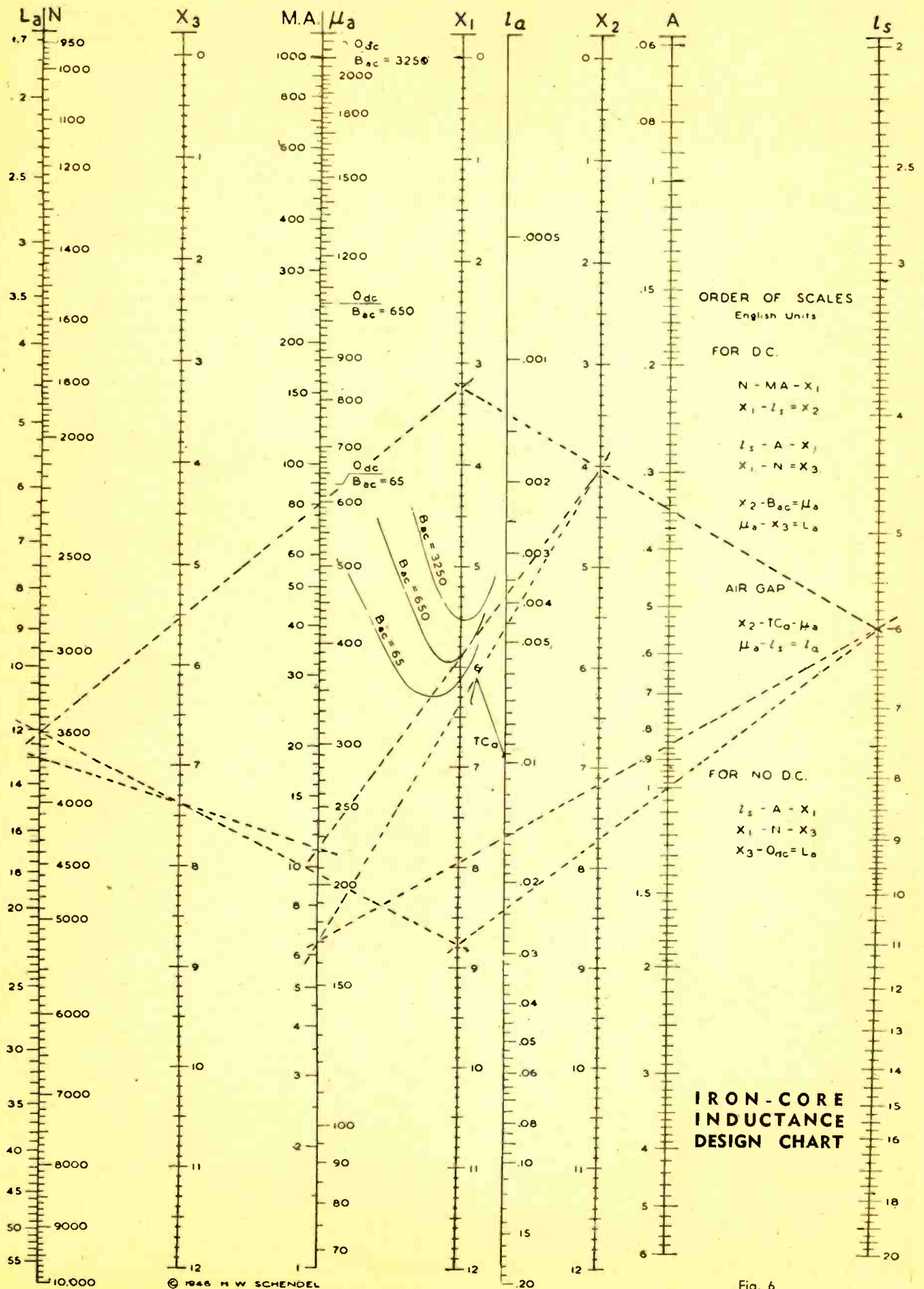




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Fig. 6

COILS, CORES AND MAGNETS

Part II—Reactor and Transformer Measurement and Design

FILTER chokes or reactors, audio frequency chokes, and audio transformers come under the classification of iron-core inductances. The unit of inductance is the *henry*. A coil has an inductance of one henry if a current changing at the rate of one ampere in one second induces one volt in it.

Basically inductances are the same as electromagnets and use cores like the relays described in the first part of this article. The essential difference is that inductance is the main consideration. This in turn depends on the permeability of the steel or alloy.

Considerable care is required in rewinding good grade audio devices but it is a comparatively simple matter to rewind filter chokes and obtain approximate original characteristics. If a unit is rewound with original size wire, with

about the same number of turns, and close attention given the size of air gap, if any, no trouble should be encountered. When an air gap has been used its size is extremely important. In some cases a change of .001 inch in air gap total length will cause a 50 percent change in final inductance. Generally speaking it is better to err slightly oversize rather than undersize.

Much valuable information on rewinding, including a copper wire table, appeared in articles in the Aug.-Sept., October, and December 1942, and the September 1943 issues of RADIO-CRAFT.

To rewind an iron-core inductance for other than original conditions or to design one for some specific purpose involves several factors.

Windings of iron-core coils carrying only a.c. have an inductance which varies in relation to the induced flux in

a manner similar to the variation of the d.c. permeability obtained from Fig. 1, which appeared last month. Push-pull output transformers in which the d.c. effects cancel and interstage transformers which have the d.c. blocked from

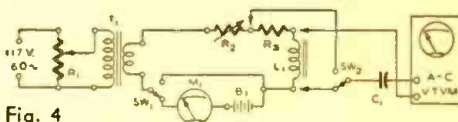


Fig. 4

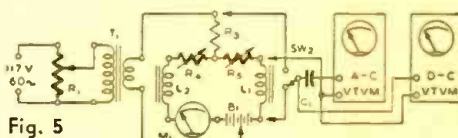


Fig. 5

- R1—500-ohm, 100-w rheostat
 R2—D.C. rheostat
 R3—Non-inductive shunt resistor
 R4,5—Two similar rheostats
 C1—1-uf (or more) paper condenser
 SW1, 2—S.p.d.f. switches
 L1—Iron-core inductance (under test)
 L2—Iron-core inductance (like L1)
 T1—Power transformer (heavy duty)
 M1—D.C. milliammeter for range needed
 B1—Battery, adjustable voltage with center tap

their windings are examples of the simple a.c. class.

Most iron-core inductance windings carry both a.c. and d.c. simultaneously—a.c. superimposed on d.c. As either of these may be varied in magnitude it is easy to see there would be an almost endless number of conditions, each resulting in a different inductance. The inductance rating of any device is accurate only when the test conditions are the same as the normal load conditions.

Curves may be prepared showing the a.c. flux density ($B_{max-a.c.}$) versus a.c. permeability (μ_{ac}) for various values of d.c. in the winding. Such curves prepared from test data on a special test core are called *incremental permeability curves*.

Due to the factors explained in connection with d.c. magnetization curves as well as other factors—eddy-current insulation, stacking factors, core shapes and sizes, and other characteristics of laminations—separate permeability curves are needed for each core design. The curves, when prepared from data obtained directly from a definite working design, using a specified steel or alloy, are called *apparent permeability curves* (μ_a). They indicate the actual permeability (not theoretical) which the design appears to have under selected working conditions.

An air gap is seldom used when the inductance is used only on a.c. except in such devices as fluorescent lamp and sunlamp ballasts. Lamp ballast design

(Continued on page 72)

SYMBOLS	ENGLISH UNITS	C.G.S. UNITS
M.M.F. (MAGNETO MOTIVE FORCE)	$= NI = R\Phi$ (IN AMPERE TURNS)	$= 0.4\pi NI = R\Phi$ (IN GILBERTS)
R (RELUCTANCE)	$= \frac{MMF}{\Phi} = \frac{l}{\mu A} = \frac{l}{0.313 \text{ FOR I.C.U. IN. OF AIR}}$	$= \frac{MMF}{\Phi} = \frac{l}{\mu A} = \frac{l}{1 \text{ FOR I.C.U. CM. OF AIR}}$
Φ (MAXWELLS FLUX, OR LINES OF FORCE IN ANY MATERIAL)	$= \frac{NI}{R} = \frac{MMF}{\frac{l}{\mu A}} = \frac{MMF \mu A}{l}$	$= \frac{0.4\pi NI}{R} = \frac{0.4\pi NI \mu A}{l}$
Φ (SAME AS ABOVE BUT FOR AIR)	$= \frac{3.19 NIA}{l}$	$= \frac{0.4\pi NIA}{l}$
P (PERMEANCE)	$= \frac{\Phi}{MMF} = \frac{\mu A}{l}$	$= \frac{\Phi}{MMF} = \frac{\mu A}{l}$
N (AMPERE TURNS FOR ANY MATERIAL)	$= \frac{H\Phi}{BA} = \frac{\Phi}{\frac{BA}{H}}$	$= \frac{H\Phi}{0.4\pi BA} = \frac{\Phi}{\frac{0.4\pi BA}{H}}$
N (AMPERE TURNS FOR AIR)	$= \frac{\Phi l}{3.19 A}$	$= \frac{\Phi l}{0.4\pi A}$
l (LENGTH— l_s —STEEL— l_a —AIR)	$= \text{INCHES} \times \text{CM} \times 3.937 = 2.54 \text{ CM}$	$= \text{CM} \times \text{INCHES} \times 2.54 = 39 \text{ INCHES}$
A (AREA)	$= \text{SQ. IN.} \times \text{SQ. CM.} \times 1.55 = 6.45 \text{ SQ. CM.}$	$= \text{SQ. CM.} \times \text{SQ. IN.} \times 6.45 = 1.55 \text{ SQ. IN.}$
B (NORMAL INDUCTION IN ANY MATERIAL)	$= \frac{3.19 \mu H}{A} = \frac{MMF}{\frac{l}{\mu A}} = \frac{MMF \mu}{l}$	$= \frac{\mu H}{A} = \frac{MMF}{\frac{l}{\mu A}} = \frac{MMF \mu}{l}$
B (MAGNETIC INDUCTION IN AIR)	$= \frac{3.19 H}{A} = \text{MAXWELLS PER SQ. IN.}$	$= \frac{H}{A} = \text{GAUSSSES}$
H (MAGNETIZING FORCE)	$= \frac{NI}{l} = \frac{B}{\mu} = \text{OERSTEDS} \times 2.02$	$= \frac{0.4\pi NI}{l} = \frac{B}{\mu} = \text{OERSTEDS} \times 0.495$
μ (PERMEABILITY FOR ANY MAT'L)	$= \frac{B}{H}$	$= \frac{B}{H}$
μ_a (APPARENT AC PERMEABILITY)	$= \frac{10^8 l_a}{3.19 N^2 A K_1}$	$= \frac{10^8 l_a}{0.4\pi N^2 A K_1}$
L_a (APPARENT INDUCT. IN HENRIES)	$= \frac{3.19 N^2 \mu_a A K_1}{10^8 l}$	$= \frac{0.4\pi N^2 \mu_a A K_1}{10^8 l}$
MISC. FORMULAE		
$L_a = \sqrt{Z^2 - R_a^2} = \frac{0.159 \sqrt{Z^2 - R_a^2}}{f}$ OR, IF R_a IS SMALL $= \frac{0.159 Z}{f}$		
$B_{ac} = \frac{10^8 E_{rms}}{4.44 f A N K_1}$ $E_{rms} = \frac{4.44 N \Phi_{max}}{10^8}$ $\Phi_{max} = \frac{10^8 E_{rms}}{4.44 f N}$ $N = \frac{10^8 E_{rms}}{4.44 f \Phi_{max}}$ $= \frac{10^8 E_{rms}}{4.44 f A B_{ac} K_1}$		
$Z = \sqrt{X_L^2 + R_a^2}$ $X_L = 2\pi f L_a$ Z = IMPEDANCE IN OHMS f = CYCLES/SEC. $\pi = 3.1416$ R_a = APPARENT RESISTANCE IN OHMS X_L = INDUCTIVE REACTANCE IN OHMS K_1 = STACKING FACTOR		

Symbols and equivalent English and C.G.S. units of common magnetic terms and formulas.

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COILS, CORES AND MAGNETS

(Continued from page 27)

must permit sufficient current to flow through the ballast for normal operation, make available enough starting voltage, yet limit the current to a safe value at all times.

Most inductances having d.c. in the windings have an air gap in the magnetic circuit. This is to increase the apparent permeability over that available without an air gap. The length of air gap which results in highest permeability and likewise highest inductance for the particular current conditions in the windings is called the optimum air gap.

Optimum air gap may be computed by proper application of the normal d.c. magnetization curve and the incremental permeability curve for a given steel and core. The procedure is rather lengthy and will not be presented here. The average experimenter would probably find it faster to use a test circuit and obtain apparent inductance, apparent permeability, and optimum air gap simultaneously.

Circuits suitable for measuring inductance, determining apparent permeability and optimum air gap, are shown in Figs. 4 and 5. The Fig. 4 circuit is suitable for low and zero direct current. D.c. saturation of the transformer core is eliminated with the Fig. 5 circuit but the circuit has the disadvantage of requiring two similar chokes.

In either circuit the d.c. is first adjusted to the normal working condition. R4 and R5, Fig. 5, must be so adjusted that no d.c. flows through R3. This can be determined by a d.c. v.t. voltmeter across R3. Sufficient a.c. voltage is applied to give the working values across

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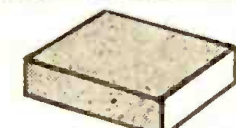


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L1, as measured by an a.c. v.t. voltmeter. Connecting it across R3 will give the voltage drop due to the a.c. flowing through L1.

The optimum air gap may now be found by varying the gap length until the a.c. voltage across R3 reaches a minimum with the a.c. voltage and direct current across L1 held to the working values. For Fig. 5 the air gaps must be the same for L1 and L2 and both varied simultaneously.

INDUCTANCE FORMULAS

The apparent inductance of L1 in henries will be $L_a = .159 \times$

$$\sqrt{\frac{(R_s E_L)^2}{E_R^2} - R_s^2} \times f$$

where R3 = d.c. resistance of voltmeter shunt in ohms, E_L = a.c. volts across L1, E_R = a.c. volts across R3, f = a.c. test frequency, and R_s = apparent resistance of L1. (R_s consists of the d.c. resistance plus resistance effects due to core losses. The latter are very low in good-grade laminated cores.) Usually R_s is small compared to the inductive reactance of the coil and could be omitted, simplifying the formula to

$$L_a = \frac{.159 R_s E_L}{f E_R}$$

Because L1 and L2, Fig. 5, are in parallel, L_a must be multiplied by 2 to obtain the value for L1.

Knowing L_a , the apparent permeability can be found to be

$$\mu_s = \frac{3.19 N^2 A K_s}{L_a}$$

where l = length of core in inches, A = area of core in square inches, N = number of turns in coil, and K_s = stacking factor (usually about .9).

The a.c. flux density in lines per square inch will be

$$B_{ac} = \frac{10^8 E_{rms}}{4.44 f N A K_s}$$

where E_{rms} = a.c. voltage across L1 and other symbols as before.

To simplify calculations for average cores an Iron-Core Inductance Design Chart has been constructed in Fig. 6. The symbols at the scale headings may be identified from the previous text. The multiplying scales X_1 , X_2 , X_3 are used to obtain readings.

The Inductance Design Chart is constructed to automatically allow a .9 lamination stacking factor. O_{ac} points, and the B_{ac} and TC turning curves were prepared from data on 29 gauge (.014-inch) steel laminations having properties similar to those on Curve 1, Fig. 1, which appeared last month. These properties were taken as an average. Some steels will give more inductance, others less. Now points and turning curves may be constructed for steels and cores with other characteristics. The balance of the chart would remain unchanged.

The previous B_{ac} formula may be used to assist in selecting one of the B_{ac} turning curves or O_{ac} points on the chart. Values of B_{ac} may be less than 65 for some interstage a.f. transformers and smoothing chokes while for some output transformers and swinging or input chokes it may go well beyond 3500. Turning curve TC₂ is used to obtain air gap length for all values of B_{ac} .

USE OF THE CHART

Assume we have a core like Fig. 3 (last month's issue) to be used for a smoothing choke. The core is 1 inch wide and stacked 1 inch high using 29 gauge (.014-inch) steel laminations, making

the area (A) = 1.0 square inch. The entire core has uniform cross-sectional area (each of the two outer legs have one-half the area of the center leg). The core length (average length around each window as indicated in Fig. 3) l_c = 6.0 inches. Window is $\frac{1}{2} \times 1\frac{1}{2}$ inch. B_{ac} = 650 will be satisfactory and there will be 80 ma d.c. in the windings. The problem is to find the maximum inductance, L_a , in henries, and the optimum air gap, l_a , in inches.

The more turns the greater the inductance but wire size, allowable re-

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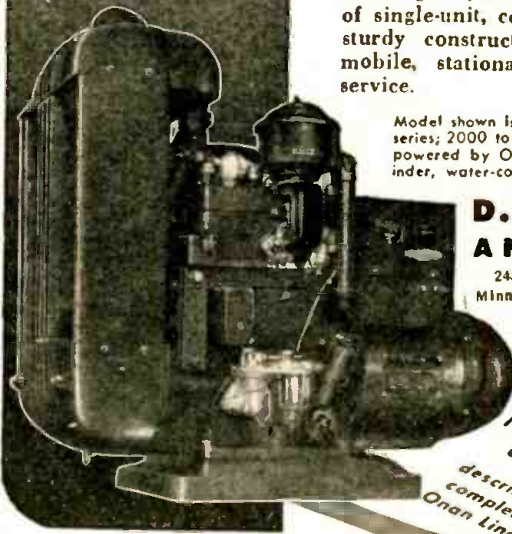
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COILS, CORES AND MAGNETS

(Continued from page 73)

sistance and window area will limit the number. Wire size and coil dissipation watts may be computed as outlined for electromagnets. If the coil resistance is too great larger wire may be used.

A fairly reliable method is to select a wire, allowing 750 to 1250 circular mils per ampere. A wire table and a few computations will show that 3500 turns, No. 32 enamel wire, would go in the window and have a resistance of about 250 ohms.

This information may now be applied to the Inductance Design Chart, Fig. 6. The column headed "Order of Scales" indicates the function of certain groups of scales and under each function is given the order in which the scales are read at each setting of a straightedge. Mistakes will be prevented by writing down the reading for each scale.

Using the group of scales "FOR D.C." set a straightedge from 3500 (no. of turns) on N to 80 (no. of milliamperes) on M.A. and read 3.23 on X_1 ; From 3.23 on X_1 to 6 (lgth. of core, inches) on l_c and read 4.02 on X_2 ; Next from 6 (core lgth.) on l_c to 1 (core area, sq. in.) on A and read 8.78 on X_1 ; From the 8.78 on X_1 to 3500 (no. of turns) on N and read 7.38 on X_2 ; From 4.02 previously obtained on X_2 over the $B_{ac} = 650$ curve and read 222 on μ_a ; From 222 on μ_a to 7.38 previously obtained on X_2 and read 13 on L_a , the apparent inductance in henries.

The optimum air gap may be found by using the "AIR GAP" group of scales. From 4.02 found above for X_2 over the point of the TC. curve read 170 on μ_a ; From 170 on μ_a to 6 (core lgth.) on l_c and read .0153 on l_a , the total

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length of the air gap, in inches. (See Fig. 3.)

Although not a part of the problem let us suppose there is no d.c. in the windings. What will be the inductance? For this we use the "NO D.C." group of scales. To proceed set a straightedge from 6 (lgth. of core) on L_1 to 1 (area of core) on A and read 8.78 on X_1 ; From 8.78 on X_1 to 3500 (no. of turns) on N read 7.38 on X_2 ; From 7.38 on

O_{ac}
 X_2 to — point on μ_s and read 37
 $B_{ac} = 65$

on L_2 , the apparent inductance in henries. If B_{ac} is nearer 650 than 65, the L_2 would be over 60 henries. No air gap would be used. Instead, the laminations would be interleaved as on any transformer.

TRANSFORMERS, SWINGING CHOKES

Audio frequency and output transformers are designed mainly on the basis of inductance of the primary winding, making the design problems similar to chokes except that secondary windings follow regular transformer procedure for impedance and turns ratios needed. Inductance values range from 2 to 50 henries and more, the higher inductance values giving better low frequency response, especially when used with tubes having high plate resistance.

Swinging chokes are often desirable when the load varies widely. The main difference between a swinging and smoothing choke is that the former, though designed for high d.c., has a shorter than optimum air gap. This shortened air gap lowers the inductance considerably at high d.c. loads and increases it at low d.c. loads when compared to a choke designed for high d.c. only.

The Fig. 6 chart is useful only for rough design of a swinging choke. Select the wire for the maximum d.c. ma and assume some value for turns to fit on the core. From the chart determine L_s at maximum d.c. and multiply the value found by 0.58 for the actual minimum swinging choke inductance. If this figure proves to be unsuitable try again using new values for turns or core.

After suitable values have been found for the maximum d.c. use all of them except that in place of the maximum d.c. ma substitute a value only 10 percent of the maximum d.c. ma and find the length of optimum air gap from the chart. Multiply the length as found by 2.6 to find the total air gap length to use for the swinging choke. Inductance ratio between maximum and 10 percent of maximum d.c. will be about 4 to 1. A shorter air gap would increase the ratio but would decrease the inductance at maximum d.c.

A handy reference chart of conversion factors and formulas (see page 27) shows some unusual variations. Unidentified symbols are explained in the text.

Acknowledgement is given Allegheny Ludlum Steel Corporation, United States Steel Corporation, and American Rolling Mill Company for information on electrical steels.



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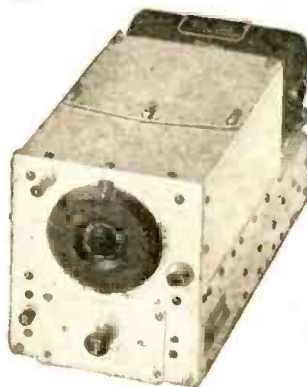
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