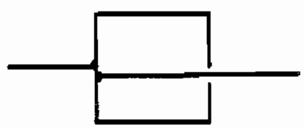
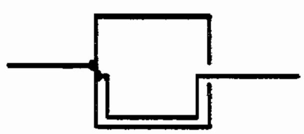


FIGURE C-15 FILTER MOUNTING LOCATION. The wall shown corresponds to wall A in Figure 1.

Table 1

LOSS OF SHIELDING EFFECTIVENESS DUE TO CONDUCTOR PENETRATION
(Open-circuit voltage V_{oc}, and short-circuit current I_{sc} are shown for loop 1)

Experiment*	V_{oc}	I_{sc}
	80 mV	5 mA
	150 mV	25 mA
	2 V	200 mA
	16 V	0.6 A
	>16 V	1.5 A

*The setup is shown schematically. Only the location of the ground return is varied. In all but the first experiment the driver was connected to the outside of the shield and the return to the inside of the shield as shown.

C. Apertures

In devising and ranking hardening techniques, it is necessary to know the importance of various types of violations or deviations from ideal design. To compare performance degradation due to a penetrating conductor to the degradation due to an aperture in the shield we cut a hole of 30 cm diameter into a side wall of the chamber. To ensure maximum excitation of the aperture we placed the aperture in the wall which was driven by the pulse generator. We conducted three experiments. First, the baseline (closed barrier) was repeated for reference. This was followed by one experiment with the aperture open, but no penetration, and one with the aperture closed, but with the ground return penetrating the shield (that is, with the ground return connected to the inside of the shield with a short pigtail). The results obtained with loop 1 as the sensor are shown in Table 2. The 30 cm aperture increased the noise level inside the chamber by only 4 dB, but the penetration caused an increase of 18 dB. It is clear from these measurements that the penetration is a much more serious violation of the barrier than the aperture.

Table 2

COMPARISON OF APERTURE AND PENETRATION
(Values are given for loop 1 open-circuit voltage and short-circuit current)

Experiment	V_{oc}	I_{sc}	Degradation
Closed barrier: ground return on outside, aperture closed (Reference)	80 mV	2 mA	0 (Ref.)
Ground return on outside; aperture open	160 mV	3 mA	4 dB
Ground return on inside (pigtail); aperture closed	>1 V	15 mA	18 dB

D. Pipes and Conduits

In EMP-hardened facilities pipes and conduits are usually circumferentially bonded to the shield they penetrate. However, in other EM disciplines a pigtail is often used. While this method of bonding is adequate for dc, it certainly is improper as far as transients are concerned. The impedance of the pigtail cannot be made low enough to prevent some of the transient noise from entering the shielded volume. To make matters worse, the pigtails may be located inside the shielded volume, allowing a large amount of the noise to enter the supposedly protected volume.

We conducted a set of experiments to demonstrate the loss in performance which might be expected. A 1-in. pipe was mounted in wall A (Figure 13) and allowed to penetrate 1 m inside the chamber. Measurements were taken with the pipe firmly and circumferentially bonded to the shield, and with the pipe insulated at the point of entry but bonded with a short pigtail either on the outside or the inside of the chamber. The signal as measured by the short-circuit current in loop 1 increased by 17 dB when comparing the pigtail on the outside to the circumferentially bonded pipe, and by 9 dB when comparing the pigtail on the inside to the one on the outside.

IV SUMMARY

The simple experiments conducted so far clearly demonstrate the importance of penetrations. To our knowledge no experiments of this kind have ever been performed, although the proper treatment of penetrations is thought to be known, at least in the EMP community. Our results not only substantiate theoretical expectations, but they also indicate that it is not meaningful to spend a great deal of effort treating apertures with sophisticated screens, honeycombs, and the like when, at the same time, untreated conductors such as signal ground conductors are permitted to penetrate a shield. We do not mean to imply that aperture treatments are unnecessary or that they are not beneficial, but only that it is more cost effective to first eliminate unnecessary penetrations, filter the ones which are necessary, and then deal with apertures and cracks in an equipment shield, an equipment cabinet, or a facility shield.

Appendix to Appendix C

INSTRUMENTATION USED IN THE EXPERIMENTS

Sensors	Largest loops as described in text
Current probe	P6021
Voltage probe	P6046 (with ×10 attenuator)
Oscilloscope	Tektronix 454A
Shielded instrument box	SRI
High-voltage pulser	FRP 50: 5 ns risetime, 2 μs decay time (with 75 Ω termination as used in the experiments the rise time was 40 ns); peak voltage used: 15 kV.

Appendix D

SYSTEM GENERATED TRANSIENTS

1. Introduction.

One of the important characteristics of an effectively impervious barrier is that it reduces the effect of sources on one side of the barrier to a level smaller than system generated interference on the other side of the barrier. Thus, the effects of these sources are masked by the ambient noise produced by the system and are either undetectable or produce less effect on the system than the routinely generated system transients. It is important, therefore, to estimate the magnitude of these routinely generated transients, since these transients set an upper bound on the amount of imperviousness required of the barrier.

As was observed in Section III-B, power switching and processing (rectification, inversion, conversion, regulation) probably produce the largest transients that occur routinely inside a facility. Therefore, switching phenomena will be analyzed to demonstrate the nature of these transients. Heavy loads such as air conditioners, space heaters, water heaters, etc., are switched on and off several times each day to regulate temperature. Inductive loads such as solenoid actuated devices, relay coils, motor and transformer windings are also energized and deenergized frequently. Other devices, such as rectifiers, converters, inverters, and even fluorescent lights, produce switching transients at the 60 Hz (or some multiple thereof) rate. In the following paragraphs, some of these switching transients are analyzed.

2. Early-Time Switching Transients.

Consider the internally generated interference caused by ac power switching and processing. Such noise originates in the space between the facility barrier and the equipment barrier — it is not reduced by either barrier in reaching this volume of interest. Transients are generated on power conductors whenever an appliance is turned on or off. This action is illustrated in Figure D-1, where the circuit, the slow 60 Hz wave, and the transient charging and discharging waves are shown. Because the 60 Hz wavelength is 5000 km, the entire energized part of the circuits is at approximately the same potential before the switch closes. If the 120 V (170 V peak) circuit is energized at the peak of the 60 Hz wave, as illustrated in Figure D-1(b), an 85 V charging step propagates down the energized circuit and an 85 V discharge wave propagates toward the 60 Hz source

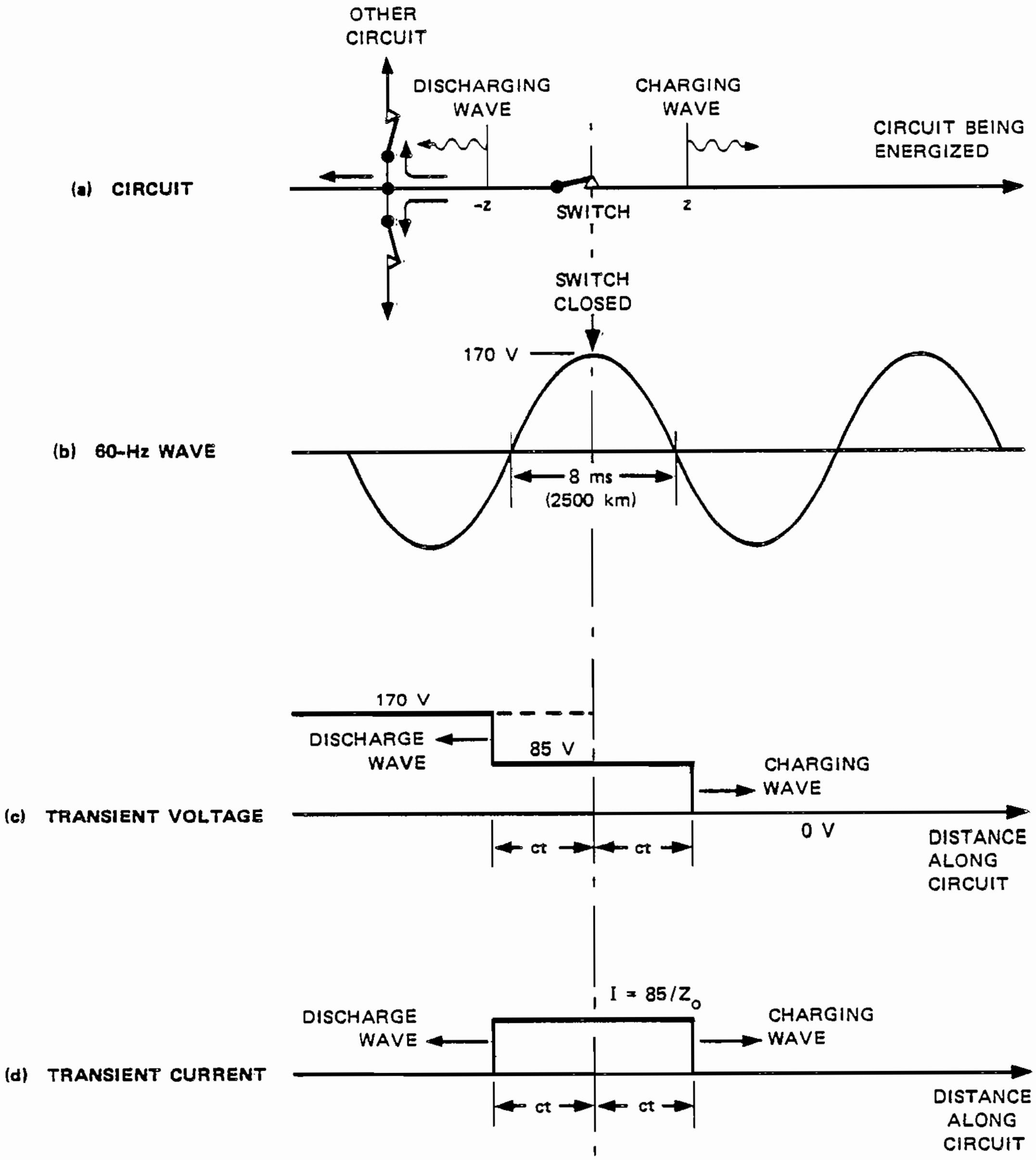


FIGURE D-1 INTERNALLY GENERATED INTERFERENCE CAUSED BY ac POWER SWITCHING AND PROCESSING

[(as illustrated in Figure D-1(c)]. When the discharging wave reaches the branch point in Figure D-1(a) where other circuits are connected to the supply system, part of the discharge wave will propagate to these other circuits. Thus, both the circuit being energized and other circuits served by the same supply will experience a transient as a result of this switched load.

A similar analysis can be made using circuit currents. Observe that the current in the charging wave will be V/Z_o, where V is the charging voltage (85 V in Figure D-1) and Z_o is the characteristic impedance of the wiring to the circuit being energized. A discharge current wave flowing in the same direction will propagate toward the 60 Hz source, as illustrated in Figure D-1(d). When the charging waves reach the end of the circuit being energized, a reflection occurs and the reflected wave sweeps across the circuit. A similar action occurs with the discharging wave and, after many reflections from the circuit ends and discontinuities, a steady state is reached.

For a simple circuit consisting of a resistive source, wiring of length ℓ, and a resistive load, two time regions (illustrated in Figure D-2) are of interest. In the early time regions, individual reflections from the load and source impedances are apparent as the current builds up in the load. The steps last $2\ell/c$ (approximately 67 ns for a 10 m wiring circuit). In the intermediate time region, the wiring can be represented as a lumped capacitance $C \approx \ell/Z_o c \approx 333$ pF for a 100 Ω line that is 10 m long. (The line behaves as a capacitor because the impedances R_1 and R are assumed to be much larger than the characteristic impedance Z_o; had they been smaller than Z_o, the line would have behaved as a lumped inductance.) This capacitance is exponentially charged toward $V_o R/(R+R_1)$ through the resistor R_1 in parallel with R. The charging time constant is $\tau \approx R_{11}C \approx 0.17$ μs when $R_1 = R = 1000\ \Omega$ and

$$R_{11} = \frac{R\ R_1}{R + R_1} \approx 500\ \Omega \quad .$$

The example used here is easy to analyze and plot because the finite line length and high-resistance load and source impedances cause neat stairsteps in the early-time waveform. A more representative case encountered in practice, however, consists of a load that appears to be a small inductance in the early time regions. Then, if $L/Z_o < 2\ell/c$, significant decay occurs between reflections and a very complicated (but commonly observed) waveform such as that shown in Figure D-3 results. In the intermediate time region, a damped oscillation at a frequency determined by the line length and the load inductance is developed (we have again assumed a source impedance large compared to the characteristic impedance Z_o). An even more realistic waveform is obtained if the source impedance is about equal to the characteristic impedance and several additional branches of different lengths are connected to the source so that additional reflections and characteristic times occur in the response. The response then becomes very complex and contains several major frequency bands.

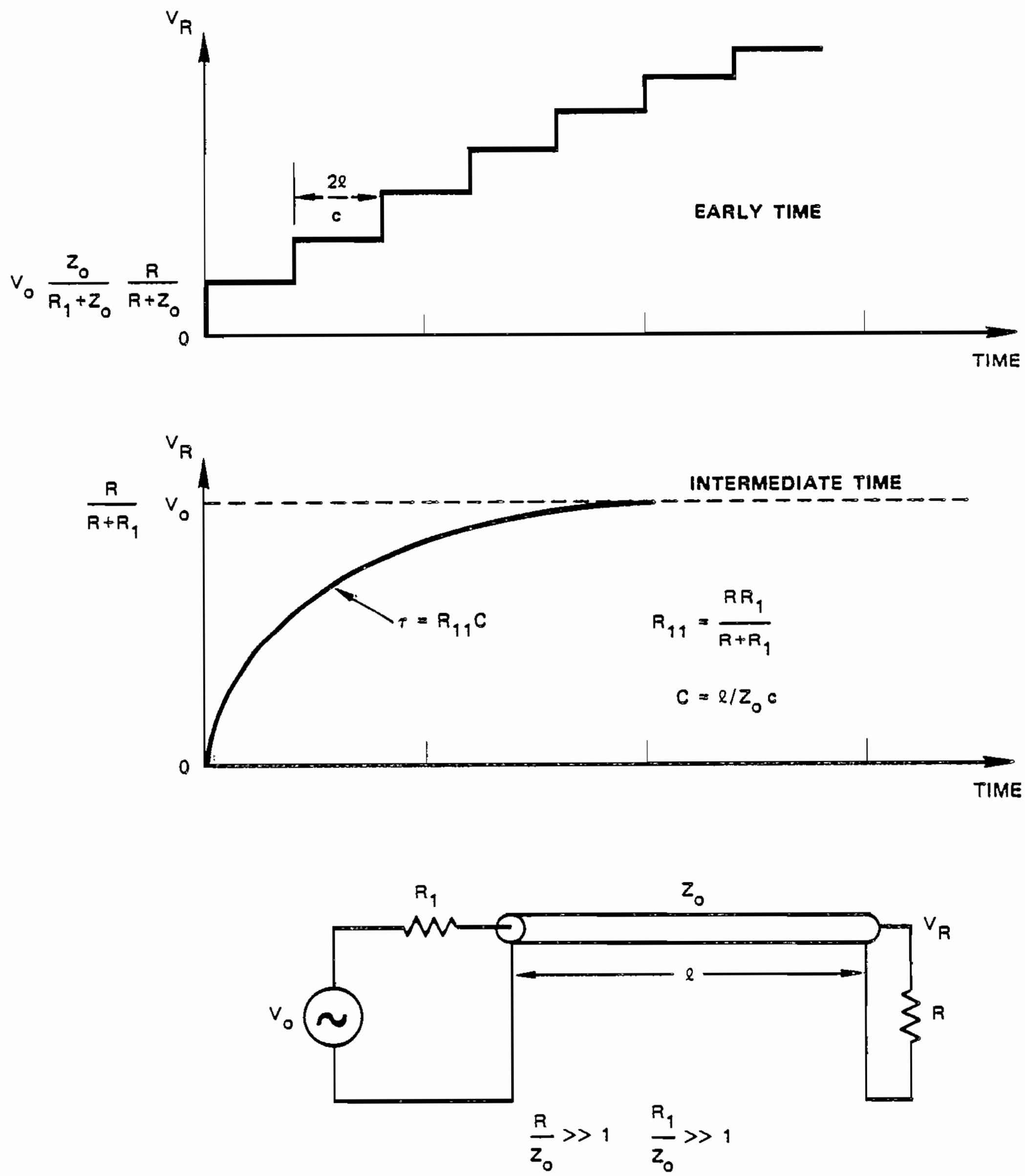


FIGURE D-2 CHARGING TRANSIENTS ON SWITCHED RESISTIVE POWER CIRCUIT

It is apparent from these examples that peak voltage changes of the order of the peak 60 Hz supply voltage can be expected from switching appliances on or off. Such transients occur in the early time regions regardless of the 60 Hz impedance of the load (they may actually occur several times because of contact bounce on switch closure). These step function transients are then modified by multiple reflections from the circuit terminations and junctions of the switched circuit and all other circuits fed from the same supply bus.

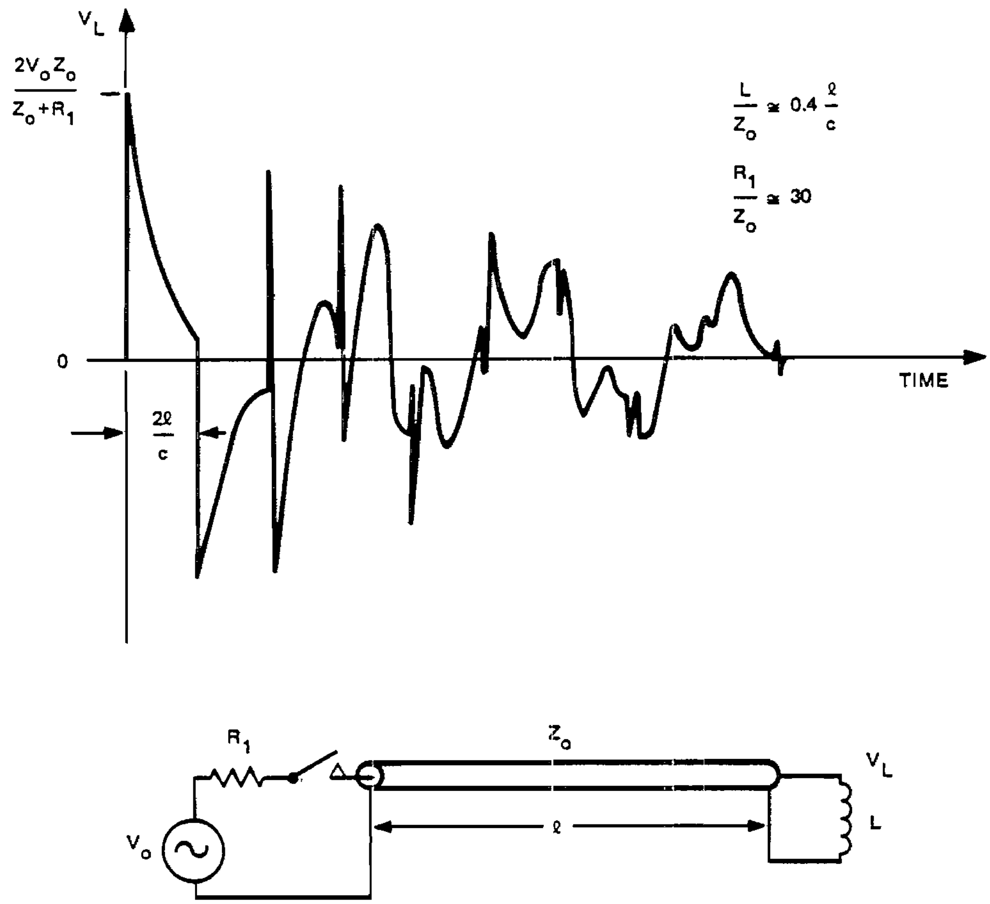


FIGURE D-3 CHARGING TRANSIENTS ON SWITCHED INDUCTIVE POWER CIRCUIT

3. Late-Time Switching Transients.

In the very late time (milliseconds), the classical 60 Hz transients may occur. At this time all of the nanosecond and microsecond transients from the early and intermediate times have usually been damped out, and all circuits appear to be electrically small. Then we can consider only lumped resistance and inductance (Figure D-4). If the switch closes when the source voltage is at its peak value, the current through the circuit will be

$$i(t) = \frac{V_o}{R(1 + \omega_o^2 t^2)} \left[\sqrt{1 + \omega_o^2 \tau^2} \cos(\omega_o t - \phi') - e^{-t/\tau}\right]$$

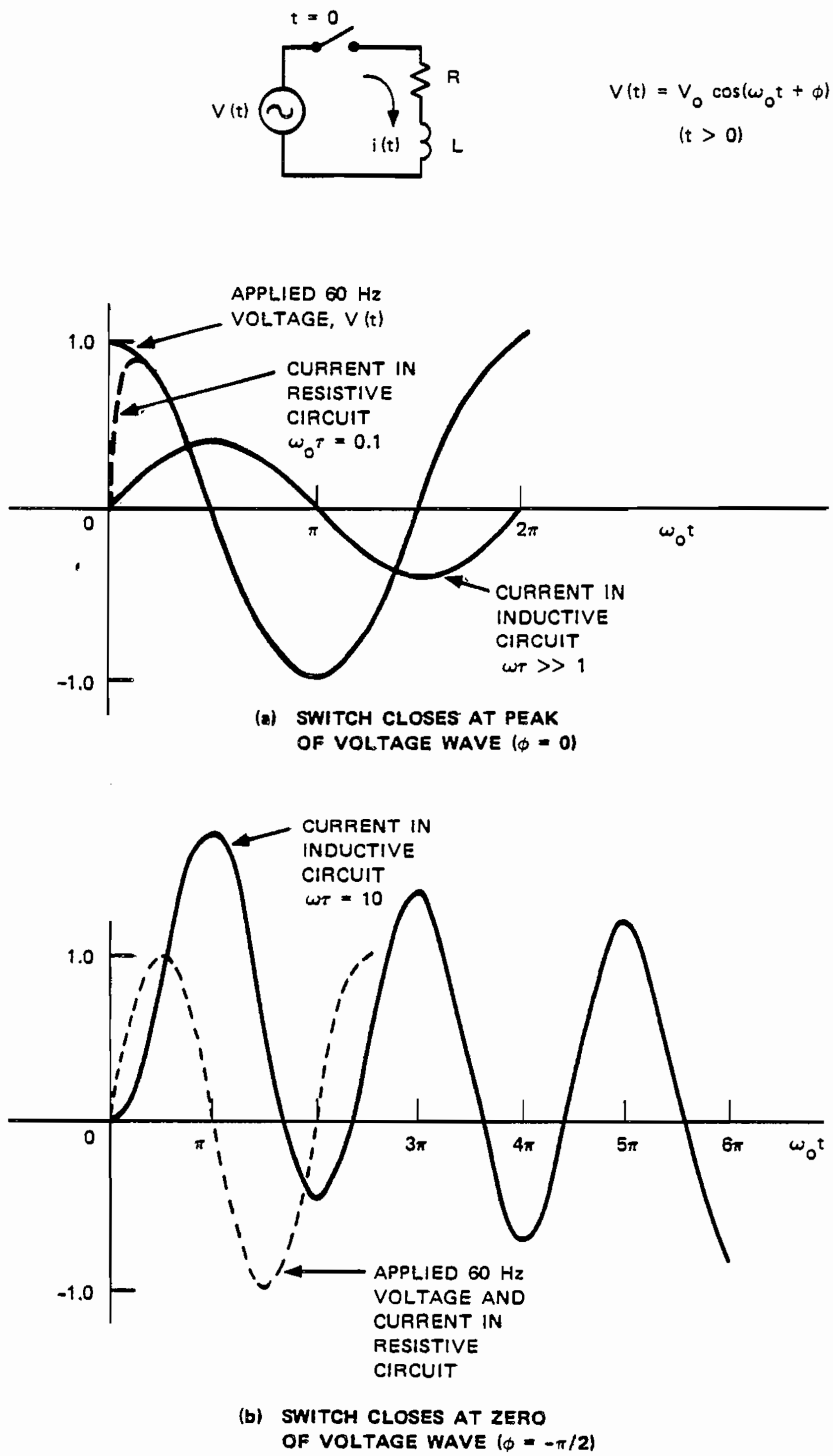


FIGURE D-4 LATE-TIME TRANSIENTS ON SWITCHED POWER CIRCUIT where $\phi' = \tan^{-1}(\omega_o\tau)$, $\tau = L/R$, $\omega_o = 2\pi f$, and $f = 60$ Hz. The applied voltage is $V_o\cos\omega_o t$ for $t > 0$.

For a high-Q circuit, $\omega_o L/R = \omega_o\tau >> 1$ and

$$i(t) \simeq \frac{V_o \sin\omega_o t}{\omega_o L} \qquad (t > 0) \quad .$$

Thus, the phase of the current lags the voltage by 90° and the magnitude of the current is the ratio of the voltage to the inductive reactance. There are no transient effects because the switch was closed when a current zero would have occurred.

For a low-Q (noninductive) circuit, $\omega_o L/R = \omega_o\tau << 1$ and

$$i(t) \simeq \frac{V_o}{R}\,[\cos\omega_o t - e^{-t/\tau}] \qquad (t > 0) \quad ,$$

which contains an exponential transient in addition to the steady-state current. However, because of the condition $\omega_o\tau << 1$, $\tau << 1/\omega_o$, the transient vanishes during the first half-period of the 60 Hz wave as illustrated in Figure D-4(a). There is no overshoot in the transient response.

If the switch closes when the 60 Hz voltage is zero, the current in the load is

$$i(t) = \frac{V_o}{R(1 + \omega_o^2 t^2)}\,[\omega_o\tau e^{-t/\tau} + \sqrt{1 + \omega_o^2\tau^2}\,\cos(\omega_o t + \pi + \phi'')] \qquad (t > 0) \quad ,$$

where $\phi'' = \tan^{-1}(1/\omega_o\tau)$. For a low-Q load impedance ($\omega_o\tau = Q = \omega_o L/R << 1$),

$$i(t) \simeq \frac{V_o \sin(\omega_o t)}{R} \qquad (t > 0)$$

and no transient is produced because the voltage and current are in phase for a resistive load. For an inductive load impedance, however, the current has a significant transient represented by the exponential term in

$$i(t) = \frac{V_o}{\omega_o L} [e^{-t/\tau} - \cos \omega_o t] \qquad (t > 0) \quad .$$

Since $\omega_o\tau >> 1$ for this case, the time constant τ may be many periods of the 60 Hz wave. As illustrated in Figure D-4(b) for $\omega_o\tau = 10$, the current in the inductive load displays a large overshoot (~75% for $\omega_o\tau = 10$) and has not subsided after three periods of the 60 Hz wave. For very inductive circuits, the transient peak current can approach twice the steady-state peak current and the transient can last for many periods.

The current spectra for each of the switch closing points and for several time constants are shown in Figures D-5 and D-6. In either case, the current magnitude decreases very rapidly above the line frequency (e.g., 60 Hz).

4. Inductive Loads.

Many appliances and devices that have primarily inductive impedances are found within typical facilities. Some examples are motors, relays, and solenoid-actuated devices (valves, time-clocks, vending machines, etc.). When such devices are energized, the current behaves as described in the preceding sections. When the switch is opened, however, the intermediate- and late-time transients may be quite different from the switch-closing transients.

When the switch opens the circuit containing the inductive load, there is a voltage Ldi/dt developed across the inductive device by the collapse of the current (di/dt). This "inductive kick," as it is sometimes called, can be quite large if the inductance is large and the switch opening time is short. While the transient voltage produced by closing a switch seldom exceeds the supply voltage (unless there is sufficient capacitance to cause resonances), opening the switch in a relay or solenoid circuit can produce voltages many times the size of the supply voltage.

The analysis of the switch opening is much less exact than that of the switch closing because the phenomena that determine di/dt during the switch arcing and arc extinguishing are nonlinear and not thoroughly understood. Nevertheless, an important difference between contact closing and opening can be identified. During closing, the maximum voltage between the contacts is the line voltage, and this voltage is not sufficient to ionize the air

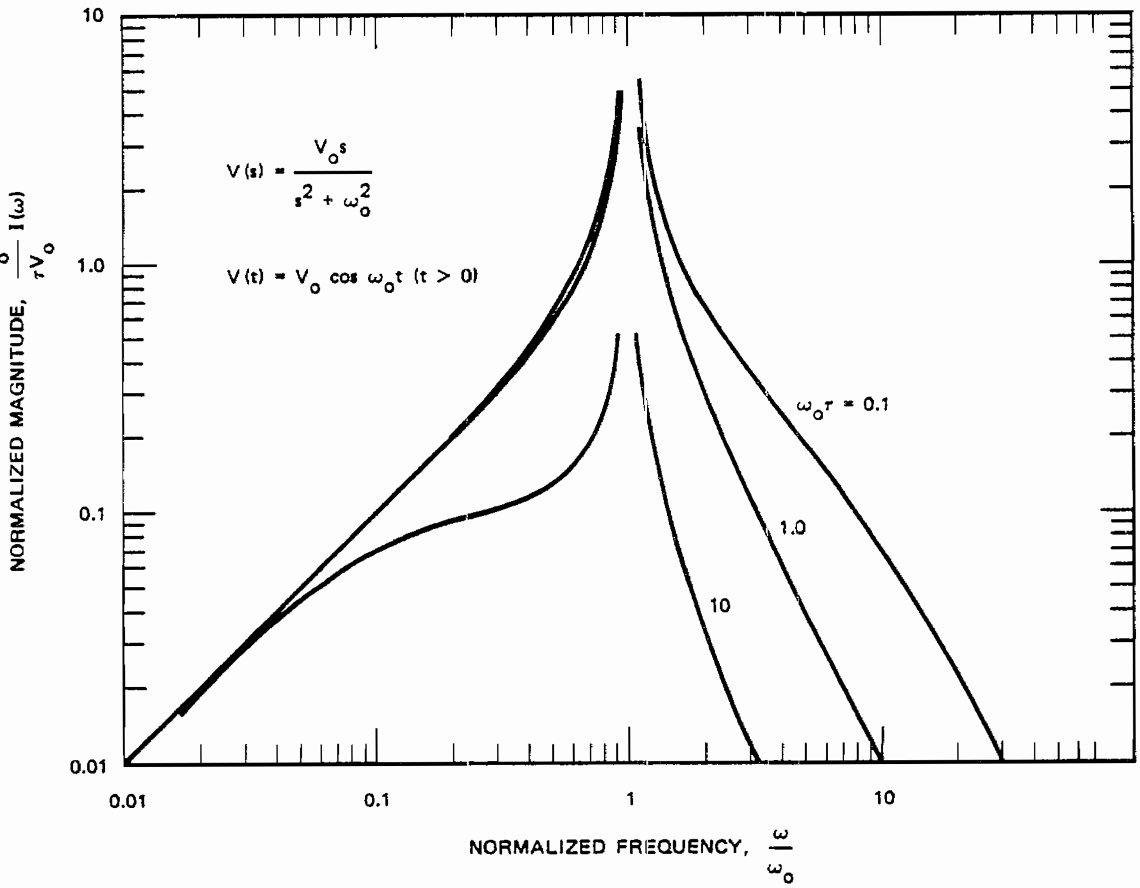


FIGURE D-5 SPECTRUM OF LATE-TIME TRANSIENTS WHEN VOLTAGE IS SWITCHED AT PEAK

between the contacts until immediately before physical contact is made. The current building up and the Ldi/dt voltages are determined mostly by the linear circuit resistance and inductance, as has been assumed in the intermediate- and late-time analyses.

During contact opening, however, the current tends towards zero when physical contact breaks, but this produces an Ldi/dt voltage across the contacts, which ionizes the space between the contacts and allows current to continue through the arc. As the contacts separate, the arc length increases and its resistance increases somewhat (but not in proportion to its length). The arc is sustained by the Ldi/dt voltage (part of which is dropped across the circuit resistance). This voltage is sufficient to sustain the arc only as long as the current is decreasing ($di/dt \neq 0$). Eventually the current goes to zero and the arc extinguishes completely. This sequence of events[6] is illustrated in Figure D-7. Thus, the effective switch opening time is not zero, but it may be much shorter than the time con-

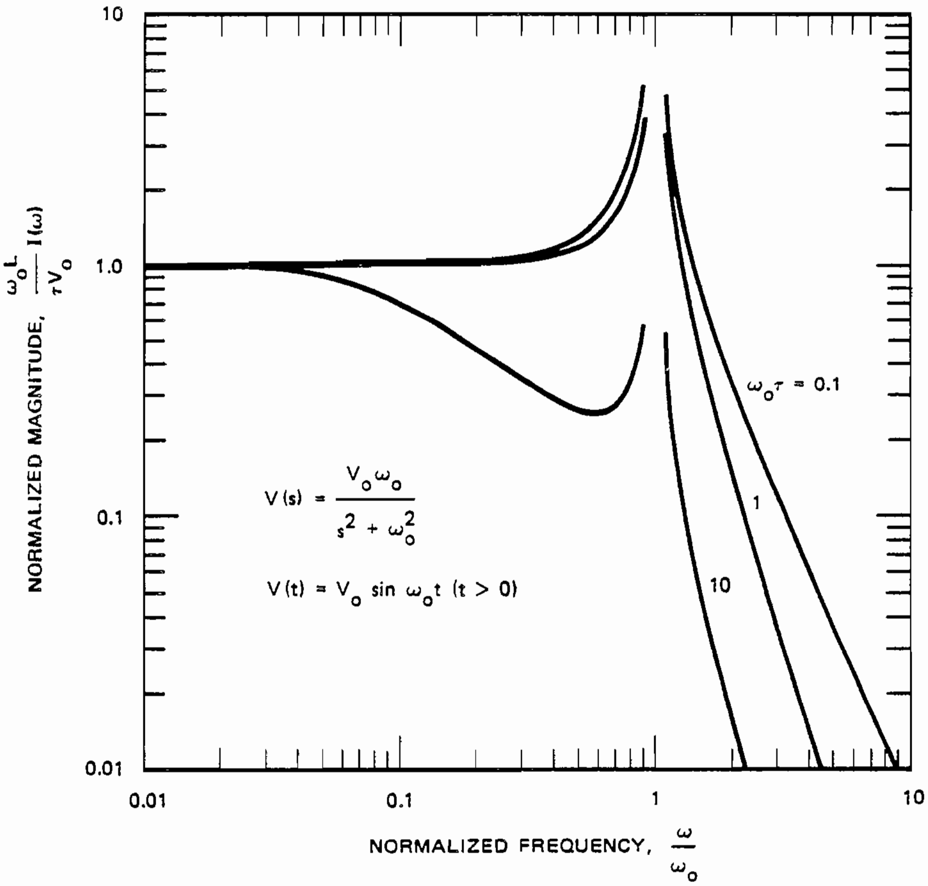


FIGURE D-6 SPECTRUM OF LATE-TIME TRANSIENTS WHEN VOLTAGE IS SWITCHED AT ZERO

stant L/R of the circuit because of the addition of the nonlinear resistance of the arc.

From such inductive devices, transient voltages of several hundred to a few thousand volts can be induced on 120 V power conductors. In principle, these transients are generated on the circuits being disconnected and are not delivered to the remainder of the power distribution system. However, because the switched circuit wiring may share the same conduits and gutters with other circuits, the transient frequently finds its way to other parts of the facility.

5. Lighting Loads.

Incandescent lamps with tungsten filaments draw much larger initial currents than their equilibrium operating currents. The operating temperature for tungsten filaments is

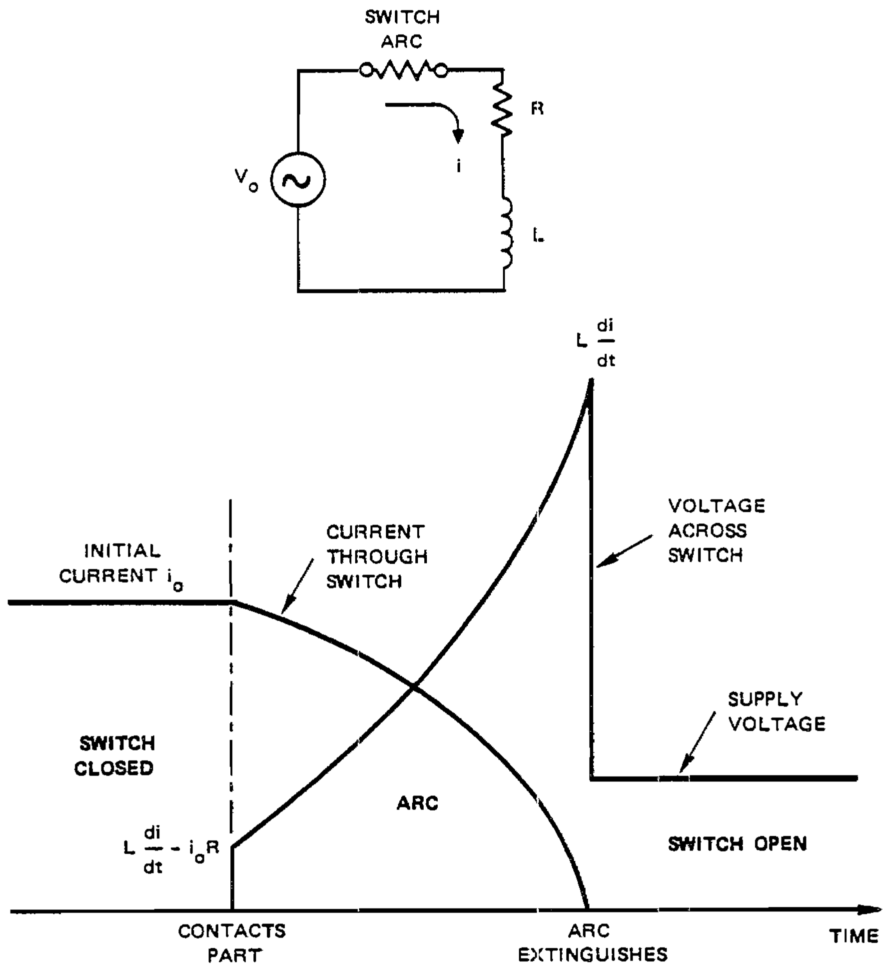


FIGURE D-7 TRANSIENT PRODUCED BY OPENING AN INDUCTIVE CIRCUIT

usually 2500°C or greater, and at this temperature the resistance of the filament is 10 to 15 times its resistance at room temperature. The time required to reach 90% of the steady-state operating temperature is tens to hundreds of milliseconds — a few to several periods of the 60 Hz wave. Filament resistance, temperature, and current calculated for 120 Vdc applied across the filament (assuming no heat losses) are shown in Figure D-8.

Although the current risetime is assumed to be zero in Figure D-8, the early-time phenomena discussed above will occur during the nanosecond region, and the series inductance of typical wiring may cause the current risetime to be a few microseconds or longer. The peak current observed in a typical installation may therefore be somewhat smaller than that shown for zero risetime.

Fluorescent lights, which are low-pressure mercury arc tubes, produce distortion of the current during normal operation. Because the low-pressure arc tube is a nonlinear device that virtually extinguishes and restrikes each half-period of the power frequency, the

TUNGSTEN FILAMENT

Resistivity at 20°C:	$5.6 \times 10^{-6}\ \Omega$ cm
Temperature coefficient of resistivity:	$0.0045\ (°C)^{-1}$
Specific heat:	0.035 cal/g°C
Specific gravity:	19
Length:	5 cm

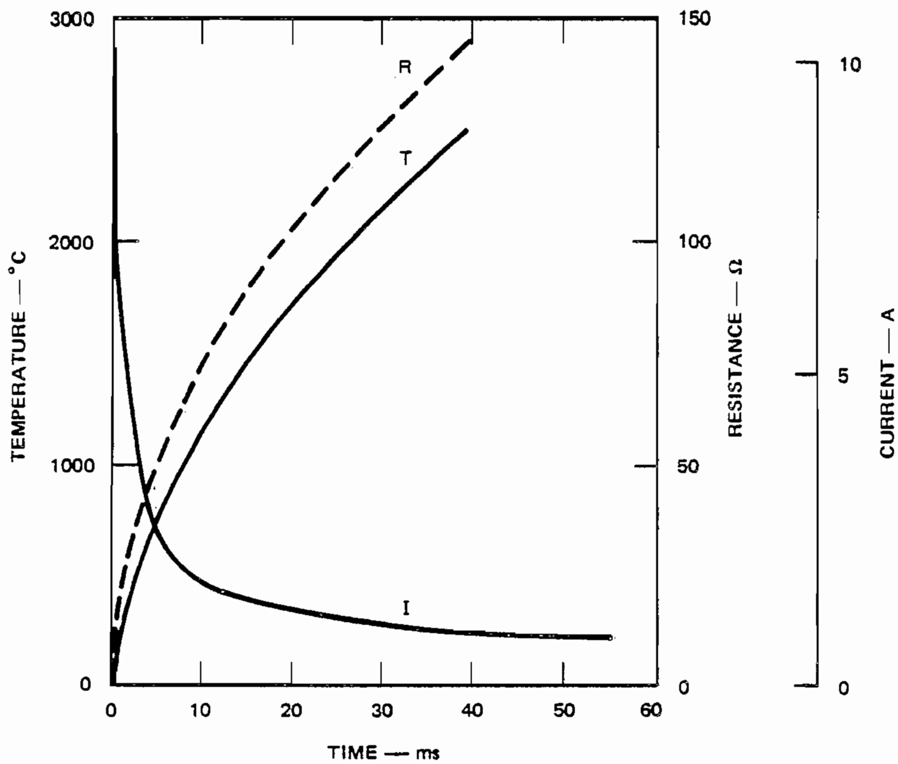


FIGURE D-8 APPROXIMATE FILAMENT RESISTANCE R, TEMPERATURE T, AND CURRENT I WHEN A 100 W INCANDESCENT LAMP IS TURNED ON

current through the tube resembles the current through a gas tube full-wave rectifier. Crude RFI suppression is provided in some fluorescent light ballasts with capacitors across the tube. The interference produced by operation of the fluorescent lamps is rich in the harmonics of the ac power supply frequency. Starting fluorescent lamps causes transients in the voltage across the tube, but the starting currents are modest.

6. Rectifiers.

Facilities requiring large quantities of dc power and facilities using "uninterruptible power systems" contain polyphase rectifiers that frequently produce interference rich in the harmonics of the ac supply frequency. As with fluorescent lights, this noise is continuously present.

The dc output of the rectifier is often filtered so that it is not a source of interference to the dc equipment. However, the rectifier also produces interference on the ac supply because of the nonlinear behavior of the rectifier. The ac supply lines may also be filtered if the rectifier causes malfunctions in other equipment. Frequently, however, the rectifier transformer provides sufficient isolation so that malfunctions in associated equipment are avoided. In spite of this, the ambient noise delivered to the power mains may be quite large.

7. Miscellaneous Sources of Interference.

There are, of course, many other sources of interference inside a facility. Doorbells, buzzers, copying machines, electrostatic discharges, welders, etc., all contribute to the noise environment inside a facility. In the hospital environment, diathermy machines are notorious sources of interference. In communications facilities, high-power transmitters and modulators are often the source of large interference signals. In areas where moving belts, dust, or aerosols can produce charge separaton, large electrostatic discharges can occur. Vehicle ignition systems produce similar high-voltage, moderate energy discharges that interfere with electronic circuits.

Aside from the electrostatic discharges, which are often unpredictable, and the high-power RF sources, which are usually known and may even be shielded, these sources are usually smaller in peak value than the switching transients described above. Therefore, the peak voltages and currents normally encountered in a facility will be determined by these switching transients and will normally be proportional to the supply voltage. That is, the switching transients in a 240 V system will be roughly twice as large as those in a 120 V system.

The fluorescent lights, rectifiers, and the multitude of miscellaneous sources contribute to the ambient broadband noise that exists long after transients from the energizing of individual circuits or the de-energizing of solenoids have disappeared. This background noise is not ordinarily capable of damaging equipment, but because it is a factor in determining the signal-to-noise ratio on equipment signal lines, it may affect the performance of the equipment.

8. Distribution of Transients.

The transients associated with switching ac or dc power are generated on the power wiring and can propagate throughout the power system to all equipment supplied from the switched power system. That is, transients of the type illustrated in Figures D-1 through D-4, modified by the transmission properties of the wiring, may be seen at the power terminals of any equipment in the facility. Experienced equipment designers are aware of this and routinely install filters on the incoming power leads. Thus, transients do not usually affect commercial equipment, but occasionally equipment designed by the inexperienced is found to malfunction.

A more subtle and insidious path for these transients to enter the equipment is on the signal and control wiring. Because the transient currents and voltages induced on the power wiring possess large derivatives, they are easily coupled to nearby signal and control wiring through mutual capacitance (Cdv/dt) and mutual inductance (Mdi/dt), as illustrated in Figure D-9. Thus, signal wiring routed in the same cable tray or in the same bundle as the power wiring will be exposed to this derivative coupling. Note that since the time domain operators d/dt transform to $j\omega$ in the frequency domain, the high-frequency interference spectrum is emphasized by the mutual coupling process — regardless of the equipment operating frequencies.

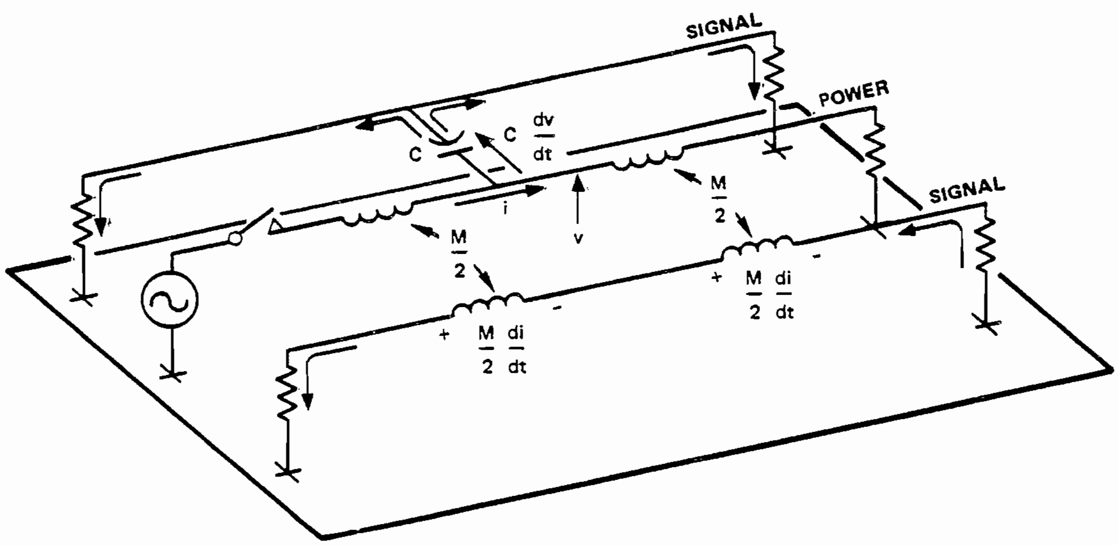


FIGURE D-9 MUTUAL COUPLING BETWEEN POWER WIRING AND ADJACENT SIGNAL WIRING

The mutual coupling can be reduced by keeping power wiring separate from signal wiring, by shielding the signal wiring (but only with closed shields), and by using balanced twisted pairs and common-mode rejection for signal wiring and/or power wiring as well as traditional filtering and other after-coupling treatments. Experienced designers use these techniques generously to control "crosstalk" between the power and signal circuits.

Another subtle path by which the interference may enter the electronic circuits is through an ill-conceived grounding system. This mechanism is illustrated in Figure D-10, where a commonly used perversion of the single-point grounding system serves as an interference distribution system. The transient produced by switching the circuit on the left of Figure D-10 propagates in the transmission line mode between the black and white wires. As indicated by the arrows and dotted lines, a portion of the transient propagates onto the "signal reference" that has been (unnecessarily) installed to "ground" the electronic circuits in the equipment on the right. Although the conductor serves no useful purpose, it does provide a path for interference to propagate virtually unattenuated from the ground point G into the electronic circuit inside the equipment cabinet. As was mentioned in Section I, this grounding conductor violates the closed barrier topology; it must be eliminated or treated in some manner so that the barrier is preserved. (However, since this grounding conductor serves no useful purpose, installing it and then treating it to make it acceptable adds cost but no benefit.)

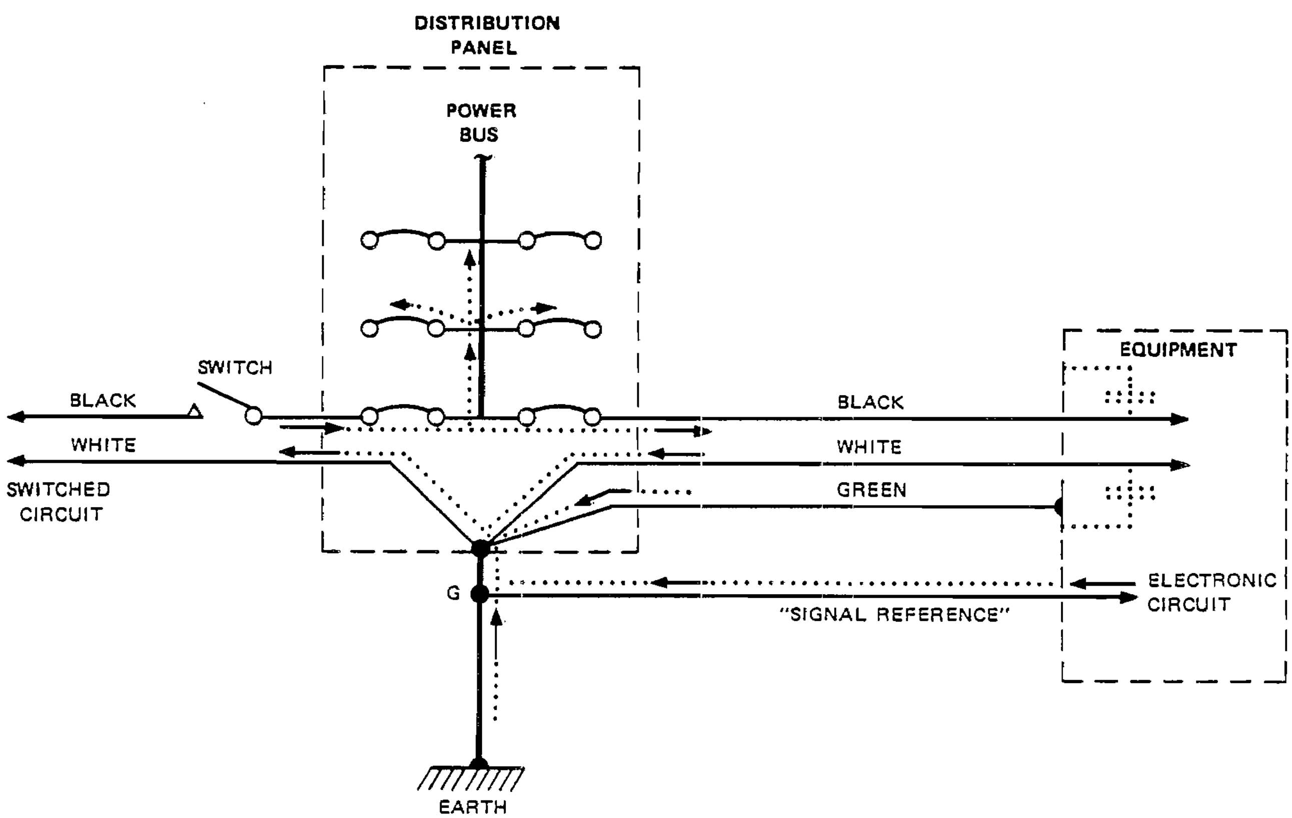


FIGURE D-10 INTERFERENCE DISTRIBUTION THROUGH AN ILL-CONCEIVED GROUNDING SYSTEM

These three modes of distribution — propagation on power conductors, propagation on grounding conductors, and mutual coupling to signal conductors — usually dominate internal interference distribution processes. Other processes that are usually much weaker than these also occur and in special cases may be significant. Thus, for example, the interference current propagating on the green wire or on power wires that are treated at the equipment entry flows onto the equipment case and through its mounting hardware to structural metal. Such currents may interact with internal circuits through apertures in the equipment shield.

In addition, although most of the transient energy inside a facility is propagated along the conductors, some will be radiated from the source. This radiated transient energy propagates from the source and is reflected from the walls and other equipment; it can be received by any conductor exposed to the radiated field. While this mechanism is often credited with being an important interaction mechanism,[7] it is doubtful that it is comparable to propagation along conductors — directly or after inductive coupling through mutual capacitance and inductance — except perhaps at microwave frequencies.

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