PETER MAHLOW

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New Procedure for Designing Linear and Swinging Chokes

Presented here is a simple, widely usable procedure which can save appreciable time in the design of linear and swinging chokes. Tables and curves, verified by use in a design organization, are illustrated with examples to permit the procedure's direct use by the engineer.

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Transformer Division
N. J. E. CORPORATION
Kenilworth, New Jersey

1 Oersted = 2.021 AT./inch
1 amper turn = 1.257 GILBERT
K G/inch² = K LINES x .155/inch²
1 TESLA = 10 KG

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Magnetic Conversion Factors

Flux Density (B)
To convert lines per square inch to gauss, multiply by 0.155.

Magnetic Intensity (H)
To convert ampere-turns per inch to oersteds, multiply by 0.495.
To convert ampere-turns per centimeter to oersteds, multiply by 1.257.
To convert ampere-turns per centimeter to ampere-turns per inch, multiply by 2.54.
One oersted is equivalent to one gilbert per centimeter.

Magnetomotive Force ($\mathfrak{F}$)
To convert ampere-turns to gilberts, multiply by 1.257.

Permeability
In cgs units, in air, $\mu=1$ and $H=B$.
In English units, in air, $H=0.313B$.

IN THE DESIGN OF AIR-GAP CHOKES carrying both direct and alternating current, C. R. Hanna's curves*, although widely used by transformer engineers, are of somewhat limited value in several respects:

1. They are available for only a few of the most common silicon steels. The engineer must therefore seek a different design method when the use of other core materials is more advantageous.
2. They are usually available only for values of flux density between 10 and 1000 gauss. This is an undesirable restriction when a high volt-per-turn ratio results in a density in excess of 1000.
3. They do not permit the design of swinging chokes with predictable swings.

A simple and more broadly utilizable design procedure is therefore desirable. Presented here is such a procedure with tables which give sufficient information to enable the designer to completely specify a linear or swinging choke in minimum time.

General Theory. The inductance of an iron-core choke carrying d-c and having an air gap may be expressed in the form:

$$\boxed{L = \frac{3.19\, N^2 A_c \mu_{eff} 10^{-8}}{l_c}} \tag{1}$$

where L = inductance in henrys
N = number of turns
A_c = net cross section of the core in square inches (gross area times stacking factor)
μ_{eff} = effective permeability of core and air gap combined
l_c = length of magnetic path of core in inches

The inductance may also be expressed by:

$$L = \frac{3.19\, N^2 A_c\, 10^{-8}}{l_g + l_c/\mu_\Delta} \tag{2}$$

for 120HZ use 2.5 instead of 3.19

where l_g = length of air gap in inches
μ_Δ = incremental permeability of the core

By equating (1) and (2), μ_{eff} may be determined as follows:

$$\mu_{eff} = \frac{l_c\, \mu_\Delta}{l_c + l_g\, \mu_\Delta} \tag{3}$$

*"Design of Reactances and Transformers which Carry Direct Current," C. R Hanna, *Transactions*, AIEE, Vol. 46, February 1927, p. 128.

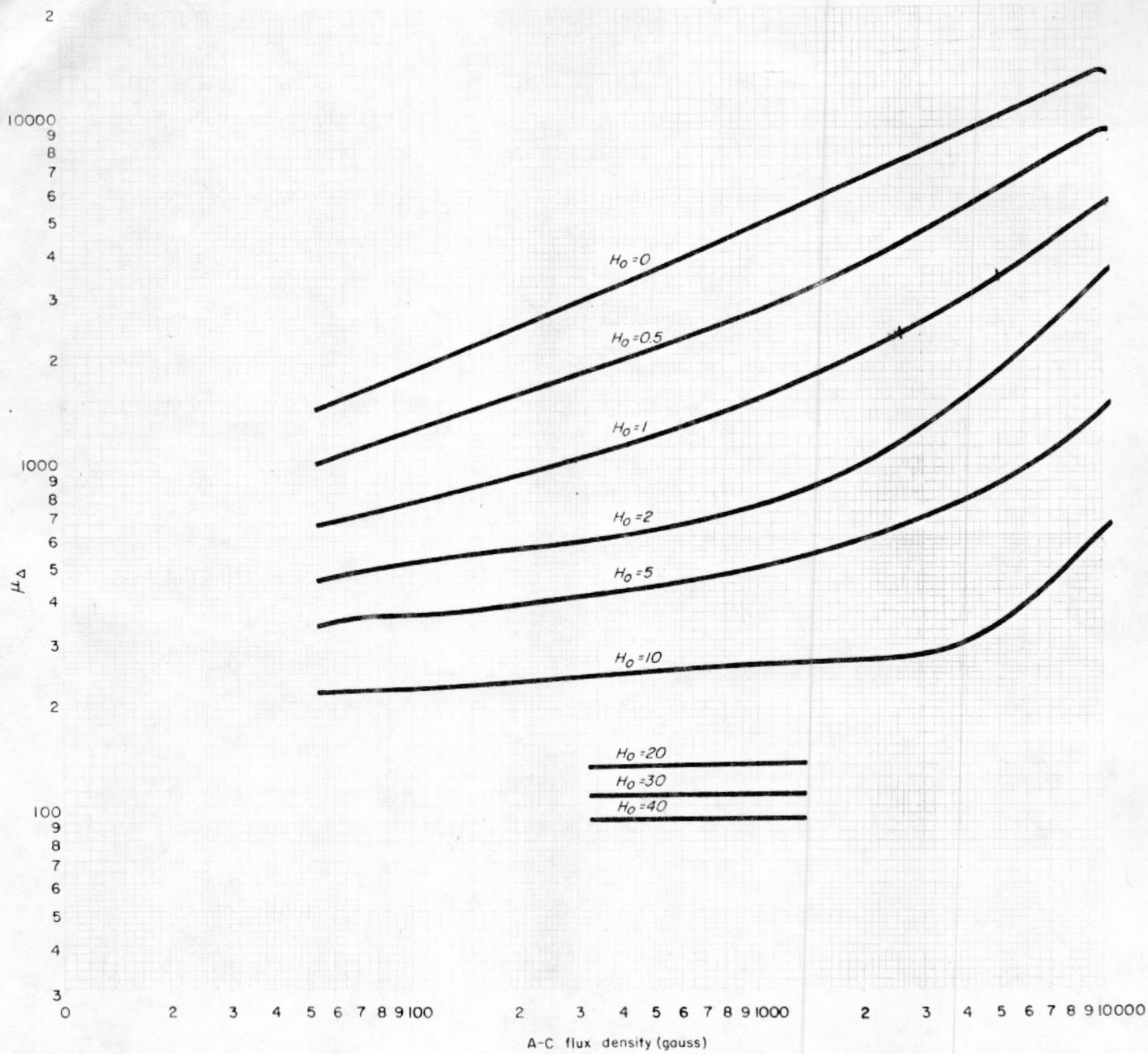

Fig. 1—Incremental permeability (μ_Δ) at 60 cps for EI laminations of 29-page, grain-oriented silicon steel (AISI M7).

Equation (3) may be rearranged to obtain an expression for l_g which is also very often useful.

$$l_g = \frac{l_c}{\mu_{eff}} - \frac{l_c}{\mu_\Delta} \tag{4}$$

Values of μ_Δ are obtainable for the various grades of steel from steel and lamination suppliers. Figure 1 shows the family of curves for incremental permeability at 60 cycles for 29-gage, grain-oriented silicon steel (AISI M7). To use the curves in Fig. 1 it is necessary to know B_{ac}, the a-c flux density, and H_o, the d-c magnetic intensity for the core. The flux density may be determined for cores with or without gaps from:

$$B_{ac} = \frac{3.49\ E_{ac}\ 10^6}{f\ A_c\ N} \text{ gauss} \tag{5}$$

where f = frequency
E_{ac} = excitation voltage

The magnetic intensity for constructions without gaps may be found from:

$$H_o = \frac{N\ I_{dc}}{2.02\ l_c} \text{ oersted} \tag{6}$$

where I_{dc} = direct current in amperes

In a choke with an air gap, the d-c magnetomotive force is expended in both the core and the gap in accordance with the relation:

$$\mathfrak{F} = H_o l_c + H_g l_g \tag{7}$$

where H_g is the magnetic intensity for the gap. Since the permeability of air is 1, B_g is equal to H_g; and equation (7) may be written

$$\mathfrak{F} = H_o\ l_c + B_g\ l_g \text{ gilberts} \tag{8}$$

In English units B_g must be multiplied by 0.313 and equation (8) becomes

$$\mathfrak{F} = H_o\ l_c + 0.313\ B_g\ l_g \text{ ampere-turns} \tag{8a}$$

The magnetomotive force may also be computed from

$$\mathcal{F} = 1.257\, NI_{dc} \text{ gilberts} \tag{9}$$
$$= NI_{dc} \text{ ampere-turns} \tag{9a}$$

Assume a construction for which the number of turns, the direct current, the a-c flux density, the length of air gap, and the length of the magnetic circuit in the iron are known, and the inductance is unknown. If the magnetomotive force is evaluated in equation (9) and substituted in (8), the latter is left with two unknowns, H_o and B_g. The d-c magnetization curve for the core material used also relates H_o and B_g since the flux in the air gap equals the flux in the steel if the effects of leakage, though not necessarily of fringing, are neglected. Since the d-c magnetization curve constitutes a graphical equation that is simultaneous with equation (8), the evaluation of the two unknowns is possible.

The d-c magnetization curve for 29-gage oriented silicon steel (AISI M7) is given in Fig. 2. It is to be particularly noted that the axes of this curve are linear. The logarithmic scale by which magnetization curves are usually presented is useless for a graphical solution. Note also that English units are used. See box for conversion factors.

The graphical solution of the two simultaneous equations is easily accomplished. If we let $H_o l_c = 0$, equation (8a) becomes

$$\mathcal{F} = 0.313\, B_g\, l_g = 0.313\, B_y\, l_g \tag{10}$$

and

$$B_y = \frac{\mathcal{F}}{0.313\, l_g} \text{ lines per sq in.} \tag{11}$$

where B_y signifies the point of intersection of equation (8a) with the Y axis in Fig. 2. Similarly, for the condition that $B_g l_g = 0$, we obtain

$$\mathcal{F} = H_o\, l_c = H_x\, l_c \tag{12}$$

and

$$H_x = \frac{\mathcal{F}}{l_c} \text{ ampere-turns per in.} \tag{13}$$

where H_x is the point of intersection of equation (8) with the X axis.

B_y and H_x are now located on their respective axes and a straight line is drawn between them. The point of intersection of this line with the magnetization curve is the solution of equation (8), and the Y coordinate of this point is H_o. Having determined H_o we may now find μ_Δ from the incremental permeability curve in Fig. 1. Knowing μ_Δ we may evaluate μ_{eff} and hence L.

An alternate approach to the solution of equation (8a) is often advantageous where H_o is fixed at some arbitrary value but l_g is unknown. The first step in this approach is to equate (8a) and (9a) and solve for l_g.

$$NI_{dc} = H_o\, l_c + 0.313\, B_g\, l_g$$
$$l_g = \frac{NI_{dc} - H_o\, l_c}{0.313\, B_g} \text{ in.} \tag{14}$$

Using a value of intensity of 1 oersted or 2.02 ampere-turns per in., a value of 100 kilolines per sq in. for B_g may be obtained from Fig. 2. Equation (14) then becomes

$$l_g = 3.2\,(NI_{dc} - 2.02\, l_c)10^{-5} \text{ in.} \tag{15}$$

Table I provides formulas for the rapid calculation of air gap in inches for various values of magnetic intensity in oersteds for 29-gage oriented silicon steel (AISI M7).

The foregoing discussion is applicable to all iron-core, air-gap chokes regardless of the excitation frequency. In the balance of this article consideration will be limited to chokes operating at 120 cycles. When other frequencies are specified, appropriate data on incremental permeability for such frequencies must be obtained. As frequency increases, incremental permeability decreases. Table II is a rough guide to this variation. It gives the approximate ratio of μ_Δ at various frequencies to the value of μ_Δ at 60 cycles at the same flux density.

The Air Gap. In the final determination of the air gap, consideration must be given to the effect of leakage and fringing fluxes. These fluxes are a function of the gap dimensions, the shape of the pole faces and the shape, size and location of the winding. Their net effect is to shorten the air gap.

Computation of these fluxes or of their effect on the reactor is lengthy and inconclusive. It is therefore more practical to make a final determination of the actual gap length on the test bench. Where l_g is computed at about 0.003 in. or less, the irregularities of the pole faces will compensate for the fringing flux. However, for larger values of l_g, the actual gap required to obtain the computed inductance will average about 150 per cent of the computed gap or more where l_g approaches or exceeds ⅛ in.

For practical reasons the air gap is actually composed of sheets of paper or other insulation which make up a separator of the desired thickness. The separator is stretched across the pole faces between the sections of the lamination stack. Since a separator enters the magnetic circuit twice, its thickness should be half what is required. Thus, if $l_g = 0.050$ in., the thickness of the separator for the initial testing of the choke should be 0.0375 in., allowing the factor of 150 per cent for fringing and leakage fluxes.

Although twice the actual thickness of the separator inserted in the magnetic path of the core may be greater than the theoretical value for l_g, it is to be emphasized that the inductance obtainable from the construction will be the inductance computed for the theoretical value of l_g.

Table I—Formulas for Air Gap Lengths for Various Magnetic Intensities

H_o, oersteds	l_g, in.
0.5	3.51 $(NI - 1.01\, l_c)10^{-5}$
1.0	3.2 $(NI - 2.02\, l_c)10^{-5}$
2.0	3.07 $(NI - 4.04\, l_c)10^{-5}$
5.0	2.94 $(NI - 10.1\, l_c)10^{-5}$
10	2.84 $(NI - 20.2\, l_c)10^{-5}$
20	2.73 $(NI - 40.4\, l_c)10^{-5}$
30	2.66 $(NI - 60.6\, l_c)10^{-5}$
40	2.63 $(NI - 80.8\, l_c)10^{-5}$

Use of Tables. Tables III through XI are based on the use of EI laminations of AISI M7 steel in square stack (gross build equals tongue width). The tables provide full design information for approximately 250 chokes in a range of values between 835 henrys at 23 ma d-c to 900 micro-henrys at 79 amp d-c. These tables also provide a starting point for extrapolation in the design of other linear and swinging chokes. The tables are computed on the basis of the following assumptions:

Wire insulation is plain enamel, single Formvar or other insulation of single thickness except that square wire

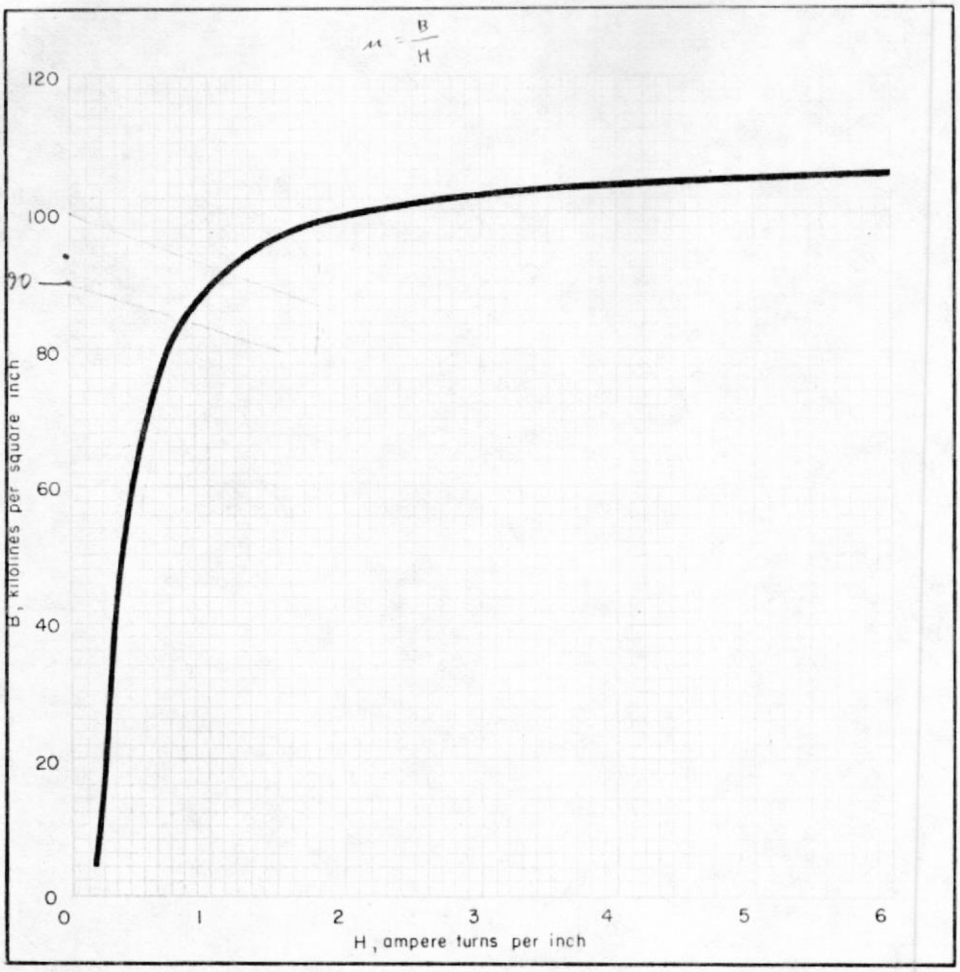

Fig. 2—D-C magnetization curve for 29-gage, grain-oriented silicon steel (AISI M7).

Table II—Ratio of Incremental Permeability (μ_Δ) at Various Frequencies to Value at 60 cps.

Frequency, cps	Per cent of value at 60 cps
120	78
180	75
360	60
800	50
2400	40

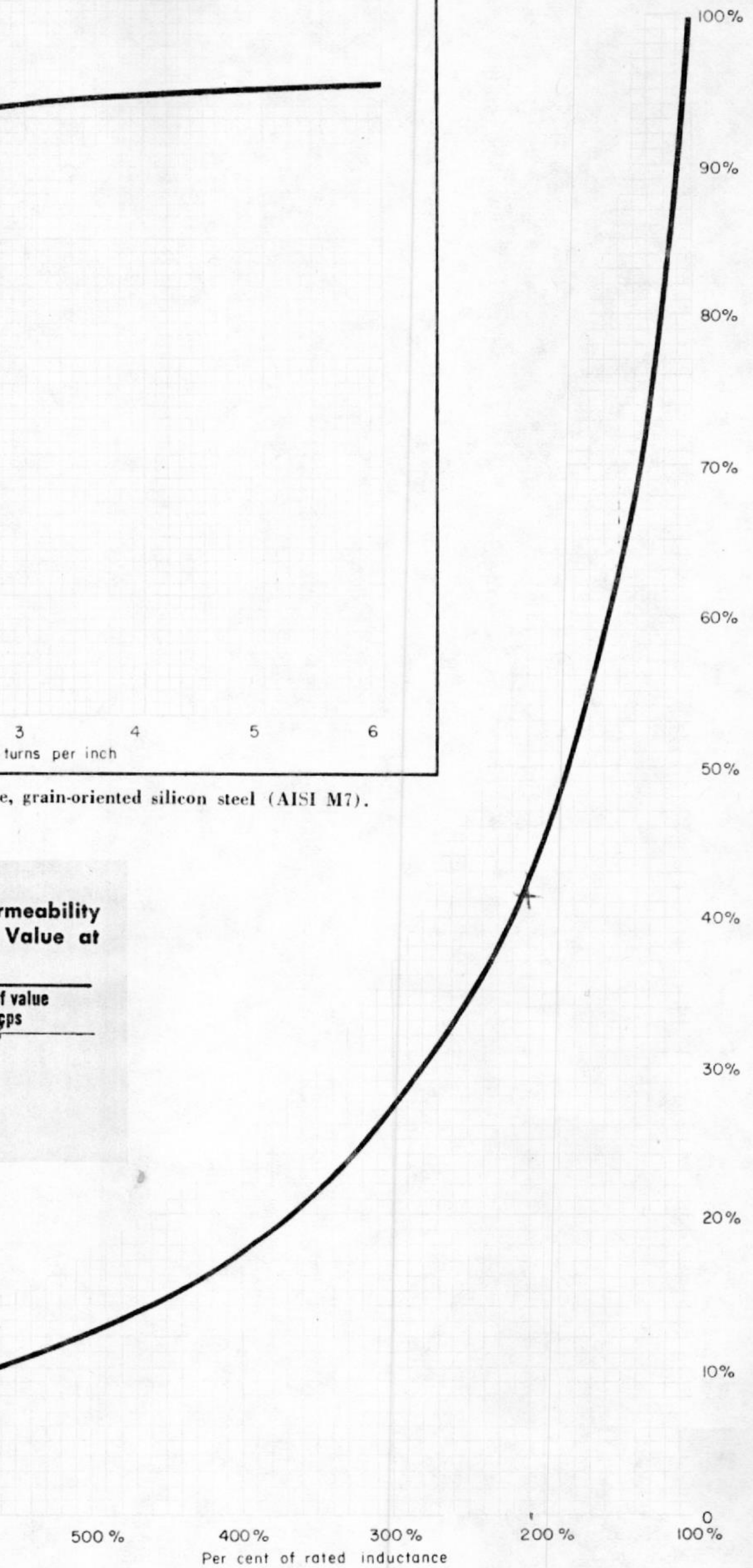

Fig. 3—Inductance of choke obtained by adjustment of gap for $H_o = 1$ oersted at values of direct current less than rated and constant a-c flux density.

is assumed to have double cotton, double glass or other double insulation.

The number of turns per layer is based on a winding factor varying from 88 per cent for the finest and heaviest gages to 92 per cent for intermediate gages.

The following margins have been assumed:

Wire Size No.	Margin, in.
8 square and heavier	0.312
9 square through 15 round	0.250
16-18 AWG	0.187
19-21 AWG	0.156
22-31 AWG	0.125
32-37 AWG	0.093
38 AWG and lighter	0.062

The number of layers is based on a maximum build factor of 90 per cent. Thickness of core tube is indicated on each table. Coil wrap has been taken in all cases at 0.025 in.

It is assumed that square wire will be random wound and that layer insulation will be employed in the following thickness for round wire:

AWG Size	Thickness, in.
10-16	0.010
17-19	0.007
20-21	0.005
22-23	0.003
24-27	0.002
28-33	0.0015
34 and finer	0.001

The construction indicated permits operation at not less than 350 rms working volts for all chokes. If the working voltage is to be in excess of this value, additional insulation or margins may be needed, resulting in a reduction of the number of wire turns and a decrease in inductance.

The direct current listed in the tables for any given wire size will result in a winding temperature rise of about 50 to 55 C based on an uncased construction. The heating effect of the a-c component of the current is considered to be negligible.

The inductance shown is approximately the maximum obtainable for the construction and current indicated. It is based on a gap length such that H_o is 1 oersted. Excitation voltage has been taken at $1/10$ the number of turns for uniformity of a-c flux density and incremental permeability. (In instances where fine wire is used, this exciting voltage would be in excess of rated working voltage.) Excitation frequency is assumed to be 120 cycles.

Other data given in the tables include:

L_w = length of lamination window, in.
W_w = width of lamination window, in.
l_c = mean length of magnetic path of the core, in.
A_c = net core area, sq in. (gross area times stacking factor)
l_m = mean length of turn of the winding, in.
Fe = core weight for square stack, lb
Cu = approximate weight of copper in the winding, lb

The formula for air gap determination, in which the length of magnetic path of the specific lamination has been substituted, is also presented for each table. These formulas are based on $H_o = 1$ oersted.

Figure 3, which is to be used in conjunction with the tables, is a plot of per cent of rated inductance obtained for the per cent of rated d-c current applied to the coil.

Design Example—Linear Choke

Assume that it is desired to build a linear choke having the following characteristics:

L = 19.6 henrys
I_{dc} = 110 ma
E_{ac} = 300 volts
f = 120 cycles per sec
R = 150 ohms (when operating at equilibrium temperature under load)

(a) Determine effective current for temperature rise considerations.

$$I_{ac} = \frac{E_{ac}}{2\pi f L} = \frac{300}{2\pi \times 120 \times 19.6} = 0.0203 \text{ amp}$$

$$I_{eff} = \sqrt{I^2_{dc} + I^2_{ac}} = \sqrt{0.110^2 + 0.020^2} = 0.112 \text{ amp}$$

The effective current for winding temperature rise in this example is therefore almost identical with the direct current.

(b) Choose core and coil. Experience indicates the choice of Table VI for a choke of the specified characteristics. The use of 2630 turns of 29 AWG wire yields a choke that should meet the resistance requirements. For this construction, the table lists a rated d-c current of 0.266. The coil will therefore be operating at $0.110/0.266 = 41.5$ per cent of the rated value. From Fig. 3 it is determined that this current will result in an inductance 210 per cent of the rated value given in Table VI or $2.1 \times 6.7 = 14.1$ henrys. Since inductance varies with stack build, the original 1-in. build should be increased by the ratio of inductance desired to inductance obtained so 19.6/14.1 times 1 in. = 1.39 in. A build of $1\frac{3}{8}$ in. will be used as a starting point. The temperature of the winding will be quite small since the effective current of 112 ma determined in step (a) is considerably less than the rated current of 266 ma.

(c) Using the formula given in the table, l_g can be calculated as follows:

$$l_g = 3.2(NI_{dc} - 12.1)10^{-5} \text{ in.}$$
$$= 3.2(2630 \times 0.110 - 12.1)10^{-5} \text{ in.} = 0.0089 \text{ in.}$$

(d) The a-c flux density may be calculated from equation (5).

$$B_{ac} = \frac{3.19\, E_{ac}\, 10^6}{f\, A_c\, N} = \frac{3.49 \times 300 \times 10^6}{120 \times (0.95 \times 1.375) \times 2630}$$
$$= 2530 \text{ gauss}$$

(e) Using $H_o = 1$ oersted and $B_{ac} = 2530$ gauss, μ is obtained from Fig. 1 as 2400.

(f) The effective permeability μ_{eff} can be calculated from (3).

$$\mu_{eff} = \frac{l_c \mu_\Delta}{l_c + \mu_\Delta l_g} = \frac{6 \times 2400}{6 + (2400 \times 0.0089)} = 527$$

(g) Inductance can now be computed from equation (1). However, to compensate for the fact that the incremental permeability curves in Fig. 1 are based on 60 cycles and this choke is to operate at 120 cycles, and also to compensate for possible variation in quality of the steel, an empirical correction factor is used. The constant of 3.19 in equation (1) is thus changed to 2.5 and the equation for L becomes:

$$\boxed{L = \frac{2.5\, N^2\, A_c\, \mu_{eff}\, 10^{-8}}{l_c}}$$
$$= \frac{2.5 \times 2630^2 \times (0.95 \times 1.375) \times 527 \times 10^{-8}}{6}$$
$$= 19.9 \text{ henrys}$$

Using the ratio of calculated μ_{eff} to that obtained from Table VI and the build ratio, the inductance

350 VAC, 50-55 °C TEMP. RISE   HO = 1 oersted

NOTE AT 100 °C Resistance ≈ 1.3 × R at 20 °C

Table III—Lamination EI 625

AWG	Turns per layer	Number of layers	N	Ohms 20 C	I_{dc}	l_g	μ_{eff}	L
40	198	49	9700	2940	0.0295	0.009	382	88
39	178	45	8000	1930	0.0363	0.0095	365	57.5
38	158	41	6480	1240	0.0454	0.0095	365	37.4
37	135	38	5130	780	0.0572	0.0095	365	23.5
36	120	34	4080	490	0.0721	0.0095	365	15.0
35	109	31	3380	323	0.089	0.0095	365	10.3
34	96	28	2680	203	0.112	0.0095	365	6.5
33	85	24	2040	122	0.145	0.0095	365	3.74
32	76	22	1670	79.5	0.179	0.0095	365	2.47
31	64	20	1280	48.0	0.230	0.0095	365	1.46
30	57	18	1025	30.7	0.288	0.0095	365	0.940
29	50	16	800	19.0	0.367	0.0095	365	0.575
28	46	15	690	13.0	0.443	0.010	348	0.410
27	41	13	533	7.7	0.576	0.010	348	0.235
26	36	12	432	5.1	0.708	0.010	348	0.159
25	32	11	352	3.3	0.880	0.010	348	0.105
24	29	10	290	2.2	1.08	0.010	348	0.073
23	26	8	208	1.2	1.46	0.0095	365	0.039
22	23	7	161	0.75	1.85	0.0095	365	0.0226
21	19	6	114	0.42	2.46	0.009	382	0.0122
20	17	6	102	0.30	2.92	0.0095	365	0.0091
19	15	5	75	0.18	3.76	0.009	382	0.0052
18	12	4	48	0.089	5.35	0.0085	405	0.0023
17	11	4	44	0.065	6.26	0.009	382	0.0018

L_w	0.937 in.	Fe	0.378 lb	H_s	0.212 ∓ (AT/in.)
W_w	0.312 in.	Cu	0.091 lb	l_g	3.2 $(NI_{dc}-7.8)$ 10^{-5} in.
H_o	1 oersted			E_{ac}	$N/10$
l_c	3.75 in.			B_{ac}	7850 gauss
A_c	0.37 in.^{2}	Core tube	0.025 in.	$\mu\Delta$	4840
l_m	3.36 in.	Wrap	0.025 in.	I^2R	2.55 W (20 C)

Table IV—Lamination EI 75

AWG	Turns per layer	Number of layers	N	Ohms 20 C	I_{dc}	l_g	μ_{eff}	L
40	244	61	14890	5435	0.027	0.013	317	207
39	220	56	12310	3540	0.0336	0.013	317	141
38	195	51	9950	2285	0.0418	0.0135	306	89
37	169	47	7940	1445	0.0526	0.0135	306	56.5
36	151	43	6500	940	0.0652	0.0135	306	37.6
35	136	39	5300	617	0.0806	0.0135	306	25.5
34	120	35	4200	381	0.1025	0.014	296	15.4
33	107	30	3210	231	0.131	0.0135	306	9.2
32	96	27	2590	171	0.153	0.0125	329	6.48
31	83	25	2065	93	0.207	0.0135	306	3.87
30	73	22	1605	58	0.263	0.013	317	2.57
29	66	20	1320	38	0.324	0.0135	306	1.57
28	59	19	1120	26	0.392	0.014	296	1.10
27	53	16	848	15.2	0.513	0.014	296	0.63
26	47	15	705	10.0	0.632	0.014	296	0.43
25	42	13	546	6.3	0.796	0.014	296	0.26
24	37	12	444	4.0	1.00	0.014	296	0.167
23	34	10	340	2.4	1.29	0.014	296	0.101
22	31	9	279	1.57	1.60	0.0145	287	0.065
21	25	8	200	0.89	2.12	0.0135	306	0.035
20	22	7	154	0.55	2.70	0.0135	306	0.021
19	20	6	120	0.34	3.43	0.013	317	0.0134
18	16	6	96	0.22	4.26	0.013	317	0.0085
17	15	5	75	0.17	4.85	0.0115	362	0.0060
16	13	4	52	0.059	8.22	0.0135	331	0.00296
15	10	4	40	0.045	9.43	0.0125	329	0.00152
14	9	3	27	0.024	12.9	0.011	369	0.00079
13	8	3	24	0.017	15.3	0.012	341	0.00057

L_w	1.125 in.	Fe	0.65 lb	H_s	0.1765 ∓ AT/in.
W_w	0.375 in.	Cu	0.18 lb	l_g	3.2 $(NI_{ac}-9.09)$ 10^{-5} in.
H_o	1 oersted			E_{ac}	$N/10$
l_c	4.5 in.			B_{ac}	5450 gauss
A_c	0.533 in.^{2}	Core tube	0.025 in.	$\mu\Delta$	3750
l_m	4.18 in.	Wrap	0.025 in.	I^2R	4.0 W (20 C)

Table V—Lamination EI 87 or EI 11

AWG	Turns per layer	Number of layers	N	Ohms 20 C	I_{dc}	l_g	μ_{eff}	L
40	290	72	20840	8880	0.0254	0.017	281	420
39	261	66	17230	5810	0.0314	0.018	267	272
38	232	60	13910	3730	0.039	0.018	267	180
37	202	55	11100	2360	0.049	0.018	267	113
36	181	50	9050	1525	0.061	0.018	267	74.5
35	163	46	7500	1000	0.076	0.018	267	51.7
34	144	41	5910	626	0.096	0.018	267	31.4
33	128	35	4790	402	0.119	0.018	267	21.3
32	115	32	3680	246	0.152	0.018	267	12.2
31	101	30	3030	160	0.189	0.019	254	8.0
30	89	27	2400	101	0.238	0.019	254	5.2
29	80	24	1920	63.8	0.300	0.019	254	3.2
28	72	22	1584	41.8	0.370	0.019	254	2.2
27	64	19	1216	25.4	0.475	0.019	254	1.3
26	58	17	985	16.4	0.591	0.019	254	0.85
25	51	16	816	10.7	0.732	0.019	254	0.58
24	46	14	644	6.7	0.924	0.019	254	0.36
23	41	12	492	4.0	1.20	0.019	254	0.21
22	37	11	407	2.7	1.46	0.019	254	0.17
21	31	9	279	1.45	1.99	0.018	267	0.071
20	27	8	216	0.89	2.54	0.018	267	0.043
19	24	7	168	0.55	3.23	0.018	267	0.025
18	20	6	120	0.31	4.30	0.017	281	0.014
17	18	6	108	0.22	5.10	0.018	267	0.0104
16	16	5	80	0.13	6.64	0.017	281	0.0062
15	12	5	60	0.078	8.57	0.017	281	0.0035
14	11	4	44	0.045	11.3	0.016	297	0.0020
13	10	4	40	0.033	13.2	0.017	281	0.0015
13sq	9	4	36	0.024	15.4	0.018	261	0.0012

L_w	1.312 in.	Fe	1.035 lb	H_s	0.151 ∓ AT/in.
W_w	0.437 in.	Cu	0.250 lb	l_g	3.2 $(NI_{ac}-10.6)$ 10^{-5} in.
H_o	1 oersted			E_{ac}	$N/10$
l_c	5.26 in.			B_{ac}	4000 gauss
A_c	0.726 in.^{2}	Core tube	0.025 in.	$\mu\Delta$	3150
l_m	4.86 in.	Wrap	0.025 in.	I^2R	5.73 W (20 C)

Table VI—Lamination EI 100 or EI 12

AWG	Turns per layer	Number of layers	N	Ohms 20 C	I_{dc}	l_g	μ_{eff}	L
40	336	85	28600	13900	0.023	0.021	258	835
39	302	78	23600	9100	0.028	0.022	247	545
38	269	71	19100	5850	0.035	0.022	247	356
37	236	65	15350	3730	0.043	0.021	258	239
36	211	59	12450	2400	0.054	0.022	247	151
35	190	54	10250	1570	0.067	0.022	247	103
34	168	48	8060	975	0.086	0.022	247	63.5
33	149	41	6100	586	0.110	0.022	247	36.3
32	133	38	5050	384	0.136	0.022	247	24.8
31	118	35	4130	250	0.168	0.022	247	16.6
30	105	31	3280	157	0.213	0.022	247	10.4
29	94	29	2630	100	0.266	0.022	247	6.7
28	85	26	2210	66.5	0.327	0.023	237	4.57
27	76	23	1745	41.7	0.413	0.023	237	2.86
26	68	21	1428	27.0	0.513	0.024	229	1.85
25	60	19	1140	17.1	0.645	0.024	229	1.17
24	54	17	918	10.9	0.808	0.024	229	0.77
23	48	15	720	6.8	1.02	0.024	229	0.465
22	43	13	559	4.2	1.30	0.023	237	0.290
21	36	11	396	2.35	1.74	0.024	229	0.141
20	33	10	330	1.55	2.14	0.023	237	0.101
19	29	9	261	0.98	2.69	0.023	237	0.063
18	25	8	200	0.59	3.47	0.022	247	0.0383
17	22	7	154	0.36	4.44	0.022	247	0.0232
16	20	6	120	0.22	5.68	0.022	247	0.0137
15	15	5	75	0.11	8.03	0.019	282	0.0062
14	13	5	65	0.076	9.66	0.020	269	0.0044
13	12	4	48	0.045	12.5	0.019	282	0.0025
13sq	11	4	44	0.034	14.4	0.020	269	0.0020
12sq	10	4	40	0.025	16.8	0.022	247	0.00157

L_w	1.50 in.	Fe	1.54 lb	H_s	0.132 ∓ (AT/in.)
W_w	0.50 in.	Cu	0.45 lb	l_g	3.2 $(NI_{dc}-12.1)$ 10^{-5} in.
H_o	1 oersted			E_{ac}	$N/10$
l_c	6.0 in.			B_{ac}	3060 gauss
A_c	0.95 in.^{2}	Core tube	0.030 in.	$\mu\Delta$	2660
l_m	5.57 in.	Wrap	0.025 in.	I^2R	7.1 W (20 C)

ALL LAMINATIONS □ STACKING. AC INCLUDES STACKING FACTOR (.95)

L-125

Table VII—Lamination EI 125

AWG	Turns per layer	Number of layers	N	Ohms 20 C	I_{dc}	l_g	μ_{eff}	L
36	271	75	20350	4890	0.043	0.028	237	486
35	245	69	16900	3230	0.052	0.028	237	334
34	217	62	13460	2040	0.066	0.029	231	206
33	192	53	10176	1220	0.086	0.028	237	122
32	173	48	8304	790	0.106	0.028	237	81
31	154	44	6770	505	0.133	0.029	231	63.5
30	137	40	5480	328	0.165	0.029	231	33.7
29	122	36	4390	209	0.207	0.029	231	22.0
28	110	33	3630	137	0.256	0.030	223	14.5
27	98	29	2840	85	0.325	0.030	223	8.8
26	88	26	2288	54	0.408	0.030	223	5.75
25	78	23	1794	34	0.515	0.030	223	3.52
24	70	22	1540	23	0.625	0.031	217	2.53
23	62	18	1116	13.2	0.826	0.030	223	1.37
22	56	17	952	8.9	1.01	0.031	217	0.97
21	48	14	672	5.0	1.34	0.029	231	0.51
20	43	13	559	3.3	1.65	0.030	223	0.343
19	38	11	418	1.96	2.14	0.029	231	0.200
18	33	10	330	1.22	2.71	0.029	231	0.125
17	29	9	261	0.77	3.42	0.029	231	0.0775
16	26	8	208	0.48	4.33	0.029	231	0.0490
15	21	7	147	0.27	5.77	0.027	245	0.0263
14	19	6	114	0.17	7.27	0.027	245	0.0158
13	17	6	102	0.12	8.66	0.028	237	0.0122
13sq	15	6	90	0.087	10.1	0.029	231	0.0092
12sq	13	5	65	0.051	13.2	0.028	237	0.0048
11sq	12	4	48	0.029	17.6	0.027	245	0.0027

L_w	1.875 in.	Fe	3.00 lb	H_z	0.106 ∓ (AT/in.)
W_w	0.625 in.	Cu	1.00 lb	l_g	3.2 (NI_{dc}—15.15) 10^{-5} in.
H_o	1 oersted			E_{ac}	N/10
l_c	7.5 in.			B_{ac}	1980 gauss
A_c	1.485 in.^{2}	Core tube	0.030 in.	$\mu\Delta$	2100
l_m	6.96 in.	Wrap	0.025 in.	I^2R	9W (20 C)

L-138

Table VIII—Lamination EI 138

AWG	Turns per layer	Number of layers	N	Ohms 20 C	I_{dc}	l_g	μ_{eff}	L
34	241	69	16629	2765	0.0625	0.034	215	332
33	213	58	12354	1630	0.0814	0.032	227	186
32	191	53	10123	1060	0.101	0.033	221	122
31	172	49	8428	700	0.124	0.033	221	83.5
30	153	44	6732	445	0.156	0.034	215	52.0
29	136	40	5440	287	0.194	0.034	215	34.0
28	123	37	4551	189	0.239	0.035	209	23.4
27	110	32	3520	116	0.310	0.035	209	13.9
26	98	29	2842	74	0.382	0.035	209	8.9
25	88	26	2288	47.2	0.478	0.035	209	5.9
24	78	23	1794	29.5	0.605	0.035	209	3.63
23	69	20	1380	17.9	0.777	0.035	209	2.15
22	62	18	1116	11.5	0.970	0.035	209	1.39
21	54	15	810	6.6	1.28	0.033	221	0.78
20	48	14	672	4.35	1.58	0.034	215	0.51
19	43	12	516	2.65	2.02	0.033	221	0.31
18	37	11	407	1.66	2.55	0.033	221	0.187
17	33	10	330	1.07	3.18	0.034	215	0.126
16	29	8	232	0.60	4.25	0.032	227	0.065
15	24	8	192	0.39	5.26	0.032	227	0.044
14	21	7	147	0.24	6.70	0.032	227	0.026
13	19	6	114	0.146	8.60	0.031	234	0.0163
13sq	17	6	102	0.109	9.95	0.033	221	0.0124
12sq	15	6	90	0.077	11.8	0.034	215	0.0093
11sq	13	5	65	0.044	15.7	0.033	221	0.0049
10sq	12	4	48	0.026	20.4	0.031	234	0.0028
9sq	11	4	44	0.017	25.2	0.035	209	0.0021
8sq	9	3	27	0.0091	32.9	0.028	255	0.0010
7sq	8	3	24	0.0063	41.4	0.031	234	0.00073

L_w	2.062 in.	Fe	4 lb	H_z	0.0963 ∓ (AT/in.)
W_w	0.687 in.	Cu	1.33 lb	l_g	3.2 (NI_{dc}—16.7) 10^{-5} in.
H_o	1 oersted			E_{ac}	N/10
l_c	8.25 in.			B_{ac}	1630 gauss
A_c	1.785 in.^{2}	Core tube	0.030 in.	$\mu\Delta$	1908
l_m	7.66 in.	Wrap	0.025 in.	I^2R	10.8 W (20 C)

L-150

Table IX—Lamination EI 150 or EI 13

AWG	Turns per layer	Number of layers	N	Ohms 20 C	I_{dc}	l_g	μ_{eff}	L
32	216	58	12500	1435	0.09	0.036	219	202
31	190	54	10250	933	0.112	0.037	215	133
30	169	48	8100	583	0.141	0.036	219	84.7
29	151	44	6650	381	0.175	0.037	215	55.7
28	136	40	5440	247	0.217	0.037	215	37.8
27	121	35	4230	153	0.276	0.037	215	22.8
26	109	32	3490	100	0.341	0.038	209	15.0
25	97	29	2810	63.5	0.428	0.038	209	9.6
24	86	26	2236	41.0	0.533	0.038	209	6.14
23	77	22	1695	24.0	0.697	0.038	209	3.56
22	69	20	1380	15.6	0.864	0.038	209	2.36
21	59	17	1005	9.0	1.14	0.037	215	1.29
20	53	15	795	5.6	1.44	0.037	215	0.80
19	47	13	610	3.45	1.84	0.036	219	0.48
18	41	12	492	2.20	2.30	0.036	219	0.31
17	37	11	407	1.44	2.84	0.037	215	0.211
16	33	9	297	0.84	3.72	0.035	225	0.117
15	27	8	216	0.48	4.92	0.034	231	0.064
14	24	8	192	0.34	5.86	0.036	219	0.049
13	21	7	147	0.21	7.45	0.035	225	0.028
13sq	19	7	133	0.156	8.64	0.037	215	0.0226
12sq	17	6	102	0.096	11.0	0.036	219	0.0135
11sq	15	6	90	0.066	13.3	0.039	205	0.0098
10sq	13	5	65	0.038	17.5	0.036	219	0.0055
9sq	12	4	48	0.021	23.5	0.036	219	0.0029
8sq	11	4	44	0.016	27.0	0.037	215	0.0024
(2)10sq	6	5	30	0.0088	36.4	0.035	225	0.0012
(2)9sq	6	4	24	0.0053	46.8	0.036	219	0.00074
(2)8sq	5	4	20	0.0036	56.9	0.037	215	0.00050

L_w	2.250 in.	Fe	5.2 lb	H_z	0.0883 ∓ (AT/in.)
W_w	0.750 in.	Cu	1.8 lb	l_g	3.2 (NI_{dc}—18.2) 10^{-5} in.
H_o	1 oersted			E_{ac}	N/10
l_c	9.0 in.			B_{ac}	1360 gauss
A_c	2.14 in.^{2}	Core tube	0.035 in.	$\mu\Delta$	1760
l_m	8.4 in.	Wrap	0.025 in.	I^2R	11.65 W (20 C)

L-163

Table X—Lamination EI 36

AWG	Turns per layer	Number of layers	N	Ohms 20 C	I_{dc}	l_g	μ_{eff}	L
25	115	50	5750	161	0.30	0.055	178	33.4
24	102	45	4590	102	0.38	0.055	178	21.2
23	91	39	3549	62.8	0.48	0.054	181	12.7
22	82	35	2870	40.2	0.60	0.055	178	8.3
21	70	30	2100	23.3	0.79	0.053	185	4.6
20	63	27	1701	15.0	0.98	0.053	185	3.04
19	55	24	1320	9.2	1.25	0.053	185	1.83
18	48	21	1008	6.0	1.55	0.050	194	1.12
17	44	19	836	3.6	2.00	0.053	185	0.73
16	39	17	663	2.3	2.50	0.053	185	0.46
15	33	15	495	1.37	3.25	0.051	191	0.266
14	29	14	406	0.89	4.03	0.052	188	0.177
13	26	12	312	0.54	5.16	0.051	191	0.105
13sq	23	12	276	0.40	6.00	0.053	185	0.080
12sq	21	11	231	0.27	7.30	0.054	181	0.055
11sq	18	10	180	0.16	9.50	0.054	181	0.033
10sq	16	9	144	0.103	11.8	0.054	181	0.0207
9sq	15	8	120	0.066	14.8	0.056	176	0.0144
8sq	13	7	91	0.041	18.7	0.054	181	0.0085
7sq	11	6	66	0.023	25.0	0.053	185	0.0046
6sq	10	6	60	0.017	29.1	0.055	178	0.0036
5sq	9	5	45	0.010	38.0	0.054	181	0.0021

L_w	2.625 in.	Fe	7.45 lb	H_z	0.0723 ∓ (AT/in.)
W_w	1.250 in.	Cu	5.00 lb	l_g	3.2 (NI_{dc}—22.2) 10^{-5} in.
H_o	1 oersted			E_{ac}	N/10
l_c	11.0 in.			B_{ac}	1160 gauss
A_c	2.51 in.^{2}	Core tube	0.040 in.	$\mu\Delta$	1640
l_m	10.4 in.	Wrap	0.025 in.	I^2R	14.4 W (20 C)

INCLUDES STACKING FACTOR

1☐ STACKING

may also be calculated from the value of 6.7 henrys given in the table.

$$L = 6.7 \times 527/247 \times 1.375 = 19.7 \text{ henrys}$$

(h) The thickness of spacers between the "E" and "I" core sections will be $0.0089 \times 1.5/2 = 0.0065$ in.

(i) The resistance of the coil is determined by adding 0.75 in. (twice the $\frac{3}{8}$ in. increase in build) to the mean length of turn l_m from the table and multiplying the resistance from the table by the ratio of the increased l_m to the original l_m.

$$\text{Resistance} = \frac{(5.57 + 0.75)}{5.57} \times 100 = 113 \text{ ohms at}$$

20 C

Design Example—Swinging Choke

Assume that it is desired to build a swinging choke having the following characteristics:

Condition 1:	Condition 2:
$L = 1.74$ henrys	$L' = 0.87$ henrys
$I_{dc} = 100$ ma	$I_{dc}' = 500$ ma

$R = 25$ ohms (at equilibrium temperature)
$E_{ac} = 38.5$ volts
$f = 120$ cycles per sec

A choke with the required swing can usually be obtained from a core and coil which, as a linear choke, would have mean inductance at maximum current. The

Table XI—Lamination EI 19 L-177

AWG	Turns per layer	Number of layers	N	Ohms 20 C	I_{dc}	l_g	μ_{eff}	L
25	130	71	9230	311	0.31	0.091	130	61.7
24	116	64	7424	198	0.39	0.092	129	39.6
23	103	55	5665	120	0.50	0.093	128	23.0
22	93	50	4650	78	0.62	0.092	129	15.5
21	81	42	3402	45.5	0.81	0.085	139	9.05
20	74	39	2886	30.6	0.99	0.091	130	5.90
19	66	33	2178	18.3	1.28	0.085	139	3.70
18	58	30	1740	11.1	1.64	0.090	132	2.22
17	51	28	1428	7.5	2.00	0.091	130	1.47
16	46	23	1058	4.4	2.61	0.084	140	0.87
15	39	21	819	2.7	3.33	0.084	140	0.513
14	35	19	665	1.75	4.14	0.084	140	0.339
13	31	17	527	1.10	5.22	0.084	140	0.216
13sq	27	18	486	0.85	5.94	0.092	129	0.170
12sq	25	16	400	0.56	7.32	0.093	128	0.114
11sq	22	14	308	0.34	9.40	0.092	129	0.067
10sq	20	13	260	0.23	11.4	0.095	125	0.046
9sq	17	11	187	0.12	15.8	0.094	126	0.024
8sq	16	10	160	0.087	18.6	0.095	125	0.0181
7sq	13	9	117	0.050	24.5	0.091	130	0.0099
6sq	12	8	96	0.032	31.2	0.095	125	0.0064
5sq	11	7	77	0.021	37.6	0.092	129	0.0042
(2)7sq	6	9	54	0.011	52.2	0.090	132	0.00215
(2)6sq	6	8	48	0.008	61.2	0.093	128	0.00155
(2)5sq	5	7	35	0.0048	79	0.088	134	0.00091

L_w	3.000 in.	Fe	10.3 lb	H_x	0.061 $\mathfrak{I}$ (AT/in.)
W_w	1.750 in.	Cu	8.6 lb	l_g	3.2 (NI_{dc}—26.25) 10^{-5} in.
H_o	1 oersted			E_{ac}	$N/10$
l_c	13.0 in.			B_{ac}	1000 gauss
A_c	2.91 in.^{2}	Core tube	0.045 in.	μ_Δ	1540
l_m	12.5 in.	Wrap	0.025 in.	I^2R	30 W (20 C)

desired construction will therefore be equivalent to a linear choke with 1.3 henrys at 500 ma d-c.

(a) Determine effective current for temperature rise considerations.

$$I_{ac} = \frac{E_{ac}}{2\pi f L} = \frac{38.5}{2\pi \times 120 \times 0.87} = 0.059 \text{ amp}$$

$$I_{eff} = \sqrt{I^2_{dc} + I^2_{ac}} = \sqrt{0.500^2 + 0.059^2} = 0.503 \text{ amp}$$

Here, as in the first example, the effect of the a-c on the winding temperature rise is negligible compared to the d-c component.

(b) Using the method described in step (b) of the first example, it is determined from Table V that a coil with 985 turns of No. 26 wire with a stack build of $1\frac{1}{8}$ in. will have approximately the desired inductance and d-c current ratings. The net cross section for the core will be

$$A_c = \frac{1\frac{1}{8}}{\frac{7}{8}} \times 0.726 = 0.934 \text{ sq in.}$$

(c) The next step will be to determine the required μ_{eff} for condition 1 and compute the gap length for this μ_{eff}. Then the degree of saturation resulting with this gap may be estimated for the current of condition 2.

$$\mu_{eff} = \frac{L' l_c\, 10^8}{2.5\, N^2 A_c} = \frac{1.74 \times 5.26 \times 10^8}{2.5 \times 985^2 \times 0.934} = 404$$

Consider equation (4) for the computation of l_g. Since the saturation (H_o) of the steel will be quite small for the relatively low current in condition 1, we may expect μ_Δ to be a large number compared to l_c. Equation (4) under these circumstances may be abbreviated to:

$$l_g \approx 90 \text{ per cent} \frac{l_c}{\mu_{eff}} = \frac{0.9 \times 5.26}{404}$$

$$\approx 0.0118 \text{ in.}$$

We now compute a brief table of air gaps for condition 2 for various degrees of saturation, where $N = 985$, $I = 0.5$, and $l_c = 5.26$ in.

H_o, oersteds	l_g, in.
1	$3.2\ (NI - 2.02\ l_c)10^{-5} = 0.0154$
2	$3.07(NI - 4.04\ l_c)10^{-5} = 0.0145$
5	$2.94(NI - 10.1\ l_c)10^{-5} = 0.0129$
10	$2.84(NI - 20.2\ l_c)10^{-5} = 0.0109$

We thus find that the gap (0.0118 in.) tentatively chosen to satisfy condition 1 would result in a saturation of about 7.5 oersteds when the d-c is 0.5 amp as in condition 2.

(d) It is now possible to check to see whether, for $H_o = 7.5$ oersted and $l_g = 0.0118$ in., the inductance requirement of condition 2 is met. In Table V, B_{ac} is given as 4000 gauss. This must be reduced for the increase in build, or 0.875/1.125 and by the ratio of rated voltage (38.5) to the voltage on which the table is based ($N/10 = 98.5$). Thus

$$B_{ac} = 4000 \times 0.875/1.125 \times 38.5/98.5 = 1215 \text{ gauss}$$

From Fig. 1, we find that, for $H_o = 7.5$ and $B_{ac} = 1215$, μ_Δ is approximately 350. Then, using equation (3),

$$\mu_{eff} = \frac{5.26 \times 350}{5.26 + (350 \times 0.0118)} = 196$$

It is obvious that the stack height of 1⅛ in. is approximately correct for condition 2, since

$$L' = 1.74 \times 196/404 = 0.845 \text{ henrys}$$

This result is only about 3 per cent too low. If 0.87 is the minimum acceptable value for condition 2, the calculations to this point must be repeated using a slightly larger stack height. Assuming, however, that this value is satisfactory, we can proceed to see whether or not condition 1 is satisfied.

(e) Using the graphical solution of equation (8), determine H_o.
Since

$$\mathcal{F} = NI = 985 \times 0.1 = 98.5 \text{ ampere-turns}$$

from equations (11) and (13)

$$B_y = \frac{\mathcal{F}}{0.313\, l_g} = \frac{98.5}{0.313 \times 0.0118} = 26.7 \text{ kilolines per sq in.}$$

$$H_x = \frac{\mathcal{F}}{l_c} = \frac{98.5}{5.26} = 18.7 \text{ ampere-turns/in.}$$

If on Fig. 2 a straight line is drawn between 18.7 on an extension of the abscissa and 26.7 on the ordinate, the line intersects the curve at approximately 0.2 ampere-turns per in. This is approximately equivalent to 0.1 oersted, which represents the degree of saturation of the core in condition 1.

(f) Using $B = 1215$ gauss and $H = 0.1$ oersted we obtain by interpolation in Fig. 1 a value for μ_Δ of about 5000. It is now possible to evaluate μ_{eff}.

$$\mu_{eff} = \frac{5.26 \times 5000}{5.26 + (5000 \times 0.0118)} = 409$$

It can thus be seen that the assumption in step c that

$$l_g = 90 \text{ per cent } \frac{l_c}{\mu_{eff}}$$

was a good approximation. It is also seen that a μ_{eff} of 409 will yield slightly more than the required inductance of 1.74 henrys.

(g) The spacer to be used in the air gap should have a thickness of approximately

$$\frac{1.5 \times 0.0118}{2} = 0.009 \text{ in.}$$

○ ○ ○

CHOKE DESIGN IRVING RICHARDSON METHOD M-7

$$\underset{(KG)}{B_{AC}} = \frac{3.49\ E_{ac}\ 10^3}{f\ A_c\ N} = \frac{3.49 \times 10^3 \times}{\qquad} = \quad KG$$

$$\underset{(lines)}{B_y} = \frac{NI}{.313\ g} = \qquad \times .155 \times 10^{-3} = \quad KG.$$

$$H_x = \frac{NI}{l} = \frac{\qquad}{\qquad} = \quad AT/inch \ \times .495 = \quad oerst$$

from CURVE H_o =

from CURVE μ_Δ =

$$\underset{(60\,HZ)}{\mu\ eff.} = \frac{l\,\mu_\Delta}{l + g\,\mu_\Delta} =$$

$$\underset{(mh)}{L} = \frac{3.19\ N^2\ A_c\ 10^{-5}}{l} \times \underset{}{\mu_{eff}}^{(60\,HZ)}$$

FOR 120 HZ μ_{eff} = .78 × μ_{eff} (60HZ

180 = .75

360 = .60