THE TECHNICAL BASIS FOR SELECTING A SHIELDING ENCLOSURE

Introduction

The purpose of this article is to provide the conceptual technical basis underlying the selection of shielding enclosures so that manufacturers' claims of performance can be evaluated intelligently. This need arises, not because of unfounded claims by manufacturers, but because there are many varieties of enclosures and a number of variations upon testing techniques (even to a given standard) to "prove" their performance. Testing methods will be covered by another article in ITEM; basic technical factors which determine performance will be treated here, but accessory items common to all types of enclosures, such as powerline filters, are not included.

Let us now lay the groundwork for understanding these factors. The physical basis for electromagnetic (EM) shielding is simply that an incident EM wave induces current to flow in the shielding material such that the resulting magnetic field opposes the incident field on the non-incident side of the shield. Although the physical basis is readily understood, it is not readily adapted to direct calculation of effects. Accordingly, the commonly used, but often missapplied, transmission theory of shielding will be followed. It is commonly used because it is directly analogous to transmission line theory which is inherent in the formal training of most electronics engineers; hence, it is readily grasped. This theory correctly considers transmission of an electromagnetic (EM) wave through a shield to be like the transmission of current and voltage along a two-conductor line. It is misapplied because many people overlook the fact that this theory was derived for a uniform shield, i.e., one without metallic discontinuities, such as mechanically clamped seams between panels or finger-stock seams around doors, and without metallic irregularities, such as at welded, brazed or soldered seams. In reality, conventional theory represents the performance of the basic material, not an overall shielding structure. This performance can be, and in practice generally is, influenced by performance at seams (and at other points of RF leakage).

With this consideration in mind, let us review briefly EM shielding theory to highlight salient features, and to discuss the modification of theoretical shielding performance by actual leakage paths. This foundation prepares us to understand the performance characteristics of various types of shielding-enclosure construction and the considerations necessary to evaluate performance claims made by manufacturers. Let us later discuss and summarize the major technical considerations in the selection of a shielding enclosure.

Shielding Theory - For Material Only

The transmission theory of shielding has been presented many times, for example (1-4). Rather than repeat it here, let us examine properties of the basic equation for a single-layer uniform shield, expressed in dB. The shielding effectiveness S in dB is

$$S = A + R + B, \qquad (1)$$

where

A = Penetration loss through the shield (microscale heat dissipation)
$= 8.686\sqrt{\pi\mu\sigma f}\ \ell$

R = Reflection loss at both sides of shield (air-metal interfaces)
$= 20 \log |k+1|^2 / 4|k| \approx 20 \log |k| / 4$ for $|k| >> 1$

B = Correction term due to re-reflections (negligible for A>15 dB)
$\approx 10 \log (1\text{-}2\times10^{-0.1A}\cos 0.23A + 10^{-0.2A})$ for $|k| >> 1$

and

$k = Z_w/\eta$, Z_w (wave impedance) = E/H, η (intrinsic impedance)
$= \sqrt{j\omega\mu/\sigma}$.

The notation is standard and units are MKS.

TABLE 1

CALCULATED PENETRATION LOSS AND REFLECTION LOSS OF METAL SHEET

FREQUENCY	IRON (SAE 1045) μ_r	PENETRATION LOSS/MIL THICKNESS (dB/mil) COPPER $\sigma_r = 1, \mu_r = 1$	IRON $\sigma_r = 0.17$	PLANE-WAVE REFLECTION LOSS (dB) COPPER $\mu_r = 1$, $\sigma_r = 1$	IRON $\sigma_r = 0.17$
60 Hz	1000	0.026	0.334	150.	112.
1 kHz	1000	0.106	1.37	138.	110.
10 kHz	1000	0.334	4.35	128.	90.5
150 kHz	1000	1.29	16.9	117.	78.8
1 MHz	700	3.34	36.3	106.	72.1
15 MHz	400	12.9	106.	96.4	62.7
100 MHz	100	33.4	137.	88.2	60.5
1.5 GHz	10	129.	168.	76.4	58.8
10 GHz	1	334.	137.	68.2	60.5

NOTE: Other values of μ_r for iron are 600 at 3 MHz, 500 at 10 MHz and 50 at 1 GHz.

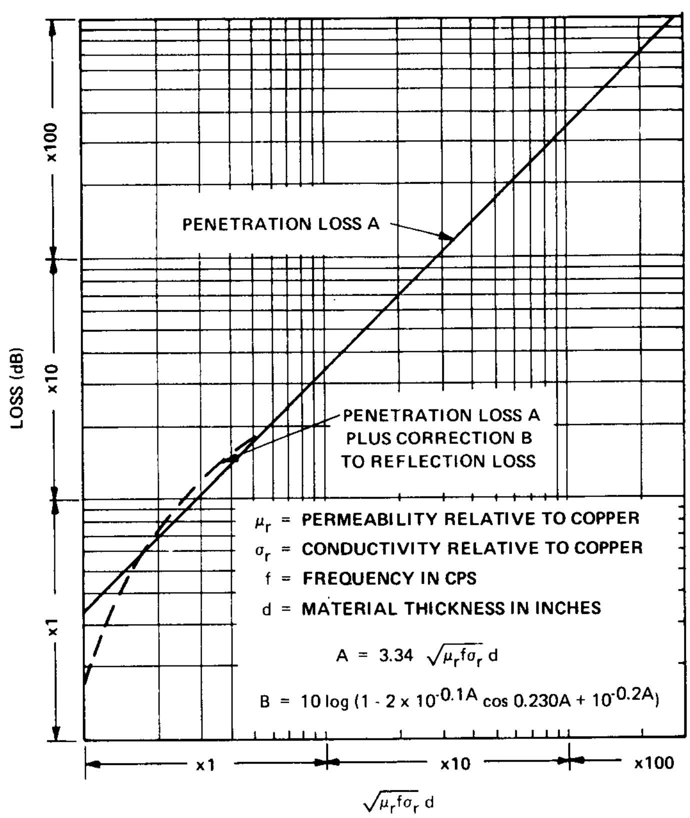

Figure 1. Penetration Loss (Plus Correction to Reflection Loss)

Consider now the separate shielding-effectiveness terms. The penetration loss A depends upon only two basic factors: the material (electrical characteristics of incremental magnetic permeability μ and electrical conductivity σ, and physical thickness ℓ) and the frequency (f). Note that this term is independent of impedance of the incident EM wave and, thus, does not depend on the specific application of the shield. The term is expressed graphically in Figure 1. Typical calculated values for copper and iron are given in Table 1.

The reflection-loss term R is a function only of the ratio k of wave impedance Z_w (=E/H) of the incident wave to the intrinsic impedance η of the shielding material. The user of a shielding enclosure seldom has control over the impedance Z_w of the incident wave, but he does have some control over the intrinsic impedance of the shielding material by proper selection of an enclosure. A typical value of intrinsic impedance for copper ($\mu = 4\pi \times 10^{-7}$ h/m, $\sigma = 5.8 \times 10^{7}$ mhos/m) is

$$|\eta_{cu}| = 4.52 \times 10^{-7} \sqrt{f(\mathrm{Hz})} \text{ ohms} \qquad (2)$$

Obviously, $|\eta_{cu}|$ is extremely small at low frequencies where low-impedance waves may exist, and is much less than a plane-wave impedance (377 ohms) at the higher frequencies where enclosures encounter primarily plane waves. (Even at 10 GHz, $|\eta_{cu}|$ = 0.0453 ohm). Thus, the ratio $|k|$ is, in almost all cases, much greater than one well into the gigahertz range due to the values of electrical parameters for metals. Even though $|k|$ is much greater than unity, note that the magnitude does depend upon the wave impedance. For a high-impedance wave, $|k|$, and therefore R, will be greater than for a low-impedance wave. Thus, the reflection-loss term R depends upon the specific application of the shield. It is expressed graphically for a plane-wave source in Figure 2.

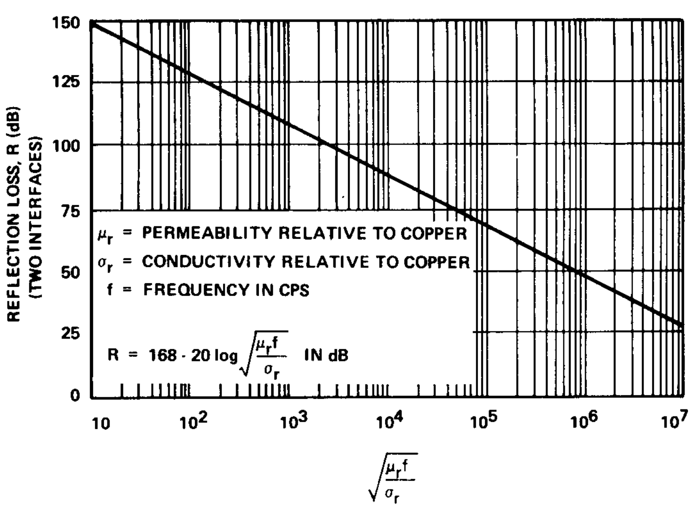

Figure 2. Reflection Loss for Plane-Wave Source

The correction term B depends only on the penetration loss A (for practical cases where $|k| >> 1$) and is thus independent of the specific application of the shield. It becomes negligible whenever the penetration loss exceeds 15 dB. This condition holds over the useful frequency range of commonly-used enclosures; the correction term need not normally be considered further (unless an enclosure is to be used at extremely-low frequencies, where A may be under 15 dB). If required, it can be used to modify the penetration-loss term as shown in Figure 1.

The shielding expression (1) indicates an increasing degree of performance with frequency. At the lower frequencies, calculated and measured values of shielding effectiveness are in good agreement; here, performance is material-limited.

Leakage

As the frequency is increased, the theoretical performance of the shielding material becomes better; however, the shielding enclosure is no longer able to achieve its theoretical potential. The reason is that shielding joints or seams, even if fused, permit small portions of electromagnetic energy to bypass the highly effective shielding material. (The better the material performance, the less leakage is required to cause degradation.) In addition, other paths of leakage exist, examples of which are shown in Figure 3. The sum of all leakage signals has both amplitude and phase effects, which are dramatically illustrated by results of tests on two small shield cans, Figure 4. At the lower frequencies, shielding performance is basically that of the material itself, but at the higher frequencies performance is determined by leakage. In between, a resonance-type effect is observed when the magnitudes of leakage and material penetration paths are similar, but the phases are substantially different (due to widely different phase velocities between EM waves in metal and air). High-frequency shielding effectiveness, depending upon seam quality and existence of bypasses, typically ranges from 30 dB (for poor seams) to 100 dB or greater, depending upon control of all leakage paths.

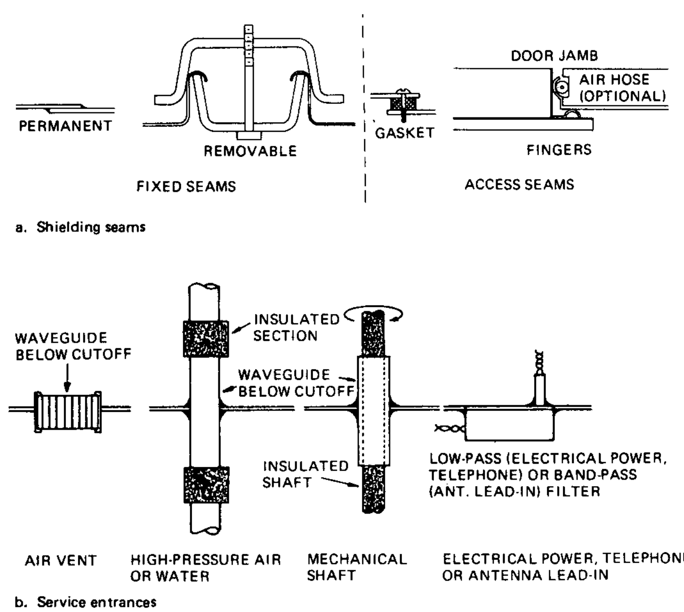

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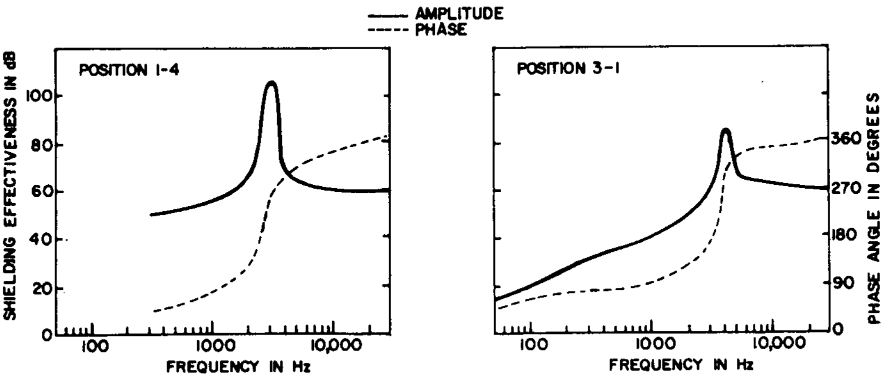
Figure 3. Typical RF Leakage Paths

To date, there has been no satisfactory analytical study of seam leakage. Experimental data to derive equivalent transmission-line values for seam leakage, postulated as a second transmission line in parallel with the shield material transmission line, resulted from an incompleted study (5, 6).

Other investigations related to this problem include an early empirical study of holes in shielding (7) and several more recent studies of apertures (such as Reference 8) related to electromagnetic pulse (EMP) problems. Such evidence of progress gives rise to hope that a serious attack upon the seam-leakage problem lies in the near future.



a. Annealed Co-Netic can, 1/32 in thickness, with ¼ in hole

b. Annealed Co-Netic can, 1/32 in thickness, with two ¼ in notches in bottom lip

Courtesy Microwave Journal

Figure 4. Relationship of Amplitude and Phase for Shield-Can Penetration

Non-seam leakage is not nearly so significant since it normally yields to conventional design. Let us, however, call attention to a common design error affecting the EM performance of ventilation ducts. Air flow between the inside and the outside of enclosures generally occurs through waveguides below cutoff, often in a grouping of the order of 1000. These represent, in the worst case, 1000 or so parallel paths, but design is frequently based upon below-cutoff attenuation of just one. The resulting error could be as much as 30 dB. This difficulty can be overcome by overdesigning single waveguides by an amount as great as the degradation.

Classification of Enclosures

Three common methods of classifying shielding enclosures are used: by frequency range, by performance level, and by construction type. Of these, let us consider first classification by frequency range of application: low-frequency, general purpose, and high-frequency.

Low Frequency. From the strictly technical point of view, the term "low-frequency" includes all frequencies well below the lowest frequency at which leakage signals are equal in magnitude to signals which penetrate the shielding material itself. Thus, "low-frequency" may be confined to the low end of the audio range for a shield of high-performance material but with excessive leakage, as in Figure 4. On the other hand, it may extend up to 100 MHz for a shield of poor-performance material with low leakage, such as a thin vapor-deposited metallic film. This technical concept of low frequency is little used by buyers of enclosures. Being applications oriented, they usually consider "low frequency" to include the range below some arbitrary fixed value, say 10 kHz. This over-simplified applications approach will be followed here in conformity with conventional usage, but with the realization that the other technical approach is more descriptive from the viewpoint of performance characteristics.

It has already been noted that performance at low frequencies is limited by material characteristics. Of the two major shielding terms, the penetration loss A (Equation 1) is proportional to the material characteristics $\sqrt{\mu\sigma\ell}$. The reflection less term R is proportion to $\log\sqrt{\sigma/\mu}$. Both of these increase with conductivity σ. Only the first increases with permeability μ; the latter decreases with increase in μ, although at a much slower rate. The net effect is an overall increase with both μ and σ, but more rapidly with σ. Thus, desirable shielding material for low frequencies is high conductivity, high permeability, and of substantial thickness. Frequently, heavy steel plate is used, with welded seams.

High Frequency. Enclosures specifically for HF use suffer, not only from leakage effects, but also from internal reflections which tend to create standing waves within the enclosure. For this reason, such enclosures normally embody small size to raise the lowest resonance, or anechoic absorbing material to decrease reflections by absorbing some of the energy. The anechoic material is usually used to line the inside of an enclosure. Because of its substantial depth (often one to six feet), it severely diminishes the usable workspace.

Several alternative (but not technically equivalent) methods have been used. One embodies a stepping motor to rotate a large internal vane to resonate the enclosure maximum field at some internal measurement point. The other embodies continuously rotating vanes (much as in a microwave oven) to stir up internal modes for repeatability of measurements (9).

General Purpose. General purpose enclosures span the frequency spectrum, some more so than others. The most common range is from 10 kHz to 10 GHz. Within this sub-class, both of the remaining two methods of classification are commonly used.

Classification of Enclosures by Performance

For clamped-seam enclosures, three different performance levels are commonly available: 70 dB for a simple shielding layer; 100 dB for an exceptionally-well-clamped single shield (of sheet material); and 120 dB for a double shield, cell-type or double-isolated, with special features peculiar to each. For a steel welded-seam enclosure, levels of 120 dB are generally available, depending to a large extent upon the type of door seams utilized.

Classification of Enclosures by Construction Details

Let us consider these primary construction characteristics: shielding material, single or double wall, panel seams, door seams, microwave absorber.

Shielding material. From shielding theory, it is obvious that high penetration-loss performance requires a shielding material with a high permeability-conductivity ($\mu\sigma$) product and substantial thickness (ℓ). Using electrical parameters relative to copper, a figure of merit for shielding material can be taken as

$$F_\ell = \sqrt{\mu_r \sigma_r}\,(10^3\ \ell\ ) \qquad (\text{or } F_d = \sqrt{\mu_r \sigma_r}\,(10^3 d)), \qquad (3)$$

where ℓ is in meters; d, inches. With this as a measure, the anticipated relative performance of different materials can be assessed (see Table 2 for values of $\sqrt{\mu_r \sigma_r}$). Most-commonly-used materials include copper screening, zinc-clad sheet steel, and steel plate. Other materials such as sheet copper and sheet aluminum are used less frequently. Since copper screening is not a sheet material, the figure-of-merit expression is usable only with a thickness value equivalent to that for sheet material. An easy way to determine this is to compare copper screening with the same surface area and weight of sheet copper and use the sheet thickness in the figure-of-merit expression. When equation (3) is used with zinc-clad steel, it results in a somewhat understated figure of merit, since cladding results in a laminated sheet which provides performance superior to a plain sheet.

Single or Double Wall. The theoretical equation (1) was presented for a single metal thickness. However, the shielding performance of a double wall is simply that of single wall of double thickness for frequencies where the spacing between walls is small compared with a quarter-wavelength. For example, consider a double wall with 3.8 cm (1.5in) spacing. Then the maximum frequency for which equivalence holds is

$$f << 3(10)^{10}/4x3.8 = 2(10)^9. \qquad (4)$$

TABLE 2

ELECTRICAL PROPERTIES OF VARIOUS SHIELDING MATERIALS

METAL	RELATIVE CONDUCTIVITY σ_r	LOW-FREQUENCY RELATIVE PERMEABILITY μ_r	LOW-FREQUENCY/ HIGH FREQUENCY $\sqrt{\mu_r \sigma_r}$
Silver	1.05	1	1.03
Copper, Annealed	1.00	1	1.00
Copper, Hard-Drawn	0.97	1	0.99
Gold	0.70	1	0.84
Aluminum	0.61	1	0.78
Magnesium	0.38	1	0.62
Zinc	0.29	1	0.54
Brass	0.26	1	0.51
Cadmium	0.23	1	0.48
Nickel	0.20	1	0.45
Phosphor-Bronze	0.18	1	0.42
Iron	0.17	1000	13/0.41
Tin	0.15	1	0.39
Steel, SAE 1045	0.10	1000	10/0.32
Beryllium	0.10	1	0.32
Lead	0.08	1	0.28
Hypernik	0.06	80,000	69/0.25
Monel	0.04	1	0.20
Mu-Metal	0.03	80,000	49/0.17
Permalloy	0.03	80,000	49/0.17
Steel, Stainless	0.02	1000	4.5/0.14

With the usual engineering interpretation of "much less than" as "at least one order of magnitude less" (one tenth), the maximum frequency becomes

$$f_{max} = 200 \text{ MHz}. \qquad (5)$$

Above this frequency, resonance-type effects occur which theoretically permit the enclosure to exceed the single-shield type performance at many frequencies, but likewise cause it to be degraded at some others. In practice, these effects are generally not experienced in good enclosures because the high shielding performance of wall materials, far in excess of enclosure performance, is degraded by overriding leakage effects at seams (even good ones) and elsewhere.

Panel Seams. Panels are electrically joined by two basic methods: mechanical clamping and fusion. A wide variety of mechanical clamping methods are available, but these will not be reviewed in detail. Instead, let us just consider the requirements of a good system. The overall objective is to provide an electrical contact continuous along a seam, without interruption or variation in contact resistance, and of at least as high electrical conductivity as the shielding material itself. This objective appears impractical to meet with mechanical clamping. The practical approach is to use mechanical clamping at frequent intervals along a seam and tolerate the degradation between clamps. Even at clamps, the objective of electrical conductivity as high as the shielding material itself is generally not met. Despite these problems, shielding manufacturers generally provide seams of high-enough performance to meet a large range of application requirements. (Seams are usually the downfall of the do-it-yourselfer.) To maintain performance, such seams may require retightening over long intervals, or even disassembly and recleaning in corrosive environments.

With respect to the placement of seams, let us first consider a dihedral corner of a rectalinear enclosure. Current flow around a corner tends to crowd the interior angle as in Figure 5. Since the current uses less of the metal thickness here than along a flat surface, resulting effective lower conductivity means poorer shielding performance at the corners (the effect is enhanced at a trihedral corner). If, in addition, a seam were to be placed along a corner, the difficulty would be compounded due to even decreased conductivity. For this reason, some modern shielding enclosures utilize formed corners and have seams only on flat surfaces, as in Figure 6.

Fused seams will, generally speaking, achieve higher performance than mechanical seams since the electrical conductivity can usually be made higher. Even with fused seams, ideal objectives have not been achievable, even under laboratory experimental conditions. (The best known seam results from electron-beam welding, whereby the parent metal pieces are joined in a vacuum without the use of any foreign binder material.) Even so, welded steel and brazed (or soldered) copper seams, capable of providing over 100-dB enclosures, are commercially available.

Door Seams. Door seams for frequent entry generally do not utilize gasket material since frequent use causes the gasket to lose its compressibility and, with that, its shielding performance. In order to achieve low leakage, most door seams for frequent use utilize high-conductivity spring-contact fingers, usually around at least a double periphery. Spring fingers are made of beryllium-copper or phosphor-bronze stock, often silver-plated. Any such material is a compromise between high electrical conductivity, good contacting surfaces, and adequate spring retention for many thousands of operations. In normally-encountered environments, the contacting surfaces are kept clean automatically by means of a wiping action between the fingers and a door jamb; good contact can be assisted by means of an inlaid compressed-air hose to provide high contact pressure. One difficulty with contact fingers is that they are exposed to passing objects and are easily broken. Some manufacturers now provide a construction where fingers are well protected.

Microwave Absorber. Although not strictly a shielding application, microwave absorber material placed within an enclosure not only reduces internal reflections but also generally aids the shielding property by providing additional reduction of microwave energy which penetrates the shield itself. Desired energy loss which occurs in both reflection and penetration requires a considerable volume of RF-lossy material, and substantially reduces working volume within the enclosure.

(Since internal reflections cause undesirable standing waves, another approach has been devised to destroy their effects within an enclosure by use of a mode stirrer, commonly used in microwave ovens, but not yet common in shielding enclosures.)

EMP Applications

The question sometimes arises as to the usefulness of shielding enclosures for EMP protection. In other words, what protection is afforded against a single large transient impulse, compared with steady-state signals for which the conventional shielding enclosure is designed? The physical relationship for a transient is that the incident field induces a current in the shield as in the steady-state case, but with this difference. The induced current and the field it creates both lag the incident field so that there is no secondary opposing field to cause a shielding effect at initial incidence. Consequently, the very initial portion of the incident pulse is expected to be transmitted through the shield without attenuation. As the induced current increases, so also does the associated secondary field; the incident field is increasingly opposed with attendant shielding. The resulting effect is for an RF shield to transmit the extreme initial portion of the incident EMP pulse and then to oppose transmission of the remainder; in other words, an initial sharp spike will be transmitted, but substantial shielding will be presented to the remaining EMP.

Performance Claims

To evaluate performance claims of manufacturers, consider the following actions, in whole or in part:

- Check for reasonableness of claims using the preceding material as a guide.
- Request a report of tests previously done by independent testing organization.
- Request the identity of other purchasers of similar enclosures and ask about their experience.

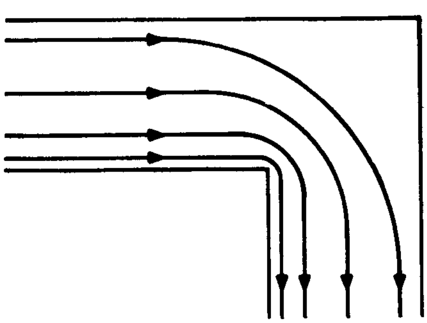


Figure 5. Current Flow Around Corner

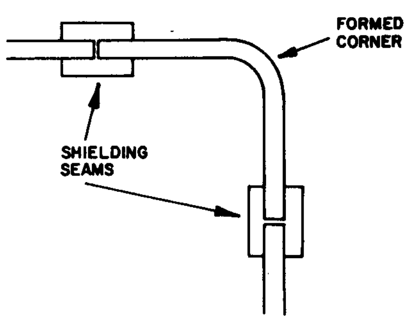


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Figure 6. Corner Arrangement for Shielding Enclosure

- Review reports of tests on enclosures after installation, if available.
- Check conformance of test methods with applicable standard, such as IEEE standard 299 or MIL-STD-285, and determine if these satisfy specific requirements.

Major Technical Considerations

In selecting a shielding enclosure for a given frequency range, check the following points:

- Material performance must exceed requirements at the lowest operating frequency (Equation 1).
- Weakest seam performance must exceed requirements at the highest operating frequency. (Use test data.) For screening type enclosures, screen leakage may be the overriding factor; screening performance generally deteriorates above 400 MHz (9).
- Type of seams should be adequate for the physical and atmospheric environment at the place of installation.

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ELECTRICALLY ISOLATED DOUBLE SHIELDED ROOM

There has been a long-standing controversy over the advantage of completely separate layers, electrically isolated, in the double-shielded room as opposed to the cell-type room. Some think that the test reports which show no difference in attenuation factors between an Electrically Isolated Room and the Not Isolated Room made of exactly the same materials, are both misleading and a misrepresentation of test results. One point which is almost universally agreed upon is that regardless of the type of construction, no shielded room is better than the effectiveness of its filter, door and seams.

Whenever specialists or "experts" on RF shielded enclosures congregate, you can expect endless discussion on the test methods. There is a standing argument that you might conceivably leave the subject of test methods, test procedures and instrumentation where it was 20 years ago because what was true in 1951 is still true today, that is; "The test is only as good as the skill and integrity of the engineers who conduct the test." One should not make the mistake of comparing a 0.015 inch thick copper screen Double Electrically Isolated room with a plywood room laminated with two layers of 18 guage or 24 guage steel, or comparing a plywood room with a single layer 0.125 inch thick solid steel room having welded seams and joints. Illustrations of the three types of rooms are shown in Figure 4.

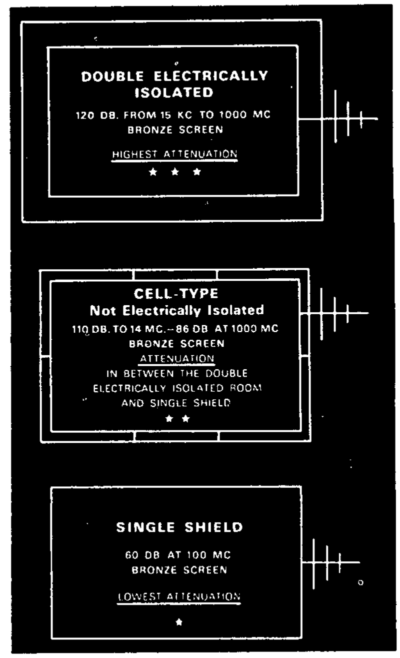

Fig. 4: Three of the most popular types of r-f shielded rooms currently in use are diagrammed here.

The case for the Double isolated room is well presented in a book entitled "Contemporary R.F. Enclosures", written and published by Erik A. Lindgren in 1967. (Copies are available from Erik A. Lindgren & Associates, Inc.) The book points out that no meaningful comparative test has ever been made on Cell-type and Isolated rooms since 1951 except those published therein comparing the performance of the Isolated and the Not Isolated construction. Actually, Naval Air Development Center Report 3908, dated 14 November, 1951, shows the test results between two Not Isolated Rooms.

The test results shown in Figures 5 & 6 are considered to be significant because they show a comparison between different constructions using the same materials. The figures also show that the materials used also affect the performance of the room. If the use of a screen is considered as a separate factor, and the use of a solid metal another factor, five factors will then be available in order to evaluate the three types of constructions as shown in figure 4. These factors are:

1. Double Electrically Isolated
2. Double Not Isolated
3. Single Shield
4. Screen Shield
5. Solid Shield

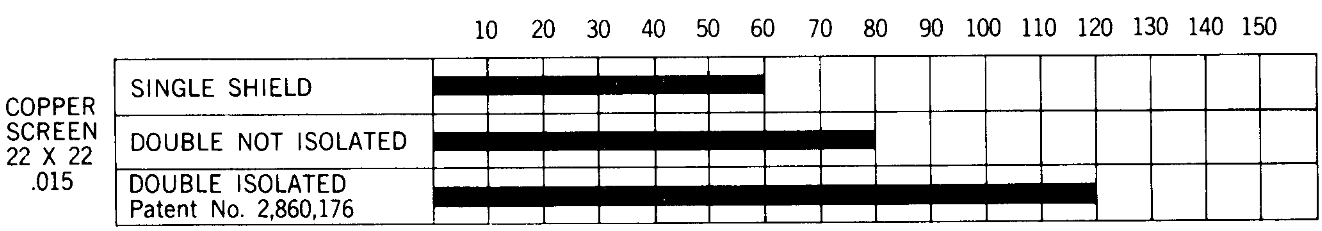

Figure 5

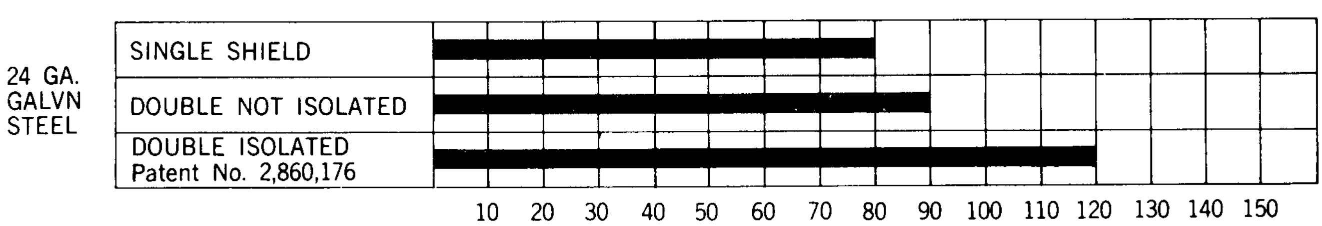

Figure 6