CHAPTER 21

Electromagnetic Shielding Materials

21.1 Introduction

Electromagnetic shielding materials are the structural constituents of the so-called *electromagnetic shields* used for the purpose of confining electromagnetic energy within the bounds of a specific region and/or to prevent the proliferation of such energy into a designated locale. Electromagnetic energy, in general, manifests as:

- Energy associated with static and/or time-varying electric force field
- Energy associated with static and/or time-varying magnetic force field
- Radiated electromagnetic energy

Depending on the shielding requirements *vis-a-vis* the interference due to any of the above forms of electromagnetic (EM) energy, a variety of materials have been developed and deployed in the fabrication of shielding partitions or enclosures which confine the EM energy within a specified region, thereby preventing its invasion elsewhere. Apart from the partition or enclosure configurations, shielding is also facilitated for cables and connectors to avoid electromagnetic interference through mutual and/or external coupling. Tailoring shield designs for use in cables and connectors dictates specific material needs to match the geometrical and mechanical constraints.

The basic requirement of an EM shielding material is that a shield fabricated with this material should meet the *electromagnetic compliance* (EMC) aspects of achieving a specified extent of shielding under a given *electromagnetic interference* (EMI) ambient. The choice of EM shielding material is in general decided by:

- Electromagnetic properties of the material to provide a given *shielding effectiveness* (SE)
- Its compatibility for specific shielding applications *vis-a-vis* interference due to electric, magnetic, or electromagnetic (radiated) fields
- Geometrical considerations, namely, shape and size
- Mechanical considerations such as rigidity, flexibility, weight, structural mating (fastening and joints), and withstandability against shocks and vibration
- Performance under hostile thermal environments
- *Bandwidth* of operation; that is, the effective frequency range with acceptable shielding performance
- Ease of fabrication of the shields
- Cost-effectiveness

21.2 Mechanisms of EM Shielding

21.2.1 Shielding the time-varying electromagnetic waves [1,2]

As indicated earlier, the electromagnetic energy could be associated with static and/or time-varying electric and magnetic force fields (known as *induction fields*) in the vicinity of the source; or it could be a radiated field detatched from the source. Illustrations of these force fields are presented in Figure 21.1.

Pertinent to the various modes of EM field forces as depicted in Figure 21.1 the choice of a material in each case to shield the relevant field is distinct, inasmuch as the shielding mechanism involved is different for each of the EM force fields illustrated.

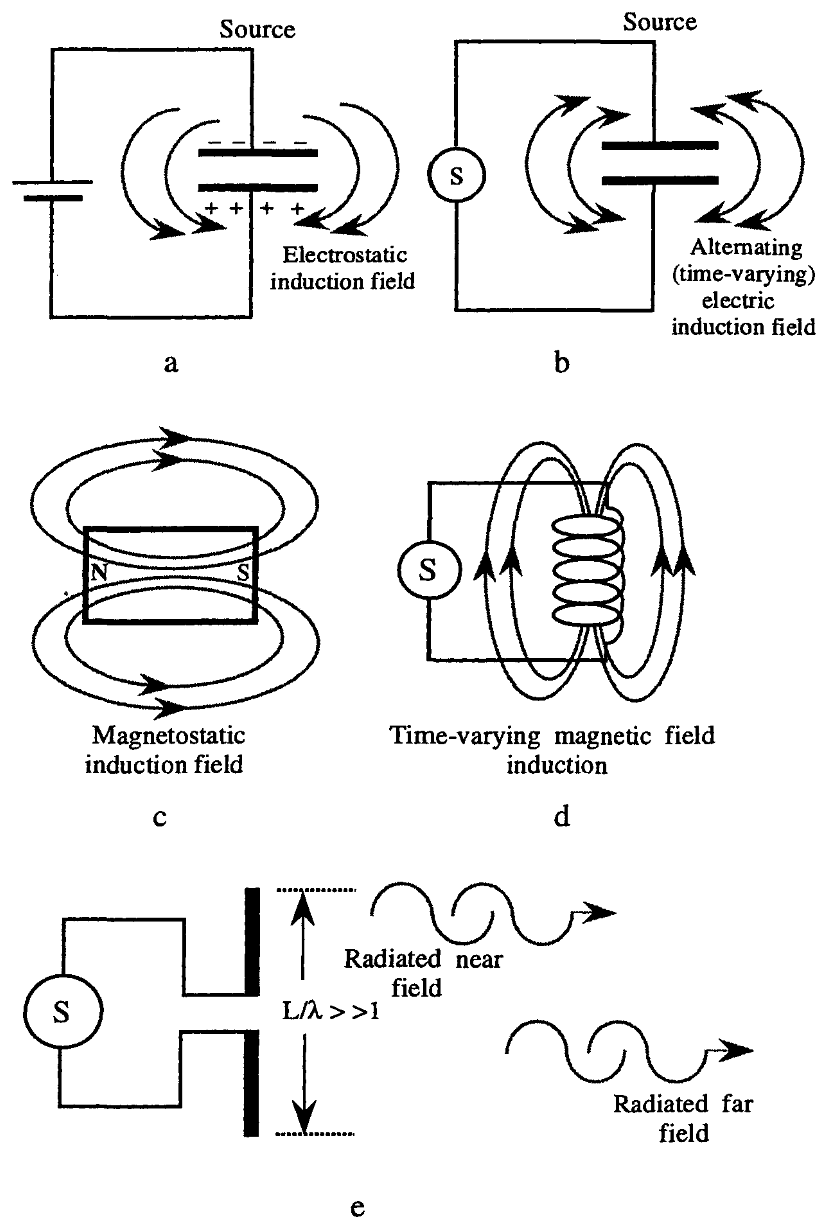

Figure 21.1 Electromagnetic interference fields.
(a) Electrostatic (d.c.) induction field. (b) Time-varying electric induction field.
(c) Magnetostatic induction field. (d) Time-varying magnetic induction field. (e) Radiated near and far electromagnetic fields.

To accommodate the electromagnetic field conditions as depicted in Figure (21.1), the electromagnetic field can be distinguished as two regimes:

- Quasistatic energy (with very low frequency, f or very large wavelength λ) specified as the induction or near-field components
- Radiated far-field components pertinent to high frequency or small wavelength electromagnetic energy

In reference to time-varying fields, a *wave impedance (intrinsic impedance) parameter* (Z_w or Z_o) can be defined for the medium in terms of the electric *(E)* and magnetic *(H)* field intensities. That is, Z_w or Z_o = $|E/H|$ ohms. When the source is a capacitive (potential-dependent)-type dipole (as shown in Figure 21.2), the associated E field is large leading to a high wave impedance ambient. On the other hand, a current-dependant loop source offers an extensive H field with the result the corresponding wave impendance of the medium tends to be small.

The mechanism of shielding is that the shielding medium (of appropriate material and geometry) when placed in the region of electromagnetic field should offer a barrier impedance Z_m sufficiently large in comparision with the wave impedance Z_w in the case of an electric field dominant ambient so that the wave is impeded sufficiently and shielded off from entering the region beyond the shielding barrier as illustrated in Figure 21.2.

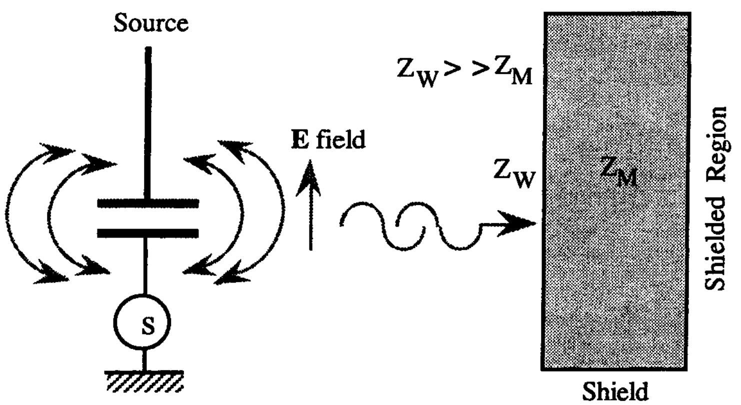

Figure 21.2 Electric field dominant ambient.

Likewise, in the case of magnetic field caused by current-dependent loop source, the effective shielding can be achieved by a shield (of appropriate material and geometry) with a barrier admittance Y_m well in excess of Y_w (Figure 21.3) where $Y_w = 1/Z_w$.

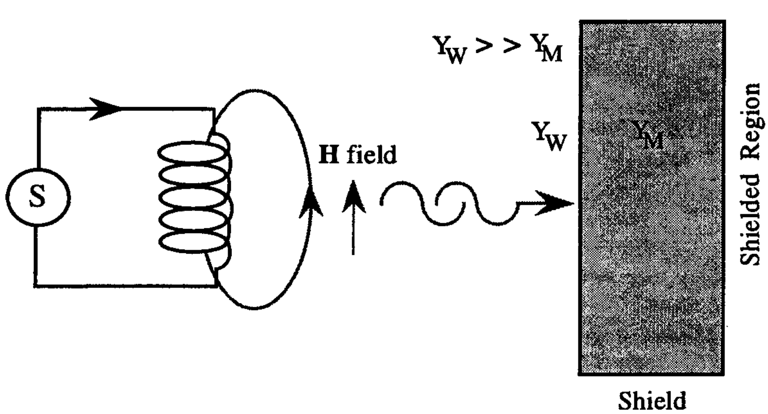

Figure 21.3 Magnetic field dominant ambient.

The primary considerations of electromagnetic shielding for time-varying fields are the proper choice of material and the geometry of the shield to provide the necessary barrier-immittance parameter. The shield geometry implicitly includes the thickness of the shield and the disposition of the shield (in terms of distance/wavelength ratio) from the source. The material and the geometry cohesively accomplish the shielding by the following mechanisms:

- Absorption of electromagnetic energy in the shielding medium (absorption loss)
- Reflection of the electromagnetic energy back into the source side with minimal transmission into the region being shielded (reflection loss)

21.2.2 Static fields

There are circumstances which warrant the shielding of static electric and magnetic fields. In such conditions, the relevant field is "blocked" from entering the region to be shielded by techniques distinctly different from the absorption loss and/or reflection loss modes. This is because, with static fields, there is no field energy being dissipated (and absorbed) and no reradiation (reflection) is feasible. Therefore, for electric and/or magnetic static fields the following shielding principles are advocated: Considering a static electric field, by placing a metal (or a good conductor) medium in the field area, the electric flux lines would terminate on the induced surface charges (normal to the plane of the surface) as illustrated in Figure 21.4.

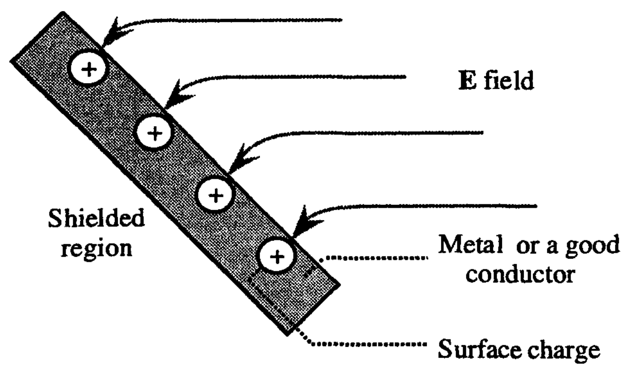

Figure 21.4 Electrostatic shielding.

The metal (or the good conductor) is a *equipotential medium* with zero potential gradient (or E field) in it. Therefore, the electric field terminates on the surface of the material and does not penetrate inside. Thus, a simple, high-conductivity medium can effectively provide *electrostatic shielding*.

Pertinent to static magnetic field, the shielding medium made of high permeability material accommodates the flux lines within itself by providing a low *magnetic reluctance* path. Thus, the field leakage into the region being shielded is negligible if relative permeability and the thickness of the shield are chosen to confine the flux lines as depicted in Figure 21.5.

Thus, to meet specific conditions (static or time-varying fields), shielding materials should be chosen appropriately as per the details furnished in the following sections.

21.3 Characteristics of Shielding Materials

As discussed earlier, the properties of shielding materials *vis-a-vis* time-varying electromagnetic fields are specified by the barrier immittance parameters, namely, Z_m and Y_m. Required values of these parameters are decided by the design value of the shielding effectiveness (SE) defined as the ratio of incident EM power density on the shield and the transmitted power density, normally expressed in *decibels* (dB). That is:

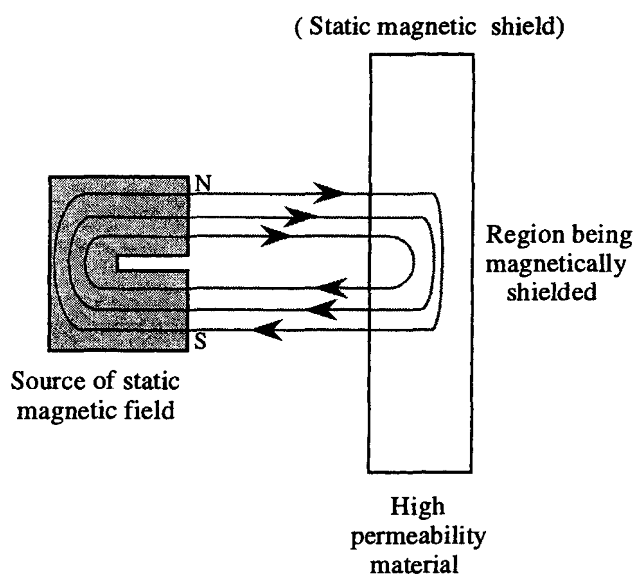

Figure 21.5 Magnetostatic shielding.

$$(SE)_{dB} = 10 \log_{10} (\text{Incident EM power density/Transmitted EM power density}) \tag{21.1}$$

where the incident power density refers to the power density at a measuring locale before the shield is in place and the transmitted power density corresponding to the measured power density at the same locale after the shield is in place. The power density ratio can also be expressed in terms of the ratio of field strengths as follows:

$$\begin{aligned}(SE)_{dB} &= 20 \log_{10} (E_1/E_2) \\ &= 20 \log_{10} (H_1/H_2)\end{aligned} \tag{21.2}$$

where (E_1,H_1) are electric and magnetic field strengths at a point, respectively, prior to installing the shield and (E_2,H_2) refer to the corresponding fields at the same point after the shield is installed.

Depicting the incident wave immittance parameters as (Z_w, Y_w) and the barrier immittance parameters of the shield as (Z_m, Y_m), the complex reflection coefficient at the shield boundary (Figure 21.6) is given by:

$$\begin{aligned}\Gamma &= (Z_m - Z_w)/(Z_m + Z_w) \\ &= (Y_m - Y_w)/(Y_m + Y_w)\end{aligned} \tag{21.3}$$

assuming no multiple reflections within the shield at its boundary surfaces. More rigorously, by considering multiple reflections as well as absorption due to EM energy dissipation with in the shield, Γ can be rewritten as:

$$\Gamma = [\exp(-\alpha d)]\,[4K/(1 + K)^2]\,[1 - \{(K - 1)/(K + 1)\}^2 \exp(-2\gamma d)]^{-1} \tag{21.4}$$

where $K = Z_w/Z_m$ (or Y_w/Y_m), $\gamma = (\alpha + j\beta)$ with α, β being the *attenuation and phase constant,* respectively, and d is the shield thickness. In Equation 21.4, $[\exp(-\alpha d)]$ depicts the EM energy absorption in the shield, $4K/(1 + K)^2$ refers to the reflection back to the source side and the third term is a coefficient arising from multiple reflections within the shield.

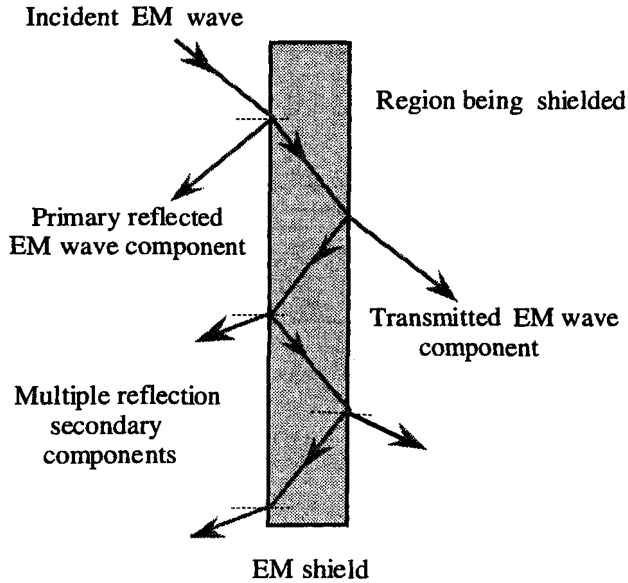

Figure 21.6 EM wave reflection at a shield boundary.

For effective shielding therefore the three major design parameters are:

- Z_w/Z_m (or Y_w/Y_m) ratio pertinent to the shielding materials
- Attenuation constant of the shield
- Thickness of the shield

Further, the choice of Z_w/Z_m or Y_w/Y_m is dictated by whether the shielding required corresponds to high frequency or low frequency (quasistatic) conditions as discussed earlier.

Shielding material for time-varying EM shielding can be a monolithic medium or a composite medium which offers optimum values of α (field attenuation constant) and Z_w/Z_m (or Y_w/Y_m) to realize the design specifications on shielding effectiveness. The attenuation constant (α) is decided by the effective conductivity (σ) and permeability μ of the shielding medium and the frequency (f) of operation. It is given by:

$$\alpha = (\pi f \mu \sigma)^{1/2} \tag{21.5}$$

if the material has an effective conductivity $\sigma >> \omega\varepsilon$, where ε is the effective permittivity of the medium and $\omega = 2\pi f$. The parameter m in Equation (21.5) is equal to $\mu_o \mu_r$ where μ_o is the absolute permeability of free space and μ_r is the relative permeability of the medium.

The absorption loss (A) part of the shielding effectiveness, $(SE)_{dB} = 20 \log_{10} (1/\Gamma)$ is given by:

$$\begin{aligned}(A)_{dB} &= 8.68\, \alpha d \\ &= 3.338(d)_{mils} (f_{MHz}\, \mu_r\, \sigma_r)^{1/2}\ dB \\ &= 1314.3\ (d)_{cm} (f_{MHz}\, \mu_r\, \sigma_r)^{1/2}\ dB\end{aligned} \tag{21.6}$$

where $\mu_r = \mu/\mu_o$, with $\mu_o = 4\pi \times 10^{-7}$ henry/meter (absolute permeability of free space) and $\sigma_r = \sigma/\sigma_c$ with σ_c the conductivity of copper at room temperature equal to 5.80×10^{-7} siemen/meter.

The barrier immittance parameters (Z_m, Y_m) depend on the *skin depth* (δ) of EM energy penetration into the shielding medium, frequency of operation (f), and the conductivity (σ) and permeability (μ) of the shielding material. The barrier immittance parameters are given by:

$$Z_m = 1/Y_m = 369\,(\mu_r f_{MHz}/\sigma_r)^{1/2}[1 - exp(-\tau/\delta)]^{-1} \text{ microohm/square} \qquad (21.7)$$

where δ is the skin depth defined as the surface thickness of a material at a given frequency at which the EM energy penetrating into the medium attenuates to an extent of $(1 - 1/e) \Rightarrow$ 63.2%. It is given by :

$$\begin{aligned} \delta &= 0.0066/(f_{MHz}\,\mu_r\,\sigma_r)^{1/2}\ cm \\ &= 2.6/(f_{MHz}\,\mu_r\,\sigma_r)^{1/2}\ mils \end{aligned} \qquad (21.8)$$

Pertinent to the quantitative aspects of shielding as described above, there are three phenomena which can be regarded as responsible for effective shielding. They are:

- Conductive reflection: The time-varying magnetic field component of the incident EM energy induces electric current in the shielding material and these currents in turn provide opposing magnetic field (as per the Faraday-Lenz's law) minimizing the total field beyond the shield.
- Magnetic reflection: In the event that the shielding material offers high magnetic permeability, the magnetic flux lines (time-varying or static) are confined as conductive (low reluctant) paths through the shield and do not link to the region being shielded.
- Conductive energy absorption: This refers to the energy dissipated in the conductive shielding medium manifesting as the field attenuation.

Choice of material for shielding time-varying EM field depends on the aforesaid phenomenological considerations and a chosen material could accomplish effective shielding on either one or combinations of these mechanisms.

To comply with the loss mechanisms stated above, the materials adopted commonly for effective shielding fall under the following wide categories:

- Metallic or alloy-based conductors
- Non-metallic conductors
- Conducting polymers and metal-infused paints
- Polymeric composites with metallic and nonmetallic (conducting) inclusions
- Concrete/polymer concrete hybrid composites
- Metal-included ceramics
- Multilayered laminates of boron/boron tungstates or graphite fibers in an epoxy matrix
- Intercalated graphite fiber composites
- Ferromagnetic materials
- Metal-included fabrics

21.4 Metallic and Alloy-Based Shielding Materials

These include both ferromagnetic and diamagnetic materials with significant electrical conductivity (σ). Typical shielding metals and alloys are listed in Table 21.1.

Table 21.1 Metals Used in EM Shields

Metal	Conductivity Relative to Copper $\sigma_r = \sigma/\sigma_{cu}$ ($\sigma_{cu} = 5.26 \times 10^6$ siemen/meter)	Remarks
Silver	1.05	
Copper	1.00	
Gold	0.70	
Magnesium	0.36	
Zinc	0.29	Diamagnetic
Brass	0.26	
Bronze	0.18	
Tin	0.15	
Lead	0.08	
Aluminum	0.61	Paramagnetic
Nickel	0.20	
Iron	0.17	
Steel (SAE1045)	0.10	Ferromagnetic
Stainless steel	0.02	

Metallic shielding could be done in various forms as indicated below:
1. Metal sheet or foils
2. Zinc arc-sprayed coating
3. Vacuum metallization coating
4. Cathode-sputtered coating
5. Electroless plating
6. Apertured sheets
7. Metallic wire screens
8. Metallized fabrics

21.5 Description of Metal-Based Shields

Homogeneous metal sheets or foils for enclosure-type or overlay applications are used. Popularly, shielding enclosures have been constructed with welded steels with the attempts to realize a standard shielding effectiveness of 60 to 80 dB (as per NSA 73-2A specification) possibly over a frequency range of 10 KHz to 1 GHz. Copper and aluminum sheets or foils enjoy prominence in RF shielding techniques [3].

The nonmagnetic metals and alloys provide relatively low attenuation to transmission of EM wave as decided by the $(\sigma_r \mu_r)^{1/2}$ product (where σ_r is the relative conductivity of the material with respect to copper and μ_r is its relative permeability). The ferromagnetic metals/alloys (with large μ_r) therefore offer higher attenuation, especially at low frequencies. At higher frequencies, (>100 KHz) μ_r degrades for most of the ferromagnetic metals/alloys with the consequence of absorption attenuation being comparable or less than those of nonmagnetic metals/alloys.

Metals and alloys available in sheet stock form have a range of thickness from 1/64 in. (0.4 mm) or less to about 1/8 in. (3.2 mm) or more. In foil form (with thickness from 1 (25.4 μm) to 10 mil (254 μm)) shielding metals are available as sheets and tapes and as adhesive-backed foil rolls. Nonmagnetic foils are widely used in RF shielding. At low frequency magnetic fields such foils, however, pose little attenuation.

Metal-based shielding of large spaces (such as rooms) is done normally with metal-foil wallpaper (MFWP) in conjunction with pressure-sensitive metal-foil tapes and conductive adhesives/epoxies/caulking compounds. Typical MFWP shieldings are characterized in Table 21.2.

Table 21.2 MFWP Shielding Characteristics

MFWP Material	Thickness (mils/microns)	Electrical Characteristics	Shielding Effectiveness (dB) MIL-STD-285
Aluminum		Paramagnetic Good conductor	25-40 dB for magnetic field at 200 KHz
Copper	2-3/51-76	Diamagnetic Very good conductor	80-100 dB for electric field over 200 KHz to 10 MHz
Stainless steel		Ferromagnetic Poor conductivity	60-80 dB for plane wave above 400 MHz

21.6 Process-Based, Inhomogeneous Metal Shields

The different types of metallic coating on surfaces to realize EM shielding have invariably the process-induced inhomogeneity in them. The extent of such inhomogeneity determines the effectiveness of shielding offered by these materials. The corresponding shielding characteristics are controlled by the surface resistance of the coating, the quality of which is decided by the process adopted, surface characteristics of the substrates, type of metal being coated, and the thickness of the coating advocated.

The various coating processes of metallic shielding materials are characterized as follows [4-6]:

1. *Zinc-arc spraying*: This process involves electrically isolated wires which are continuously fed into a gun so that only the tips of the wire come into contact. Upon reaching critical distance from each other an intense arc across the tips melt them so that an air jet from the gun carries the metal particles and deposits them on the surface being coated.

Zinc-arc sprays give good conductivity and high-dB attenuation to EM fields and accommodate dense coatings. However, it is expensive and arcing products are highly toxic warranting special precautions. Also, zinc sprays are poorly adhesive with cracking and pitting problems.

2. *Vacuum metallizing*: This process allows the deposition of a pure metallic films (such as aluminum) in a vacuum chamber. This method also offers surfaces with good conductivity and continuously homogeneous coatings. Lack of abrasion and poor corrosion resistance specify the demerits of this technique.

3. *Cathode sputtering*: This is similar to vacuum evaporation. An inert gas is set within the coating chamber. When the chamber pressure is reduced, an arc strikes at the coating

material to vaporize it. Upon condensation, the vaporized metal forms a film on the substrate. This method again yields surfaces of good conductivity and offers a good adhesivity of coating. Expensive equipment and cracking of the coatings at higher temperatures are the limitations of this process.

4. *Electrodeless plating*: This refers to an immersion technique of the substrate in a suitable aqueous solution wherein a controlled autocatalytic chemical reduction permits the deposition of metal films (of copper and/or nickel) onto a substrate. The resulting coating offers excellent shielding effectiveness over a wide range of frequencies (65 to 120 dB). The coating is also uniform in thickness with adequate recess and side wall coverage. It provides an excellent contact for grounding and also offers a good corrosion resistance. It is applicable to substrates with complex surfaces.

21.7 Apertured Metal Panel Shields

Perforated metal sheets with apertures of small sizes (relative to wavelength) are useful as lightweight shields. The performance of these shields is dictated by the aperture-to-metal area ratio and the thickness of the metal used. Metals with punched-hole perforations or of honeycomb structures and as interwoven lattices constitute feasible shielding structures of this category. For the perforated panels, the shielding effectiveness is given by:

$$(SE)_{dB} = 32t/g + 4 + 20 \log_{10}[(D/g)^3/N] \qquad (21.9)$$

where t is the thickness of the shield, g is the size of the perforations, D is the lateral size of the square panel and N is the total number of perforations. The above formulation refers to low impedance magnetic fields independent of frequency.

21.8 Wire-Mesh Screens as EM Shields

These are even more lightweight in comparision with apertured metal shields. Flexible wire-mesh screens (such as chicken wire-mesh screens) with metal-to-air area ratio on the order of 0.05 to 0.5 are popular as shields constituting the so-called *Faraday cages*. The mesh size is decided by the wavelength (λ) of operation such that, at the operating frequency, the screen offers a cutoff window at each air-gap region to the EM wave incident on it. The shielding effectiveness is given by:

$$\begin{aligned}(SE)_{dB} &= 20 \log_{10}(0.5\lambda/g)\ dB \text{ for } g \leq \lambda/2 \\ &= 0 \text{ for } g \geq l/2 \qquad (21.10)\end{aligned}$$

where g is the size of the airgap in the mesh.

When the frequency decreases (or wavelength increases), the shielding effectiveness does not increase indefinitely but levels off at about 110 dB for copper and aluminum screens and at about 150 dB for galvanized steel. These limiting values correspond to the situation that the screen can be regarded as a homogeneous material at wavelength $\lambda >> g$.

21.9 Metallized Fabrics/Textiles as EM Shields

The shielding effectiveness of metallized fabrics and textiles (both woven and nonwoven) depends on the geometry of the fabric (for example, pore size and thickness), and the amount of metal present in the fabric. These materials are useful as personnel wear to protect people from EM irradiation (also known as *nonionizing radiation*). Also, they are used as sheet covers for equipment or a space to be protected from electromagnetic fields. The uses of metallized fabric EMI shields are [7-9]:

- (Partial) shields for equipment cases
- Shielding and grounding curtains

- Torso contacts for electromedical sensors, and probes
- Electrostatic discharge wipers
- Protective clothing for personnel working under high-voltage magnetic fields and/or in RF/microwave environment
- Flexible shielded shrouds, smocks, stockings, and boots
- Accordian-type (collapsible) EMI-protected walkways

21.10 Generic EMI Shielding Fabrics

The major divisions of EMI shielding fabrics are: (i) Metal-coated fabrics and (ii) metal interwoven fabrics. Silver and copper are the candidate materials normally blended with the textiles. The basic requirement of the shielding fabrics is that they are electrically conductive. Examples of EMI shielding fabrics are:

- Silver-metalized woven nylon fabrics
- Blend of 75% wool plus 25% of conductive (metallic) alloy fibers
- Blend of 85% polyster plus 15% of conductive (metallize fibers)
- Blend of 85-90% of syntheic textile plus 15-10% of stainless steel fibers

Typical surface resistances of different shielding textile materials are listed in Table 21.3.

Magnetic field shielding: Woven type shielding fabrics (of the types described in Table 21.3) provide almost nil shielding effectiveness to magnetic fields below 10 MHz.

Electric field shielding: Metal-coated fabrics are akin to metallic foils in offering electric field shielding

Characteristic requirements of shielding fabrics should meet the following general requirements:

- The clothing should offer effective and adequate EM shielding.
- The clothing itself should not pose an hazard.
- The shielding limit should be flexible, comfortable, light in weight, and unrestricting to the wearers.
- The fabric must be conducive for the making of suits such as an overalls with integral hood, gloves, and oversocks with no leakage of EM energy through zippers etc. Caution should be exercised in compliance with: ANSI C95 1973 standard which specifies "In very intense fields, arcs will occur between folds in the fabric and between the arm and body, etc. These arcs will burn holes in the suit, exposing the wearer to harmful radiation".

Corresponding to the four types of shielding fabrics blends as detailed in Table 21.3, the measured values of shielding effectiveness at microwave frequencies are presented in Table 21.4.

Allowable limits of exposure of suits to radiation to avoid arcing are: 200 mw/cm^2 (U.S Navy Limit) and 1 mw/cm^2 averaged over any 60 second period for frequencies above 30 MHz (Australian RF Exposure Standard AS 2772-1985 is specified as the corresponding personnel exposure). The above stipulations warrant the suit to provide at least 23 dB of shielding effectiveness with all its opening, if any.

Table 21.3 Surface Resistance of Shielding Fabrics

Type of Fabric Blend	Mean Surface Resistance (ohm/sq)	Fiber Size (μm)	Wave Orientation
1. 75% Wool + 25% conducting fiber	~1.0	~10.0	
2. 85% Polyster + 15% conducting fiber	~8.0	~8.0	Warp/weft/diagonal
3. 85% Synthetic fabric + 15% stainless steel fiber	~65.0	~7.5	
4. 90% Synthetic fabric + 10% Stainless steel	~55.0	~7.5	

Table 21.4 Measured Shielding Effectiveness at Microwave Frequencies

Fabric Blends (of Types in Table 21.3)	SE (dB) at 4 GHz	SE (dB) at 10 GHz
Type 1	48	43
Type 2	43	42
Type 3	41	38
Type 4	33	37

Normally at high frequencies, the conductive suits offer 20 dB or more shielding effectiveness. At low impedance (low frequency) conditions, the fabrics should be more conductive to provide a shielding effectiveness of 20 dB or more. Further requirements are:

- The conductive suit should be nonflammable.
- The suits should assure normal ventilation.
- The personnel-wear fabrics should offer no threat of corona or other breakdowns under high voltage operations.

21.11 Modeling Metallized Fabric Shields

Due to the extensive geometry dependence of the shielding characteristics *vis-a-vis* the conductive fabric, exact formulations to deduce the shielding effectiveness are rather sparse. Expressions have been developed on the basis of plane wave shielding theory of meshed or perforated conducting panels with appropriate empirical changes to accommodate the surface resistivity, pore size, and thickness of the fabric material. A functional form of relation derived to depict the shielding effectiveness of conductive fabrics both at high and low frequencies is given by:

$$(SE)_{dB}\ (Fabric\ Material) = exp\ (-0.129\ L\sqrt{f})\ (SE)_{Foil} +$$

$$[1 - exp\ (-0.129\ L\sqrt{f})\ (SE)_{Aperture} \qquad (21.11)$$

where L is the aperture dimension of the fabric and f is the frequency of operation. Further $(SE)_{Foil}$ and $(SE)_{Aperture}$ depict the shielding effectiveness of a metallic foil (of the same thickness (t) as the fabric) and that of an aperture (of size $L \times D$) subjected to a plane wave excitation. They are given by:

$$(SE)_{Foil} = 20\ log_{10}\ [(1 + K)^2/4K]\ [1 - (K - 1)^2/(K + 1)^2]\ exp(-2t/\delta) \quad dB \qquad (21.12)$$

where $K = Z_w/Z_s$ (ratio of wave impedance to shield impedance) and δ is the skin depth.

$$(SE)_{Aperture} = 100 - 20\ log_{10}(L \times f) + 20\ log_{10}\ [1 + ln(L/s)] + 30\ D/L \quad dB \qquad (21.13)$$

where L is the maximum pore size, s is the minimum pore size and D is the depth of the aperture.

Alternative form of expression derived for the shielding effectiveness of a conductive fabric is :

$$(SE)_{Fabric} = (A_a + R_a + B_a + K_1 + K_2 + K_3) \quad dB \qquad (21.14)$$

where
A_a = attenuation introduced by a discontinuity in dB
R_a = aperture (single reflection) loss in dB
B_a = multiple reflection correction term in dB
K_1 = correction term to account for the number of like discontinuities in dB
K_2 = low frequency correction term to account for skin depth (in dB), and
K_3 = correction term to account for coupling between adjacent holes in dB

Explicit expressions for the terms in Equation 21.14 are:

$A_a = 27.3\ (D/L)$ for an incident wave below cutoff for a rectangular opening
(D and L in meters)
$R_a = 20\ log_{10}\ |(1 + 4K^2)/4K|$
($K = j\ 6.69 \times 10^{-3}\ f \times L$, f in MHz, L in meter)
$K_1 = -10 log_{10}\ (a \times n)$
(a = Mesh area in square meters and n is the density of the meshes per square meter)
$K_2 = -20 log_{10}\ (1 + 35\ p^{-2.3})$
(p = fiber diameter/skin depth)
$K_3 = 20\ log_{10}\ [coth\ (A \times a/8.686)]$

Typical variations of shielding effectiveness (SE) *versus* the metal content, and geometrical parameters over the frequency of fabric-type shields are presented in Figure 21.7.

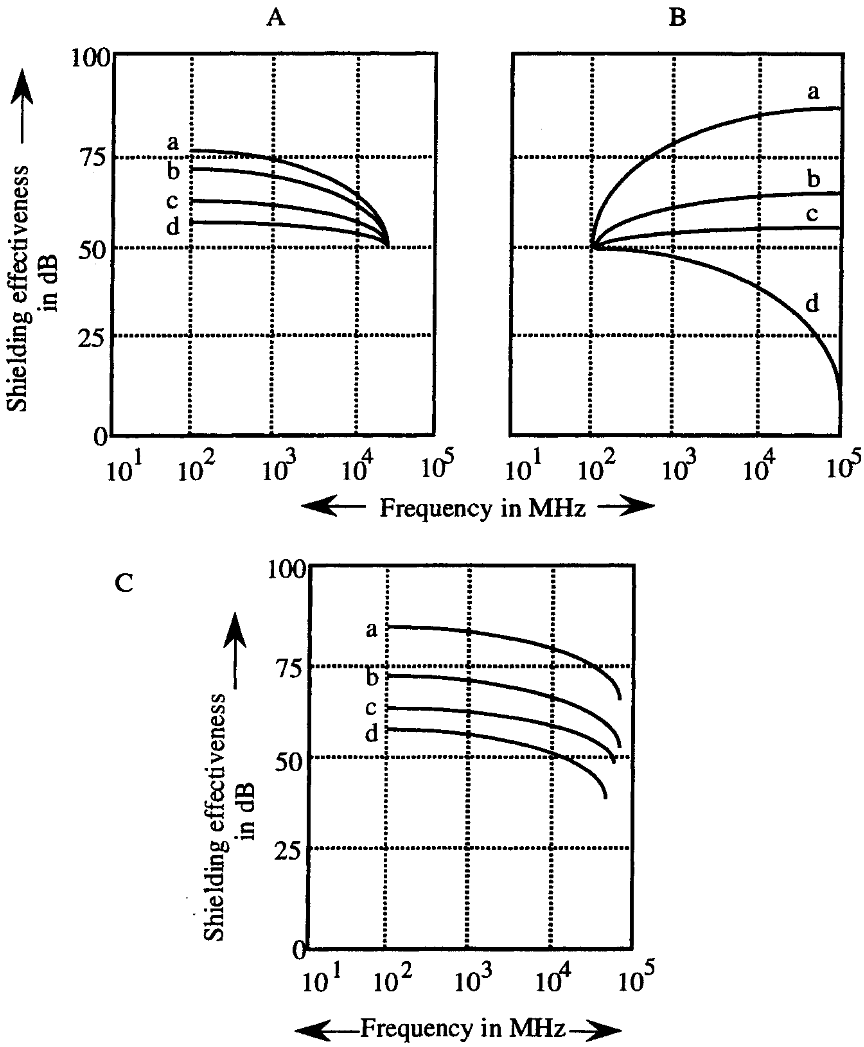

Figure 21.7 Shielding effectiveness *versus* frequency of a fabric-type EM shield.
A: Effect of metal content – Examples with L: Maximum pore size ≈ 160 μm; s: Minimum pore size ≈ 106 μm; D: Depth of the aperture ≈ 90 μ/m.
(a) Copper content /meter^2 = C_{cu} = 1.0; (b) C_{cu} = 0.8; (c) C_{cu} = 0.6, and (d) C_{cu} = 0.4.
B: Effect of maximum pore size – Examples with C_{cu} = 1; D ≈ 90 mm and L/s ≈ 1.5.
(a) L = 50 μm; (b) L = 100 μm; (c) L = 200 μm and (d) L = 400 μm.
C: Effect of aperture depth – Examples with L ≈ 250 μm; L/s = 1.5 and C_{cu} ≈ 1.
(a) D = 400 μm; (b) D = 200 μm; (c) D = 100 μm, and (d) D = 50 μm.

21.12 Conductive Paints for Shielding

Conductive paints are used as conductive surface coatings on carefully prepared surfaces such as plastics, woods, ceramics, and other base materials so that the coated material offers EM shielding. Normally these paints are prepared with the suspension of conductivity inclusions such as graphite and silver particles in a medium like lacquer, elastomer, silicon resin, vinyl base, acrylic fluid, or latex. Conductive coatings are done on prepared surfaces *via* dipping, spraying, silk-screening, roller-coating, brushing, or aerosol spraying. Typical conducting paints and their characteristics are presented in Table 21.5.

The need for conductive coating arises mainly due to the current practice of using plastics for electrical/electronic equipment enclosures (*in lieu* of metallic boxes). Such plastic enclosures as such do not offer EMI shielding and therefore warrant an application of conductive coating on their surfaces. Further, plastics are prone to *electrostatic propensiveness* (see Chapter 20). Conductive coating facilitates the bleed-off of static charges accumulated on the plastic surfaces.

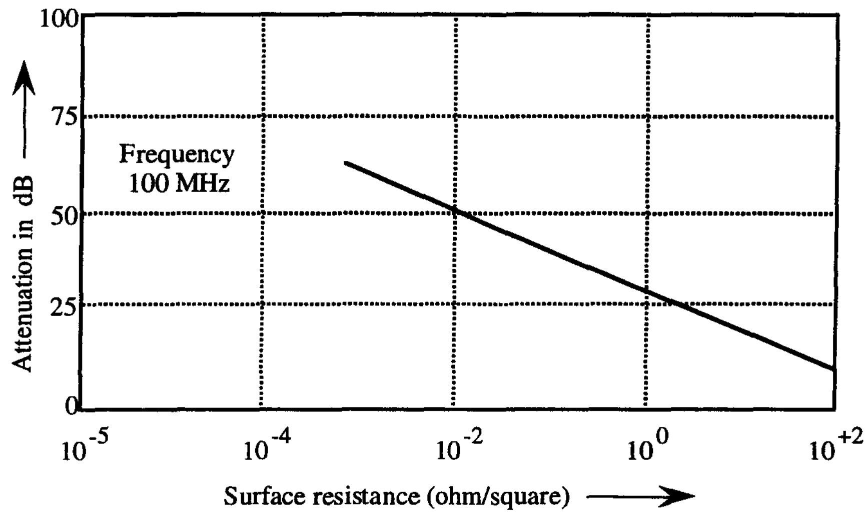

Figure 21.8 Attenuation of EM wave *versus* surface resistance of conductive coating at 100 MHz.

Table 21.6 Coating Thickness Requirements

Type of Coating	Coating Thickness (micrometer)	Function	Surface Resistance (ohm/square)
Silver paint	40-80	EMI/RFI Shielding	1
	50-80	Grounding	10
	20-100	Electrostatic Bleed-off	50-150

The general requirements of a conductive coating are:

- Adequate surface conductivity
- Operation over a wide range of temperature
- Stability in most environments
- Stability against mechanical shocks and abrasions
- Facilitation of easy grounding
- Presenting an aesthetic appearance
- Uniformity of coating thickness
- Ease of application

The coating thickness required depends on the type of shielding required. For example, requirements of silver-coating thickness are specified in Table 21.6.

21.13 Surface Resistance of Conductive Paints

Surface resistance (R_s) of conductive paint coating is expressed in ohms/square. In terms of the specimen's length (ℓ) and width (w) and the bulk resistance R, the surface resistance (R_s) is expressed as

$$R_S \text{ (ohms)} = R \text{ (ohms)} (\ell/w) \tag{21.15}$$

(ℓ and w should have the same units, cm, meter, or inches).

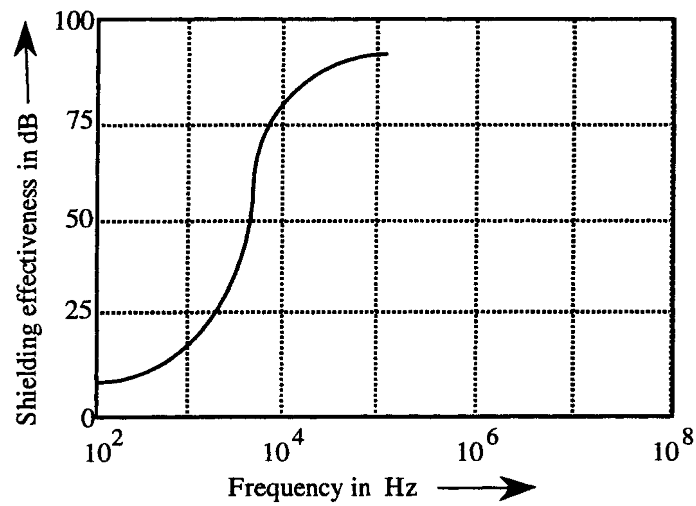

Figure 21.9 Magnetic field shielding effectiveness of a conductive paint coated enclosure with full integrity and no openings *versus* frequency.

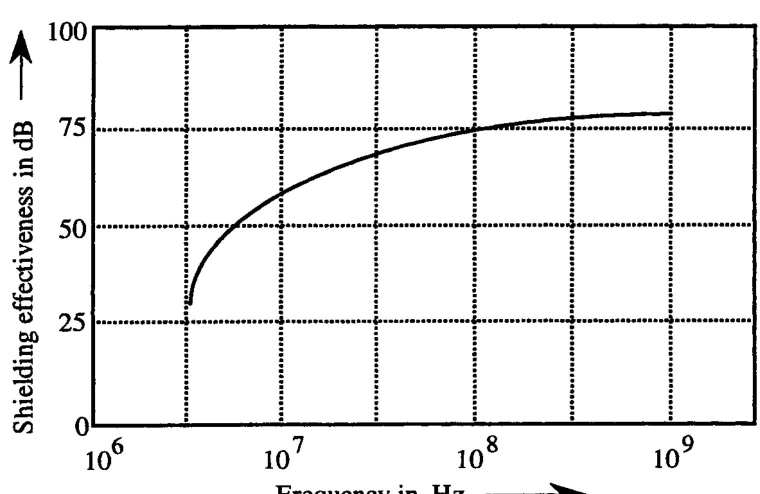

Figure 21.10 Electric field shielding effectiveness *versus* frequency of a conductive paint coated enclosure with full integrity.

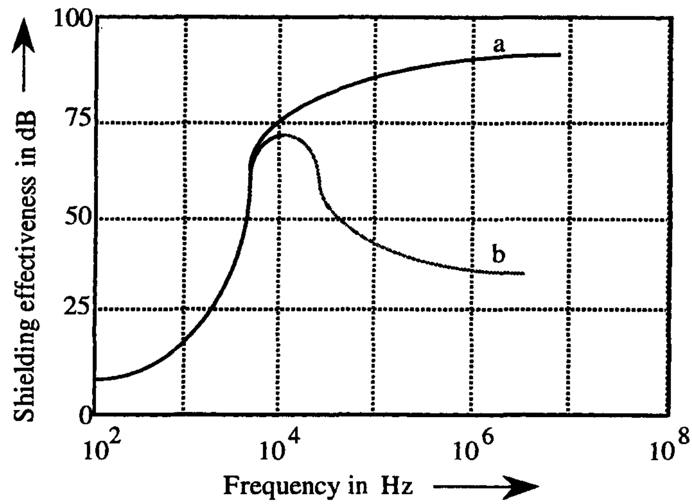

Figure 21.11 Plane wave attenuation *versus* frequency offered by a conductive paint coated enclosure. (a) Enclosure with full integrity; (b) Enclosure with partial openings.

Surface resistance is the quality index of conductive coatings specifying the uniformity of coating and the extent of shielding effectiveness of the specimen. The dependence of EM field attenuation *versus* surface resistance is a function of frequency and at 100 MHz, typical attenuation as a function of sheet resistance is shown in Figure 21.8.

Shielding effectiveness *(SE)* at low impedance (low frequency) conditions offered by conductive paint coating may degrade with openings in the shielding enclosures. A typical low frequency magnetic field shielding effectiveness *versus* frequency of conductive paint (such as acrylic-based silver paints) is depicted in Figure 21.9.

The electric field attenuation (expressed in terms of shielding effectiveness) due to conductive paint (acrylic-based silver paint) coated structures as a function of frequency is presented in Figure 21.10.

Plane wave attenuation due to conductive coating is also affected by the loss of integrity due to openings in the shielding enclosures. For a typical conductive paint coated enclosure, variation of shielding effectiveness *versus* frequency is shown in Figure 21.11.

21.14 Properties of Conductive Pigments/Fillers

Paints, like plastics on which they are coated, are inherently nonconducting and therefore provide no shielding effect unless suspended with conductive fillers/pigments. As indicated by Hart [10] that no single property of the conductive pigment assumes overriding importance and the materials used are normally chosen because they exhibit a combination of properties which fit the requirements of the specific application. The cost of the pigment is also very important depending on the mission involved. The pigments chosen are of materials with high electrical conductivity. Table 21.7 gives the electrical conductivities of typical pigment materials relative to that of copper.

When the conducting particles are suspended in a paint, the coating realized is a thin organic film in which the particles are dispersed as random chains in the organic vehicle. Therefore, the effective surface resistance offered by the coating depends on the mode dispersion of the conductivity particles as decided by their volume fraction, shape, size, and surface conditions of the substrate.

Table 21.7 Relative Electrical Conductivities of Pigment Materials

Pigment Materials	Relative Conductivity (σ/σ_{cu})
Silver	1.05
Copper	1.00
Gold	0.70
Aluminum	0.61
Nickel	0.21

Adjunct considerations that determine the shielding properties of the coating the chemical properties of the pigment materials. Such properties determine the surface condition of the particles. Materials which are resistant to corrosion and oxidation are capable of presenting clean metallic particulate surfaces with minimal contact resistance between the dispersed particles in the vehicle medium, whereas materials like aluminum particles due to surface oxidation contribute high particle-to-particle contact resistance, thereby offering a low surface conductance. Silver on other hand presents good chemical properties and mostly nonreactive with the vehicle medium. Therefore silver-based paints show better storage stability and facilitate stable conductive coatings.

Though copper particles offer excellent conductivity in the suspended phase, their chemical stability is rather poor leading to deterioration of initial high conductivity properties on storage and in aggressive environments due to oxidation and corrosion. Surface-treated copper pigments have been developed to combat against the aforesaid chemical activity *versus* conductivity characteristics.

Pigment materials should also offer stable mechanical properties to the coating against wrinkling, blistering, pitting, corrosion, cracking, and peeling.

Though gold pigments are excellent conductors, their usage in conductive paints are limited due to prohibitively high cost considerations.

Aluminum has inherently high electrical conductivity and presents a stable coating. However, aluminum particles form insulating oxide films degrading the effective conductivity of the films.

Despite nickel having lower conductivity, it has become a popular pigment material due to its excellent chemical properties. Its chemical integrity offers low contact resistance between the particles suspended in an organic vehicle. Nickel withstands extreme and aggressive environments and remains stable over a long storage period.

Though graphite has good chemical properties, its applications are limited due to its poor conductivity and its application is not aesthetically pleasing on surfaces intended for consumer products. Further, graphite has a tendency to "loosen out" and gets shed from the coated surface.

21.15 Composite Shielding Materials

Composite shielding materials can be classified into two major groups, namely, the host-inclusion system and multilayered "stack-up" system. The first category refers to a host material in which another material (in the form of particles, fibers, or flakes) is dispersed so that the volume fraction of the constituent materials, their electrical characteristics, and the shape and size of the inclusions determine cohesively the shielding effectiveness of the composite. In the second type, selective materials are stacked up as layers to yield a desired shielding property [11-14].

Particulate-blended shielding composites are constituted by metallic inclusions like silver, aluminum, nickel, or copper particles heterogeneously mixed in a host medium such as polymer/plastic, epoxy resin, or concrete. Nonmetallic inclusions like graphite, pyrolized organic fiber (polyacrylonitrile), boron/boron tungstate, or conductive polymers have also been advocated for similar applications. For high temperature applications suitable candidate materials for the host matrix are:

1. MIL-C-28840 Series (thermoset and thermoplastic resins)

Polyether-ether-ketone	282°C
Liquid crystal polymer	240°C
Polyphenylene sulfide	232°C
Polyamide-imide	220°C
Polyimide	204°C

2. MIL-C-38999 Series IV (thermoset and thermoplastic resins)

Polyther-sulfone	180°C
Polyaryl-sulfone	180°C
Polyther-imide	180°C

3. Portland Cement

4. Epoxy Resin, PVC, nylon

5. Ceramics
   Barium titanate
   Titanium dioxide
   Ferrite materials

As inclusions a variety of metals, metal-coated nonmetals and alloys in different particulate shapes have been studied in synthesizing composite shielding materials. A list of such materials are as follows:

Doped conductive polymers
(poly-p-phenylene-benzobis-thiozole, PBT)
Carbon/graphite fiber, carbon powder
Pyrolyzed organic fiber
(Polyacrylonitrile)
Nickel-coated graphite/polycarbonate fibers
Iron oxide powder
Indium/tin oxide (ITO) powder
Nickel flakes/powder
Aluminum powder/flakes/fibers
Stainless steel fibers (300 and 400 series)
Alloy fibers (Nichrome, Inconel, Hastelloy X, Carpenter 20CB3, 80/20 nickel chromium)
Titatium Tantulum fibers
Boron and boron tungstate fibers
Chopped copper wires

The shielding characteristics of different combinations of host-inclusion systems as measured and reported are presented in Table 21.8.

The choice of host material and/or inclusions depends on the type of the shield, its application, and the shielding effectiveness warranted. Specific to the inclusions, the main requirements of their suitability in a shielding composite can be listed as follows:

- Significant electrical conductivity

- Availability in different forms (powder, fibers, or flakes)
- Minimum chemical interaction with the base matrix
- Minimal alteration of base material properties
- Shrinkage compatible with the host medium
- Excellent abrasion strength
- Corrosion resistance
- Shelf-life durability with no "shedding off" from the composite
- Cost-effectiveness

The host medium is expected to have:

- High dielectric and/or magnetic loss characteristics
- Good bonding with the inclusions
- High strength and impact resistance
- Moldability
- Chemical stability
- Noninteraction (chemically) with the inclusions
- Heat resistance (against warping and cracking)
- Coloration with pigments for aesthetic appearance

The physical forms of inclusions significantly influence the effective conductivity of the composite material. Therefore, the design of shielding composites can be controlled (to achieve a specified shielding effectiveness) with proper choice of particulate shapes of the inclusions (see Chapter 6). Typically, the following particle geometries are considered in practice:

1. Spherical or near-spherical fine or coarsed particles
2. Spheroidal or elliposoidal particles
3. Flakes or disks
4. Fibers or needles
   - *Tows* –fibers of continuous strands of multiple-end filaments
   - Sized and chopped fibers
   - Air-laid *web* –a nonwoven, randomly arrayed fiber web
   - Continuous filament yarn

21.16 Shielding Effectiveness of Particulate-Blended Composites

The shielding performance of these composites is decided by the effective conductivity (σ_{eff}) of the composite material. As discussed in Chapters 6, the value of σ_{eff} is controlled by the volume fraction, conductivity, and shape of the inclusions, and by the dielectric loss of the host medium. Further, the dispositions of the dispersed particles (either in totally anisotropic or isotropic random fashion or in a textured selective orientation) also play a significant role in attenuating the electromagnetic energy passing through the composite. They also decide the polarization dependency of the attenuation realized.

In the design considerations, proper choice of constituent materials and their volume fractions, shapes, and dispositions are crucial factors to realize a specified value of shielding effectiveness. The algorithms pertinent to composite multiphase dielectrics and/or conductor-included dielectric mixtures described in Chapter 4-6 are useful in synthesizing a test composite of a specified effective conductivity (and hence the shielding effectiveness).

The choice of host medium could be based on mechanical properties of the composite being synthesized as well as on the thermal withstandability, chemical stability, and corrosion-resistant characteristics.

Following are some typical recipes of particulate-blended shielding composites and the test results on the shielding performance:

Shielding composites with doped polymers as conducting inclusions: A number of lightweight polymers which are intrinsically nonconductive become conductive upon doping are useful as EMI shielding materials. For example, when the polymer poly-p-phenylene-benzobis-thiazole (PBT) available as Pristine PBT 2002-2™, is doped with iodine *via* ion-implantation, the resulting composite offers a sheet resistivity on the order of 350 ohm/square at microwave frequencies. Typical shielding effectiveness *versus* frequency of a PBT film is depicted in Figure 21.12.

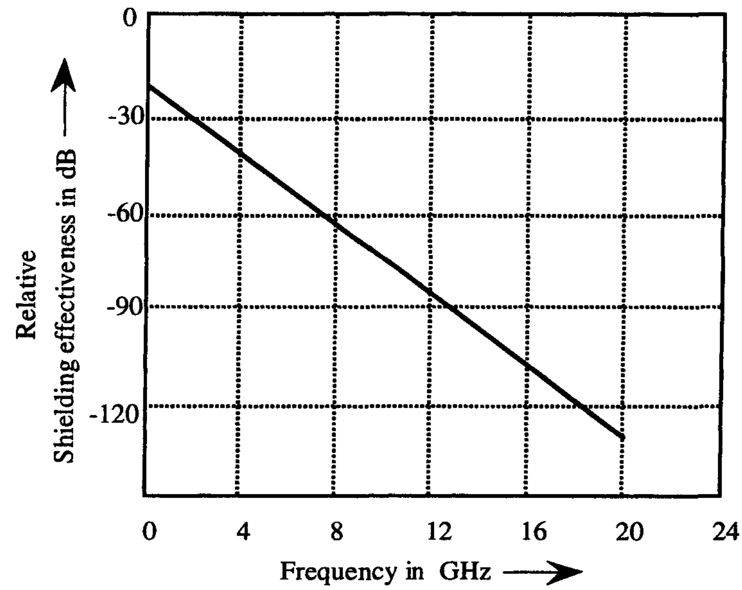

Figure 21.12 Shielding effectiveness *versus* frequency of PBT composite shield.

In addition to PBT, a variety of other conductive polymers (such as iodine-doped polyacetylene) have been reported in literature [17] (and described in Chapter 8) which can be useful for the purpose of synthesizing EMI shielding composites.

Apart from using conducting polymers as such for shielding applications, they can also be blended with thermoplastics to achieve a very high level of shielding performance. Typical blends are constituted by a matrix polymer such as polyvinyl chloride (PVC) or nylon compounded with an inherently conducting polymer (ICP) with a conductivity on the order of 1 to 10^5 siemen/cm. The resulting thermoplastic blends have conductivities as high as 20 siemen/cm which are an order of magnitude higher than those that can be obtained with carbon black-included polymers.

Volume fraction of the conducting polymer inclusions decides the effective bulk conductivity of the composite blend and hence the shielding effectiveness of the material. Shown in Figure 21.13 is the typical variation of shielding effectiveness due to conducting-polymer included blends (of different bulk conductivities) *versus* frequency. For comparison, relevant data on a blend using 6% stainless steel fiber is also presented in Figure 21.13.

The results indicate that this type of composites is suitable for low frequency electric field shielding. However, coating the shield with nickel plating provides both plane wave and electric field shielding effectiveness well in excess of 100 dB.

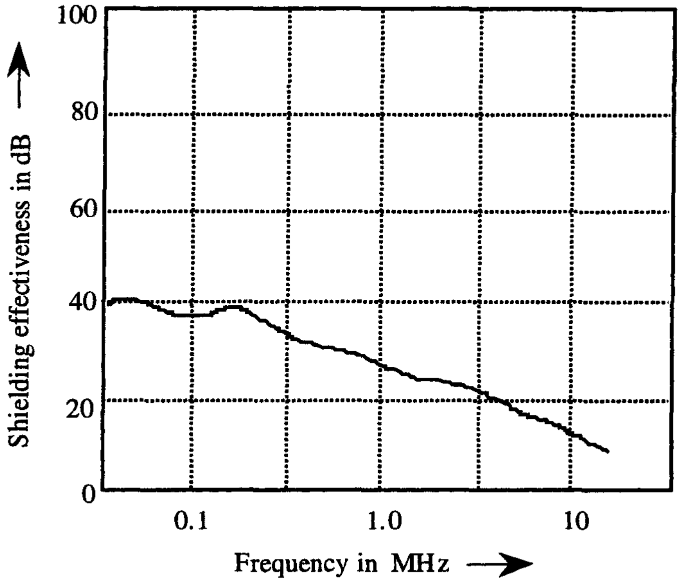

Figure 21.13 Measured data on electric field *versus* frequency of 70 mil thick shield of epoxy resin filled with 40% by weight of carbon fibers.

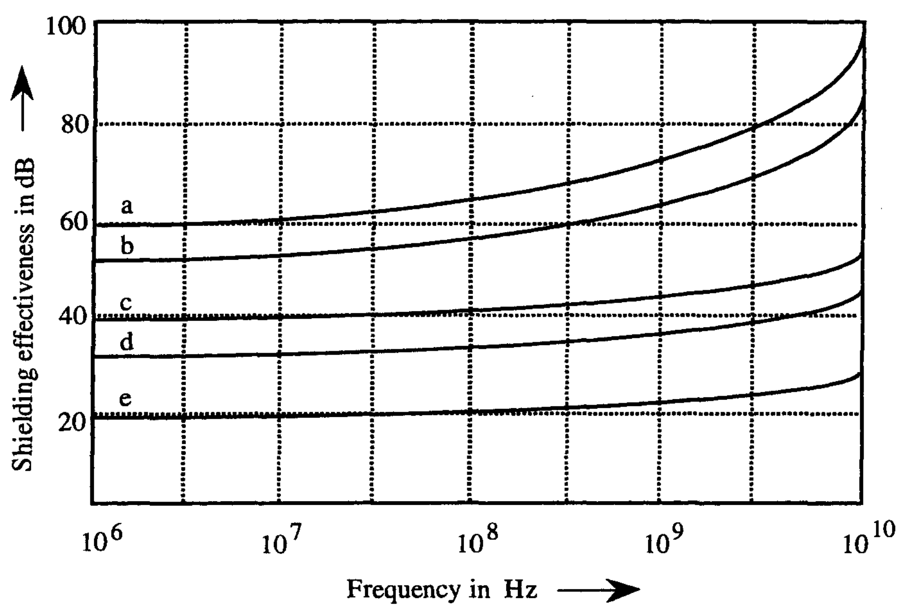

Figure 21.14 Measured far-field shielding effectiveness of conducting plastic included blends *versus* frequency.
(a) Conductivity (σ) = 7.50 siemen/cm.
(b) σ = 3.75 siemen/cm.
(c) σ = 1.00 siemen/cm.
(d) σ = 0.20 siemen/cm.

Table 21.8 Measured SE of Shielding Composites (Frequency up to 100 MHz)

Material	Shielding Effectiveness in dB	Remarks
1. (Polyether-ether-ketone, 75%) + (indium-tin oxide, 15%) + (Ni flakes, 10%)	43-45	Cu plated
2. (Polyther-ther-ketone, 75%) + (indium-tin oxide, 15%) + (Ni flakes, 10%)	36	Ag painted
3. (Polyether-ether-ketone, 75%) + (graphite, 15%) + (polycarbonate, 10%)	28	Cu plated
4. (Polyether-ether-ketone, 75%) + (graphite, 15%) + (Ni flake, 10%)	25	Cu plated

Other shielding composites of filler-added resins: Polymeric materials with a variety of conducting fillers such as indium-tin oxide (ITO), nickel-plated graphite, aluminum flakes, iron oxide powder, graphite fibers, etc. have been studied as shielding materials and Table 21.8 illustrates some of the pertinent results on the shielding effectiveness.

Carbon-filled epoxy resin shielding composites: Epoxies blended with carbon particulates (either in powder or in fiber form) constitute simple and cost-effective shielding composites. These composite materials can also be coated with silver or nickel paints to improve the shielding effectiveness. Measured data on a typical composite (as per MIL-STD-285 are shown in Figure 21.14).

21.17 Intercalated Graphite Fiber Composites

Carbon/graphite fiber composites have been successful structural materials in aircraft and spacecraft due to their low-density and high strength considerations. However, conventional carbon fiber/epoxy composites do not have sufficient electrical conductivity to offer adequate shielding performance. Therefore, such composites are made with *intercalated* graphite fibers.

Intercalation is the process of introducing guest atoms or molecules between the graphene layers of graphite. The guest species can contribute carriers (either electrons or holes) to the graphite lattice and thus increase its conductivity significantly without seriously degrading its physical/mecahnical properties. Although most intercalation compounds are usable at the temperatures needed to cure epoxies, the residual intercalation compounds which use bromine as the guest molecule have been shown to be quite stable. Lamina composites fabricated using bromine intercalated fiber show enhanced conductivity and improved shielding effectiveness. The far-field and near-field shielding effectiveness of several grades of graphite fiber/epoxy composites compared to those of metals are depicted in Figures (21.15 and 21.16) as functions of frequency [12].

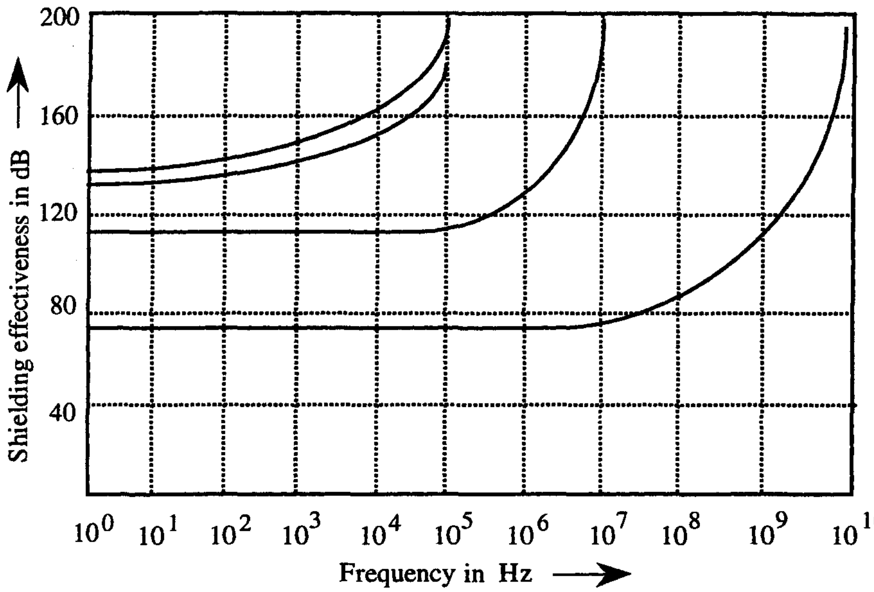

Figure 21.15 Far-field shielding effectiveness of intercalated graphite fiber composite shields *versus* frequency.
(a) PAN-based carbon fiber/epoxy; (b) P-100+Br/epoxy and intercalated pitch-based graphite fiber/epoxy; (c) Aluminum shield; (d) Copper shield.

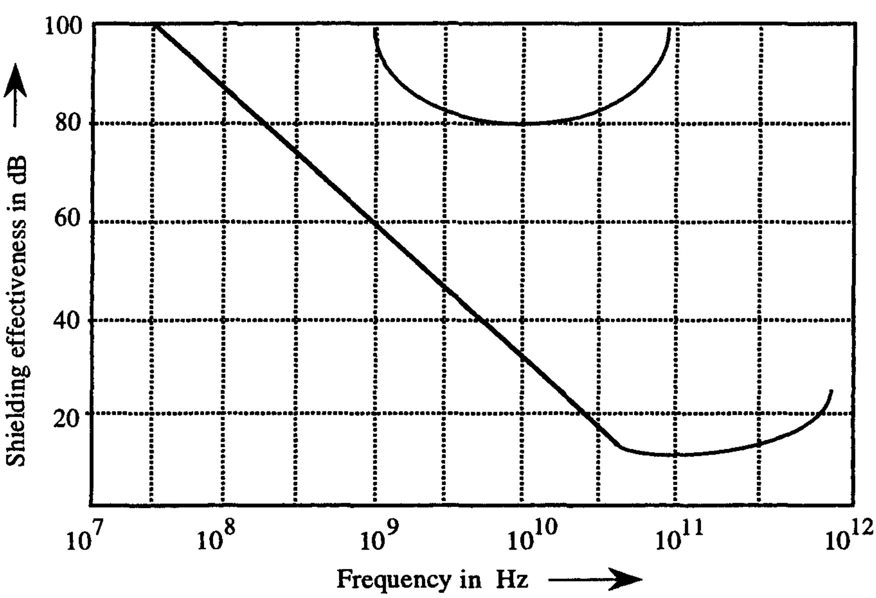

Figure 21.16 Near-field shielding effectiveness of intercalated graphite fiber composite shields *versus* frequency.
(a) p-100-Br_2; (b) PAN.

Studies indicate that far-field attenuation of EM fields of at least 70 dB in 1–12 GHz range is offered by p-100 + Br/epoxy composites. Adoption of this technology is, however, likely to be cost-critical, but with lower grade pitch fibers such as p-55 may permit synthesizing cheaper composites. Use of intercalated p-55 in a test composite has shown to yield far-field attenuation of about 55 dB over the frequency range 30-1000 MHz.

21.18 Shielding Composites with Conducting Flakes

As discussed in Chapter 6, addition of flaky or disk-like conductors to a nonconducting host medium substantially alters the effective conductivity of the blend even at low volume fractions of the inclusions. Flakes in general are superior conductivity modifiers in comparison with conductive carbon black or graphite powder or doping agents being added to plastic materials.

Typical conducting flakes are of aluminum which in a injection resin molding system can offer a resistivity variation with its percentage weight in the blend as presented in Table 21.9.

The shielding effectiveness *(SE) versus* bulk resistivity (ρ_B) of the conductive plastic shield made by a combination of aluminum flakes (such as Transmet™) plus a thermoset plastic is illustrated in Figure 21.17.

Conducting fiber-added plastics as shielding composites: Another effective method of realizing conducting plastics is to blend metal fiber with polymeric hosts. Either pure metallic or metallized glass fiber can be used for this purpose, in the form of chopped fibers.

Typical electrical resistivites of the metal fiber-filled composites fall in the range 10^{-2} to 1 ohm-cm with a shielding attenuation well over 40 dB up to 100 MHz and about 25 dB at higher frequencies.

Table 21.9 Resistivity of the Aluminum Flake-Added Plastics

Weight % of Aluminum Flakes	Resistivity (ohm-cm)
5	10^{15}
10	10^{13}
15	10^{6}
20	10^{2}
25	10^{0}
30	10^{-1}
35	10^{-2}
45	10^{-3}

Major variables crucial to achieve success in molded metal fiber-filled composites and to realize a good electrical conductivity, effective shielding performance, acceptable physical performance, and aesthetic appearance are:

- Fiber concentration
- Fiber aspect ratio and orientation
- Uniformity of dispersion

The concentration of fiber inclusions decides the probability of the fibers making effective contact with each other in establishing electrical connectivity. The aspect ratio decides the effective conductivity and permittivity properties as discussed in Chapter 6. Fiber orientation has a significant impact on shielding effectiveness. The response of the shield to EM wave of certain polarization depends on the anisotropic orientation of the fiber relative to the polarization direction of the EM energy.

Uniformity of fiber dispersion is also important to maintain a uniform shielding effectiveness over the entire area of surface exposed to EM radiation. Clumping is undesirable and fiber dispersion is controlled by the molding process involved.

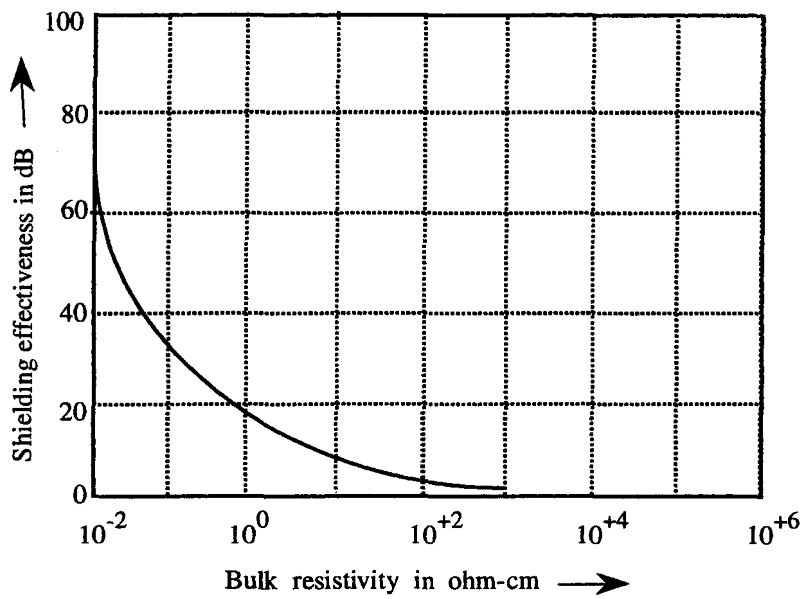

Figure 21.17 Shielding effectiveness *versus* ρ_B (frequency 0.1 to 1000 MHz) of aluminum flake-inclused thermoset plastic shields.

Conducting-filler added ceramic shielding materials: In this category, the host material chosen is one of the following ceramic materials instead of the polymeric matrix base:

- Heat resistant ceramics such as barium titanate and titanium dioxide [18]
- Portland cement concrete
- Ferrites

Heat-resistant ceramic based shielding composites: A class of composite materials constituted by conducting inclusions dispersed in a host ceramic medium (such as TiO_2) is a potential EMI shielding medium. In the existing art of electromagnetic shielding with composite materials as mentioned earlier the shielding material is constituted invariably by a polymeric base, dispersed with conducting inclusions [10] or with laminates of fibers of conducting materials (such as boron tungstate, graphite, etc.) stacked as multilayer layups in an epoxy matrix [10]. As discussed in the previous sections, the performance of such materials in shielding the radio frequency interference effectively has been adequately elucidated over a limited range of frequencies and/or at room temperature conditions. However, in view of the state-of-the-art requirements in military and space applications involving high-temperature ambients as well as interference arising from signals covering a broad spectrum of frequencies, there has been a quest for newer materials with higher temperature withstandability and better broadband EMI shielding capabilities.

Essentially, such EMI shields can be constituted by a ceramic base (of titanium-dioxide) with two categories of conducting inclusions, namely: (i) Spiky copper fibers and (ii) flaky (disk-like) aluminum foils. The TiO_2 base provides a ceramic receptacle for the composite with a high-temperature withstandibility and the conducting particles are chosen to offer different geometrical aspects and hence a controllable effective conductivity of the composite. The spiky, fibrous inclusions have a geometrical aspect ratio >>1; and the flaking inclusions have an aspect ratio <<1. The geometrical aspect together with the volume fraction and the conductivity of the inclusions (as well as the permittivity of the host medium) decide the attenuation (shielding effectiveness) offered by the composite material as a function of the frequency of the electromagnetic wave.

The host medium (TiO_2) is a dielectric (of relative permittivity ε_r) dispersed with conducting inclusions of (conductivity σ_m in siemen/meter). These inclusions are shaped either as spiky rods with an aspect ratio $a/b >> 1$ or flaky disks with $a/b << 1$. For these types of two-phase mixture system(s), the effective permittivity and conductivity can be deduced by the considerations described in Chapter 6.

Effective (relative) permittivity of the mixture:

$$\varepsilon_{eff} = (\varepsilon' - j\varepsilon'') \tag{21.16}$$

where

$$\varepsilon' = \{\varepsilon_r/[1 + (\varepsilon_r - 1)^{2u}]\}\ \{[(\sigma_m/\omega\varepsilon_o)^{\theta}(\varepsilon_r - 1)^{1-\theta} cos(n\theta/2)]^{2u} + 1\}$$

with $\varepsilon_o = (1/36\pi) \times 10^{-9}$ F/m being the permittivity of free space. Further, θ refers to the volume fraction of the inclusions.

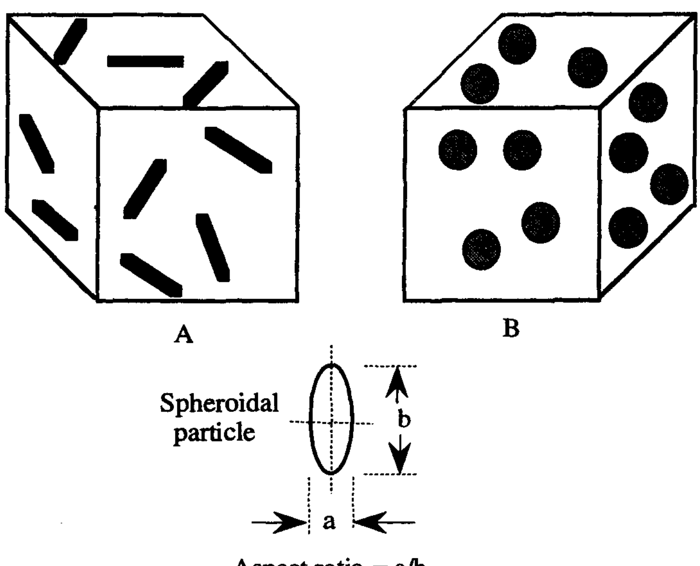

Figure 21.18 Random nonspherical conducting particulates included dielectrics. (A) Needle-like conducting inclusions. (B) Disk-like conducting inclusions.

Effective conductivity of the mixture:

$$\sigma_{eff} = \sigma_m \{[\omega\varepsilon_o(\varepsilon_2 - 1)/\sigma_m]^{(1-\theta)} sin(n\theta/2)\}^{2u} \tag{21.17}$$

and

$$\varepsilon'' = \sigma_{eff}/\omega\varepsilon_o\varepsilon_{eff}$$

In the above equations (Equations 21.16 and 21.17), u refers to an order parameter specifying the anisotropic state of randomness of the particulate dispersion [18]. It is equal to 1/3; and $\omega = 2\pi \times$ frequency of operation.

In terms of these effective mixture parameters, the transmission loss (attenuation) depicting the shielding effectiveness of the test medium of thickness τ (in meters) is given by:

$$\alpha\,(in\ dB) = 20log[(\pi/\mu_o\sigma_{eff})^{1/2}] + 20log[\tau(\varepsilon_{eff}+1)] - 20log[2\varepsilon_{eff}] \qquad (21.18)$$

where $4\pi \times 10^{-7}$ henry/meter, being the absolute permeability of free space.

For the test samples using the material constituents of Figure 21.18, the shielding effectiveness measured is shown in Figure 21.19. Depending on the conducting particulate loading, the shielding effectiveness of the composite(s) falls in the range 5-20 dB over the frequency spectrum 500 MHz to 1 GHz. The mixture formulas (Equation 21.16 and 21.17) enable the elucidation of the effective conductivity and permittivity of the composite(s); and hence the theoretical evaluation of the shielding effectiveness based on Schelkunoff's theory is made feasible *via* Equation 21.18. Sample theoretical results are also furnished in Figure 21.19.

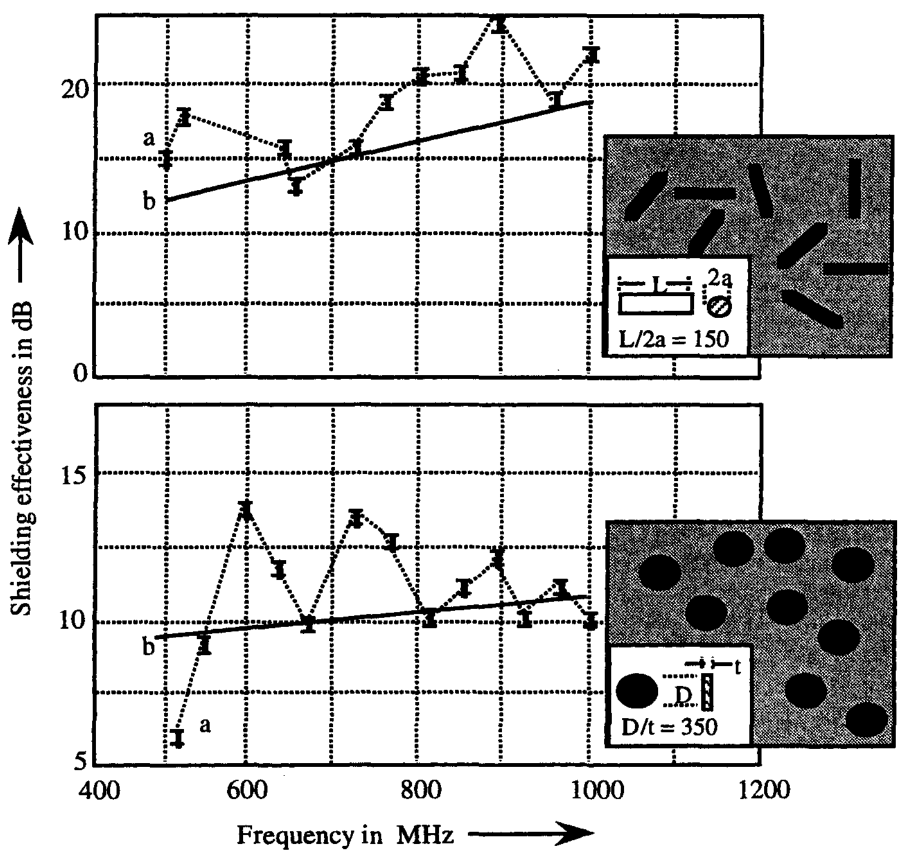

Figure 21.19 Shielding effectiveness *versus* frequency of needle-like or disk-like conducting particulates included dielectric composite shields.

Portland-cement concrete with metallic inclusions as an EMI shielding material: Concrete/polymer concrete-based hybrid composites as EMI shielding materials have been studied [15]. Being a low-cost construction material Portland cement concrete/polymer concrete mixed with chopped electrically conductive fibers has proved to be economical and viable EMI shielding composites with easily and rapidly castable characteristics endowed with unique properties to survive harsh environments over a long period of time.

Electrical conductivity of hydraulic cements in general depend on moisture content and upon over-drying. Impregnating with subsequent polymerization, the cement-based concretes can be regarded as good insulators with a dielectric constant falling in the range of 4 to 5. Apart from hydraulic cements, the so-called polymer concretes constituted of a carefully graded mixture of coarse aggregates and fine fillers bonded together by means of an ambient temperature cured, low-viscosity organic resin system (of 6 to 15% by weight) are more popular candidates for blending with metallic inclusions and culminating as a shielding composite. These polymer concretes have better mechanical properties than hydraulic cement concretes; and they have inherently high corrosion-resistant, low or *nil* capillary porosity with low moisture permeability, rapid processing and strength gain (facilitating fast demolding), and attractive cost-effectiveness. These concretes can be blended with chopped metallic fibers such as stainless steel, nickel-coated carbon, PAN carbon or with aluminum flakes. Conducting particulates such as carbon black can also be used as a filling agent. The mixing can be done with conventional vibratory-type mixers.

Ferrite-based shielding composites: Ferrites being essentially ceramics but with a high magnetic permeability can be blended as fillers with a polymeric host plus other conducting alloys having high magnetic permeability (in disk or lamellar form) to constitute a magnetic shielding medium. Such multiconstitutent shielding materials have not been studied thoroughly though, yet some theoretical considerations pertinent to the evaluation of the effective permeability of multiphase materials are available in the literature [22]. Magnetic ore falling in the category of ferrite classes such as franklinite, chromite, and ilmenite can constitute a highly desirable filler in realizing ferrite-based shielding composites.

21.19 Multilayered Shielding Composites

Multilayered structures have proved to be effective EMI shields both for high frequency (RFI) shielding purposes as well as for low frequency magnetic shielding [16].

Advanced composite shielding materials have become increasingly important in recent years because of their significant strength and relatively light weight at the same time providing adequate EMI shielding. Typically, such materials are laminates or multilayer "layups" of individual laminae. A single lamina consists of a planar array of fibers (such as graphite, boron/boron tungstate, etc.) in an epoxy matrix together with appropriate interlayer embedding of conducting (metallic or alloy) screens/wire-mesh or interlaid fiber webs or woven fiber yarns. The arrangement of the layers can be varied to suit the strength requirement as well as to control the polarization dependability of the shielding effectiveness of the laminate in given directions. Usually 0^o–90^o or 0^o–45^o–90^o layups are recommended.

The effective permittivity, permeability, and conductivity of the multilayered shields decide their shielding performance. The geometry of the multilayer layup, the electrical characteristics and volume/area fractions of individual layers cohesively control the effective electrical parameters of the composite which are also frequency dependent and largely anisotropic in nature. Therefore, modeling multilayered composites has been sparsely perfected and in many situations designing such structures is based on empirical algorithms formulated *via* experimental data. The following are examples of typical multilayered structures studied as EMI shields.

Multilayered metallic sheets (Cu + ferromagnetic alloy + Cu) sandwiched configuration: This combination has been observed to yield improvement in shielding effectiveness in comparison to using the ferromagnetic alloy alone as illustrated in Figure 21.20.

The sandwich structure has the following functional characteristics: (1) The magnetic layers provide some extent of shielding against static and/or quasistatic magnetic fields. (2) Eddy current induced in the copper sheets cancels the effects of high frequency interference. Thus, the combination of magnetic and diamagnetic materials facilitate magnetic reflection at low frequencies and conductive reflection at high frequencies.

A judicial choice of steel or a magnetic alloy and aluminum can also be considered for the sandwich structures in RF shielding systems since aluminum foil can yield RF shielding effectiveness of a medium 50 dB level (as required by NSA-73-2A specifications).

Fiber-embedded epoxy lamina plus wire-mesh layered composites: These structures can be required as alternative layups of lossy dielectrics (constituted by fiber-embedded epoxy layer and conducting screens (wire-mesh structures). EM penetration through this composite can be regarded as due to the low-pass behavior of the lossy dielectric and the high-pass behavior of the wire-mesh screens. Typical fiber-embedded layers used in advanced composites for aircraft structures are made of boron/boron tungstate in epoxy matrix or graphite (in the form of a pyrolyzed organic fiber such as polyacrylonitrile)-embedded epoxy base; and screens with 20 × 20 to 200 × 200 per inch mesh sizes made of stainless steel or aluminum have been used in the layups.

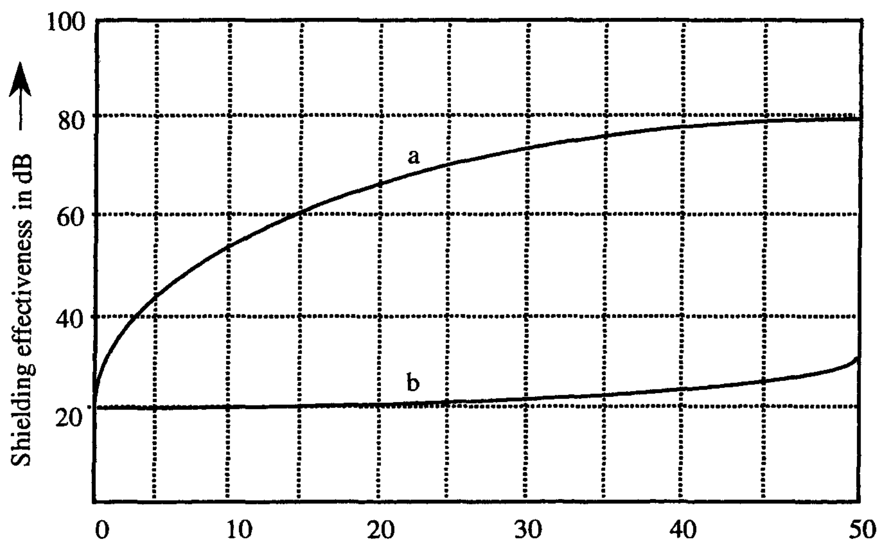

Figure 21.20 Shielding effectiveness *versus* frequency: Magnetic alloy shield sandwiched between copper sheets:
(a) Cu + 42% Ni + Cu (3.5 mil + 5 mil + 3.5 mil); (b) 42% Ni alloy (5 mil).

The shielding effectiveness of these composites has been assessed by modeling the structure as follows: The fiber-included epoxy matrix is regarded as a lossy dielectric panel and the wire-mesh screen is considered as a perforated screen. At low frequencies, an equivalent (conductivity × thickness) parameter is designated as the descriptor of the shielding performance and at higher frequencies, the mesh size becomes a critical parameter. These composites have also been analyzed for their EMP (electromagnetic pulse) shielding performance. The time-domain field transmitted through the screened composite is found to contain a contribution proportional to the derivative of the input pulse waveform as a result of the inductive component of the screen impedance. For standard EMP incident fields, the high-pass or differentiating nature of this shield leads to an early-time response (dominated by the derivative term), while the later-time response is influenced most strongly by the wire conductivity of the mesh.

The shielding performance of graphite-epoxy fiber reinforced composite (as used in modern aircraft systems) without wire-mesh layer is depicted in Figure 21.21. The shielding effectiveness in Figure 21.21 refers to the magnetic field attenuation because magnetic field penetration is much more serious in certain EMI environments.

21.20 EMI Shielding with Chiralic Media

Chiral materials are represented by the cross-coupled constitutive relations $\boldsymbol{D} = \varepsilon \boldsymbol{E} + j\xi_c \boldsymbol{B}$ and $\boldsymbol{H} = \boldsymbol{B}/\mu + j\xi_c \boldsymbol{E}$ where $\boldsymbol{D}$, $\boldsymbol{E}$, $\boldsymbol{B}$, and $\boldsymbol{H}$ are the time-harmonic electromagnetic vectors representing electric displacement, electric field intensity, magnetic flux density, and magnetic field intensity, respectively, and ξ_c is the chiral cross-coupling (admittance) coefficient. (More details on chiralic materials are presented in Chapter 25.)

Inasmuch as shielding performance depends on the reflection coefficient of the shield, the conventional approach to control the shielding effectiveness is to modify the geometry and the electrical parameters (ε, μ, σ) of the shielding medium. Relevant to this strategy, the chiralic medium offers an additional parameter ξ_c for the synthesis of a layered structure (constituting a *Salisbury shield*) with a desired shielding effectiveness. A typical example of this type of shielding is the Chiroshield™ due to Jaggard et al. as described in Chapter 25.

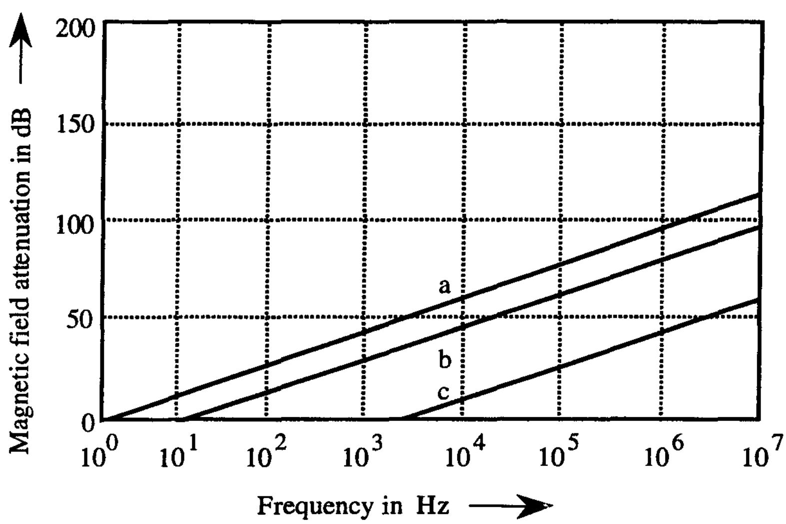

Figure 21.21 Shielding performance of graphite/epoxy composite relative to titanium and aluminum panels with number of layer = N, thickness of the layer = d, and curvature of the N^{th} layer is R_N.
(a) d = 0.5 mm; N = 4, graphite/epoxy; (b) d = 2 mm; N = 1, Ti; (c) d = 2 mm; N = 1, Al.

21.21 EMI Shielding *via* Active Surfaces: Concept of Smart Shielding

A class of composite materials constitutes the so-called active electromagnetic media whose electromagnetic characteristics can be altered with external stimuli. For example, a fast-ion conducting composite (see Chapter 16) is pyrosensitive so that upon thermal stimulation, it changes to a good conductor from being a dielectric medium. Appropriate incorporation of this material in a multilayered medium could facilitate realizing an active shield (with controllable performance through external stimulation). Suitable adaptive feedback can render such a medium as a smart shield changing intelligently its reflective/absorption of EM energy as and when required, posing thereby smart shielding characteristics. (See Chapter 23.)

21.22 Magnetic Shielding Materials

Magnetic field refers to the force-field setup by a current carrying solenoidal (loop) conductor source. Considering the ratio of the associated total electric field to the total magnetic field at a given point, it refers to the wave impedance which varies as a function of r/λ from the source where r is the physical distance between the source and the point of observation and λ is the wavelength of source excitation. Shown in Figure 21.22 is the wave impedance *versus* r/λ of a magnetic source.

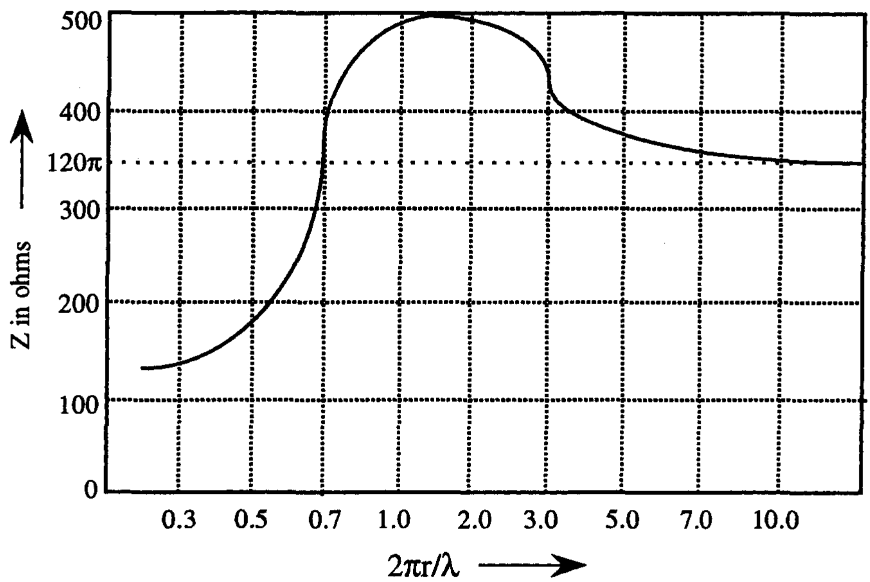

Figure 21.22 Wave impedance *versus* $2\pi r/\lambda$.

Magnetic field source exhibits low wave impedances nearby and approaches the free-space impedance (120π ohm) at large r/λ ratios.

Pertinent to this wave impedance characteristic of magnetic fields, the shielding effectiveness *(SE)* offered by a barrier of thickness d at a distance x_0 and having a magnetic relative permeability μ_r is approximately given by:

$$(SE)_{dB} = 20 \log_{10}(1 + \mu_r d/x_0) \tag{21.19}$$

A more rigorous study which accounts for nonlinear and magnetic separation behavior of the barrier (shielding) medium (of thickness d and located at x_0 from the source) yields the following expression for the shielding effectiveness:

$$(SE)_{dB} = -20 \log_{10}\{[4\mu_r/(\mu_r + 1)^2] \sum_{n=0}^{\infty} [(\mu_r - 1)/(\mu_r + 1)]^2 / [x + x_0/(x + x_0 + 2nd)]\} \tag{21.20}$$

where x is the point of observation.

From the above formulations, it is obvious that the relative permeability and the thickness of the material dictate primarily the magnetic shielding performance. For effective shielding, ferromagnetic materials with $\mu_r >> 1$ are the right choice. However, materials with very high permeabilites tend to saturate at lower flux densities than materials with lower permeabilities.

When a material saturates, its relative permeability approaches unity. Therefore, controlling the magnetic flux level is essential for effective magnetic shielding performance. This can be done by proper choice of the thickness of the shield or by a multilayer design such that the layer nearer the source should have a very high saturation level. Therefore aluminum foil is an appropriate choice as the source-side layer of a magnetic shield design.

Typical ferromagnetic materials and the accompanying shielding effectiveness are presented in Table 21.10 for $x_o = 1$ meter and $x = d$.

Table 21.10 Shielding Effectiveness of Typical Ferromagnetic Materials

Material	Relative Permeability	$(SE)_{dB}$	Remarks/Availability
Transformer core (steel) 0.01 in. lamination	15,000	6.54	–
Mild steel (2% carbon) 0.028 in. shim	2,000	3.59	–
Conetic AA™ 0.01 in. foil	30,000	9.28	Magnetic Shield Corp.
Conetic AA™ 0.006 in. foil	30,000	7.21	Magnetic Shield Corp.

Note: See Figure 21.23: $x = d$; $x_0 = 1$ meter.

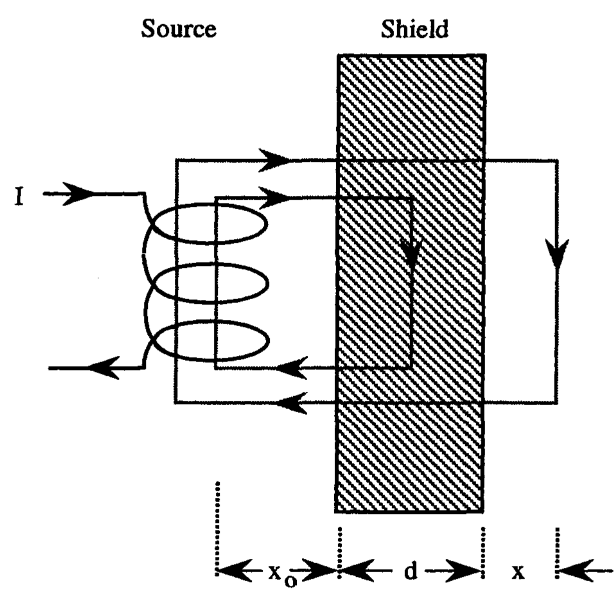

Figure 21.23 Relative dispositions of the magnetic field source with respect to the magnetic shield.

Accurate prediction of magnetic field shielding effectiveness is often hampered by the fact that the permeability of ferromagnetic materials varies nonlinearly by more than an order of magnitude as a function of the induction. For this reason, large errors are encountered in predicting the SE values unless the magnetic state inside the magnetic material is known accurately.

In designing a magnetic shield, the cost of high permeability material is often overwhelming. Thus the amount of ferromagnetic material should be minimized *via* optimum configurations.

In summary, magnetic shield design is decided by :

- High permeability characteristics
- Nonlinear variation of μ_r as a function of magnetic induction
- Saturation behavior of high permeability materials at low magnetic induction
- High cost of the magnetic materials of high permeability
- Geometry of the shield

21.23 Composite Magnetic Shields

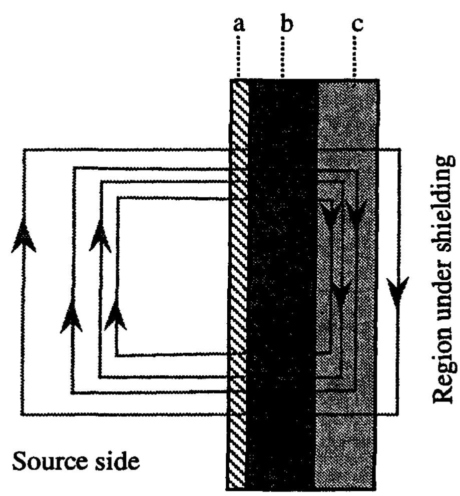

Figure 21.24 Multilayered magnetic shield.
(a) Diamagnetic (copper) or paramagnetic (aluminum) layer. (b) Low permeability steel.
(c) High permeability Ni alloy or ferrite.

The design optimization warranted to meet the above considerations has led to the development of three classes of composite magnetic shielding structures. They are:

- Multilayered metallic/alloy sheets and/or ferrite slabs
- Multiconstituent (in sheet from or otherwise) medium
- Actively compensated medium

Multilayered sheet structure: Instead of a single sheet of ferromagnetic material, if multilayers of metals/alloys/ferrites are used such that the sheet nearest to the source has the lowest permeability, the effects of saturation and nonlinearity can be reduced.

Aluminum and copper having paramagnetic and diamagnetic properties, respectively, can be the surface layer of the shield on the source side. These high conductivity materials induce eddy currents and offer a shielding barrier. Also, they provide a graded flux permeation across the multilayered structure (Figure 21.24) reducing the saturation of the high permeability inner layers.

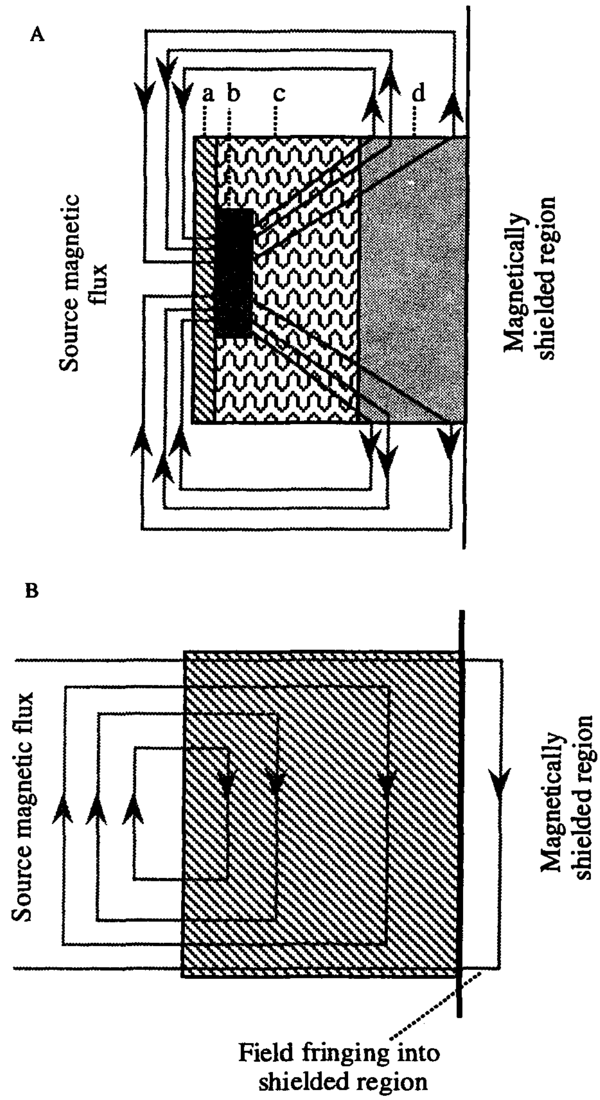

Figure 21.25 Panel-type composite, multilayered magnetic shield.
A: Composite shield; B: Convention monolithic shield.
(a) Aluminum foil; (b) High-permeability material strip; (c) Steel wool plus epoxy and ferrite oxide mixture; (d) Medium permeability steel.

Multiconstituent composite shields: Multilayered, thin-slab (flat), composite structures useful as panel-type magnetic shields are illustrated in Figures 21.25 and 21.26. The basic concept of a multilayered structure is illustrated in Figure 21.25 and 21.26. The functional aspects of each layer are as follows:

(1) **Aluminum foil on the source side**: The underlying principles of magnetic shielding indicate that the mechanism of shielding is twofold, namely, reflection loss and absorption loss, as described earlier. The reflection loss can be enhanced by providing a high conducting surface (regardless of permeability), such as aluminum (which is a high conducting paramagnetic material) as Layer 'a'.

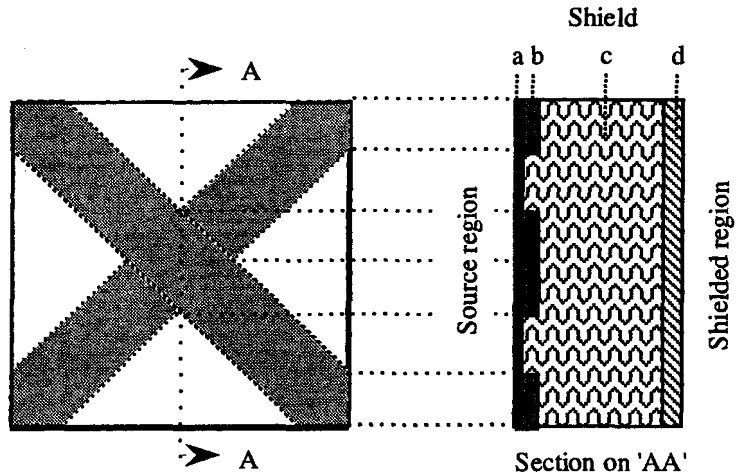

Figure 21.26 Structure of a panel-type composite magnetic shield.
(a) Aluminum foil; (b) High permeability material strips; (c) Steel wool blended with epoxy and ferric oxide; (d) Medium permeability steel.

(b) Layer 'b' is a composite medium in which two diagonal strips of high-permeability material of definite thickness (for example, 4 to 10 mil) and width are kept submerged in a lossy magnetic material composed of steel wool and a conducting polymer or epoxy (Region c).

The high-permeability metal collimates (collects) the incident magnetic field flux on the aluminum foil surface. The collected flux is "diffused" through the composite steel wool wherein magnetic absorption takes place. Different grades of this structure can be obtained by varying the width and the thickness of the diagonal high-permeability strips since the largest percentage of the cost is contributed by this layer.

(c) Layer 'd' is a medium-permeability iron/steel shim/plate (for example, of thickness 25 mil) which provides a solenoidal path to the collected flux and prevents its diffusion on the other side of the shield. This layer also serves as the base plate for the other layers. The standard size for this base plate could be 12×12 inches which would be a convenient unit size for paneling/overlay construction such as on vaults, cabinets, room walls (partial or complete), etc.

Wrap-around shielding jacket for iron/steel or PVC pipes: It is similar to flat-type structure except that this is a wrap-around jacket structure which could be exclusively designed for pipe shielding. It is compatible with heat dissipation problems associated with iron pipes enclosing high ampacity conductors. The relevant structure is depicted in Figure 21.27. It may be noted that the high-permeability material is a single peripheral strip of definite width per unit jacket length. In practice, these units can be periodically repeated as *wrap-arounds* along the pipe length.

Both structures as described above can be prefabricated in commercial applications. The user can apply them as wrap-arounds on the surface to be shielded. They are thus useful in shielding iron pipe or PVC-pipe encased transmission lines.

Though the cross-sectional/geometrical aspects of the shields for the iron and PVC pipes are identical, the basic differences are as follows:

- For the shield intended for iron pipes, the structure can have a thin base of mild steel shim/plate, just to comply with the requirements as a base support.
- On the other hand, for the shield intended for PVC pipes, this base mild steel shim/plate should have a larger thickness so as to provide a return permeable path for the flux lines

illustrated in Figure 21.27. (In the iron pipe case, the pipe itself will facilitate this requirement.)

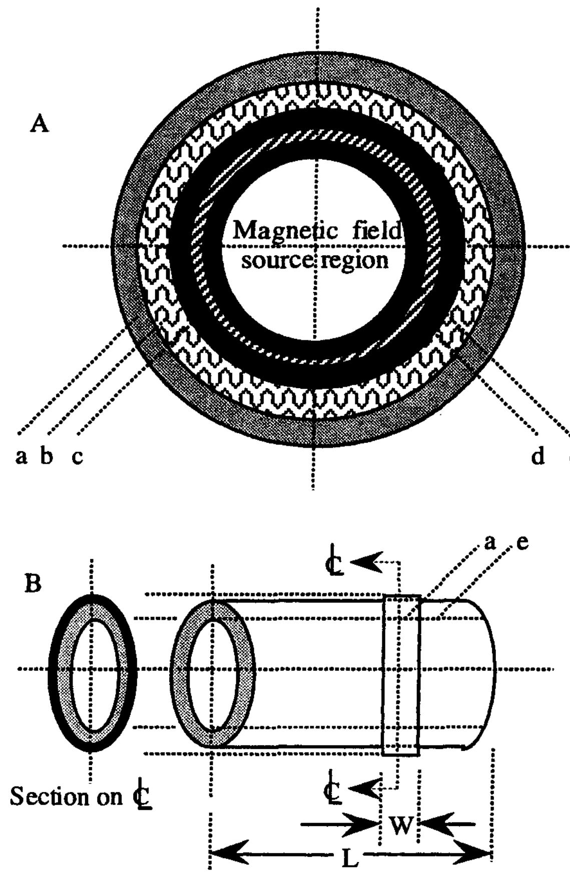

Figure 21.27 Wrap-around composite magnetic shielding jacket compatible for shielding pipes.
(a) Medium permeability steel shine; (b) Steel wool plus epoxy and ferric oxide; (c) High permeability material; (d) Aluminum foil; (e) Steel or PVC pipe.

The shielding effectiveness of a simple monolithic material as described earlier is specified as the sum of absorption, reflection, and multiple reflection losses at the shield-to-air interfaces. The composite magnetic shielding structures being layers of different materials the shielding effectiveness can be predicted as follows:

(1) If the arrangement of the different layers of the composite shield is perpendicular to the direction of an unidirectional incident magnetic field, the shielding effectiveness *(SE)* can be written as :

$$SE_U = SE_1\,\theta_1 + SE_2\,\theta_2 + \ldots + SE_n\,\theta_n \tag{21.21}$$

where SE_1, SE_2, ..., SE_n are the individual shielding effectiveness (as ratio) of the different layers and θ_1, θ_2, ..., θ_n are their respective area fractions. The method of determining the values of θ_1, θ_2, ..., θ_n depends on the specific shielding structure and is graphically represented in Figure 21.28. Since in the composite shield designated as structure I, the shielding is essentially provided by the plate of iron/steel with high-permeability strips placed on it, the *SE* is predicted by:

$$SE_U = (SE_{iron}\ \theta_1) + (SE\ \theta) \tag{21.22}$$

where θ_1 = area fraction of iron = 1 (since it is the base plate) and θ = area fraction of high-permeability strip.

(2) Similarly, when the arrangement of the layers is parallel to the direction of the incident field, the corresponding *SE* would be given by:

$$SE_L = (1/\theta_1/SE_1 + \theta_2/SE_2 + \ldots + \theta_n/SE_n) \tag{21.23}$$

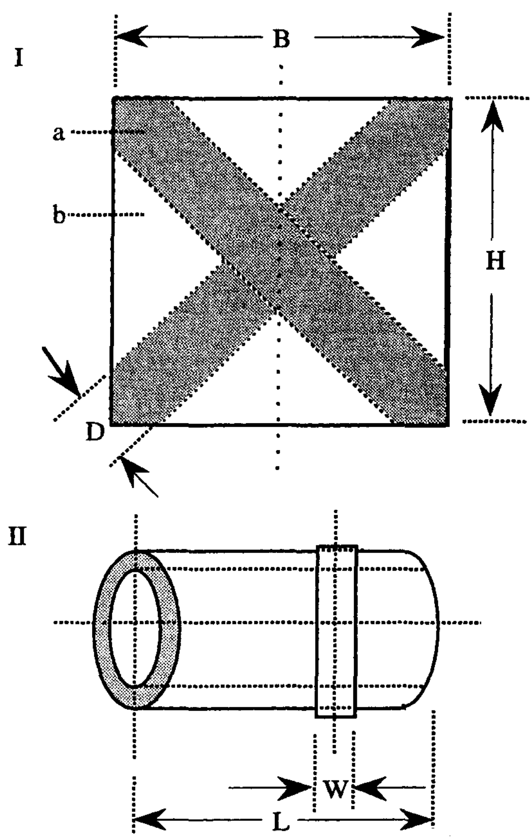

Figure 21.28 Area fraction calculations for the theoretical evaluation of magnetic shield effectiveness.
(a) High-permeability strip.
(b) Iron/steel base. If $\theta = 1$ is the area of the base plate, $\theta_1 = [2D(H^2 + B^2)^{1/2}/HB]$ is the area fraction of the high permeability material used in the flat shielding structure I. $\theta_1 = W/L$ in the wrap-around shielding structure II.

(3) In the case of an unspecified (complex) field orientations (as normally encountered in practice) incident on the shield, the *SE* could be predicted by an algorithm similar to the so-called logarithmic law of mixing (similar to that of dielectric mixture theory presented in Chapter 4), namely:

$$SE_P = \theta_1 log(SE_1) + \theta_2 log(SE_2) + ... + \theta_n log(SE_n) \tag{21.24}$$

The practical value of SE_P is bounded within the two extreme limits SE_U and SE_L corresponding to the perpendicular and parallel fields designated with respect to the shield layers.

Material selection: Essentially, the composite structure intended for magnetic shielding is composed of the following generic monolithic materials:

1. Aluminum foil
2. High permeability (high-μ) strips
3. Steel wool
4. Conducting polymer or similar epoxy adhesives
5. Ferric oxide powder
6. Mild steel shim/plates

Aluminum foil: This could be an inexpensive commercial grade/recycled aluminum foil of thickness (1 to 2 mil). No specific or special requirement is needed. Basically in large-scale manufacturing, procurement of this material should be based on cost considerations alone.

High permeability strips: This is an important constituent of the design. There are several versions available in the market. Again the selection criteria are based on the relative permeability value (on the order of 30,000 or higher) and the cost of the material. The dimensions of these strips are decided by the extent of shielding performance warranted. Examples of typical high-μ materials available are:

1. Conetic-AA™ and Netic-AA™ (Magnetic Shield Corp.), (4/10 mil)
2. Hipernorm™ (Amuneal Manufacturing Corp.)

Steel wool: This material essentially diffuses the magnetic field through the shielding structure and provides a lossy eddy current medium in conjunction with the polymeric adhesive plus ferric oxide impregnated in it. It hence provides a magnetic dissipative loss to a certain extent. A typical steel wool available commercially is International Steel Wool.

Conducting polymer/epoxy resin adhesive: This is used mainly as a bonding agent. A variety of such epoxies are commercially available. For example, Master Bond and Fiber materials Inc. are commercial sources of such materials. Again, cost considerations should be the design objective.

Ferric oxide: This medium dispersed with the bonding agent would provide partial magnetic and/or paramagnetic fluency for the magnetic flux permeation. Again, this is a low cost material available in powder form (suitable for blending with adhesives).

Mild steel shims/plates: Standard commercial grade, low-cost plates of thickness (20 to 25 mil) can be used for panel structures. For the wrap-around structures, flexible shims (4 to 10 mil) available in the market can be used.

Shielding performance: For a test structure of Figure 21.27, keeping all the dimensions as constants, the width of the high-permeability material when varied and the corresponding values of shielding effectiveness measured in each case, are presented in Figures 21.29 and 21.30 corresponding to iron pipe and PVC pipe shielding, respectively. The relative cost in each case (as a function of the strip width) is also depicted in Figures 21.29 and 21.30. In Figures 21.29 and 21.30, the test structure with a given strip width is designated as a specific grade on the basis of its relative cost factor. The theoretical estimation of the shielding effectiveness (as per Equation 21.22) is also indicated.

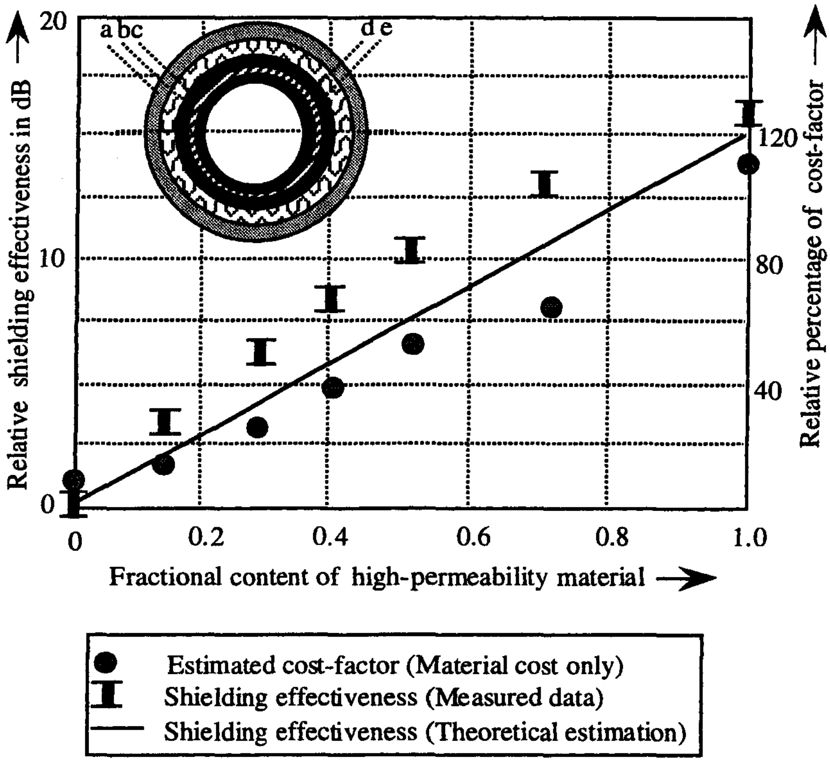

Figure 21.29 Shielding performance of a wrap-around jacket type magnetic shield on a iron pipe.
(a) Steel shim (6mm); (b) Steel wool + resin; (c) High permeability (Conetic AA™) strip (10mil); (d) Aluminum foil. (e) Iron pipe (40 mil).

These results show that a cost-effective shielding performance can be realized by controlling the width of the high-permeability material placed on a unit length of the wrap-around jacket shield. Specifically referring to Figure 21.29, it can be observed that FE composite grades 38 and 51 provide a good cost *versus* shielding compromise while in Figure 21.30 PVC composite grade 55 performs well. The unit length of the jacket shield can be fixed by considering an achievement of say, a cost factor of 55% reduction, with a width/length (W/L) ratio of 40%*.

Panel-type shields (Figure 21.25): Figure 21.31 depicts the performance test results of the panel shields with the cost factor controlled by altering the diagonal strip width of the high-permeability material used. For each cost factor, the performance grades (*SE* value) achieved are shown. Theoretical evaluation of *SE* shown corresponds to multiaxial field component formula (Equation 21.24). It can be seen that composite such as grade 45 offers the best compromise.

* The results presented on multiconstituent composite magnetic shields are the outcome of the research pursued by the author and have not been published in open literature yet.

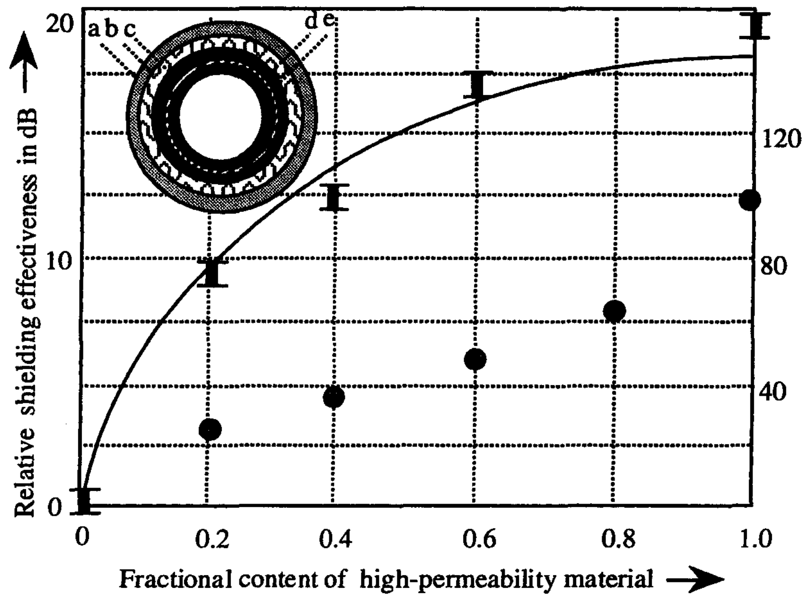

Figure 21.30 Shielding performance of a wrap-around magnetic shielding jacket for PVC pipes.
(a) Steel shim (10 mil); (b) Steel wool + resin; (c) High permeability (Conetic AA™) strip (10 mil); (d) Aluminum foil; (e) PVC tube (0.16 in. thick).

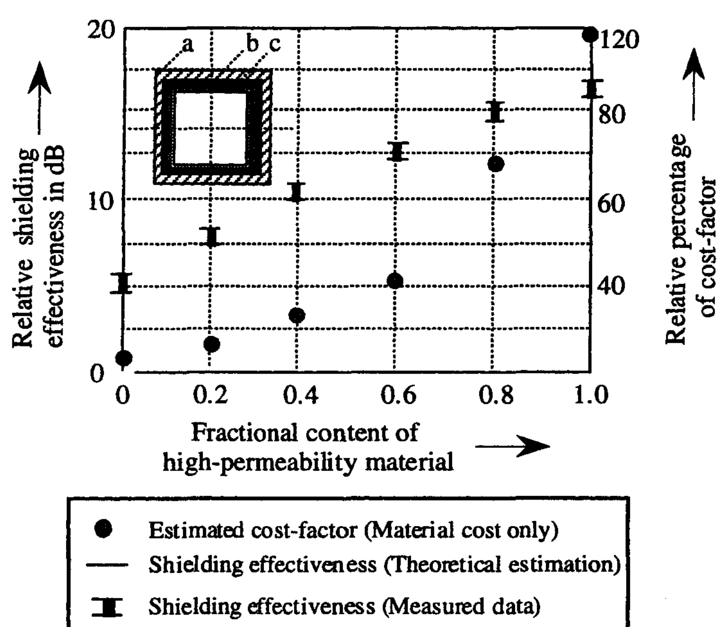

Figure 21.31 Shielding performance of panel-type shields.
(a) Steel shim 50 mil; (b) Steel wool plus resin; (c) Aluminum foil backed by high permeability (Conetic AA™) 4 mil strip.

Actively compensated magnetic shielding composites: These structures provide enhanced magnetic field shielding on the basis of *"shaking" technique* [19-21]. The technique of shaking refers to effectively increasing the permeability of a ferromagnetic material by applying a relatively strong alternating magnetic field into the material. Then the average magnetization follows an hysteresis or ideal magnetization curve, where permeability is higher. This in turn enhances shielding. The principle of shaking is illustrated in Figure 21.32. It requires shaking coils to be wound as an integral part around the shielding composite in such a manner that the generated field H_s circulates along the walls. Such active compensation against hysteresis behavior of the material would increase the effective permeability several times when biased near zero field. In case of low biasing fields, it is possible to find an optimum shaking field amplitude. The frequency of the shaking field is not, however, critical; and usually the power supply frequency (50/60 HZ) or radio frequency can be used. In designing composites which incorporate the shaking principle the following precautions should be observed:

- Shaking coil excitation should not demagnetize the shielding material
- Shaking field should not introduce interference in the region being shielded

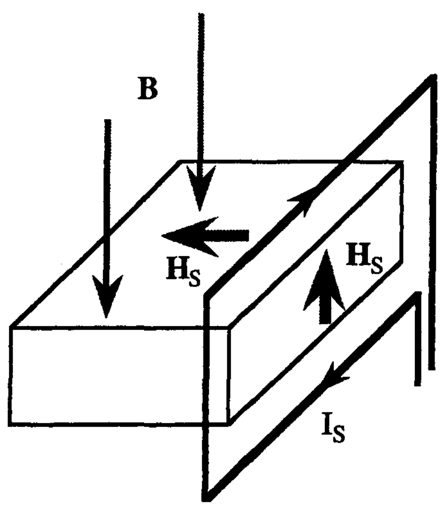

Figure 21.32 Principle of shaking.

Typical enhancement in relative permeability (μ_r) of material such as METGLAS-2705M amorphous magnetic ribbon with the application of shaking is from 3.41×10^4 to 5.27×10^5.

The principle of active shielding can be judiciously adopted to realize smart magnetic shielding inasmuch as the shaking facilitates an external mode of altering the effective permeability of the shielding composite.

21.24 Concluding Remarks

The principle of effectively using available electromagnetic materials for shielding purposes not only is governed by the electromagnetic material properties but also dictated by the geometrical outlay of the shielding media. This bifaceted requirement places stringent conditions on realizing EM shields of desirable design features, both on the choice of the materials as well as on the shielding structures. Such conditions also show new directions towards the emergence of better EM shields in the future through appropriate research.

References

[1] D. R. J. White: *A Handbook on Electromagnetic Shielding Materials and Performance.* (Don White Consultants, Inc., Gainsville, VA: 1980).