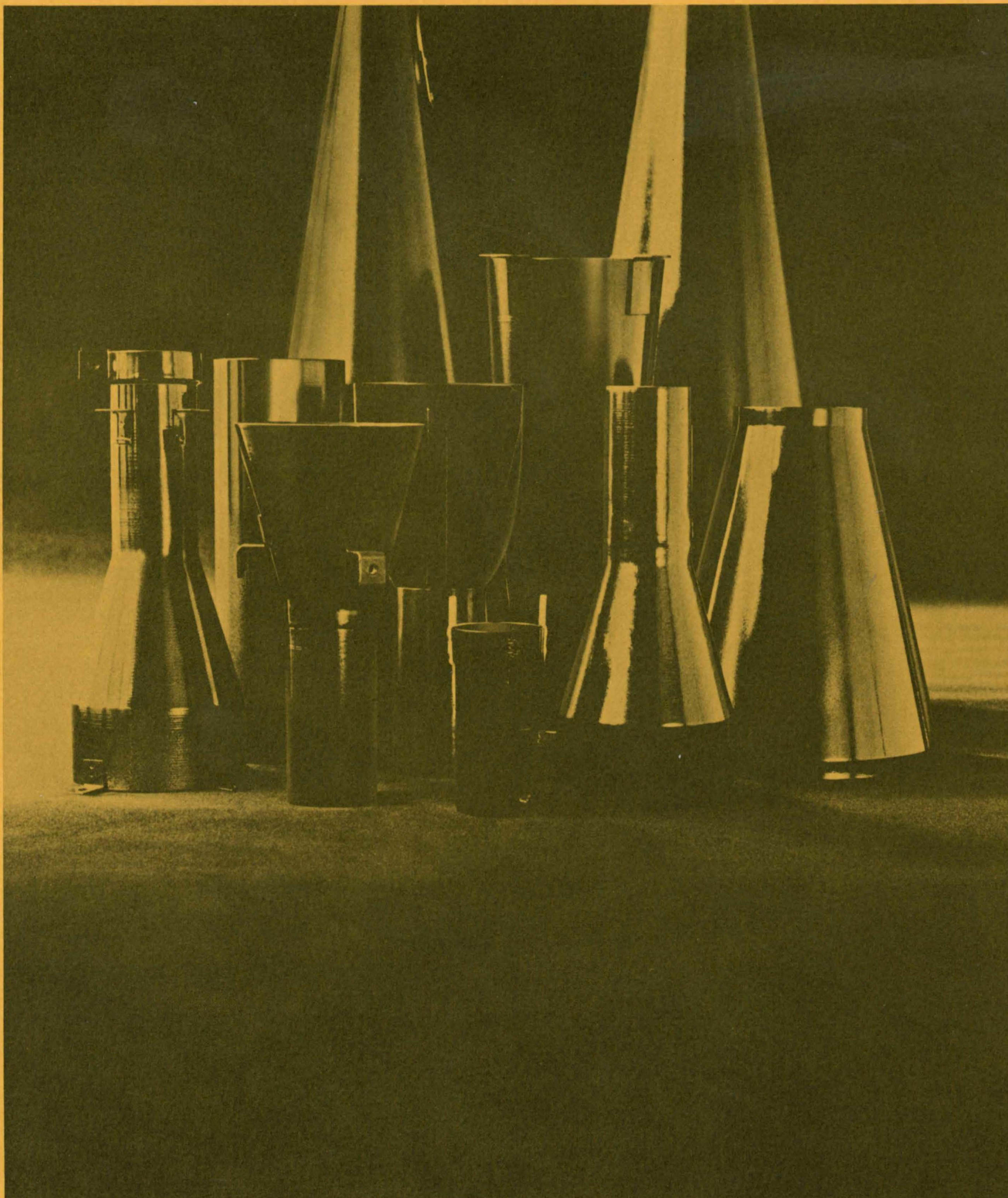
Designers Handbook:

ONE DOLLAR PER COPY

The When Why and How of MAGNETIC SHIELDING



by C. H. Arendt, Jr.

I WHAT IS SHIELDING?

A. INTRODUCTION

Operation of even the best-engineered circuits can be seriously impaired by magnetic interference from nearby components or (in very low-level applications) from the earth's magnetic field. For example, the magnetic field generated by the driving motor of a tape recorder can completely dominate the signal unless the heads are protected. The electron beam of a cathode ray tube will be deflected by the field of a transformer used in the circuit. Input transformers handling low-level signals must be protected from spurious fields.

Stray magnetic fields are a major problem in situations involving low impedance and low frequency. Typical sources of magnetic interference are:

1. Permanent magnets or electromagnets
2. Cables carrying large direct currents or high alternating currents at power frequencies
3. A-c or d-c motors and generators
4. Solenoids, reactors, transformers, or other coils

A familiar example of magnetic interference is "60-cycle hum" – the leakage of power-frequency energy into the audio circuits of amplifiers. Again, a radar monitor system may require a CRT and an electric motor in the same cabinet. Because interference from the motor can deflect the electron beam in the CRT, the interfering field must be reduced to a minimum.

This attenuation can be accomplished by *physical separation* or by *shielding*. The magnetic field intensity at any point is inversely proportional to the *cube* of the distance between that point and the field source, so physical separation can contribute significantly to reducing interference. Sensitive components (such as CRT's) will also require shields.

A magnetic shield is a ferromagnetic metal enclosure that surrounds the device as completely as possible. As good conductors of magnetic flux, shields carry the field around the device to be shielded (Figure 1). They can be used to keep the field out (such as cathode-ray tube shields) or to keep it in and prevent it from disturbing neighboring fields (such as a power-transformer or a motor shield).

Magnetic shields of this type are used in low-impedance, low-frequency (below 10,000 cps) situations. At higher impedances and frequencies, electric-field shielding of steel, copper or aluminum is used, and serves to exclude magnetic fields as well as electric fields.

Our concern here is with low-frequency magnetic shielding. Suitable shielding materials must have high permeability (μ), which can provide a very low-reluctance path for flux to pass around the device. The value of μ for a given material varies with the strength of the magnetic field in which the material is placed. Above a certain level of field strength, the material saturates, permeability falls, and the material has little additional shielding effect.

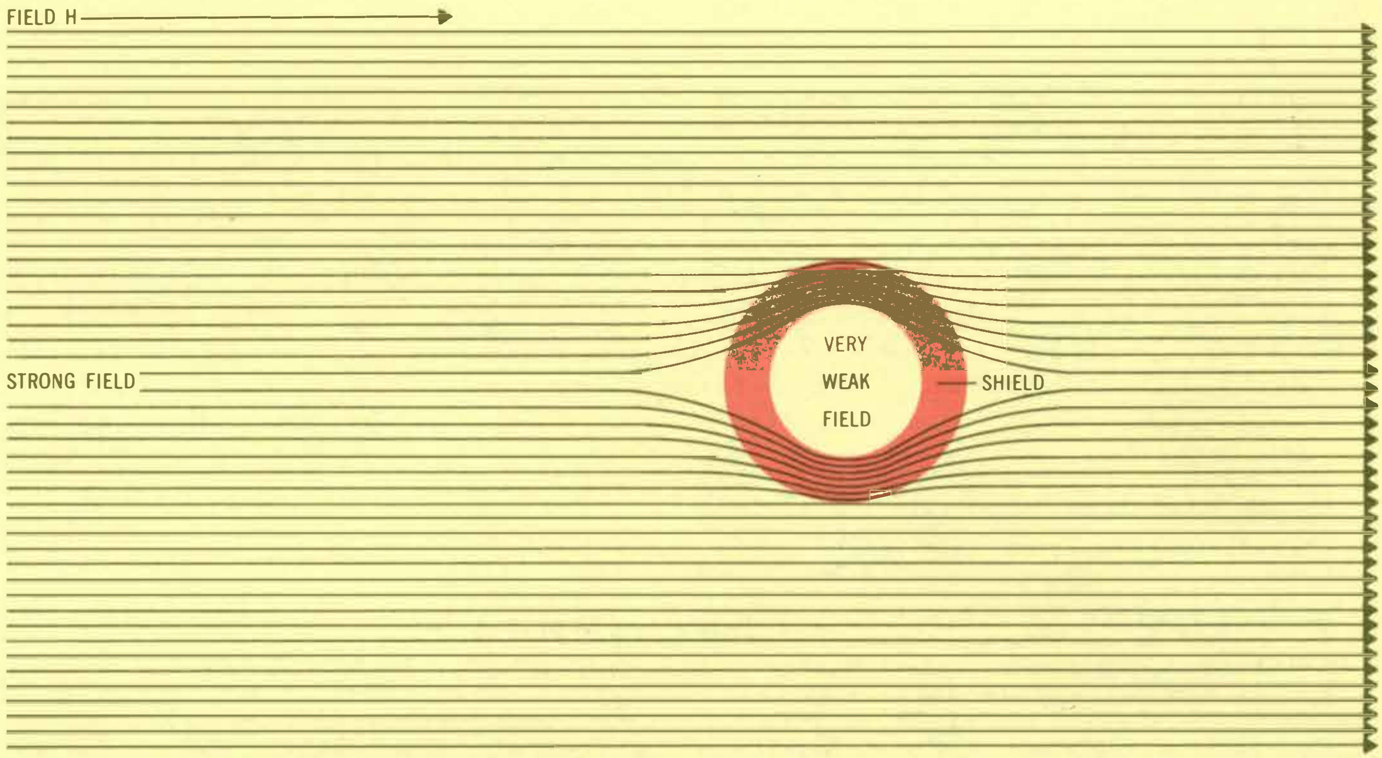


FIGURE 1. Cross section of cylindrical shield in transverse field, showing how low-reluctance path "conducts" field through the shield, protecting device inside.

For this reason, a broad range of high permeability materials, for use over a wide range of flux densities, is available. The designer must choose the material which matches his interference field.

A common strategy, when confronted with a strong field which must be reduced to a minimum value, is to use a double-layer shield. The outer layer of lower-permeability material serves to carry the initial high density magnetic field and significantly reduces its energy. The inner shield of high permeability material then attenuates the field to a minimum level without danger of saturation. Multiple shield design is discussed in Section V.

B. BASIC DESIGN PARAMETERS

The basic parameters that enter into shield design are listed in Table A. They are arbitrarily divided into Field Characteristics, Material Properties, and Physical Shield Configuration, although many of the variables are interdependent. For example, material permeability varies with field flux density, material thickness is an important consideration in shield configurations, etc.

C. THE DESIGN PROBLEM

The design we are attempting to define is the shield which will provide a given *attenuation* (g), defined as the ratio of field intensity outside the shield to intensity inside. In formal terms,

(1) $$g = \frac{H_o}{H_{in}}$$ where H_o = field intensity outside, H_{in} = field intensity inside, measured in oersteds

Shielding efficiency (S.E.) is often expressed in decibels, as:

(2) $$S.E. = 20 \log_{10} g$$
(A simple conversion table of db vs. g is given in Figure 2)

Obviously, the higher the Ho/Hin ratio, the higher the shielding efficiency, and the better the shield.

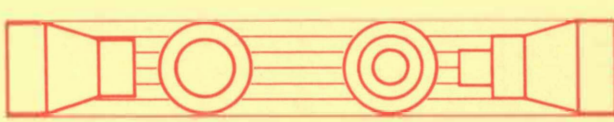
One other measure of shield effectiveness is often encountered – per cent shielding, defined as:

(3) $$\left[\frac{H_o - H_{in}}{H_o}\right] 100 = \left[1 - \frac{H_{in}}{H_o}\right] 100 = \left[1 - \frac{1}{g}\right] 100.$$

TABLE A

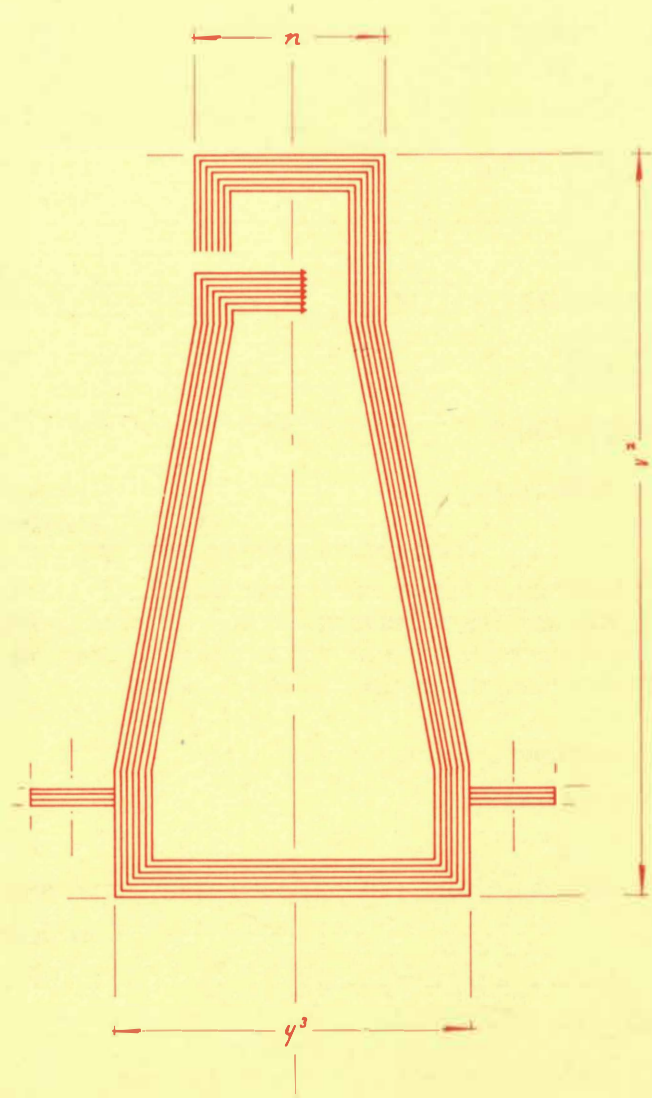
PARAMETERS TO BE CONSIDERED IN DESIGNING SHIELDS

FIELD:	
STRENGTH	(H), measured in oersteds. Depends on intensity level of source and its distance from the shield.
FLUX DENSITY	(B), measured in gauss. Measures magnetic lines of force per square centimeter. Will vary with orientation of source to shield.
FREQUENCY	
SHIELD MATERIAL:	
PERMEABILITY	(μ), measures material's capability to provide a path for magnetic lines of force. Defined as $\mu = B/H$.
MAGNETIC SATURATION LEVEL	is the flux level at which the material cannot conduct any additional lines of force.
THICKNESS	
RELUCTANCE	(R), measures a material's resistance to the passage of magnetic flux. Defined as $R = \frac{l}{\mu A}$, where l is flux path length (cm) and A is cross-sectional area (cm^2).
SHIELD CONFIGURATION:	
SHAPE	
RADIUS	
"END EFFECTS"	
NUMBER (MULTIPLE SHIELDS)	
JOINTS	



D. BASIC DESIGN PROCEDURE

1. Analyze the interference field – frequency, field strength at shielded component, distance of component from source, direction, flux density.
2. Determine interference level that can be tolerated by the component – field intensity, flux density.
3. Select a shielding material (or combination of materials) that can provide the required attenuation without saturating. Section II of this manual discusses material selection in detail.
4. Determine physical geometry and fabrication methods for the shield. Sections III to VI cover these considerations for various types of shields, including conical, cylindrical and multiple shields, and wrap-around shielding.
5. Construct a prototype shield and check performance by the method outlined in Section VII.



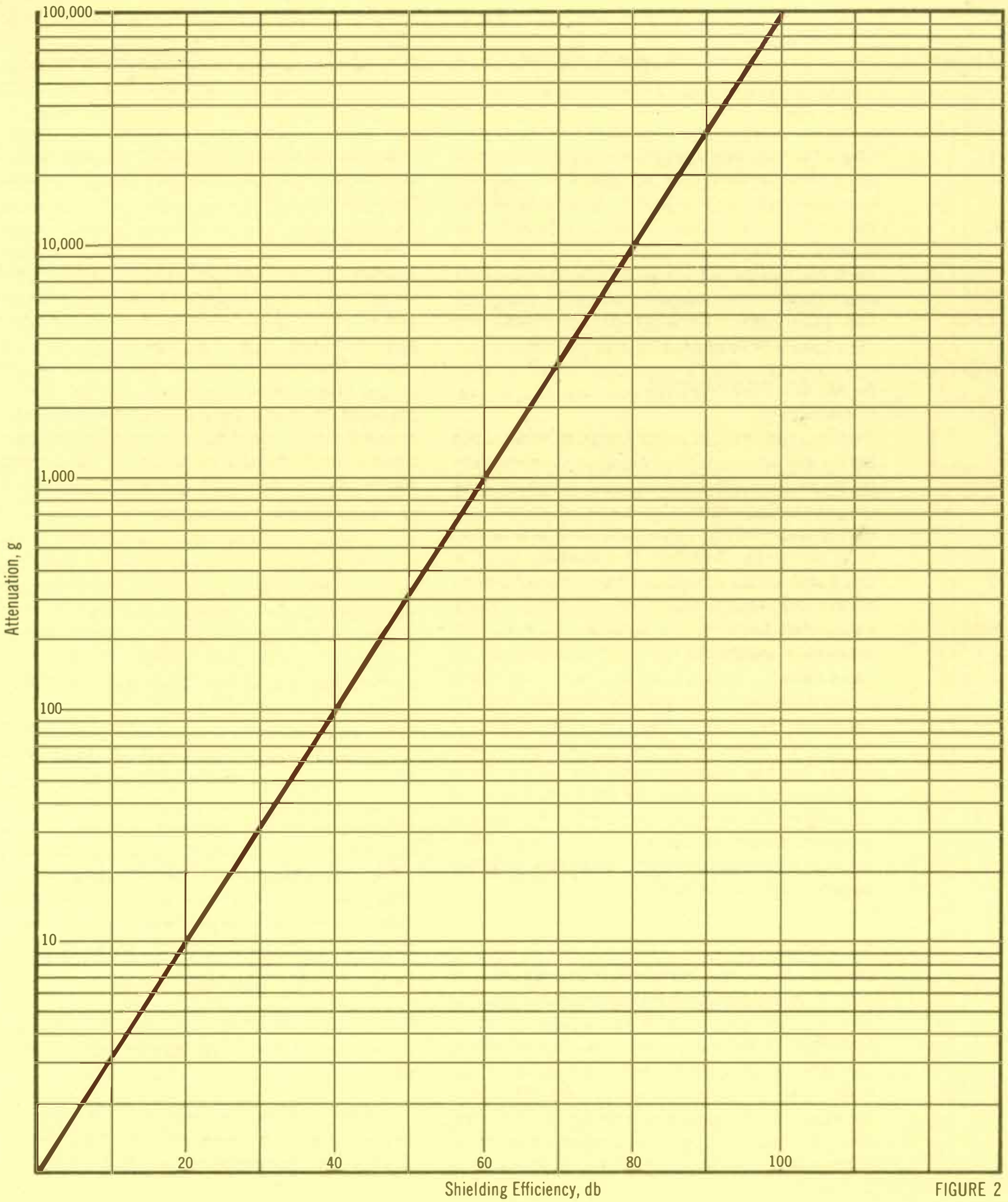

100,000
10,000
1,000
100
10
Attenuation, g
20
40
60
80
100
Shielding Efficiency, db

FIGURE 2

II CHOOSING THE SHIELD MATERIAL

The essential function of shielding materials at low frequencies is to provide a very low reluctance path for the field to pass around the device being shielded. Because reluctance is defined as $l/\mu A$, high-permeability materials such as nickel-iron alloys are most frequently used to keep reluctance as low as possible. The other alloy properties of importance are saturation, thickness, and fabricability.

A. ALLOY PROPERTIES

Permeability

The higher the material's permeability, the better the attenuation it provides. Permeability increases with field density, however (see magnetization curves, Figures 3 and 4), so that attenuation will generally improve as the field becomes stronger. The limiting point is the point of maximum permeability (the knee of the magnetization curve). As field density increases beyond the maximum point, the material's permeability decreases rapidly to saturation.

Permeability also tends to decrease with increasing frequency, and the same shield is likely to be less efficient at higher frequencies. Thus, the permeability used for calculations must be the right value for the frequency and density of the field, as well as for the correct material thickness. Because shielding calculations are seldom exact, however, a close approximation will suffice.

Saturation

Unfortunately, as permeabilities increase in alloys, their *saturation* levels decrease, so that the highest permeability alloys (such as HIPERNOM) have the lowest saturation values. Because a saturated shield is a poor attenuator, high-permeability alloys cannot be used for very dense fields. For a single-shell shield, then, the design "trick" is to select a material with adequate saturation characteristics, that has a permeability high enough to provide the required attenuation (without becoming prohibitively thick).

Shock Sensitivity

Another factor to be considered is material's shock sensitivity—high-permeability materials are increasingly sensitive to strain as their permeabilities rise. For high shock environments, the best choice might be a multiple shield of a lower-permeability (less sensitive) material. In normal field service, however, permeability and shielding efficiency remain adequately high. Repeated dropping will destroy effectiveness.

B. MATERIALS AVAILABLE

Table B provides a reference guide to the materials most commonly used for low-frequency shielding. Ranked from the highest permeability to the lowest, they are:

1. 80% nickel iron (Westinghouse HIPERNOM alloy)
2. 50% nickel iron (Westinghouse HIPERNIK alloy)
3. 3% silicon iron
4. Cold-rolled steel (1010 carbon steel)

The table lists maximum permeabilities (μ_{max}) and initial permeabilities (μ_{40} measured at very low field density); saturation levels; and ultimate shielding efficiency, which is the maximum value of g possible with the material. The ultimate shielding efficiency depends only on the permeability and can be expressed (for cylindrical shields) as:

$$\left.\frac{H_o}{H_{in}}\right|_{max.} = \frac{(\mu+1)^2}{4\mu} \approx 0.25\mu \qquad (5)$$

For double shields, ultimate efficiencies should be doubled. For triple shields, tripled, etc.

Using Table B, the designer can select for his application the material which will not saturate in the interference field but will provide attenuation levels required. Note that the data given is for the commonly-used .020 inch thickness of material – in all cases, heavier gauges will provide better attenuations, and these cases should be examined using the equations of Section III.

Another solution, of course, is to use several nested shields. Here, the high-permeability material nestles inside a shell of less-efficient material, which reduces the field to levels which can be handled by the high-permeability alloy. Typical double-shield combinations would be: HIPERNOM inside HIPERNIK, HIPERNIK inside silicon-iron, or HIPERNOM inside silicon-iron. Another common "sandwich" would use all three materials, with the low-saturation silicon-iron closest to the strong field.

The outer shield should be made of the highest permeability material which will not saturate in the field involved.

C. MAGNETIZATION CURVES

For selecting the right value of permeability to use in attenuation calculations, consult Figures 3 and 4. Because permeability varies with field density, frequency, and material thickness, the design value should be picked to match the expected field conditions and the chosen design thickness.

Figures 3 and 4 show magnetization curves for HIPERNOM and HIPERNIK alloys at various thicknesses. The permeability for a given set of conditions can be read from the diagonal lines. Interpolations to obtain intermediate values are sufficiently accurate for shield design.

D. OTHER MATERIALS

For shielding of extremely high fields, the silicon steels, AISI M-27 and AISI M-36 are candidates. M-27 has a saturation point of about 19,000 gauss with a permeability of 1100 in a 200-gauss field. M-36 saturation is 20,000 gauss, and its permeability in a 200-gauss field is 900.

For shielding purposes, performance of transformer and electrical grades of silicon steel are about equivalent. All of these low-permeability, high-saturation materials are good candidates for the outer layers of multiple shields. Consult manufacturer's data sheets for full information.

E. A FEW WORDS ABOUT ECONOMICS

Generally speaking, the costs of magnetic materials rise with their permeabilities. For this reason, the designer should choose the lowest permeability material that will provide the required attenuation.

It may be, though, that a thin shield of higher permeability material is cheaper after fabrication than a thicker shield of less-expensive, lower-permeability metal. These trade offs must be remembered in design. Consult material manufacturers for pricing, which varies by alloy, thickness, width required, and quantity to be purchased.

TABLE B
COMPARISON OF MAGNETIC SHIELDING MATERIALS

(d-c values at .020" thickness)

	Saturation	Permeability		Ultimate Shielding Efficiency	
Material	(gauss)	μ max	μ 40	Ho/Hin	db
80% nickel, balance iron (Westinghouse HIPERNOM®)	8,000	400,000	45,000	100×10^3	100
50% nickel, balance iron (Westinghouse HIPERNIK®)	15,000	75,000	10,000	19×10^3	85
Silicon Steel (3% Si-Fe)	20,000	5,000	3,000	1.3×10^3	62
1010 Carbon Steel	22,000	3,000	1,000	$.75 \times 10^3$	58

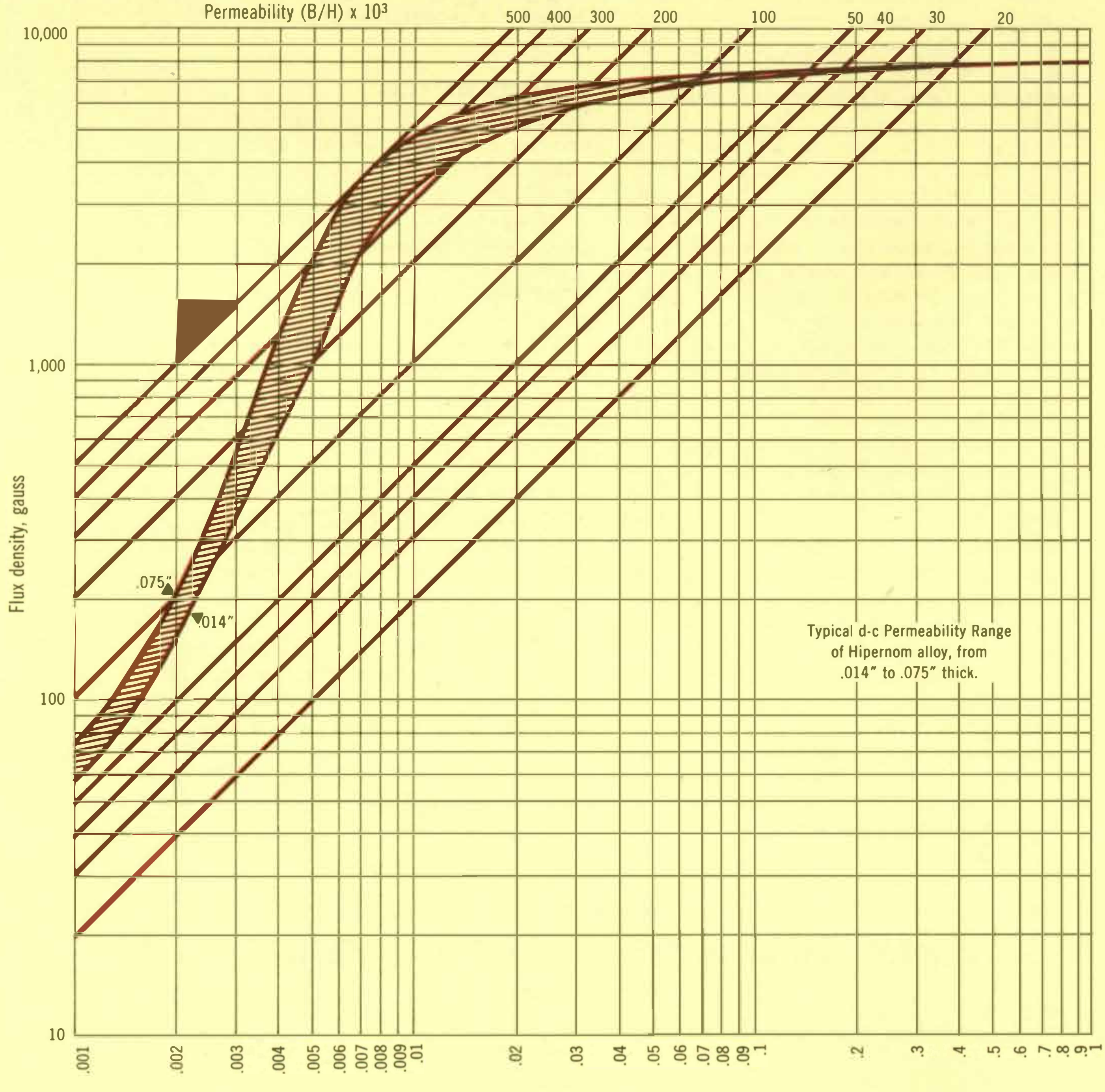

Permeability (B/H) x 10³
500
400
300
200
100
50
40
30
20
10,000
1,000
100
10
Flux density, gauss
.075"
.014"
Typical d-c Permeability Range of Hipernom alloy, from .014" to .075" thick.
.001
.002
.003
.004
.005
.006
.007
.008
.009
.01
.02
.03
.04
.05
.06
.07
.08
.09
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
Field Strength

FIGURE 3

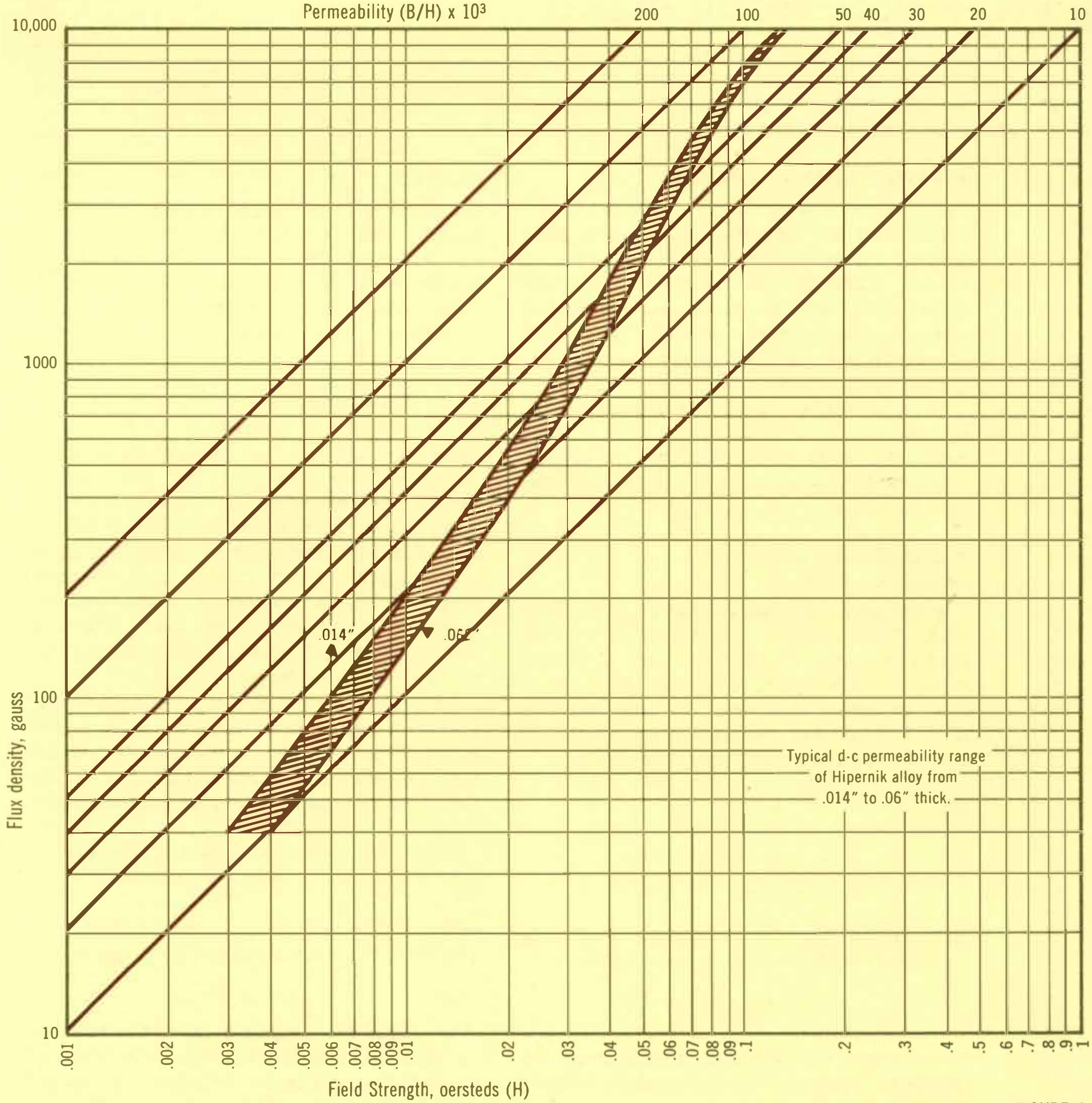

Permeability (B/H) x 10³
200
100
50
40
30
20
10
10,000
1000
100
10
Flux density, gauss
.014"
.06"
Typical d-c permeability range
of Hipernik alloy from
.014" to .06" thick.
.001
.002
.003
.004
.005
.006
.007
.008
.009
.01
.02
.03
.04
.05
.06
.07
.08
.09
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
Field Strength, oersteds (H)

FIGURE 4

III CYLINDRICAL SHIELD DESIGN

A. SHIELD CONFIGURATIONS

The most commonly used shield shapes are the cylinder and the cone. Cylinders are used to shield photomultiplier tubes, miniature vacuum tubes, motors, meters, etc. Conical shapes are most commonly found shielding cathode ray tubes. Box-shaped enclosures are used for power supplies, power transformers, reactors and the like.

Because cylindrical shields are most common, we discuss their design features in some detail, then note in later sections the adjustments that must be made in designing other configurations.

B. DESIGN CALCULATIONS

Uniform DC Field

The simplest analytical case is a uniform field impinging perpendicularly to the axis of a very long cylindrical shield (effectively infinite in length), see Figure 5. A number of investigators, including Wills (Ref. 2) and Teasdale (Ref. 7) have determined that attenuation in this "transverse field" case is given by:

(6) $$g = \left(\frac{\mu}{4}\right)\left(1 - \frac{a^2}{b^2}\right)$$

where: μ = the permeability of the material
a = the inner radius of the shield
b = the outer radius of the shield

Substituting (b - t) for a, (where t = material thickness) and simplifying, we obtain

(7) $$g = \left(\frac{\mu}{4}\right)\left(\frac{t}{b}\right)\left(2 - \frac{t}{b}\right) \approx \frac{\mu t}{2b}$$

We can see that shielding effectiveness depends *only* on the *permeability* of the material and the *ratio* of wall thickness to outer radius.

Equation (7) is accurate for extremely long cylinders (of effectively infinite length). In practice, cylinders with a length-to-diameter ratio of 4 or better can be treated in this fashion (with the adjustments discussed in Section III-C below).

A-C Field

Calculating shielding efficiency becomes slightly more complicated when the field is a-c. Following the classical analogy to the theory of traveling wave propagation on a transmission line, the shielding efficiency, S.E. in decibels, is expressed as:

(8) $$S.E. = R + A$$

where R is the total reflection loss of the wave at the surface of the shield, and A is the total absorption loss. S.E. is, of course, related to attenuation (g) by Equation (2), S.E. = 20 log g. At low frequencies, reflection losses in a single-layer shield represent at most only 6-8% of total shielding, and so for practical purposes can be ignored in our calculations. The total shielding can be assumed to result from absorption. The existence of some reflection loss, however, provides a built-in "safety factor" in a-c shield design.

Absorption loss represents the field reduction as it proceeds through the body of the shield. These losses are independent of the type of radiator emitting the field – they are the same for both electrical and magnetic fields.

The absorption loss, A, can be found from:

(9) $$A = 8.686\,\alpha\,t$$

where t is the thickness in cm. of the shield, and α is the attenuation constant, given by:

(10) $$\alpha = \sqrt{\pi G u f}$$

where G is the conductance of the material in mho/cm, u is the intrinsic inductance in henry/cm, and f is the frequency in cycles/sec. This a-c value for u is $4\pi \times 10^{-9}$ times the permeability in Gaussian units (μ) which we used for d-c calculations.

In general, the same shield will provide better attenuation of a-c fields than it does d-c fields, and it will be increasingly effective as the frequency increases.

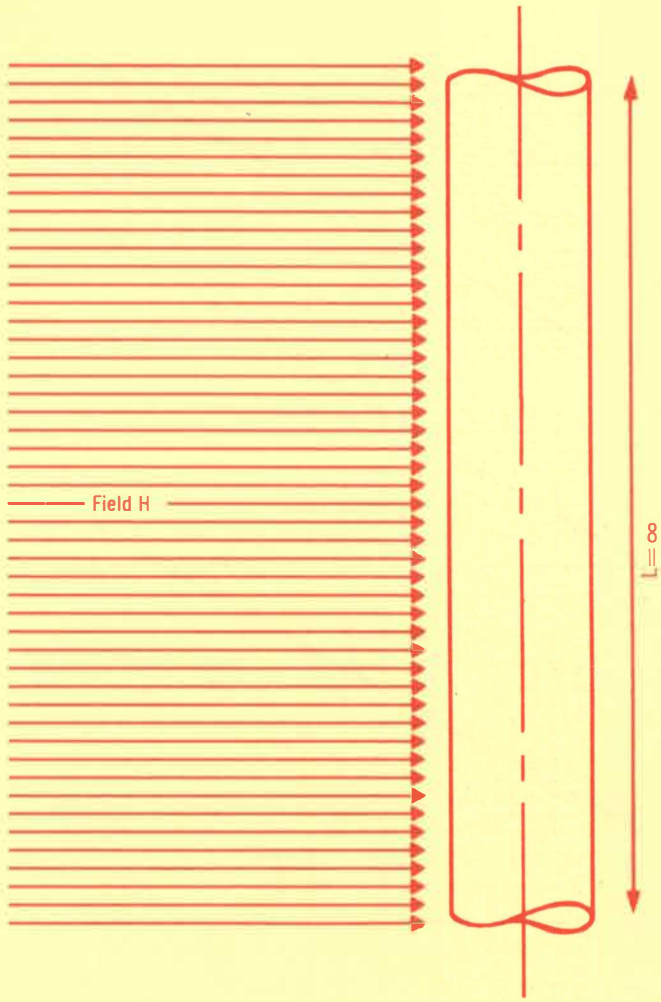


FIGURE 5
Field impinging perpendicular to axis of infinitely long cylindrical shield (transverse field).

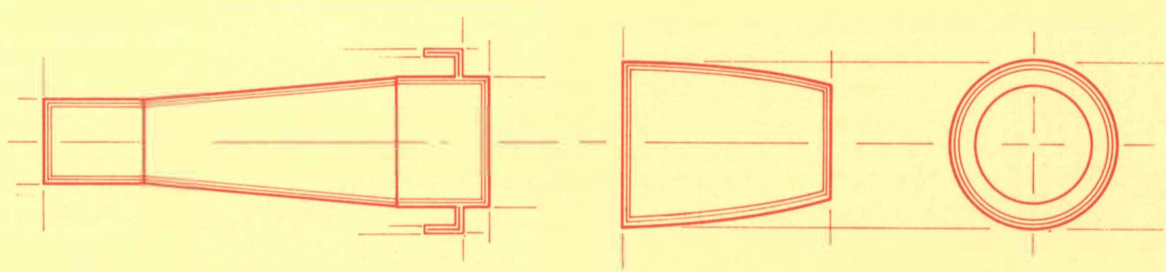
Eddy Current Effect

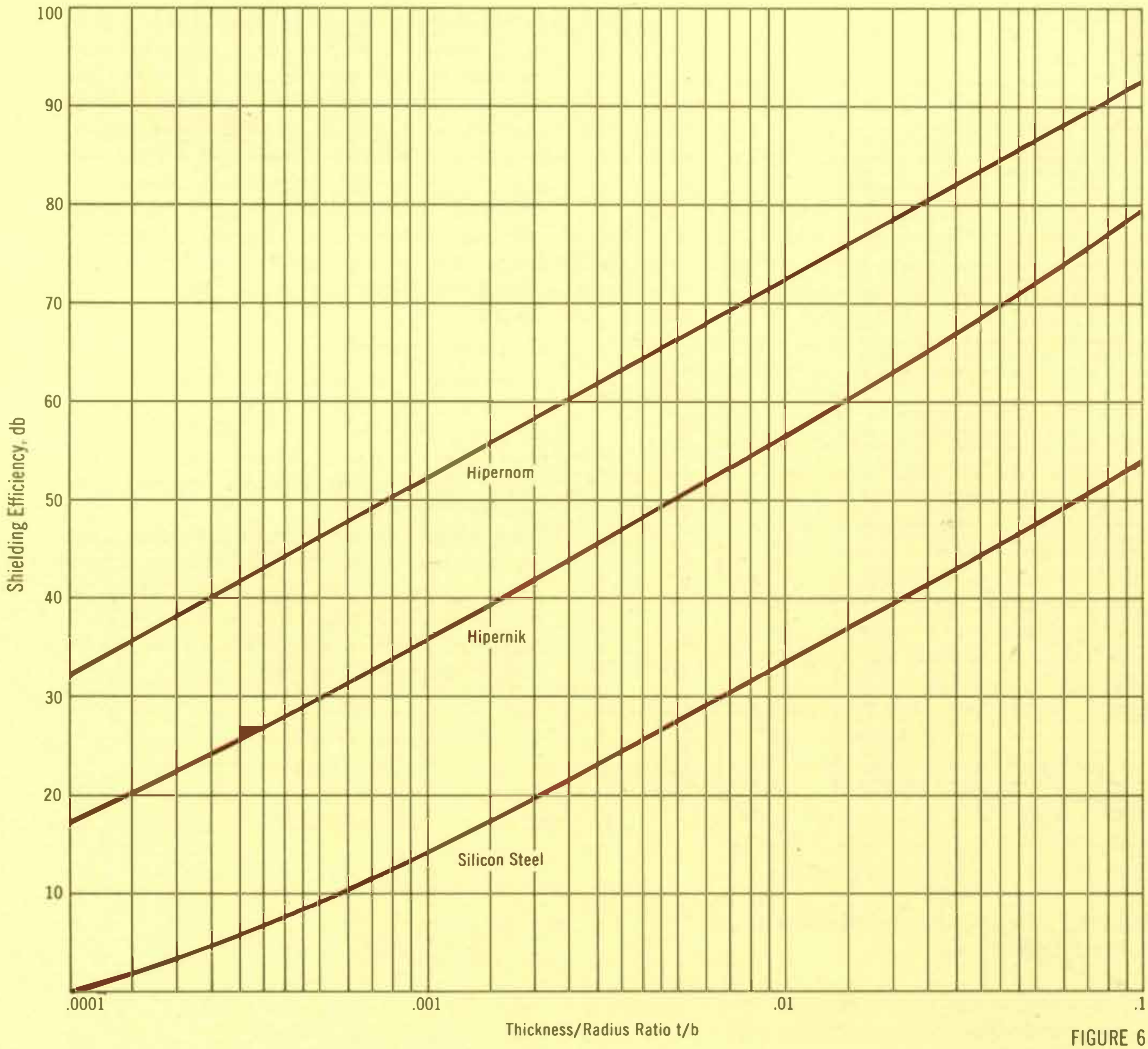
Some additional help in shielding a-c fields is provided by eddy currents set up at the field's point of entry. These eddy currents tend to restrict the flux lines entering the material, providing additional attenuation. At low frequencies (below 400 cps), however, using high-resistivity materials in thin gauges, the effects are small enough to be neglected in calculations. They provide another "safety factor" (along with reflection losses) to the shield design.

C. Shield Geometry

In deciding final design dimensions, the I.D. of the cylinder should be selected to fit as loosely as possible over the shielded device, leaving an air gap that can increase attenuation. Space considerations, however, may dictate a tight fit.

Material thickness is then selected using the formulas of Section III-B. Figure 6 provides a good rule of thumb for choosing the thickness-to-outer radius ratio (t/b) – it plots maximum shielding efficiency against t/b for various shielding materials.





Shielding Efficiency, db
100
90
80
70
60
50
40
30
20
10
Hipernom
Hipernik
Silicon Steel
.0001
.001
.01
.1
Thickness/Radius Ratio t/b

FIGURE 6

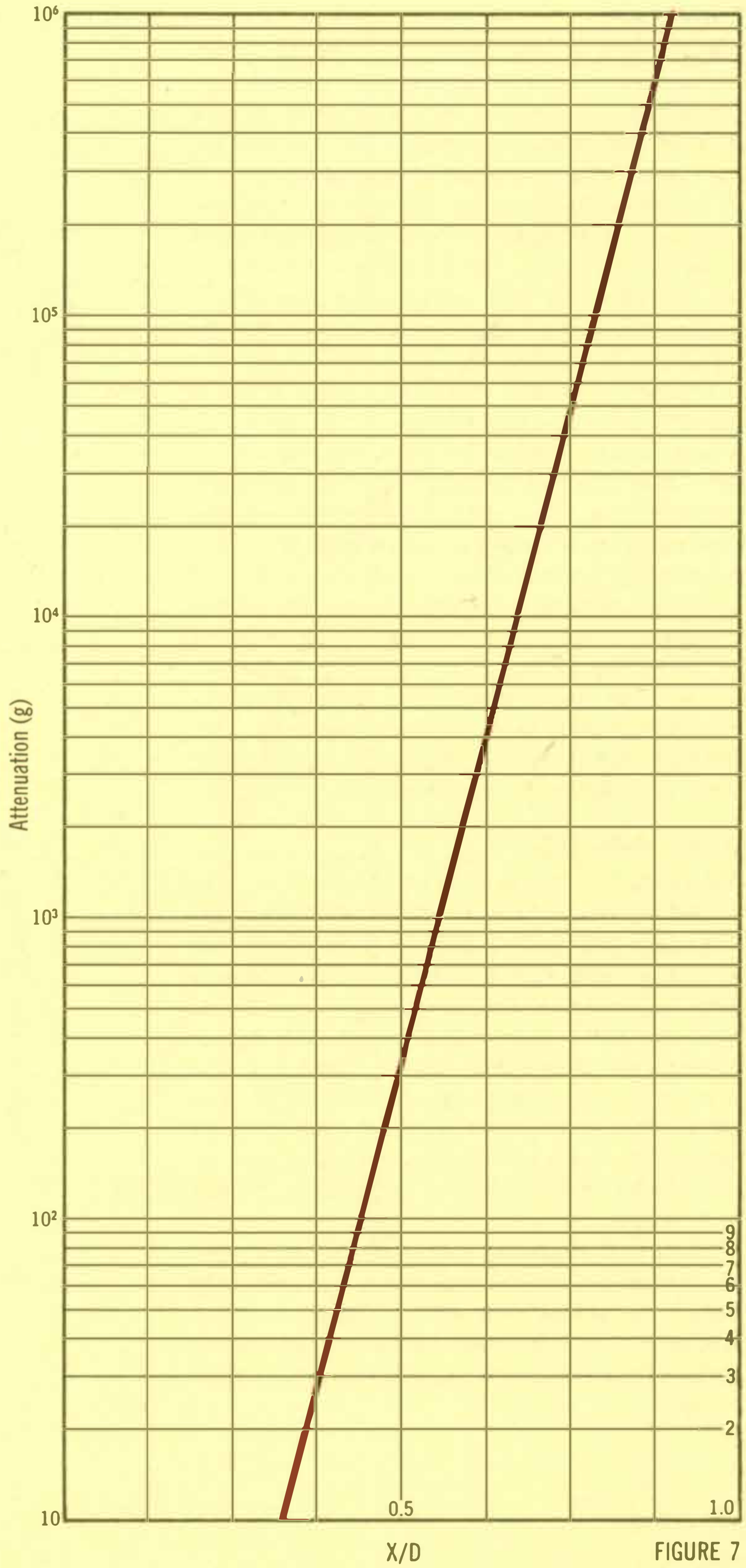


FIGURE 7

End Effects

Tube length is determined by consideration of "end effects" (for open-end cylinders). Because we are dealing with cylinders of less than infinite length, we must consider the flux that enters the open end of the cylinder.

These end effects are difficult to calculate precisely, but Wadey (Ref. 8) provides Figure 7, which gives the distance from the end of the cylinder one must measure to obtain 68% of the attenuation calculated for an infinitely long tube in a d-c field.

Figure 7 plots the ratio X/D, where X is the distance from the end of the cylinder at which g is 68% of its value for infinitely long cylinders, and D is the shield's mean diameter. To estimate how far a shield must overhang the shielded region, find the value of X/D for the required attenuation, and multiply by D.

The usual "rule of thumb" is that the shield should overhang the device by an amount equal to the radius of the cylinder (see Figure 8). The "end effects" are definitely minimized in shields with length-to-diameter ratio greater than 4, which approach the attenuations calculated for an infinitely long cylinder.

D. ATTENUATION

For fields impinging perpendicular to the cylindrical shield's axis, Teasdale (Ref. 7) established the attenuation pattern shown in Figure 9. This pattern was obtained with a relatively poor silicon-iron shield having a length-to-diameter ratio of only 2. Considerably better attenuation, over a much wider "band" in the middle of the shield, can be expected of a nickel-iron shield with an L/d ratio of 4 or better. The general characteristics of the attenuation pattern, however, will remain similar to Figure 9.

Maximum shielding is obtained in the center of the shield. Some shielding by proximity occurs for a few inches from the ends of the shield. Notice that these experimental results agree closely with the "rules of thumb" stated above.

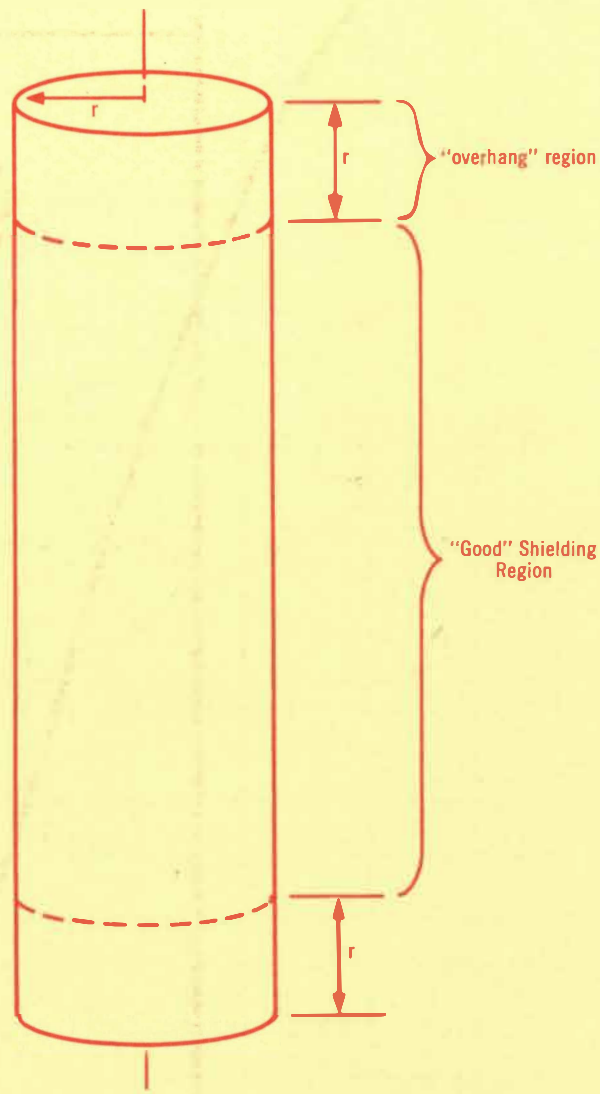


FIGURE 8

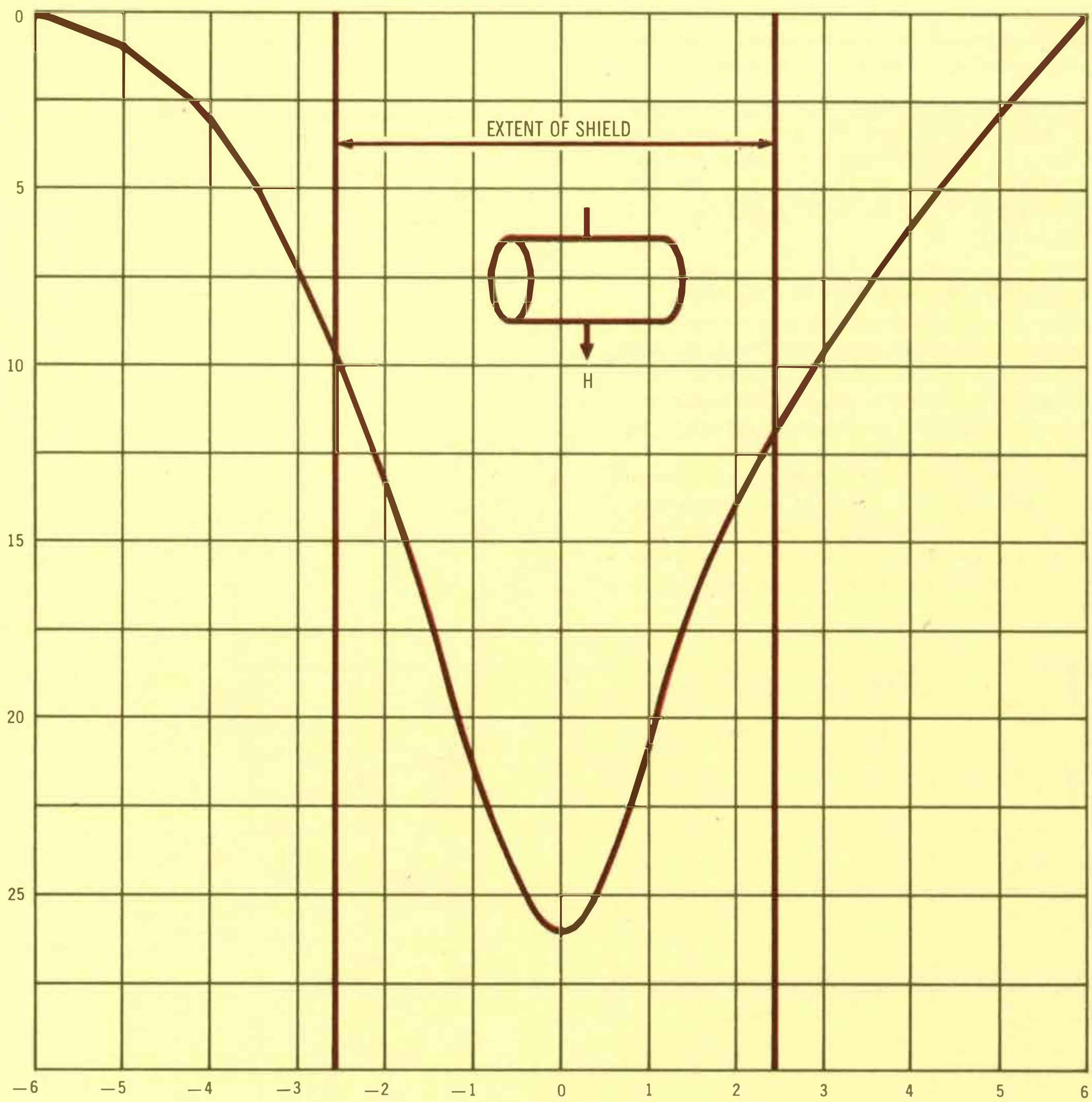


FIGURE 9

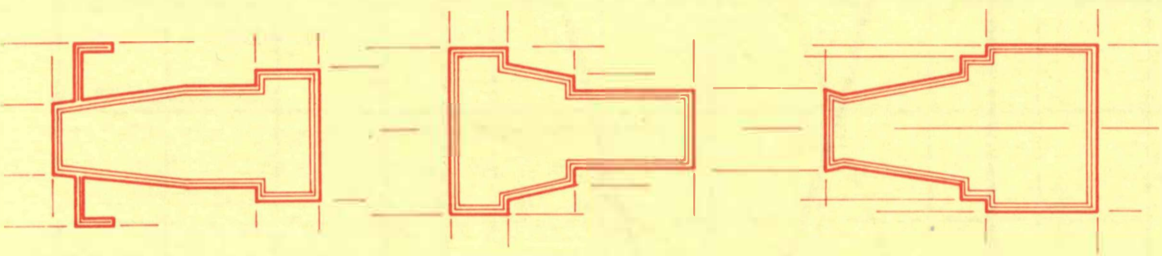
An obvious design tactic is to place the most sensitive area of the shielded device as close as possible to the center of the shield.

As examples of attenuation, Figures 10 and 11 show attenuations for single-cylindrical shields of Westinghouse HIPERNOM and HIPERNIK alloys at various field densities and thicknesses. Test shields for these data had an L/d ratio of 4.

E. SHIELD ORIENTATION IN THE FIELD

Thus far we have discussed only shields with axis perpendicular to the field. This is the optimum case and should be provided in component layout if at all possible. The worst case, from the standpoint of shielding efficiency, is the field parallel to the axis.

Teasdale (Ref. 7) found that both cylindrical and conical shields are much less efficient in axial fields. For example, shields which provided a shielding percentage of 93 percent in transverse fields provided only 60 percent in axial fields.



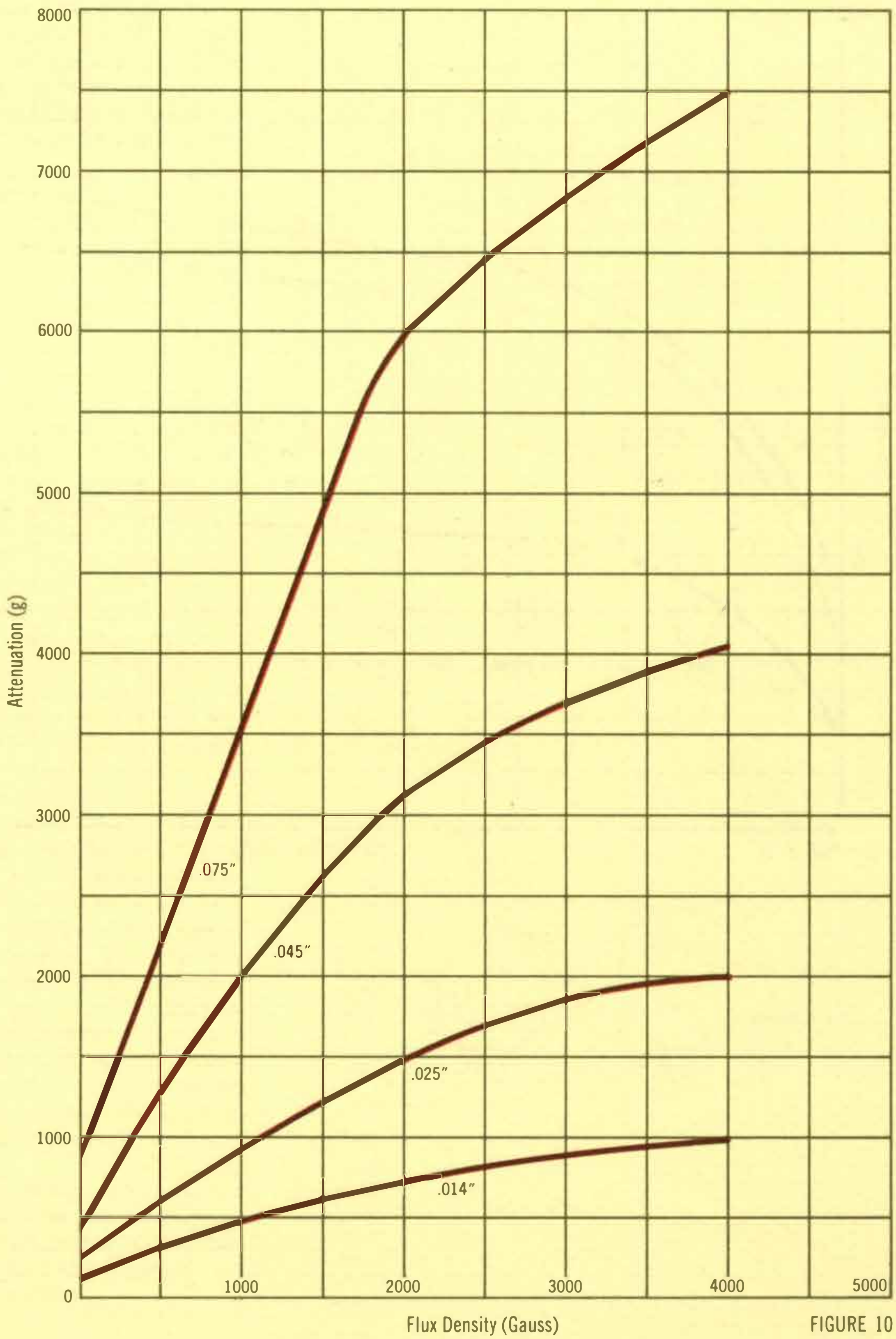
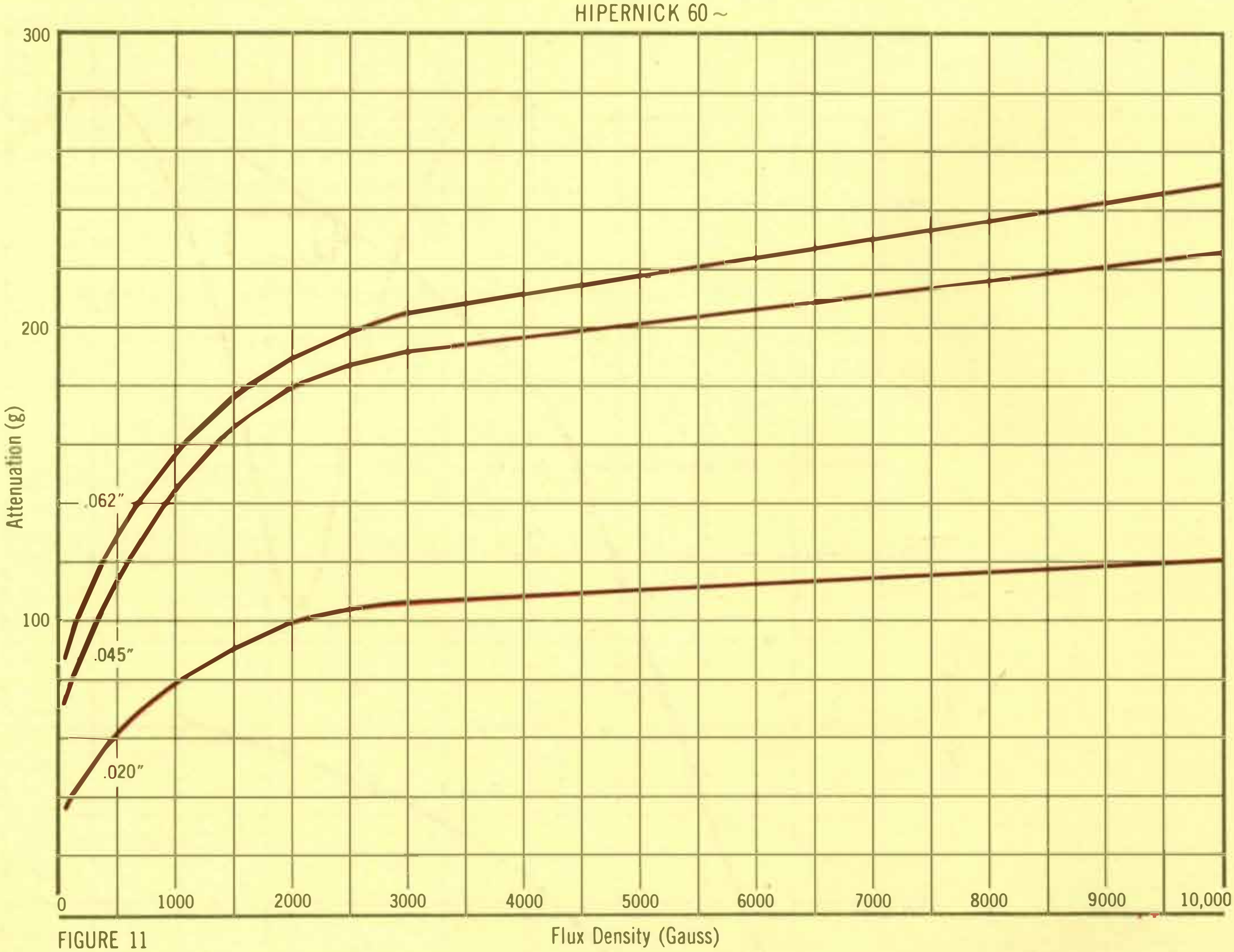

8000
7000
6000
5000
4000
3000
2000
1000
0
Attenuation (g)
.075"
.045"
.025"
.014"
1000
2000
3000
4000
5000
Flux Density (Gauss)

FIGURE 10


HIPERNICK 60~
300
200
100
Attenuation (g)
.062"
.045"
.020"
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10,000
Flux Density (Gauss)
FIGURE 11

The attenuation pattern of a cylindrical shield in an axial field is shown in Figure 12. There is no shielding by proximity for the axial case. In fact, the axial field is stronger off the edge of the shield than is the original field – the so-called "overshoot effect." All regions of importance, then, *must* be physically shielded in an axial field.

For fields impinging at some angle, θ, between the axial and transverse cases (see Figure 13), the effect can be estimated by multiplying the difference between axial and transverse attenuations by $\theta/90$, and subtracting this value from the transverse case.

If θ is greater than 45 degrees, capped ends should be considered. Geometrical considerations show that overhang might be excessively large for such angles. For θ less than 45 degrees, the designer must choose between increasing overhang slightly (see Figure 14) or capping the end. The geometrical consideration shown in Figure 14 is sufficient to make this decision, and to estimate the amount of overhang if the former course is chosen. The total overhang is approximately equal to the inside diameter times tan θ.

If openings are required in the ends for visual observations, for heat dissipation or to bring out electrical leads, a capped end with a minimum-sized hole in it is often used. Pin holes, mounting holes, and small openings for leads are sometimes incorporated in the sides of the shield as well. Such apertures should be minimized and should be physically turned to face away from the source of interference.

The optimum shield, of course, would be a sphere with no openings. Figure 15 compares the attenuations of spherical and very long cylindrical shields, providing a reasonable estimate of the improvement to be obtained with capped cylinders (completely enclosed shield). Notice that for very long cylinders (length-to-diameter ratio of 4 to 1 or better) in transverse fields, shielding efficiency is nearly the same as for completely enclosed shields.

In summary, the completely enclosed shield unquestionably provides the best attenuation. This advantage must be balanced against feasibility, fabricating costs and the easier construction of open-end shields.

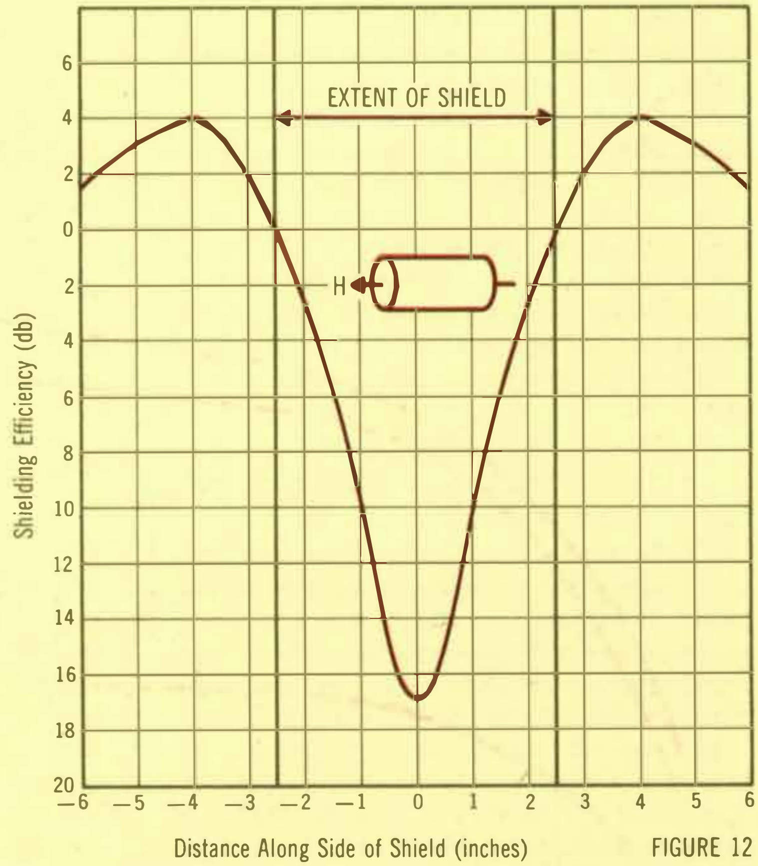
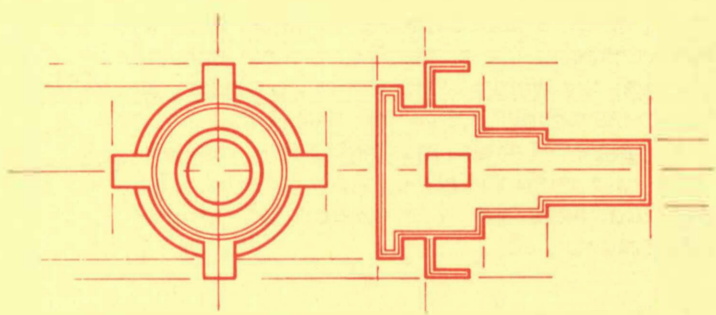


FIGURE 12



F. SHIELD FABRICATION

Cylindrical shields are most often formed from a blank of flat sheet metal. Placement of the welded joint with respect to the field must be considered in design. Because the point of greatest flux concentration falls where the shield is parallel to the field direction, joints should be turned 90 degrees to that point, where they will carry minimum flux. In any case, joints are the "weakest" part of the shield and should be kept to a minimum.

Fabricated shields are constructed in several ways:

a. Making drawn cans

b. Formed from sheet stock, with spot-welded lap joints

c. Formed with butt joints, heliarc welded.

The drawn can provides the best shield because it has no joints. Sizes are limited, however, because shielding materials harden rapidly in the drawing process. Generous radii must be provided to prevent tearing.

The second kind of shield is formed on brakes or rolls, with joints overlapped and spot welded. Generally a ⅜-inch overlap is recommended, spot welded at ½-inch intervals. Good fitting joints of this type are usually sufficient to exclude low frequency fields. Their disadvantage is that a double thickness of material is required at the joints, and some leakage may occur.

The third method, using heliarc-welded butt joints, provides a smooth can. It may, however, allow a discontinuity in shielding effectiveness at the seam. Fields may leak in, because the weldment is actually a casting of lower permeability than the shield metal.

A number of shield-making houses, besides offering a wide variety of stock shields, can provide detailed information on shield fabrication.

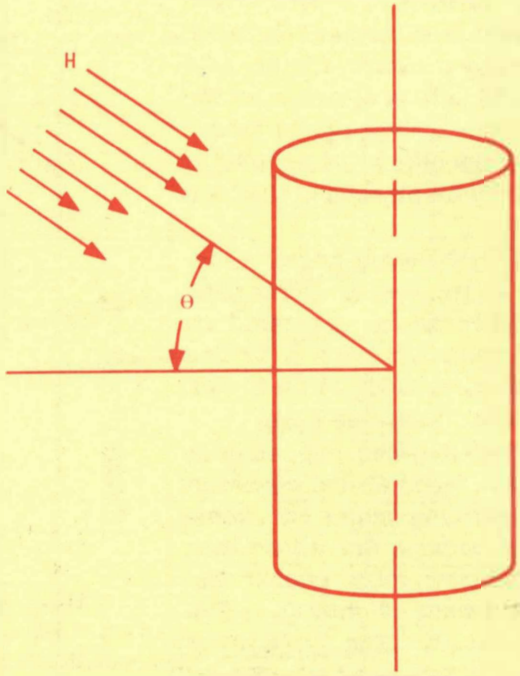


FIGURE 13

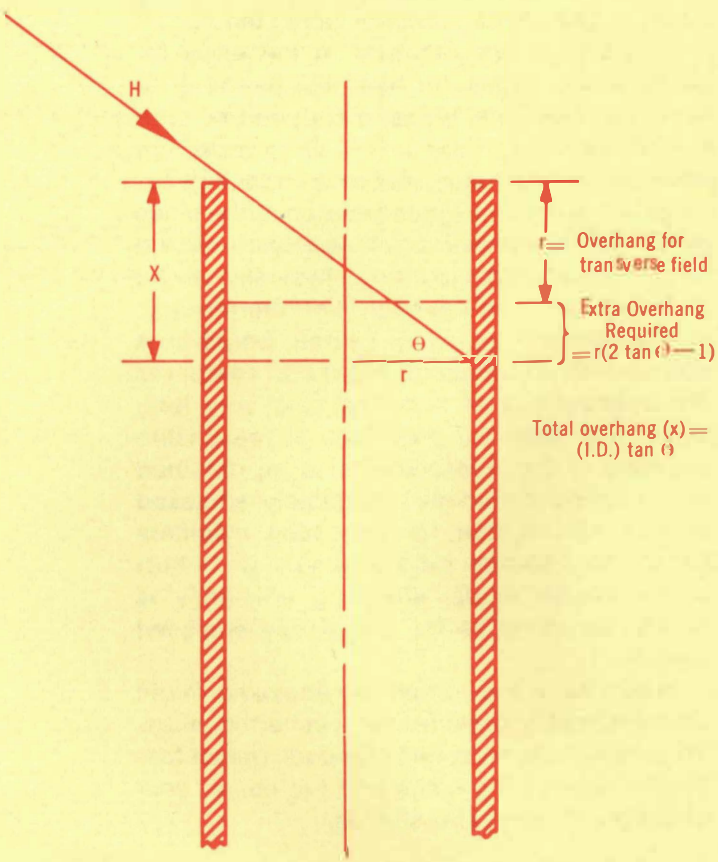


FIGURE 14

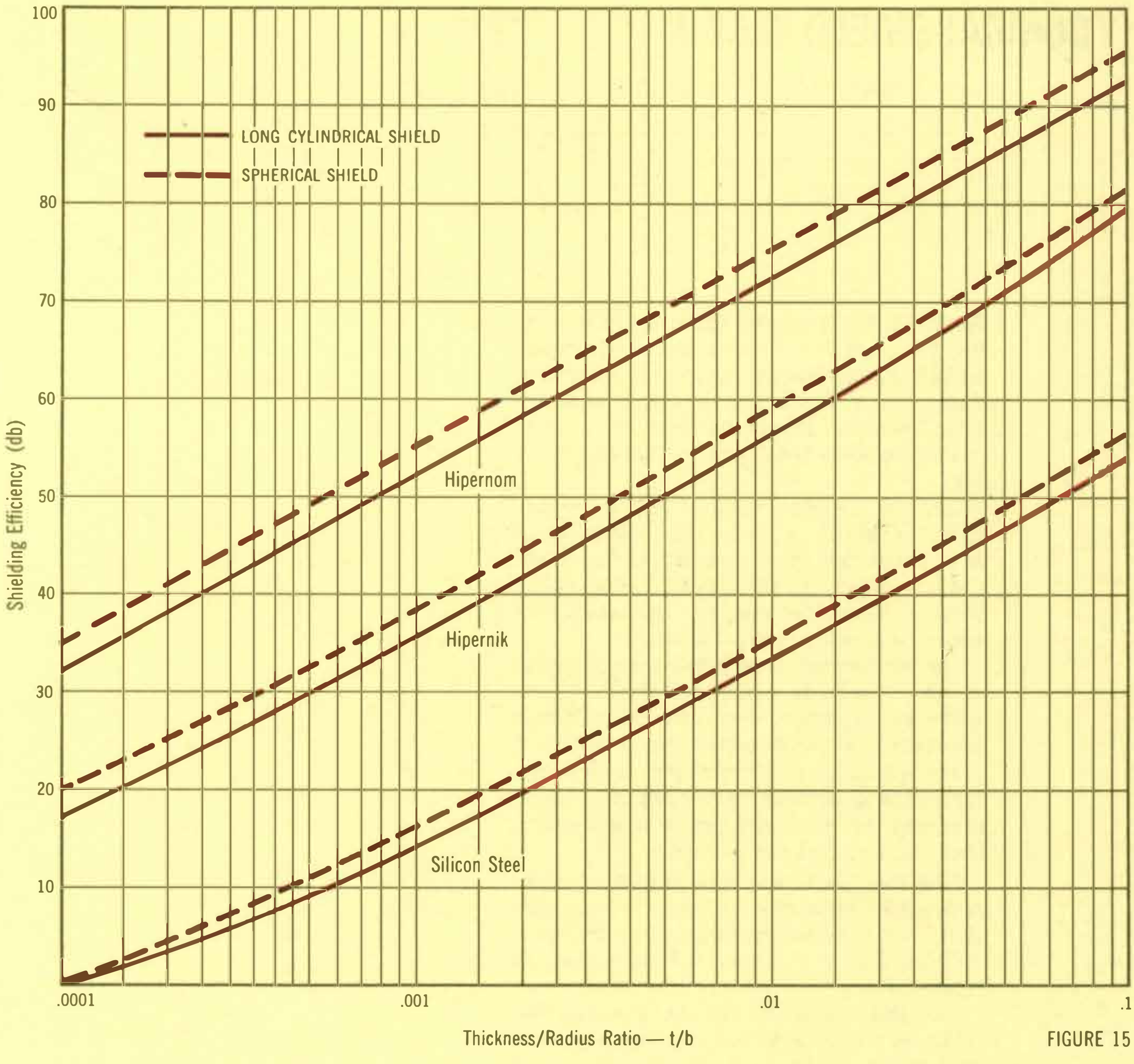

LONG CYLINDRICAL SHIELD
SPHERICAL SHIELD
Hipernom
Hipernik
Silicon Steel
Shielding Efficiency (db)
100
90
80
70
60
50
40
30
20
10
.0001
.001
.01
.1
Thickness/Radius Ratio — t/b

FIGURE 15

IV CONICAL SHIELD DESIGN

Generally, the principles applied to cylindrical shields apply to cones as well. The configuration of the shielded device will determine shield shape. The best shielding is obtained when the shield fits the contours of the components as loosely as possible (leaving an air gap).

Cathode ray tube shields often use the configuration shown in Figure 16a – essentially a three-piece design. If economy is important and space permits, the simple conical shape shown in Figure 16b may be substituted, considerably simplifying fabrication.

The attenuation pattern found by Teasdale for conical shields is shown in Figure 17. As might be expected, the point of maximum shielding is skewed toward the smaller end of the shield. As a rule of thumb for estimating overhang, assume that the region of "good shielding" for each end begins at a distance from that end equal to its radius.

Note that nickel-iron shields with a length-to-diameter ratio of 4 or better will provide considerably higher attenuation, but the characteristics of the pattern will be similar to Figure 17.

Teasdale also found that the shielding efficiency of a conical shield can be quite accurately estimated by averaging the efficiencies for two cylinders with t/b ratios equal to those of each end of the cone. For a transverse field, Teasdale found that the estimated efficiency varied from the measured efficiency by only about 2 percent.

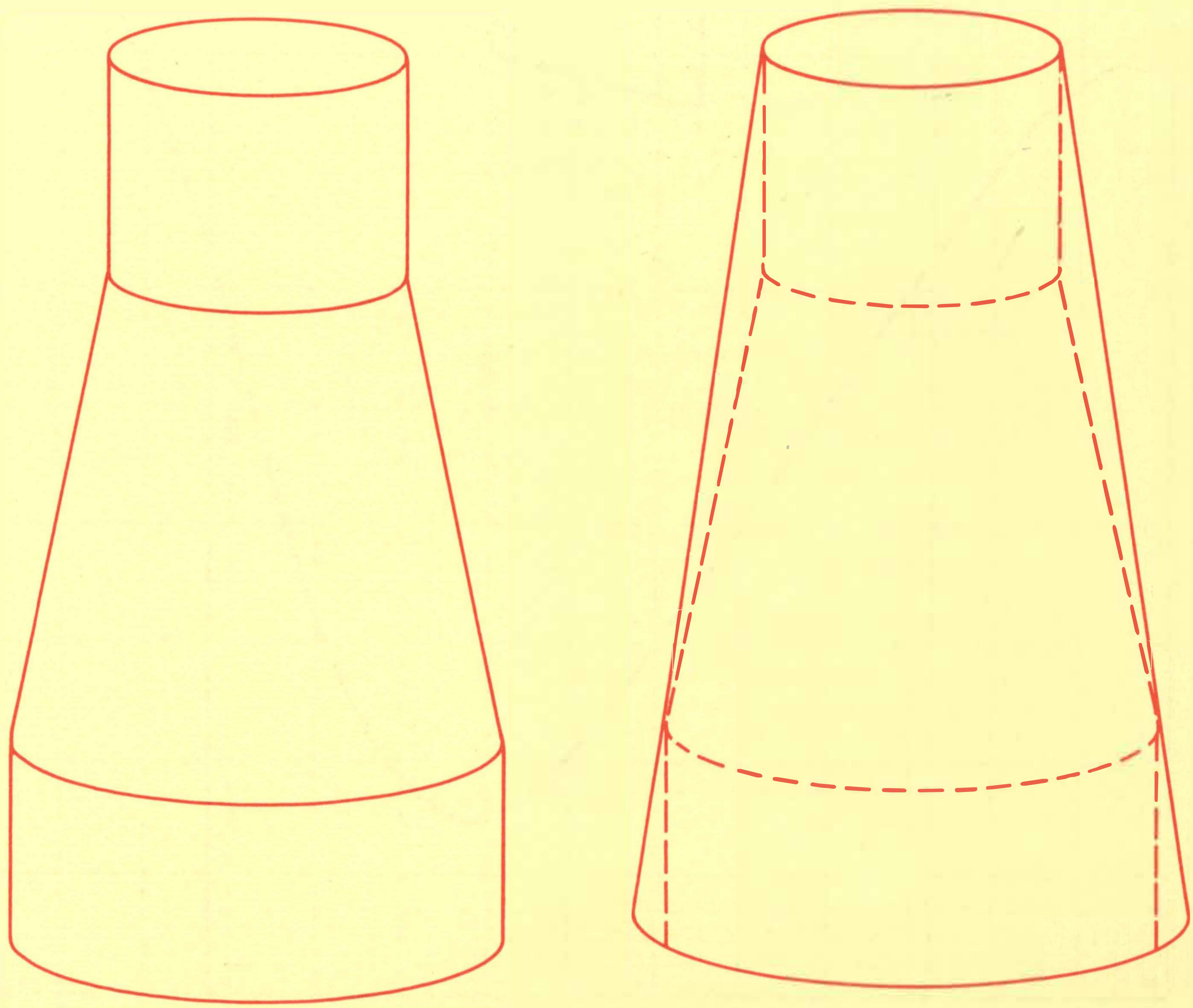
Fabrication

Fabrication of conical shields is much the same as for cylindrical ones. The same considerations apply, and the criteria for capped versus open ends are identical.

FIGURE 16

a. Typical CRT Shield

b. Conical Substitute



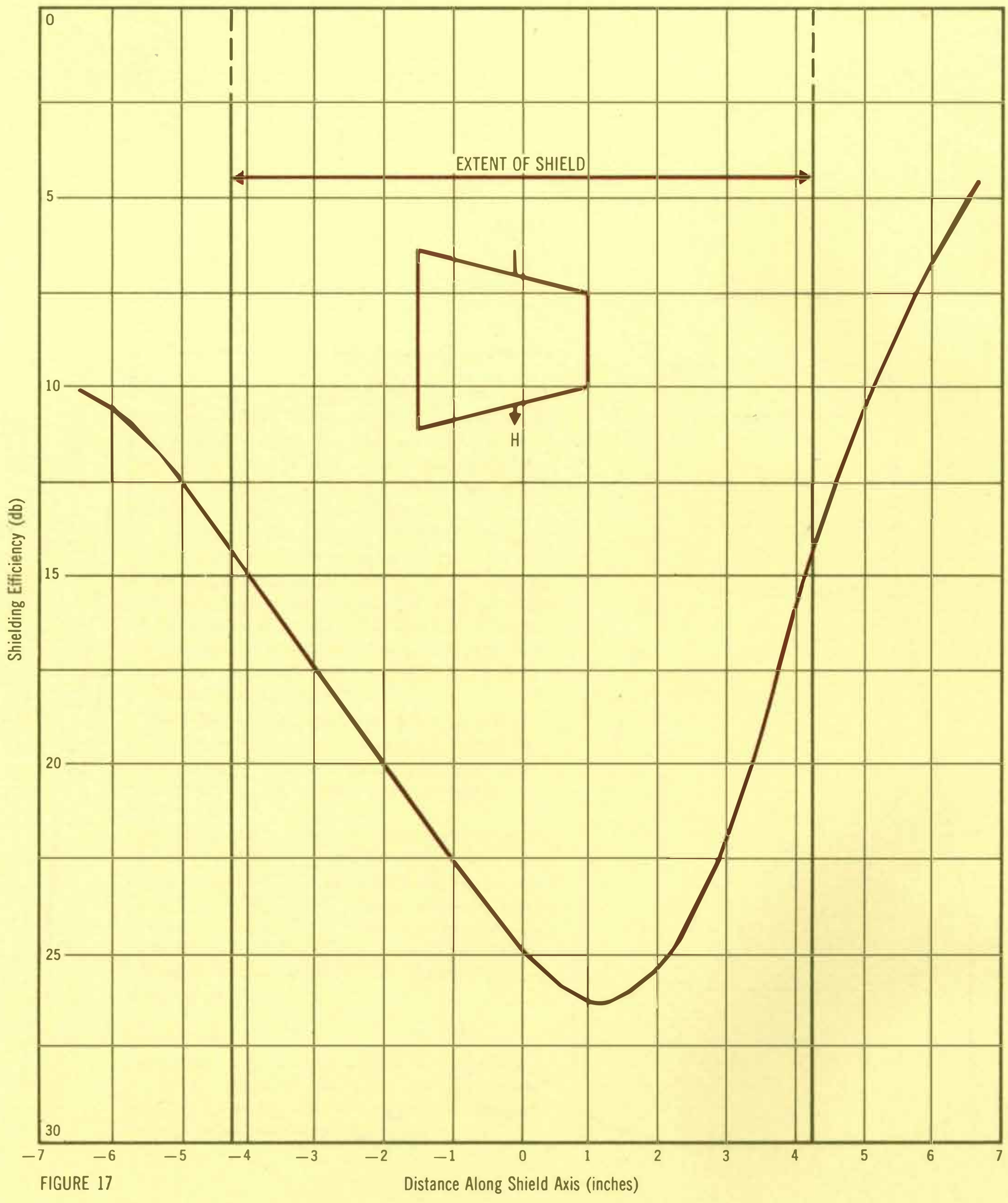
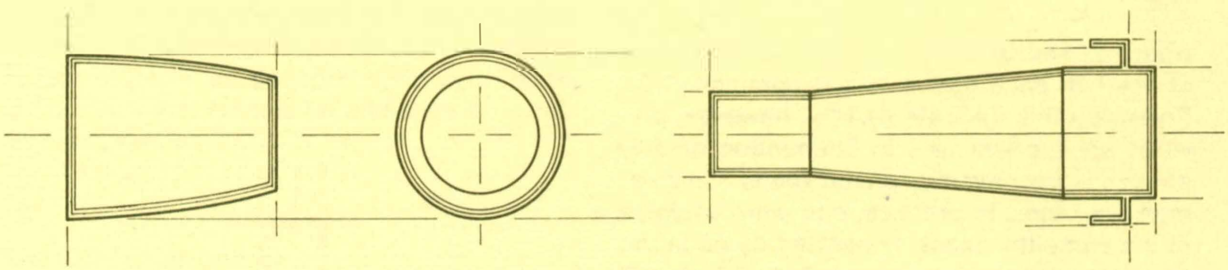

EXTENT OF SHIELD
H
Shielding Efficiency (db)
0
5
10
15
20
25
30
−7
−6
−5
−4
−3
−2
−1
0
1
2
3
4
5
6
7
Distance Along Shield Axis (inches)

FIGURE 17



V MULTIPLE (Nested) SHIELDS

In some cases, a single shield will saturate in a high-density field, cutting off its effectiveness, or else it must be made prohibitively thick to provide the required attenuation. The solution is to nest a number of thinner shields, separated by an air gap and preferably without physical (conductive) connections.

A. DESIGN CALCULATIONS

As a rule of thumb, multiple shields should be used for greatest efficiency when the thickness of a single shield exceeds $3a/2\mu$, where a is the inner radius of the shield and μ is its permeability. For optimum results, the consecutive ratio of inner and outer radii of nested shields should form a geometric series:

$$(11) \quad a_1/b_1 = b_1/a_2 = a_2/b_2 = b_2/a_3 = \ldots = a_n/b_n = K$$

where a_i and b_i are the inner and outer radii of the i th shell and K is the common ratio. Following this intricate system, however, provides an improvement in attenuation of only about 4% over evenly-spaced shells of a common thickness. In practice, concentric shields of the same thickness, separated by equal air gaps, are satisfactory, and only this type will be considered here.

D-C Fields

In the d-c case, the basic formula for attenuation of a nest of three shields made of the same material is:

$$(12) \quad g = (\mu/4)\{(1 - q_1q_2q_3) + (\mu^2/16)\, n_1\, n_{12}\, n_2\, n_{23}\, n_3$$
$$+ (\mu/4)\,[n_1\, n_3 + n_1\, n_2 - n_1\, n_2\, n_3]\, n_{12}$$
$$+ (n_1\, n_3 + n_2\, n_3 - n_1\, n_2\, n_3)\, n_{23} - n_1\, n_2\, n_{12}\, n_{23}]\}$$

where $q_i = \dfrac{a_i^2}{b_i^2}$, $q_{ij} = \dfrac{b_i^2}{a_j^2}$, $n_i = 1 - q_i$, and $n_{ij} = 1 - q_{ij}$.

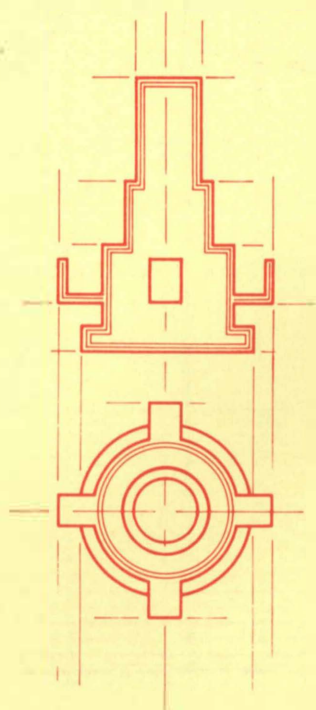
For a double shield this formula reduces to:

$$(13) \quad g = (\mu/4)\{(1 - q_1\, q_2) + (\mu/4)\, n_1\, n_2\, n_{12}\}$$

Using these expressions, the attenuation value for a nest of shields can be easily determined using a desk calculator. For nests of four or more shields, use the recursion formulas developed by Sterne (Ref. 4) and simplified by Walker (Ref. 5).

A number of practical points are worth noting. If the outer shield of a nest would be saturated by the field, an outer shell of lower-permeability material having a higher saturation value is used. For example, an outer shell of HIPERNIK (50 nickel-iron) alloy might enclose a shell of HIPERNOM (80 nickel-iron) alloy. Attenuations are calculated as for two single shields.

"End effects" for multiple shields are much the same as for a single shield, allowing for the higher levels of attenuation obtained.



A-C Fields

In a-c fields, the reflection loss factor becomes significant for multiple shields, because of the numerous metal-air or metal-metal interfaces involved. The basic formula, S.E. = R + A remains in effect. For nested shields the absorption loss, A, is given by

(14) $$A = \Sigma A_j,$$

where $A_j = 8.686\ \alpha\ t$, and α is defined as before.

The total reflection loss, R, is given by

(15) $$R = \sum_{j=1}^{n} 20 \log_{10} \frac{K_j + 1^2}{4\ K_j}, \text{ and}$$

(16) $$K_j = Z_1/Z_2$$

Z_1 and Z_2 are the impedances of the two media at the interface where reflection occurs (usually either metal/air or metal/metal). These relations account for reflection losses at *both* faces of each shell and should *not* be be multiplied by 2.

For a metal,

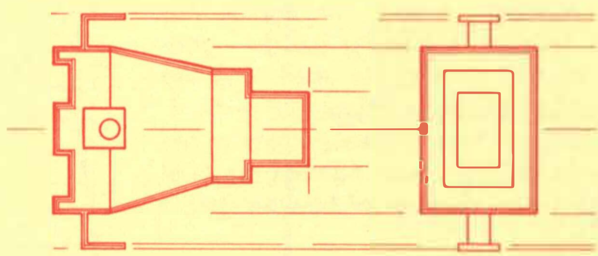
(17) $$Z = (2\pi F u 1/g)^{1/2}$$

and for a good dielectric,

(18) $$Z = 2\pi F uri$$

Where r is radius in cm, i is the square root of minus one, and the other terms are as defined in Part III-B above.

Note that equations (15) and (16) allow for calculating reflection losses in single shields, if this factor is thought to be significant.



B. SHIELD DESIGN

Selection of materials for nested shields is covered in Section II. The materials chosen may be the same for each shell, or may be a combination of high and low permeability materials.

When a device is to be protected from external fields, the lower-permeability material is placed outside to reduce the field to levels which will not saturate the higher-permeability shell. For shields designed to prevent equipment (such as power supplies) from propagating interference, the lower-permeability material is placed on the inside.

In practice, making the air gap between shields larger than 0.25 inch offers little advantage. The gap size becomes less and less critical as field intensity increases. As pointed out above, adjusting the gap by the formula of radii increasing in geometric series offers little advantage in attenuation—constant gaps between shells are nearly always used.

Separation between shells is achieved in several ways. Mounting may be adjusted to provide the air space. Kraft paper, in thicknesses such as .010 inch, may be used for separation. Spacers of non-magnetic materials such as aluminum, copper or brass are often used. In some applications, a sprayed layer of copper is inserted between shells to provide electrostatic shielding. Laminates of magnetic and high-conductivity materials are used to extend magnetic and electrical shielding into the higher frequencies.

Ideally, the optimum nested shield would be a large number of very thin shells. For mechanical reasons, a heavier gauge – generally .014 to .045 inches – is used, and the required number of shells calculated accordingly. The designer must balance costs of the larger number of thin shells against material costs for the lesser number of heavier-gauge shields.

VI WRAP AROUND SHIELDS

For smaller components, foil material is simply wrapped around the device, which is then potted or encapsulated, providing a very efficient multiple shield. Components commonly shielded in this manner include small transformers, tubes, choppers, reactors, and cables.

From the design calculation standpoint, these are simply multiple shields consisting of a series of very thin shells. The equations of Section V can be used to calculate attenuation, but it is usually simplest to procure a small quantity of foil shielding material, actually wrap the device, and measure the performance obtained.

Figures 18 and 19 show attenuations achieved with various numbers of wraps and various thicknesses of HIPERNOM foil. These are experimental data, taken with metal wrapped around a 4-inch square by 12-inch long form. Considerably better attenuations can be expected from cylindrical wrappings or enclosed wrappings.

The right thickness and number of wraps needed to achieve a required level of attenuation can be read directly from Figures 18 and 19. For further technical information on HIPERNOM and HIPERNIK alloys, see Westinghouse data sheets 52-161 and 52-162.

By cross-wrapping, as shown in Figure 20a, an almost completely enclosed shield can be obtained. Cables are easily shielded by wrapping as shown in Figure 20b.

If field levels tend to saturate the higher-permeability foil such as HIPERNOM, an outer layer of several wraps of lower permeability material (HIPERNIK) can be used.

Wrap around shielding is one of the most versatile, effective, and space-saving shielding techniques available.

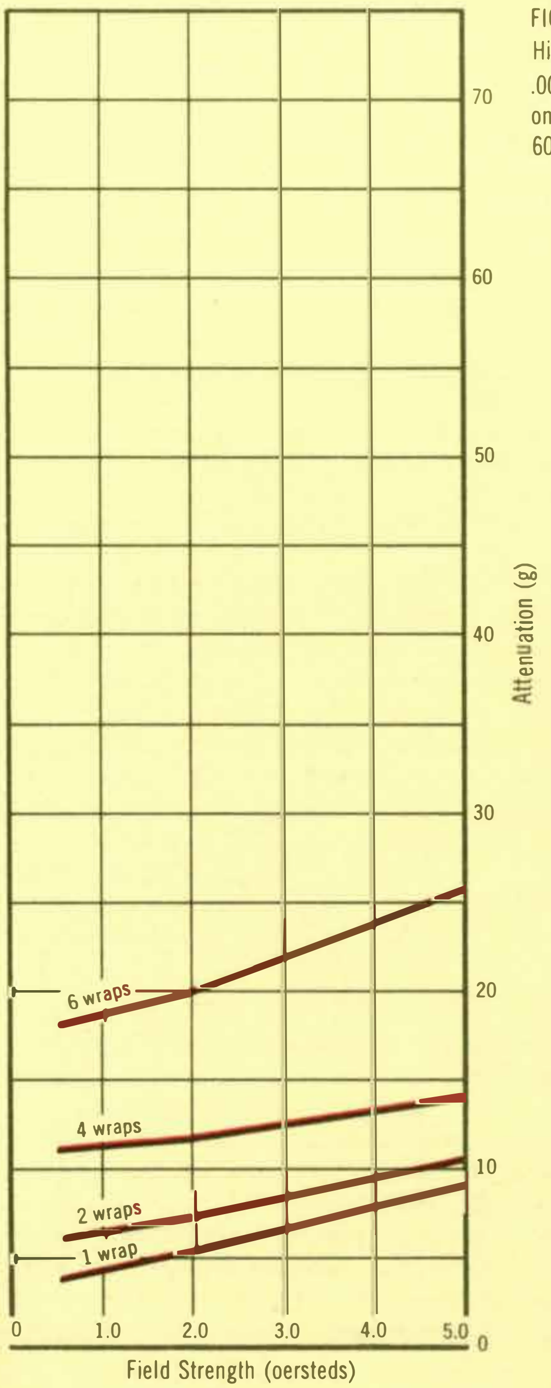


FIGURE 18
Hipernom alloy, .004" thick, tested on square form at 60 cps.

FIGURE 19
Hipernom alloy, .006" thick, tested on square form at 60 cps.

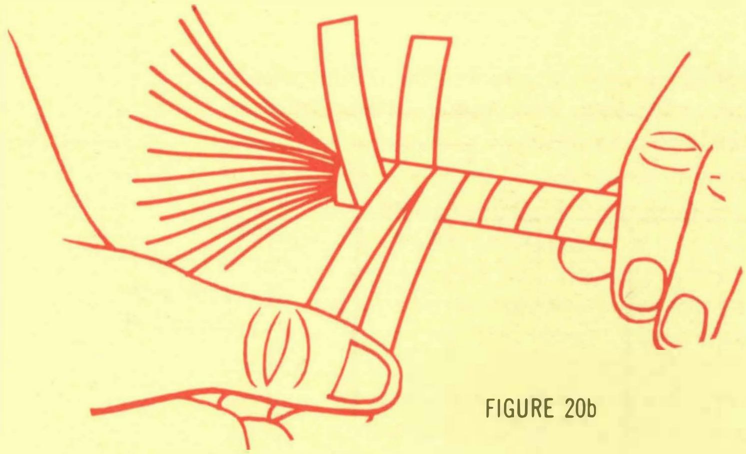


FIGURE 20b

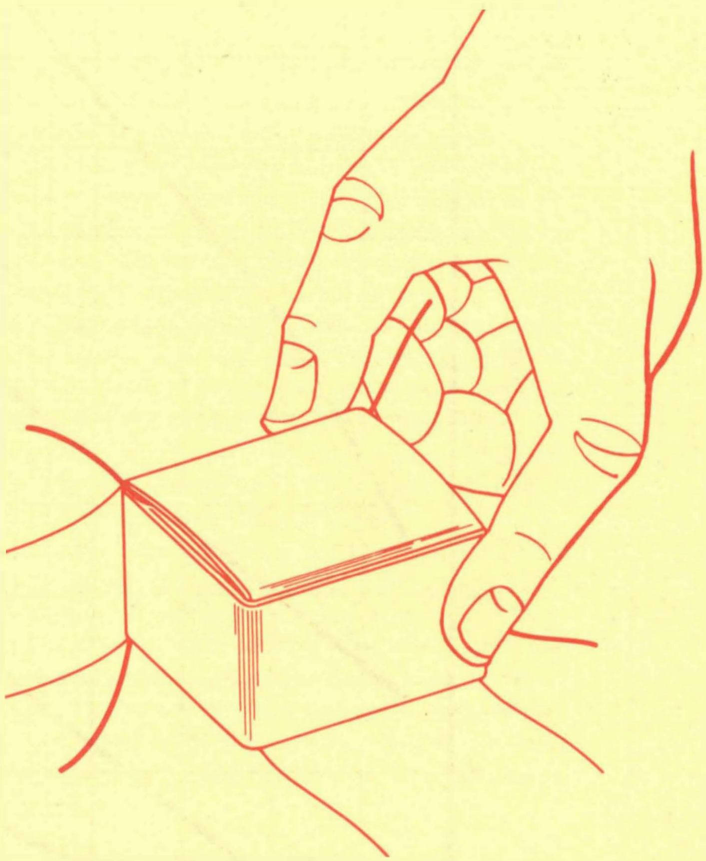
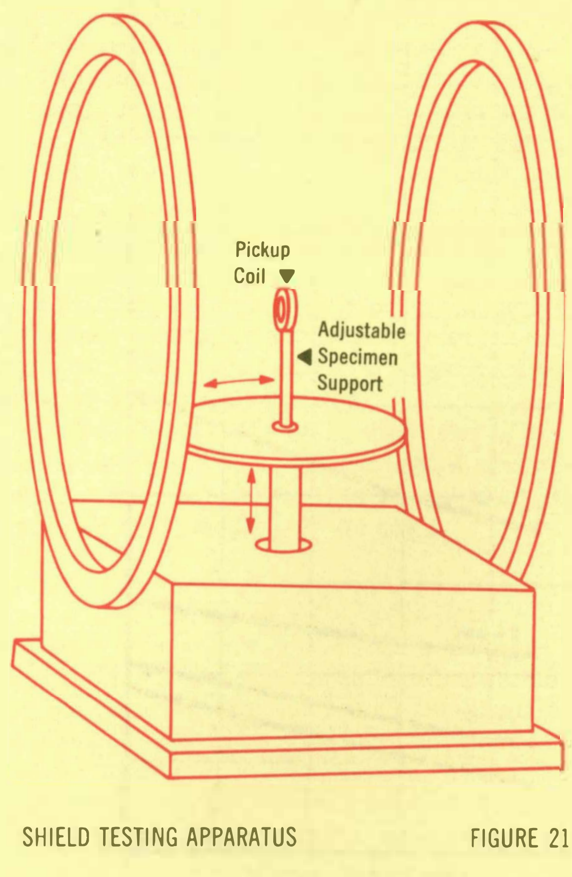


FIGURE 20a



SHIELD TESTING APPARATUS FIGURE 21

VII EVALUATING SHIELD PERFORMANCE

As might be expected, the calculated attenuation values for any given shield usually turn out to be somewhat different from the actual values measured after the shield is constructed. This variance stems partly from the limiting assumptions of the theory, partly from normal variations in commercially-produced metals, and also from joints, apertures, and discontinuities in the fabricated shield. For these reasons, it is wise to actually fabricate prototype shields once a design has been formulated, and to test them as outlined below, before putting them into production.

ASTM specification 346-64, "Standard Methods of Test for Magnetic Shielding," outlines a standard shield test procedure. To summarize briefly, the standard test apparatus (Figure 21) consists of two four-foot diameter Helmholtz coils set coaxially and separated by a distance equal to the coil radius. Forty-eight turns of #14 varnish-insulated wire are wound on a cylindrical form, and the coils are connected series aiding.

This arrangement produces a uniform field midway between the coils equal to:

(19) $$H = 0.8992 \frac{NI}{R}$$

Where N is the number of turns per coil (=96), I is the d-c or a-c peak current, and R is the mean radius of the coils in cm.

The pickup coil is wound to have a value of area turns of 50,000 sq. cm. turns, and is covered with thin non-magnetic foil (copper or aluminum) which is connected to system ground. Pickup diameter is less than ½ the test specimen diameter, and less than one-tenth the Helmholtz coil radius.

Most tests are conducted, for greatest accuracy, with d-c current or at 60 cps. A vacuum-tube voltmeter is used to measure the induced voltage in the pickup coil before and after insertion of the test shield. The attenuation, g, is read directly as:

(20) $$g = \frac{E_1}{E_2}$$

Where E_1 is voltage measured without the shield in position and E_2 is measured with the test shield in place. The shielding efficiency in decibels can be calculated from Equation (2) in Section II.

The test should be conducted in a place where stray magnetic fields are minimized. Stray pick-up voltage should be very small compared to test voltage (at least 1 to 100). The VTVM should be isolated from field-generating equipment such as oscilloscopes. Care must be taken to insure that the shield is the only magnetic material present – watch out for metal stools, benches, carts, tools, other test specimens, file cabinets, etc. which are near the test coils.

The shield itself should be demagnetized before testing. Handle it carefully, because all high-permeability materials are somewhat strain-sensitive. For reproducibility of results, the shield should be demagnetized between each test, to eliminate residual fields in the shield.

During testing, the shield should be kept entirely within the uniform field. Portions protruding from the field will give inaccurate results.

For complete details of the procedure, consult ASTM Specification 346-64.

VIII HEAT TREATMENT AFTER FABRICATION

High permeability materials are strain-sensitive in proportion to their permeabilities. Fabrication or processing will reduce shielding effectiveness. In the case of very high permeability materials, rough handling or physical deformation will do the same. Thus, to obtain the optimum properties of the material, fabricated shields must be given a final heat treatment after all processing is complete.

The annealing procedure requires an atmosphere of dry hydrogen or dissociated ammonia, with a dew point of at least −50°C (−58°F). Recommended temperature for HIPERNOM is 1150°C (2100°F) for four hours; for HIPERNIK, 1175°C (2150°F) for four hours.

Controlled cooling rates are essential to develop maximum inherent magnetic properties. Figure 22 shows the effect of cooling rate on the permeability of HIPERNOM alloy. Recommended cooling rates are 5°C per minute (9°F per minute) to 300°C (575°F) for Westinghouse HIPERNOM and HIPERNIK alloys.

Because annealing at these temperatures may cause welding, the shields in the annealing box should be separated by a pure calcined oxide of aluminum powder or similar substance. The shields should also be arranged and (if necessary) supported, to prevent distortion during the anneal. They should be removed carefully, to avoid handling strains which might adversely affect high permeability alloys.

Care should be taken during annealing to avoid contamination of the alloy. In addition, sulphur-bearing lubricants should be avoided during fabrication, and shields should be thoroughly degreased before heat treatment.

For further details of heat treatment, see Westinghouse Technical Data Bulletins 52-161 and 52-162.

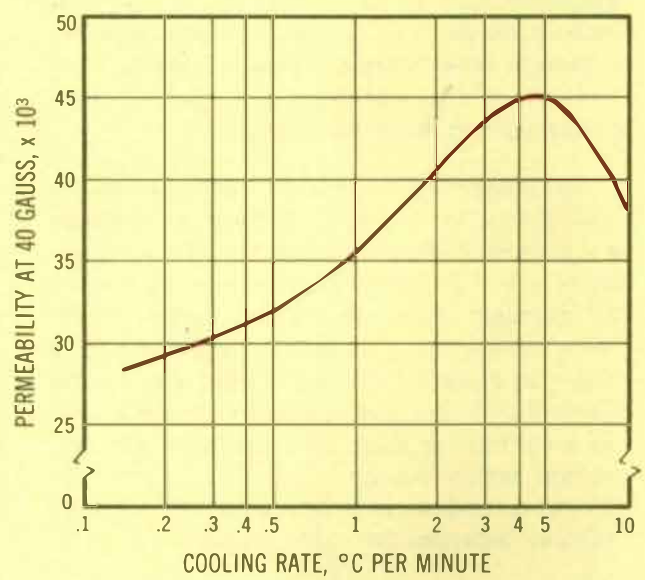


FIGURE 22 Effect of final-anneal cooling rate on permeability of HIPERNOM alloy — (.014" thick).

BIBLIOGRAPHY

Many of the techniques and theories discussed in this manual are covered in greater depth in the references below. Although excellent shields can be designed using the techniques covered, designers facing unusually complex problems will want to consult the following:

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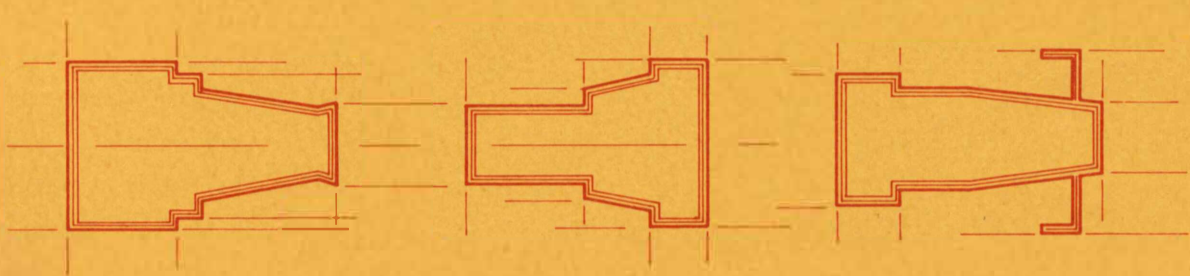

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