Interaction Notes

Note 306

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# Shielding and Grounding Topology for Interference Control

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## ABSTRACT

Protection of electronic equipment from interference originating from lightning and the nuclear EMP requires that a small-signal environment for electronic equipment be provided even though large transient fields and currents may be developed outside the cabinet or building. A shield may be used to separate the electromagnetic environment inside the cabinet or building from the harsh outside environment. In light of the large iR and Ldi/dt voltages developed in grounding conductors by lightning and the EMP, the shield potentials may vary over a many-kilovolts range; it is not feasible to prevent these fluctuations. However, even though the shield potential varies widely during transient excitation, the potential of everything inside the shield also varies in the same way so that there are no potential differences (except those generated by internal sources) within the shielded region. Undesired potential drifts or fluctuations caused by charge displacements or other internal sources can be controlled by electrically interconnecting all internal conductors with the shield (i.e. "grounding" them to the shield). Thus the shield prevents internal potential fluctuations caused by external sources, and "grounding" controls internal potential fluctuations of internal origin.

In practice, several levels of shielding and grounding may be used. These often consist of a building shield with its internal electrical grounding system, a cabinet shield with its internal electronics grounding system, and perhaps shielded components within the cabinet. At each level, the shielding and grounding topology portrays the shield as a barrier to its external environment and the grounding system as a means of controlling potentials from internal sources.

Also in practice, the shields must be compromised by conductors that carry power and information through the shield and by access doors, ducts, cracks, etc. incumbent in fabricating and servicing facilities or equipment. Application of shielding and grounding topology permits these compromises to be readily identified (even if they are quite subtle); in addition it can be used to determine how filters, surge arresters, and other protective devices should be installed and grounded to preserve the integrity of the shield. Most important, however, is the fact that shielding and grounding topology is useful in explaining some of the interference problems that have been reported, as well as how these problems may be avoided in the future.

# SHIELDING AND GROUNDING TOPOLOGY
# FOR INTERFERENCE CONTROL

## I INTRODUCTION

Small-signal electronic circuits, whether they use discrete component or integrated circuits, are susceptible to malfunction or damage caused by transient interference. These problems are particularly common in data processing circuits because these circuits often cannot distinguish between a spurious transient and a legitimate signal, and because these circuits are designed for small switching levels to conserve power and reduce heat dissipation problems. Logic levels are often a few volts or a few tens-of-milliamperes in these circuits.

On the other hand, transients associated with lightning and switching on power lines and buried communication cables commonly have peak currents of tens of kiloamperes and peak voltages of megavolts.[1] Similar peak values are associated with the nuclear electromagnetic pulse. Thus if small-signal electronic circuits are to be operated by commercial ac power, in buildings supplied with ac power, or in systems that are interconnected by long buried or overhead cables, it is apparent that the structure between the outside cables or power conductors and the small-signal electronic circuits must be capable of reducing the transients by over 100 dB.

In addition, grounding electrodes such as ground rods, ring grounds, counterpoises, etc. typically have impedances of a few ohms, while grounding electrode impedances of tens or hundreds of ohms are not uncommon. In series with this soil impedance is the inductance of the grounding conductor, which is typically a few microhenries (about 1 μH per meter of ground wire). Thus the $Ri + Ldi/dt$ voltages developed across the grounding impedance when lightning strikes a power line may be of the order of 100 kV even if a good grounding electrode is used. Therefore, as illustrated in Figure 1, even the best electrical grounding practices cannot prevent wide fluctuations in the potential of a building ground point if lightning strikes the building, or if it strikes the power lines or cables near the building.

For electronic systems to operate reliably in this environment, therefore, we must be able to accommodate these wide fluctuations in building ground-point potential and reject the severe transients on external power lines and cables. In addition, however, we must be able to supply power to the electronic circuits and provide means of getting information into and out of these circuits. To achieve these goals, a systematic approach to shielding and grounding is required.

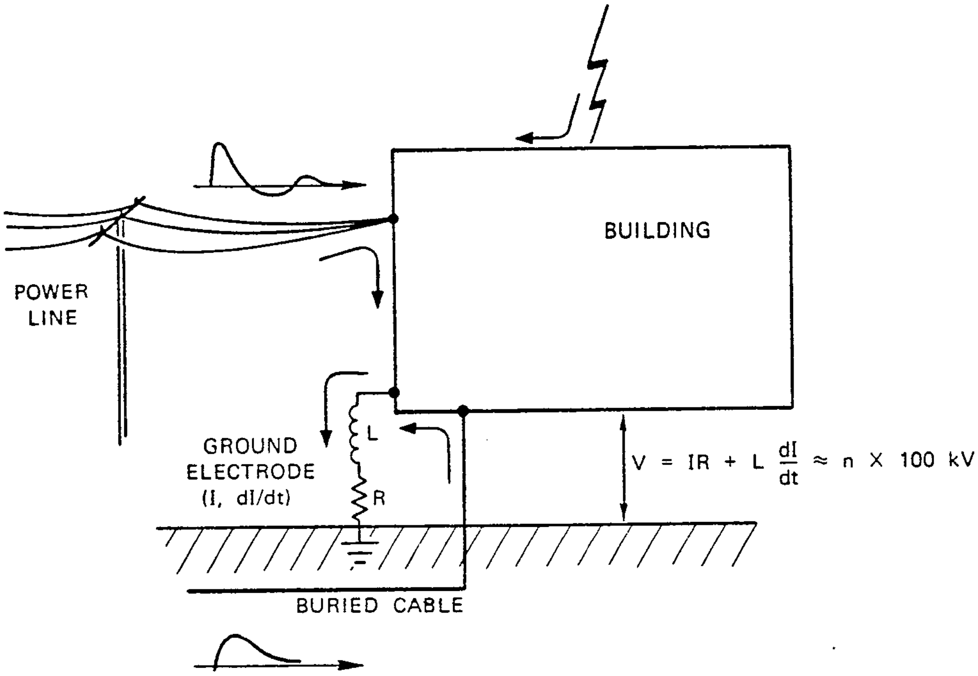
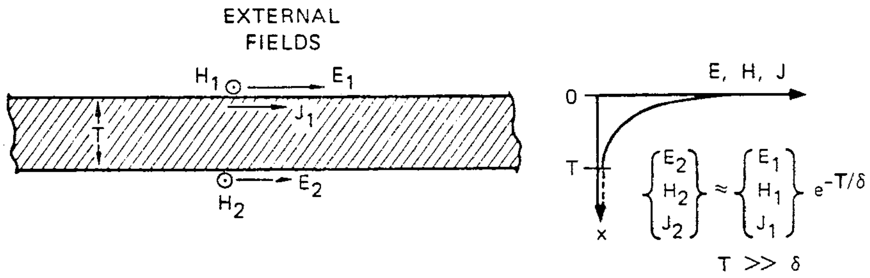


FIGURE 1 BUILDING POTENTIAL PRODUCED BY LARGE TRANSIENTS

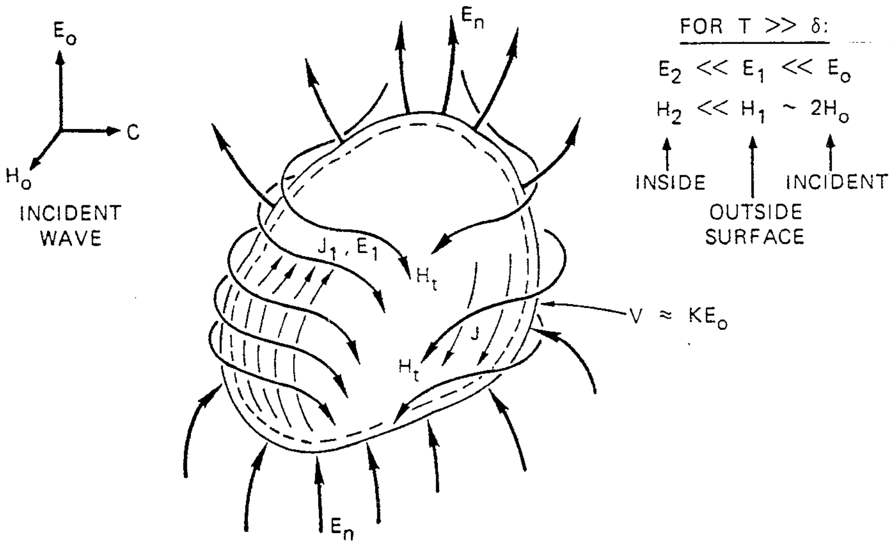
## II DEVELOPMENT OF SHIELDING AND GROUNDING PHILOSOPHY

If the walls of the building in Figure 1 are perfectly conducting so that there is no penetration of either electric or magnetic field through the walls, the potential of the entire building and all of the space inside it will be the same, regardless of whether that potential is zero or 100 kV. The importance of this fact is that there are no potential differences within the building even though the potential of the building with respect to the earth may fluctuate widely. The perfectly conducting shield is thus an electrodynamic Faraday shield that isolates the enclosed space from external influences, whether these be fields, currents, or voltages. All external fields are totally reflected by the walls and all current or charge injected on the outside surface remains on the outside surface (the skin depth in a perfect conductor is zero).

If the walls are not perfectly conducting, the external fields are not quite completely reflected, and currents injected on the outer surface penetrate into the walls. Nevertheless, as illustrated in Figure 2, when the wall thickness is large compared to the skin depth $\delta$, the fields (or potential gradients) inside the shield are much smaller than those outside the shield.



(a) DECAY OF ELECTROMAGNETIC FIELDS AND CURRENT DENSITY IN SHIELD



(b) EXTERNAL FIELDS ABOUT A CLOSED SHIELD

FIGURE 2 ELECTRODYNAMIC SHIELD

The electrodynamic shield thus provides a barrier between the external environment and the internal environment. Hence in the region enclosed by an ideal shield there are no gradients or potential differences caused by sources outside the shield. However, there may be gradients in the enclosed region caused by sources or charge displacements within the shielded region. For example, if the building in Figure 1 contains a battery or some other power source, this source can produce gradients or potential differences. Similarly, if there is mechanical motion inside the building, electrostatic charging may occur and produce potential differences. But these potential differences are caused by internal sources; the shield has no effect on them, and they are unrelated to the outside environment.

To control potential differences of internal origin so that they do not pose shock or explosion hazards or induce electrical malfunction because of circuit potential drift, circuit common and internal structures such as equipment cabinets, cable trays and shields, conduits, and other metal structure may be connected to each other and to the shield as indicated in Figure 3. This "grounding" of internal conductors and circuits eliminates (or reduces) undesired potential differences caused by sources inside the shielded region.

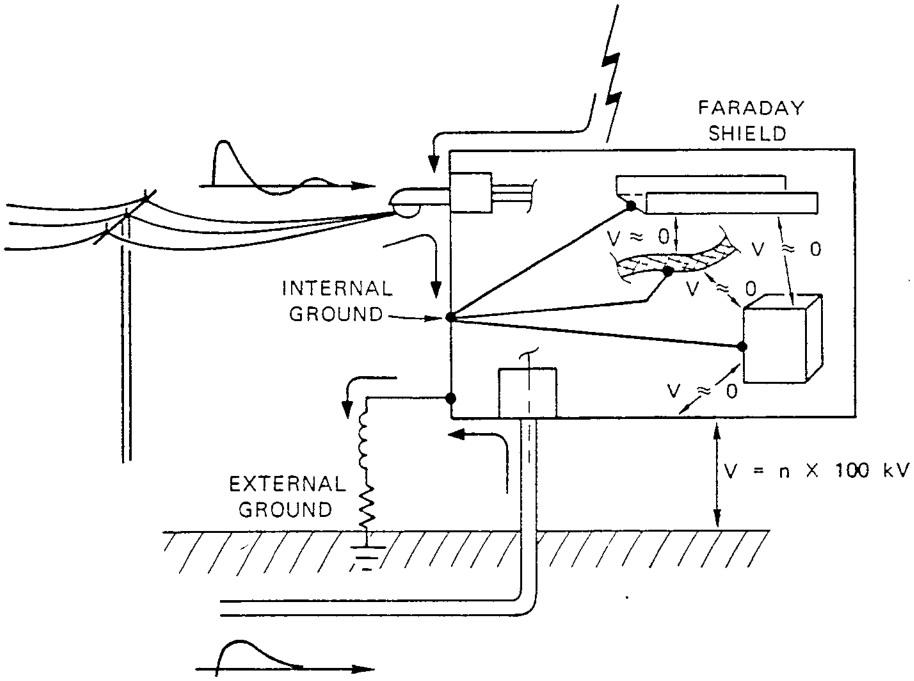


FIGURE 3 INTERNAL GROUND SYSTEM FOR EQUIPOTENTIAL REGION

The essence of an effective shielding and grounding philosophy has thus been developed. The shield is used to control internal potential differences of external origin, and grounding is used to control internal potential differences of internal origin.

## III SHIELDING AND GROUNDING TOPOLOGY

The shields discussed above were assumed to be completely closed. As was remarked in the introduction, however, we must supply power to and communicate with the equipment inside the shield. For shielded buildings we must also provide openings for ventillation and for entrance and egress, as well as plumbing for water, sewage, heat or fuel, and other accouterments. Each of these openings and penetrating conductors represents a compromise of the shield; as a result a single shield and internal grounding system is often inadequate to provide the 100 dB or more of interference reduction required by electronic circuits.

To achieve a greater degree of interference reduction, additional shields with their internal grounding systems may be used. One can thus envision a set of nested shields such as is illustrated schematically in Figure 4. The set of nested shields partitions the space about the electronic equipment into environmental zones.[2-4] Within each zone, the potential differences produced by sources in the zone are controlled by connecting all metal in the zone, including the shield enclosing the next inward zone, to the inside surface of the shield. For example, all metal in Zone 1 of Figure 4, including shield 2, is connected to the inside of shield 1; and all metal in Zone 2, including shield 3, is connected to the inside of shield 2.

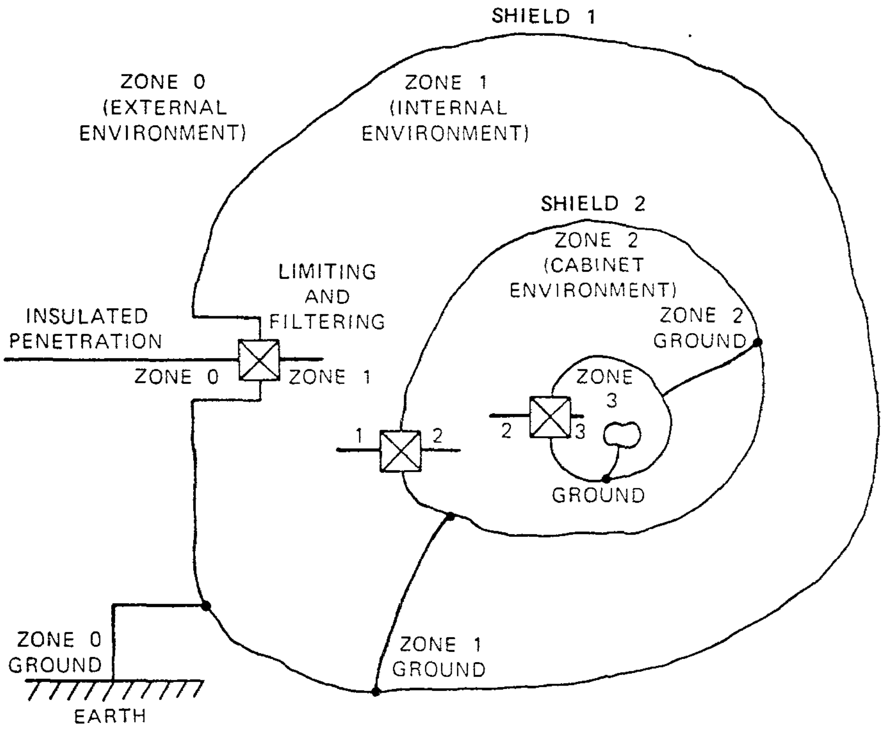
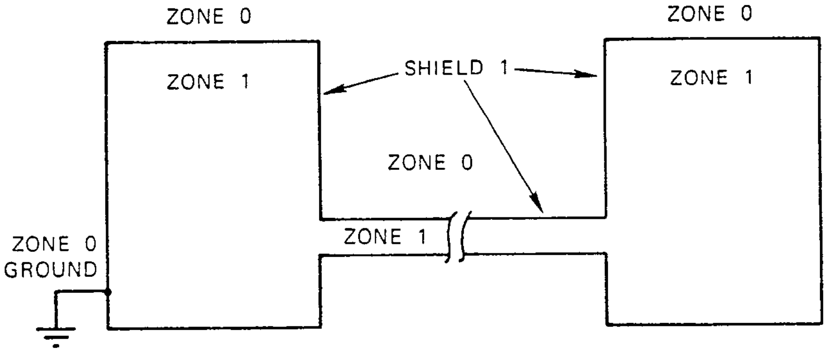
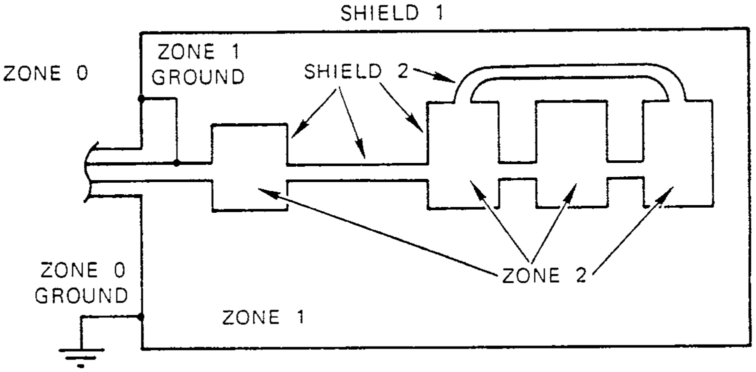


FIGURE 4 SHIELDING AND GROUNDING ZONES IN A COMPLEX FACILITY

Shielded regions at any level may be irregular in shape or they may be interconnected as illustrated in Figure 5. Topologically, the two shielded buildings in Figure 5(a), interconnected with a shielded cable, form one continuous shielded region. Similarly, the equipment cabinets in Figure 5(b), together with their shielded interconnecting cables or ducts, form a contiguous Zone 2 region. Also illustrated in Figure 5(b) is the use of doubly shielded cable to extend the Zone 2 region "outside" the building yet topologically inside two levels of shielding.



(a) SHIELDED BUILDINGS CONNECTED BY SHIELDED CABLE

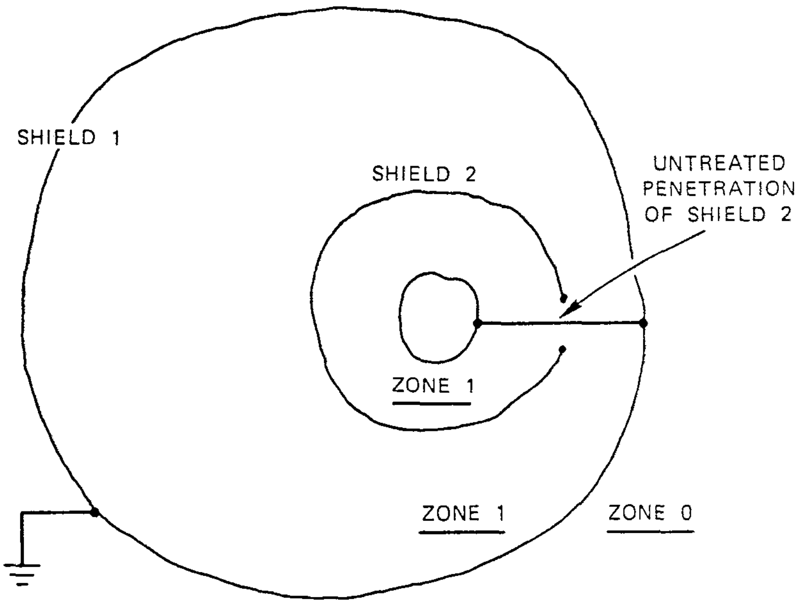


(b) INTERCONNECTED CABINETS

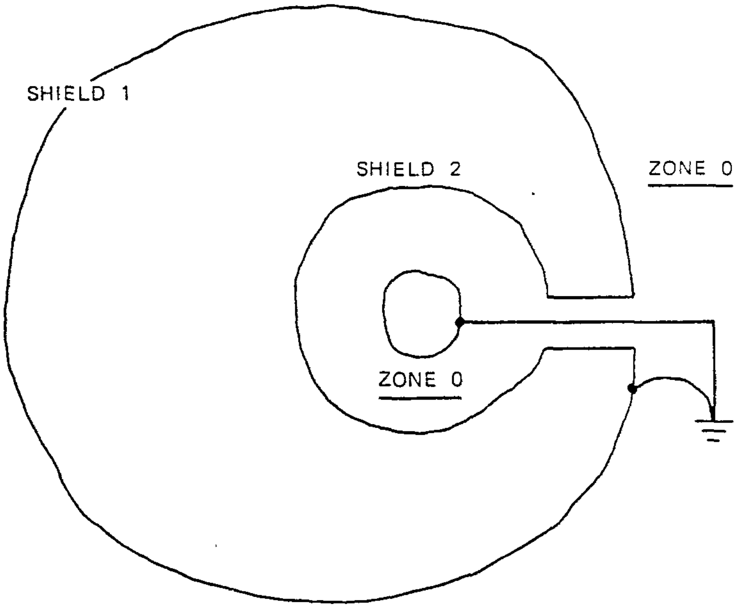
FIGURE 5 TOPOLOGY OF INTERCONNECTED REGIONS

It is useful to examine some violations of the shielding and grounding system. In Figure 6(a), components inside shield 2 have been grounded to shield 1 through an opening in shield 2. Therefore, topologically, shield 2 does not exist (i.e., it is not effective) because the grounding conductor carries the Zone 1 environment into the region enclosed by shield 2. Figure 6(b) illustrates a more serious violation because both shield 1 and shield 2 have been made to vanish by the penetrating grounding conductor. Topologically, shield 1 and shield 2 form only one shield, but this shield encloses only the region between the shields--it excludes the region inside shield 2!

These examples illustrate an important rule of effective shielding and grounding practice: Topologically, grounding conductors should never penetrate shield surfaces.



(a) COMPROMISE OF SHIELD 2 BY UNTREATED PENETRATION



(b) COMPROMISE OF BOTH OUTER SHIELDS BY EXTERNAL GROUND CONNECTIONS

FIGURE 6 COMMON VIOLATIONS OF SHIELDING AND GROUNDING TOPOLOGY

## IV SOME IMPORTANT COROLLARIES

Inherent in the theory of electrodynamic shields is the fact that current in conductors attached to the shield flows predominantly on the surface to which the conductor is attached. This phenomenon, illustrated in Figure 7, is a manifestation of the skin effect in conductors. It is

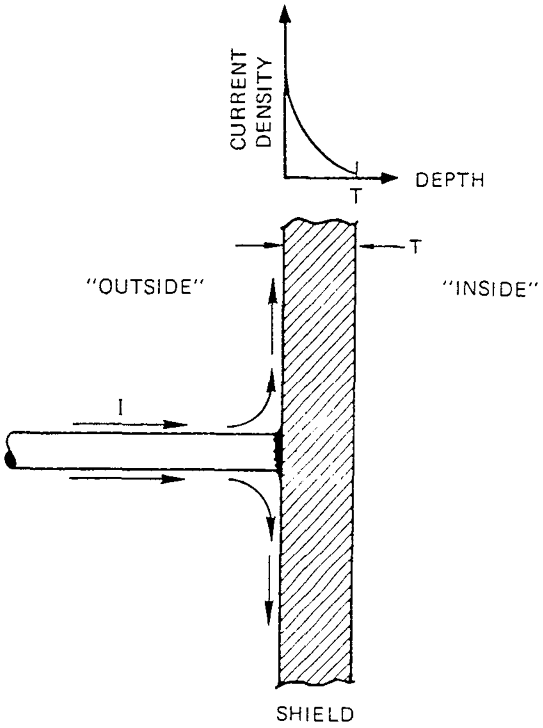


FIGURE 7 CONFINEMENT OF CONDUCTOR CURRENT TO "OUTSIDE" SURFACE BY SKIN EFFECT

very important in the application of the shielding and grounding topology developed above because it permits interference currents on conductors outside the shield to be diverted to the outside surface of the shield. Notice the difference, for example, between the situation depicted in Figure 7 and that shown in Figure 8, where the conductor is brought through the shield and connected to the "inside" of the shield. In the latter example, the conductor current flows to the "inside" surface, where it is again confined by skin effect.

Several examples of the correct application of this principle are given in Figure 9 along with some common violations of the shield. Note that each of the violations permits the harsh currents on the outside conductors to flow into the protected zone inside the shield. It should be observed that filters and surge arresters behave the same as any other connection of a penetration to the shield; that is, they divert harsh interference currents to the outside surface of the shield, thereby

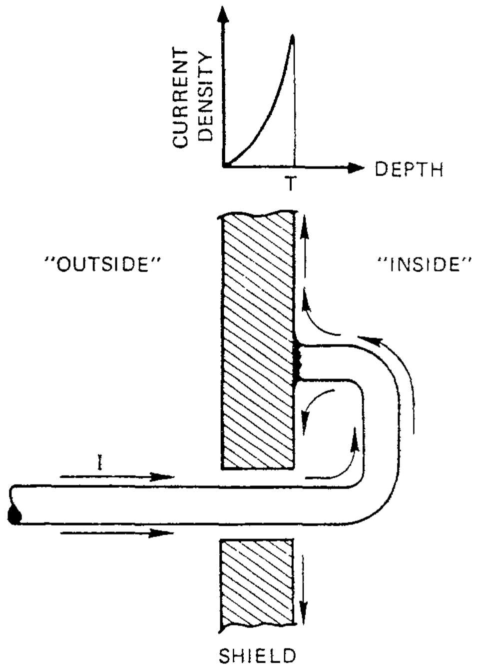
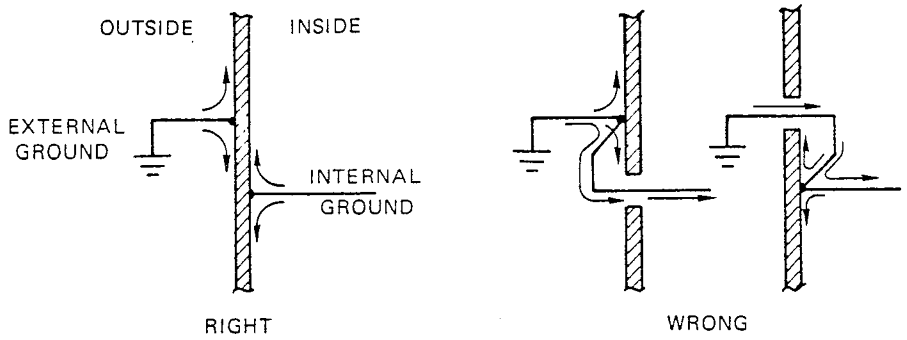


FIGURE 8 CONDUCTOR CURRENT INJECTED ON THE "INSIDE" OF A SHIELD

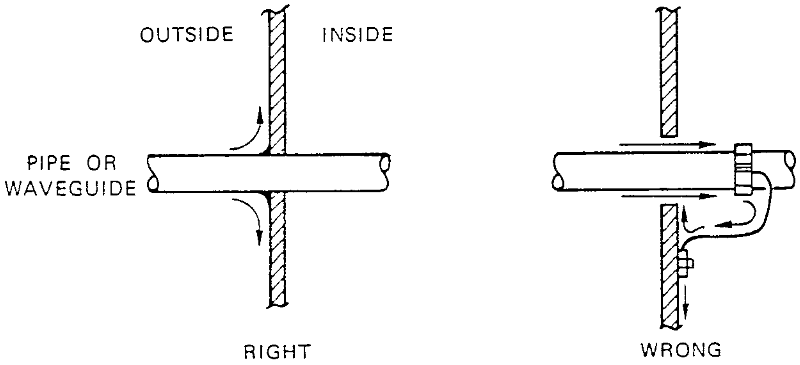
preventing these currents from entering the protected region. Because power and signal-carrying conductors cannot be continuously connected to the shield, they must be momentarily connected (when a certain threshold is exceeded) or connected only at frequencies not used for power or signals (i.e. through a filter). In any case, the diverted interference currents must flow to the outside surface of the shield, as illustrated in Figure 9(c), if shield integrity is to be preserved. The importance of this current diversion is shown in Figure 10 where the currents on the penetration inside the shield with and without diversion are compared.

Confinement of shield current to the surface is also useful in tracing shield topology. Identification of the shield topology is facilitated if it is assumed that current injected on a surface of the shield must flow only on that surface as it does on a perfectly conducting shield (i.e., that it cannot flow through the shield from the outside surface to the inside surface, or vice versa). One may then trace the continuous surface in the vicinity of peculiar shapes, such as those in Figure 11, to identify the shield topology. Shading (as in Figure 11) or coloring is sometimes useful when the physical geometry of the shield is complicated.

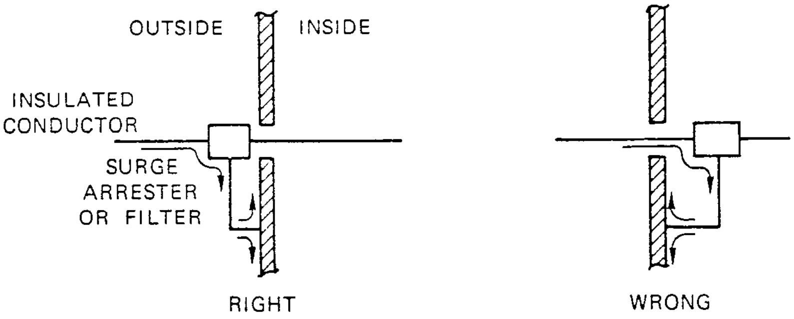
A second corollary of shielding theory is that fields cannot diffuse through shields that carry no current. The electric and magnetic fields parallel to the shield surface are both related to the current density in the shield through the intrinsic impedance of the shield material, and



(a) GROUNDING CONDUCTORS



(b) "GROUNDABLE" PENETRATION



(c) INSULATED PENETRATION

FIGURE 9 CONNECTIONS THAT PRESERVE SHIELDING INTEGRITY (right) AND COMPROMISE THE SHIELD (wrong)

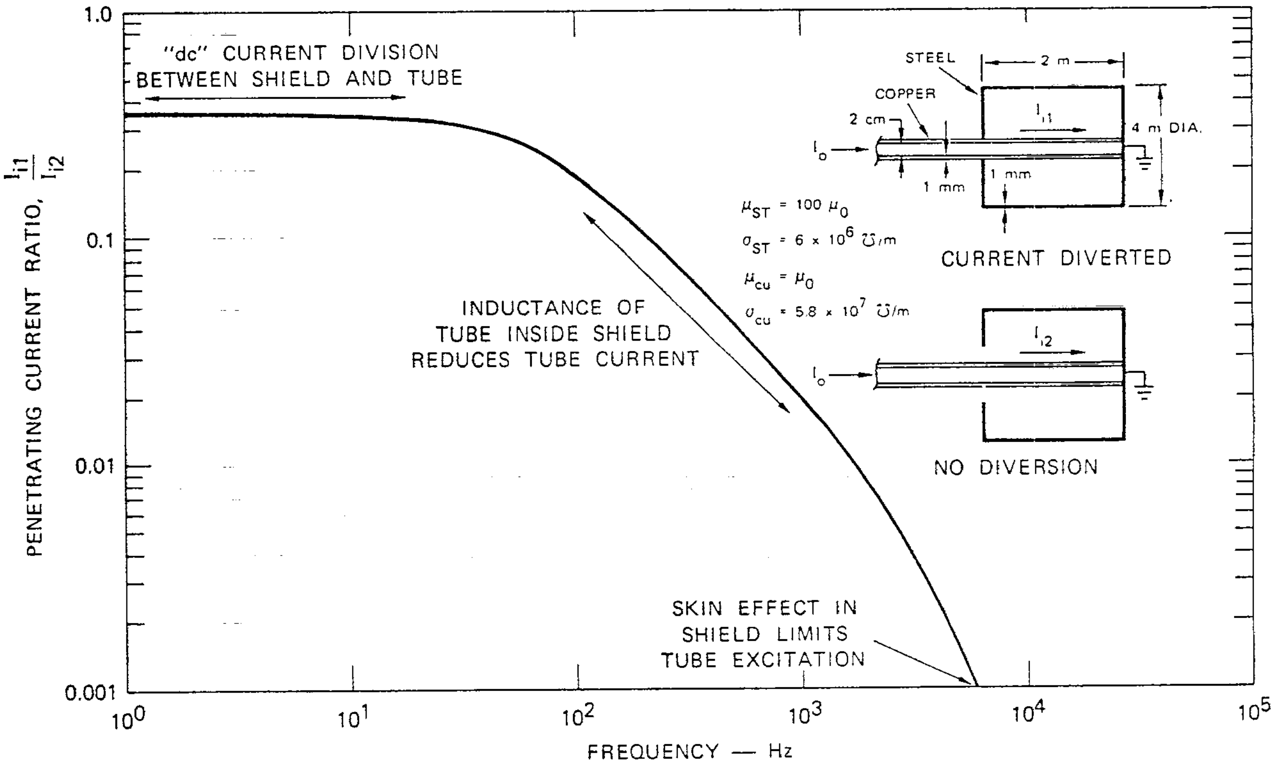


FIGURE 10  RATIO OF CURRENT PENETRATING SHIELD WALL ($I_{i1}$) TO CURRENT CONDUCTED THROUGH WALL ($I_{i2}$)

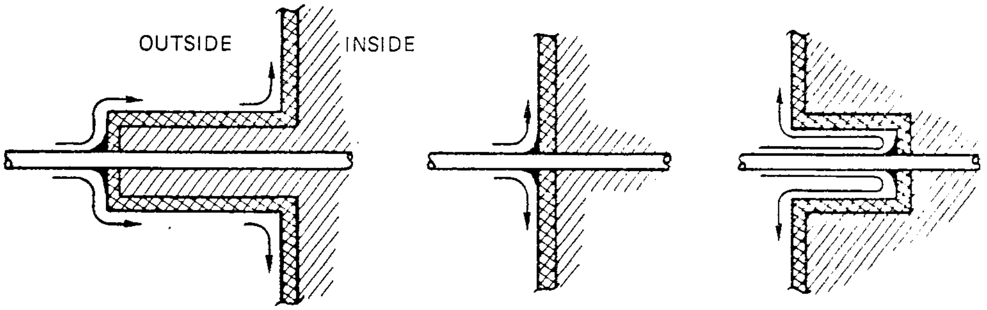


FIGURE 11  TOPOLOGICALLY IDENTICAL SHIELD PENETRATIONS

when the current density is zero, both of these fields are also zero. Therefore, the performance of the shield can be enhanced if large interference currents are prevented from flowing through large areas of the shield--particularly if the shield has many openings (e.g., a mesh or a metal building with many doors, windows, or poorly bonded joints--see Figure 12).

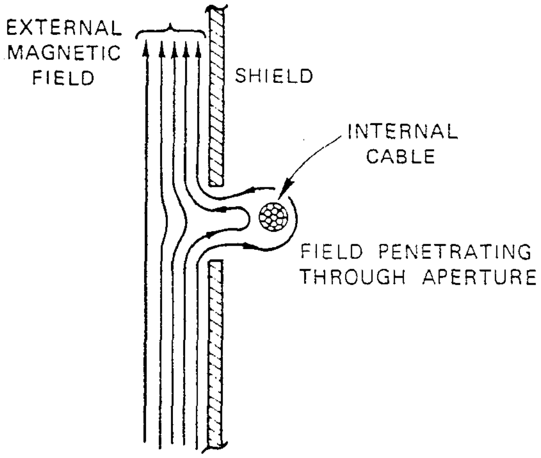
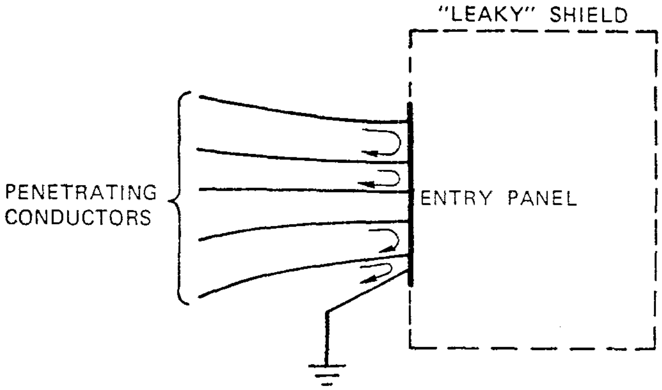
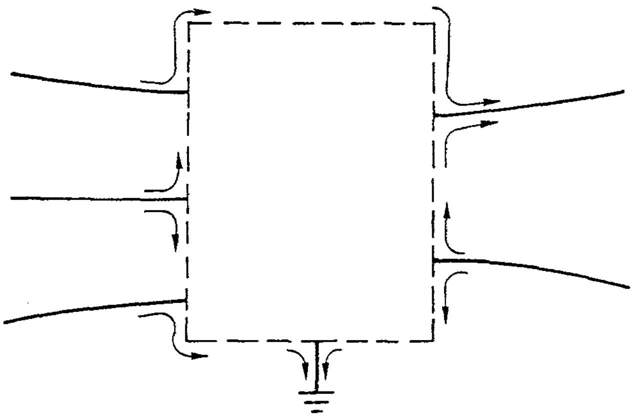


FIGURE 12 MAGNETIC FIELD PENETRATION OF SMALL APERTURES

Implementation of this principle has led to the concept of a single entry panel through which all penetrating conductors enter the shield at one small, controlled area. Figure 13(a) illustrates the entry panel with all penetrating conductors and the external grounding conductor congregated at one face of the shield. Current flowing over the shield is small because there is no exit path on the opposite face--the shield is an open-circuit to the combined penetration currents. The current entering on one penetration must either be reflected back on the same conductor or leave through another penetration or through the grounding conductor. By contrast, when the random entry illustrated in Figure 13(b) is used, heavy current flowing toward the shield on one conductor may flow across the shield, exciting any leaks in its path, and exit on a conductor on the opposite face of the shield. Hence the random entry approach permits excitation of any flaws in the shield by the external interference currents, while the single entry panel approach concentrates these currents on the entry panel where almost flawless shielding can be maintained. Conversely, if the single entry panel is used, poorer quality shielding on the remainder of the shield can often be tolerated.



(a) SINGLE ENTRY PANEL



(b) RANDOM ENTRY

FIGURE 13 PENETRATION CURRENT PATHS ON SHIELDS

## V APPLICATION TO SYSTEMS

A set of nested shields, such as that shown schematically in Figure 4, often occurs in the course of constructing the facility and the electronic equipment. For example, shield 1 of Figure 4 might be the building or equipment shelter (van); shield 2 would then be the metal equipment cabinets or housing; and shield 3 would be specially shielded circuits or components within the equipment cabinet. (Shield 3 would normally be provided by the equipment manufacturer to provide extra protection for very sensitive, or very small signal, circuits and components.) Outside shield 1 is the harsh external environment described earlier.

Between shield 1 and shield 2 is the building or room environment. This region, labeled Zone 1 in Figure 4, normally contains electric power circuits operating at service voltages of 120/240 V, 120/208 V 3-phase, etc., as well as the normal transients associated with switching and regulating the equipment operated from this power. In this region, it is desirable to limit transient voltages to levels comparable to the electric power voltages (i.e., a few hundred volts) to avoid overstressing low-voltage insulation inside the facility. In this region it is also important to interconnect all exposed metal (equipment housings, conduits, and other structures) to avoid shock and explosion hazards. The interference environment in this region might thus be limited to a few amperes or a few hundred volts on conductors and to fields of a few hundred volts/meter.

Inside shield 2 (the equipment cabinets) is the small-signal region called Zone 2 in Figure 4. This region contains the small-signal electronic circuits that are subject to malfunction at interference levels of a few volts or a few tens of milliamperes. Therefore, the peak transient interference levels on conductors entering these circuits must be smaller than those values if the circuits are to operate reliably.

When the primary and secondary shielding surfaces have been selected, it is important to examine the topology of these surfaces to

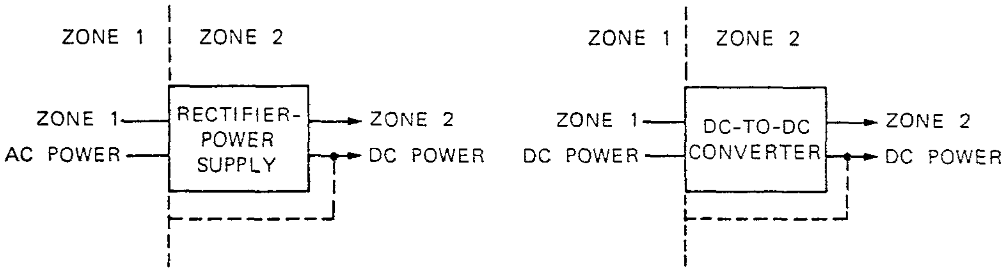
1. determine that they are topologically two separate shields rather than one with a reentrant region as in Figure 6(b) .

2. identify all penetrations and apertures that will be necessary to accommodate the system.

In the context of the second purpose, the function of the penetrating conductor (i.e., whether it is for electrical, mechanical, or hydraulic use) is immaterial to its ability to violate the shield; any conductor--even a grounding conductor--that penetrates the shield compromises the integrity of the shield.

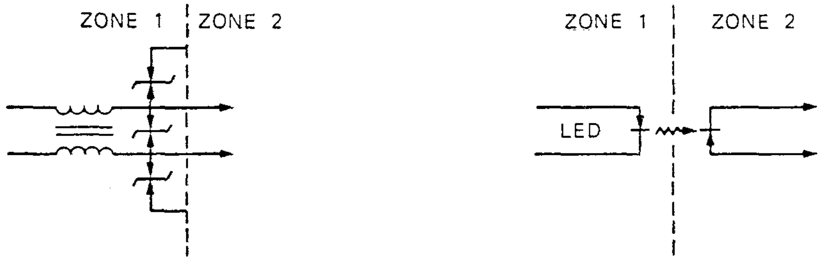
Penetration treatments such as those illustrated in Figure 9 should be considered for each penetration of the primary and secondary shields. Because of the extremely high voltages possible on external conductors such as power lines and communication cables, high-current surge arresters are usually necessary for insulated conductors penetrating the primary shield. At the secondary shield (e.g., the equipment cabinet), a variety of interference-rejection devices may be used. Some of these may be provided as a normal functional part of the equipment. For example, dc power supplies may serve to isolate the electronic circuit from the interference on ac power conductors, and dc-to-dc converters can perform a similar role when the primary power is dc. These and some other secondary-shield penetration treatments are illustrated in Figure 14. Cable shields and other "groundable" conductors may be treated at the secondary shield in much the same manner as they are treated at the primary shield--see Figure 9(a) and (b).

Of particular interest are the ac power entry and grounding provisions. Topologically proper methods of treating these penetrations are shown in Figure 15. Figure 15(a) illustrates the topology of the primary shield at



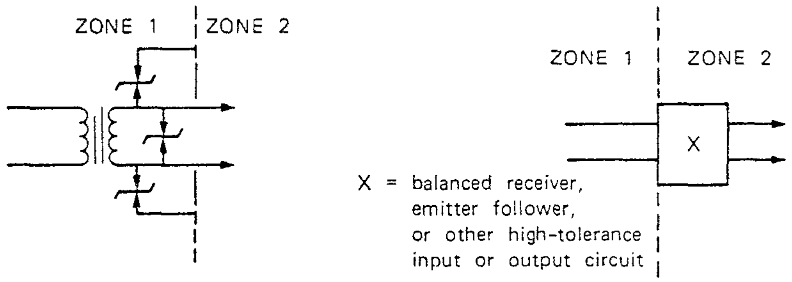
(a) RECTIFIER/POWER SUPPLY

(b) DC-TO-DC CONVERTER



(c) COMMON-MODE REJECTION TRANSFORMER

(d) PHOTON COUPLER

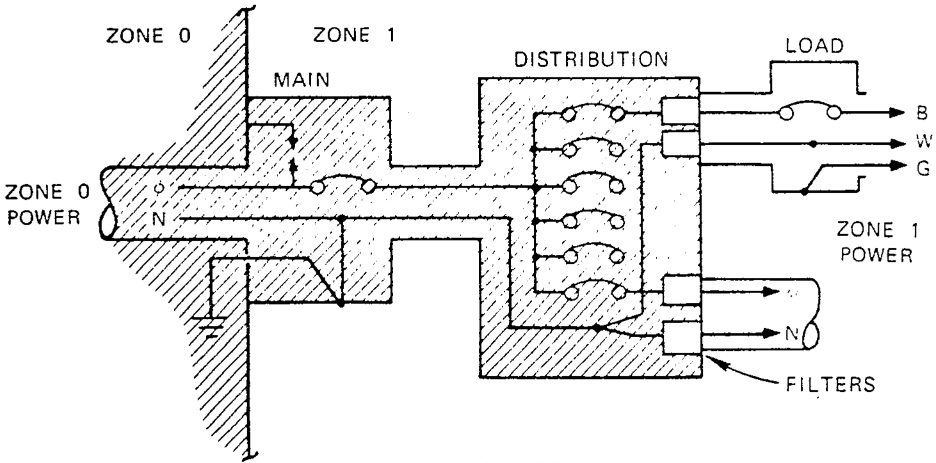


X = balanced receiver,
emitter follower,
or other high-tolerance
input or output circuit

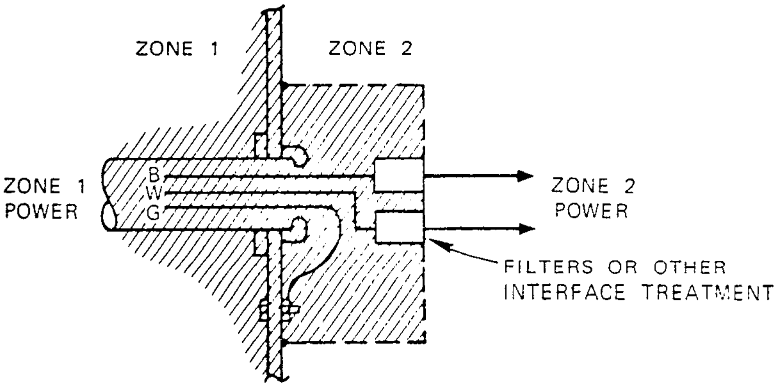
(e) ISOLATION TRANSFORMER

(f) OTHER

FIGURE 14 TREATMENTS FOR SECONDARY SHIELD PENETRATIONS



(a) BUILDING ENTRY



(b) EQUIPMENT ENTRY

FIGURE 15 AC POWER PENETRATIONS AND GROUNDING CONDUCTORS

the service entrance. For this installation the main disconnect and distribution panel are outside the shield since the power conductors are not filtered until they leave the distribution panel. Two options for the grounding conductor are shown; in the upper right, a Zone 1 electrical ground (green wire) is derived in a load center serving the electronic equipment, while in the lower right, the conduit serves as the grounding conductor. In Figure 15(b) the two options for the grounding conductor (conduit or green wire) are also shown, although they are combined in one picture (both are not needed). Note that the preferred equipment entry utilizes a junction box or back-plane region to shield the interior of the cabinet from the unfiltered power conductors and green wire connection.

## VI CONCLUSIONS

The topological approach to shielding and grounding is a rational and systematic method of providing the high degree of isolation required between external conductors exposed to lightning or other harsh environments and small-signal circuits susceptible to transients of a few volts.

It is clear that primary protection from externally-generated interference is obtained from shielding; grounding is not a good deterrent to this interference. In fact, improper grounding procedures (e.g., Figure 6) may aggravate the problem rather than solve it. Although the diversion of penetrating conductor currents to a shield (see Figure 9) is often considered an aspect of grounding, the topological approach shows that it is in fact a method of preserving the integrity of the shield.

Topologically, grounding has no effect on externally-generated interference. Grounding serves only to equalize the potentials of otherwise insulated metal parts within a shield. In so doing, it helps control spurious potentials generated by sources inside the shielded region.

Because the topology of shielding and grounding dictates that grounding conductors should not penetrate shield surfaces, some of the problems encountered in past grounding practices can now be understood. The circuit upset and damage problems associated with the common practice of connecting small-signal ground (Zone 2) to the building electrical ground electrode (Zone 0) are readily understood from the topological picture in Figure 9(b). According to this picture, any natural shielding that might have been provided by the building (shield 1) or equipment cabinet (shield 2) has been circumvented by the grounding conductor, thereby exposing the small-signal circuits to the harsh outside environment.

It is also interesting that attempts to alleviate this problem have often been concentrated on reducing the grounding electrode impedance--thereby reducing the n-hundred kV in Figure 1--rather than on improving the integrity of the shields by eliminating the offending grounding conductor. An important advantage of the shielding and grounding philosophy enunciated here is that system performance is completely independent of the grounding electrode impedance. The properties of the grounding electrode can therefore be left to the discretion of power and communication utilities.

It is noteworthy that the single-entry concept alleviates the requirement for a high-quality overall shield if the principal source of interference is large currents on outside conductors such as power lines and communication cables. By diverting these currents at the entry panel rather than allowing them to flow through the shield, a moderate-quality shield (e.g., structural steel or reinforcing steel) may suffice for many installations. If high intensity interference fields, as well as conductor currents, prevail as in the nuclear EMP environment, a high-quality shield may be required.

Finally, implementation of the shielding and grounding approach described in this paper does not entail costly new equipment and processes.

On the contrary, it may eliminate some of the costly grounding electrode installations and extravagent use of heavy copper bars and cables frequently specified in the name of "good grounding." The essence of the approach and its principal advantage is that it provides a rational method of achieving the maximum interference protection from the structural metal, housings, etc., that would usually be provided even if interference were not a consideration. The principal effort required to implement the approach is, therefore, in configuration control. Thus the approach promises improved circuit protection, hence improved system reliability and reduced maintenance costs, as well as potentially lower initial costs.

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