RF SHIELDING CONCEPTS AND TESTING: AN INTRODUCTION

Basic shielding principles and testing techniques are presented. Essential components of shielded rooms are described, with emphasis on integrating subsystems into the shielded enclosure without compromising shielding performance.

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INTRODUCTION

An earth free of any and all interference would constitute an environment where conditions such as aerodynamics, friction, transmission loss and receiver reception characteristics are of no concern. Unfortunately, a purely interference-free environment only exists in an engineer's dream.

To increase the speed of objects, designers learned to use a branch of dynamics referred to as aerodynamics, which deals with the motion of air and other gaseous fluids and the forces acting on bodies in motion relative to such fluids. By applying principles of aerodynamics, cars, boats, trains and airplanes have become faster and more efficient.

Aerodynamics is only one area of science which helps vehicles become faster and more efficient. In the world of electronics, aerodynamics would be of no help in making a system operate faster or more efficiently. Efficiency and speed of electronic systems increase with such practices as replacing tubes with transistors, replacing switches with gates, and reducing interference with ferrites and shielding.

Current trends of electronic miniaturization leave circuits and entire systems susceptible to interference which can dramatically affect their efficiency and operation. One method frequently used to reduce susceptibility or interference to a harmless level is shielding.

A shield is essentially a shelter or cover which provides protection from ambient electromagnetic (non-ionizing) radiation. This protection prevents conducted or radiated energy from entering or exiting a specific region.

For a shield to be efficient, numerous precautions must be exercised in the design and assembly. Additionally, provisions must be included for the introduction of communication lines, signal and electrical lines, liquids, gases and a method of ingress and egress.

Determining the effectiveness or efficiency of a shield is typically performed using radiated techniques. The test process is performed in accordance with current Military Standards or National Security Agency procedures. Occasionally the frequencies and attenuation levels are modified to meet specific requirements. Essentially, the shield effectiveness or efficiency test is equivalent to calibrating electronic (test) equipment. As with periodically calibrating test equipment, a shield should be recalibrated to determine if its effectiveness or efficiency has decreased or has been degraded.

RF SHIELDING

A simple definition of a shield is "a protective cover or shelter." This protective cover is designed to prevent electromagnetic energy from entering a specific area or to confine energy to a specific region.

To provide shielding, the shelter or cover must be designed with ferrous or non-ferrous materials that display the ability to absorb and/or reflect electromagnetic energy. The material used is determined by the undesired frequencies or fields that exist within a specific area. The field strength of the signal being shielded will also determine the material thickness used.

A shield can be as simple as a metallic braid or foil wrapped around an insulated wire, such as coaxial cable, or as complex as a building four stories high. In the case of the latter, steel plates of uniform thickness are continuously welded to provide continuity between adjoining plates. The steel plates are arranged in a manner that, when complete, is analogous to the assembly of a large six-sided box. Once all welding is complete, no electromagnetic energy (to a certain level) can enter or exit the box.

This would be the ultimate shield, as it would have no penetrable apertures. Unfortunately, this ultimate shield would serve no useful purpose as there would be no way to enter or exit it. To make this shield a useful tool, provisions must be made to allow personnel and equipment to enter and exit. Additionally, AC/DC power lines, communication lines, HVAC (heating-ventilation-air-conditioning), water and various gases may be required to enter or exit the shielded region. This can be accomplished by using shielded doors, electrical filter networks, honeycomb (hexcell) vent material and waveguide (beyond cutoff) penetrations.

RF shields are not limited to building or coaxial cables. Coaxial/waveguide connectors, cabinets, partitions and equipment covers can also shield electromagnetic energy effectively. However, each shield will only provide the amount of shielding effectiveness for which it was designed.

The shielding effectiveness of a shielding aid can be mathematically modeled with a high degree of accuracy. Unfortunately, items such as windows, doors, joints, penetrations and filters can negate the predicted level of shielding effectiveness. Therefore, to determine the absolute level of shielding effectiveness, a test should be performed. The test can be a simple insertion loss-type measurement (of a length of cable), or as involved as a multiple frequency/field radiated test.

SHIELDING MEDIA

Metallurgical engineers have made vast strides in developing hybrid metals and refining existing metals. Many of these metals are well-suited for providing protection from electromagnetic energy. Metals such as "Mumetal," "4-79 Permalloy" and "Supermalloy" display some of the highest levels of shielding effectiveness to low frequency magnetic fields, whereas copper, brass, aluminum and gold display low levels of magnetic field shielding effectiveness while displaying high levels to electric fields (due to reflection loss).

Recent additions to this list of suitable shielding materials are conductive coatings or "thin films." These materials are typically applied in layers of various thicknesses and may also be over-coated with different materials. The materials commonly used are copper, nickel, aluminum, zinc and silver. These materials can be applied in different combinations or applied as one material. Application of these conductive coatings is performed by spray painting techniques, electroless plating (a chemical reduction process) and arc/flame spray. These materials are not self-supporting, and thus require a host material such as plastic, wood or fabric.

Typical shielding media commonly used are copper, cold/hot rolled steel, galvanized steel, aluminum and, occasionally, brass/bronze. Copper, aluminum and bronze screening are also used. However, their recent applications seem to be limited to aperture openings such as view windows or special application enclosures.

Thus, at least 100 different materials are useful for shielding. Additionally, these materials can be used in combinations, thereby increasing the number of shielding media. One such combination is "Magnetic Copper" (manufactured by Texas Instruments). This material is unique in the sense that it will attract and/or hold a magnet to its surface. Through metallurgical bonding, a layer of iron is bonded between two layers of copper.

With such a variety of shielding materials available, it can be very difficult determining which material will perform to the desired performance level. Prior to "picking" a material, it is essential that the designer/engineer determine which frequencies and fields the shield must attenuate, the type of construction that is most suited for the area, the anticipated life span of the shielded area, the flexibility of the shield system, the cost of the shield system (or material), disassembly (if required) and whether the shielded area is required to blend into its surroundings.

SHIELDING JOINT CONSTRUCTION

Regardless of the shielding media or materials used, if the joining of material edges is not properly designed or executed, the shield will not display its intended level of protection. Shielded seams or joints should be of a design which will afford a connection that is mechanically and electromagnetically tight. Any gaps or noncontact points along the seam or joint will degrade the overall performance (or shielding effectiveness) of the shield. Gaps or noncontact points are often the result of faulty welds, mating surfaces that were not properly cleaned or fastening devices (screws/bolts) that were not properly tightened or had too great center-to-center spacing.

As with shielding media/materials, the joining system should be designed to meet the required performance. The type of joint or seam used is determined by the shielding material composition (solid plates/sheets or single/double skin "sandwich" panels), site conditions, permanence of the installation, requirements for installation or removal of equipment within the shielded area, and the current or anticipated required levels of shielding effectiveness.

The optimum joint yields an RF impedance equal to the impedance of the shielding material to be joined. If the impedance of the joint is higher than that of the shielding material, RF voltages can develop across the seam from currents and allow electromagnetic energy to enter or exit the shielded area. The occurrence of impedance mismatches can be reduced by using bonding and joining techniques that complement the shielding media used.

Joining or bonding a single layer type material can be accomplished

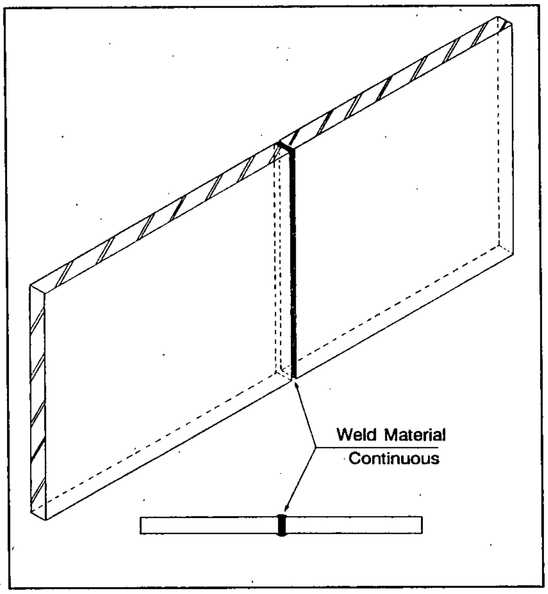

Figure 1. Butt Joint.

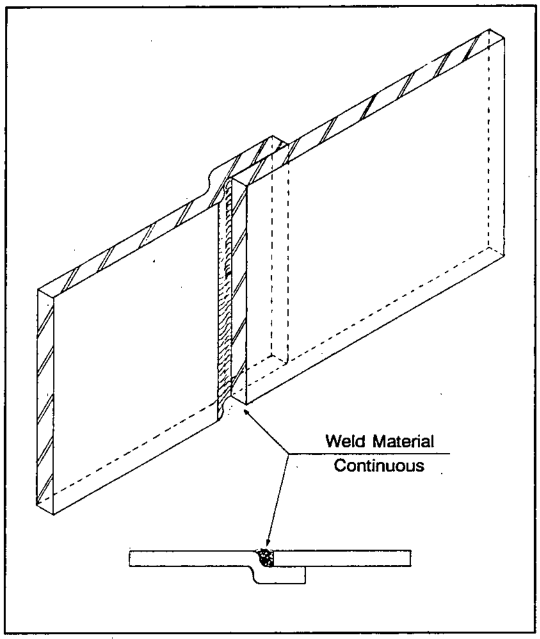

Figure 2. Overlap Stepped Joint.

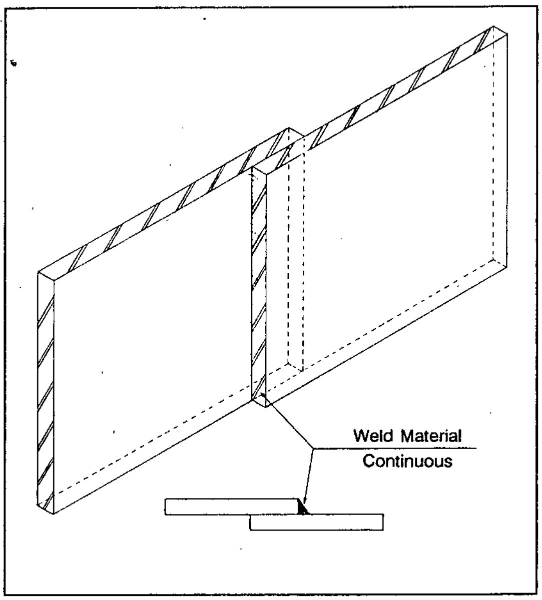

Figure 3. Overlap Joint, No Step.

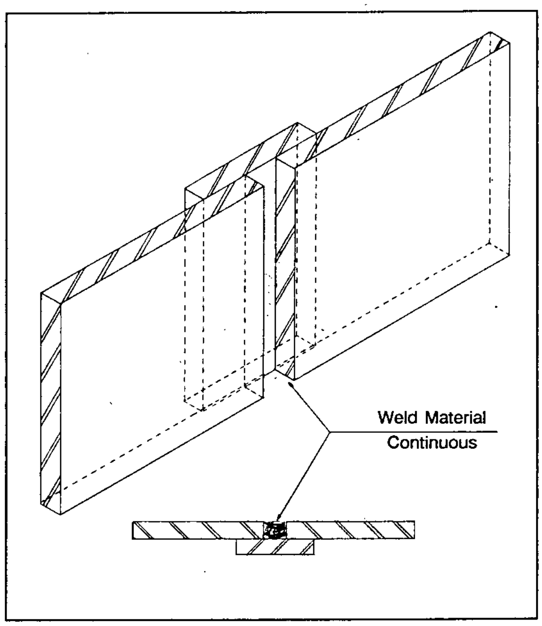

Figure 4. Back-Up Plate.

using spot welds, continuous welds, brazing and sweating or soldering. When bonding single layer materials, a butt joint, overlapped step or no step joint, or a back-up plate joint can be used. (See Figures 1 through 4.) The joint type used depends on factors such as load bearing, span, location and cost.

The joining of light gauge materials (single or multilayer) which require a frame or host material for support is typically accomplished using compressive electromechanical joints. A through-bolted joint or overlapped clamp joint (hat and flat) can be used to attain the required electromechanical properties. (See Figures 5 and 6.) Depending upon the material and backing, or host, soldering, screwing or electrically conductive tapes can be used.

Depending upon the performance level and the joining system used, gasketing may be required to attain a high level of conductivity between joining members. If gaskets are used, their composition must be compatible with surfaces they contact, thus eliminating any corrosion that can eventually decrease the overall shielding effectiveness of the shield.

UTILITY ENTRANCES

The selection of waveguides, utility entrances and doors, like shielding materials and joining systems are

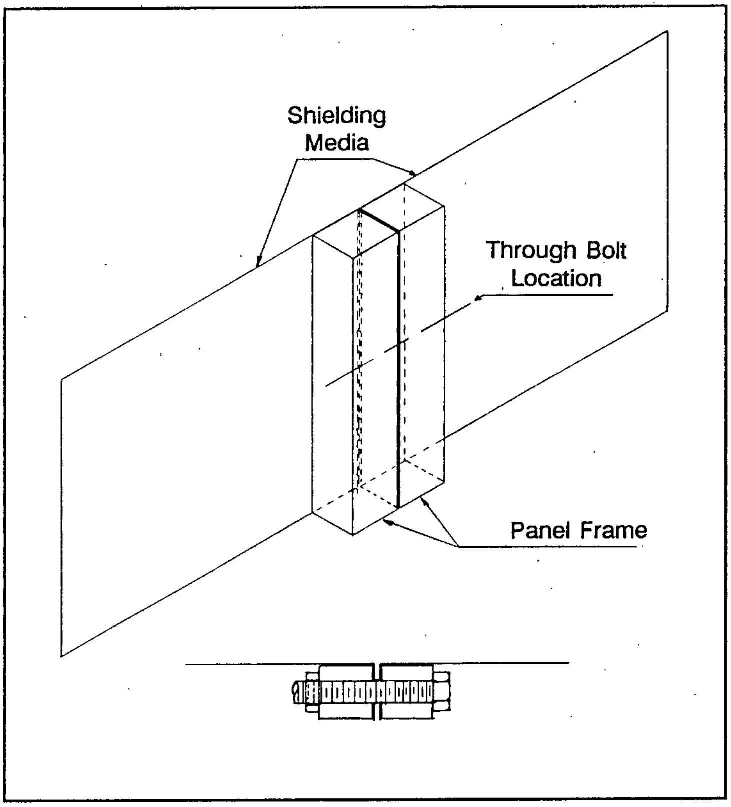

Figure 5. Through-Bolt, Single Skin.

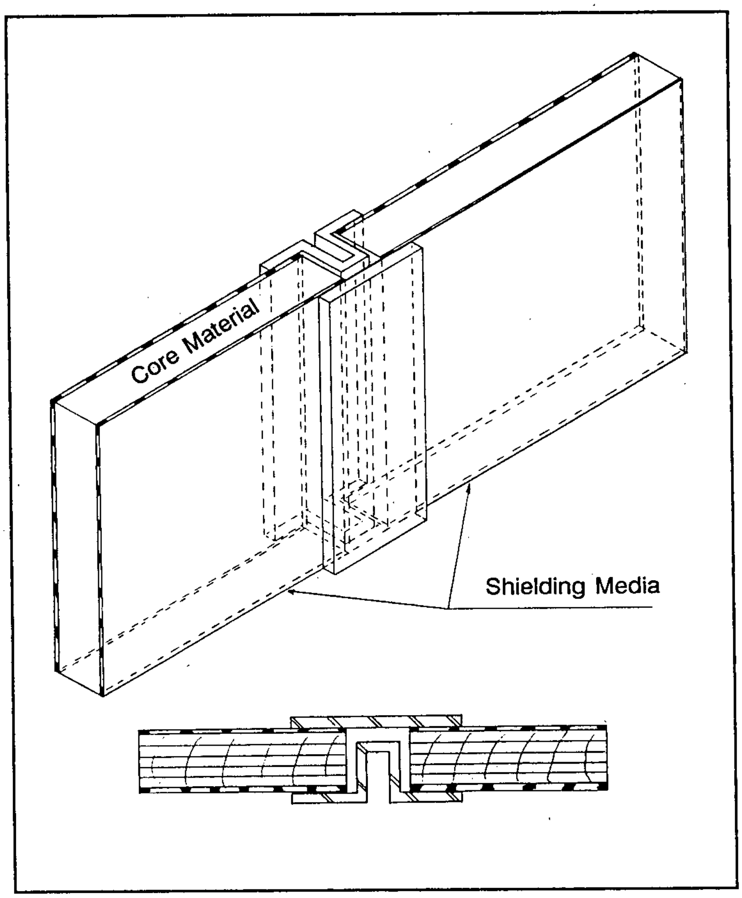

Figure 6. "Hat and Flat" Joint.

determined based on frequency/field performance. If the proper precautions are not taken in selecting these items, the engineering time, planning and money applied toward the shielded environment will have been wasted. The shield performance or protection level will be severely degraded if component performance does not equal or exceed that of the shield.

WAVEGUIDES

Introducing fluids and gases into or out of the shielded environment is accomplished using single or multicell waveguides. Waveguides display characteristics similar to an electrical "high pass filter" which allows energy above its cutoff frequency to pass, while substantially reducing or rejecting frequencies below its designed cutoff.

Typically, waveguides are rectangular, circular or hexagonal in their cross section. (See Figures 7 through 10.) The use of rectangular and circular waveguides is normally limited to allowing fluids, high pressure gases, fiber optic cables, and, occasionally, RF energy to enter or exit the shielded environment. Hexagonal waveguides are normally supplied in a cluster which looks similar to a "honeycomb." Hexcell or honeycomb waveguides are used for low pressure stabilization between adjoining areas, and supplying an entry or exit penetration for heating, ventilation and air conditioning (HVAC) through the shielded wall or environment.

Regardless of the cross section profile, the waveguide material must be conductive and display the ability to interface with the shielding media through which it must pass. If electrical conduction is not attained between mating surfaces, the waveguide may display the characteristics of an antenna.

For a waveguide to be effective, it must be designed or sized in relation to the highest frequency it must attenuate. A simple formula for de-

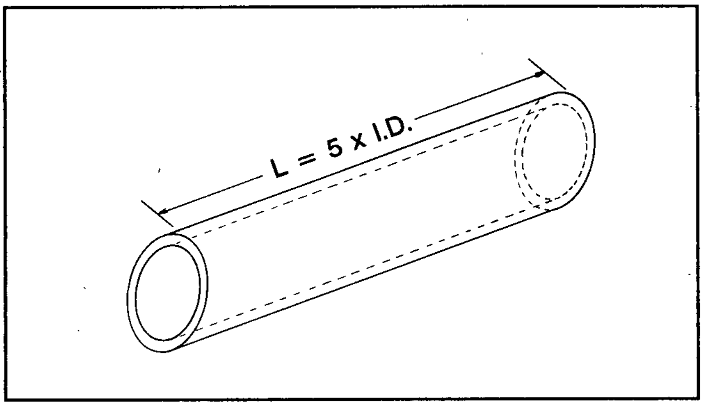

Figure 7. Circular Waveguide.

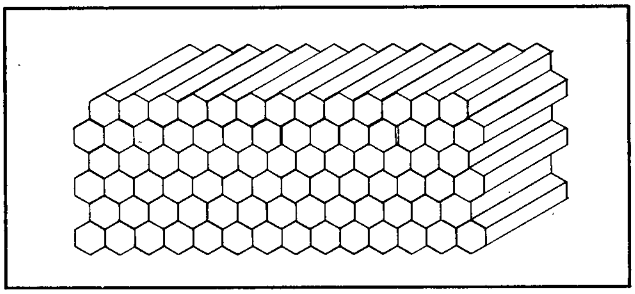

Figure 9. Hexcell or Honeycomb Vent Material.

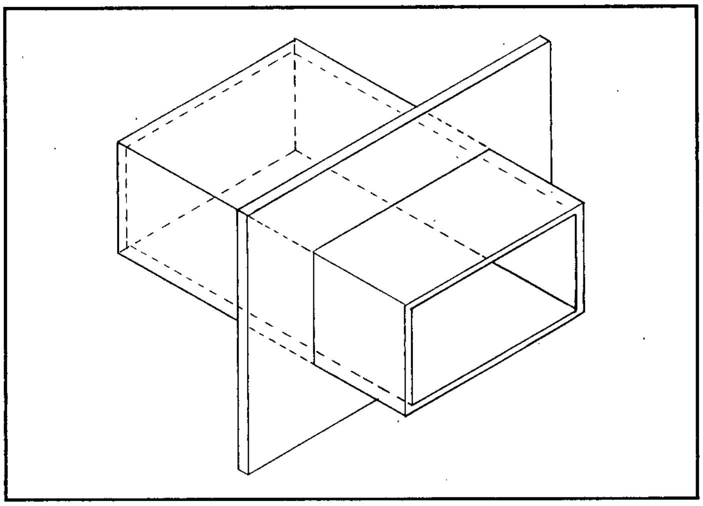

Figure 8. Rectangular Waveguide with Mount Flange.

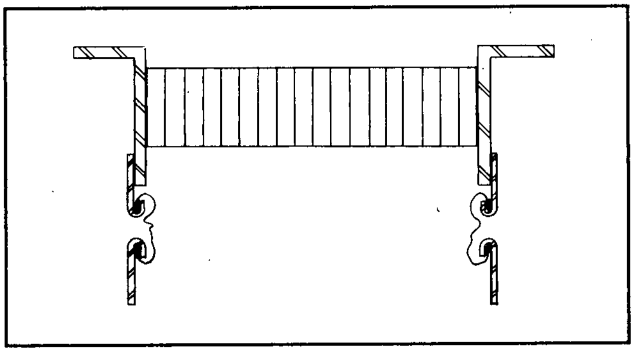

Figure 10. Mounting Flange with Dielectric Collar.

signing or dimensioning a waveguide is: L = 5 x (I.D.) where L = length and I.D. is the inside diameter or the diagonal dimension of a rectangular or square opening. In either case, the I.D. should not exceed the half wavelength of the highest frequency to be shielded or attenuated. This formula is quite basic and will provide a level greater than 100 dB of attenuation for an open-ended waveguide at its cutoff frequency and below. For frequencies above cutoff, the attenuation characteristics are dependent upon the length of the waveguide, skin effect of the waveguide material, space loss and geometry of the waveguide.

In certain applications, a waveguide can be installed within a waveguide. One application of this concept is a plumbing vent tube or pipe which has an inside diameter greater than a full wavelength of the highest frequency to be shielded. Since this is a low pressure application, a section of honeycomb or hexcell vent material can be installed within the waveguide vent pipe. If the vent material is installed in a manner that provides a continuous electromechanical bond where it contacts the waveguide pipe walls, the assembly will provide a level of attenuation equal to that of the honeycomb.

ELECTRICAL FILTERS

Communication, data and power (AC/DC) lines are common utilities that are intentionally introduced into a shielded environment. If these insulated (dielectric) wires are allowed to pass through a waveguide or conduit into the shielded environment, the shield's level of effectiveness is severely degraded.

With no protection of these lines, they conduct ambient electromagnetic energy, thus becoming antennas. To reduce or control conducted energy, electrical filters are utilized. Filters commonly used with shielded environments are designed to have a specific bandpass which allows certain frequencies or DC to pass with little or no opposition while blocking (reject band) other frequencies.

Electrical filter circuits or networks consist of capacitors, inductors, and resistors, or any combination of these. The network design is dependent upon the required voltage, current, impedance, frequency characteristics and attenuation or insertion loss. Regardless of the network design, the filter components must be encased in a metallic container. This container's seams must be electromechanically bonded so no ambient energy bypasses the filter network. Filters should be mounted directly to the shield to reduce the chance of leakage and provide a ground for the filter case.

Filters for shielded enclosure applications are generally designed to provide a minimum insertion loss of 100 dB over the frequency range of 14 kHz to 10 GHz when tested in accordance with MIL-STD-220A. Filters are available with smaller frequency range coverage and lower insertion loss values. If lower insertion loss filters are used, the shielded environment will only provide a level of protection equal to the insertion loss of the filter. Therefore, it is of the utmost importance that the insertion loss of the filters meet or exceed the shielding effectiveness level of the RF shield.

(Insertion loss is defined as 20 log10 E1/E2. E1 is the output voltage of a signal source with the filter [or other device] in the circuit and E2 is the output voltage of the signal source without the filter [or other device] in the circuit.)

SHIELDED DOORS

Of all the major components that are associated with an RF shielded enclosure, the door or utility entrance is possibly the most critical. This is the one item that is in a state of constant use for access to the shielded environment. Regardless of the door's design or construction, it is imperative that the interface components between the door and door frame be kept clean and in good repair. If the interface components are allowed to deteriorate, the performance of the shield will suffer. Lack of door maintenance is the number one cause of shield integrity failure.

Of the door types available, the three most common designs are the recessed contact mechanism (RCM), the exposed finger door and the concealed jamb-mounted contact. Each of these doors provides a specific level of shielding effectiveness and is designed for applications within this level. As with any group of "like" items, each must be evaluated for compatibility with the shield design, maintainability and required performance.

For any of these door types to be effective, electrical contact must be maintained around the entire door periphery. This electrical contact must be continuous about the edges of the door. Mounts for these electrical contacts must be of a design that affords exceptional electrical conduction between the mounting surfaces and the contact. This can be accomplished by compression, soldering or conductive tapes. When using conductive tapes, it is important that the contacts be designed to be used with these tapes.

RCM TYPE DOOR

The RCM type door is by far the most commonly used door for wide range performance. Typically, a door of this design will provide shielding effectiveness levels greater than 100 dB in the frequency range of 1 kHz to 18 GHz (electric and plane wave fields). Magnetic field performance (if ferrous materials are used as door "skins") at 1 kHz is normally >20 dB and attains a level of >100 dB at 200 kHz. If higher levels of magnetic field performance are required, the "RCM" is the ideal door design for modifications to attain the required performance.

Unique to this door is the design of the electrical contact mechanism. To attain conduction, the electrical contacts (typically two sets of "fingers") are placed within a recessed pocket assembly that is electromechanically attached to the door frame. The door itself is banded with a metallic assembly that has an appendage set at a right angle to the door face. This appendage is referred to as a "knife edge" and provides the electrical pathway between the door frame and the door (when in the closed position). Conduction takes place as the leading edge of the knife is driven between the two sets of opposing electrical contacts (or fingers).

This driving or wiping action provides a self-cleaning action which assists in maintaining the door's effectiveness level. With the electrical contacts (or fingers) recessed in a protective pocket, the likelihood of damage is significantly reduced. If damage occurs, the electrical contacts are easily replaced with a pocket knife or screwdriver (depending on the manufacturer).

EXPOSED FINGER TYPE DOOR

The door-mounted contact or exposed finger door provides various levels of shielding effectiveness. This door is manufactured in two varieties. One style uses one row of contacts, while the other uses two rows which are in line with one another or are placed at right angles. Shielding effectiveness of these doors is between 50 dB to 100 dB in the frequency range of 1 kHz to 10 GHz.

In the single contact configuration, the contacts are attached directly to the door's edges by soldering or are soldered to a mounting angle which is mechanically attached to the door. These angles are typically supplied in sections that are 16" in length. The fingers are mounted in a manner such that they wipe the inner surface of the door frame. This wiping action maintains conduction between the door and the door frame.

The dual row configuration is similar to the single row in that the first row is attached in the same manner. The second row is placed in front of the first or is mounted on a metallic member which, when attached, places this second set at a right angle to the first. If both rows are adjacent to one another, the same wiping action occurs as with the single row. If the second row is placed at a right angle, wiping and compression occurs. The wiping finger provides conduction to the inner surface of the door frame and the compression finger provides conduction to the face of the door frame.

With either the single or dual row exposed finger door, inspection and cleaning of the contacts is simplified due to their exposure. If the electrical contacts are soldered directly to the door, repairs must be made with a soldering iron. If repairs are required to the door bottom, the door must be taken down. If the fingers are soldered to a mounting angle, repairs are accomplished with a screwdriver.

CONCEALED JAMB-MOUNTED CONTACT TYPE DOOR

The concealed jamb-mounted contact type door provides shielding effectiveness levels of >100 dB from 1 MHz to 200 MHz and decreases to 45 dB at 10 GHz. This hybrid door has exposed electrical contact fingers which are recessed in the door jamb and are protected by the door stop.

Conduction between the door and the door frame is attained by the door edge wiping the contacts which are located on the inner door frame. The contacts are "clipped" on a metallic mounting bar. This contact bar assembly is attached to the inner surface of the door frame and the contact tips are concealed below the door stop.

As with the exposed finger door, inspection and cleaning of the contacts is simplified due to their semi-exposure. Repair is similar to that of the "RCM" and is accomplished with a screwdriver and pocket knife. One variety of this door type is supplied with a removable door bottom that simplifies repairs if damage should occur to the door bottom contacts.

Regardless of the door style used, performance should meet or exceed the performance levels of the shielded enclosure.

ATTENUATION

Attenuation is a theoretical concept for determining the actual shielding effectiveness of a shielded environment. Attenuation is a ratio, expressed in decibels (dB), of received power on opposite sides of a shield that is illuminated by electromagnetic energy. Calculations of shielding attenuation can be made with any of the following formulas:

Attenuation (dB) =
20 log10 E1/E2 (electric fields)

where E1 is the electromagnetic field intensity in microvolts per unit of length on one side of the shield, and E2 is the field intensity in microvolts per unit on the other side of the shield.

Attenuation (dB) =
20 log10 H1/H2 (magnetic fields)

where H1 is the magnetic field strength or intensity in microvolts per unit of length on one side of the shield, and H2 is the field intensity in microvolts per unit on the other side of the shield.

Attenuation (dB) =
10 log10 P1/P2

where P1 is the power intensity of the electromagnetic field in watts per unit of area on one side of the shield, and P2 is the power density of the field on the other side of the shield.

When testing is performed, attenuation or shielding effectiveness of the shielded environment can be determined. Testing consists of setting transmit and receive antennas at a specified distance and frequency. The received signal level with no shield between the antennas is the reference level. The shield is then placed between the antennas. The difference between the reference level and the signal received with the shield in place is the attenuation or shielding effectiveness of the shielded environment.

SHIELDING EFFECTIVENESS

Shielding effectiveness is the level of electromagnetic energy reduction provided by a shield. The reduction of electromagnetic energy is referred to as attenuation and is the result of three functions of the shield material. Shielding material displays absorption loss, reflection loss and re-reflection (or internal reflected wave) loss. Thus, shielding effectiveness, in dB is:

$$S/E = A + R + B$$

where

A = absorption loss
R = reflection loss
B = re-reflection (or internal reflected wave) loss.

Absorption is defined as "the dissipation or loss of electromagnetic energy in the medium through which energy passes." Reflection is defined as "the loss of electromagnetic energy due to reflection at the air-metal boundary of a shield." The efficiency of the reflecting shield is a "complex function of the wave and shield impedances."

Absorption loss occurs after the wave has entered the shield and the impedance of the shield medium governs the E/H (electric/magnetic field) ratio. Absorption loss is independent of the type of wave (electric or magnetic) illuminating the shield.

Reflection loss depends upon the surface impedance and wave impedance, which is a function of the source, electric or magnetic, and the distance from the source to the shield.

Re-reflection or internal reflected wave loss occurs when a wave strikes an impedance discontinuity where a portion of the energy is reflected. Therefore, after the wave has traveled through the shield and has been attenuated, the remainder is subject to reflection at the other surface. Some of the energy exits or passes through the shield, while some is reflected back into the shield.

Where degrees of shielding effectiveness are required, multiple shields are usable. Higher performance results from absorption loss (the loss is calculated for the total thickness of the shield materials) and reflections which now occur at each surface of the shield. The additional reflection is attributed to the shield surfaces being separated by dielectric material or air.

SHIELDING PERFORMANCE TESTING

Performance verification of a shielded environment is possibly the most important phase of an enclosure installation, yet it is often viewed as a nuisance or an enigma. In reality, a performance test is very simple and is identical to an insertion loss type test (MIL-STD-220A), or measuring the resistive properties of a resistor. The difference is the equipment used to perform the test.

The ultimate goal of a shield is to provide an environment that is free of interference so equipment can function properly or to provide an area for equipment to operate so it will not interfere with other equipment. In the attempt to achieve this goal, time, energy and resources (people and money) have been utilized. If the enclosure fails to provide an environment free of interference, all investments have been wasted.

Fortunately, standards have been established by military and security agencies which describe the test methodology, equipment and performance at specific frequencies and fields. With minor modifications, these test procedures can be tailored to any shielded installation. These standards were developed to protect the enclosure owner/user from the individual who shows up to perform the shielding effectiveness test with an FM radio receiver, tunes the receiver to a local FM radio station, walks into the enclosure, shuts the door and all that is heard is static. The "tester" walks around the enclosure and states "the enclosure is good for 100 dB." The tester then packs up his FM radio and is never seen again. The standards also protect the owner/user of the enclosure from the tester who states "why test magnetic frequencies and fields when the shielding material is known or designed to shield the required magnetic fields and frequencies. Obviously, this tester does not realize that the enclosure may have been assembled with joints, waveguides, electrical filters or a door. These examples may seem ridiculous, but are actual occurrences.

To ensure the performance of a shield enclosure, the owner/user should insist that testing be performed in accordance with applicable standards and, if required, modified to meet the specific requirements of the site. Two common test procedures for attenuation/shielding effectiveness performance verification are MIL-STD-285 and NSA 65-6. Both procedures describe the proper equipment arrangement, and specify the frequencies of test and the level of shielding effectiveness required. Additionally, they describe locations which should be tested and the necessary conditions. NSA 65-6 also dictates the door perimeter, electrical service entry, HVAC entry points, penetrations and panel seams. Regardless of the procedure followed, it is a good practice to test the door edges (6 points), electrical filter location(s), waveguides, seams or joints and any viewing or access ports. As mentioned earlier, specific fields, frequencies and levels of attenuation or shielding effectiveness can be found in MIL-STD-285 and NSA 65-6. The frequencies, fields and attenuation or shielding effectiveness levels of these specifications can be modified to cover any shielded installation requirement or owner/user requirements.

If the enclosure is scheduled to receive interior finishes, it is a good practice to perform two tests. The first test is performed upon completion of the enclosure installation (prior to attachment of finishes). Ideally, the second test is performed when all finishes are complete and all enclosure support systems are operational. With systems operational, all electrical filters can be (RF radiated) tested under load conditions.

CONCLUSION

Numerous factors must be considered when designing a shielded enclosure system. Openings for power and communication lines, water lines and HVAC must not compromise the integrity of the shield. Doors, windows and utility entrances, as well as waveguides, pose special problems which should be addressed in *the design stages* of the project. A careful comparison of available materials and styles for each component is essential.

Military Standards and National Security Agency Specifications can be used as a basis for testing procedures. Tests should be made both before and after support systems are installed to isolate any problem areas. ■