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Nomograms Solve Tough Problems of Shielding

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Even nonexperts can design shielded enclosures.
Charts help any engineer to quickly determine the thickness
of metal required to eliminate interference or evaluate design.

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Protecting sensitive electronic systems and circuits against extraneous fields is a difficult and complex design problem because a detailed analysis of a shielding problem usually requires cumbersome equations or time-consuming graphical methods. Since the results are not always satisfactory, the work is usually left to specialists in shielded enclosure design.

Now, armed with a newly developed set of nomograms, an engineer who has a knowledge of the frequency and type of field to be suppressed can determine quickly the thickness of metal shield needed to do the job or to evaluate the effectiveness of a shield.

Shielding effectiveness

A metal enclosure can protect against interference caused by the electromagnetic fields that are generated in nearby circuits. These fields may store energy equally in the electric or magnetic components or, as is more usual, they may be predominantly electric or magnetic fields. Although an enclosure's shielding effectiveness varies with the type of field, there are reflection and absorption factors which are important in any shielding problem.

When a field impinges on a shielding material, some of the field's energy is reflected from the outer surface, some is absorbed at the shield's inner surface and the remainder gets through. The shield's effectiveness, S is given by

$$S = R + A + B$$

where all terms are in decibels, R, the loss due to reflection, is a function of the material, frequency, and the type of field. Absorption losses A, are a function of the material and frequency but are independent of the type of field. If the absorption loss is greater than 10 db the secondary reflection loss, B, at the shield's inner surface can be ignored. Consequently

$$S - R + A$$

where R will be represented as R_E, R_H, or R_P depending on whether the incident field is an electric (E) field, magnetic (H) field, or a radiated plane-wave field (P).

Four nomograms have been designed to make calculating shielding effectiveness easy. The nomograms supply values of the variables needed in the equation. The nomogram on page 98 determines the absorption loss for any Type of field. One of three other nomograms is used to determine the reflection loss-R_E, R_H. or R_P -for the particular type of interfering field.

The nomograms are based on equations developed by Schelkunoff and expanded for engineering required over the years. A recent study indicates that the shielding theory is valid even at extremely low frequencies. The nomograms indicate maximum values of R_E, R_H, R_P, and A.

Reflection losses

Reflections and associated losses, R, are caused by a difference in characteristic impedance between an incident field and the shield. This is analogous to the situation that occurs in a transmission line not terminated in its characteristic impedance. When the impedance of the incident field is much higher or lower than that of the shield, reflection losses are very high.

At all frequencies, electric fields are high impedance and magnetic fields are low impedance.

A shield's characteristic impedance varies with the frequency and the material's permeability and conductivity. Generally the impedance is low at low frequencies and high at high frequencies.

At low frequencies, magnetic reflection losses R_H, are small because there is a reasonably good match between the low impedance of the shield and the field. Thus most of the energy is coupled to the shield. For good shielding effectiveness, it is usually necessary to employ ferromagnetic materials with high absorption losses. As the frequency increases, the impedance mismatch becomes greater and R_H increases.

For low-frequency electrical fields, the mismatch between field and shield impedance is large and R_E is large. As the frequency increases, R_E decreases because the shield's impedance gradually increases.

R_H and R_E nomograms

The equation for reflection loss in an electric field is given by

$$R_E = 353.6 + 10 \log_{10} \left[\frac{G}{f^3 \mu r^2}\right]$$

For magnetic fields, the reflection loss is

$$R_E = 20 \log_{10} \left[\frac{0.462}{r}\left(\frac{\mu}{fG}\right)^{1/2} + 0.136\, r \left(\frac{\mu}{fG}\right)^{-1/2} + 0.354\right]$$

R_E and R_H are expressed in decibels. In these equations

r = distance in inches between the source of energy and the shield.
μ = Material permeability relative to copper.
G = material conductivity relative to copper.
f = frequency in hertz.

Both R_E and R_H ran have negative values, which indicate enhanced coupling to the shield rather than reflection loss. Such increases in coupling have been observed experimentally and are caused by a resonance between shield and source.

Similar procedures are followed for determining either R_E on page 96 or R_H on page 95. For example, determine the electric field reflection loss at 1 Mhz caused by a copper shield 40 inches from a source.

- Locate a point on the G/μ scale corresponding to copper. If a desired metal is not listed, compute G/μ and plot on the numerical scale.
- Locate the distance between the energy source and the shield an the "r" scale (r = 40 inches).
- Place a straightedge between r and G/μ and locate point P on the blank scale.
- Place a straightedge between point P and the desired frequency on The f scale (f = 1 Mhz in this example).
- Read the reflection loss from the R_E or $R_H$scale. (in this example, the loss, R_E, is 142 db.) By pivoting the straightedge on point P, R_E or PH as a function of frequency can be determined.

Plane-wave reflection losses

The nomogram for plane-wave losses should be used when the source of radiation is located more than 5 or 6 wavelengths away from the shield. The distance requirement is for simple antennas that have gains equal to Or less than a dipole.

The equation for reflection losses in decibels for a plane wave impinging on a metallic shield is

$$R_p = 168.2 + 10 \log_{10} \left(\frac{G}{\mu t} \right)$$

To use the nomogram on above/below, the procedure is as follows:

- Locate a point on the G/μ scale corresponding to one of the listed metals.
- Place a straightedge between the G/μ scale and the desired frequency.
- Read the plane-wave reflection losses from the R_p scale.

Absorption losses

Absorption losses, caused by attenuation through the material, are given by

$$A\ (\text{db}) = 3.38 + 10^{-3}\ t\ (\mu G f)^{1/2}$$

where t is the metal thickness in mils (10^{-3} inches). For a given thickness magnetic materials like steel have higher absorption losses than non nonmagnetic materials like copper. Therefore, relatively thick, high-permeability materials are needed to increase the absorption loss for good shielding.

As an example of applying the absorption loss nomogram on page 98, assume that it is necessary to determine the thickness of metal needed to give a 10 db absorption loss at 100 kilohertz. The steps are as follows:

- Locate the frequency (100 khz) on the frequency scale and the desired absorption loss (10 db) on the A scale.
- Using a straightedge, extend a line through these two points until it intersects the unmarked scale at point P.
- Draw a line connecting the desired metal on the Gμ scale and point P and extend it to the left to intersect the t scale. By pivoting the straightedge around point P, thicknesses for a number of metals can be rapidly determined. In this example t is 9.2 mils for copper and 5.2 mils for commercial iron. In the reverse process, the nomogram yields the absorption loss if the frequency, type of material, and thickness are known.

Frequency dependence

Good shielding against electric fields is possible at low frequencies because reflection losses, R_H. are inherently high even though absorption losses, A, are small. In fact since most of the incident energy is reflected, the absorption loss ran be neglected at low frequencies.

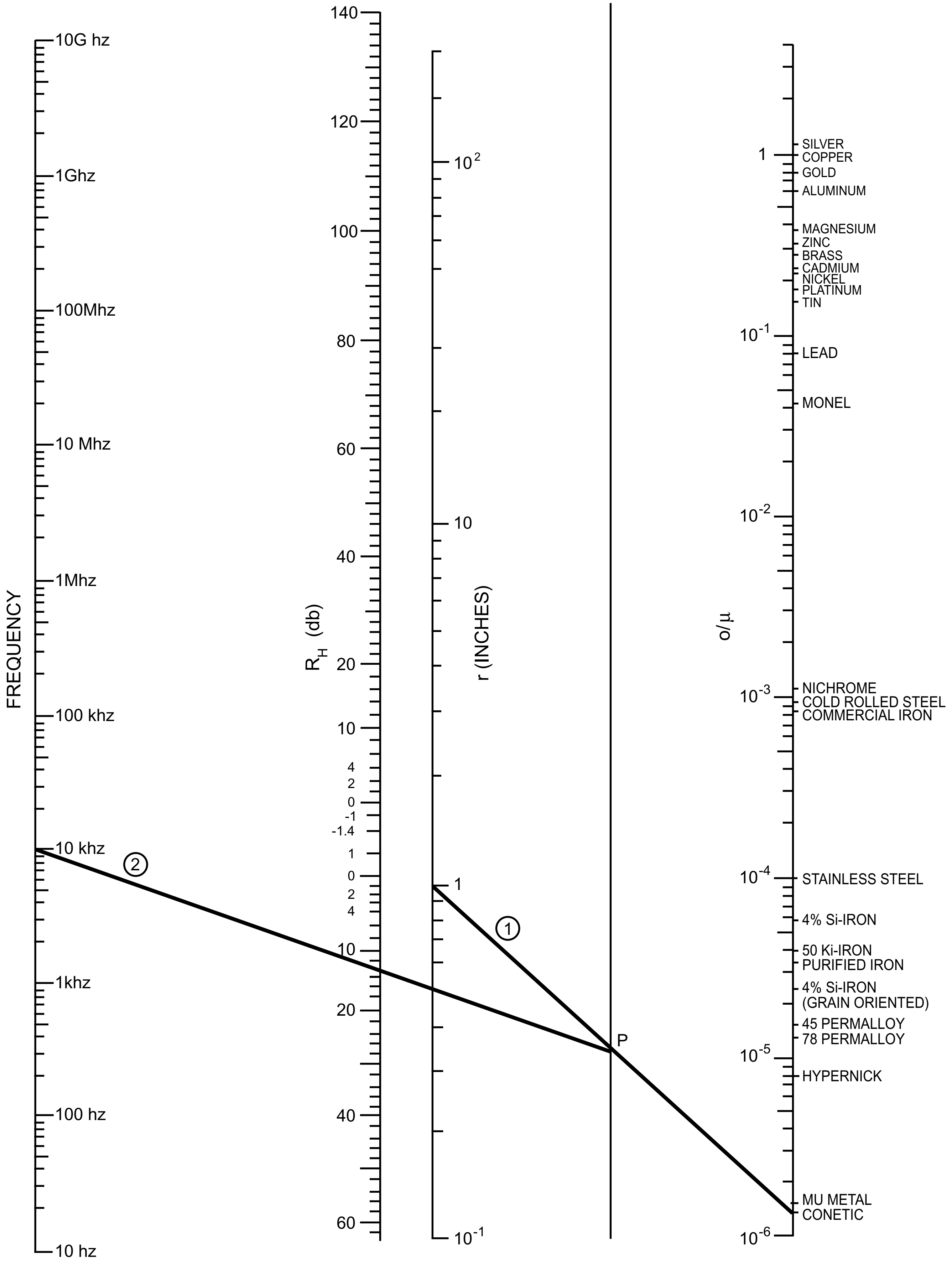
In contrast, at high frequencies, electric fields undergo small reflection losses but large absorption losses. Thus, even though most of the transmitted energy is coupled to the shield, effective shielding is still possible. In shield against high-frequency fields, the main problem is to maintain high absorption by eliminating all nonconductive openings in the shield. This prevents leakage currents from flowing on the supposedly shielded side of the metal surface.

R_E for copper 40 inches from source

Frequency	R_E (db)	Required A (db)	Required t (mils)	A (db) for t = 1.2	$S_E = A^{+}R_E$ (db)
1.5 khz	227	0		0.15	227.0
100 khz	172	0		1.3	173.3
1 Mhz	142	0		4.0	146.0
10 Mhz	112	10	1.0	13.0	125.0
100 Mhz	83	37	1.2	40.0	123.0
1,000 Mhz	53	68	0.62	130.0	182.0

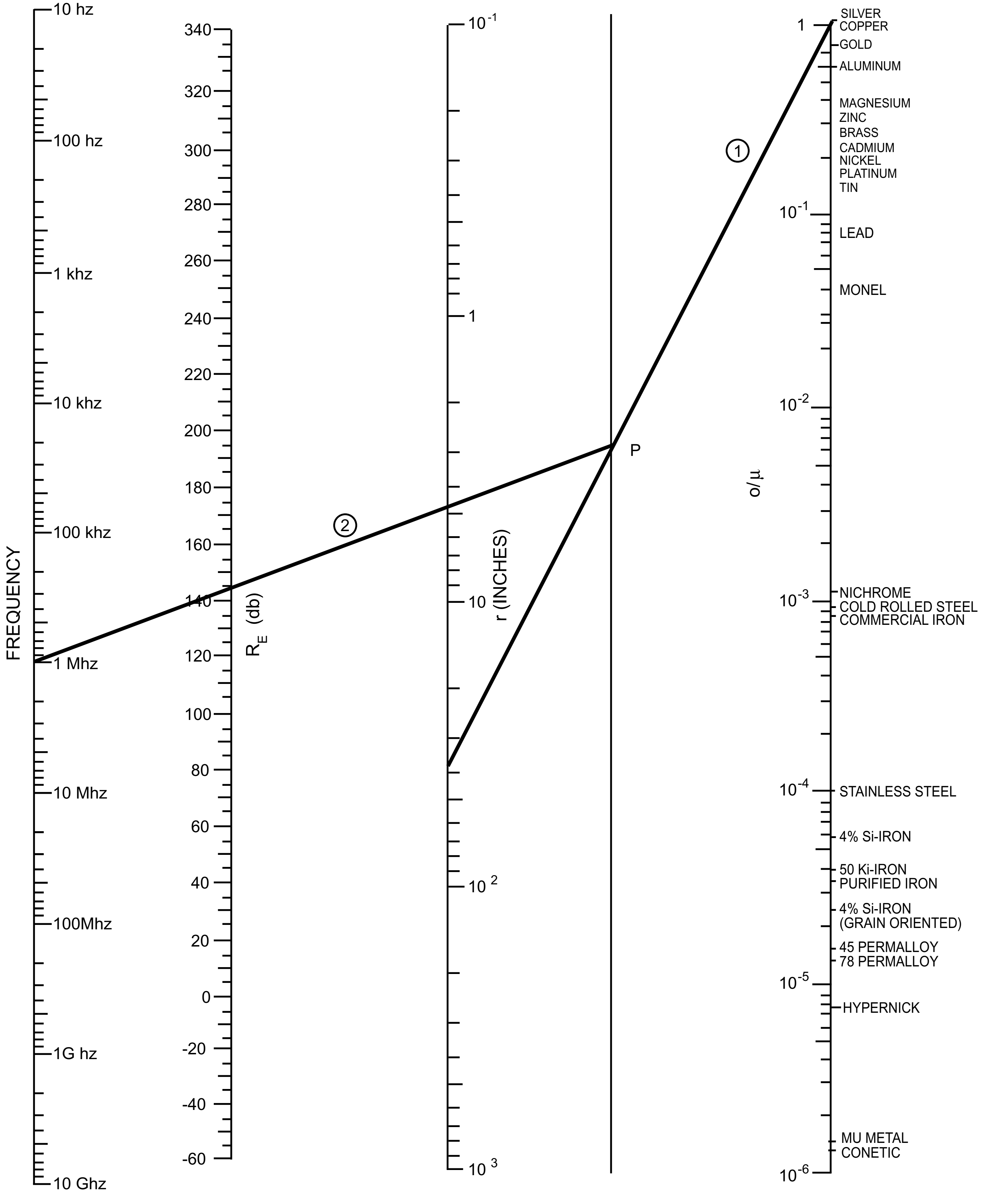
For magnetic fields, both The absorption losses and reflection losses R_H, are small at low frequencies. As with electric fields, eliminating all nonconductive openings in the shield maintains the benefit of high absorption losses. At higher frequencies, both R_H and A become very large and shields perform very well.

MAGNETIC FIELD REFLECTION LOSSES R_H



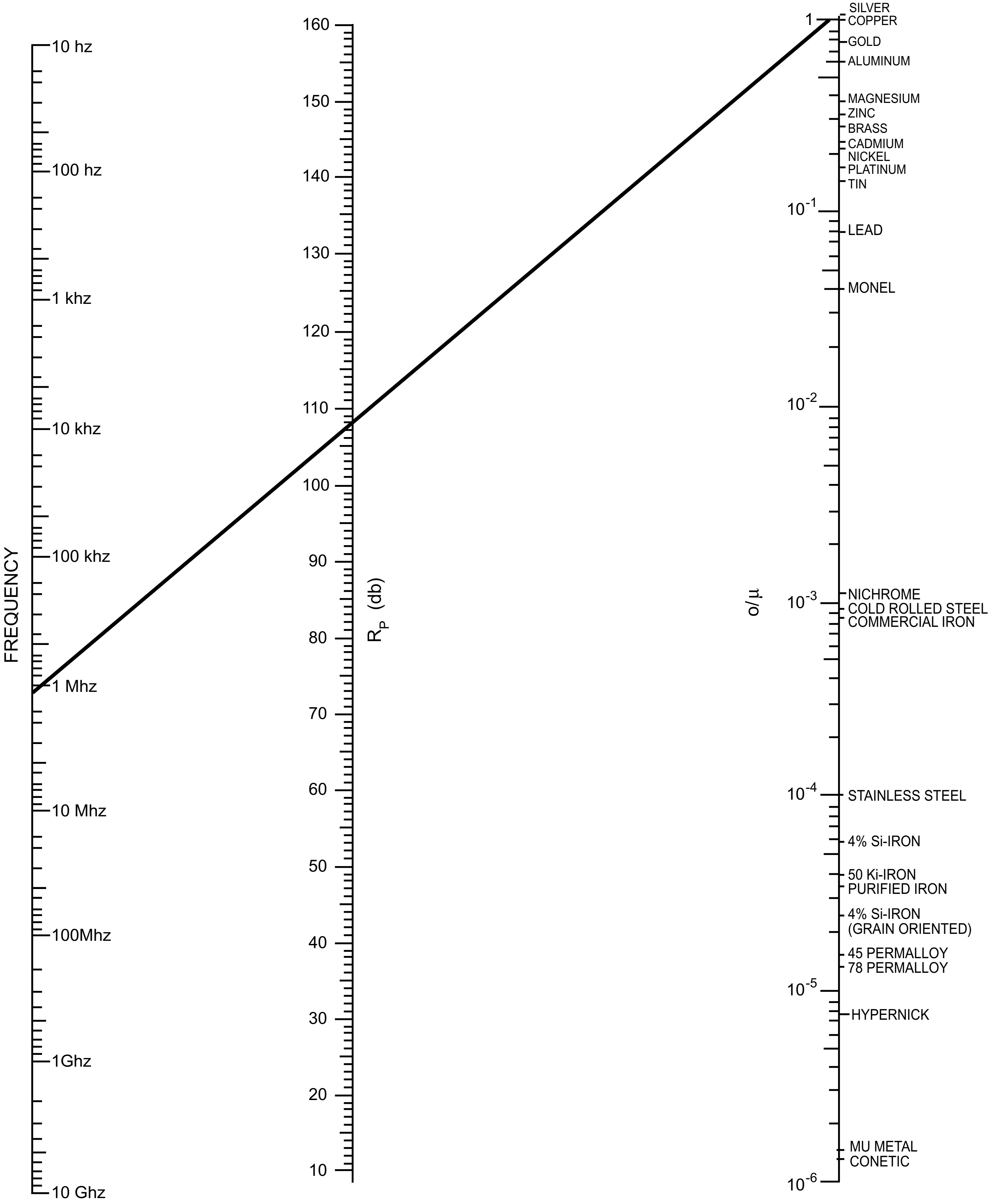
Magnetic field reflection loss Rh is calculated in the same way as the electric field loss. Solid line is for a Conetic shield located 1 inch from a source of a magnetic field. Line 1 fixes point P on unmarked scale. This point and frequency fixes line 2 and the value of Rh (-13DB).

ELECTRIC FIELD REFLECTION LOSSES R_E



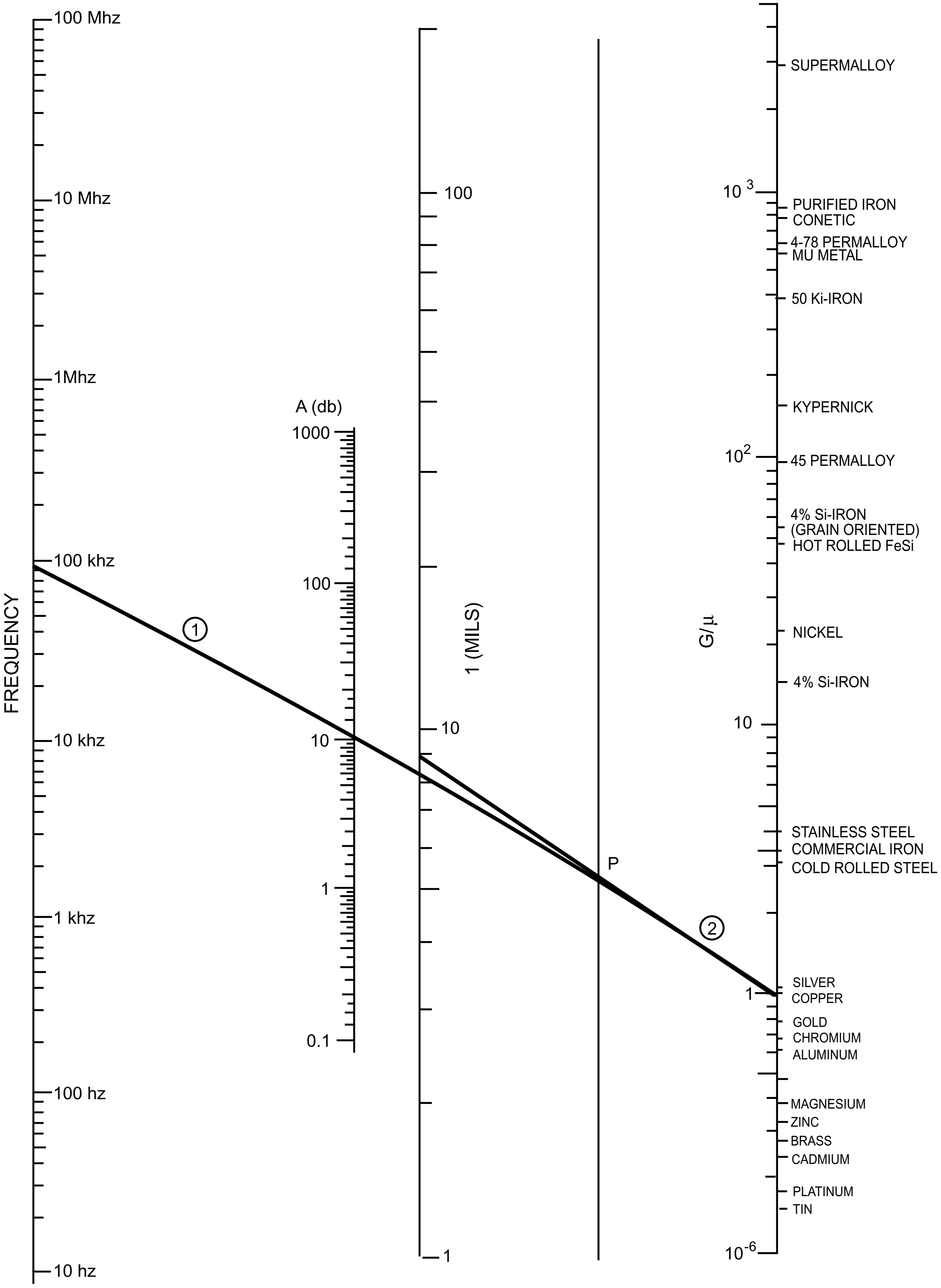
Electric field reflection loss is determined from this nomogram. The distance from source r is 40". Line 1 is drawn from material to source r intersecting the unmarked scale at P. Line 2 is drawn from point P to 1 MHZ. Reflection loss is read from scale Re (DB)

PLAIN WAVE REFLECTION LOSSES R_P



Plane wave reflection losses Rp are calculated easily by a line connecting the frequency with the appropriate value of G/u. A plane wave will exist only if the source is located at least five or six wave lengths from the circuit that is to be shielded. An enclosure designed for magnetic or electric fields is also usually effective for plane wave fields.

ABSORPTION LOSSES: A



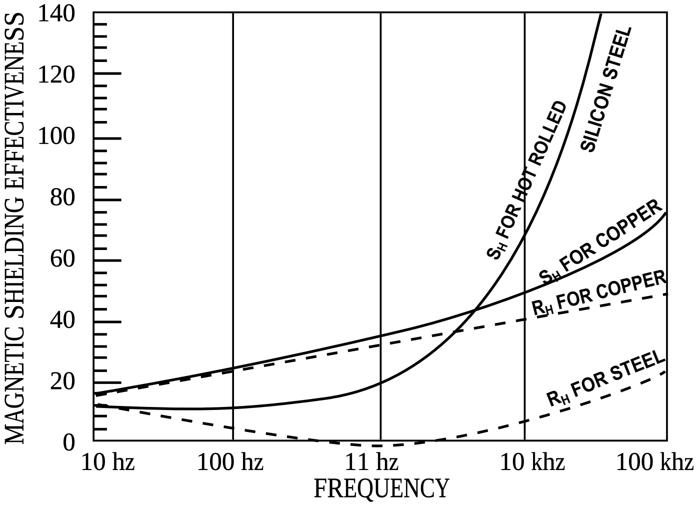
This graph selects material or material thickness for a specified absorption loss. Draw a line connecting the desired metal on the G/u scale to intersect the t scale. By pivoting the straightedge around point P, thicknesses for a number of metals can be rapidly determined. In this sample, t is 9.2 mils of copper or 5.2 mils for commercial iron. In the reverse process, the nomogram yelds the absorption loss if the frequency, type of material and thickness is known.

Magnetic shielding for materials 1 inch from source

Frequency	Copper			Commercial Iron			Purified Iron			Conectic			4% silicon-iron		
	R_H (db)	A (db)	t (mils)	R_H (db)	A (db)	t (mils)	R_H (db)	A (db)	t (mils)	R_H (db)	A (db)	t (mils)	R_H (db)	A (db)	t (mils)
1.5 khz	13	67	>1,000	0	80	300	10	70	22	22	58	21	11	69	90
100 khz	22	58	160	-1	81	120	3	7	8.5	13	67	7.5	4	76	32
1 Mhz	32	48	45	4	76	<120	-1.4	82	3	5.5	74.5	2.6	-1	81	11
10 Mhz	42	33	12	12	68	<120	2	78	3	-1	81	< 1	1	79	< 11
100 Mhz	62	18	1	32	48	<120	18	62	< 3	6	74	< 1	17	63	< 11
1,000 Mhz	82	10	1	52	28	<120	38	42	< 3	24	56	< 1	36	44	< 11

Selecting a shield

Generally the amount of attenuation required is known, and it is desired to determine the material and the material thickness. In some applications, it may be necessary to find a number of materials that will give the desired shielding effectiveness, and the final choice is based on other factors such as weight strength, and cost.



Magnetic Welding is plotted for copper and hot rolled silicon steel 25 inches from source of interference. Broken lines are reflection losses; solid lines plot sum of absorption and reflection losses.

The following example outlines a typical procedure for selecting a material. Assume that a sensitive circuit, highly susceptible to electric fields, is located near a high-voltage terminal. An enclosure located 40 inches from the terminal must provide 140 db of shielding at 1.5 khz and 120 db at all other frequencies between I khz and 2 gigahertz.

From the nomogram for R_E and with r = 40 inches, determine R_E as a function of frequency for copper, and list the values as in the table on page 94. The shielding at 1.5 khz is already greater than the 140 db desired. However, since R_E falls off with frequency, the thickness required is one that provides sufficient absorption loss to bring the shielding effectiveness up to 120 db at the higher frequencies. Values of A are computed from A = 120 - R_E and are listed in the required A column. With these values of A determine the thickness t from the absorption loss nomogram.

The highest value of t-1.2 mils-maintains the level of shielding at 120 db. To determine the actual shielding effectiveness, values of A are computed using this thickness. The effectiveness against an electric field, S_E, for this thickness is indicated in the last column of the table.

The above example results in an extremely thin shield that is not mechanically self-supporting. For mechanical strength the actual design would need either a much greater thickness of copper or some other material.

As another example, consider the design of a magnetic shield that is one inch from a source. Shielding effectiveness must be greater than 80 db from 1 khz to 10 Ghz. The table above lists values of magnetic reflection lossR_H, required A and t for various materials. Again the largest value of t in each column determines the thickness of the material.

Copper-and typically all nonferrous material-would be over I inch thick to produce 80 db of shielding. Commercial iron is inexpensive, but requires a 300 mil thickness and would be very heavy. Purified iron-22 mils thick-would be economical. The more expensive Conetic and 4% grain oriented silicon-iron appear to offer no advantages.

Careful does it

No material should be ruled out in a given application. In some situations copper is a better magnetic shield Than some ferrous materials. This is particularly true at some very low frequencies where R_H for copper is high.

In the case of a shield located 15 inches from a high-intensity magnetic source, copper 30 mils thick is more effective than 30 mils of hot rolled silicon steel at all frequencies below approximately 3 khz as indicated by the lines cut in the graph at the left.

Selecting a material is only part of the problem in designing a shielded enclosure. In practice, gaps appear in the metal. These are openings for components mounted on the enclosure or seams between metal plates. Low- or high-frequency energy leaking past these discontinuities may seriously degrade the shielding effectiveness.

Although careful design overcomes many of the difficulties resulting from these breaks in the surface, no one has completely solved this portion of the shielding problem. In some applications a simple test fixture can be used to evaluate materials such as gaskets or plates with holes.

For more complicated structures, an r-f signal can be fed directly into an enclosure to determine its shielding effectiveness. An antenna-receiver system outside the unit can measure the signal that leaks out.

Properties of magnetic and electric fields

in any simple AC circuit there is an electric field vector associated with the voltage and a magnetic field vector associated with the current. These field components can interfere with nearby circuits which then must be shielded to prevent trouble.

When the field varies with time. The electric and magnetic components exist simultaneously, although one of the field components can be stronger than the other. If most of the energy is stored in the electric component, the field is referred to as an electric field. If most of the energy is stored in the magnetic component, the field is magnetic.

In general a field that is Predominantly magnetic or electric will occur close to the generating source-within one wavelength. For frequencies up to about 1.000 Mhz. a wavelength is a relatively large distance and such fields will cut across many circuits. For example, at 1 Gigahertz a wavelength is 1 foot long: at 1 megahertz a wavelength is about 950 feet long. As a consequence many shielding problems involve predominantly electric or magnetic fields.

At a distance of about six wavelengths from a simple radiating source, the field may propagate as a plane wave, in which the field energy is divided equally between the magnetic and electric components. A shield that is effective for either magnetic or electric fields is also usually effective for plane-wave fields.

A useful quantity in any discussion of field theory is the characteristic impedance-defined as the ratio of the electric to the magnetic field components. For a plane wave in free space the characteristic impedance is 377 ohms. For a predominantly electric field the characteristic impedance is greater than 377 ohms and the field is said to be a high impedance field. A magnetic field has an impedance that is less than 377 ohms, and is said to be a low impedance field.

Strong magnetic fields are associated with circuits characterized by low impedance, high current flow, and small voltage drops. A low-impedance magnetic field transfers energy readily to a surface or circuit with low impedance.

High intensity electric fields are produced by conductors with large series impedance, high voltages, and little current flow. Such fields couple energy most readily into a high impedance conductor or surface.