Magnetic Shielding of Transformers at Audio Frequencies

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The first part of this article is a descriptive discussion of magnetic shielding in general. Formulae are then given for the calculation of shielding efficiency of cylindrical shells for steady and alternating magnetic fields. By means of these formulae the shielding efficiency for various types of cylindrical shields has been calculated for a steady magnetic field.

The second part of the article contains experimental information on various types of transformer shields. This information supplements the theory in connection with factors which would be very laborious to treat theoretically.

The theory and the experimental data are coordinated in such a manner that the shielding efficiency of a particular shield can be calculated with an accuracy which is sufficient for practical purposes.

IN connection with the development of repeaters for long distance telephone lines it is found that noise is introduced into the telephone lines due to magnetic pick-up by transformers and coils in the repeaters. This applies also to sound pictures equipment, public and private address systems, etc., where high gain amplifiers are used. The stray magnetic field causing this pick-up may be produced by neighboring generators, transformers, rectifiers and other power equipment. It may also be produced by other amplifier transformers and coils or by relays located in the vicinity of the disturbed coil. The intensity of the disturbing field may frequently be of the order of 0.1 oersted at the point of pick-up. However, a field intensity of the order of 0.02 oersted often causes objectionable noise and under extreme conditions values as low as 0.001 oersted may be undesirable. As the gain of the amplifier increases and the demand for good quality becomes greater, it becomes increasingly important to control magnetic pick-up. The limiting of this pick-up is in fact today one of the important problems to be considered in the design of high-gain amplifiers.

One method by which the magnetic pick-up can be decreased is by arranging the core structure and winding distribution of the transformer in such a way that the voltages induced by an external field are at least partially neutralized. In many cases, however, this impairs other important characteristics of the transformer and is therefore undesirable.

Another method is by shielding the transformer from the disturbing magnetic field. It is the object of this paper to consider such shielding and to present some data in this connection that may be of general interest.

Theory

When a transformer is placed in an a.c. magnetic field, there will, in general, be a voltage induced in the windings. This voltage is proportional to the intensity of the magnetic field. Therefore, if the intensity of the magnetic field in the space occupied by the transformer is reduced, the induced voltage will be correspondingly reduced. This can be accomplished by enclosing the transformer in a case made of material which shields against magnetic flux. Let H_i be the intensity of the field inside the case and H_e the intensity of the field when the case is removed. The ratio H_e/H_i will then indicate the shielding efficiency of the case. Expressed in decibels:

$$\text{Shielding efficiency} = 20 \log_{10} H_e/H_i. \tag{1}$$

The shielding efficiency of the case depends primarily upon the permeability and conductivity of the material, and the mechanical construction of the case.

A high permeability material provides a magnetic path in the walls of the case of much less reluctance than the air space inside the case. The greater part of the flux will, therefore, follow the low reluctance path, and only a small part will enter the space inside the case. The higher the permeability is, the less the flux that will enter the space inside the case.* With a steady magnetic field all the shielding is due to this cause.

An alternating magnetic flux induces eddy currents in the material of the case as shown in Fig. 1. These eddy currents are a function of the conductivity and permeability of the material. They may increase or decrease the shielding efficiency of the case. That is, the eddy currents i_{e1} (Fig. 1), which are due to the component of the magnetic field perpendicular to a wall of the case, will set up a counter mmf. which will oppose flux entering the case. In a copper case, the shielding is primarily due to such eddy currents. On the other hand, the eddy currents i_{e2} (Fig. 1), which are due to the component of the field parallel to a wall of the case will set up a counter mmf.

* It is assumed here, of course, that the source of the magnetic flux is at some distance so that the amount of flux leaving the source is not appreciably affected by the case.

which will oppose the flux following the low reluctance path in the walls of the case, or what is the same thing, decrease the effective permeability of this path and will, in that way, decrease the shielding efficiency. In a case made of high permeability material the latter eddy currents, i_{e2}, obviously should be reduced as much as possible.

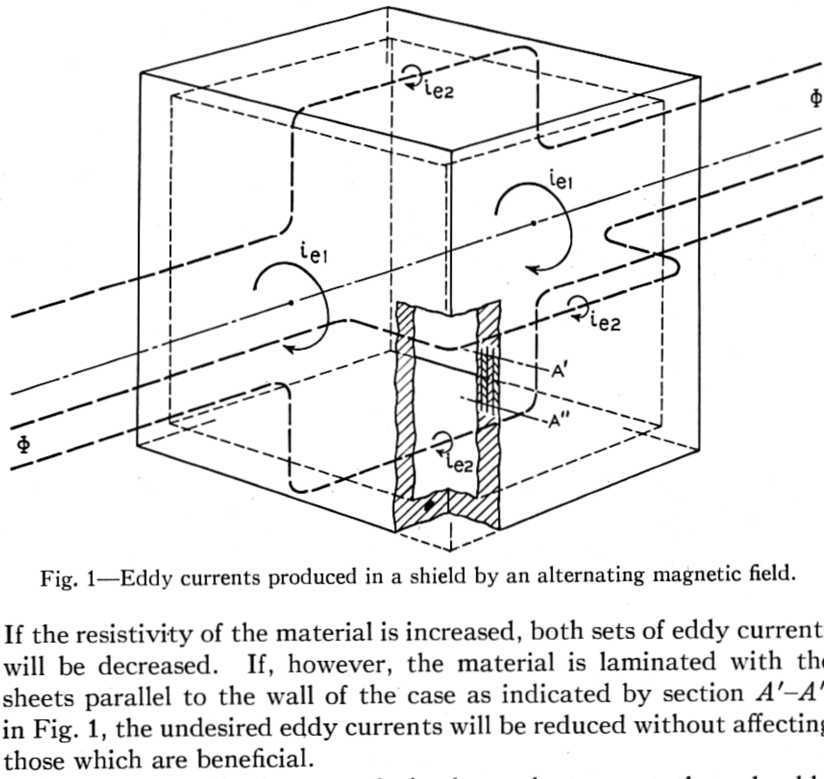

Fig. 1—Eddy currents produced in a shield by an alternating magnetic field.

If the resistivity of the material is increased, both sets of eddy currents will be decreased. If, however, the material is laminated with the sheets parallel to the wall of the case as indicated by section A'–A'' in Fig. 1, the undesired eddy currents will be reduced without affecting those which are beneficial.

The relative effectiveness of the low reluctance path and eddy currents in securing good shielding efficiency against magnetic fields depends mainly upon the frequency of the magnetic field. As a general rule, we can say that at low frequencies, the effect of the low reluctance path predominates, while the shielding effect of the eddy currents, i_{e1}, increases as the frequency increases.

This way of looking at the effect of permeability and conductivity in a magnetic shield is intended to be purely descriptive and probably would not be practicable for a mathematical treatment. It is, however, very suggestive to the design engineer.

As an illustration of the way in which the mechanical construction of the case may affect the shielding efficiency it is at once clear that the ratio between the reluctance of the magnetic path in the walls around the case and the path through the interior of the case depends upon the size of the case. Also, any openings in the case will obviously affect its shielding efficiency.

When a magnetic transformer core is placed inside the case, the reluctance through the interior of the case will decrease and the shielding efficiency of the case will also decrease. It is therefore evident that with one type of magnetic core a case might have a different shielding efficiency than with another.

To obtain general mathematical relations between the shielding efficiency and the various factors mentioned above is very difficult. By making some simplifying assumptions, however, relations can be obtained that will be useful from a practical standpoint, although they will necessarily be somewhat limited in application.

A great deal of work on the shielding efficiency of shields constructed of different magnetic materials has been done by various investigators.* Except in a few of the more recent papers,† consideration has been restricted to a steady, uniform, magnetic field where no eddy currents are produced and where, therefore, the shielding is due entirely to the magnetic properties of the material. They have also usually limited themselves to spherical and cylindrical shields. The cylinders have been considered of infinite length with the direction of the disturbing magnetic field perpendicular to the axis of the cylinder. However, with cylinders of finite length they have found that for moderate shielding efficiencies, at points inside a cylinder at a distance from the end equal to its diameter the shielding efficiency is approximately that of an infinite cylinder. The ratio between the shielding efficiency of a cylinder and that of a sphere, the radii of the two, the permeability, the thickness and construction of the walls being the same, varies from approximately 4 : 3 in favor of the sphere for very thin shells to 9 : 8 in favor of the cylinder for very thick shells. This gives some idea of how the shape of the shield affects the shielding efficiency.

Investigations by the various investigators referred to above show that the shielding efficiency of two or more concentric cylinders or spheres may be vastly greater than that of one cylinder or sphere, the amount of magnetic material being the same. They have given mathematical relations between the shielding efficiency, the permeability and the mechanical dimensions of both spheres and cylinders. Although these relations have been derived for a steady magnetic field, they may also be applied with certain limitations to an alternating

* See Bibliography.

† The most important exceptions are articles No. 18, 19, 21, and 28 in the Bibliography.

magnetic field. The permeability used in this case will, of course, be the effective permeability for the particular conditions and frequency under consideration. These relations refer only to that portion of the shielding effect which is independent of the eddy currents i_{e1} (Fig. 1), and the total shielding effect will, in general, be somewhat greater.

In an article in the *Physical Review* of October, 1899, A. P. Wills considers the cases of three concentric cylinders and spheres. Due to the fact that spherical shields are less suited for our purpose I will give the equations for cylindrical shields only. Wills' formula for three cylinders for large values of permeability is given by the following equation:

$$g = 1/4\,\mu\,\{(1 - q_1q_2q_3) + 1/16\,\mu^2 n_1n_{12}n_2n_{23}n_3 + 1/4\,\mu[(n_1n_3 + n_1n_2 - n_1n_2n_3)n_{12} + (n_1n_3 + n_2n_3 - n_1n_2n_3)n_{23} - n_1n_3n_{12}n_{23}]\} + 1. \quad (2)$$

In this equation

$$g = \frac{H_e}{H_i}, \quad (3)$$

where H_e is the density of the magnetic field at a point P with the shield removed and H_i is the density of the magnetic field at that point when enclosed by the shield. μ is the permeability of the material at the frequency in question. We have

$$\begin{aligned} q_1 &= r_1^2/R_1^2, & n_1 &= 1 - q_1, \\ q_2 &= r_2^2/R_2^2, & n_2 &= 1 - q_2, \\ q_3 &= r_3^2/R_3^2, & n_3 &= 1 - q_3, \\ q_{12} &= R_1^2/r_2^2, & n_{12} &= 1 - q_{12}, \\ q_{23} &= R_2^2/r_3^2, & n_{23} &= 1 - q_{23}, \end{aligned} \quad (4)$$

where r_1, R_1, r_2, etc., are the various radii of the cylinders as shown by Fig. 2.

By making $q_3 = 1$ (or $n_3 = 0$), in (2), we get the relation for two concentric cylinders.

$$g = 1/4\,\mu(1 - q_1q_2 + 1/4\mu n_1n_2n_{12}) + 1. \quad (5)$$

By making $q_2 = 1$ (or $n_2 = 0$), (5) changes into an equation for one shell only

$$g = 1/4\,\mu(1 - q) + 1. \quad (6)$$

It has been shown (A. P. Wills, *Phys. Rev.*, vol. 24, page 243, February 1907) that for a shield of predetermined size, that is when the smallest and the largest radii (r_1 and R_3 in the case of three cylinders, Fig. 2) are specified, the radii of the surfaces of the successive

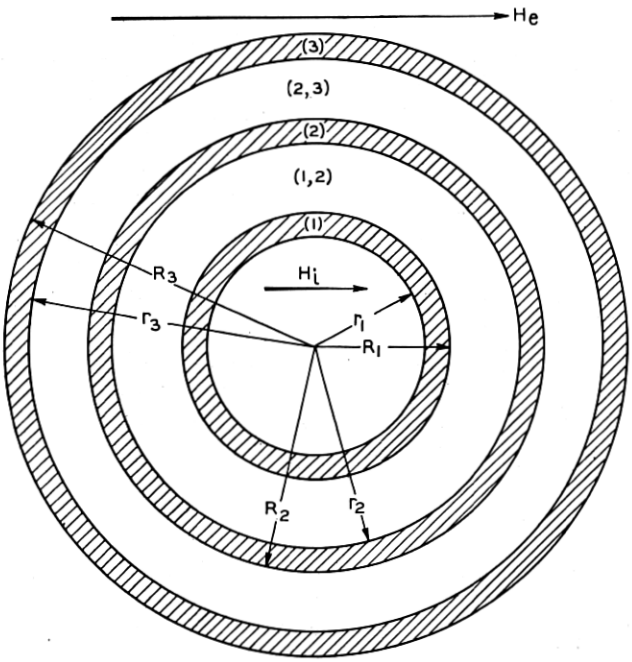

Fig. 2.

cylinders should be in a geometric progression to give the most efficient shield. That is, we should have $q_1 = q_2 = q_3 = q_{12} = q_{23} = q$. Equation (2) then becomes

$$g = 1/4\ \mu(1 - q^3 + 1/16\ \mu^2 n^5 + \mu n^3 + 3/4\ \mu n^4) + 1. \tag{7}$$

For two cylinders we get

$$g = 1/4\ \mu(1 - q^2 + 1/4\ \mu n^3) + 1. \tag{8}$$

In these equations, the following relations hold between r_1 and R_3 for (7) and r_1 and R_2 for (8)

$$R_3 = r_1/\sqrt{q^5}, \qquad R_2 = r_1/\sqrt{q^3}. \tag{9}$$

The effect upon the shielding efficiency of varying s (Fig. 3) from zero to P keeping $r_1/R_1 = r_2/R_2$ can be obtained by means of the following equation

$$g = 1/4\,\mu\left[1 - \frac{k^2}{q_{12}} + 1/4\,\mu\left(1 - \frac{k}{\sqrt{q_{12}}}\right)^2 n_{12}\right] + 1, \tag{10}$$

where

$$k = \frac{r_1}{R_2}.$$

If R_1/r_2 (that is $\sqrt{q_{12}}$) is varied from 1 to R_2/r_1 the desired result is obtained.

Assume in Fig. 3 the thickness of the two cylinders to be the same, that is, $R_1 - r_1 = R_2 - r_2$. The variation in shielding efficiency vs. s,

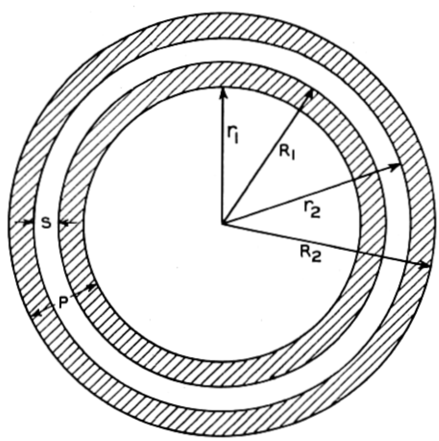

Fig. 3.

or $\sqrt{q_{12}}$, is then given by equation (5), with q_2 expressed in terms of q_{12} and q_1 as follows:

$$\sqrt{q_2} = \frac{1}{1 + \sqrt{q_{12}}[1 - \sqrt{q_1}]}. \tag{11}$$

In an article in the *Philosophical Magazine* of February 1933 L. V. King has developed relations for the shielding efficiency of spherical and cylindrical shells taking into account the effect of induced currents. The following equations for an infinitely long metallic cylinder have been picked from his paper. For a non-magnetic shell, the thickness of which is small compared to its radius, the shielding ratio, g, is given by

$$g = |\cosh (ka) + 1/2\, ka \sinh (kd)|, \tag{12}$$

where a is the radius and d the thickness in cm. k is given by

$$k = 2\pi \sqrt{\frac{f}{\rho \cdot 10^9}}(1 + i), \tag{13}$$

where f is frequency in cycles and ρ is resistivity in ohms per centimeter cube. At low frequencies (12) reduces to

$$g = \left| 1 + i \frac{4\pi^2 fad}{\rho} 10^{-9} \right|, \tag{14}$$

which is good up to about 10^5 cycles. The direction of the disturbing magnetic field in (12) and (14) has been assumed perpendicular to the axis of the cylinder.

Other formulæ which take into account both conductivity and permeability are also given in King's article. They are, however, rather complicated and require elaborate calculations.

Mr. S. A. Schelkunoff in an article in the October 1934 issue of the *Bell System Technical Journal* has derived formulæ which are comparatively simple although they take into account both conductivity and permeability. His treatment is quite different from that presented above and his results are expressed in terms of radial impedances. For an infinitely long cylindrical shield the diameter of which is large compared to the radial thickness of the shield the shielding efficiency, S, is given by

$$S = R + A. \tag{15}$$

In this formula R is the sum of the reflection losses at the surfaces of the shield. We have

$$R = \sum_{n=1}^{n} 20 \log_{10} \frac{|k_n + 1|^2}{4|k_n|} \text{ db}, \tag{16}$$

where k_n is the ratio of the radial impedance in the first medium to that in the second. That is,

$$k_n = \frac{Z_1}{Z_2}. \tag{17}$$

The radial impedance for a good dielectric is given by

$$Z = 2\pi f \mu \rho i \text{ ohms}. \tag{18}$$

For a metal

$$Z = \sqrt{\frac{2\pi f \mu i}{g}}. \tag{19}$$

In (18) and (19) f is the frequency in cycles, ρ is the radius in cms., g is the intrinsic conductance in mhos/cm., and μ is the intrinsic inductance in henries/cm.*

A in (16) is the sum of the attenuation losses in the successive shells. For any one shell

$$A = 8.686\alpha t \text{ db}, \tag{20}$$

where $\alpha = \sqrt{\pi g \mu f}$ and t is the radial thickness in cms.

Calculated Curves

By means of the equations (2) to (11) the shielding efficiency of various types of cylindrical shields has been calculated. The permea-

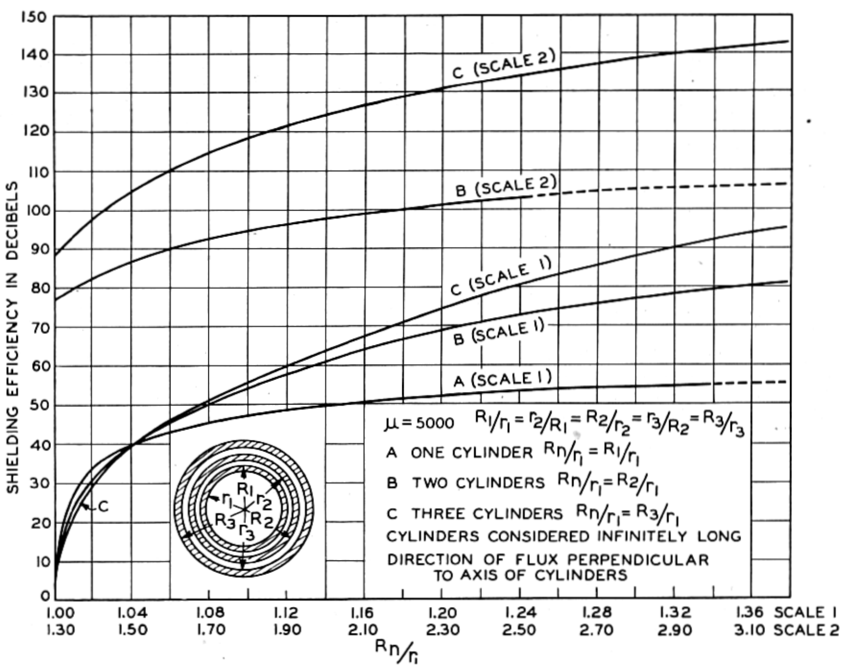

Fig. 4—Shielding efficiency of one, two, and three concentric cylinders (for zero frequency).

bility considered is 5000 which is readily obtainable at low frequencies and field strengths by means of permalloy.† The calculations are given in the form of curves in Figs. 4, 5 and 6.

* Thus in empty space (or dielectrics, approximately) $\mu = 4\pi 10^{-9}$ henries/cm. In general $\mu = 4\pi\mu_0 10^{-9}$ where μ_0 is the intrinsic permeability referred to empty space as unity.

† Arnold and Elmen, "Permalloy," *Journal Franklin Institute,* May, 1923, pp. 621–632.

The curves of Fig. 4 show the shielding efficiency of one cylinder and of two and three concentric cylinders with air space between. The shielding efficiency is given as a function of the ratio between the outside and inside radii of the shield, that is, R_n/r_1, where R_n is the outside radius of the outside cylinder and r_1 is the inside radius of the inside cylinder. These curves show the relative shielding efficiencies of 1, 2 and 3 cylinders and give numerical values for μ equal to 5000. The relative dimensions of the cylinders are such that the ratios between the inside and the outside radii of the cylinders and of the air spaces between the cylinders are in geometric progression. These curves show that when a very high shielding efficiency is desired it is not only advantageous but necessary to use two or more cylinders. Thus with one cylinder the maximum shielding efficiency that can be considered practical when $\mu = 5000$, is approximately 50 db. The maximum theoretical limit for one, two and three cylinders is 62 db, 124 db and 186 db respectively when $\mu = 5000$.

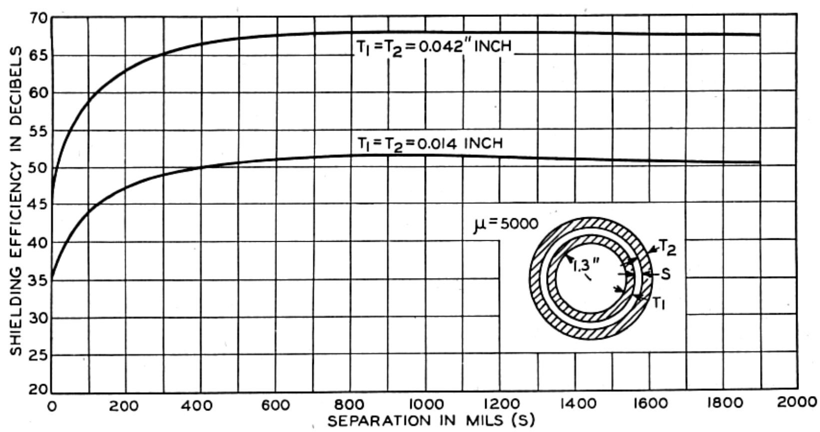

Fig. 5.—Shielding efficiency of two concentric cylinders versus the air-gap between them. Thickness of the wall of each cylinder kept constant. Zero frequency.

In Fig. 5 is shown the shielding efficiency of two concentric cylinders vs. the thickness of the air space between the cylinders. The thicknesses of the walls of the two cylinders are equal. Two thicknesses of the walls of the cylinders have been considered, namely, .014″ and .042″. An interesting fact is brought out by comparing the curves of Fig. 5 with curve "*B*" of Fig. 4. For example, when the air space is .042″, the upper curve of Fig. 5 gives a shielding efficiency of two cylinders with an air space between them, the thickness of which is the same as that of the cylinders. The ratio between the outside radius and the inside radius is 1.097. The shielding efficiency of this combination is approximately the same as that of two cylinders having the same ratio R_n/r_1 as given in Fig. 4, curve "*B*." This shows that the condition that the radii of the cylinders should be in geometric progression is not very critical, at least, not for the value of R_n/r_1 under consideration.

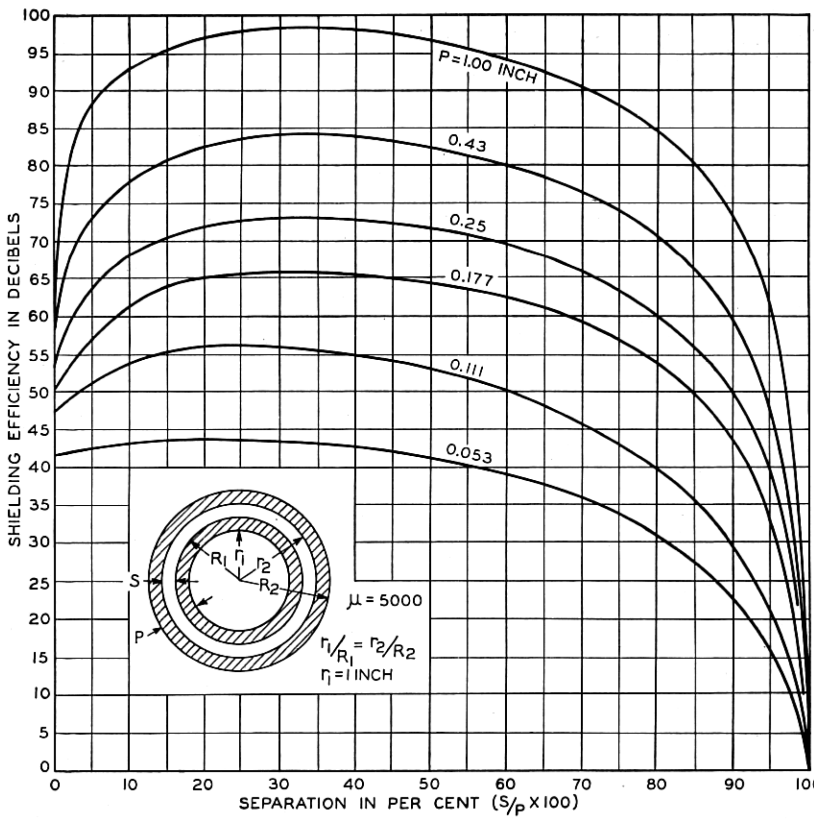

Fig. 6—Shielding efficiency of two concentric cylinders versus the air-gap between them. Overall thickness of the wall of the shield (P) kept constant. Zero frequency.

The curves of Fig. 6 also show the shielding efficiency of two concentric cylinders vs. the air-gap between them. In this case, however, the total thickness P of the wall of the double cylindrical shield is kept constant and the air-gap is increased from zero to P at the expense of the cylinders. When the air-gap is zero, the shielding efficiency is therefore that of a solid cylinder, the thickness of the wall of which is P. When the air-gap is equal to P, the thickness of the two cylinders is zero, and hence the shielding efficiency is zero. The air-gap is so located that the radii of the two cylinders are in geometric progression.

Experimental Data

From the discussion under "Theory" it is evident that although the equations (2 to 11 incl.) were derived with the assumption of a steady magnetic field the above calculated values apply equally well to an alternating magnetic field if the effective permeability is used. However, the results are far from sufficient to determine the shielding efficiency of a magnetic shield for a transformer. The shielding due to the eddy currents, i_{e1} (see Fig. 1), is not included. To include this the formulæ (12) to (20) inclusive must be used. The equations have been derived with the assumption that the length of the cylinders is infinite. In practical applications this is obviously not so. Covers, however, approximately counterbalance the effect of the finite length of the cylinders. The magnetic core of the transformer also materially affects the shielding efficiency. In connection with such factors as these which would be very laborious to treat theoretically some experimental information will now be given. The frequency range of the disturbing magnetic field was limited to from 50 to 4000 cycles.

The shielding efficiency has previously been defined as follows:

$$\text{Shielding Efficiency} = 20 \log_{10} H_e/H_i. \tag{1}$$

From the standpoint of the shielding of transformers we are primarily interested in the reduction of the transformer terminal voltage which is caused by the disturbing magnetic field. For this reason it will be found convenient to define the shielding efficiency in connection with transformers in decibels as follows:

$$\text{Shielding Efficiency} = 20 \log_{10} E_e/E_i, \tag{21}$$

where E_e is the terminal voltage due to the disturbing magnetic field with the shield removed and E_i the corresponding voltage with the transformer inside the shield. In addition, E_e and E_i are restricted to the maximum terminal voltages, with respect to position, that is, the transformer is assumed to be in that angular position with respect to the direction of the magnetic field, in which the maximum terminal voltage is obtained. With an unshielded shell type transformer, for example, this position would be that in which the axis of the winding coincides with the direction of the disturbing magnetic field. This restriction is necessary for the definition (21) to be of any value.

With a small air core coil and an infinite cylinder the axis of which is perpendicular to the axis of the winding and to the direction of the disturbing magnetic field the two definitions are equivalent.

The circuit used in making measurements consists of a field coil producing a magnetic field, a pick-up coil and a vacuum tube voltmeter. The field coil is a loop two feet in diameter consisting of 500 turns of wire. The magnetic field at the center of this coil is uniform over a space sufficiently large for the purpose. The pick-up or search coil when placed in the magnetic field will have a voltage produced across its terminals. This voltage is measured with the vacuum tube voltmeter and E_e and E_i in equation (21) are thus obtained. The size of the shell type core on which the pick-up coil is wound is 3″ × 1 29/32″ × 1″ where the 1 29/32″ dimension is parallel to the axis of the winding, the 1″ dimensions being the pile-up of laminations. Unless otherwise mentioned this coil was used in all of the following measurements.

Permalloy having an initial permeability of the order of 5000 at low frequencies was employed for both the core and the shield throughout this investigation.

Permalloy Cases

In Fig. 7 is shown the shielding efficiency vs. frequency of a rectangular permalloy case which consists of five contiguous layers of

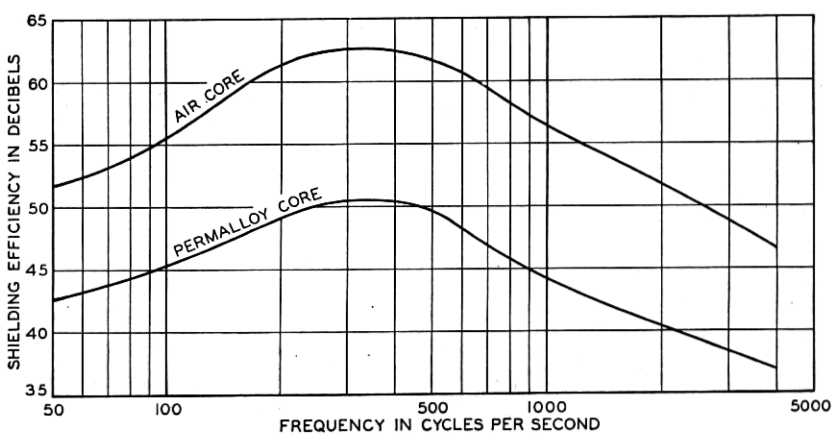

Fig. 7—Observed shielding efficiency of laminated permalloy case.

.014″ thick permalloy sheet. The size of this case is approximately 2 3/8″ × 2 1/2″ × 3 1/4″ and the position of the coil inside the case is such that the axis of the winding is parallel to the 2 1/2″ dimension. The relative size of the coil and case is such that there is approximately

1/8″ clearance between the core of the coil and the case. The shielding efficiency is given for a coil having a permalloy core and also for a coil having a non-magnetic core. These curves illustrate the effect of the magnetic core upon the shielding efficiency. At low frequencies the shielding is mainly due to the magnetic properties of the shield material. As the frequency increases, however, the effect due to the eddy currents, i_{e1} (Fig. 1), increases and the shielding efficiency increases. At approximately 300 cycles a maximum is reached and from here on up to 4000 cycles the shielding efficiency decreases. This is due to the fact that at these frequencies the eddy currents, i_{e2} (see Fig. 1), decrease the effective permeability of the material at a greater rate than the shielding efficiency is increased due to the eddy currents i_{e1}. The slope of the curves at 50 cycles is not zero. This shows that even at 50 cycles there is a considerable shielding effect due to the beneficial eddy currents.

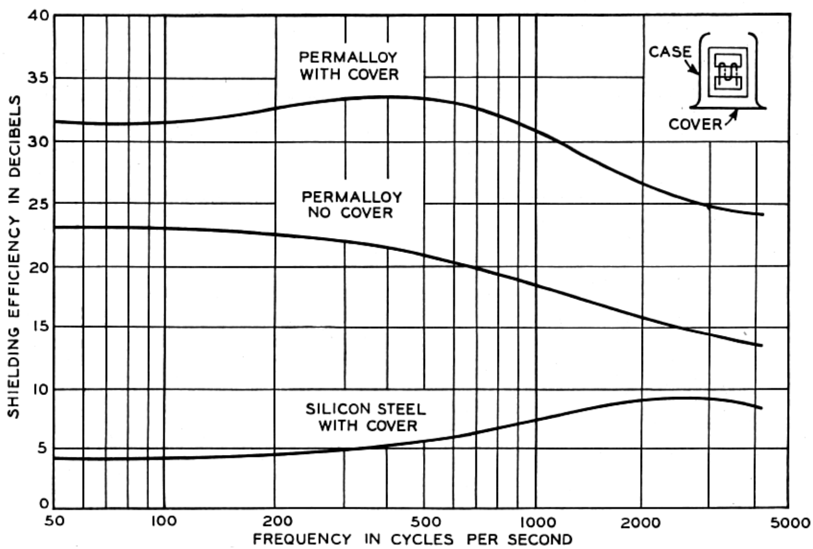

Fig. 8—Observed shielding efficiency of cases made of 1/32″ thick permalloy and silicon steel sheet.

The curves of Fig. 8 show the shielding efficiency vs. frequency of a cylindrical permalloy case, the thickness of the walls of which is 1/32″. The approximate dimensions of this case are 3 1/4″ high × 2 5/8″ diameter and the relative dimensions of the case and core are such that there is approximately 1/8″ clearance between the core and the case. A comparison between the two curves for permalloy shows the effect of the cover upon the shielding efficiency.

A comparison between the curve for permalloy and that for silicon steel on Fig. 8 gives a striking example of the advantage of using permalloy instead of steel.

Effect of Air-Gap Between Core and Shield

It has been pointed out previously that the magnetic core decreases the reluctance through the interior of the case and in that way decreases the shielding efficiency. When the size of the core is such as to almost fill the case, that is, when the air-gap between the core and the case is small, this effect becomes large. In Fig. 9 are given some

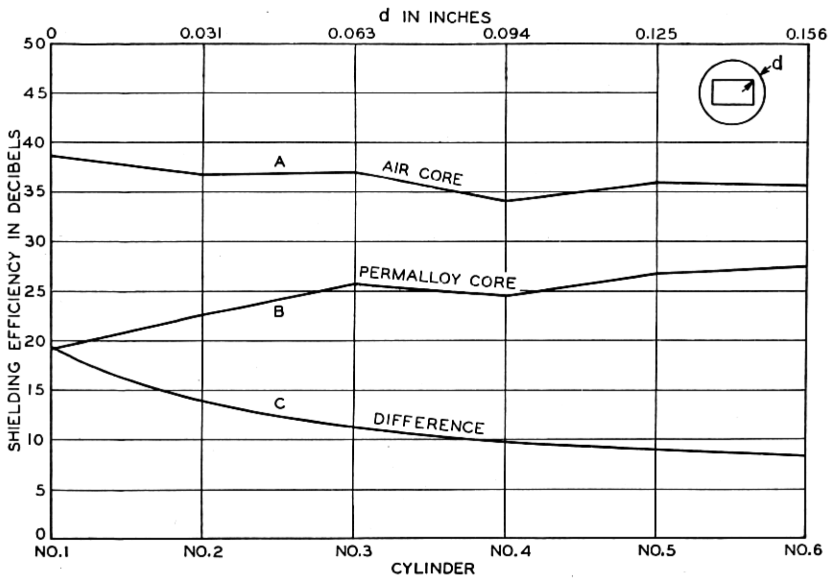

Fig. 9—Observed effect of air-gap between core and shield. Cylindrical shield. Frequency 70 cycles.

data in this connection for cylindrical shields. Six permalloy cylinders were used in this illustration. They are so constructed as to fit over each other, the smallest fitting snugly over the transformer core ("d" = 0). Each cylinder consists of two layers of .014″ thick permalloy sheet. The cylinders have been numbered 1 to 6 from the smallest to the largest, respectively. Curve "A" of Fig. 9 shows the shielding efficiency with a non-magnetic core and curve "B" gives the corresponding information with the permalloy core having a permeability of approximately 5000 at 70 cycles and low field strengths which are the conditions under which the measurements were made.

These curves have been drawn discontinuously because the shielding efficiency is a function not only of "*d*" but of other factors such as permeability, size of the cylinders, etc. Curve "*C*" on the other hand is primarily a function of "*d*" and has, therefore, been drawn continuously. This curve gives the difference between the shielding efficiency with an air core and with a permalloy core and shows the advantage of increasing the air-gap between the core and the cylinder. Thus, for example, in this particular case approximately 8 db better shielding efficiency is obtained with an air-gap of 1/16″ than if there is no air-gap.

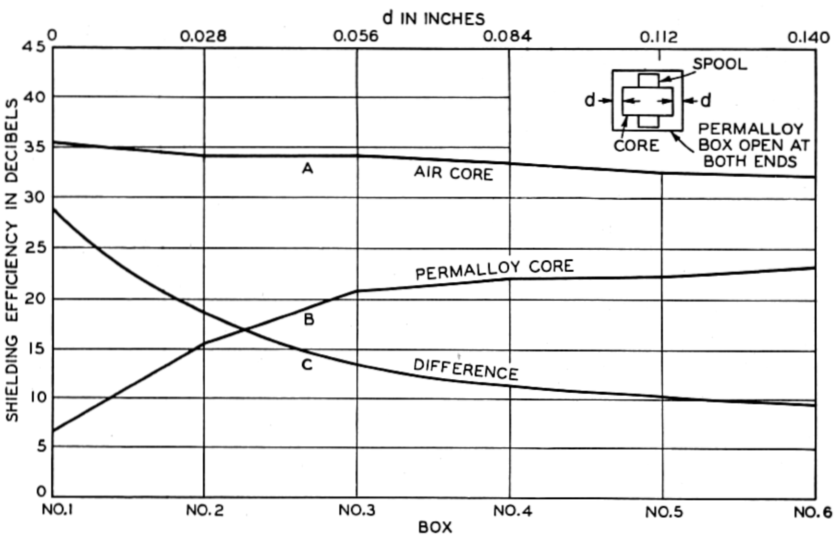

Fig. 10—Observed effect of air-gap between core and shield. Rectangular shield. Frequency 70 cycles.

Similar curves are given in Fig. 10 for rectangular boxes of the same height and same wall thickness as the cylinders. The measurements were made at 70 cycles per second. Due to the larger contact area between the core and the shield the effect of the air-gap is much greater here than with cylinders.

As the effective permeability of the walls of the shield increases the effect of an air-gap increases, other things being equal. In general it may also be said that as the shielding efficiency increases (due to increased thickness of the walls, for example) the effect of an air-gap increases.

If there is an appreciable air-gap between the core and the shield a large variation in the effective permeability of the core will affect the shielding efficiency very little. That is, practically the same results will be obtained with a silicon steel core, having a permeability of 400 as with a permalloy core having a permeability of 5000. On the other hand if the silicon steel core is replaced by an air core the change in the shielding efficiency will be of such an order as is indicated by Fig. 7. The reason for the small effect of changing from a permalloy core to a silicon steel core as compared to the changing from a silicon steel core to an air core is, of course, due to the fact that in the first case there is a decrease in permeability of 12.5 : 1 while in the second case the corresponding reduction in permeability is 400 : 1.

High Efficiency Shields

A shielding efficiency of from 20 to 50 db is, for many purposes, sufficient in connection with the shielding of transformers. Occasions arise, however, when a shielding efficiency much greater is desired.

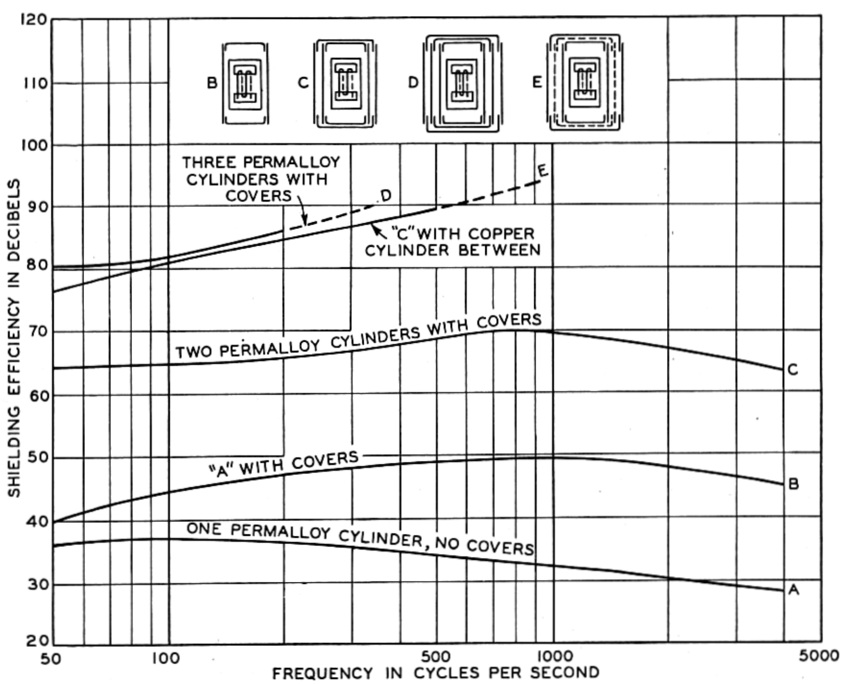

Fig. 11—Observed shielding efficiency of various high-efficiency shields.

To accomplish this by means of a simple case, magnetic material having a permeability much greater than is now readily available would be needed. The curve *B* of Fig. 11 gives the shielding efficiency of a permalloy cylinder which has a permeability of approximately 5000. This cylinder is 4.5″ high, inside diameter 2.5″, and thickness of wall equal to .07″. By increasing the thickness of the wall the efficiency would be only slightly increased. This is evident from a study of Fig. 4. However, by placing a second cylinder over "*B*" a substantial improvement is obtained (Curve *C*). Still greater shielding efficiency is obtained by placing a third cylinder over the former two as shown by curve *D*. The dimensions of the second and third cylinders are such that the ratios between the outside and inside radii of the three cylinders and of the air-gaps between them are approximately in geometric progression. The height of the second and third cylinders is also 4.5″ and the effective permeability at low frequencies and field strengths approximately 5000.

Since the effective permeability of the permalloy used in the above shields is close to 5000 we can compare these data with the theoretical curves of Fig. 4, which were calculated with the permeability assumed equal to 5000. This comparison shows that the theoretical analysis of the shielding of infinite cylinders against steady magnetic fields may be applied to the shielding of transformers. Due to such factors as a magnetic core inside the shield, eddy current shielding, end effects etc. only an approximate check can be expected. At 50 cycles per second the measured values for one cylinder and for two and three concentric cylinders are 40, 64, and 80 db respectively. Corresponding calculated values as given by Fig. 4 are 41.5, 66, and 89 db respectively.

It is evident from the effect of the copper cylinder between two permalloy cylinders as shown by curve *E* (Fig. 11) that three permalloy cylinders with copper cylinders between the inner and middle and between the middle and outer will give a shielding efficiency of the order of 100 db (voltage ratio $E_e/E_i = 10^5$) from 50 to 4000 cycles.

Effect of Covers

The information given in Fig. 12 shows the importance of covers. This figure gives the shielding efficiency of a cylinder which consists of two layers of .014″ permalloy sheet. Curve *A* gives the shielding efficiency without any covers and curve *B* shows the advantage of adding covers which overlap 1/2″ and consist of two layers of .014″ permalloy sheet. The two curves *C* give the shielding efficiency of the same cylinder provided with flat plate covers, C_1 representing covers .014″ thick and C_2 covers .028″ thick. The relative size of the coil and cylinder is such that there is a clearance of approximately 1/16″ between the core and the magnetic shield. It is evident that in this particular instance the covers are very important. Regarding

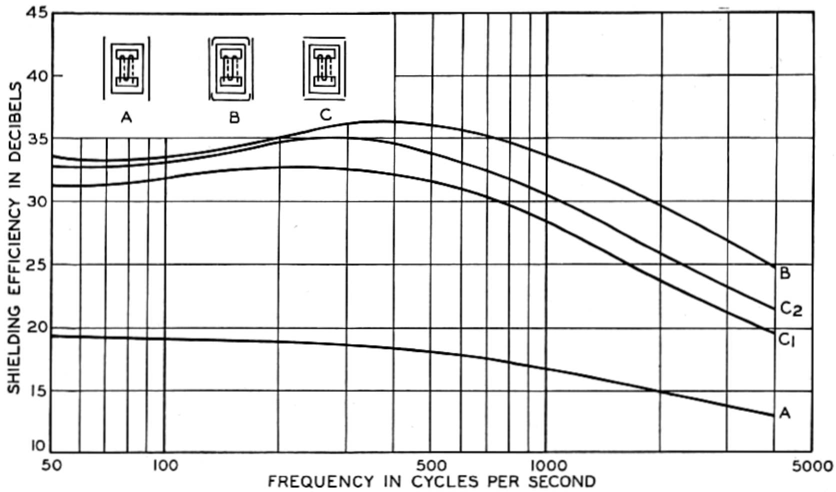

Fig. 12—Observed effect of covers on cylindrical shields.

contact between the cover and the cylinder it may be shown that at low frequencies this is immaterial while at higher frequencies the reverse is true. However, even at these higher frequencies a small overlap (as for *B*) is sufficient.

Examples of the effect of covers upon the shielding efficiency are also given by Figs. 8 and 11. The effect of covers on a copper cylinder as shown by curves *A* and *B* (Fig. 13) is of special interest.

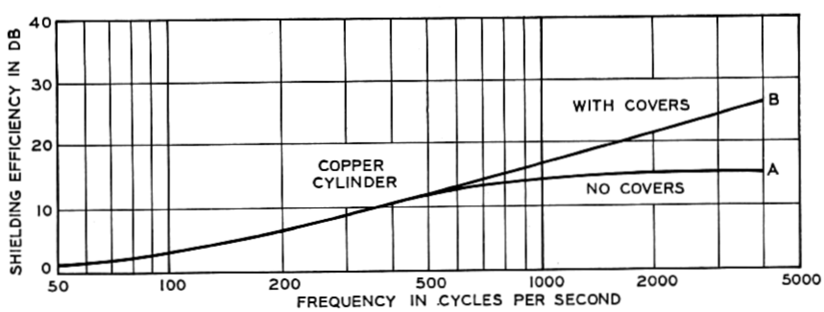

Fig. 13—Observed shielding efficiency of a copper cylinder.

Use of Copper

The curves *A* and *B* of Fig. 13 give the shielding efficiency vs. frequency of a cylinder made of copper. This cylinder has an inside diameter of 2 5/8″ and is 4.5″ high. The thickness of the wall is 1/16″. The shielding efficiency is here entirely due to the eddy currents, i_{e1} (Fig. 1). Curve *B* shows that, after the effect due to the open ends of the cylinder is eliminated by means of covers, the shielding efficiency is approximately proportional to the logarithm of the frequency.

Although copper has a very low shielding efficiency at low frequencies when used alone, tests show that under certain conditions it is very effective when used in conjunction with permalloy. This is illustrated by a comparison between the curves *C* and *E* of Fig. 11. The copper cylinder is similar to the one referred to above except that the thickness of the wall is only 1/32″. The permalloy cylinders are those for which the shielding efficiency is given by curve *C* of the same figure.

Another striking example of the use of copper in conjunction with permalloy is furnished by Fig. 14. The curve *A* gives the observed

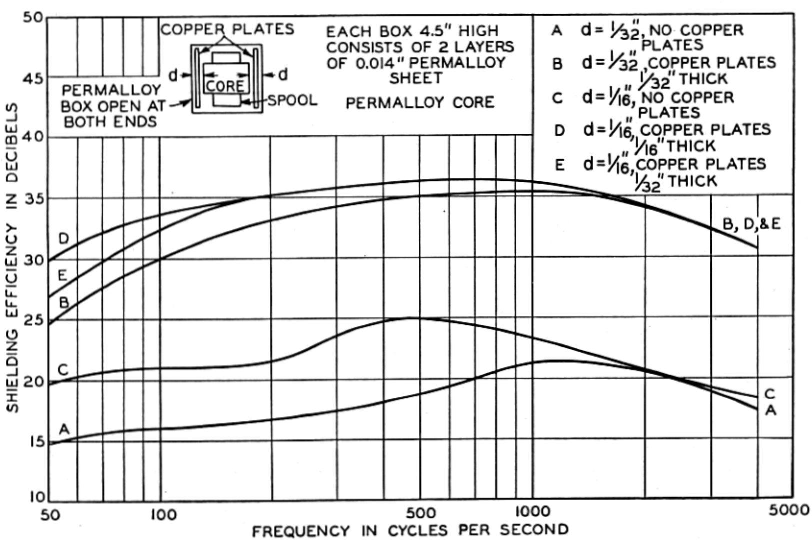

Fig. 14—Observed effect of copper between core and permalloy shield.

shielding efficiency of a permalloy box when there is an airspace between the core and the box of 1/32″ ($d = 1/32''$). If 1/32″ thick copper plates are inserted between the core and the box (see Fig. 14), there is a great improvement in the shielding efficiency as a comparison between the curves *A* and *B* shows. This improvement is 10 db at 50 cycles although the effect of the copper plates alone would be of the order of one db, as is evident from the curves on Fig. 13. At higher frequencies the improvement is still better. It is approximately 15 db between 100 and 4000 cycles. Approximately the same results are obtained with a spacing of 1/16″. A comparison between the curves C and E shows the improvement which is obtained in this case with 1/32″ copper plates. The effect is somewhat less than with a spacing of 1/32″, at least at frequencies below 1000 cycles. At low frequencies copper plates, 1/16″ thick, show a slight improvement over the 1/32″ copper plates as is shown by the curve D.

Curve B on Fig. 10 shows that if the airspace between the core and the box is small the shielding efficiency is very low. In a case like this a copper spacer is very effective. For example, a 5 or 10-mil copper plate replacing an airspace of the same thickness will greatly improve the shielding efficiency.

General

The foregoing is a discussion of the magnetic shielding of transformers from external magnetic fields. The reverse problem of shielding a transformer or coil so as to prevent its magnetic field from affecting other apparatus has not been considered. However, it is safe to assume that approximately the same degree of shielding will be obtained, provided the leakage field does not produce excessive saturation in the shield. That is, assuming that a power transformer is producing a disturbing magnetic field in the space occupied by an input transformer, then a shield over the power transformer will produce approximately the same effect as a shield over the input transformer, where each shield has been constructed in accordance with the information on the foregoing pages. This has been demonstrated experimentally in an article by J. E. R. Constable in the *Wireless World* of February 26, 1937.

Although this paper has been restricted to the magnetic shielding of transformers it is equally applicable to any apparatus which is susceptible to inductive pick-up. This is because in any apparatus where there is inductive pick-up there is in effect a coil. It may be an actual coil and it may be only a loop of lead wires.

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