Interaction Notes

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On Electromagnetic Interference Control

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ABSTRACT

The use of shield topology concepts to design interference control is described. Starting with the postulate that electromagnetic environment can be separated by closed-shield surfaces, the proper design of essential compromises such as insulated power and signal conductors and openings for access and ventilation are deduced. The role of grounding is described and the relation of grounding conductors to shield surfaces is deduced. Some guidelines are given for determining how effective the shield needs to be. It is concluded that the effectiveness of a shield is usually limited most by interference propagating on insulated conductors passing through the shield, followed by leakage through apertures and diffusion through the shield walls.

ELECTROMAGNETIC INTERFERENCE CONTROL

I INTRODUCTION

Small-signal electronic circuits, whether they use discrete components or integrated circuits, are susceptible to malfunction or damage caused by transient interference. The 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 (EMP). Thus, if small-signal electronic circuits are to be operated by commercial ac power, or used 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 transient peaks by over 100 dB.

In addition, grounding electrodes such as ground rods, ring grounds, counterpoises, etc., typically have impedances of a few ohms, although grounding electrode impedances of tens or hundereds of ohms are not uncommon. In series with this soil impedance is the inductance of the grounding conductor, which is typically several microhenries (about 1 μH per meter of ground wire). Thus the $Ri + Ldi/dt$ voltages developed across the grounding impedance by the EMP or lightning may be of the order of 1 to 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 in a lightning or EMP environment.

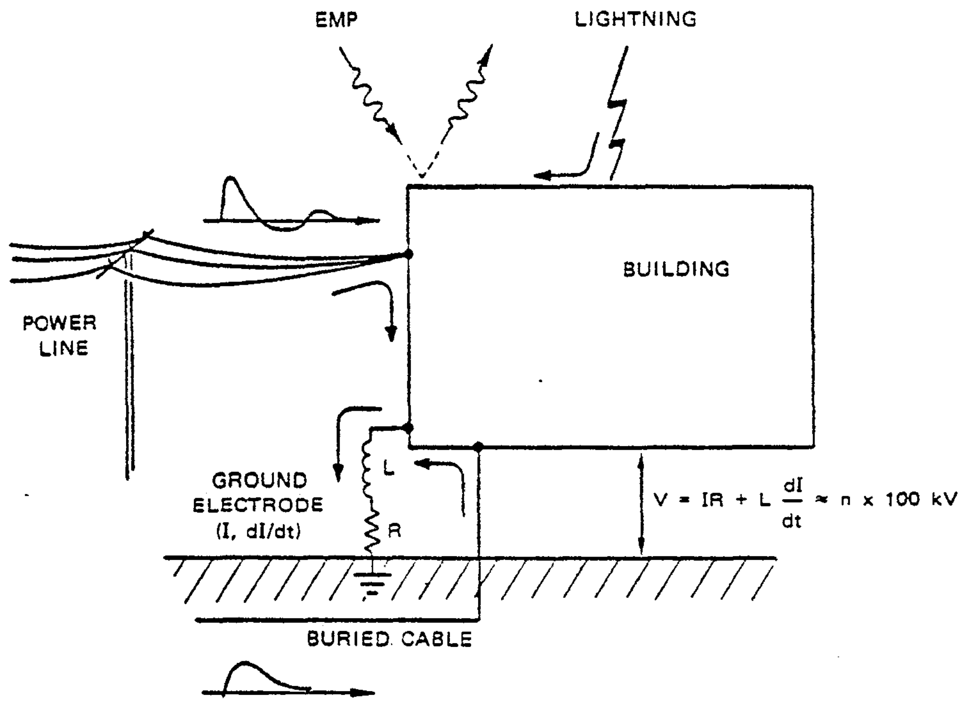


FIGURE 1 BUILDING POTENTIAL PRODUCED BY LARGE TRANSIENTS

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 induced on external power lines and cables or impinging directly on the facility. 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 interference control is required.

II THE FUNCTION OF ELECTROMAGNETIC SHIELDS

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. Thus, 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).

The perfect electrodynamic shield thus would provide a barrier between the external environment and the internal environment. The only gradients in the enclosed region would then be caused by sources or charge displacements within the shielded region. These internal sources fall into two categories: those associated with the normal operation of internal equipment such as rectifiers, transmitters, relays, solenoids, switches, and similar devices which may introduce interference into internal circuits; and those related to the buildup of static electricity and to power faults.

Those internal sources associated with the operation of itnernal equipment are part of the normal functioning of the system. Interference from very strong sources of this type may be confined by enclosing the sources in shields; the shield in this case separates the sources inside the shield from the space outside, so that there are no gradients outside the shield produced by sources inside the shield. The use of shields to exclude and to confine interference waves is illustrated in Figure 2.

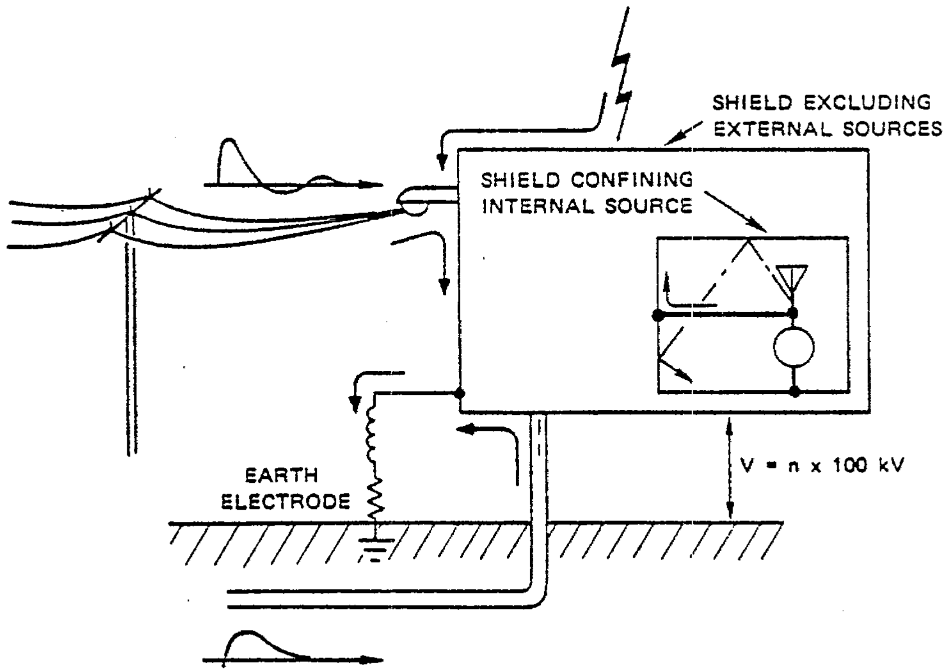


FIGURE 2 USE OF SHIELDS TO EXCLUDE EXTERNAL SOURCES AND TO CONFINE INTERNAL SOURCES

Internal sources associated with static electricity and power faults constitute personnel, fire and explosion hazards which are controlled by interconnecting all structural metal and electrical equipment frames and cabinets as illustrated in Figure 3. Thus sparks and personnel shocks are avoided, and fault-current paths sufficient to ensure the operation of circuit breakers and fuses are provided. Since this interconnection of electrical and structural conductors traditionally includes a connection to earth, such interconnections are called "grounding." Grounding has little to do with interference control although improper grounding may, indeed, introduce additional sources of interference. Also some of the beneficial acts that are frequently called grounding are in fact acts of preserving shielding integrity.

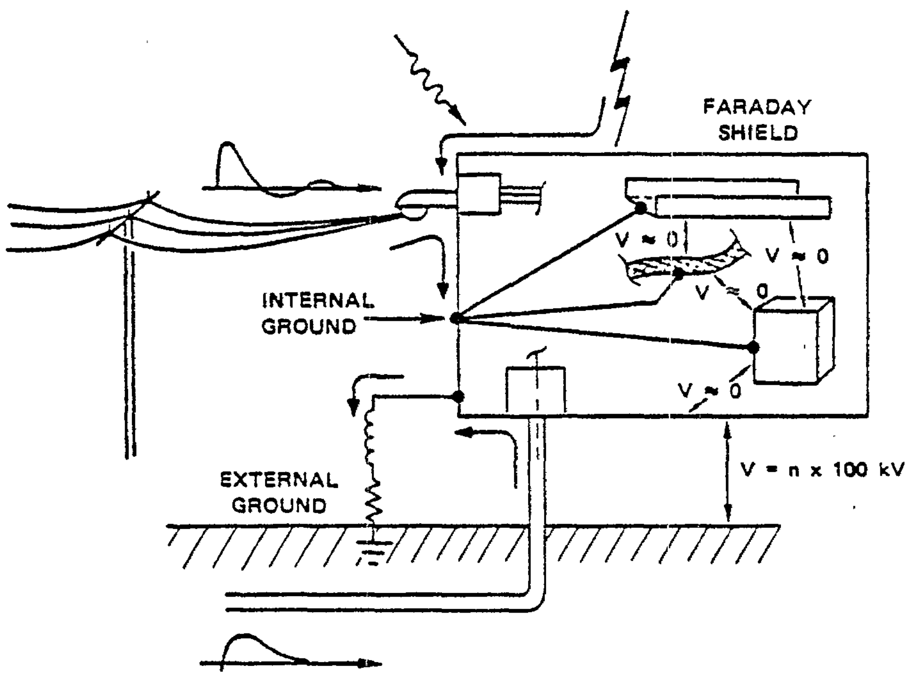


FIGURE 3 INTERNAL GROUND SYSTEM FOR EQUIPOTENTIAL REGION

III SHIELD DESIGN CRITERIA

The shields discussed above were assumed to be perfectly conducting and completley 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 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 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] The interference environment becomes ever more benign as one progresses from the lowest level of shielding toward the highest. 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 continuous 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. As is suggested in Figures 4 and 5, two levels of shielding can often be identified in facilities. The first level may be a welded steel liner in a ground based facility, the metal skin of an aircraft or rocket, or the steel hull of a ship. The second level of shielding is usually defined by the electrical and electronic equipment cabinets and their associated interconnecting cable shields, ducts, or conduits.

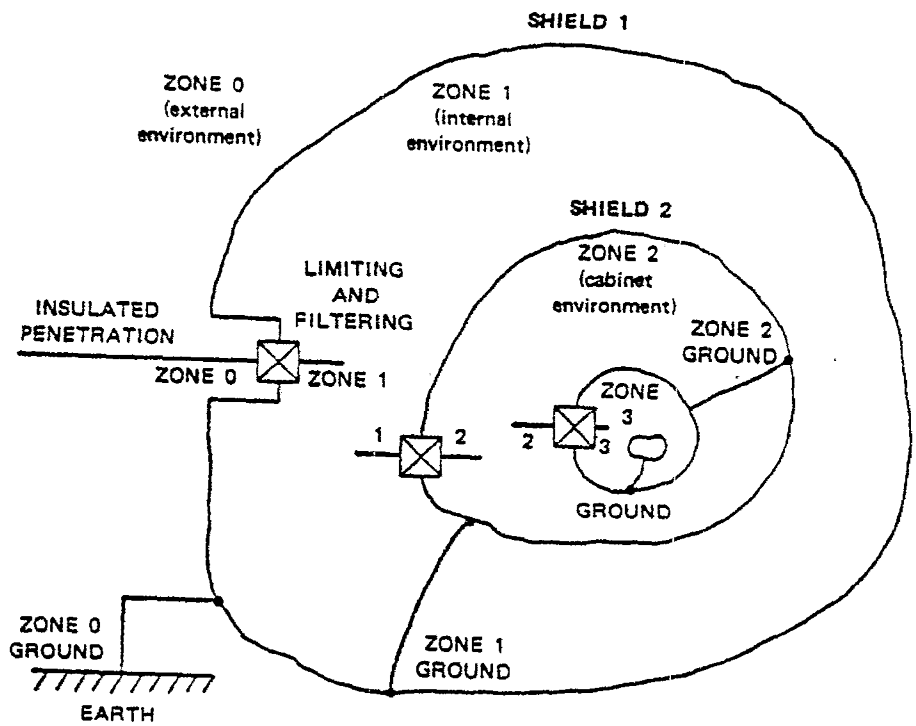
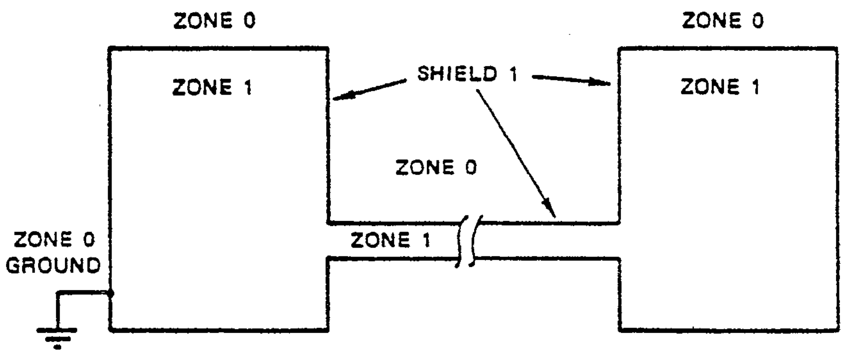
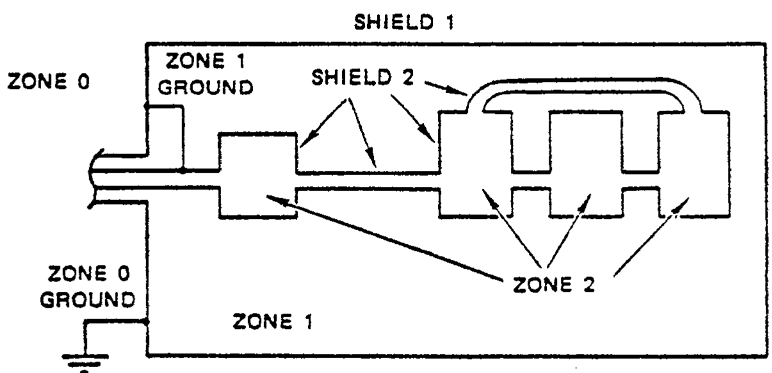


FIGURE 4 SHIELDING AND GROUNDING ZONES IN A COMPLEX FACILITY



(a) SHIELDED BUILDINGS CONNECTED BY SHIELDED CABLE



(b) INTERCONNECTED CABINETS

FIGURE 5 TOPOLOGY OF INTERCONNECTED REGIONS

The first-level shield spearates the harsh external environment of Zone 0 from the room or cabin environment, Zone 1. The shield accomplishes this separation by diverting or absorbing interference that would otherwise enter the system. However, there are practical bounds on the amount of interference reduction required of the first shield. This shield (including its penetrating conductor and aperture treatments) should provide at least enough interference reduction to prevent insulation breakdown or other damage to components inside the shield. Frequently, equipment inside the shield, such as low voltage wiring and equipment operated directly from low-voltage power circuits, can tolerate peak voltages of 500 to 1,000 volts. Thus the minimum interference reduction required of the first level of shielding is that necessary to prevent damage to components enclosed by the shield.

On the other hand, there is little benefit to be gained from reducing externally generated interference to levels much smaller than those produced by internal sources. In many facilities peak voltages of a few hundred volts are generated in Zone 1 by switches, relays, solenoids, rectifiers, and other devices essential to station operation;[5] hence reduction of the externally generated interference to levels more than a reasonable safety margin (say 20 dB) below these interference levels is not warranted.

This criterion is based on the postulate that any internal equipment must tolerate the ambient internal environment without upset or failure. If it can't, then either the equipment must be hardened or the internally generated interference must be reduced; in either case the criterion is to reduce the externally generated interference below the level of the internally generated interference. The internally generated interference may be reduced by confining the strongest or most offensive sources inside shields as discussed earlier.

The second-level shield separates the room or cabin environment from the sensitive small-signal circuits. Since these circuits may be upset or may develop an unacceptible error rate at peak interference levels of a few volts, the second level shield must be capable of reducing the voltages induced on Zone 2 conductors by the room-level environment to less than a few volts. As before, however, little benefit accrues from reducing the cabinet interference produced by external sources (i.e. sources external to the cabinet) to levels more than a reasonable safety margin (again about 20 dB) below the internal interference level produced by the small-signal circuits. Internal interference of the order of 100 mV is often produced by fast switching devices in counters, clocks, etc., in the small-signal circuits.

Note that this approach to interference control requires the equipment, with its interconnecting cabling, to be capable of tolerating a normal room or cabin environment--a fairly modest requirement. The approach also requires that the facility or vehicle shield be sufficiently effective that the voltages induced on internal conductors by external sources (or whatever origin) be no larger than the switching transients and other interference generated by internal equipment--again, a fairly modest requirement.

To implement these criteria, it is necessary to estimate and control the voltage induced on internal conductors as a result of (in order of importance):

1. propagation along conductors passing through the shield (including grounding conductors and nonelectrical conductors)
2. fields penetrating apertures and interacting with internal conductors (these apertures may include the openings in meshes and reinforcing steel and the imperfections at riveted or bolted joints in aircraft, missiles, and ships)
3. fields diffusing through the metal walls of the shield and interacting with internal conductors.

It is also necessary to estimate the internally generated interference levels in the room or cabin, and in the small-signal electronic circuits.

IV MAINTAINING SHIELDING INTEGRITY

A. Cable Entry Points

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 6, is a manifestation of the skin effect in conductors. It is very important in the application of the shielding topology 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 6 and that shown in Figure 7, 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 may interact with internal components.

Several examples of the correct application of this principle to interference-excluding shields are given in Figure 8 along with some common compromises and violations of the shield. Note that each of the compromises 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 penetrating conductor to the shield; that is, they divert harsh interference currents to the outside surface of the shield, thereby 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 at the left in Figure 8(c), if the shield integrity is to be preserved.

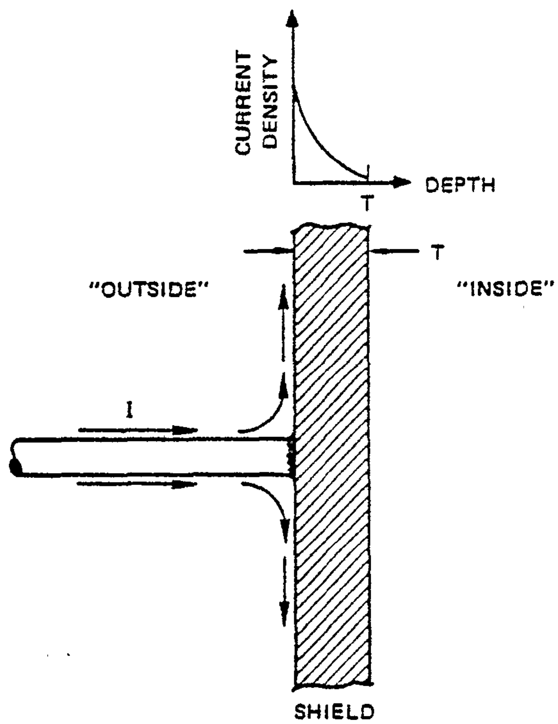


FIGURE 6 CONFINEMENT OF CONDUCTOR CURRENT TO "OUTSIDE" SURFACE BY SKIN EFFECT

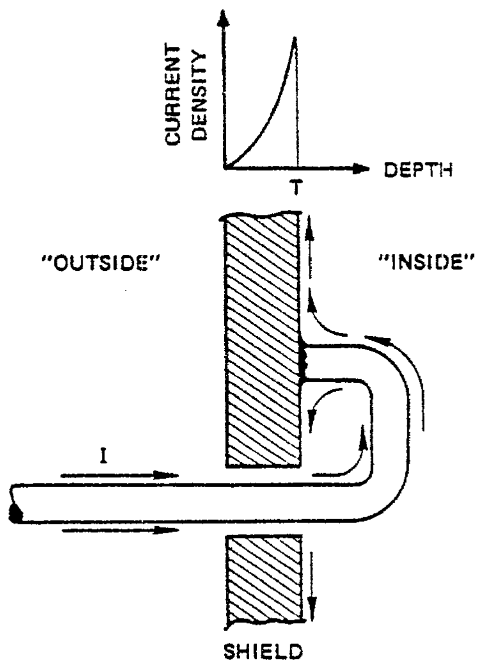
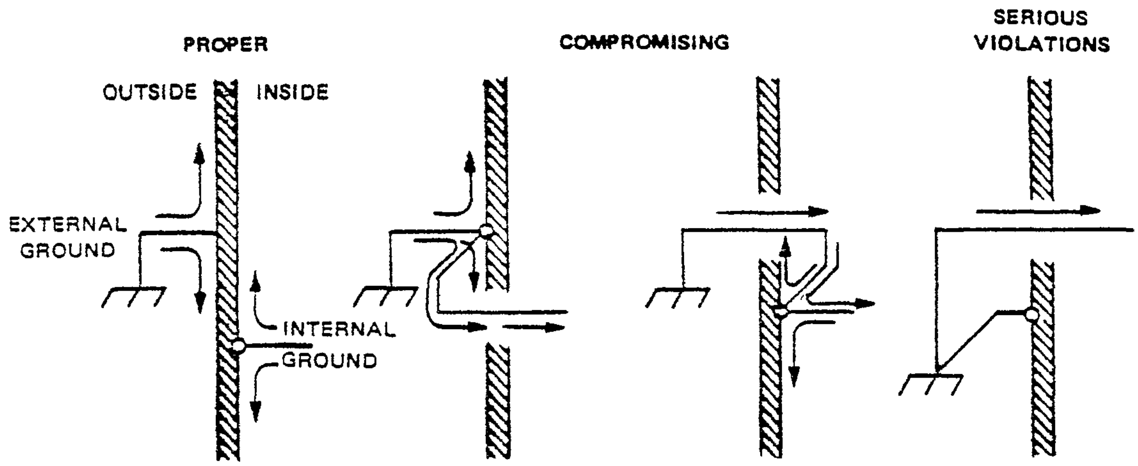
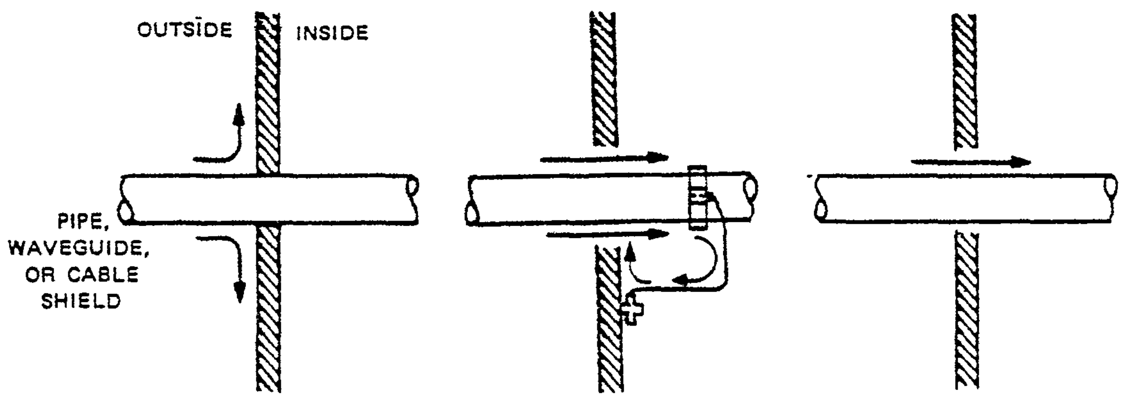


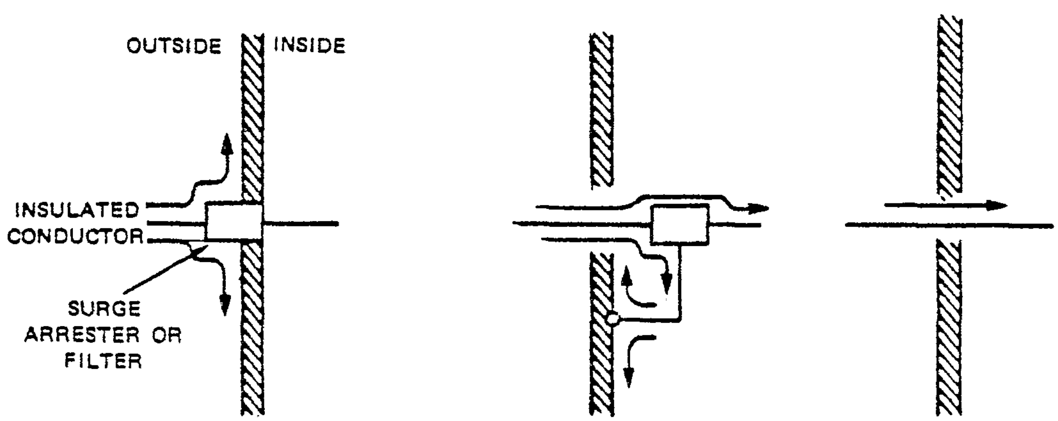
FIGURE 7 CONDUCTOR CURRENT INJECTED ON THE "INSIDE" OF A SHIELD



(a) GROUNDING CONDUCTORS



(b) "GROUNDABLE" CONDUCTORS



(c) INSULATED CONDUCTORS

FIGURE 8 SHIELDING INTEGRITY NEAR INTERFERENCE-CARRYING EXTERNAL CONDUCTORS

The importance of this current diversion is shown in Figure 9 where the currents on the penetrating conductor inside the shield with and without diversion are compared.

Only "short-circuit" devices, those that divert the conductor current to the shield, have been illustrated here because at the first level of shielding the interference levels caused by the EMP and lightning are very large. "Open-circuit" devices, such as chokes and dielectric gaps, must be capable of withstanding voltages approaching 1 MV at the first shield. Devices designed for these voltages are expensive and require considerable maintenance, whereas the "short-circuit" devices are cheap and require much less maintenance. (For water and sewage plumbing, however, plastic piping can be subtituted for metal piping to eliminate the conductor.)

At secondary and tertiary shields where the open-circuit voltages are less severe (i.e., hundreds of volts instead of MV), current-interruption techniques can be applied quite satisfactorily. Several current-interruption techniques are illustrated in Figure 10, where the open-circuit voltage impressed across the current-interrupting device is also indicated. Such techniques are usually applied only to insulated conductors such as power and signal conductors; "groundable" conductors such as cable shields, plumbing, and waveguides are economically and reliably treated with the current-diversion approach of Figure 9(b).

There are, of course, many other input/output circuits that can serve as buffers or isolators at the secondary and tertiary shields. Many of these are functional components of the system or electronic circuit that can be adapted to shielding purposes. Rectifier power supplies and dc-to-dc converters may serve to isolate the primary power conductors from the conditioned power supplied to the small-signal circuits. Tuned RF amplifiers and mixers serve as narrow-band filters to exclude interference on the input conductors. Well designed electronic equipment often contains balanced transmitters and receivers, emitter followers, or other high-tolerance buffer stages to protect the small-signal circuits from interference propagating toward the input/output

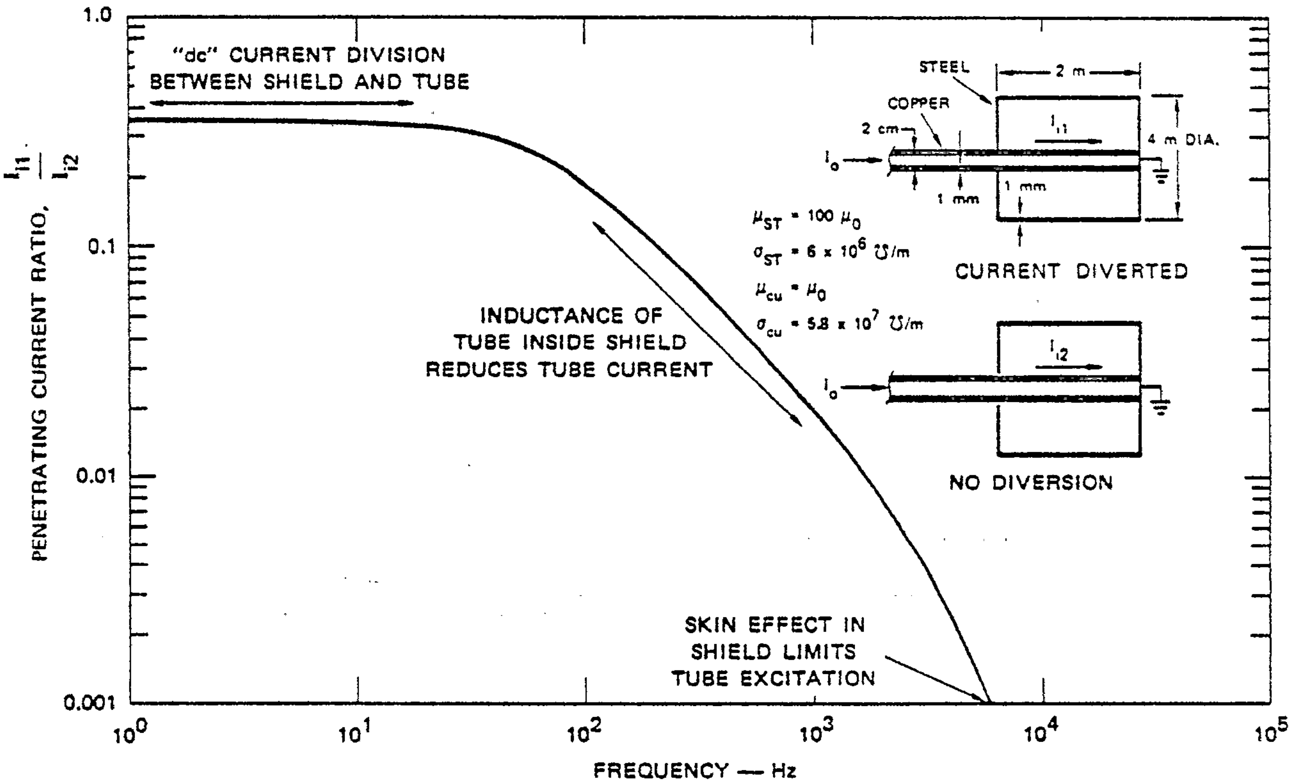


FIGURE 9 RATIO OF CURRENT PENETRATING SHIELD WALL (I_{i1}) TO CURRENT CONDUCTED THROUGH WALL (I_{i2})

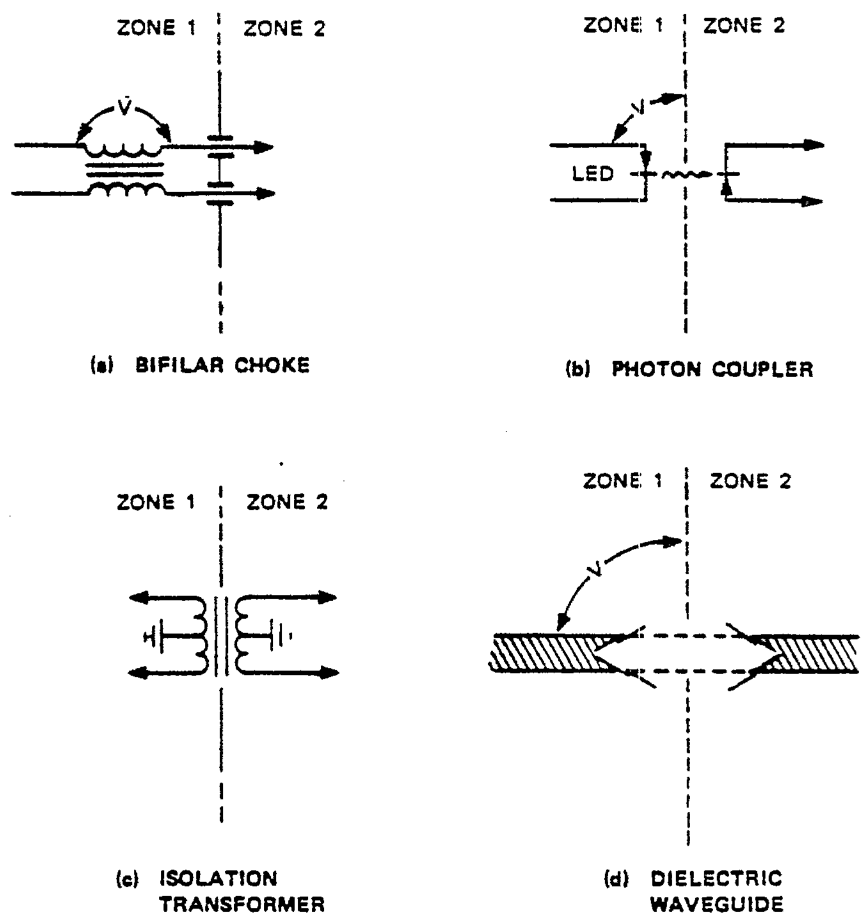


FIGURE 10 CURRENT-INTERRUPTION TREATMENTS FOR SECONDARY SHIELD PENETRATIONS

terminals. Indeed one approach to interference control is to make the electronic equipment "inherently immune" by providing high integrity shielding in the cabinets and using high-tolerance input/output circuits.

If the purpose of the shield is to confine an interference source, rather than to exclude the effects of an external source, the same principles hold, and the examples in Figures 8 and 10 apply if "outside" and "inside" are interchanged in Figure 8 and "Zone 1" and "Zone 2" are interchanged in Figure 10. However, there are many system modules in which the module shield is required to provide both a confining and an excluding role. Some examples are encrypting and decrypting units and many avionics modules which require a limit on emanations as well as a tolerance to external interference.

For these dual-role shields, the treatment of grounds and groundable conductors shown in Figure 8 are appropriate since the "proper" techniques shown obviously perform equally well in either direction. A careful examination of the shield topology in the vicinity of the insulated conductor treatments in Figure 8(c) and Figure 10 will show that as interference barriers, most of these devices can also be bilateral devices. A possible exception to this conclusion is the combination of a nonlinear surge arrester with linear, passive devices at the interfaces, but this combination is used for the case where the peak interference on one side of the barrier is expected to be much larger than that on the other side of the barrier. There appears to be no requirement in practice for such treatments to be bilateral, because if the peak interference fields were comparable on both sides of the shield, the shield is probably serving no useful function.

A typical interference-control design for controlling both internal and external sources might look like Figure 11. Here a building or room shield provides primary protection against the external sources associated with the EMP, lightning, and switching and the induced effects of lightning and the EMP on external cables. A particularly offensive source inside the room is cordoned off by a shield that confines the offensive source or excludes it from the remainder of the interior space.

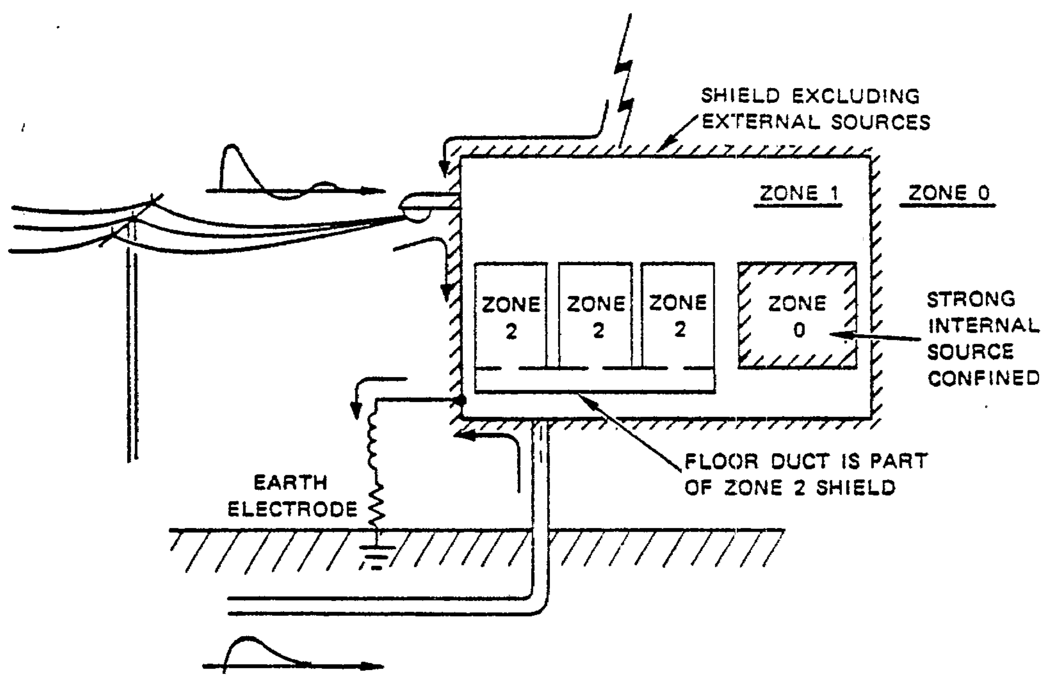
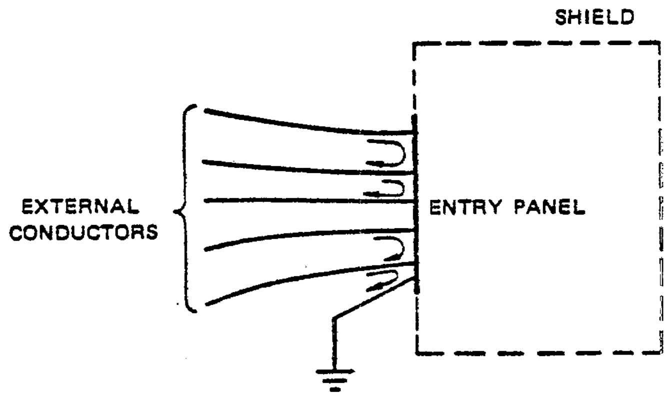


FIGURE 11 USE OF SHIELDS TO EXCLUDE EXTERNAL SOURCES AND TO CONFINE INTERNAL SOURCES

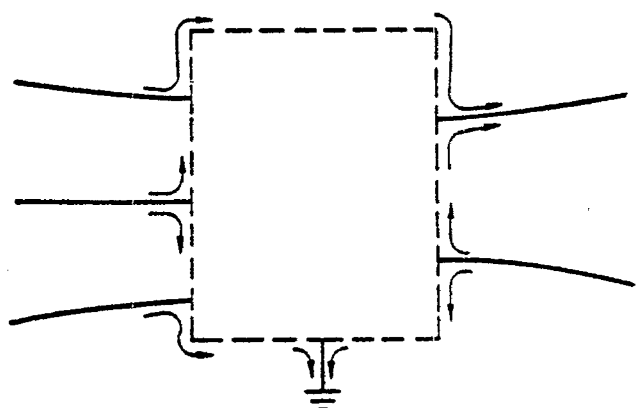
The second-level shield then separates the small-signal circuits in the cabinets and their interconnecting cabling in the floor duct from the room environment. In addition, the Zone 1/Zone 2 interface treatments serve to confine any sources within the cabinet so that emanations from the circuits in the cabinet are controlled. It is reiterated that these emanations may propagate on grounding conductors and unintentional conductors as well as power and signal lines. Thus the shielding integrity is preserved (and interference is controlled) only if all of these conductors are properly treated.

Another corollary of shielding theory is that <u>fields cannot diffuse through shields that carry no current</u>. 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 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).

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 12(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 conductor must either be reflected back on the same conductor or leave through another appendage or through the grounding conductor. By contrast, when the random entry illustrated in Figure 12(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



(a) SINGLE ENTRY PANEL



(b) RANDOM ENTRY

FIGURE 12 EXTERNAL-APPENDAGE CURRENT PATHS ON SHIELDS 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.

It will be enlightening at this point to examine some violations of the shield topology that have been encountered. One of these is a perversion of the single-point-ground concept that demands that signal common, a small-signal conductor, be connected by a single insulated conductor to the electrical ground electrode. The topology of this situation is depicted in Figure 13, where it is apparent that the signal-common grounding conductor penetrates both levels of shielding. Therefore, the environment of the small-signal circuits has been degraded to that of Zone 0, the harsh external environment. Note that a closed shield is formed by shields 1 and 2 in Figure 13, but it excludes the interior of shield 2! Proper treatment of grounding conductors at the shield is illustrated on the left in Figure 8.

A second example is illustrated in Figure 14 where the electric power service entrance and ground are shown. In this case, the phase conductor is properly protected with a surge arrester and filter in the distribution panel. At the equipment cabinet, however, the filter on the phase conductor is installed so that the interference current diverted through the filter is delivered to the inside of the cabinet, (the small-signal zone) rather than to the outside. A much more severe violation of the shields is evident in the neutral and ground conductor circuit, however. This conductor has been provided no surge protection or filtering at either shield penetration, although a long, inductive path to earth and to the equipment cabinet has been provided. Because there is little voltage limiting or current diversion on this conductor, it carries the external environment (zone 0) through both the building shield and the cabinet shield into the small signal area (zone 2). It thus behaves in much the same undesirable manner as the "grounded" signal common in the previous example.

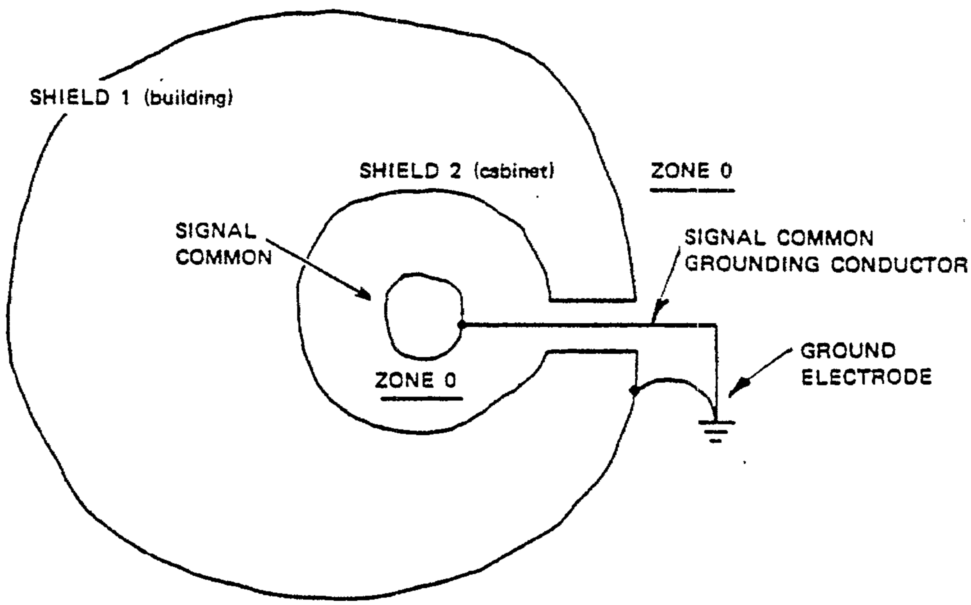


FIGURE 13 SHIELD TOPOLOGY WHEN SIGNAL-COMMON IS CONNECTED TO POWER GROUND ELECTRODE

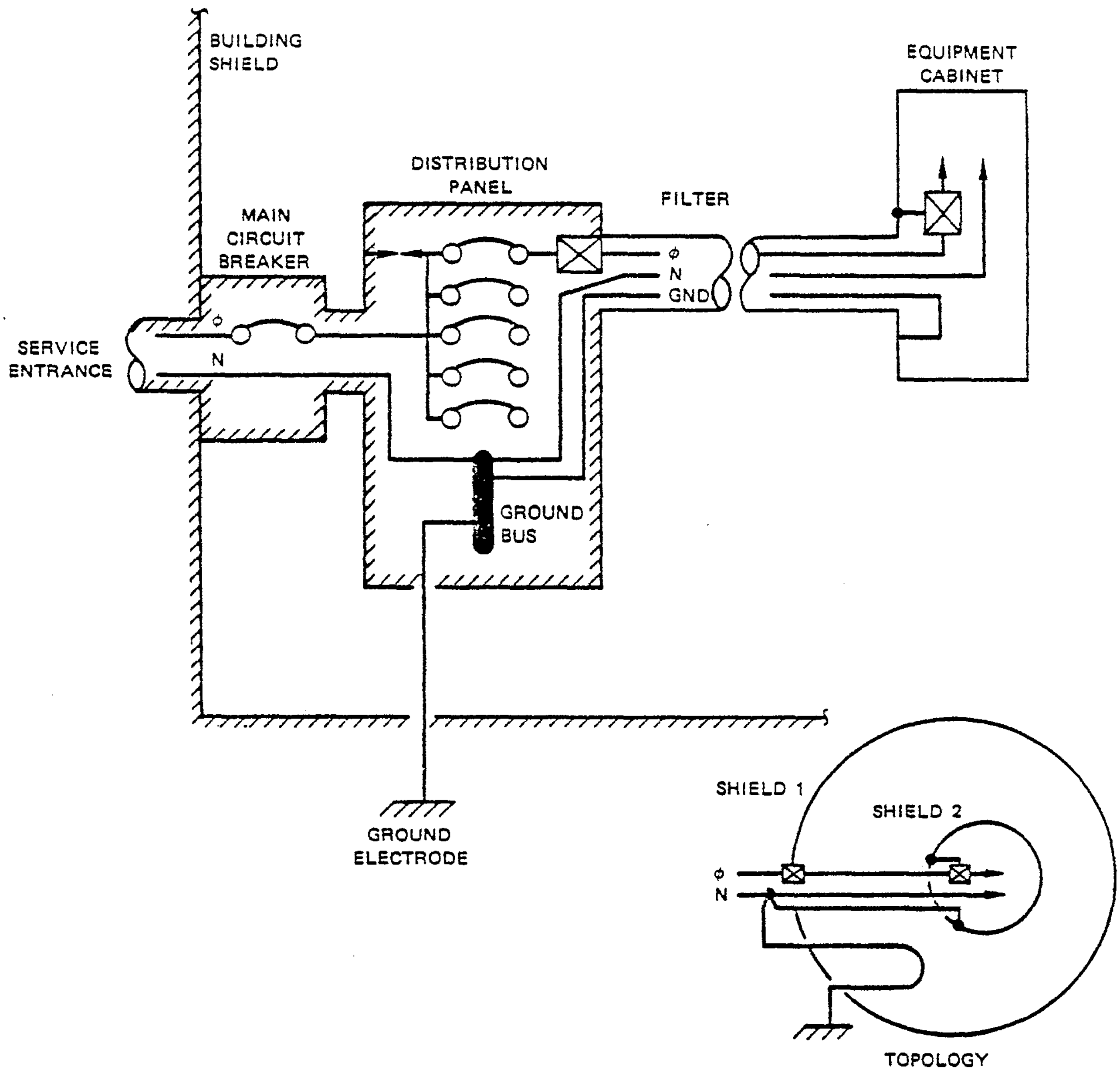


FIGURE 14 ELECTRIC POWER SERVICE VIOLATING BOTH LEVELS OF SHIELDING

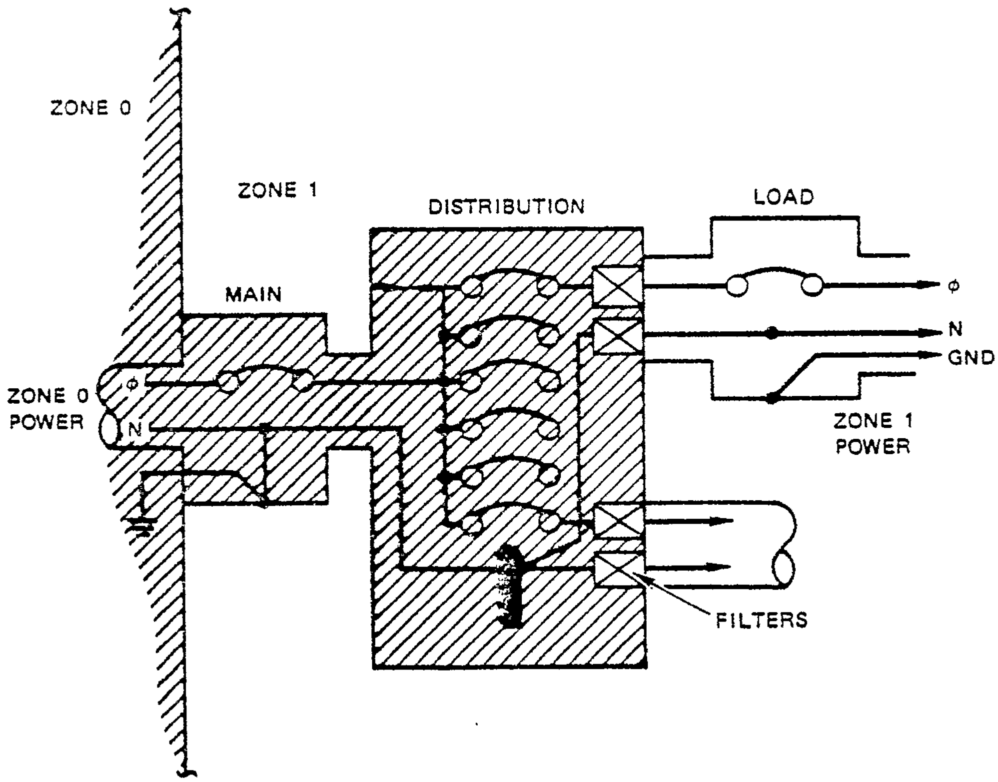
Another violation of the shield in Figure 14 is the exposed grounding conductor between the distribution panel and the ground electrode. This is a particularly offensive Zone 0 conductor routed through the interior of the first shield zone by means of two penetrations of the shield. This might have been done to avoid routing the grounding conductor through a steel conduit, thereby increasing its inductance; however it could have been routed back through the conduit from the main circuit breaker without increasing its inductance or compromising the shield.

Figure 15 illustrates proper preservation of shielding integrity at the power entry to the building and to the equipment. Shading is used to identify the topology of the shield. All of the shaded area in Figure 15 is outside the shielded space, since the protected interface is at the load side of the distribution panels in Figure 15(a) and the right side of the entry box in Figure 15(b).

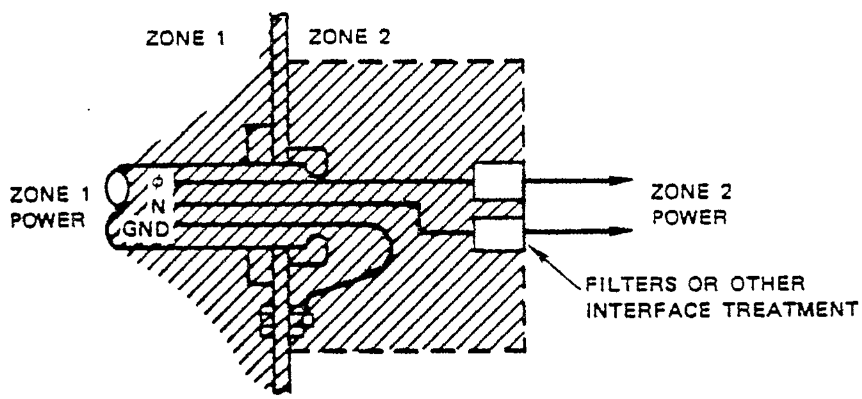
In both of these examples, the offending conductors were grounding conductors. Such conductors are often erroneously thought to be innocuous, when in fact they can be among the most offensive sources of interference. Therefore an important rule of effective shielding and grounding practice is that topologically, grounding conductors should never penetrate shield surfaces.

B. Aperture Control

Most facilities require windows, doors, ventillation openings, access hatches, etc., which may also compromise the integrity of the shield. The penetration of external fields through apertures that are small compared to a wavelength is illustrated in Figure 16. As shown in Figure 16(a), part of the electric field that would otherwise terminate on the outside surface of the shield penetrates through the aperture, where it may induce charge on internal cables. Similarly, some of the magnetic field that would otherwise be bounded by the surface current in the shield is permitted to pepetrate through the aperture, link an internal cable, and thereby induce a voltage in the cable, see Figure 16(b).

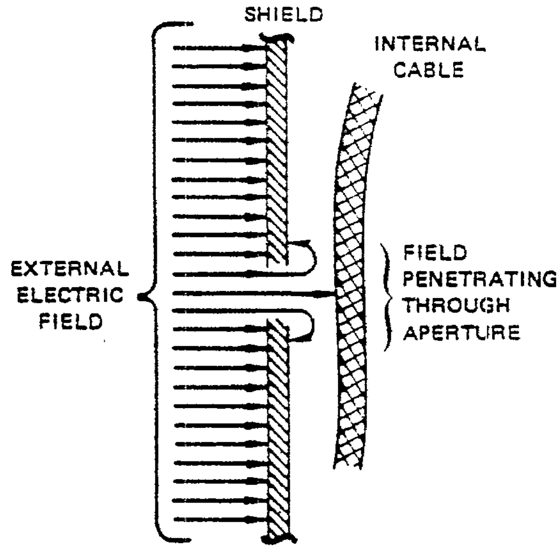


(a) BUILDING ENTRY

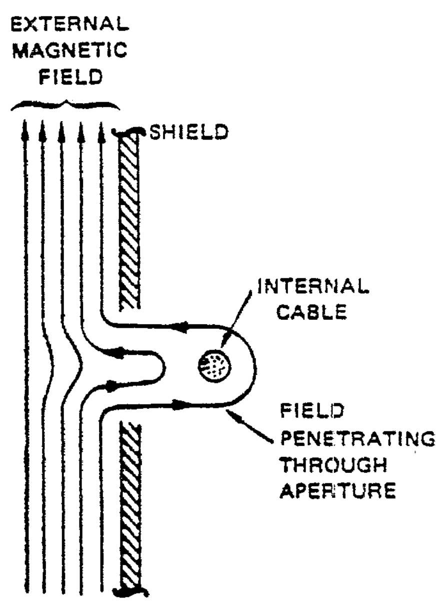


(b) EQUIPMENT ENTRY

FIGURE 15 PROPER ELECTRIC POWER SERVICE WITHOUT COMPROMISING SHIELDS



(a) ELECTRIC FIELD



(b) MAGNETIC FIELD

FIGURE 16 ELECTROMAGNETIC PENETRATION OF SMALL APERTURES

If the aperture is large compared to a wavelength, the incident wave can propagate through the aperture as illustrated in Figure 17. Because the shortest wavelengths of concern in EMP hardening typically are of the order of 1 meter, shine-through is usually significant only at large windows and doors. Because the shine-through wave is attenuated very little in the direction of propagation of the incident wave, however, almost the full incident EMP peak field strength may be transmitted to the interior of the shield through large apertures.

The fields penetrating a small aperture depend on the aperture size. Therefore, if a given area of wall opening is subdivided into, say ten, small openings having the same total area, the penetrating fields at an interior point will be about $1/\sqrt{10}$ as large for the ten small openings as for the single large opening. Thus one common treatment for such openings is to cover them with a conducting screen or mesh, so that the large opening is converted into a multitude of small openings.

More reduction can be obtained with sacrifices in optical transparency and increased resistance to air flow by adding thickness to the screen. Then each small aperture becomes a tube through the wall and behaves as a waveguide beyond cutoff. Fields transmitted through a waveguide beyond cutoff are attenuated approxiamtely exponentially with distance along the guide, so that very large attenuation may be achieved by using many small tubes welded or brazed together in a honeycomb structure. Sketches of the magnetic field in the vicinity of a single aperture, an array of small apertures, and an array of waveguides beyond cutoff are shown in Figure 18.

Shield boundaries in the immediate vicinity of apertures are ill defined because the electromagnetic fields vary over a wide range in these regions and there is no physical barrier to make a distinct separation of the internal and external regions. However, a boundary can often be drawn to indicate the region inside which the aperture fields are smaller than those permissible inside the shield. Thus another treatment for penetration through apertures is to form an exclusion zone about the aperture. No internal coupling elements such

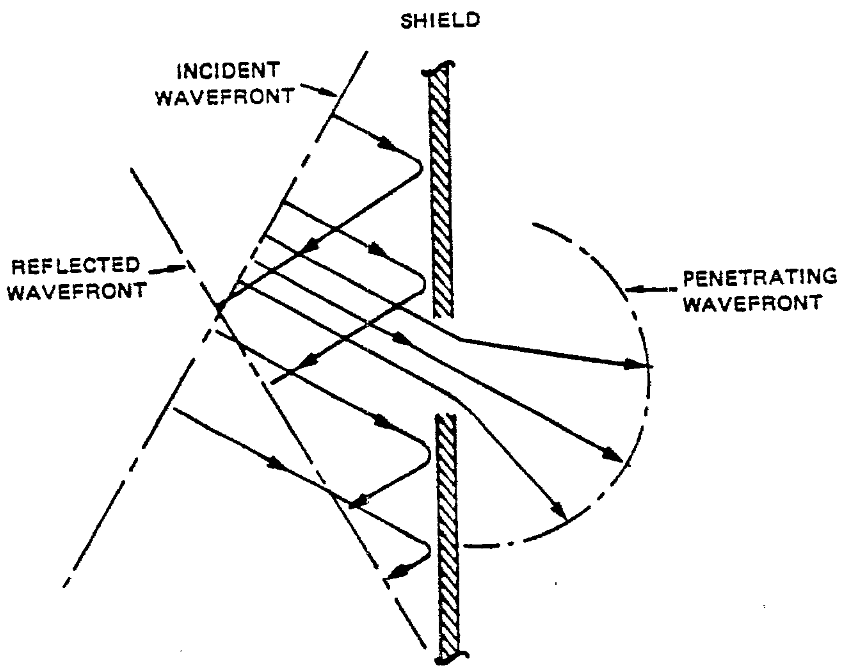


FIGURE 17 ELECTROMAGNETIC PENETRATION OF LARGE APERTURE

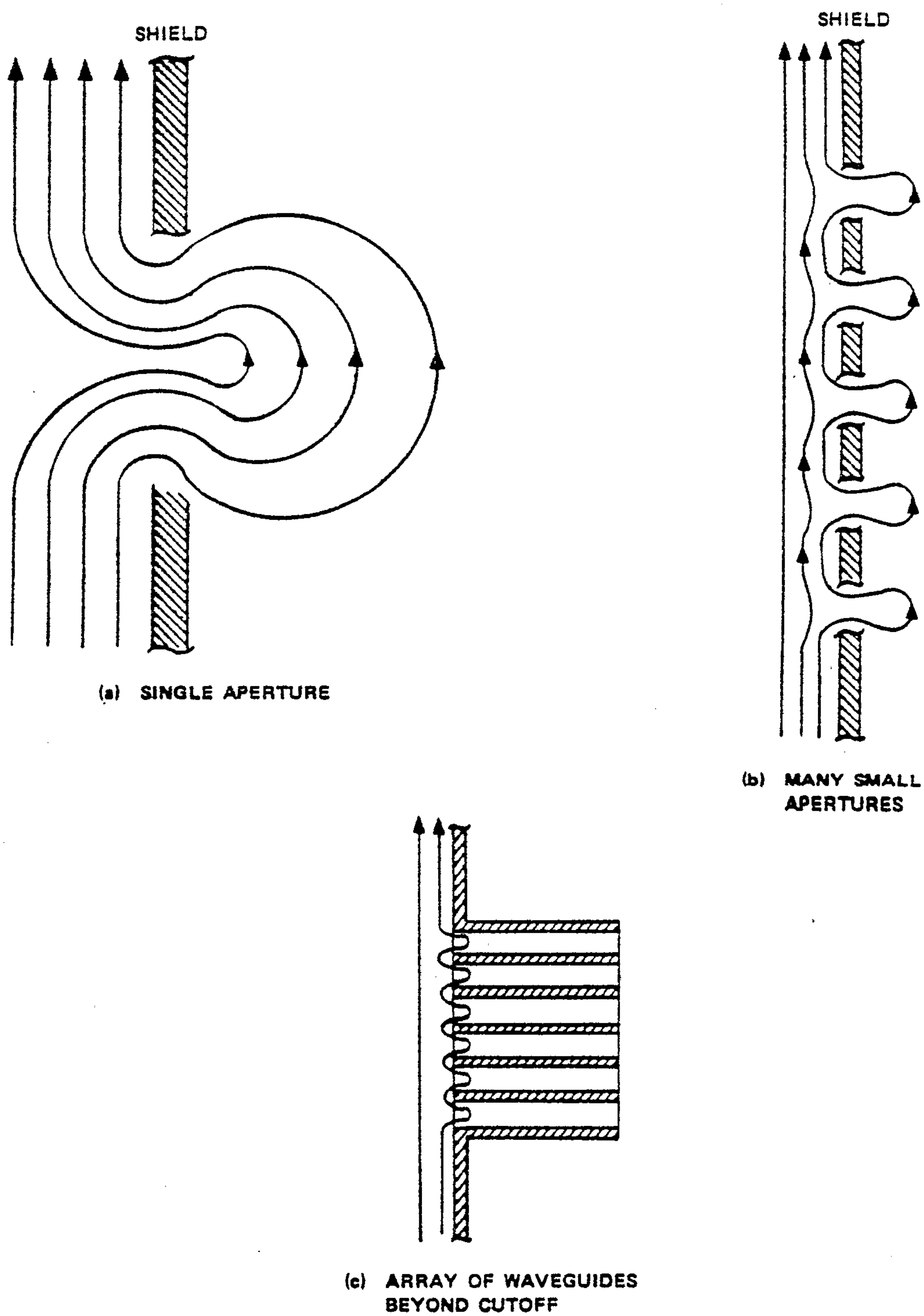


FIGURE 18 MAGNETIC FIELD PENETRATION OF APERTURES

as cables or sensitive components are permitted to occupy or pass through this exclusion zone. Therefore the interaction of internal components with the fields of external origin in the vicinity of the aperture is limited by avoiding the regions where strong interaction can occur.

C. Diffusion Through Shield Walls

Continuous, closed sheet-metal shields are, by far, the most effective electromagnetic shields because they severely limit the penetration of energy in the spectrum above $f_\delta = (\pi\mu\sigma d^2)^{-1}$ and they are good reflectors of propagating waves throughout the spectrum. However, these remarks and the discussion in this section apply only to continuous closed shields; the effects of apertures, penetrating conductors, and other imperfections discussed above are usually much more important than diffusion through the walls.

The ratio of the magnetic field inside the shield to the magnetic field incident on the outside of the shield is, when expressed in decibels, defined as the shielding effectiveness of the shield. This shielding effectiveness depends on the shape of the shield structure and the conductivity, permeability, and thickness of the sheild wall. The shape of the body determines the concentrating effect the body has on the external fields. For example, an infinite plane sheet does not concentrate the fields at all, the long cylinder concentrates in two dimensions, and the sphere in three. The shielding effectiveness factors attributable to reflection for these shapes are (in decibels)

plane: $$R \approx 108 + 10 \log \left(\frac{\sigma_r}{\mu_r f_{MHz}} \right)$$

circular cylinder: (infinite length) $$R \approx 75 + 10 \log \left(\frac{\sigma_r f_{MHz} a^2}{\mu_r} \right)$$

sphere: $$R \approx 70 + 10 \log \left(\frac{\sigma_r f_{MHz} a^2}{\mu_r} \right)$$

for $10^{R/20}\, d/\delta \gg 1$ and $a/\mu_r \delta \gg 1$, where d is the wall thickness, a is the radius of the cylinder or sphere, σ_r and μ_r are the relative conductivity and permeability ($\sigma_r = 1$ for copper, $\mu_r = 1$ for vacuum), and f_{MHz} is the frequency in megahertz. These results are developed from formulas derived in Reference 6. The remainder of the shielding factor is related to the attenuation A of the fields within the wall and to multiple reflections F within the wall:

$$A + F = 20 \log \left| 2 \sinh (1+j)\, d/\delta \right|$$

$$= 8.69\, d/\delta + 10 \log \left(1+e^{-4d/\delta} - 2e^{-2d/\delta} \cos 2d/\delta \right)$$

where δ is the skin depth $\left[\delta = (\pi f \mu \sigma)^{-\frac{1}{2}} \right]$.

The total shielding effectiveness is thus

$$S = R + A + F = 20 \log \left| \frac{H_{incident}}{H_{inside}} \right|$$

Since the spherical shell more nearly represents the shape of a facility shield (in that it has no infinite dimensions), we may use the shielding factors for the sphere to estimate the voltage induced on conductors inside a facility.

This shielding effectiveness of spherical shells has been calculated and plotted in Reference 7 as a function of a normalized frequency $2\pi\tau_s f$ for various values of a "size and material" factor $C = a/3\mu_r d$, where $\tau_s = \mu\sigma d^2$ is the shield diffusion time constant. These shielding effectiveness data are shown in Figure 19.

The inverse Fourier transform of the shielding effectiveness data, giving the waveform of the magnetic field at the center of the sphere when a unit impulse of magnetic field is incident on the sphere, is shown in Figure 20 (from Reference 7). Because $\tau_s \geq 10$ μs for most shield materials and thicknesses, if the incident pulse width is less than 10 μs the internal response will be the impulse response.

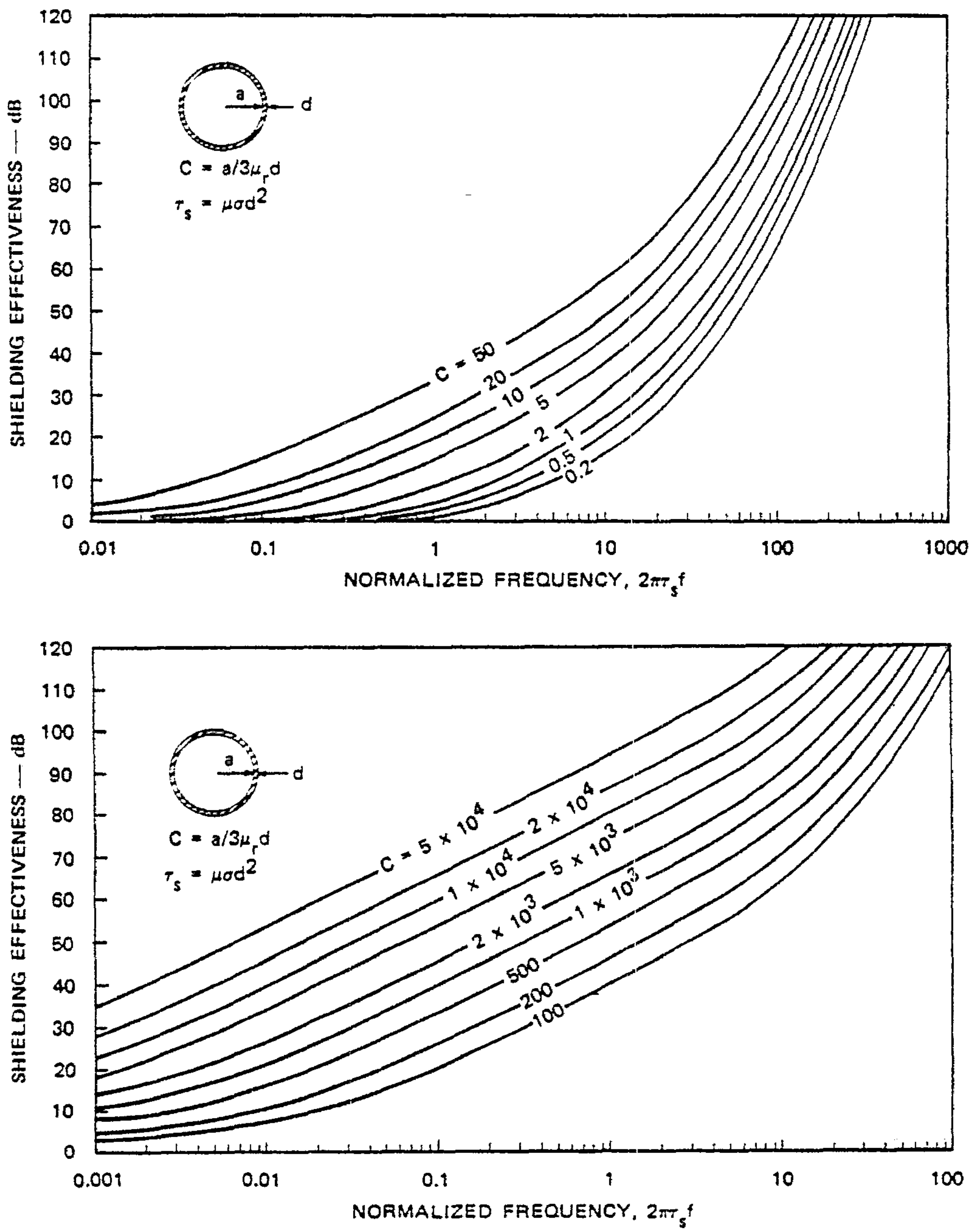


FIGURE 19 MAGNETIC SHIELDING EFFECTIVENESS FOR SPHERICAL SHELL ENCLOSURE VS NORMALIZED FREQUENCY FOR VARIOUS VALUES OF PARAMETER C (Ref 7)

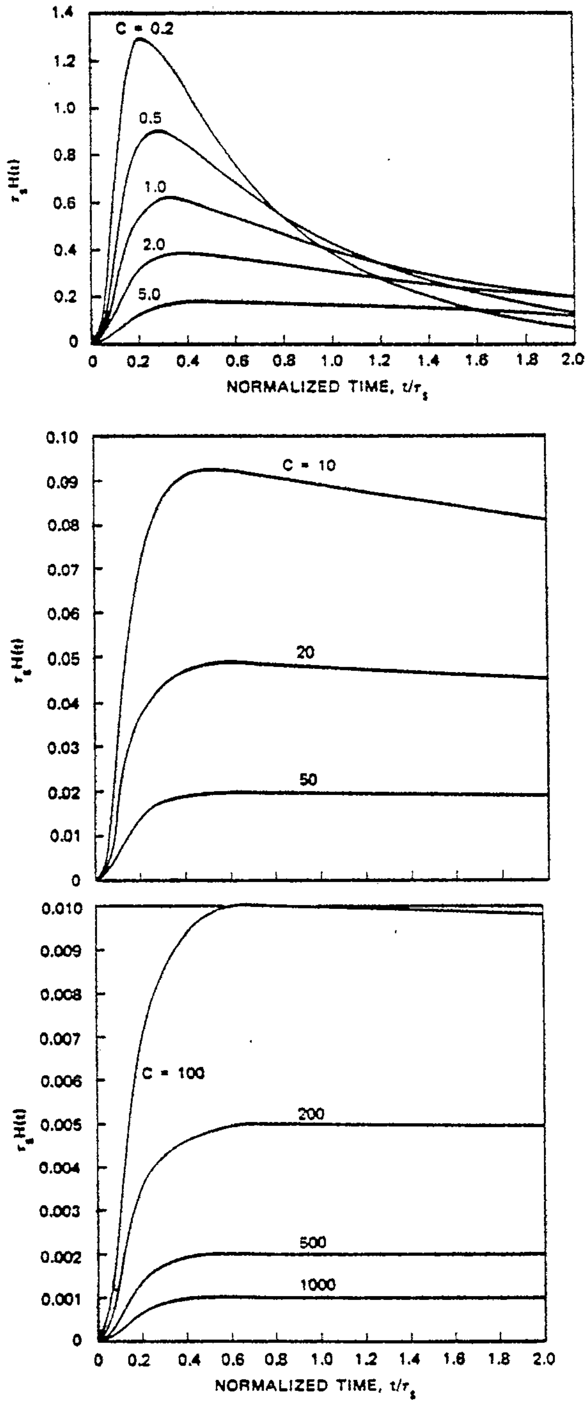


FIGURE 20 WAVEFORMS OF MAGNETIC FIELD AT THE CENTER OF A SPHERICAL SHIELD WHEN A UNIT IMPULSE OF MAGNETIC FIELD IS INCIDENT ON THE OUTER SURFACE OF THE SPHERE (Ref 7)

For a closed metal shield, we can estimate the voltage induced on conductors inside the shield from the peak voltage induced in a loop of area πa^2 by this impulse. This voltage is

$$V_{pk}(t) \approx \mu_o \pi a^2 H_o \tau \ \frac{H_{pk}}{t_{pk}}$$

where H_{pk} is the peak internal magnetic field, t_{pk} is the time at which this peak occurs, and $H_o\tau$ is the value of the incident impulse. For the high altitude EMP, the incident impulse is

$$H_o\tau = \int_o^\infty H(t)dt \approx 3.5 \times 10^{-5} \text{ As/m}$$

The peak voltage induced in a loop inside a 10-m radius spherical shield by the high altitude EMP is shown in Table 1 for 3 wall thickness (0.2, 1, and 5 mm) and 3 materials (copper, aluminum, and steel). As the table illustrates, a very thin shield will suffice to reduce the EMP-induced voltages to well below the levels of internally generated voltages if only diffusion through the walls is considered. For this reason, shield thickness may be determined more by structural considerations (or by other electromagnetic considerations such as lightning) than by electromagnetic pulse considerations.

Table 1

PEAK VOLTAGE INDUCED ON 10m RADIUS LOOP INSIDE 10m RADIUS SPHERICAL SHIELD BY THE HIGH ALTITUDE EMP (BY DIFFUSION THROUGH WALLS ONLY)

Shield Thickness	Internal Voltage Induced in Loop		
	Copper (5.8×10^7)mho/m	Aluminum (3.7×10^7)mho/m	Steel $\begin{pmatrix} 6 \times 10^6 \\ \mu_r = 200 \end{pmatrix}$ mho/m
d= 0.2mm	0.34V	0.85V	0.076V
d= 1.0mm	2.6mV	6.4mV	1.1mV
d= 5mm	21μV	51μV	15μV

V CONCLUSIONS

Since interference control is primarily a matter of providing adequate shielding barriers between the interference sources and potential victims, the techniques used tend to be relatively independent of the source or victim. That is, interfering signals of a given amplitude and spectral content will produce similar undesirable effects regardless of whether the source is the EMP, lightning, or an internal device such as a solenoid or rectifier. The goal of both EMP hardening and electromagnetic compatibility work is to limit the amount of undesirable signal that reaches a victim circuit to levels that the circuit can tolerate without impaired performance. In the EMP invironment the source is outside the space to be protected, while in the EMC case the source may be either outside or inside this space. The shield in either case is used to separate the source from the protected space.

A systematic approach to interference control has as its foundation identification of the topology of the shielding surfaces. The integrity of these shield surfaces is to be preserved in spite of requirements for insualted power and signal conductors to pass through the shield, or of requirements for doors, access hatches, etc., to be cut in the shield wall. Much of interference control technology is therefore devoted to accommodating these compromises of the shield without unnecessarily degrading the shield's ability to separate the internal environment from the external environment.

Finally, a rationale has been developed for determining how much shielding is necessary for a given interference source based on the insulation strength inside the shield and the expected tolerance of the victim equipment. Thus the shield must at least reduce the interference level to that which the insulation can withstand, but it need not reduce the interference to much below the ambient interference level generated in the protected region by internal equipment.

REFERENCES

1. E. F. Vance, "Coupling to Cables," DNA 2114, Chapter 11 (revised), Defense Nuclear Agency, Washignton, D.C. (December 1974).

2. F.M. Tesche, et al, "Internal Interaction Analysis: Topological Concepts and Needed Model Improvements," Interaction Note 248, Air Force Weapons Laboratory, Kirtland AFB, New Mexico (July 1975).

3. C. E. Baum, "How to Think about EMP Interaction," Proceedings of the 1974 FULMEN Meeting, Air Force Weapons Laboratory, Kirtland AFB, New Mexico (April 1974).

4. C. E. Baum, "The Role of Scattering Theory in Electromagnetic Interference Problems," P.L.E. Uslenghi, (Editor) Electromagnetic Scattering, Academic Press (1978).

5. F. D. Martzloff and G. J. Hahn, "Surge Voltages in Residential and Industrial Power Circuits," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-89, No. 6, pp. 1049-1056 (July/August 1970).

6. H. Kaden, Wirbelströme und Schirmung in der Nachrichtentechnik 2nd Edition, Chapter C, Springer-Verlag, Berlin (1959).

7. "EMP Engineering and Design Principles" Bell Telephone Laboratories, Whippany, N.J. (1975).