MAGNETIC SHIELDING

Shielding is the use of specific materials in the form of enclosures or barriers to reduce field levels in some region of space. In traditional usage, *magnetic shielding* refers specifically to shields made of *magnetic* materials like iron and nickel. However, this article is more general because it covers not just traditional magnetic shielding but also shielding of alternating magnetic fields with conducting materials, such as copper and aluminum. In typical applications, shielding eliminates magnetic field interference with electron microscopes, computer displays (CRTs), sensitive electronics, or other devices affected by magnetic fields.

Although shielding of electric fields is relatively effective with any conducting material, shielding of magnetic fields is more difficult, especially at extremely low frequencies (ELF). The ELF range is defined as 3 Hz to 3 kHz (1). The selection of proper shield materials, shield geometry, and shield dimensions are all important factors in achieving a specified level of magnetic field reduction. Placing a shield around a magnetic field source, as shown in Fig. 1(a), reduces the field magnitude outside the shield, and placing a shield around sensitive equipment, as shown in Fig. 1(b), reduces the field magnitude inside the shield. These two options are often called shielding the source, or shielding the subject, respectively.

Both examples in Fig. 1 illustrate closed shield geometry. In many applications, it is impractical or impossible (due to physical constraints) to use an enclosure, and open shield geometries, also called partial shields, are required. Figure 2 shows two basic partial shield geometries, a flat plate shield (a), and a channel shield (b). For these configurations, the region where shielding occurs may be limited because the shield does not fully enclose the source or the subject, resulting in *edge effects*. A discussion of the geometrical aspects of shielding is contained in (2).

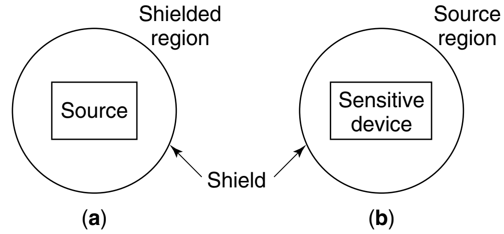


Figure 1. (a) Shielding the source. Placing a shield around a field source reduces the fields everywhere outside the shield. (b) Shielding the subject. A shield placed around a sensitive device reduces the fields from external sources.

ELF SHIELDING VERSUS HIGH-FREQUENCY SHIELDING

Electric and magnetic fields radiate away from a source at the speed of light c. In the time it takes a source alternating with frequency f to complete one full cycle, these fields have traveled a distance λ, known as the electromagnetic wavelength:

$$\lambda = c/f \tag{1}$$

At distances from a field source on the order of one wavelength and larger, the dominant parts of the electric and magnetic fields are coupled as a propagating electromagnetic wave. If a shield is placed in this region, shielding involves the interaction of electromagnetic waves with the shield materials. Any mathematical description must be based on the full set of Maxwell's equations which involves calculating both electric and magnetic fields. Shielding of electromagnetic waves is often described in terms of reflection, absorption, and transmission (3). Because wavelength decreases with increasing frequency, shielding at radio frequencies in the FM band (88 MHz to 108 MHz) and higher typically involves the interaction of electromagnetic waves with shield materials.

At distances much less than one wavelength, the nonradiating portion of the fields is much larger than the radiating portion. In this region, called the reactive near-field region, the coupling between electric and magnetic fields can be ignored, and the fields may be calculated independently. This is called a quasistatic description. At 3 kHz (the upper end of the ELF band), a wavelength in air is 100 km. Thus, for ELF field sources, one is in the reactive near-field region in all practical cases, and a full electromagnetic solution is not re-

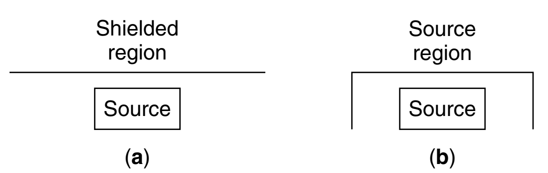


Figure 2. Examples of open shield geometries: (a) flat plate shield, (b) inverted channel shield.

quired. Instead, one need focus only on interaction of the magnetic field or the electric field with the shield material, depending on which field is being shielded. In some cases, shielding of the electric field with metallic enclosures is required. This article deals specifically with the shielding of dc and ELF magnetic fields.

MAGNETIC FIELDS

Moving electric charges, typically currents in electrical conductors, produce magnetic fields. Magnetic fields are defined by the Lorentz equation as the force acting on a test charge q, moving with velocity $\mathbf{v}$ at a point in space:

$$\mathbf{F} = q(\mathbf{v} \times \mu\mathbf{H}) \tag{2}$$

in which $\mathbf{H}$ is the magnetic field strength with units of amperes per meter and μ is the permeability of the medium. By definition of the vector cross-product, the force on a moving charge is at right angles to both the velocity vector and the magnetic field vector. Lorentz forces produce torque in generators and motors and focus electron beams in imaging devices.

Unwanted, or stray magnetic fields deflect electron beams in the same imaging devices, often causing interference problems. Sources that use, distribute, or produce alternating currents, like the 60 Hz currents in a power system, produce magnetic fields that are time-varying at the same frequency.

Magnetic fields are vector fields with magnitude and direction that vary with position relative to their sources. This spatial variation or field *structure* depends on the distribution of sources. Equal and opposite currents produce a field structure that can be visualized by plotting lines of magnetic flux, as shown in Fig. 3. The spacing between flux lines, or line density, indicates relative field magnitudes, and the tangent to any flux line represents field direction. Another way to visualize field structure is through a vector plot, shown in Fig. 4. Lengths of the arrows represent relative field magnitudes, and the arrows indicate field direction.

Shield performance, or field reduction, is measured by comparing field magnitudes before shielding with the field magnitudes after shielding. In general, field reduction varies with

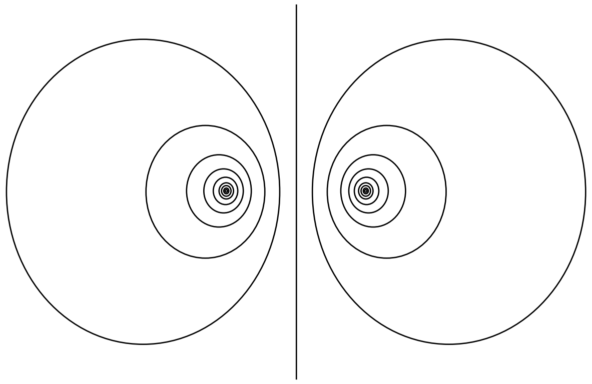


Figure 3. The lines of magnetic flux illustrate the field structure associated with one or more sources. The density of flux lines indicates the relative field strength and the tangent to any line indicates the field direction at that point.

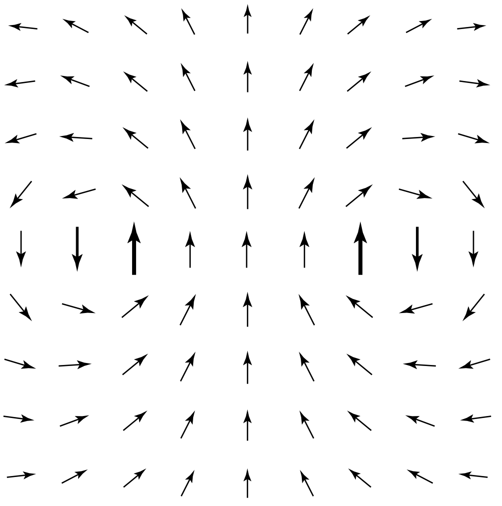


Figure 4. A vector plot graphically illustrates both field strength and direction as a function of position.

position relative to the source and shield. The shielding factor s is defined as the ratio of the shielded field magnitude $\mathbf{B}$ to the field magnitude $\mathbf{B}_0$ without the shield present at a point in space:

$$s = |\mathbf{B}|/|\mathbf{B_0}| \tag{3}$$

The shielding factor represents the fraction of the original field magnitude that remains after the shield is in place. A shielding factor of zero represents perfect shielding. A shielding factor of one represents no shielding, and shielding factors greater than one occur at locations where the field is increased by the shield. It is incorrect to define the shielding factor as the ratio of the fields on opposite sides of a shield. Shielding factor is often called shielding effectiveness, expressed in units of decibels (dB):

$$\text{s.e. (dB)} = -20\log_{10}|\mathbf{B}|/|\mathbf{B_0}| \tag{4}$$

Shielding effectiveness is sometimes alternatively defined as the inverse of the shielding factor, the ratio of unshielded to shielded fields at a point, but it is really a matter of preference. For example, a shielding effectiveness of two defined in this manner represents a twofold reduction, that is, the field is halved by the shield and the shielding factor is 0.5. When fields are time-varying, shielding is typically defined as the ratio of rms magnitudes.

SHIELDING MECHANISMS

Although shielding implies a *blocking* action, dc and ELF magnetic field shielding is more aptly described as altering or restructuring magnetic fields by the use of shielding materials. To illustrate this concept, Fig. 5(a) shows a flux plot of a uniform, horizontal, magnetic field altered (b) by the introduction of a ferromagnetic material.

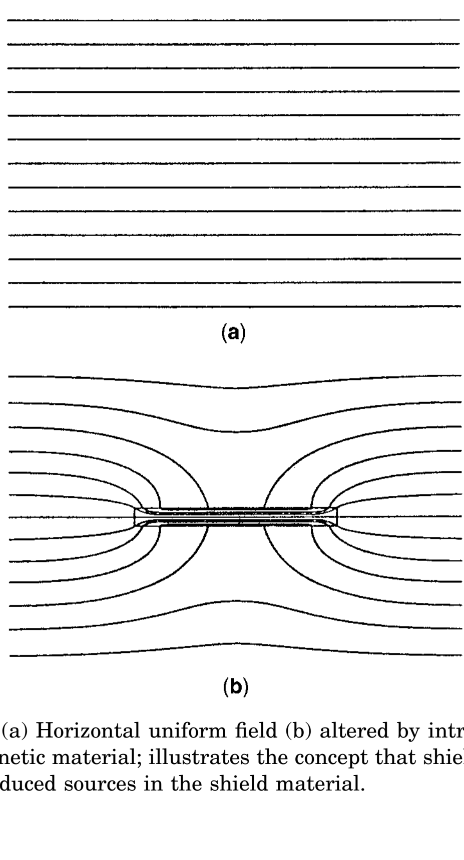
There are two basic mechanisms by which shield materials alter the spatial distribution of magnetic fields, thus providing shielding. They are the flux-shunting mechanism and the induced-current mechanism (5).

Flux Shunting

An externally applied magnetic field induces magnetization in ferromagnetic materials. (All materials have magnetic properties, but in most materials these properties are insignificant. Only ferromagnetic materials have properties that provide shielding of magnetic fields.) Magnetization is the result of electrons acting as magnetic sources at the atomic level. In most matter, these sources cancel one another, but electrons in atoms with unfilled inner shells make a net contribution, giving the atoms a magnetic moment (6). These atoms spontaneously align into groups called domains. Without an external field, domains are randomly oriented and cancel each other. When an external field is applied, the Lorentz forces align some of the domains in the same direction, and together, the domains act as a macroscopic magnetic field source. A familiar magnetic field source is a bar magnet, which exhibits permanent magnetization even without an applied field. Unlike a permanent magnet, most of the magnetization in ferromagnetic shielding materials goes away when the external field is removed.

Basic ferromagnetic elements are iron, nickel, and cobalt, and the most typical ferromagnetic shielding materials are either iron-based or nickel-based alloys (metals). Less common as shielding materials are ferrites such as iron oxide.

Induced magnetization in ferromagnetic materials acts as a secondary magnetic field source, producing fields that add vectorially to the existing fields and change the spatial distribution of magnetic fields in some region of space. The term *flux-shunting* comes from the fact that a ferromagnetic shield alters the path of flux lines so that they appear to be *shunted* through the shield and away from the shielded region, as shown by the example in Fig. 6. Flux-shunting shielding is often described in terms of magnetic circuits as providing a low-reluctance path for magnetic flux.



(a)

(b)

Figure 5. (a) Horizontal uniform field (b) altered by introduction of a ferromagnetic material; illustrates the concept that shielding is the result of induced sources in the shield material.

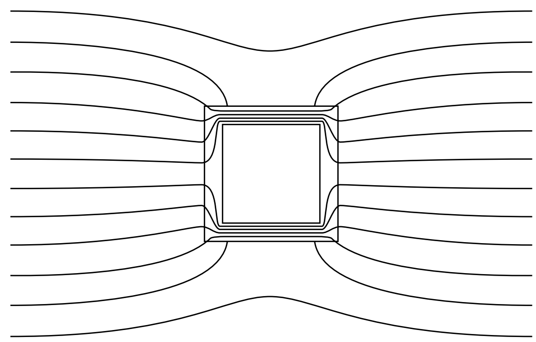


Figure 6. Example of the flux-shunting mechanism. The region inside a ferromagnetic duct is shielded from an external, horizontal magnetic field.

Permeability μ is a measure of the induced magnetization in a material. Thus, permeability is the key property for flux-shunting shielding. The constitutive law

$$\mathbf{B} = \mu \mathbf{H} \tag{5}$$

relates magnetic flux density **B** to the magnetic field strength **H**. More typically used, relative permeability is the ratio of permeability in any medium to the permeability of free space, $\mu_r = \mu/\mu_0$. Nonferrous materials have a relative permeability of one, and ferromagnetic materials have relative permeabilities much greater than one, ranging from hundreds to hundreds of thousands. In these materials, permeability is not constant but varies with the applied field **H**.

The nonlinear properties of a ferromagnetic material can be seen by plotting flux density **B**, as the applied field **H** is cycled. Figure 7 shows a generic **B–H** plot that illustrates hysteresis. When the applied field is decreased from a maximum, the flux density does not return along the same curve, and plotting one full cycle forms a hysteretic loop. A whole family of hysteretic loops exists for any ferromagnetic material as the amplitude of field strength **H** is varied. The area of a hysteretic loop represents the energy required to rotate magnetic domains through one cycle. Known as hysteretic losses, this energy is dissipated as heat in the shield material.

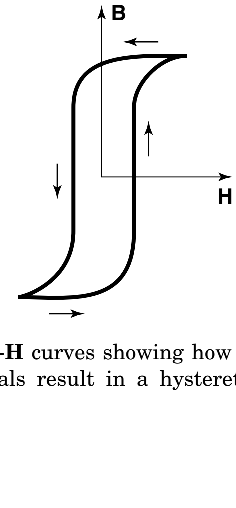


Figure 7. Typical **B–H** curves showing how nonlinear properties of ferromagnetic materials result in a hysteretic loop as the applied field **H** is cycled.

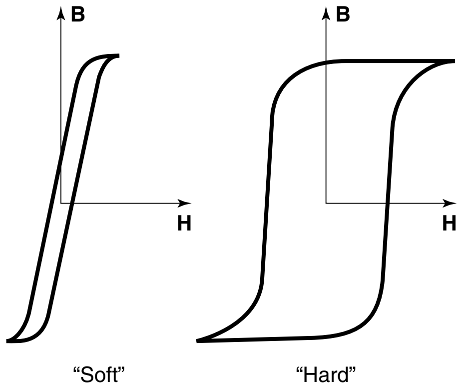


Figure 8. Examples of hysteretic loops for *soft* and *hard* ferromagnetic materials.

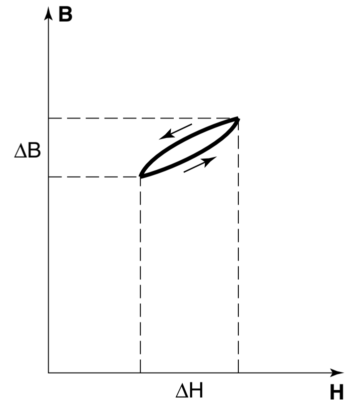


Figure 10. Hysteretic loop formed by a small ac field in the presence of a larger dc field.

For effective flux-shunting shielding, the flux density in a magnetic material should follow the applied field closely. However, it is obvious from the hysteretic loop of Fig. 7 that **B** does not track **H**. **B** lags **H**, as seen by the fact that there is a residual flux density (nonzero **B**) when **H** has returned to zero and that **B** does not return to zero until **H** increases in the opposite direction. Thus, *soft* ferromagnetic materials with narrow hysteretic loops are best for shielding, in contrast to *hard* ferromagnetic materials with wide hysteretic loops, typically used as permanent magnets and in applications such as data storage. Hysteretic curves illustrating "soft" and "hard" ferromagnetic materials are shown in Fig. 8.

At very low field levels relative permeability starts at some initial value (initial permeability) increases to a maximum as the applied field is increased, and then decreases, approaching a relative permeability of one as the material saturates, as shown in Fig. 9. Saturation occurs because there is a limit to the magnetization that can be induced in any magnetic material. In Fig. 7, the decreasing slope at the top and bottom of the curves occurs as the limit of total magnetization is reached. When a material saturates, it cannot provide additional shielding.

For shielding alternating magnetic fields via flux-shunting, the key property is ac permeability, $\Delta B/\Delta H$ through one cycle. Although Fig. 7 shows a hysteresis curve that swings from near saturation to near saturation in both directions, a hysteresis curve caused by a very small alternating field in the presence of a larger dc field might look like Fig. 10. In this case, the ac permeability is less than the dc permeability, **B**/**H**. In addition, the dc field creates a constant magnetization that affects the time-varying magnetization. Figure 11 shows how ac permeability for a small alternating field is reduced with increasing dc field. This plot, called a *butterfly* curve, is generated by measuring the ac permeability at different levels of dc field. The dc field is increased from zero to a maximum, reversed to the same maximum in the opposite direction, and then reduced to zero, and the ac permeability is measured at different points to generate the *butterfly* curve. The extent to which the ac permeability is affected depends on the properties of each ferromagnetic material. In general, the better ferromagnetic materials are more sensitive. This type of curve is relevant for shielding small ac fields in the presence of a larger dc field.

To gain an understanding of how flux-shunting varies with shield parameters, one can look at the analytical expression for the shielding provided by a ferromagnetic spherical shell with radius a, shield thickness Δ (that is much smaller than the radius), and relative permeability μ_r:

$$s = \frac{3a}{2\mu_r\Delta} \tag{6}$$

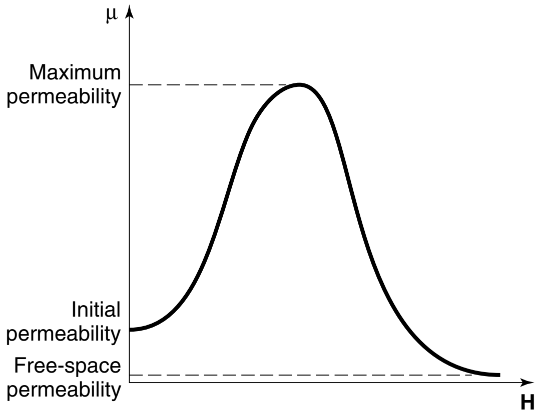


Figure 9. Permeability as a function of applied field strength.

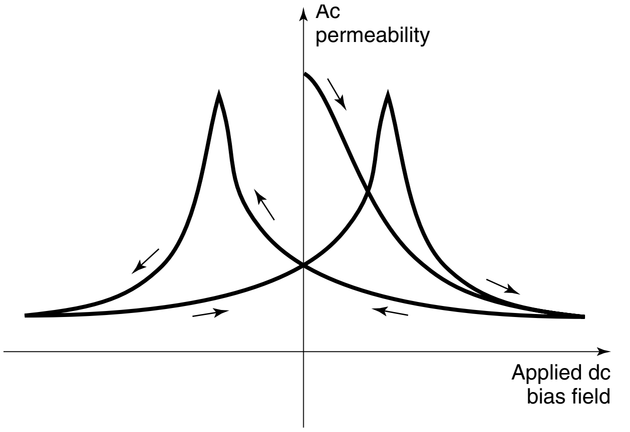


Figure 11. *Butterfly* curve illustrates how the ac permeability changes as a much larger dc field is applied and removed.

Table 1. Properties of Typical Shielding Materials

Name	Material Type	Max. Relative Permeability	Saturation Flux Density, T	Conductivity, S/m	Density, kg/m^3
Cold-rolled steel	Basic steel	2,000	2.10	1.0×10^7	7880
Silicon iron	Electrical steel	7,000	1.97	1.7×10^6	7650
45 Permalloy	45% nickel alloy	50,000	1.60	2.2×10^6	8170
Mumetal	78% nickel alloy	100,000	0.65	1.6×10^6	8580
Copper	High conductivity	1	NA	5.8×10^7	8960
Aluminum	High conductivity	1	NA	3.7×10^7	2699

From Hoburt (8).

Equation (6) shows that shielding improves (shielding factor decreases) with increasing relative permeability and increasing shield thickness. It also shows that shielding gets worse with increasing shield radius. From the perspective of magnetic circuits, shielding improves as the reluctance of the flux path through the shield is lowered. Increasing permeability and thickness reduce the reluctance, improving shielding. Increasing shield radius increases reluctance by increasing the path length of the magnetic circuit, making shielding worse. In short, the flux-shunting mechanism works best in small, closed-geometry shields.

Flux-shunting shielding has been studied for a long time. A journal article (7) dating back to 1899 describes an effect whereby increased shielding is obtained using nested shells of ferromagnetic material with nonmagnetic materials or air gaps between the ferromagnetic shells. In other words, by changing the shield from a single thick layer to thinner double or triple layers, one can in some cases enhance the shielding effectiveness although using the same amount or even less ferromagnetic material. This effect occurs mainly with configurations where the total shield thickness is within an order of magnitude of the shield radius.

In some cases, a double layer shield is used to avoid saturation of the layer closest to the field source where the fields are strongest. For example, a steel material might be used as the first shield layer, whereas a high-performance nickel alloy is used as the second layer. The steel lowers the field enough that the nickel-alloy layer is not saturated. Saturation flux densities of typical shield materials are listed in Table 1.

Induced-Current Mechanism

Time-varying magnetic flux passing through a shield material induces an electric field in the material according to Faraday's law:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{7}$$

In electrically conducting materials, the induced electric field results in circulating currents, or eddy currents, in the shield according to the constitutive relationship:

$$\mathbf{J} = \sigma \mathbf{E} \tag{8}$$

where $\mathbf{J}$ is the current density, σ is the material conductivity, and $\mathbf{E}$ is the electric field induced according to Eq. (7). The fields from these induced currents oppose the impinging fields, providing field reductions. Figure 12 shows a flat plate in a uniform field. Induced-current shielding appears to exclude flux lines from the shield, providing field reductions adjacent to the shield on both sides. Because the induced currents are proportional to the time rate-of-change of the magnetic fields, induced-current shielding improves with increasing frequency. Thus, at higher frequencies, magnetic fields are more easily shielded via the induced-current mechanism. In the limit of infinite conductivity or infinite frequency, flux lines do not penetrate the shield as shown in Fig. 13.

In a conducting shield, the magnetic field and induced-current magnitudes decrease exponentially in the direction of the shield's thickness with a decay length called the skin depth δ:

$$\delta = \sqrt{\frac{1}{\pi f \sigma \mu}} \tag{9}$$

which involves not only frequency f and conductivity σ but also permeability μ because it affects the flux density which induces the circulating currents. Because of exponential de-

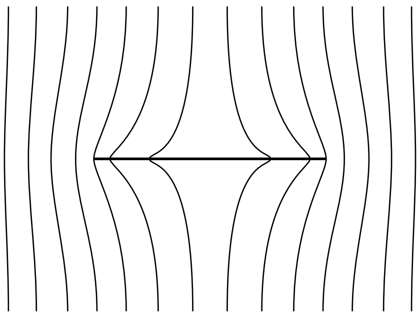


Figure 12. Conducting plate in an alternating vertical field tends to exclude flux from passing through the plate, thus providing shielding.

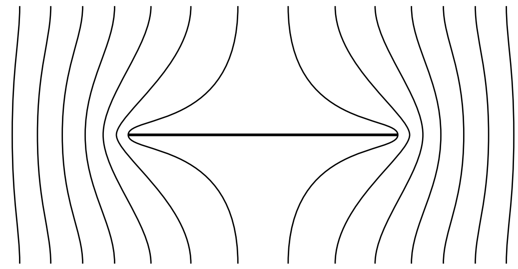


Figure 13. In the limit of zero resistivity or infinite frequency, a conducting shield totally excludes flux lines.

cay, shield enclosures with thickness on the order of a skin depth or thicker provide good shielding. For shield thicknesses much less than a skin depth, the induced current densities are constant across a shield thickness. However, significant shielding can still be obtained from thin conducting shields in some situations where the shield is sized properly. In these cases the shielding is a result of induced currents flowing over large loops.

The shielding factor equation for a nonferrous, conducting, spherical shield with radius a, thickness Δ, and conductivity σ provides insight into how these parameters affect the induced-current mechanism:

$$s = \frac{1}{\sqrt{1 + \left(\frac{2\pi f \mu_0 \sigma a \Delta}{3}\right)^2}} \tag{10}$$

Because all parameters are in the denominator of Eq. (10), induced-current shielding improves (shielding factor decreases) with increasing frequency f, increasing shield thickness, and increasing shield radius. The effect of shield radius is opposite to that for flux-shunting shielding, and although flux-shunting shields static fields, the induced-current mechanism does not. In general, induced-current shielding is more effective for larger source-shield configurations whereas flux-shunting is more effective for smaller shield configurations.

Combined Shielding Mechanisms

Until now, the shielding mechanisms have been discussed separately. Equations (6) and (10) are the shielding factor equations for flux-shunting and induced-current shielding alone. In many shields, both mechanisms are involved. For example, most ferromagnetic materials, being metals, also have significant conductivity in addition to high permeability. Or a shield might be constructed using two materials, one layer of a high permeability material and one layer of a high conductivity material. In these cases both shielding mechanisms contribute to the shielding to an extent that depends on material properties, frequency of the fields, and details of the shield configuration.

To illustrate the combined effect of both shielding mechanisms, Fig. 14 shows the shielding factor, calculated by a method described in Ref. 8, as a function of shield radius for a spherical steel shield in a 60 Hz uniform field. For these calculations steel is assigned a conductivity of 6.76×10^6 S/m, a relative permeability of 180, and the shield thickness of 1 mm is held constant as the shield radius is varied. Flux-shunting dominates at the smaller radii, induced-current shielding dominates at the larger radii, and there is a worst case radius of about 0.4 m where a transition occurs between the dominant shielding mechanisms.

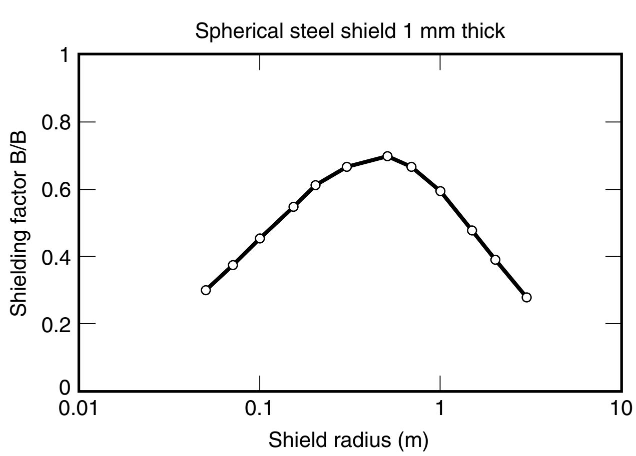


Figure 14. Calculated 60 Hz shielding factor for a spherical steel shell in a uniform magnetic field as a function of shield radius. The shield thickness of one millimeter is held constant.

The combined effect of both flux-shunting and induced-current shielding can be exploited with multilayer shields made from alternating ferromagnetic and high-conductivity materials. Also using the method described in Ref. 8, one can explore this type of shield construction. Alternating thin layers of high permeability and high conductivity perform like a single-layer shield made with a material with enhanced properties.

SHIELDING MATERIALS

Basic magnetic field shielding materials can be grouped in two main categories: ferromagnetic materials and high conductivity materials. For dc magnetic fields, ferromagnetic materials are the only option. They provide shielding through the flux-shunting mechanism. For ac magnetic fields, both ferromagnetic and high conductivity materials may be useful as shielding materials, and both shielding mechanisms operate to an extent determined by the material properties, operating frequency, and shield configuration.

The practical high conductivity materials are those commonly used as electrical conductors, aluminum and copper. Copper is almost twice as conductive as aluminum, but aluminum is about 3.3 times lighter than copper and generally costs less than copper on a per pound basis. For shielding that depends on the induced-current mechanism, conductivity across a shield is paramount and copper has the advantage that it is easily soldered whereas aluminum is not—it should be welded. Mechanical fasteners can be used for connecting aluminum or copper sheets, but the longevity of these connections is questionable due to corrosion and oxidation.

Although there appears to be a large variety of ferromagnetic shielding materials, most fit into one of five basic types:

- Basic iron or steel—typically produced as coils and sheet for structural uses
- Electrical steels—engineered for good magnetic properties and low losses when used as cores for transformers, motors, etc.
- 40 to 50% nickel alloys—moderately expensive materials with very good magnetic properties
- 70 to 80% nickel alloys—highest cost materials with the best magnetic properties, often referred to generically as mumetal, although this was originally a trade name.
- Amorphous metals—noncrystalline metallic sheet formed by an ultrarapid quenching process that solidifies the molten metal; the noncrystalline form provides enhanced ferromagnetic properties.

Different manufacturers produce slightly different compositions of these basic materials, and they have different procedures for heat treating, but the percentages of the main elements, iron or nickel, are similar. There are only a few large producers of nickel-alloy materials. Shielding manufacturers typically purchase materials from a large producer, heat the materials in a hydrogen atmosphere (hydrogen annealing) to improve the ferromagnetic properties, and then utilize the metal to fabricate a shield enclosure or shield panels. Smaller shields are often annealed after fabrication because the fabrication process may degrade the magnetic properties.

Important properties for ferromagnetic shield materials are the initial permeability, the maximum permeability, and the magnetic field strength (or flux density) at which the material saturates and further shielding cannot be obtained. Because the ferromagnetic properties are nonlinear, the operating permeability depends on the magnitude of the magnetic field being shielded. In general, increasing magnetic properties go hand in hand with increasing cost, lower saturation levels, and lower conductivity. Table 1 shows nominal values of maximum permeability, saturation flux density, conductivity, and density for basic shielding materials including copper and aluminum (9). Note that the initial permeabilities of ferromagnetic materials are often one and two orders of magnitude smaller than the maximum permeabilities (see Table 1).

SHIELDING CALCULATIONS

Because there are an infinite variety of shield-source configurations and a wide variety of shield materials for building effective magnetic field shields, shielding calculations are a key part of practical shield design. Elaborate experiments need not be made to characterize the performance of each unique shield design. Extensive experiments are not only impractical but unnecessary. However, closed-form analytical expressions exist only for a limited set of ideal shield geometries, such as cylindrical shells, spherical shells, and infinite flat sheets. Even for these ideal shield geometries, the expressions can be quite complicated, especially solutions for shields with more than one material layer. For general shielding calculations, one must either select a simple approximation to obtain an order of magnitude shielding estimate or utilize more complex numerical methods to solve the shielding problem.

In high frequency shielding, calculations for plane waves propagating through infinite sheets are used to arrive at shielding estimates. Because the resulting equations are analogous to transmission line equations, this method is often called the transmission line approach (10). As described previously, this approach is not relevant to ELF shielding except for a limited set of conditions. Reference 8 describes a technique similar to the transmission line approach, but specifically tailored to ELF magnetic field shielding calculations for ideal shield geometries with multiple layers having different material properties. This method is well suited for calculations involving nested cylindrical or spherical shields or shields constructed from alternating layers of conducting and ferromagnetic materials.

Another technique found in literature is the circuit approach (11). In this method typically used to calculate ELF induced-current shielding, the shield enclosure is viewed as a shorted turn that can be characterized by an inductance and resistance. This method suffers from the assumption that significant details of field structure for the shielding problem are known a priori to properly set the circuit parameters. This severely limits application of the method.

General modeling of ELF magnetic field shielding amounts to calculating magnetic fields in the presence of conducting and ferromagnetic materials. The computation must account for induced currents and magnetization throughout the shield material. This involves solutions to the quasistatic form of Maxwell's equations for magnetic fields over a continuum that represents the problem region. In differential form the basic equations to be solved are the following:

$$\nabla \times \mathbf{H} = \mathbf{J} \tag{11}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{12}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{13}$$

along with the constitutive relationships for permeability, Eq. (5), and conductivity, Eq. (8), which describe the macroscopic properties of shield materials. This quasistatic description, which ignores the displacement current term $\partial\mathbf{D}/\partial t$, normally on the right-hand side of Eq. (11), is valid as long as an electromagnetic wavelength is much larger than the largest dimension of the shield. General solutions to these equations are often called *eddy current* or *magnetic diffusion* solutions. At zero frequency or zero conductivity in the shield, there are no induced currents. Only permeability restructures the magnetic field. This simplification is called the magnetostatic case, and solutions must satisfy only Eq. (11) and Eq. (12), along with the constitutive relationship that defines permeability, Eq. (5).

In finding exact solutions to the governing magnetic field equations previously described, one approach is to define a vector potential $\mathbf{A}$ that satisfies Eq. (12):

$$\nabla \times \mathbf{A} = \mathbf{B} \tag{14}$$

Substituting Eq. (14) in Eq. (13),

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} \tag{15}$$

Combining Eqs. (8), (11), (14), (15), and using a vector identity gives the following:

$$\nabla^2\mathbf{A} - \mu\sigma\frac{\partial \mathbf{A}}{\partial t} = -\mu\mathbf{J_s} \tag{16}$$

in which $\mathbf{J_s}$ is the known distribution of source currents producing magnetic fields that require shielding.

When the source currents are sinusoidal, $\mathbf{A}$ and $\mathbf{J_s}$ can be represented as phasors, and the time derivative in Eq. (16) is replaced by $j\omega$:

$$\nabla^2\mathbf{A} - j\omega\mu\sigma\mathbf{A} = -\mu\mathbf{J_s} \tag{17}$$

When the shield material has zero conductivity or the magnetic fields are constant (zero frequency), Eq. (17) becomes

$$\nabla^2\mathbf{A} = -\mu\mathbf{J_s} \tag{18}$$

Equation (17) can be used for the general case where a shield provides field reduction through both flux-shunting and induced-current mechanisms. Equation (18) is only for flux-shunting. The shielding factor for a specific source-shield configuration is determined by first solving for the magnetic vector potential **A** without the shield in the problem and then solving for **A** with the shield. Using Eq. (14), one calculates the flux densities from both vector potential solutions. Ratios of the field magnitudes as in Eq. (2) define the field reduction provided by the shield as a function of position.

NUMERICAL SOLUTIONS FOR SHIELDING

Except for the ideal shield geometries mentioned previously, solving the governing equations requires numerical methods. Two common numerical techniques are the finite-element method and the boundary-integral method (12,13,14).

In the finite-element method, the problem region is subdivided into elements—typically triangles for two-dimensional problems and tetrahedra for three-dimensional problems—that form a *mesh.* The continuous variation of vector potential **A** over each element is approximated by a specified basis function. Then the unknowns become the coefficients of the basis function for each element. Variational concepts are used to obtain an approximate solution to the governing partial differential equation, for example, Eq. (17), across all elements. The net result is a system of algebraic equations that must be solved for the unknowns. Finite-element software is commercially available, and features that provide automatic meshing, graphical preprocessing, and visualization of results make it an accessible and useful general shield calculating tool for some shield problems, especially problems that can be modeled in two-dimensions or problems with symmetry about an axis. Figures 3, 5, 6, 12, and 13 were produced with finite-element software.

However, there are weaknesses to the finite-element method. Shield geometries typically involve very thin sheets of materials with much larger length and width dimensions. This, along with the need to accurately model significant changes in field magnitudes across the shield thickness, requires large numbers of elements in the shield region. Shielding problems are also characterized by large regions of air and complicated systems of conductors that are the field sources for the problem. In terms of energy density, the fields in the shielded region are negligible compared with fields near the sources, so one cannot rely on energy as the criterion for determining when an *adequate* solution has been obtained. Finally, solving the partial differential equations means that the problem region must be bounded and a boundary condition must be specified at the edges. The problem region must be made large enough that the boundary conditions do not affect the solution in the region where shielding is being calculated. This results in more unknowns and a larger problem to solve.

Instead of differential equations, it is also possible to use the integral form of the quasistatic equations. For determining magnetic fields in air due to some distribution of currents, one can derive an integral equation, often called the Biot–Savart law, that gives the magnetic field contribution at a point in space due to a differential *piece* of current density:

$$\mathbf{H} = \frac{1}{4\pi}\int_{V'} \frac{\mathbf{J}(\mathbf{r}') \times (\mathbf{r}-\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|^3}\,dv' \tag{19}$$

in which $\mathbf{J}(\mathbf{r}')$ is the current density in the problem as a function of position defined by the vector $\mathbf{r}'$ (from the origin to the integration point) and **r** defines the point where the magnetic field is being evaluated (vector from origin to the field evaluation point). Integrating over all of the currents in the problem gives the total field at one point in space. This equation is not valid when shield materials, that is, conducting and ferromagnetic materials, are introduced into the problem region. The boundary integral method overcomes this difficulty by replacing the effect of magnetization or induced-currents within the materials with equivalent sources at the surface of the materials where discontinuities in material properties occur. In contrast to the finite-element method, only the surfaces are divided into elements. Basis functions are used to approximate a continuous distribution of equivalent sources over these surfaces, and a system of equations is developed in which the unknowns are the coefficients for the basis functions. After solving for the unknown sources on the shield surface, one can then calculate the new magnetic field at any point by combining the contributions of all sources—the original field sources and the induced sources in the shield—to obtain the *shielded* magnetic field distribution.

The key advantages of the boundary-integral method are that only the surfaces of the shield need to be subdivided into elements and that the method is ideal for open boundary problems with a large air region. The method is also ideally suited for complex systems of currents. Thus, the boundary-element method is better suited for three-dimensional problems than the finite-element method. The main weakness of the boundary-integral method is that it results in a full system of equations that is more difficult to solve than the sparse system produced by the finite-element method. An integral method based on surface elements, developed expressly for solving three-dimensional quasistatic shielding problems, is described in (15).

The underlying theoretical basis for shield calculations is as old as electricity itself and goes back to Faraday and Maxwell. Although materials science is a rapidly changing area with developments in composite materials and materials processing, the basic materials for shielding of dc and ELF magnetic fields have, for the most part, remained unchanged. For basic shield configurations, calculations are straightforward. However, actual application of shielding requires practical expertise in addition to theoretical knowledge. For example, construction methods used to fabricate a shield from multiple sheets must ensure that conductivity and permeability are maintained across the entire shield surface, especially in critical directions. Edge effects and holes in shields for conduits, doors, windows, etc. degrade shield performance and must be accounted for early in the design process. With proper shield calculating tools and proper construction practices, shields can be designed that attenuate magnetic fields by factors ranging from 10 to 1000 (shielding factors ranging from 0.100 to 0.001), thus eliminating problems with stray or unwanted magnetic fields.

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