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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-697

Revision 1

Simplified Cut Core Inductor Design

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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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Colonel W. T. McLyman

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PREFACE

The work described in this report was performed by the Guidance and Control Division of the Jet Propulsion Laboratory.

ACKNOWLEDGMENT

The author wishes to express his thanks to Dr. G. W. Wester for support in gathering data and his technical aid.

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FIGURES

LIST OF SYMBOLS

A_c	effective iron area, cm^2
A_p	area product, $W_a \times A_c$, cm^4
A_t	surface area, cm^2
A_w	wire area, cm^2
AWG	American Wire Gauge
B_{ac}	alternating current flux density, teslas
B_{dc}	direct current flux density, teslas
B_m	flux density, teslas
E	voltage
Eng	energy, watt seconds
f	frequency, Hz
F	fringing flux factor
I	current, amps
I_o	load current, amps
J	current density, amps/cm^2
K	constant
K_j	current density coefficient
K_s	surface area coefficient
K_u	window utilization factor
K_v	volume coefficient
K_w	weight coefficient
L	inductance, henry
l_g	gap, cm
l_m	magnetic path, cm
ℓ	linear dimension, cm

MLT	mean length turn, cm
N	turns
P_{cu}	copper loss, watts
P_{fe}	core loss, watts
P_{in}	input power, watts
P_o	output power, watts
Ψ	heat flux density, watts/cm^2
P_Σ	total loss (core and copper), watts
R	resistance, ohms
S_1	conductor area/wire area
S_2	wound area/usable window
S_3	usable window area/window area
S_4	usable window area/(usable window area + insulation area)
T	flux density, teslas
μ_Δ	effective permeability
μ_m	core material permeability
μ_o	absolute permeability
μ_r	relative permeability
Vol	volume, cm^3
W_a	window area, cm^2

ABSTRACT

Although filter inductor designers have routinely tended to specify moly permalloy powder cores for use in high frequency power converters and pulse-width modulated switching regulators, there are significant advantages in specifying C cores and cut toroids fabricated from grain oriented silicon steels which should not be overlooked. Such steel cores can develop flux densities of 1.6 tesla, with useful linearity to 1.2 tesla, whereas moly permalloy cores carrying d.c. current have useful flux density capabilities only to about 0.3 tesla. The use of silicon steel cores thus makes it possible to design more compact cores, and therefore inductors of reduced volume, or conversely to provide greater load capacity in inductors of a given volume.

For years manufacturers have rated their cores with a number that represents its relative energy-handling ability. This method assigns to each core a number which is the product of its window and core cross-section area, and is called "Area Product A_p." The author has developed a correlation between the A_p numbers and current density J for a given temperature rise. Also, the author has developed straight-line relationships for A_p and Volume, A_p and surface area A_t and, A_p and weight. These relationships can now be used as new tools to simplify and standardize the process of inductor design. They also make it possible to design inductors of small bulk and volume or to optimize efficiency.

The adoption by NASA of the metric system for dimensioning to replace the long-used English units imposes a requirement on the U.S. transformer designer to convert from the familiar units to the less familiar metric equivalents. Material is presented to assist in that transition in the field of transformer design and fabrication.

I. INTRODUCTION

Designers have routinely tended to specify moly permalloy powder cores for filters inductors used in high frequency power converters and pulse-width modulated (PWM) switched regulators because of the convenient availability (in the literature of the manufacturers of such core materials) of tables, graphs and examples which simplify the design task. Such solutions do not necessarily result in inductors optimized for size and weight.

There are significant advantages in effecting such optimization by use of C core and cut toroids fabricated from grain-oriented silicon steel, despite such disadvantages as the need for banding and gapping materials and the use of bonding tools, mounting brackets and winding mandrels. Grain-oriented silicon steels provide greater flexibility in the design of high frequency inductors because the air gap can be adjusted to any desired width and because the relative permeability is high even at high dc flux density. Such steels can develop flux densities of 1.6 tesla, with useful linearity to 1.2 tesla. Moly permalloy* cores carrying dc current have useful flux density capabilities only to about 0.3 tesla.

As shown in Figure 1 (page 2), moly permalloy powder cores operating with a dc bias of 0.3 tesla have only about 80% of original inductance with very rapid falloff at higher densities. In contrast, the steel core has approximately four times the useful flux density capability while retaining 90% of original inductance at 1.2 tesla. Because of the interdependence and interaction of parameters, judicious design tradeoffs are necessary to achieve optimization.

*Reference 1

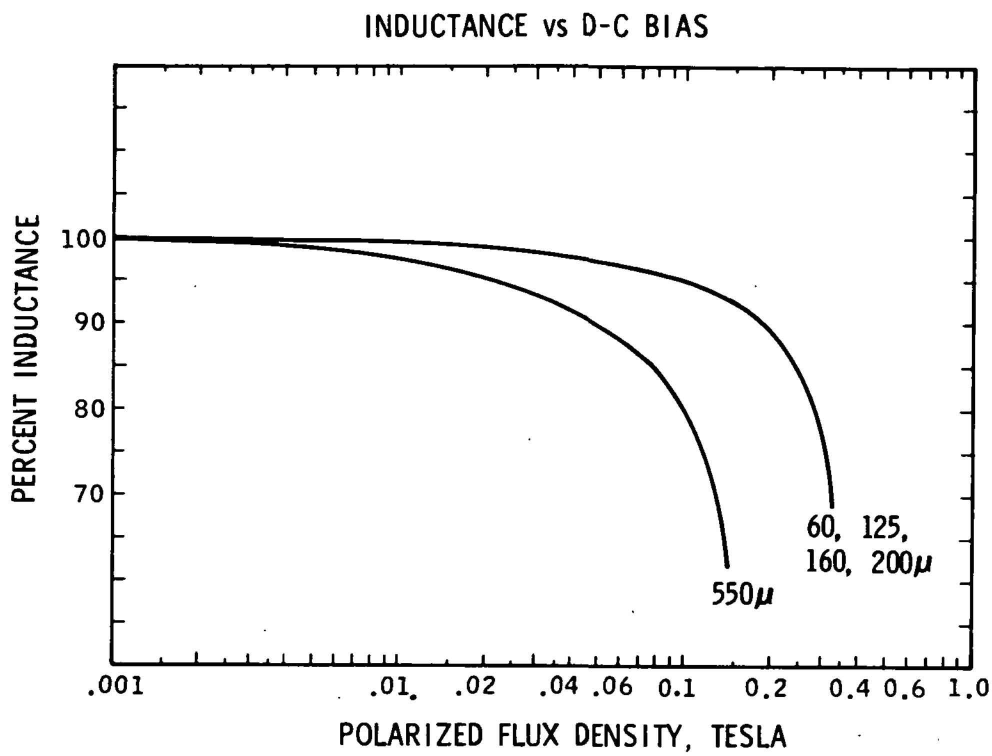


Fig. 1. Inductance vs dc bias.

Various inductor designers have used different approaches in arriving at suitable designs. For example, in many cases a rule of thumb is used for dealing with current density. Typically, an assumption is made that a good working level is 1000 circular mils per ampere. This may be practical in many instances but the wire size needed to meet this requirement may produce a heavier and bulkier inductor than desired or required. The information presented herein makes it possible to avoid the use of this and other rules of thumb and to develop a more economical design with great accuracy.

The adoption by NASA of the metric system for dimensioning to replace the long used English units imposes a requirement on the U. S. transformer designer to convert from the familiar units to the less familiar metric equivalents. Material is present to assist in that transition in the field of transformer design and fabrication.

Manufacturers have for years assigned numeric codes to their cores which represent the relative energy handling ability. This method assigns to each core a number which is the product of its window area and core cross section area and is called "Area Product", A_p.

Over the last few months, the author became aware of unique relationships between the "Area Product", A_p, characteristic number for inductor cores and several other important parameters which must be considered in inductor design. These numbers were developed by core suppliers to summarize dimensional and electrical properties of C-cores and are listed in their catalogs. Such numbers are available for more than 200 different C-core sizes and configurations.

The author has developed relationships between the A_p numbers and current density J for a given temperature rise. The area product A_p is a dimension to the fourth power ℓ^4, whereas volume is a dimension to the third power ℓ^3 and surface area A_t is a dimension to the second power ℓ^2. Straight-line relationships have been developed for A_p and volume, A_p and surface area A_t, and A_p and weight.

These relationships can now be used as new tools to simplify and standardize the process of inductor design. They make it possible to design inductors of smaller bulk and volume or to optimize efficiency. While developed specifically for aerospace applications, the information has wider utility and can be used for the design of non-aerospace inductors as well.

Because of its significance, area product, A_p, is treated extensively. Additionally a great deal of information is presented for the convenience of the designer. Much of the material is in graphical or tabular form to assist the designer in making the tradeoffs best suited for his particular application in a minimum amount of time.

THE AREA PRODUCT (A_p)

The A_p* of a C-type core is the product of the available window area (W_a) of the core in square centimeters (cm^2) multiplied by the effective cross-sectional area (A_c) in square centimeters (cm^2) which may be stated as:

$$A_p = W_a A_c \qquad \left[cm^4\right] \qquad (1)$$

Figure 2 shows in outline form a C-core type inductor typical of those shown in the catalogs of suppliers and uses the letter designations accepted by the industry to indicate certain significant dimensions from which the A_p area product is calculated. From this it can be seen that W_a is the FG product and A_c is the DE product.

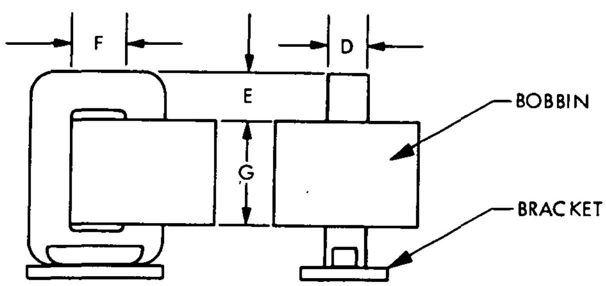


Fig. 2. Outline form C-core inductor.

RELATIONSHIP OF A_p TO INDUCTOR ENERGY HANDLING CAPABILITY

According to the newly developed approach the energy handling capability of a core is related to its area product A_p by a equation which may be stated as follows.

*References 2, 3

$$A_p = \left(\frac{2(Eng) \times 10^4}{B_m K_u K_j}\right)^{1.14}$$

K_j = current density coefficient
395 for 25°C rise
569 for 50°C rise

K_u = window utilization factor
0.4 in most cases

B_m = flux density, tesla

Eng = energy, watt seconds

From the above it can be seen that factors such as flux density, window utilization factor K_u (which defines the maximum space which may be occupied by the copper in the window) and the constant K_j (which is related to temperature rise), all have an influence on the inductor area product. The constant K_j is a new parameter that gives the designer control of the copper loss. Derivation is set forth in detail in Appendix B.

FUNDAMENTAL CONSIDERATION

The design of a linear reactor depends upon three related factors.

1. Desired inductance
2. Direct current
3. Alternating current ΔI

With these requirements established, the designer must determine the maximum values for B_{dc} and for B_{ac} which will not produce magnetic saturation, and must make tradeoffs which will yield the highest inductance for a given volume. The core material which is chosen dictates the maximum flux density which can be tolerated for a given design. Magnetic saturation values for different core materials are shown in Table 1, as follows.

Table 1. Magnetic material

Material Type		Flux Density (tesla)
Magnesil	3% Si, 97% Fe	1.6
Orthonal	50% Ni, 50% Fe	1.5
48 Alloy	48% Ni, 50% Fe	1.2
Permalloy	79% Ni, 17% Fe, 4% Mo	0.75

It should be remembered that maximum flux density depends upon $B_{dc} + B_{ac}$ in manner shown in Figure 3.

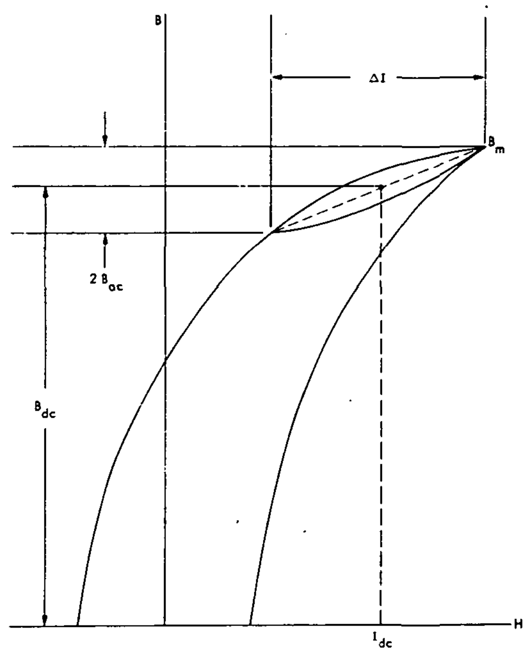


Fig. 3. Flux Density versus $I_{dc} + \Delta I$

$$B_{max} = B_{dc} + B_{ac} \text{ tesla}$$

$$B_{dc} = \frac{0.4\pi N I_{dc} \times 10^{-4}}{l_g + \frac{l_m}{\mu_r}} \quad [\text{tesla}] \qquad (1)$$

$$B_{ac} = \frac{0.4\pi N \frac{\Delta I}{2} \times 10^{-4}}{l_g + \frac{l_m}{\mu_r}} \quad [\text{tesla}] \qquad (2)$$

combining Eqs. (1) and (2)

$$B_{max} = \frac{0.4\pi N I_{dc} \times 10^{-4}}{l_g + \frac{l_m}{\mu_r}} + \frac{0.4\pi N \frac{\Delta I}{2} \times 10^{-4}}{l_g + \frac{l_m}{\mu_r}} \quad \text{[tesla]} \qquad (3)$$

The inductance of an iron-core inductor carrying dc and having an air gap may be expressed as:

$$L = \frac{0.4\pi N^2 A_c \times 10^{-8}}{l_g + \frac{l_m}{\mu_r}} \quad \text{[henry]} \qquad (4)$$

Inductance is dependent on the effective length of the magnetic path which is the sum of the air gap length (l_g) and the ratio of the core mean length to relative permeability (l_m/μ_r).

When the core air gap (l_g) is large compared to relative permeability (l_m/μ_r), because of the high relative permeability (μ_r) variations in μ_r do not substantially effect the total effective magnetic path length or the inductance. The inductance equation then reduces to:

$$L = \frac{0.4\pi N^2 A_c \times 10^{-8}}{l_g} \quad \text{[henry]} \qquad (5)$$

Final determination of the air gap requires consideration of the effect of fringing flux which is a function of gap dimension, the shape of the pole faces and the shape, size and location of the winding. Its net effect is to shorten the air gap.

Fringing flux decreases the total reluctance of the magnetic path and therefore increases the inductance by a factor F to a value greater than that calculated from equation (5). Fringing flux* is a larger percentage of the total for larger gaps. The fringing flux factor is:

$$F = \left(1 + \frac{l_g}{\sqrt{A_c}} \log_e \frac{2G}{l_g}\right) \tag{6}$$

where G is a dimension defined in Figure 2. (This equation is also valid for laminations.)

Equation (6) is plotted in Figure 4 below.

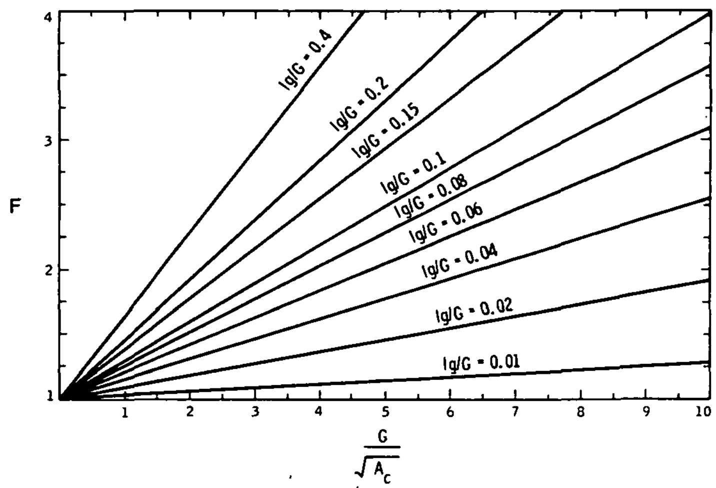


Fig. 4. Increase of reactor inductance with flux fringing at the gap.

Inductance L computed in equation (5) does not include the effect of fringing flux. The value of inductance L' corrected for fringing flux is:

$$L' = \frac{0.4\pi N^2 A_c F \times 10^{-8}}{l_g} \quad [\text{henry}] \tag{7}$$

*Reference 4

Effective permeability may be calculated from the following expression:

$$\mu_{\Delta} = \frac{\mu_m}{1 + \frac{l_g}{l_m} \mu_m} \tag{8}$$

μ_m = core material permeability

Curves which have been plotted for values of l_g/l_m from 0 to 0.005 are shown in Figure 5.

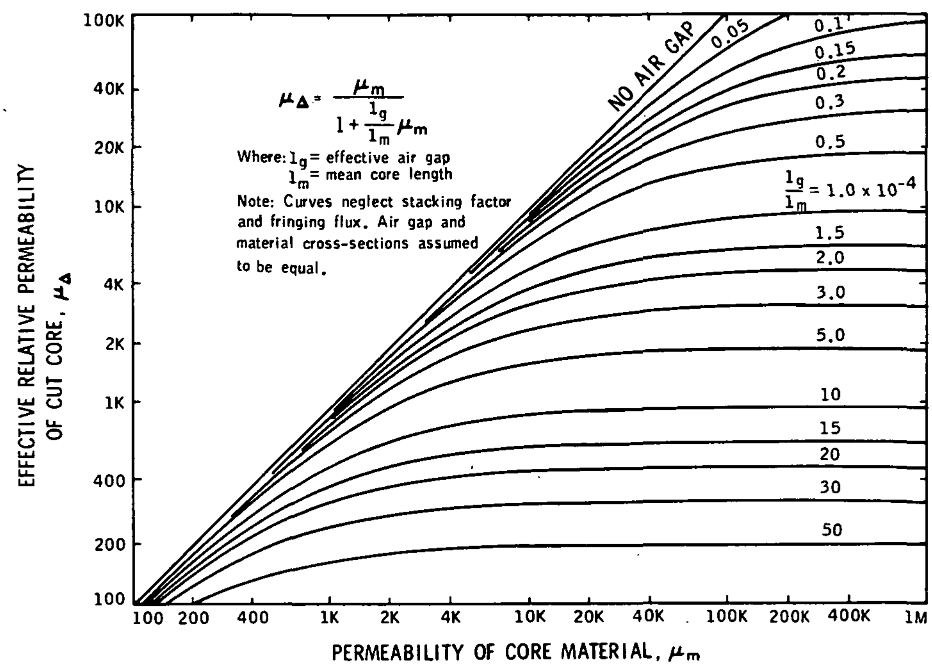


Fig. 5. Effective permeability of cut core vs permeability of the material

The effective design permeability for a butt core joint structure for material permeabilities ranging from 100 to 1,000,000 are shown. Effective permeability variation as a function of core geometry is shown in the curves plotted in Figure 6.

After establishing the required inductance and the dc bias current which will be encountered, dimensions can be determined. This requires consideration of the energy handling capability which is controlled by the area product A_p. The energy handling capability of a core is derived from

$$\frac{LI^2}{2} = \text{Energy} \tag{9}$$

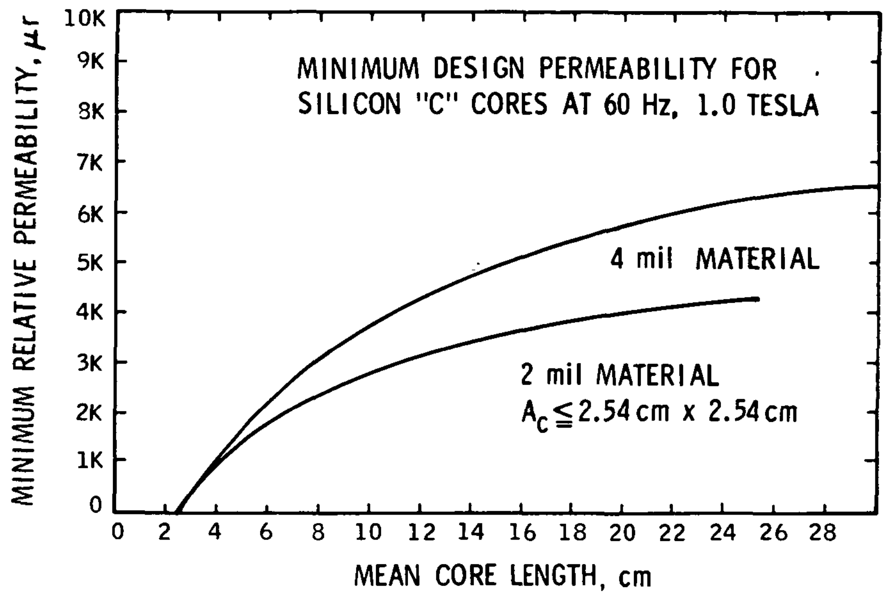


Fig. 6. Minimum design permeability

and

$$A_p = \left(\frac{2(\text{Eng}) \times 10^4}{B_m K_u K_j}\right)^{1.14} \quad [cm^4] \tag{10*}$$

in which:

B_m = maximum flux density ($B_{dc} + B_{ac}$)

K_u = window utilization factor

K_j = current density coefficient

Eng = Energy, watt seconds

*Derivation of equation (10) is shown in Appendix A and B.

DESIGN EXAMPLE

For a typical design example, assume:

1. Inductance 0.015 henrys
2. dc current 2 amp
3. ac current 0.1 amp
4. 25°C rise
5. Frequency 20 KHz

The procedure would then be as follows:

Step No. 1 Calculate the energy involved from equation (9):

$$\text{Eng} = \frac{LI^2}{2} \tag{11}$$

$$\text{Eng} = \frac{0.015(2.0)^2}{2}$$

$$\text{Eng} = 0.030 \qquad \text{[watt second]}$$

Step No. 2 Calculate the area product A_P from equation (10):

$$A_P = \left(\frac{2(\text{Eng}) \times 10^4}{B_m K_u K_j}\right)^{1.14} \qquad [\text{cm}^4]$$

$$A_P = \left(\frac{2(0.03) \times 10^4}{(1.2)(0.4)(395)}\right)^{1.14} = 3.72 \qquad [\text{cm}^4]$$

A core which has an area product closest to the calculated value is the AL-10 which is described in Table G9. That size core has an area product A_P of 3.85 cm^4 (A_C = 1.34 effective cm^2 X W_a = 2.87 cm^2).

After the A_P has been determined, the geometry of the inductor can be evaluated as described in Appendix D for weight, Appendix C for surface area and Appendix E for volume, and appropriate changes made, if required.

Step No. 3 Determine the current density from:

$$J = K_j A_P^{-0.125} \tag{12}^*$$

$$J = 395(3.72)^{-0.125} = 335 \text{ amps/cm}^2$$

Step No. 4 Determine the wire size from:

$$\text{Wire size} = \frac{I_{dc}}{\text{amp/cm}^2}$$

$$\text{Wire size} = \frac{2}{335} = 0.00597 \qquad [\text{cm}^2]$$

Select the wire size from Table F1. The rule is that when the calculated wire size does not all close to those listed in the table, the next smallest size should be selected.

The closest wire size to 0.00597 is AWG No. 20

$$\text{Area} = 0.005188 \text{ (bare)} \qquad [\text{cm}^2]$$

Step No. 5 Calculate the number of turns.

The number of turns per square cm for No. 20 wire is 98.9, based on 60% wire fill factor data taken from Table F1 column J.

$$\text{effective window} \times \text{turns/cm}^2$$

$$2.58 \times 98.9 \doteq 255$$

$$\text{Total number of turns} = 255$$

*Derivation of equation (12) is shown in Appendix B.

Step No. 6 The air gap dimension is determined from equation (5) by solving for l_g as follows:

$$l_g = \frac{0.4\pi \; N^2 A_c \times 10^{-8}}{L}$$

$$l_g = \frac{1.26(255)^2(1.342) \times 10^{-8}}{(0.015)}$$

$$l_g = 0.0733 \qquad [\text{cm}]$$

Gap spacing is usually maintained by inserting Kraft paper. However this paper is available only in mil thicknesses. Since l_g has been determined in cm, it is necessary to convert as follows:

$$\text{cm} \times 393.7 = \text{mils (inch system)}$$

substituting values:

$$0.0733 \times 393.7 = 28.8 \qquad [\text{mils}]$$

An available size of paper is 15 mil sheet. Two thicknesses would therefore be used, giving equal gaps in both legs.

The effect of fringing flux upon inductance can now be considered. As mentioned, the data shown in Figure 4 were developed to show graphically the effect of gap length l_g variation on fringing flux. In order to use this data, the ratio of l_g to window length G must be determined. For the AL-10 size, Table G9 shows a G value of 3.015 cm. Therefore:

$$\frac{l_g}{G} = \frac{0.0733}{3.015} = 0.0243 \qquad [\text{cm}]$$

and accordingly

$$\frac{G}{\sqrt{A_c}} = \frac{3.015}{1.16} = 2.60$$

The fringing flux factor F from Figure (4) may be stated:

$$F = 1.28$$

The recalculated number of turns can be determined by rewriting equation 7 as:

$$N = \sqrt{\frac{l_g L}{0.4\pi A_c F \times 10^{-8}}}$$

and by inserting the known values

$$N = \sqrt{\frac{(0.0733)(0.015)}{(1.26)(1.342)(1.28) \times 10^{-8}}} = 226$$

Step No. 7 Calculate the ac and dc flux density from equation (3)

$$B_{max} = \frac{0.4\pi N\left(I_{dc} + \frac{\Delta I}{2}\right) 10^{-4}}{l_g} \quad \text{[tesla]}$$

$$B_{max} = \frac{(1.26)(226)(2 + 0.05) \times 10^{-4}}{(0.0733)} \quad \text{[tesla]}$$

$$B_{max} = 0.793 \quad \text{[tesla]}$$

Step No. 8 Calculate core loss. This may be determined from Figure G24, in conjunction with equation (11), below:

$$B_{ac} = \frac{0.4\pi N \frac{\Delta I}{2} \times 10^{-4}}{lg} \quad \text{[tesla]}$$

$$B_{ac} = \frac{(1.26)(226)(0.05) \times 10^{-4}}{(0.0733)} \qquad [\text{tesla}]$$

$$B_{ac} = 0.0194 \qquad [\text{tesla}]$$

The ac core loss for this value can be found by reference to the graph shown in Figure G24, which is based upon solutions of the following expression for various operating frequencies:

$$P_{fe} = \frac{\text{milliwatts}}{\text{gram}} \times W_t$$

Referring to Table G9 for the AL-10 size core, the weight of the core is 110 grams. The core loss in milliwatts per gram is obtained from:

$$P_{fe} = (2.1)(110) = 230 \text{ milliwatts}$$

Step No. 9 Calculate copper loss and temperature rise.

The resistance of a winding is the mean length turn in cm multiplied by the resistance in micro ohms per cm and the total number of turns. Referring to Table G9 for the AL-10 size core for the mean length per turn (MLT) and the wire table F1 for the resistance of No. 20 wire then:

$$R = \text{MLT} \times N \times (\text{Column C}) \times 10^{-6} \qquad [\Omega]$$

$$R = 8.33 \times 226 \times 332 \times 10^{-6}$$

$$R = 0.625 \qquad [\Omega]$$

Since power loss is: $P = I^2R$

$$P = (2)^2(0.625) = 2.50 \qquad [\text{watts}]$$

$$P_{\Sigma} = P_{cu} + P_{fe}$$

$$P_{\Sigma} = 2.50 + 0.230$$

$$P_{\Sigma} = 2.73 \qquad \text{[watts]}$$

From Appendix C the surface area A_t required to dissipate waste heat (expressed as watts loss per unit area) is:

$$A_t = \frac{P_{\Sigma}}{\Psi}$$

$$\Psi = 0.03 \text{ W/cm}^2 \text{ @ } 25°\text{C rise}$$

Referring to Table G9 for the AL-10 size core, the surface area A_t is 79.39 cm^2.

$$\Psi = \frac{P_{\Sigma}}{A_t}$$

$$\Psi = \frac{2.73}{79.39} = 0.0344 \qquad [\text{W/cm}^2]$$

which will produce the required temperature rise.

(In a test sample made to prove out this example, the measured inductance was found to be 0.0159 hy and had a resistance of 0.600 ohms.)

With the reduction in turns resulting from consideration of fringing flux in some cases the designer may be able to increase the wire size and reduce the copper loss.

This completes the explanation of the example.

Much useful information which the designer needs can only be found in a scattered variety of texts and other literature. To make this information more conveniently available, helpful data has been gathered together and reproduced in Appendix G which contains 23 Tables and 25 Figures. The index has been prepared to make it possible for the designer to locate specific pertinent information more readily.

APPENDIX A

LINEAR REACTOR DESIGN WITH AN IRON CORE

After calculating the inductance and dc current, select the proper size core with a given $LI^2/2$. The energy handling capability of an inductor can be determined by its area product A_p where W_a is the available core window area in cm^2 and A_c is the core effective cross sectional area cm^2. The W_aA_c or area product A_p relationship is obtained by solving $E = LdI/dt$ as follows:*

$$E = L\frac{dI}{dt} = N\frac{d\phi}{dt} \tag{A1}$$

$$L = N\frac{d\phi}{dI} \tag{A2}$$

$$\phi = B_m A_c{}' \tag{A3}$$

$$B_m = \frac{\mu_o NI}{l_g{}' + \frac{l_m{}'}{\mu_r}} \tag{A4}$$

$$\phi = \frac{\mu_o NI A_c{}'}{l_g{}' + \frac{l_m{}'}{\mu_r}} \tag{A5}$$

$$\frac{d\phi}{dI} = \frac{\mu_o N A_c{}'}{l_g{}' + \frac{l_m{}'}{\mu_r}} \tag{A6}$$

$$L = N\frac{d\phi}{dI} = \frac{\mu_o N^2 A_c{}'}{l_g{}' + \frac{l_m{}'}{\mu_r}} \tag{A7}$$

*Symbols marked with a prime (such as H') are mks (meter kilogram second) units.

$$\text{Energy} = \frac{1}{2}\, LI^2 = \frac{\mu_o N^2 A_c' I^2}{2\left(l_g' + \frac{l_m'}{\mu_r}\right)} \tag{A8}$$

If B_m is specified,

$$I = \frac{B_m\left(l_g' + \frac{l_m'}{\mu_r}\right)}{\mu_o N} \tag{A9}$$

$$\text{Eng} = \frac{\mu_o N^2\, A_c'}{2\left(l_g' + \frac{l_m'}{\mu_r}\right)} \left(\frac{B_m\left(l_g' + \frac{l_m'}{\mu_r}\right)}{\mu_o N}\right)^2 \tag{A10}$$

$$\text{Eng} = \frac{B_m{}^2\left(l_g' + \frac{l_m'}{\mu_r}\right)A_c'}{2\mu_o} \tag{A11}$$

$$I = \frac{K_u W_a' J'}{N} = \frac{\left(B_m\left(l_g' + \frac{l_m'}{\mu_r}\right)\right)}{\mu_o N} \tag{A12}$$

Solving for $(l_g' + l_m'/\mu_r)$

$$\left(l_g' + \frac{l_m'}{\mu_r}\right) = \frac{\mu_o K_u W_a' J'}{B_m} \tag{A13}$$

Substituting into the energy equation

$$\mathrm{Eng} = \frac{B_m^{\,2}\left(\frac{\mu_o K_u W_a{}' J'}{B_m}\right) A_c{}'}{2\mu_o} \tag{A14}$$

$$\mathrm{Eng} = \frac{B_m^{\,2} A_c{}'}{2\mu_o} \times \frac{\mu_o K_u W_a{}' J'}{B_m} \tag{A15}$$

$$\mathrm{Eng} = \frac{B_m K_u W_a{}' A_c{}' J'}{2} \tag{A16}$$

let

W_a = window area, cm^2

A_c = core area, cm^2

J = current density, $amps/cm^2$

H = magnetizing force, amp turn/cm

l_g = air gap, cm

l_m = magnetic path length, cm

$W_a{}' = Wa \times 10^{-4}$

$A_c{}' = Ac \times 10^{-4}$

$J' = J \times 10^4$

$l_m{}' = l_m \times 10^{-2}$

$l_g{}' = l_g \times 10^{-2}$

$H' = H \times 10^2$

Substituting into the energy equation

$$\mathrm{Eng} = \frac{W_a A_c B_m J K_u}{2} \times 10^{-4} \tag{A17}$$

Solving for $A_p = W_a A_c$

$$A_p = \frac{2(\mathrm{Eng})}{B_m J K_u} \times 10^{4} \tag{A18}$$

APPENDIX B

INDUCTOR CURRENT DENSITY

Current density J of an inductor can be related to the area product A_p of a C-core transformer for a given temperature rise. The straightline logarithmic relationship shown in Figure B1 below, has been plotted from the data shown in Table G1.

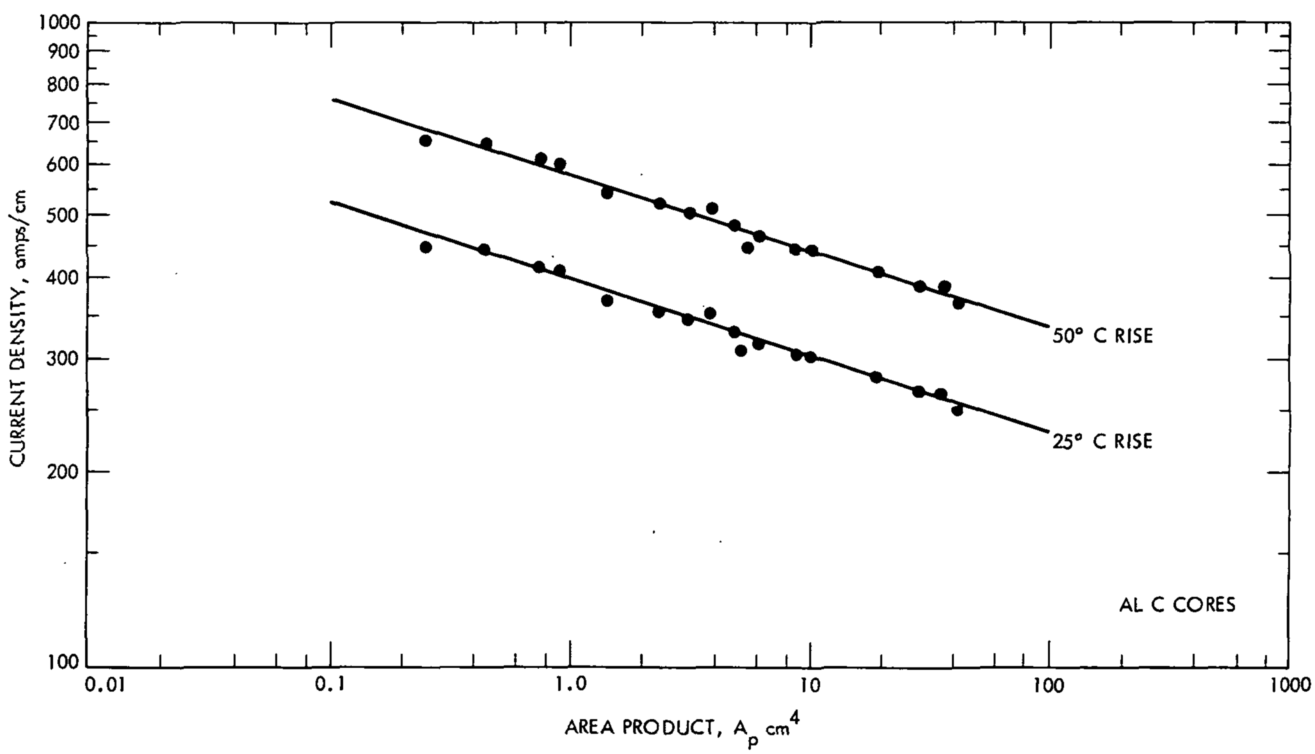
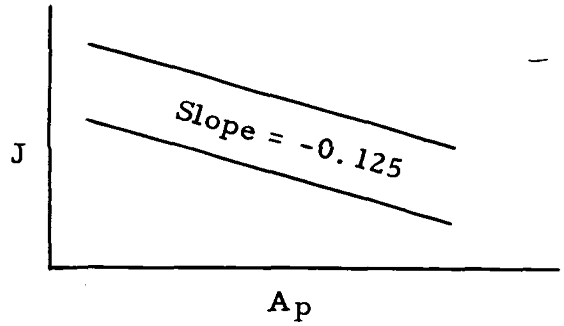


Fig. B1. Current density vs area product A_p for a 25°C and 50°C rise

The relationship is obtained from the conventional slope relationship:

$$\text{Slope} = \frac{\text{Log } J_1/J_2}{\text{Log } A_{p1}/A_{p2}}$$

according to:



The relationship is:

$$J = K_j A_p^{-0.125} \tag{B1}$$

where:

K_j for 25°C rise is 395 and K_j for 50° rise is 569 from the data of Table G1 in columns 3 and 6 and 3 and 10. This expression may now be inserted in equation (A18) from Appendix A which is:

$$A_p = \frac{2(Eng) \times 10^4}{K_u B_m J} \tag{B2}$$

yielding:

$$A_p = \frac{2(Eng) \times 10^4}{K_u B_m \left(K_j A_p^{-0.125}\right)} \tag{B3}$$

$$A_p^{0.875} = \frac{2(Eng) \times 10^4}{K_u B_m K_j} \tag{B4}$$

$$A_p = \left(\frac{2(Eng) \times 10^4}{K_u B_m K_j}\right)^{1.14} \tag{B5}$$

APPENDIX C

RELATIONSHIP OF A_p TO CONTROL OF TEMPERATURE RISE

Temperature Rise

Not all of the P_{in} input power to the inductor is delivered to the load as the P_o. Some of the input power is converted to heat by the resistance of the winding.

The generated heat produces a temperature rise which must be controlled to prevent damage to or failure of the windings by breakdown of the wire insulation at elevated temperatures. Such heat is dissipated only from the exposed surfaces of the inductor by a combination of radiation and convection, and thus is dependent upon the total exposed surface area of the core and windings.

Calculation of Temperature Rise

Temperature rise in an inductor winding cannot be predicted with complete precision, despite the fact that many different techniques are described in the literature for its calculation. One reasonably accurate method for open core and winding construction is based upon the assumption that core and winding losses may be lumped together as:

$$P_{\Sigma} = P_{fe} + P_{cu} \tag{C1}$$

and the assumption that thermal energy is dissipated throughout the surface area of the core and winding assembly. The losses in an inductor due to ac flux density are very low compared to the copper loss. It is then assumed that majority of the losses are copper.

$$P_{cu} >> P_{fe} \tag{C2}$$

Transfer of heat by radiation occurs because any body raised to a temperature above its surroundings emits heat energy in the form of waves. In accordance with the Stefan-Boltzmann law,* this may be expressed as:

$$W_r = K\epsilon\,(T2^4 - T1^4) \tag{C3}$$

in which

W_r = watts per square inch of surface

K = 3.68×10^{-11}

ϵ = emissivity factor

T2 = hot body temperature in absolute degrees

T1 = ambient or surrounding temperature in absolute degrees.

Transfer of heat by convection occurs when a body is hotter than the surrounding medium, which usually is air. A thin layer of air in intimate contact with the hot body is heated by conduction and expands, rising to take the absorbed heat with it. The next layer being colder, replaces the risen layer, and in turn on being heated also rises. This continues until all of the medium surrounding the body is at the body temperature. Transfer of heat by convection* is stated as:

$$W_c = KF\theta^{\eta}\sqrt{p} \tag{C4}$$

in which:

W_c = watts loss per square inch

K = 1.4×10^{-3}

F = air friction factor (unity for a plane surface)

θ = temperature rise, degrees C

---

*Reference 5

p = relative barometric pressure (unity at sea level)

η = exponential value ranging from 1.0 to 1.25, depending on the shape and position of the surface being cooled.

The total loss dissipated from a plane vertical surface is expressed by the sum of equations (C7) and (C8),

$$W = 3.68 \times 10^{-11} \epsilon (T2^4 - T1^4) + 1.4 \times 10^{-3} F\theta^{1.25} \sqrt{p} \qquad \text{(C5)}$$

Temperature Rise Versus Surface Area Dissipation

The temperature rise which may be expected for various levels of power loss is shown in the nomograph of Figure Cl below. It is based on equation (C5)

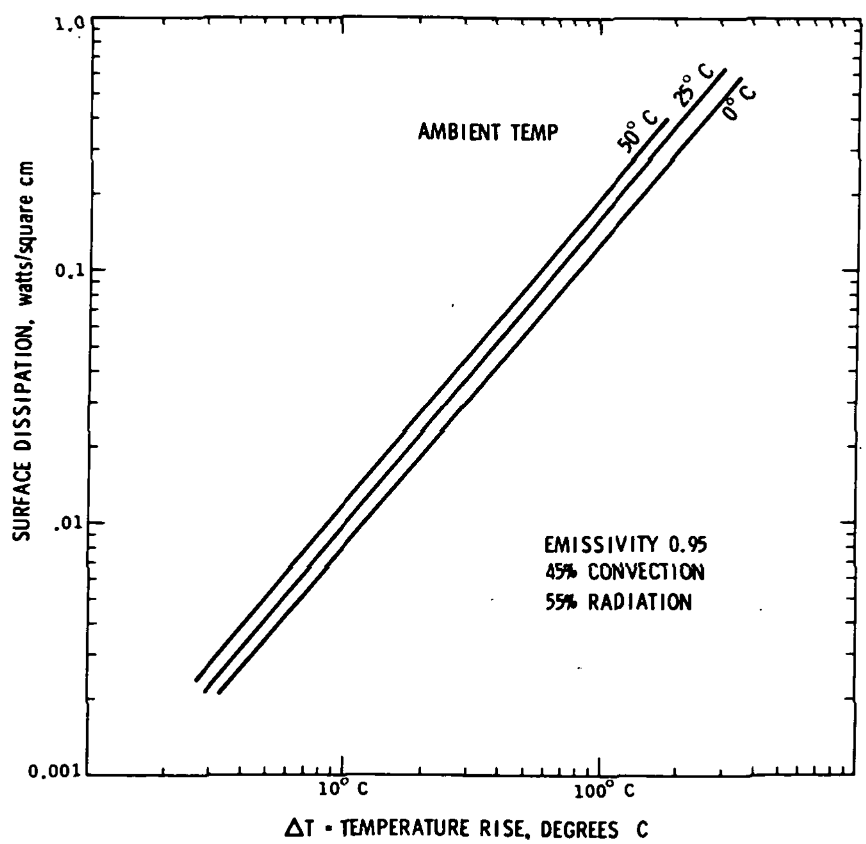


Fig. Cl. Temperature rise vs surface dissipation relying on data obtained from Reference 5 for heat transfer effected by a combination of 55% radiation and 45% convection, from surfaces having an emissivity of 0.95, in an ambient of 25°C, at sea level. Power loss (heat dissipation) is expressed in watts/cm^2 of total surface area. Heat dissipation by convection from the upper side of a horizontal flat surface is on the order of 15 to 20% more than from vertical surfaces. Heat dissipation from the underside of a horizontal flat surface depends upon surface area and conductivity.

Surface Area Required for Heat Dissipation

The effective surface area A_t required to dissipate heat (expressed as watts loss per unit area) is:

$$A_t = \frac{P_\Sigma}{\Psi} \tag{C6}$$

in which Ψ is the power density or the average power lost per unit area of the heat dissipating surface of the inductor and P_Σ is the total power lost or dissipated.

Surface area A_t of an inductor can be related to the area product A_p of a C-core inductor. The straightline logarithmic relationship shown in Figure C2 below, has been plotted from the data shown in Table G1.

The relationship is obtained from the conventional slope relationship:

$$\text{Slope} = \frac{\text{Log } A_{t2}/A_{t1}}{\text{Log } A_{p2}/A_{p1}}$$

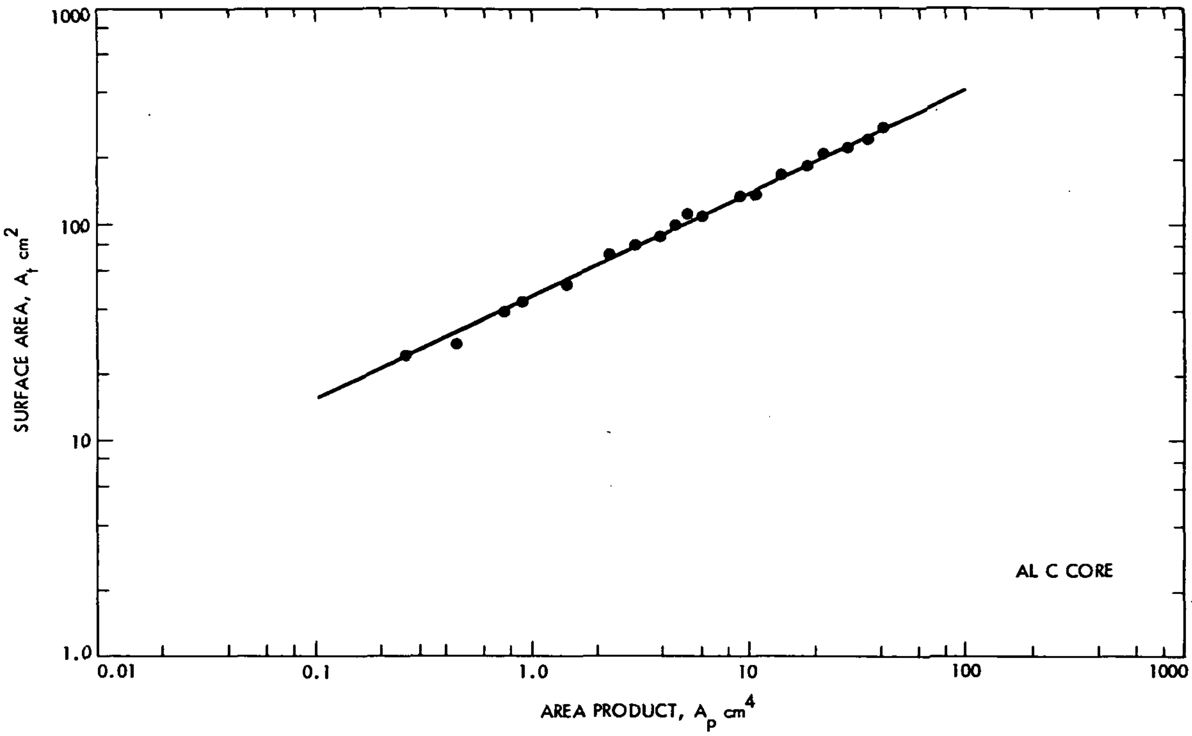
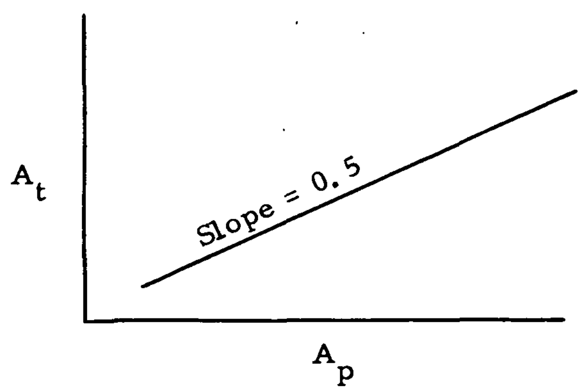


Fig. C2. Surface area vs area product A_p

according to:



in which the subscripts denote the extremes of the values in each of the columns 2 and 3.

From this it appears that:

$$A_t = K_s(A_p)^{0.5} = \frac{P_\Sigma}{\Psi} \tag{C7}$$

and that (from Fig. C1)

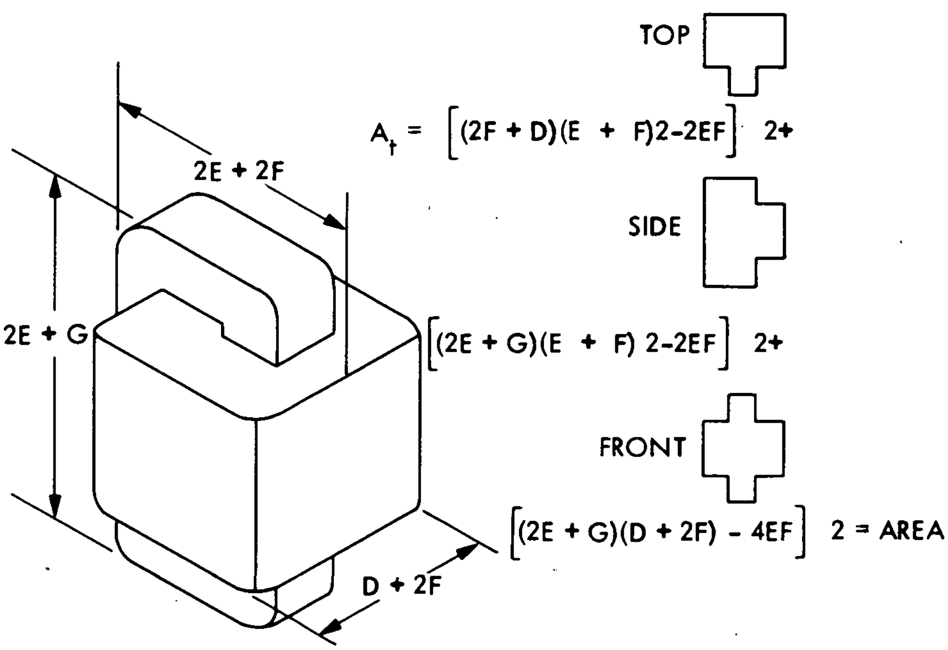
$$\Psi = 0.03\ \mathrm{W/cm^2}\ @\ 25°\mathrm{C\ rise}$$

$$\Psi = 0.07\ \mathrm{W/cm^2}\ @\ 50°\mathrm{C\ rise}$$

in which the constant K_s has been derived empirically by averaging the data presented in Table G1, columns 2 and 3. Column 3 was increased to account for the gross area of the iron and K_s therefore is 44.5.

<u>Calculation of Surface Area of C-Cores</u>

Table G1 is a tabulation of data relating to selected C-cores of standard manufacture. The surface areas A_t of those cores were calculated in accordance with the dimensional relations shown in Figure C3 which derive from the geometry of the core and windings of C-type core inductors as fabricated to industry standards.



REDUCES TO

$$A_t = 2\left\{ 2(E+F)\left[(D+2F)+(G+2E)\right]+(G+2E)(D+2F)-8EF\right\}$$

Fig. C3. Surface area of a C-core

Figure C4 utilizes the efficiency rating in watts loss in terms of two different, but commonly used allowable temperature rises for the inductor over ambient temperature. The data presented are used as bases for indicating the needed inductor surface area A_t (in cm^2).

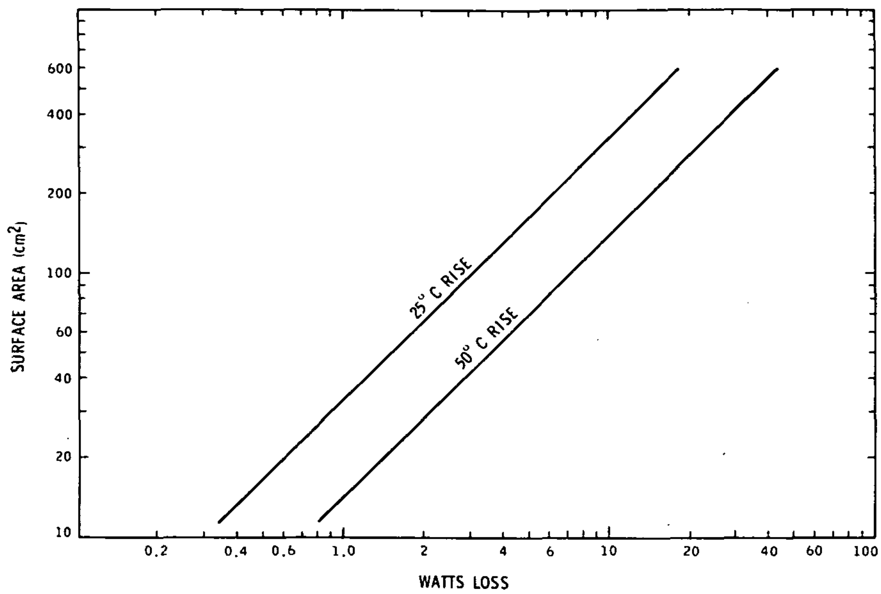


Fig. C4. Surface area versus total watt loss for a 25°C and 50°C rise

APPENDIX D

INDUCTOR WEIGHT

The total weight W_t of an inductor can be related to the area product A_p. The straightline logarithmic relationship shown in Figure D1 below, has been calculated from the data shown in Table G1.

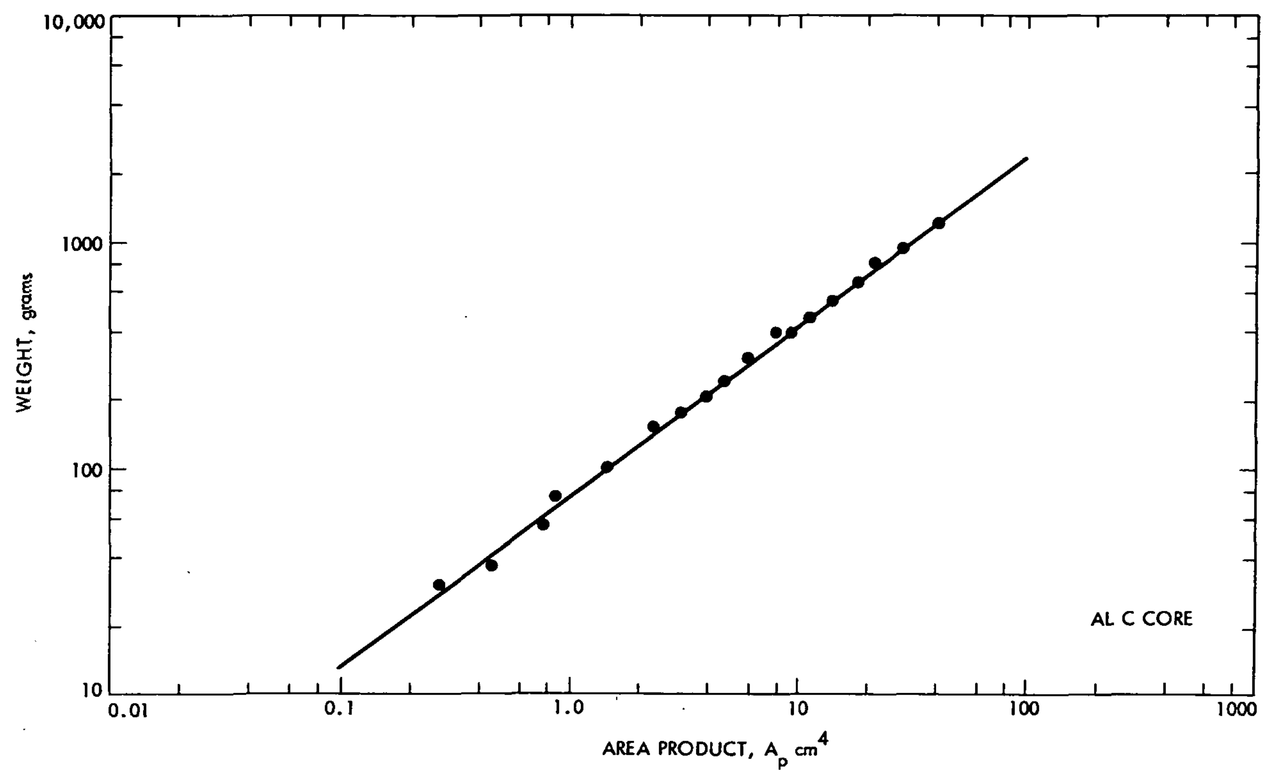


Fig. D1. Inductor total W_t versus area product A_p

This relationship is obtained from the conventional slope relationship:

$$\text{Slope} = \frac{\text{Log}(W_{t2}/W_{t1})}{\text{Log}(A_{p2}/A_{p1})}$$

in which the W_t and A_p values are the extremes of the data shown in columns 14 for weight, and column 3 for area product.

The relationship is:

$$W_t = K_w A_p^{0.75} \tag{D1}$$

in which the constant K_w has been derived empirically by averaging the data presented in columns 3 and 14 of Table G1 and is 76.6.

Derivation of the relationship is according to the following: Weight W_t varies in accordance with the cube of any linear dimension ℓ (designated ℓ^3 below), whereas, area product A_p varies as the fourth power:

$$W_t = K_1 \ell^3 \tag{D2}$$

$$A_p = K_2 \ell^4 \tag{D3}$$

$$\ell^4 = \frac{A_p}{K_2} \tag{D4}$$

$$\ell = \left(\frac{A_p}{K_2}\right)^{0.25} \tag{D5}$$

$$\ell^3 = \left[\left(\frac{A_p}{K_2}\right)^{0.25}\right]^3 = \left(\frac{A_p}{K_2}\right)^{0.75} \tag{D6}$$

$$W_t = K_1 \left(\frac{A_p}{K_2}\right)^{0.75} \tag{D7}$$

$$K_w = \frac{K_1}{K_2{}^{0.75}} \tag{D8}$$

$$W_t = K_w A_p^{0.75} \tag{D9}$$

in which K_1 is a constant depending upon the core material, and K_2 is related to core and window dimensions.

APPENDIX E

INDUCTOR VOLUME

The volume of an inductor can be related to the area product A_p of a C-core inductor, treating the volume as shown in Figure E1 below as a solid cube quantity without subtraction of anything for the core window.

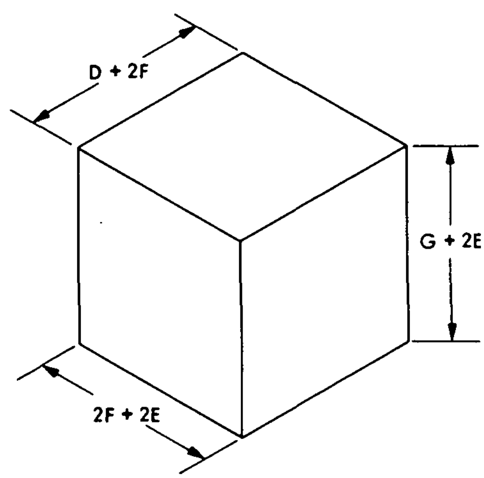


Fig. E1. C-core volume

The straight-line logarithmic relationship plotted in Figure E2 below, has been calculated from data in Table G2 through G21, using the outline shown in Figure E1 above.

The relationship is obtained from the conventional slope relationship:

$$\text{Slope} = \frac{\text{Log (Vol. 2/Vol. 1)}}{\text{Log } (A_p 2/A_p 1)}$$

in which the Vol. and A_p values are the extremes of the data shown in column 15 for volume, and column 3 for area product.

The volume/area product relationship is:

$$\text{Vol.} = K_v A_p^{0.75} \tag{E1}$$

in which K_v is a constant related to core configuration. It is 25.6 for a C-core which has been derived by averaging the values in Table G1.

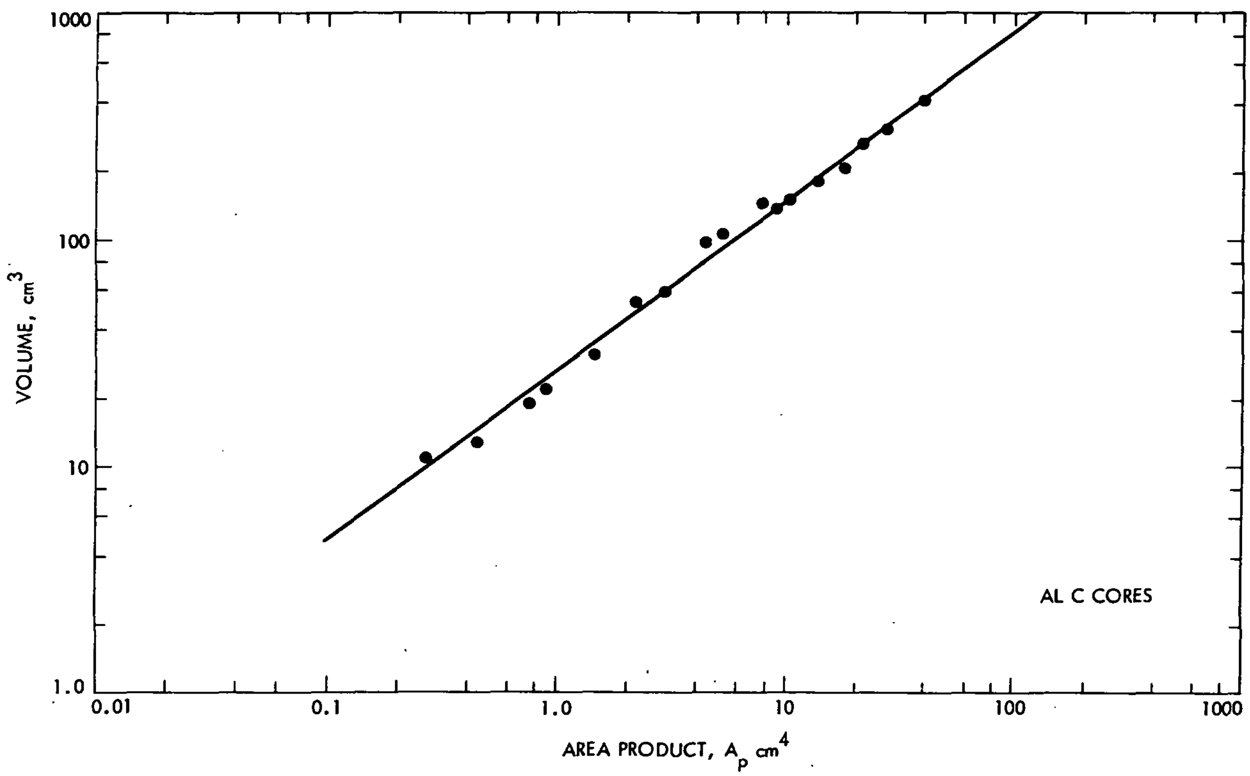


Fig. E2. Inductor volume vs area product A_p

APPENDIX F

WINDOW UTILIZATION FACTOR

The fraction K_u of the available core window space which will be occupied by the winding (copper) is calculated from areas S_1, S_2, S_3, and S_4:

$$K_u = S_1 \times S_2 \times S_3 \times S_4 \tag{F1}$$

where

$$S_1 = \frac{\text{conductor area}}{\text{wire area}}$$

$$S_2 = \frac{\text{wound area}}{\text{usable window area}}$$

$$S_3 = \frac{\text{usable window area}}{\text{window area}}$$

$$S_4 = \frac{\text{usable window area}}{\text{usable window area + insulation area}}$$

in which

conductor area = copper area

wire area = copper area + insulation area

wound area = number of turns $\times$ wire area of one turn

usable window area = available window area minus residual area which results from the particular winding technique used

window area = available window area

insulation area = area usable for winding insulation

S_1 is dependent upon wire size. Columns A and D of Table F1 may be used for calculating some typical values such as for AWG 10, AWG 20, AWG 30 and AWG 40.

CONVERSION DATA FOR WIRE SIZES FROM #10 to #44

Columns A and B in Table F1 give the bare area in the commonly used circular mils notation and in the metric equivalent for each wire size. Column C gives the equivalent resistance in microhms/centimeter ($\mu\Omega$/cm or $10^{-6}\Omega$/cm). Columns D to L relate to coated wires showing the effect of insulation on size and the number of turns and the total weight in grams/centimeter.

The total resistance for a given winding may be calculated by multiplying the MLT (mean length/turn) of the winding in centimeters, by the microhms cm for the appropriate wire size (Column C), and the total number of turns. Thus

$$R = (MLT) \times (N) \times (\text{Column C}) \times 10^{-6} \qquad [\text{ohms}]$$

The weight of the copper in a given winding may be calculated by multiplying the MLT by the grams/cm (Column L) and by the total number of turns Thus

$$W_t = (MLT) \times (N) \times (\text{Column L}) \qquad [\text{grams}]$$

Turns per square inch and turns per square cm are based on 60% wire fill factor.

Table F1. Wire table

Awg Wire Size	Bare Area		Resistance	Heavy Synthetics								
				Area		Diameter		Turns-Per		Turns-Per		Weight
	$cm^2 10^{-3}$ (footnote b)	CIR-MIL[a]	$\frac{10^{-6}\,\Omega}{cm\ at\ 20°C}$	$cm^2 10^{-3}$	CIR-MIL[a]	cm	Inch[a]	cm	Inch[a]	cm^2	$Inch^2$	gm/cm
10	52.61	10384	32.70	55.9	11046	0.267	0.1051	3.87	9.5	10.73	69.20	0.468
11	41.68	8226	41.37	44.5	8798	0.238	0.0938	4.36	10.7	13.48	89.95	0.3750
12	33.08	6529	52.09	35.64	7022	0.213	0.0838	4.85	11.9	16.81	108.4	0.2977
13	26.26	5184	65.64	28.36	5610	0.190	0.0749	5.47	13.4	21.15	136.4	0.2367
14	20.82	4109	82.80	22.95	4556	0.171	0.0675	6.04	14.8	26.14	168.6	0.1879
15	16.51	3260	104.3	18.37	3624	0.153	0.0602	6.77	16.6	32.66	210.6	0.1492
16	13.07	2581	131.8	14.73	2905	0.137	0.0539	7.32	18.6	40.73	262.7	0.1184
17	10.39	2052	165.8	11.68	2323	0.122	0.0482	8.18	20.8	51.36	331.2	0.0943
18	8.228	1624	209.5	9.326	1857	0.109	0.0431	9.13	23.2	64.33	414.9	0.07472
19	6.531	1289	263.9	7.539	1490	0.0980	0.0386	10.19	25.9	79.85	515.0	0.05940
20	5.188	1024	332.3	6.065	1197	0.0879	0.0346	11.37	28.9	98.93	638.1	0.04726
21	4.116	812.3	418.9	4.837	954.8	0.0785	0.0309	12.75	32.4	124.0	799.8	0.03757
22	3.243	640.1	531.4	3.857	761.7	0.0701	0.0276	14.25	36.2	155.5	1003	0.02965
23	2.588	510.8	666.0	3.135	620.0	0.0632	0.0249	15.82	40.2	191.3	1234	0.02372
24	2.047	404.0	842.1	2.514	497.3	0.0566	0.0223	17.63	44.8	238.6	1539	0.01884
25	1.623	320.4	1062.0	2.002	396.0	0.0505	0.0199	19.80	50.3	299.7	1933	0.01498
26	1.280	252.8	1345.0	1.603	316.8	0.0452	0.0178	22.12	56.2	374.2	2414	0.01185
27	1.021	201.6	1687.6	1.313	259.2	0.0409	0.0161	24.44	62.1	456.9	2947	0.00945
28	0.8046	158.8	2142.7	1.0515	207.3	0.0366	0.0144	27.32	69.4	570.6	3680	0.00747
29	0.6470	127.7	2664.3	0.8548	169.0	0.0330	0.0130	30.27	76.9	701.9	4527	0.00602
30	0.5067	100.0	3402.2	0.6785	134.5	0.0294	0.0116	33.93	86.2	884.3	5703	0.00472
31	0.4013	79.21	4294.6	0.5596	110.2	0.0267	0.0105	37.48	95.2	1072	6914	0.00372
32	0.3242	64.00	5314.9	0.4559	90.25	0.0241	0.0095	41.45	105.3	1316	8488	0.00305
33	0.2554	50.41	6748.6	0.3662	72.25	0.0216	0.0085	46.33	117.7	1638	10565	0.00241
34	0.2011	39.69	8572.8	0.2863	56.25	0.0191	0.0075	52.48	133.3	2095	13512	0.00189
35	0.1589	31.36	10849	0.2268	44.89	0.0170	0.0067	58.77	149.3	2645	17060	0.00150
36	0.1266	25.00	13608	0.1813	36.00	0.0152	0.0060	65.62	166.7	3309	21343	0.00119
37	0.1026	20.25	16801	0.1538	30.25	0.0140	0.0055	71.57	181.8	3901	25161	0.000977
38	0.08107	16.00	21266	0.1207	24.01	0.0124	0.0049	80.35	204.1	4971	32062	0.000773
39	0.06207	12.25	27775	0.0932	18.49	0.0109	0.0043	91.57	232.6	6437	41518	0.000593
40	0.04869	9.61	35400	0.0723	14.44	0.0096	0.0038	103.6	263.2	8298	53522	0.000464
41	0.03972	7.84	43405	0.0584	11.56	0.00863	0.0034	115.7	294.1	10273	66260	0.000379
42	0.03166	6.25	54429	0.04558	9.00	0.00762	0.0030	131.2	333.3	13163	84901	0.000299
43	0.02452	4.84	70308	0.03683	7.29	0.00685	0.0027	145.8	370.4	16291	105076	0.000233
44	0.0202	4.00	85072	0.03165	6.25	0.00635	0.0025	157.4	400.0	18957	122272	0.000195
	A	B	C	D	E	F	G	H	I	J	K	L

[a] This data from REA Magnetic Wire Datalator (Ref. 6).

[b] This notation means the entry in the column must be multiplied by 10^{-3}.

TEMPERATURE CORRECTION FACTORS

The values shown in Fig. F1 are based upon a correction factor of 1.0 at 20°C. For other temperatures the effect upon wire resistance can be calculated by multiplying the resistance value for the wire size shown in column C of Table 2 by the appropriate correction factor shown on the graph. Thus, Corrected Resistance = $\mu\Omega$/cm (at 20°C) $\times\ \zeta$.

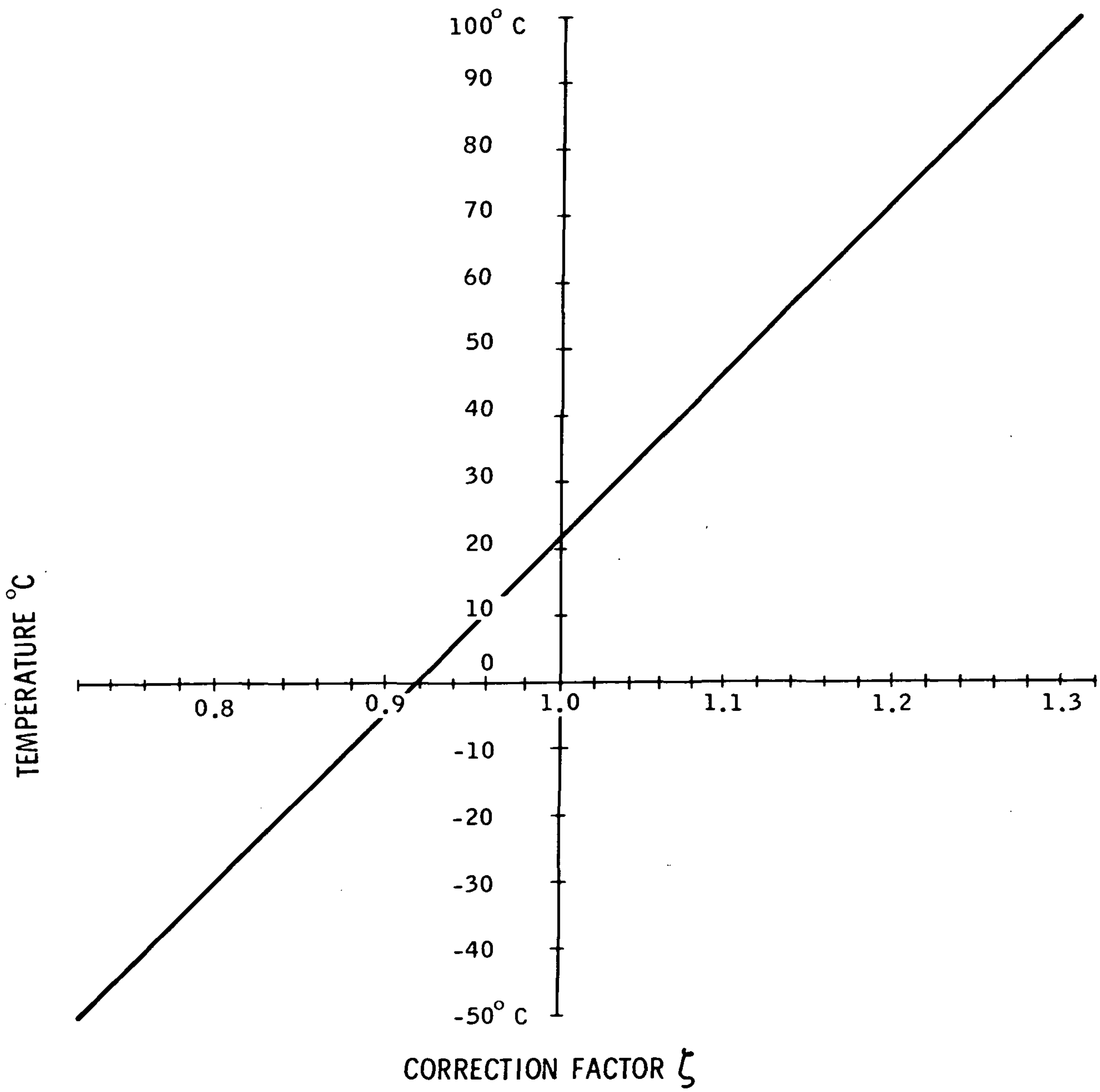


Fig. F1. Resistance correction factor (ζ, zeta) for wire temperature between -50° and 100°C

Thus:

$$\text{AWG 10} = \frac{52.61\ \text{cm}^2}{55.90\ \text{cm}^2} = 0.941\ ;$$

$$\text{AWG 20} = \frac{5.188\ \text{cm}^2}{6.065\ \text{cm}^2} = 0.855\ ;$$

$$\text{AWG 30} = \frac{0.5067\ \text{cm}^2}{0.6785\ \text{cm}^2} = 0.747\ ;\ \text{and}$$

$$\text{AWG 40} = \frac{0.04869\ \text{cm}^2}{0.0723\ \text{cm}^2} = 0.673\ .$$

S_2 is the fill factor for the usable window area. It can be shown that for circular cross-section wire wound on a flat form that the ratio of wire cm^2 to the area required for the turns can never be greater than 0.91. In practice, the actual maximum value is dependent upon the tightness of winding, variations in insulation thickness, and wire lay. Consequently, the fill factor is always less than the theoretical maximum.

As a typical working value for copper wire with a heavy synthetic film insulation, a ratio of 0.60 may be safely used.

The term S_3 defines how much of the available window space may actually be used for the winding. The winding area available to the designer depends on the bobbin configuration. A single bobbin design offers an effective W_a between 0.835 to 0.929 while a two bobbin configuration offers an effective W_a between 0.687 to 0.872. A good value to use for both configurations is 0.75.

The term S_4 can vary from 1.0 to 0.80 and defines how much of the usable window space is actually being used for insulation. If the transformer has multiple secondaries having significant amounts of insulation S_4 could be as low as 0.8.

A typical value for the copper fraction in the window area is about 0.40. For example, for AWG 20 wire, $S_1 \times S_2 \times S_3 \times S_4 = 0.855 \times 0.60 \times 0.75 \times 1.0 = 0.385$, which is very close to 0.4.

This may be stated somewhat differently as:

$$0.4 = \underbrace{\frac{A_w \text{ Bare}}{A_w \text{ Total}}}_{(S_1)} \times \underbrace{\text{Fill Factor}}_{(S_2)} \times \underbrace{\frac{W_{a(eff)}}{W_a}}_{(S_3)} \times \underbrace{\text{Insulation Factor}}_{(S_4)}$$

Table G1. C-Core Characteristics

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	Core	$A_t cm^2$	$A_p cm^4$	MLT_{cm}	$N/_{AWG}$	Ω @ 50°C	P_Σ	$I \quad \sqrt{\frac{W}{\Omega}}$	ΔT 25°C J = I/cm^2	Ω @ 75°C	P_Σ	$I = \sqrt{\frac{W}{\Omega}}$	ΔT 50°C J = I/cm^2	Total Weight	Volume cm^3	$A_c cm^2$
1	AL-2	24.6	0.265	4.47	83 20	0.138	0.737	2.31	445	0.151	1.72	3.37	651	29.1	10.7	0.264
2	AL-3	27.6	0.410	5.10	83 20	0.158	0.828	2.28	441	0.173	1.93	3.34	644	37.4	12.5	0.406
3	AL-5	38.1	0.767	5.42	119 20	0.238	1.14	2.18	422	0.262	2.67	3.19	615	59.2	19.7	0.539
4	AL-6	41.9	1.011	6.06	119 20	0.266	1.26	2.17	420	0.292	2.93	3.16	611	73.8	21.9	0.716
5	AL-124	51.8	1.44	6.56	175 20	0.426	1.55	1.90	368	0.468	3.63	2.78	537	98.8	30.8	0.716
6	AL-8	72.8	2.31	7.06	255 20	0.669	2.18	1.80	348	0.734	5.10	2.63	508	148.0	53.5	0.806
7	AL-9	78.4	3.09	7.69	255 20	0.728	2.35	1.79	346	0.799	5.49	2.62	505	178.0	59.5	1.08
8	AL-10	83.9	3.85	8.33	255 20	0.788	2.52	1.78	345	0.866	5.87	2.60	502	206.0	65.4	1.34
9	AL-12	101.0	4.57	9.00	327 20	1.09	3.03	1.66	321	1.20	7.07	2.42	468	244.0	92.1	1.26
10	AL-135	110.0	5.14	9.50	370 20	1.31	3.30	1.58	306	1.43	7.70	2.32	447	273.0	107.0	1.26
11	AL-78	110.0	6.08	8.15	406 20	1.23	3.30	1.63	316	1.35	7.70	2.38	460	304.0	81.3	1.34
12	AL-18	142.0	7.87	7.51	564 20	2.14	4.26	1.41	272	2.35	9.94	2.05	396	398.0	147.0	1.25
13	AL-15	136.0	9.07	10.1	444 20	1.66	4.08	1.56	302	1.83	9.52	2.28	440	400.0	136.0	1.80
14	AL-16	143.0	10.8	10.7	444 20	1.77	4.29	1.55	300	1.94	10.0	2.27	438	451.0	147.0	2.15
15	AL-17	158.0	14.4	12.0	444 20	1.97	4.74	1.55	299	2.20	11.1	2.24	433	555.0	168.0	2.87
16	AL-19	182.0	18.1	13.0	563 20	2.71	5.46	1.41	274	2.97	12.7	2.06	399	660.0	212.0	2.87
17	AL-20	205.0	22.6	13.6	563 20	2.84	6.15	1.47	284	3.12	14.4	2.14	414	785.0	259.0	3.58
18	AL-22	228.0	28.0	13.6	704 20	3.56	6.84	1.38	267	3.91	16.0	2.02	390	924.0	294.0	3.58
19	AL-23	246.0	35.0	15.9	704 20	3.89	7.38	1.37	265	4.27	17.2	2.00	387	1024.0	326.0	4.48
20	AL-24	282.0	40.0	14.6	1026	5.57	8.46	1.23	238	6.11	19.7	1.79	346	1233.0	401.0	3.58

Table G1 C-core characteristics were generated from the data in Tables G2 through G21 and Figures G1 through G20.

Definitions for Table G1

Information given is listed by column as:

1. Manufacturer part number
2. Surface area calculated from Figure C3
3. Area product effective iron area times window area
4. Mean length turn on one bobbin
5. Total number of turns and wire size for a single bobbin using a window utilization factor $K_u = 0.40$
6. Resistance of the wire at 50°C
7. Watts loss is based on Figure C1 for a ΔT of 25°C with a room ambient of 25° C surface dissipation times the transformer surface area, total loss is P_{cu}
8. Current calculated from column 6 and 7
9. Current density calculated from column 5 and 8
10. Resistance of the wire at 75°C
11. Watts loss is based on Figure C1 for a ΔT of 50°C with a room ambient of 25°C surface dissipation times the inductor surface area, total loss is P_{cu}
12. Current calculated from column 10 and 11
13. Current density calculated from column 5 and 12
14. Effective core weight plus copper weight
15. Inductor volume calculated from Figure E1
16. Core effective cross-section

C CORE AND BOBBIN MAGNETIC AND DIMENSIONAL SPECIFICATION

A. Definitions for Tables G2 through G21

Tables G2 through G21* show magnetic and dimensional specifications for twenty C cores. Information given is listed by line as:

1 Manufacture and part number
2 Units
3 Ratio of the window area over the iron area
4 Product of the window area times the iron area
5 Window area Wa gross
6 Iron area Ac effective
7 Mean magnetic path length lm
8 Core weight of silicon steel multiplied by the stacking factor
9 Copper weight single bobbin
10 Mean length turn
11 Ratio of G dimension divided by the square root of the iron area (Ac)
12 Ratio of the Wa eff/Wa
13 Inductor overall surface area A_t
14-17 "C" core dimensions
18 Bobbin manufacturer and part number** †
19 Bobbin inside winding length†
20 Bobbin inside build†
21 Bobbin winding area length times build†
22 Bracket manufacturer and part number††

B. Nomographs for 20 C core sizes

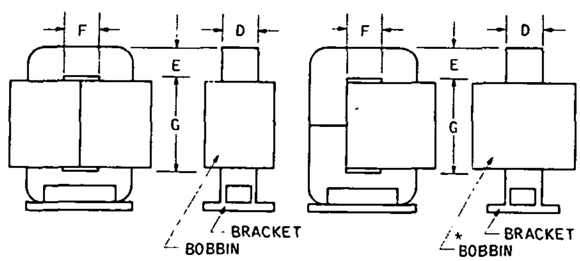
Figures G1 through G20 are graphs for 20 different "C" cores. The nomographs display resistance, number of turns, and wire size at a fill factor of $K_2 = 0.60$. These graphs are included to provide a close approximation for breadboarding purposes.

*References 7, 8

**The first number in front of the part number indicates the number of bobbins.
†Dorco Electronics, 15533 Vermont Ave., Paramount, Calif. 90723.
††Hallmark Metals, 610 West Foothill Blvd., Glendora, Calif. 91740.

Table G2. "C" core AL-2

"C" CORE	AL-2			
	ENGLISH		METRIC	
Wa/Ac			3.32	
Wa x Ac	0.0073	in^4	0.265	cm^4
Wa	0.156	in^2	1.006	cm^2
Ac (effective)	0.041	in^2	0.264	cm^2
lm	2.233	in	5.671	cm
CORE WT	0.027	lb	12.23	grams
COPPER WT	0.371	lb	16.87	grams
* MLT FULLWOUND	1.76	in	4.47	cm
$G/\sqrt{Ac}$			3.08	
Wa (effective) /Wa			0.835	
A_T	3.80	in^2	24.56	cm^2
D	0.250	in	0.635	cm
E	0.187	in	0.474	cm
F	0.250	in	0.635	cm
G	0.625	in	1.587	cm
BOBBIN	DORCO ELECTRONICS * 1-L-2			
LENGTH	0.580	in	1.473	cm
BUILD	0.225	in	0.571	cm
* Wa (effective)	0.130	in^2	0.841	cm^2
BRACKET	HALLMARK METALS * 04-010-03			



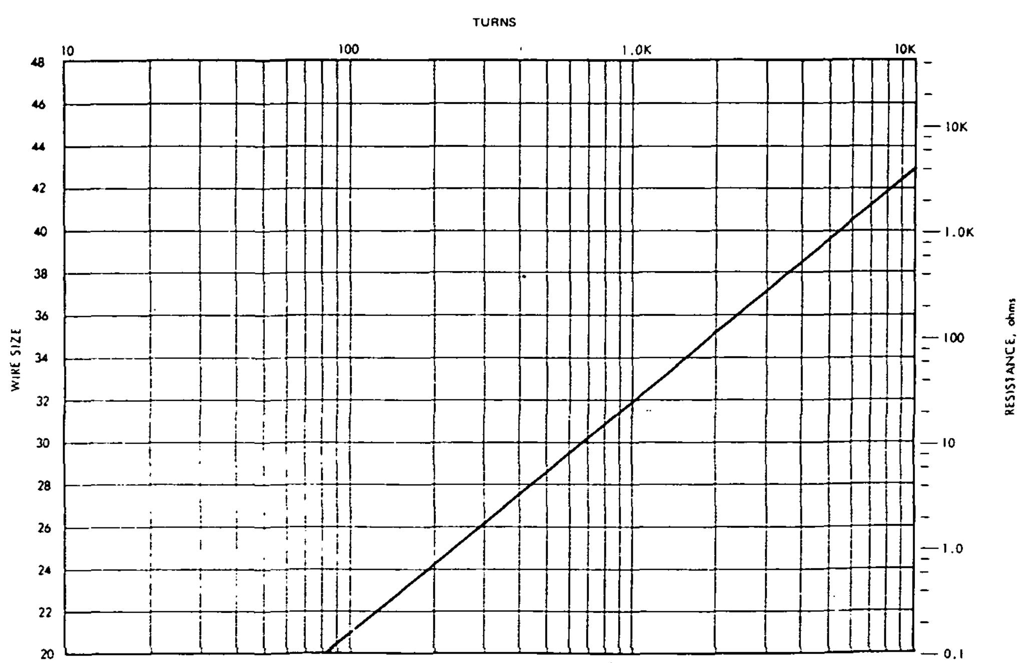
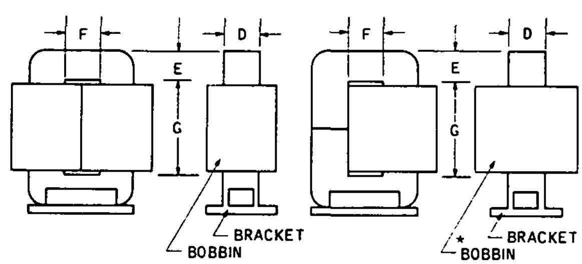


Fig. G1. Wiregraph for "C" core AL-2

Table G3. "C" core AL-3

"C" CORE	AL-3	
	ENGLISH	METRIC
Wa/Ac		2.23
Wa x Ac	0.0098 in^4	0.410 cm^4
Wa	0.156 in^2	1.006 cm^2
Ac (effective)	0.063 in^2	0.406 cm^2
lm	2.233 in	5.671 cm
CORE WT	0.04 lb	18.12 grams
COPPER WT	0.042 lb	19.25 grams
* MLT FULLWOUND	2.01 in	5.10 cm
$G/\sqrt{Ac}$		2.49
Wa (effective) /Wa		0.835
A_T	4.27 in^2	27.58 cm^2
D	0.375 in	0.952 cm
E	0.187 in	0.474 cm
F	0.250 in	0.635 cm
G	0.625 in	1.587 cm
BOBBIN	DORCO ELECTRONICS *	1-L-3
LENGTH	0.580 in	1.473 cm
BUILD	0.225 in	0.571 cm
* Wa (effective)	0.130 in^2	0.841 cm^2
BRACKET	HALLMARK METALS *	06-010-03



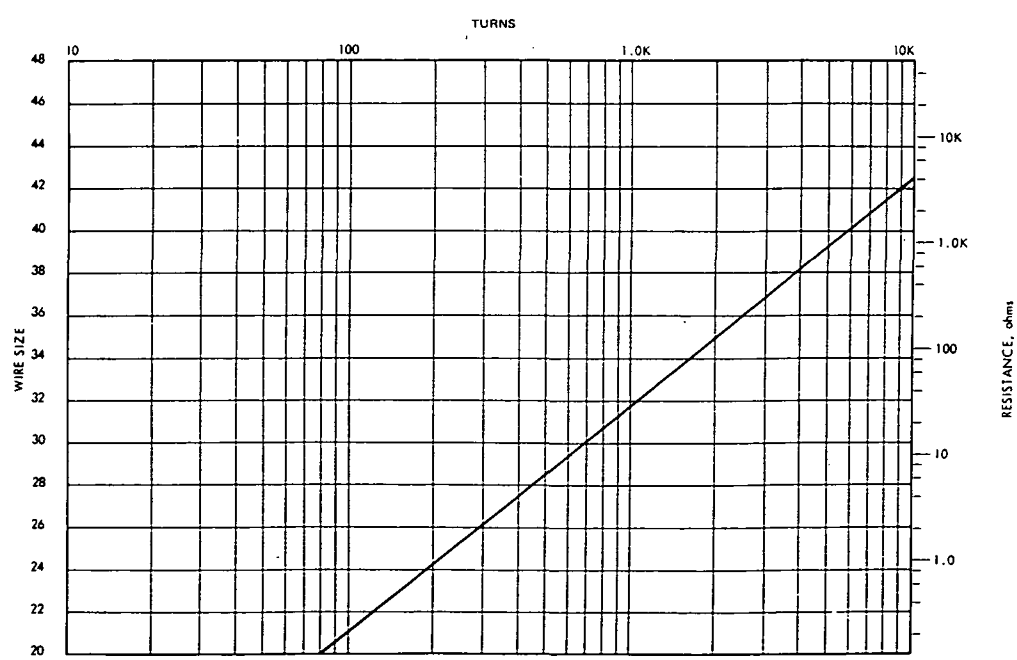
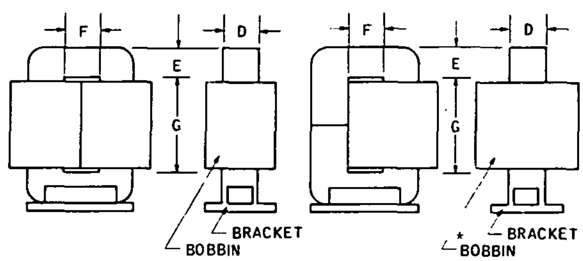


Fig. G2. Wiregraph for "C" core AL-3

Table G4. "C" core AL-5

"C" CORE	AL-5	
	ENGLISH	METRIC
Wa/Ac		2.33
Wa x Ac	0.018 in^4	0.767 cm^4
Wa	0.219 in^2	1.423 cm^2
Ac (effective)	0.0836 in^2	0.539 cm^2
lm	2.933 in	7.45 cm
CORE WT	0.067 lb	30.4 grams
COPPER WT	0.0643 lb	29.2 grams
* MLT FULLWOUND	2.13 in	5.42 cm
$G/\sqrt{Ac}$		3.026
Wa (effective) /Wa		0.843
A_T	5.90 in^2	38.1 cm^2
D	0.375 in	0.952 cm
E	0.250 in	0.635 cm
F	0.250 in	0.635 cm
G	0.875 in	2.22 cm
BOBBIN	DORCO ELECTRONICS #	1-L-5
LENGTH	0.830 in	2.11 cm
BUILD	0.225 in	0.571 cm
* Wa (effective)	0.186 in^2	1.20 cm^2
BRACKET	HALLMARK METALS #	06-012-04



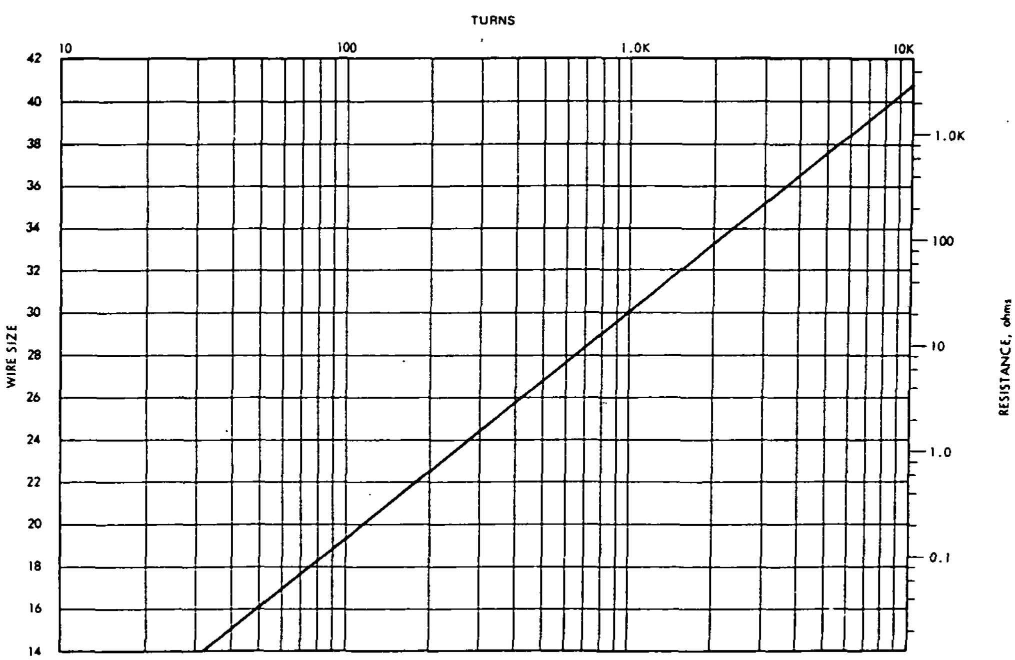
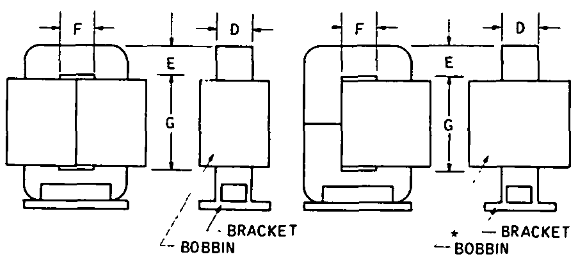


Fig. G3. Wiregraph for "C" core AL-5

Table G5. "C" core AL-6

"C" CORE	AL-6			
	ENGLISH		METRIC	
Wa/Ac			1.75	
Wa x Ac	0.024	in^4	1.011	cm^4
Wa	0.219	in^2	1.413	cm^2
Ac (effective)	0.111	in^2	0.716	cm^2
lm	2.933	in	7.45	cm
CORE WT	0.091	lb	41.2	grams
COPPER WT	0.0719	lb	32.6	grams
* MLT FULLWOUND	2.38	in	6.06	cm
$G/\sqrt{Ac}$			2.63	
Wa (effective) /Wa			0.843	
A_T	6.50	in^2	41.9	cm^2
D	0.500	in	1.27	cm
E	0.250	in	0.635	cm
F	0.250	in	0.635	cm
G	0.875	in	2.22	cm
BOBBIN	DORCO ELECTRONICS = 1-L-6			
LENGTH	0.830	in	2.11	cm
BUILD	0.225	in	0.571	cm
* Wa (effective)	0.186	in^2	1.20	cm^2
BRACKET	HALLMARK METALS = 08-012-04			



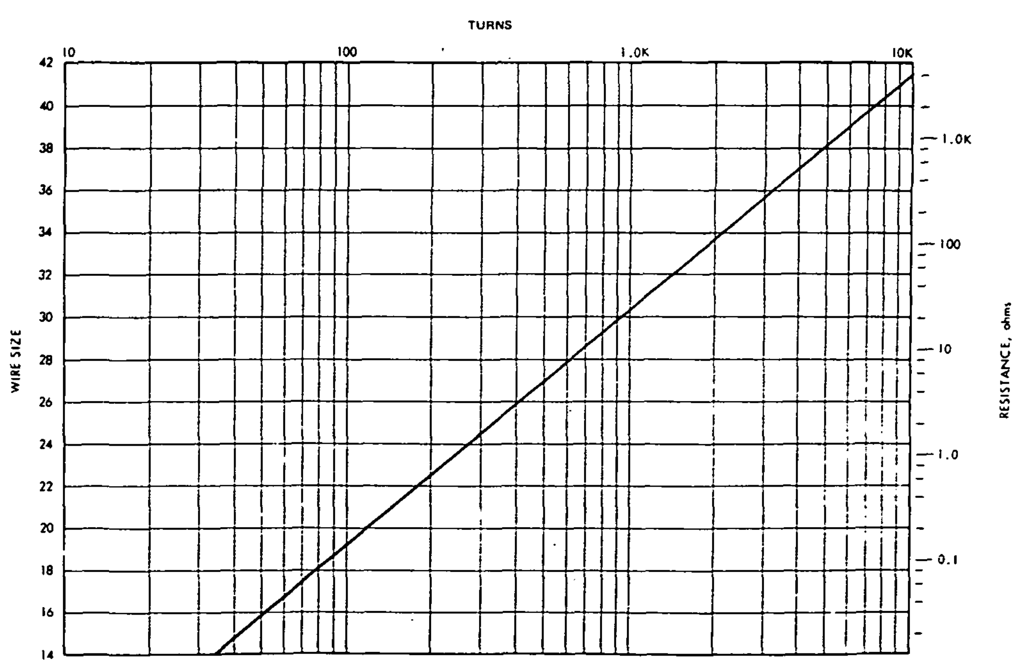
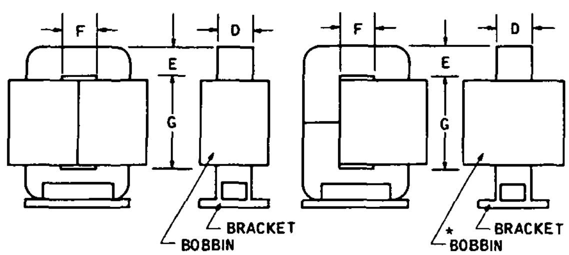


Fig. G4. Wiregraph for "C" core AL-6

Table G6. "C" core AL-124

"C" CORE	AL-124			
	ENGLISH		METRIC	
Wa/Ac			2.50	
Wa x Ac	0.0347	in^4	1.44	cm^4
Wa	0.313	in^2	2.02	cm^2
Ac (effective)	0.111	in^2	0.716	cm^2
lm	3.308	in	8.40	cm
CORE WT	0.103	lb	46.7	grams
COPPER WT	0.115	lb	52.13	grams
* MLT FULLWOUND	2.58	in	6.56	cm
$G/\sqrt{Ac}$			3.00	
Wa (effective) /Wa			0.876	
A_T	8.03	in^2	51.79	cm^2
D	0.500	in	1.27	cm
E	0.250	in	0.635	cm
F	0.313	in	0.795	cm
G	1.00	in	2.54	cm
BOBBIN	DORCO ELECTRONICS #		1-L-124	
LENGTH	0.955	in	2.425	cm
BUILD	0.288	in	0.731	cm
* Wa (effective)	0.275	in^2	1.77	cm^2
BRACKET	HALLMARK METALS #		08-013-04	



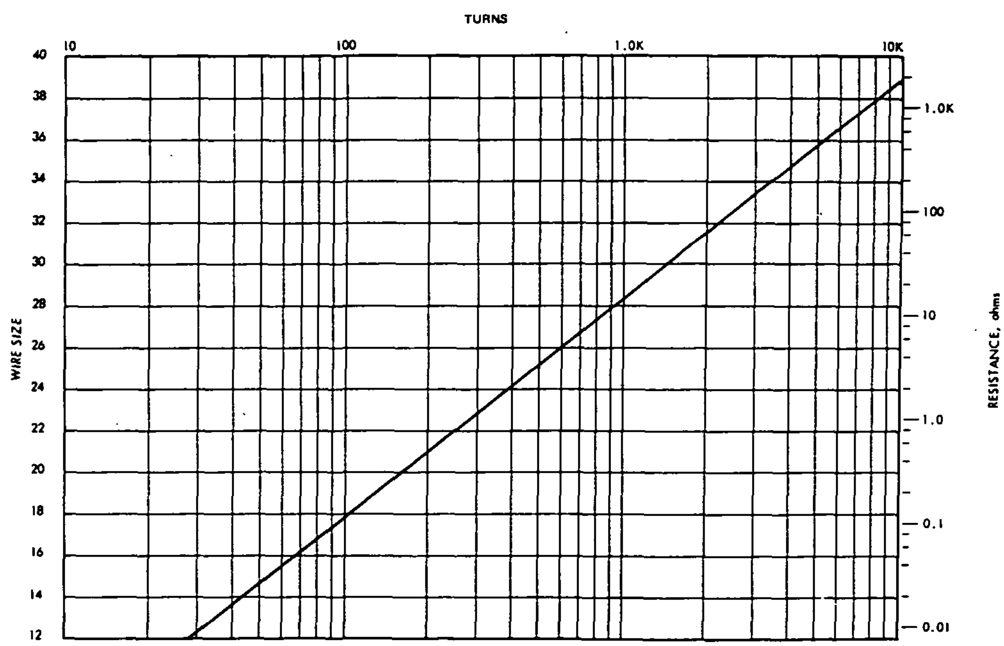
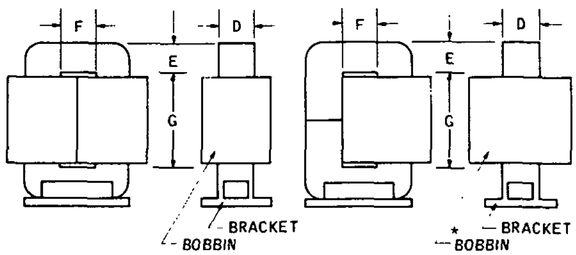


Fig. G5. Wiregraph for "C" core AL-124

Table G7. "C" core AL-8

"C" CORE	AL-8			
	ENGLISH		METRIC	
Wa/Ac			3.16	
Wa x Ac	0.056	in^4	2.31	cm^4
Wa	0.445	in^2	2.87	cm^2
Ac (effective)	0.125	in^2	0.806	cm^2
lm	4.198	in	10.66	cm
CORE WT	0.147	lb	66.59	grams
COPPER WT	0.180	lb	81.7	grams
* MLT FULLWOUND	2.77	in	7.06	cm
$G/\sqrt{Ac}$			3.36	
Wa (effective) /Wa			0.898	
A_T	11.29	in^2	72.8	cm^2
D	0.375	in	0.952	cm
E	0.375	in	0.952	cm
F	0.375	in	0.952	cm
G	1.187	in	3.015	cm
BOBBIN	DORCO ELECTRONICS #		1-L-8	
LENGTH	1.142	in	2.9	cm
BUILD	0.350	in	0.889	cm
* Wa (effective)	0.399	in^2	2.578	cm^2
BRACKET	HALLMARK METALS #		06-102-06	



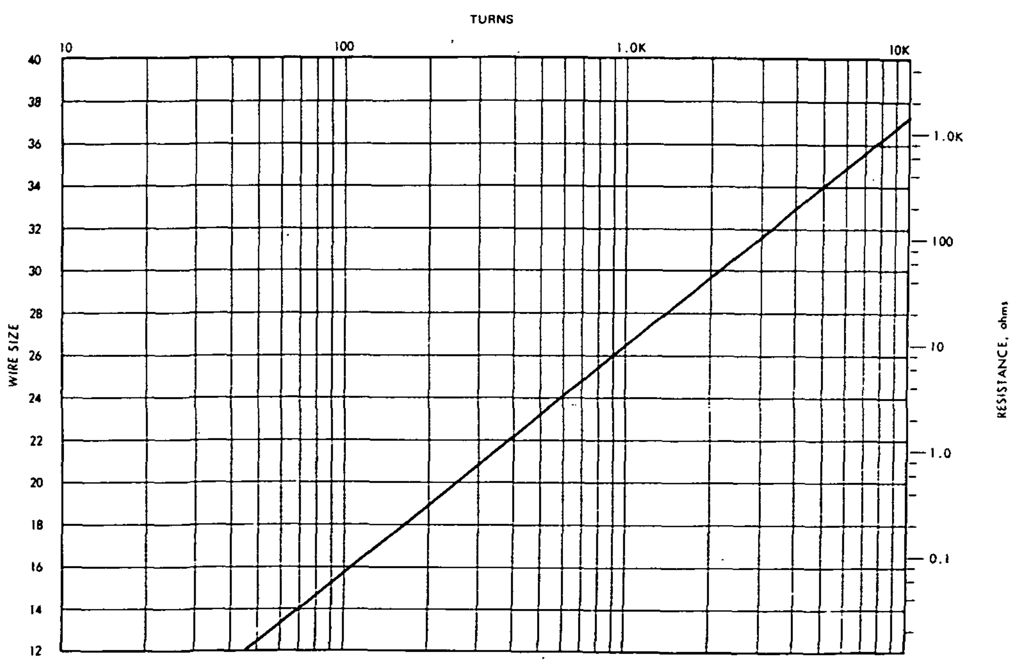


Fig. G6. Wiregraph for "C" core AL-8

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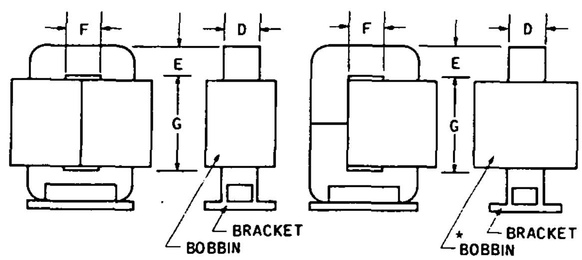
Table G8. "C" core AL-9

"C" CORE	AL-9			
	ENGLISH		METRIC	
Wa/Ac			2.37	
Wa x Ac	0.074	in^4	3.09	cm^4
Wa	0.445	in^2	2.870	cm^2
Ac (effective)	0.167	in^2	1.077	cm^2
lm	4.198	in	10.66	cm
CORE WT	0.197	lb	89.2	grams
COPPER WT	0.196	lb	89.0	grams
* MLT FULLWOUND	3.02	in	7.69	cm
$G/\sqrt{Ac}$			2.90	
Wa (effective) /Wa			0.898	
A_T	12.15	in^2	78.39	cm^2
D	0.500	in	1.27	cm
E	0.375	in	0.952	cm
F	0.375	in	0.952	cm
G	1.187	in	3.015	cm
BOBBIN	DORCO ELECTRONICS *		1-L-9	
LENGTH	1.142	in	2.90	cm
BUILD	0.350	in	0.889	cm
* Wa (effective)	0.399	in^2	2.578	cm^2
BRACKET	HALLMARK METALS *		08-102-06	



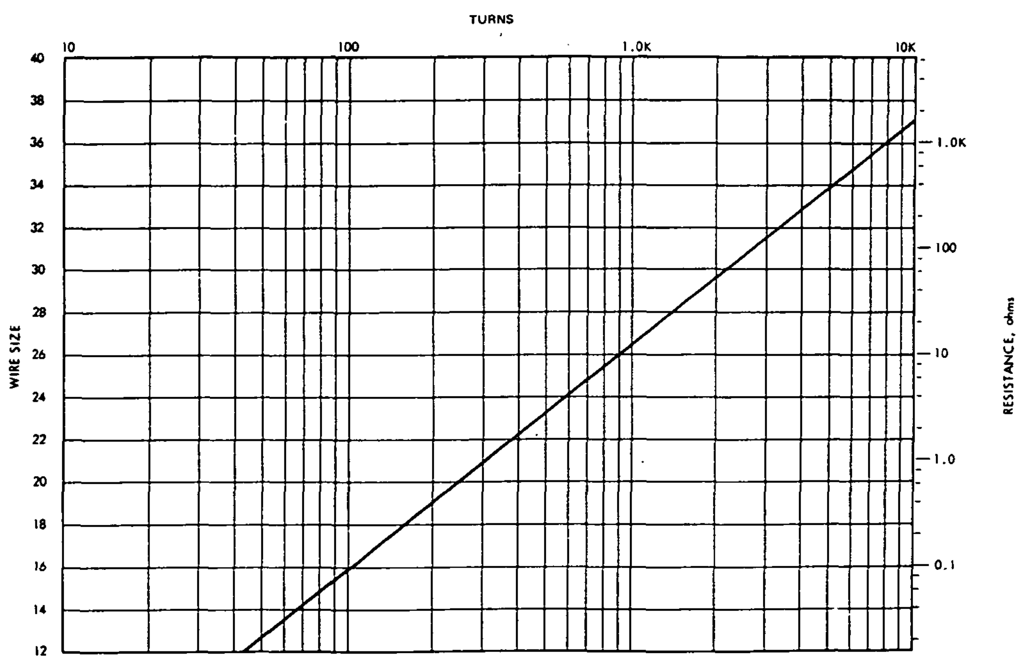
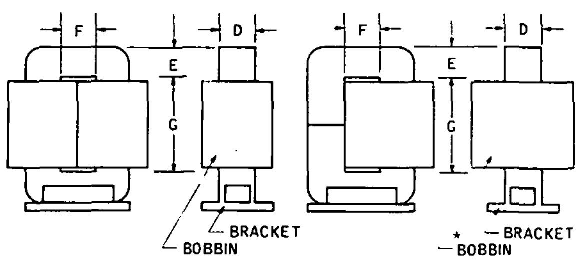


Fig. G7. Wiregraph for "C" core AL-9

Table G9. "C" core AL-10

"C" CORE	AL-10	
	ENGLISH	METRIC
Wa/Ac		1.90
Wa x Ac	0.092 in^4	3.85 cm^4
Wa	0.445 in^2	2.870 cm^2
Ac (effective)	0.208 in^2	1.342 cm^2
lm	4.198 in	10.66 cm
CORE WT	0.243 lb	110 grams
COPPER WT	0.213 lb	96.4 grams
* MLT FULLWOUND	3.27 in	8.33 cm
$G/\sqrt{Ac}$		2.603
Wa (effective) /Wa		0.898
A_T	13.01 in^2	83.9 cm^2
D	0.625 in	1.587 cm
E	0.375 in	0.952 cm
F	0.375 in	0.952 cm
G	1.187 in	3.015 cm
BOBBIN	DORCO ELECTRONICS = 1-L-10	
LENGTH	1.142 in	2.90 cm
BUILD	0.350 in	0.889 cm
* Wa (effective)	0.399 in^2	2.578 cm^2
BRACKET	HALLMARK METALS = 010-102-06	



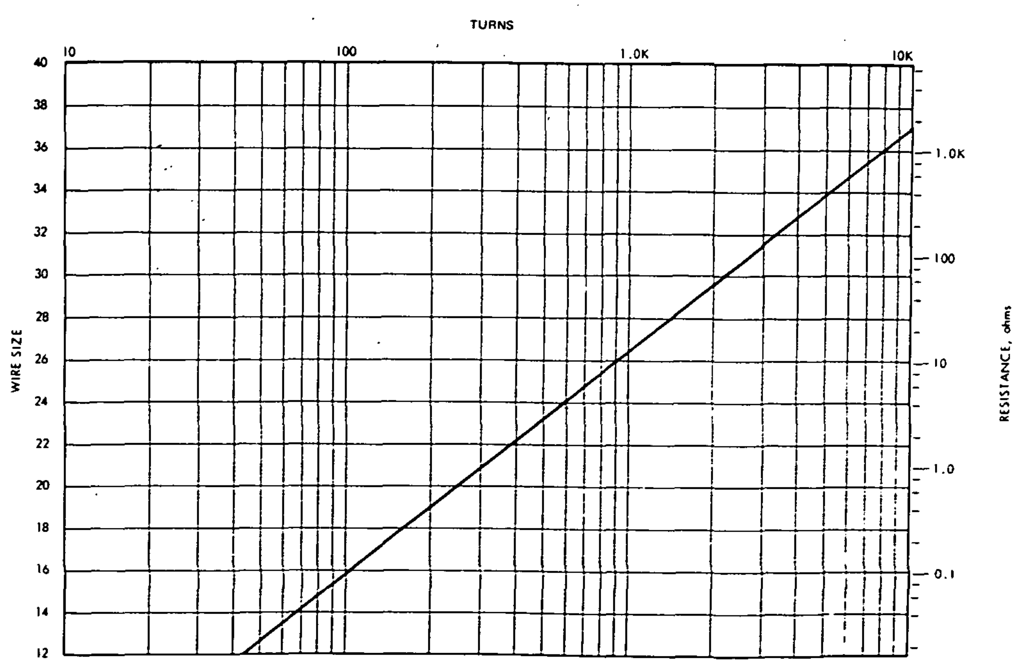
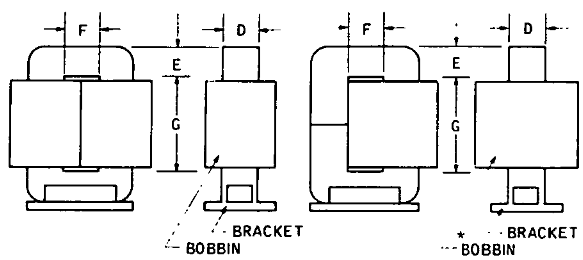


Fig. G8. Wiregraph for "C" core AL-10

Table G10. "C" core AL-12

"C" CORE	AL-12	
	ENGLISH	METRIC
Wa/Ac		2.57
Wa x Ac	0.109 in^4	4.57 cm^4
Wa	0.563 in^2	3.63 cm^2
Ac (effective)	0.195 in^2	1.26 cm^2
lm	4.523 in	11.5 cm
CORE WT	0.244 lb	110 grams
COPPER WT	0.295 lb	133.7 grams
* MLT FULLWOUND	3.54 in	9.00 cm
$G/\sqrt{Ac}$		2.55
Wa (effective) /Wa		0.911
A_T	15.61 in^2	100.7 cm^2
D	0.500 in	1.27 cm
E	0.437 in	1.11 cm
F	0.500 in	1.27 cm
G	1.125 in	2.857 cm
BOBBIN	DORCO ELECTRONICS =	1-L-12
LENGTH	1.08 in	2.74 cm
BUILD	0.475 in	1.21 cm
* Wa (effective)	0.513 in^2	3.31 cm^2
BRACKET	HALLMARK METALS =	08-106-07



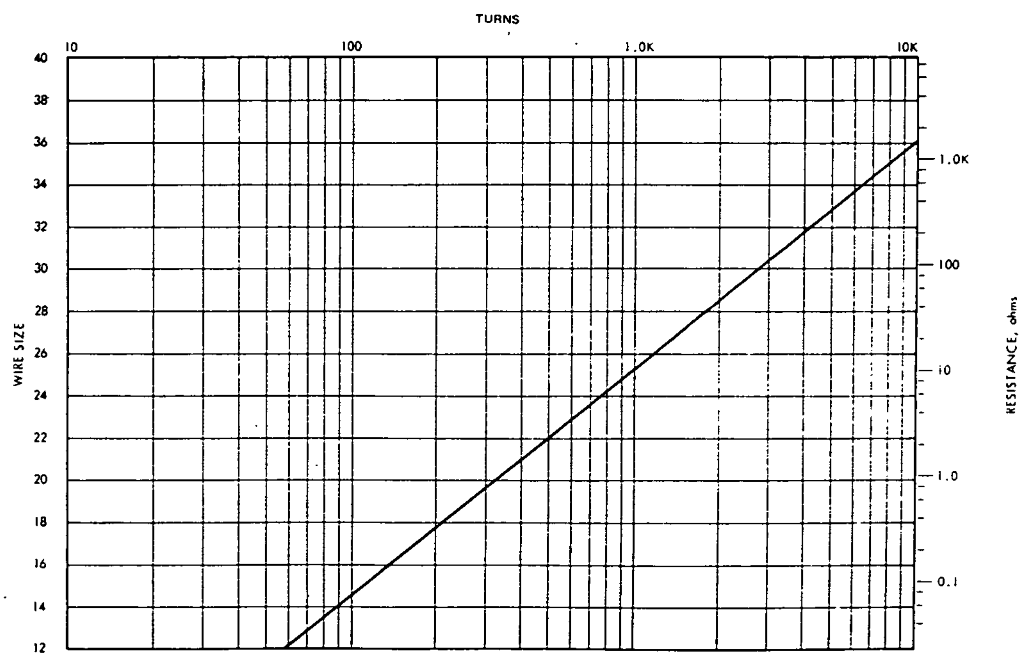
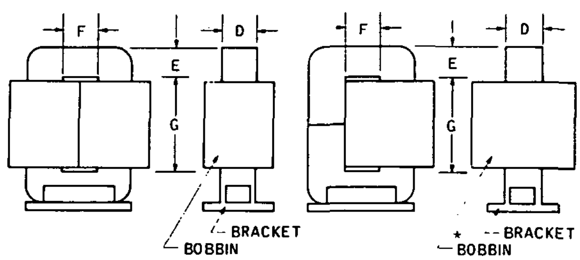


Fig. G9. Wiregraph for "C" core AL-12

Table G11. "C" core AL-135

"C" CORE	AL-135	
	ENGLISH	METRIC
Wa/Ac		2.89
Wa x Ac	0.123 in^4	5.14 cm^4
Wa	0.633 in^2	4.083 cm^2
Ac (effective)	0.195 in^2	1.26 cm^2
lm	4.648 in	11.8 cm
CORE WT	0.251 lb	114 grams
COPPER WT	0.312 lb	159 grams
* MLT FULLWOUND	3.74 in	9.50 cm
$G/\sqrt{Ac}$		2.55
Wa (effective) /Wa		0.915
A_T	17.04 in^2	110 cm^2
D	0.500 in	1.27 cm
E	0.437 in	1.11 cm
F	0.562 in	1.43 cm
G	1.125 in	2.857 cm
BOBBIN	DORCO ELECTRONICS =	1-L-135
LENGTH	1.08 in	2.74 cm
BUILD	0.537 in	1.36 cm
* Wa (effective)	0.579 in^2	3.74 cm^2
BRACKET	HALLMARK METALS =	08-107-07



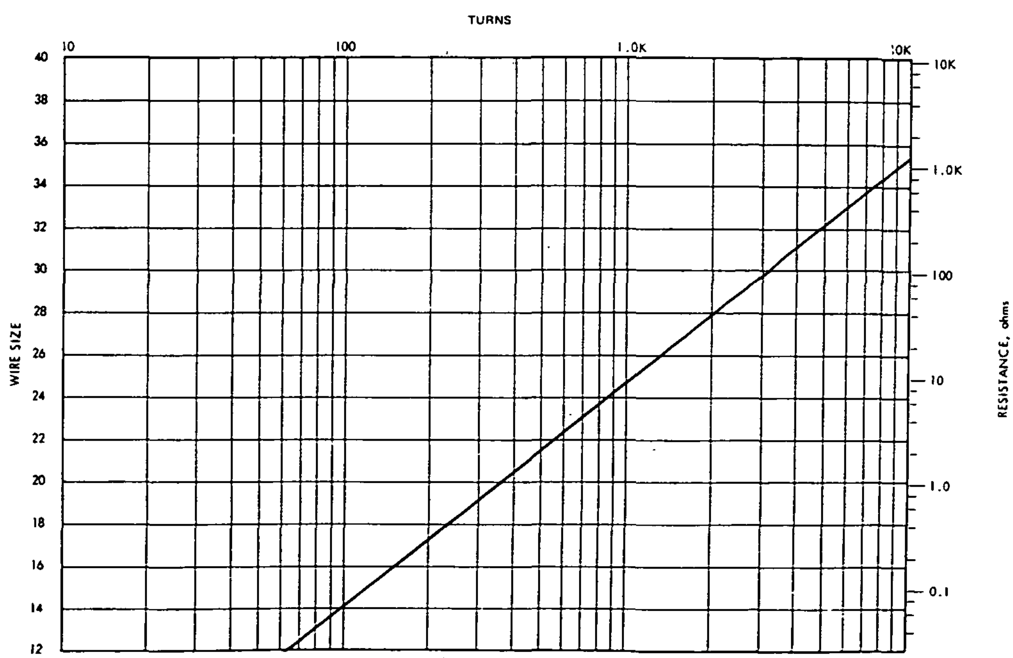
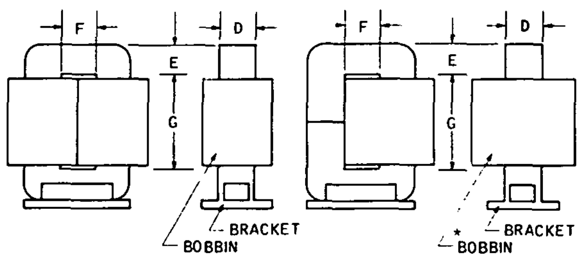


Fig. G10. Wiregraph for "C" core AL-135

Table G12. "C" core AL-78

"C" CORE	AL-78			
	ENGLISH		METRIC	
Wa/Ac			3.00	
Wa x Ac	0.146	in^4	6.07	cm^4
Wa	0.703	in^2	4.53	cm^2
Ac (effective)	0.208	in^2	1.34	cm^2
lm	5.891	in	14.96	cm
CORE WT	0.342	lb	154	grams
COPPER WT	0.331	lb	150	grams
* MLT FULLWOUND	3.21	in	8.15	cm
$G/\sqrt{Ac}$			4.93	
Wa (effective) /Wa			0.905	
A_T	16.99	in^2	109.6	cm^2
D	0.750	in	1.91	cm
E	0.313	in	0.795	cm
F	0.313	in	0.795	cm
G	2.250	in	5.715	cm
BOBBIN	DORCO ELECTRONICS *		1-L-78	
LENGTH	2.205	in	5.60	cm
BUILD	0.288	in	0.731	cm
* Wa (effective)	0.635	in^2	4.10	cm^2
BRACKET	HALLMARK METALS *		012-015-05	



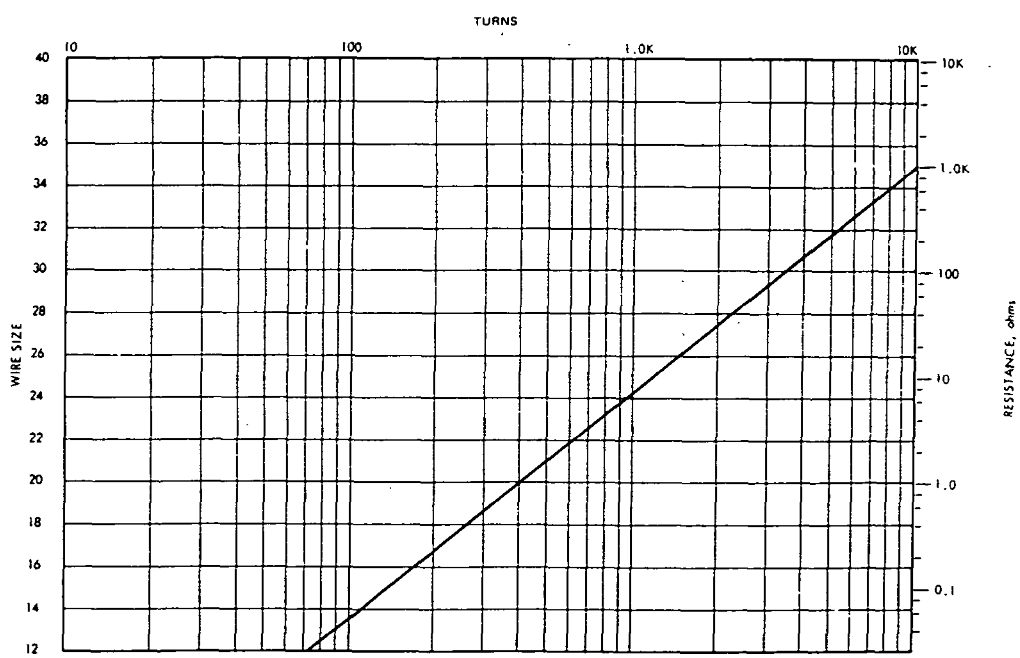
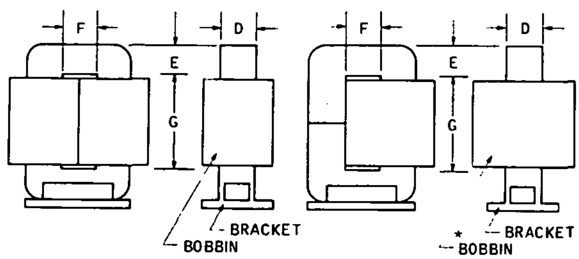


Fig. G11. Wiregraph for "C" core AL-78

Table G13. "C" core AL-18

"C" CORE	AL-18			
	ENGLISH		METRIC	
Wa/Ac			5.08	
Wa x Ac	0.189	in^4	7.87	cm^4
Wa	0.977	in^2	6.30	cm^2
Ac (effective)	0.194	in^2	1.257	cm^2
lm	5.648	in	14.34	cm
CORE WT	0.305	lb	138	grams
COPPER WT	0.575	lb	260	grams
* MLT FULLWOUND	2.95	in	7.51	cm
$G/\sqrt{Ac}$			3.502	
Wa (effective) /Wa			0.890	
A_T	21.93	in^2	141.50	cm^2
D	0.500	in	1.27	cm
E	0.437	in	1.111	cm
F	0.625	in	1.587	cm
G	1.562	in	3.927	cm
BOBBIN	DORCO ELECTRONICS *		1-L-18	
LENGTH	1.497	in	3.802	cm
BUILD	0.590	in	1.498	cm
* Wa (effective)	0.880	in^2	5.697	cm^2
BRACKET	HALLMARK METALS *		08-108-07	



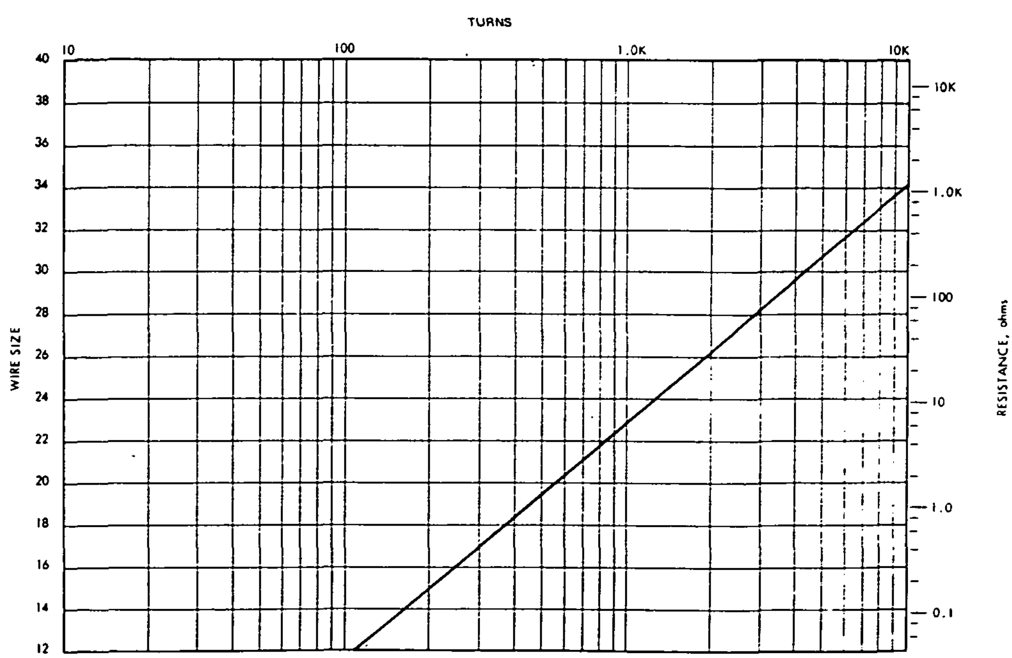
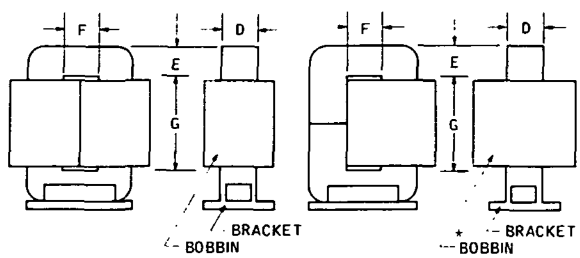


Fig. G12. Wiregraph for "C" core AL-18

Table G14. "C" core AL-15

"C" CORE	AL-15			
	ENGLISH		METRIC	
Wa/Ac			2.50	
Wa x Ac	0.218	in^4	9.07	cm^4
Wa	0.781	in^2	5.037	cm^2
Ac (effective)	0.279	in^2	1.80	cm^2
lm	5.588	in	14.2	cm
CORE WT	0.436	lb	197	grams
COPPER WT	0.448	lb	203	grams
* MLT FULLWOUND	3.97	in	10.08	cm
$G/\sqrt{Ac}$			2.96	
Wa (effective) /Wa			0.891	
A_T	21.07	in^2	135.9	cm^2
D	0.625	in	1.587	cm
E	0.500	in	1.27	cm
F	0.500	in	1.27	cm
G	1.562	in	3.967	cm
BOBBIN	DORCO ELECTRONICS *		1-L-15	
LENGTH	1.497	in	3.80	cm
BUILD	0.465	in	1.18	cm
* Wa (effective)	0.696	in^2	4.49	cm^2
BRACKET	HALLMARK METALS *		010-108-08	



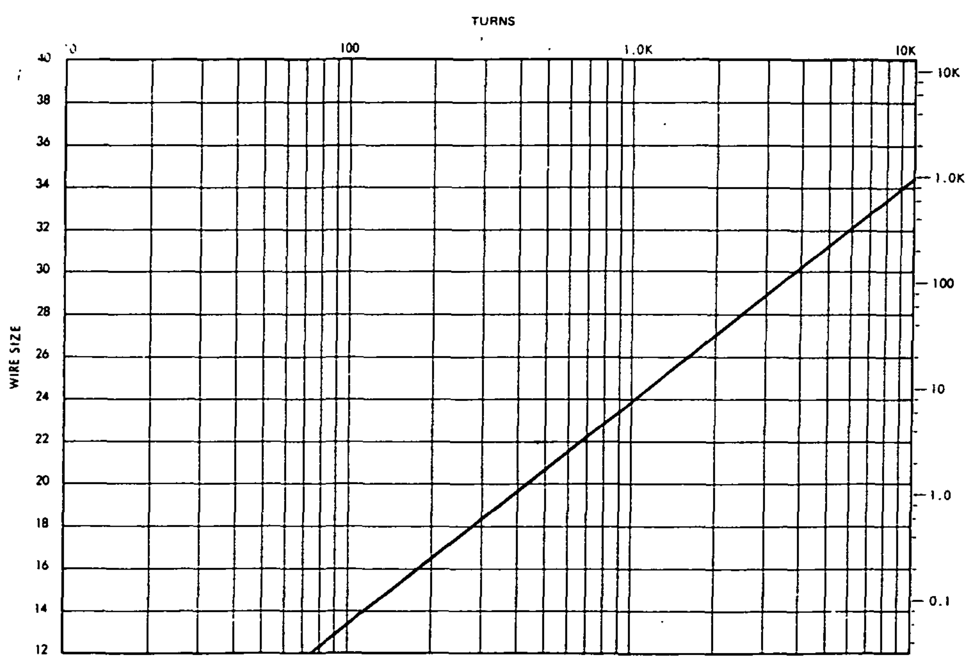
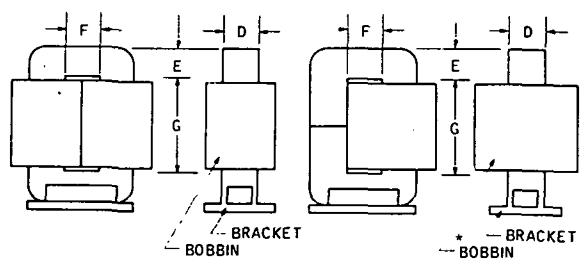


Fig. G13. Wiregraph for "C" core AL-15

Table G15. "C" core AL-16

"C" CORE	AL-16			
	ENGLISH		METRIC	
Wa/Ac			2.08	
Wa x Ac	0.26	in^4	10.8	cm^4
Wa	0.781	in^2	5.037	cm^2
Ac (effective)	0.334	in^2	2.15	cm^2
lm	5.588	in	14.2	cm
CORE WT	0.519	lb	235	grams
COPPER WT	0.476	lb	216	grams
* MLT FULLWOUND	4.22	in	10.72	cm
$G/\sqrt{Ac}$			2.70	
Wa (effective) /Wa			0.891	
A_T	22.21	in^2	143.3	cm^2
D	0.750	in	1.905	cm
E	0.500	in	1.27	cm
F	0.500	in	1.27	cm
G	1.562	in	3.967	cm
BOBBIN	DORCO ELECTRONICS *		1-L-16	
LENGTH	1.497	in	3.80	cm
BUILD	0.465	in	1.18	cm
* Wa (effective)	0.696	in^2	4.49	cm^2
BRACKET	HALLMARK METALS =		012-108-08	



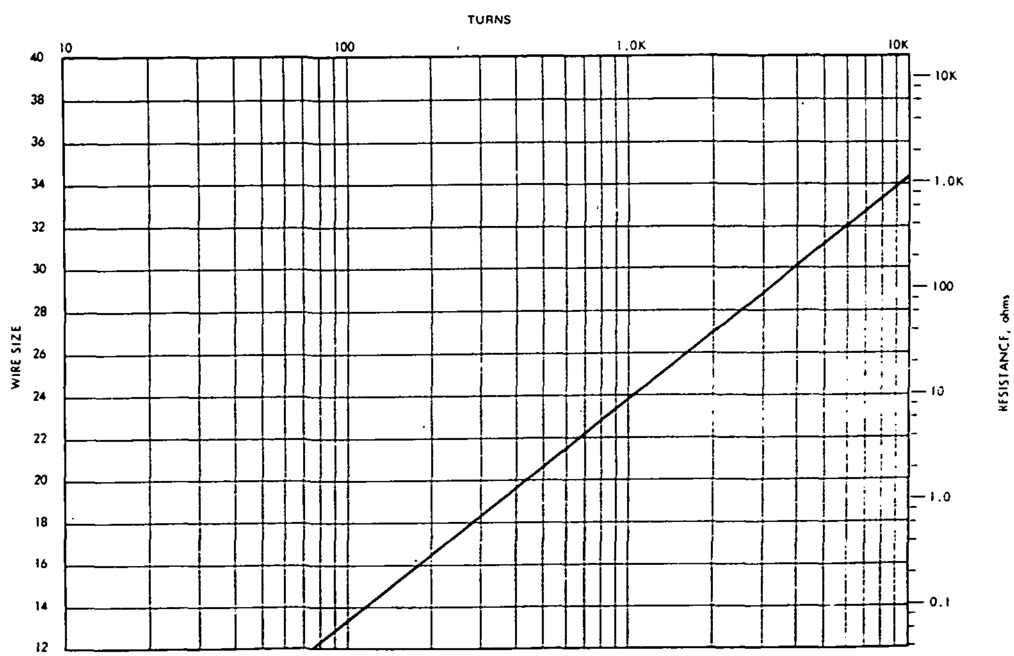
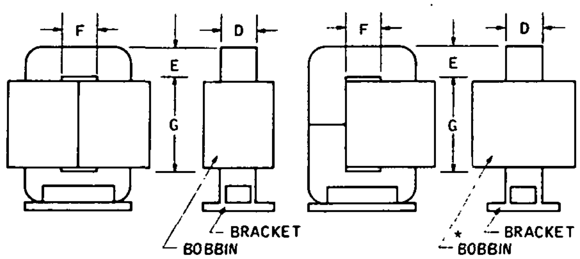


Fig. G14. Wiregraph for "C" core AL-16

Table G16. "C" core AL-17

"C" CORE	AL-17			
	ENGLISH		METRIC	
Wa/Ac			1.56	
Wa x Ac	0.35	in^4	14.4	cm^4
Wa	0.781	in^2	5.037	cm^2
Ac (effective)	0.445	in^2	2.870	cm^2
lm	5.588	in	14.2	cm
CORE WT	0.693	lb	314	grams
COPPER WT	0.533	lb	241	grams
* MLT FULLWOUND	4.72	in	11.99	cm
$G/\sqrt{Ac}$			2.342	
Wa (effective) /Wa			0.891	
A_T	24.5	in^2	158	cm^2
D	1.000	in	2.54	cm
E	0.500	in	1.27	cm
F	0.500	in	1.27	cm
G	1.562	in	3.967	cm
BOBBIN	DORCO ELECTRONICS * 1-L-17			
LENGTH	1.497	in	3.80	cm
BUILD	0.465	in	1.18	cm
* Wa (effective)	0.696	in^2	4.49	cm^2
BRACKET	HALLMARK METALS * 10-108-08			



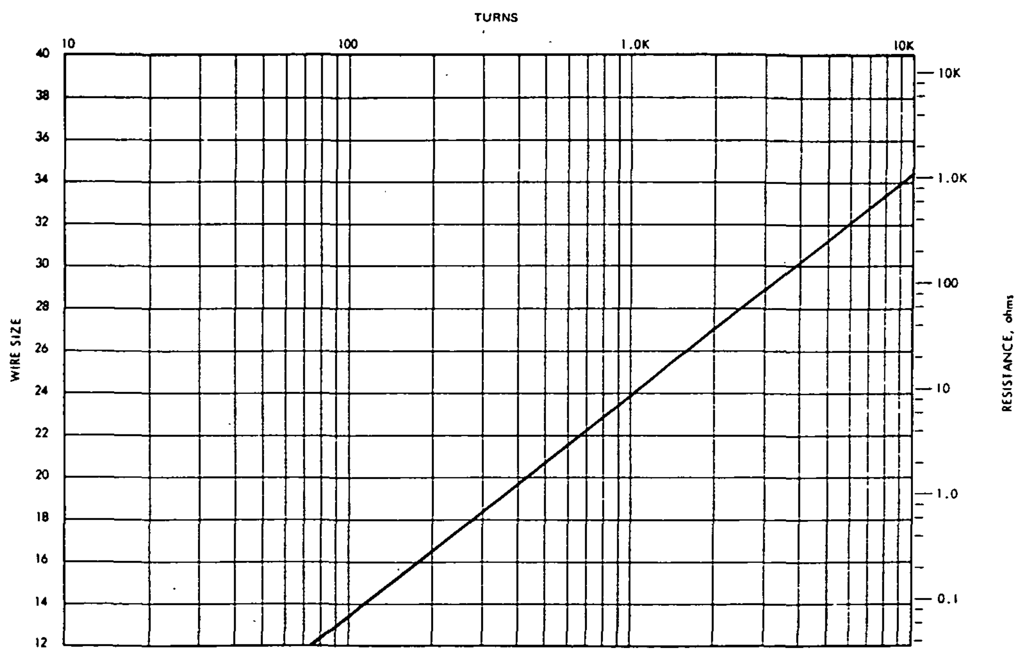
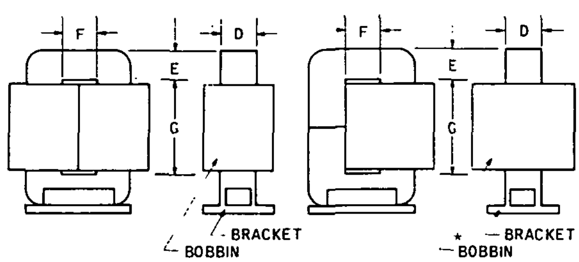


Fig. G15. Wiregraph for "C" core AL-17

Table G17. "C" core AL-19

"C" CORE	AL-19	
	ENGLISH	METRIC
Wa/Ac		1.95
Wa x Ac	0.435 in^4	18.1 cm^4
Wa	0.977 in^2	6.30 cm^2
Ac (effective)	0.445 in^2	2.87 cm^2
lm	5.838 in	14.8 cm
CORE WT	0.724 lb	328 grams
COPPER WT	0.731 lb	332 grams
* MLT FULLWOUND	5.11 in	12.98 cm
$G/\sqrt{Ac}$		2.34
Wa (effective) /Wa		0.903
A_T	28.2 in^2	182 cm^2
D	1.000 in	2.54 cm
E	0.500 in	1.27 cm
F	0.625 in	1.587 cm
G	1.562 in	3.967 cm
BOBBIN	DORCO ELECTRONICS = 1-L-19	
LENGTH	1.497 in	3.80 cm
BUILD	0.590 in	1.498 cm
* Wa (effective)	0.883 in^2	5.69 cm^2
BRACKET	HALLMARK METALS = 10-110-08	



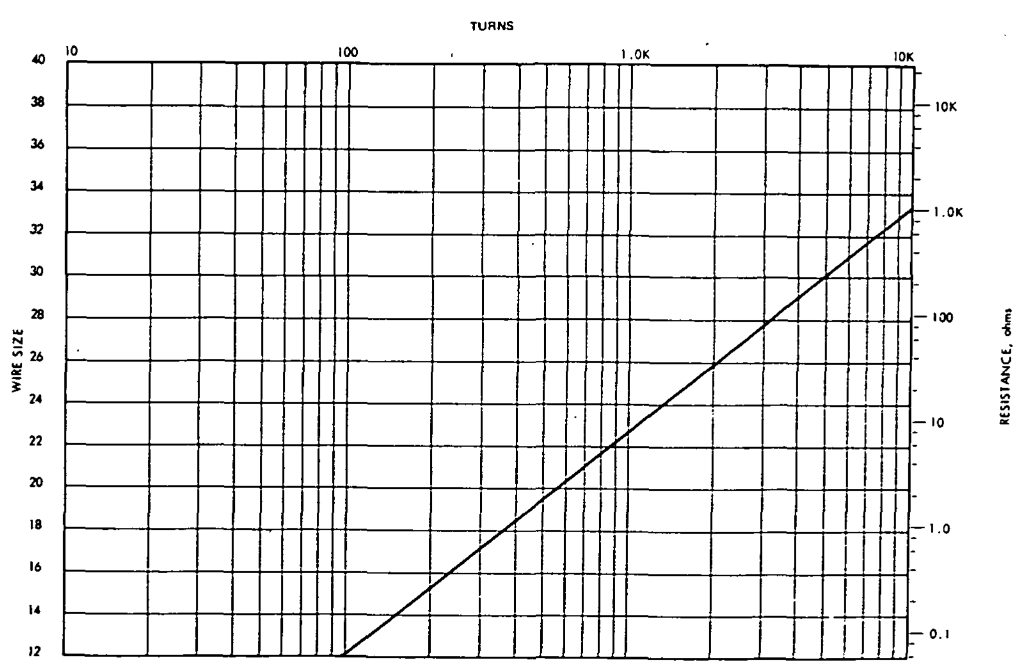
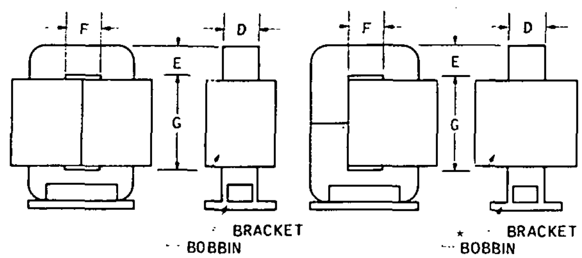


Fig. G16. Wiregraph for "C" core AL-19

Table G18. "C" core AL-20

"C" CORE	AL-20			
	ENGLISH		METRIC	
Wa/Ac			1.56	
Wa x Ac	0.543	in^4	22.6	cm^4
Wa	0.977	in^2	6.30	cm^2
Ac (effective)	0.556	in^2	3.58	cm^2
lm	6.228	in	15.8	cm
CORE WT	0.965	lb	437	grams
COPPER WT	0.767	lb	348	grams
* MLT FULLWOUND	5.36	in	13.62	cm
$G/\sqrt{Ac}$			2.09	
Wa (effective) /Wa			0.903	
A_T	31.7	in^2	205	cm^2
D	1.000	in	2.54	cm
E	0.625	in	1.587	cm
F	0.625	in	1.587	cm
G	1.562	in	3.967	cm
BOBBIN	DORCO ELECTRONICS = 1-L-20			
LENGTH	1.497	in	3.80	cm
BUILD	0.590	in	1.498	cm
* Wa (effective)	0.883	in^2	5.69	cm^2
BRACKET	HALLMARK METALS = 10-114-010			



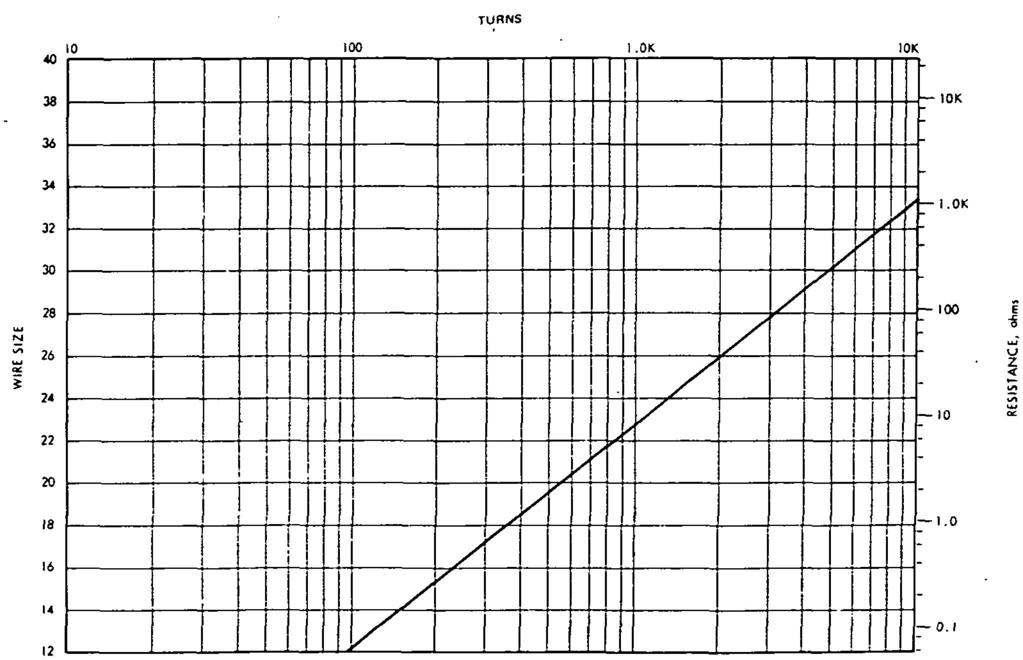
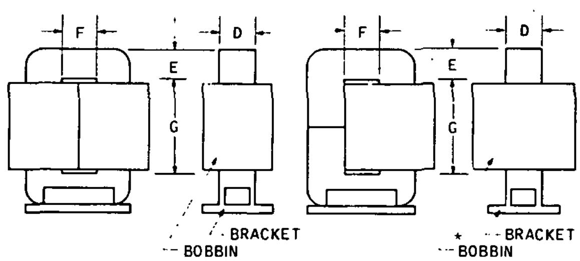


Fig. G17. Wiregraph for "C" core AL-20

Table G19. "C" core AL-22

"C" CORE	AL-22	
	ENGLISH	METRIC
Wa/Ac		1.94
Wa x Ac	0.692 in^4	28.0 cm^4
Wa	1.21 in^2	7.804 cm^2
Ac (effective)	0.556 in^2	3.58 cm^2
lm	6.978 in	17.2 cm
CORE WT	1.08 lb	489 grams
COPPER WT	0.961 lb	435 grams
* MLT FULLWOUND	5.36 in	13.62 cm
$G/\sqrt{Ac}$		2.598
Wa (effective) /Wa		0.912
A_T	35.3 in^2	228 cm^2
D	1.000 in	2.54 cm
E	0.625 in	1.587 cm
F	0.625 in	1.587 cm
G	1.937 in	4.92 cm
BOBBIN	DORCO ELECTRONICS =	1-L-22
LENGTH	1.872 in	4.75 cm
BUILD	0.590 in	1.498 cm
* Wa (effective)	1.10 in^2	7.12 cm^2
BRACKET	HALLMARK METALS =	10-114-010



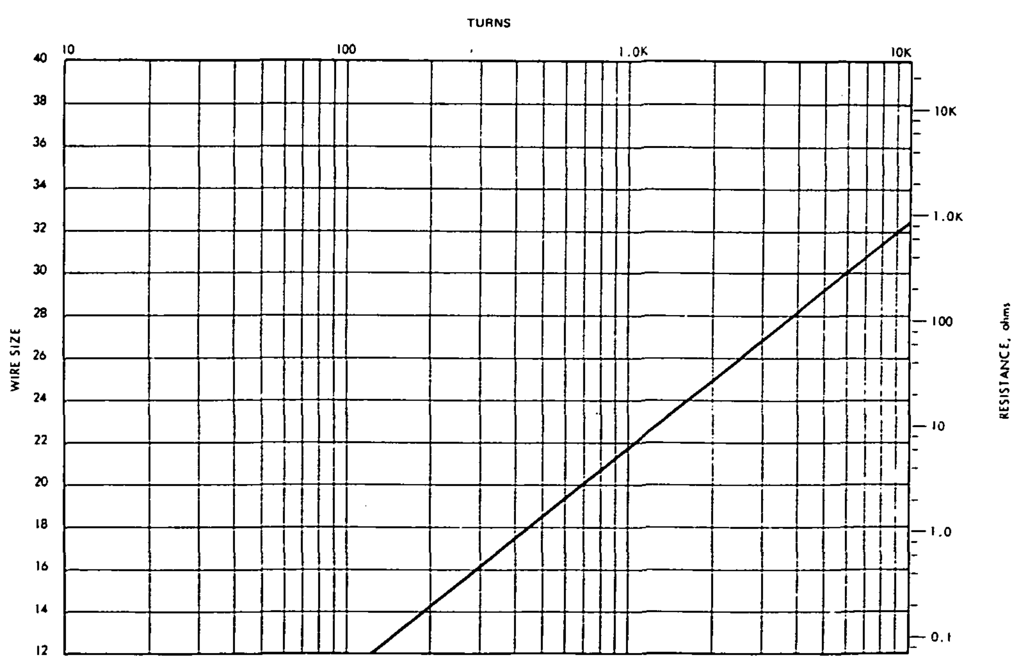
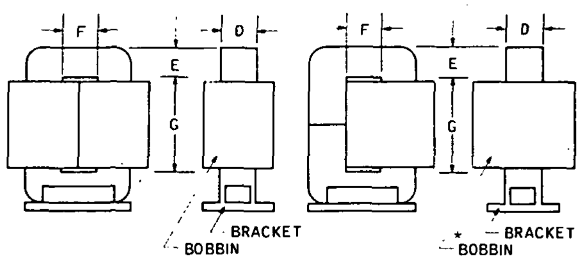


Fig. G18. Wiregraph for "C" core AL-22

Table G20. "C" core AL-23

"C" CORE	AL-23	
	ENGLISH	METRIC
Wa/Ac		1.55
Wa x Ac	0.841 in^4	34.96 cm^4
Wa	1.21 in^2	7.804 cm^2
Ac (effective)	0.695 in^2	4.48 cm^2
lm	6.978 in	17.2 cm
CORE WT	1.352 lb	612 grams
COPPER WT	1.056 lb	479 grams
* MLT FULLWOUND	5.86 in	14.89 cm
$G/\sqrt{Ac}$		2.32
Wa (effective) /Wa		0.912
A_T	38.1 in^2	246 cm^2
D	1.250 in	3.175 cm
E	0.625 in	1.587 cm
F	0.625 in	1.587 cm
G	1.937 in	4.92 cm
BOBBIN	DORCO ELECTRONICS *	1-L-23
LENGTH	1.872 in	4.75 cm
BUILD	0.590 in	1.498 cm
* Wa (effective)	1.10 in^2	7.12 cm^2
BRACKET	HALLMARK METALS *	14-114-010



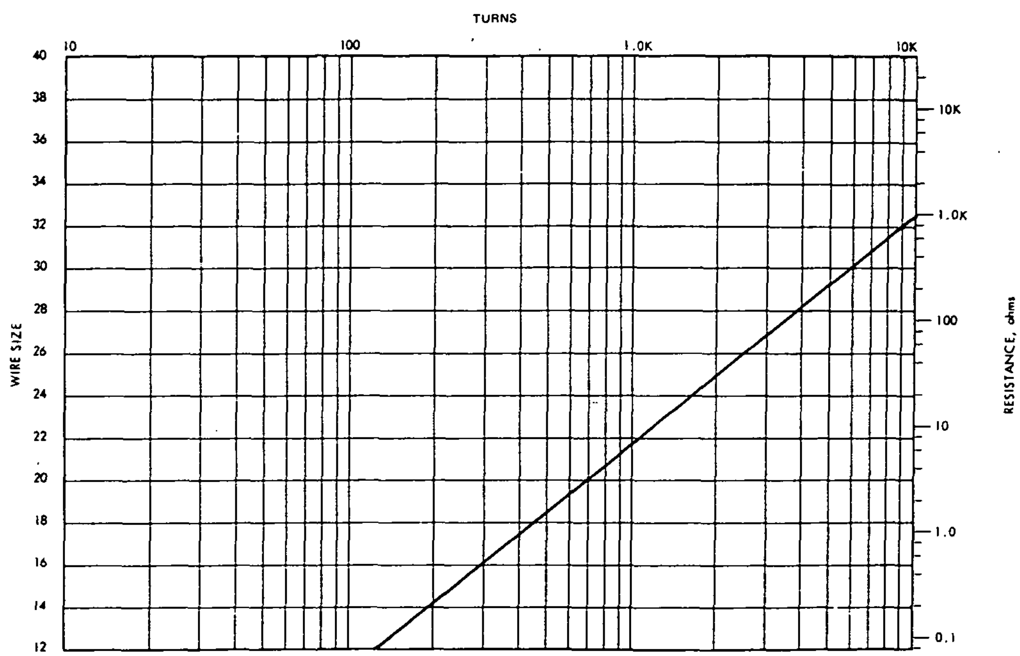
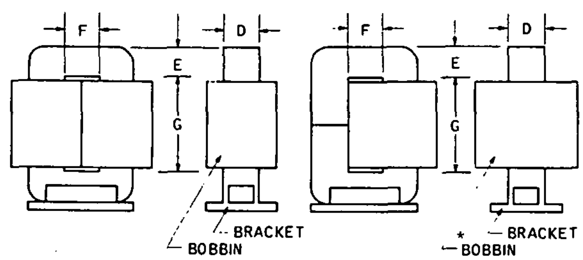


Fig. G19. Wiregraph for "C" core AL-23

Table G21. "C" core AL-24

"C" CORE	AL-24	
	ENGLISH	METRIC
Wa/Ac		2.77
Wa x Ac	0.962 in^4	40.0 cm^4
Wa	1.73 in^2	11.16 cm^2
Ac (effective)	0.556 in^2	3.58 cm^2
lm	7.871 in	20.0 cm
CORE WT	1.220 lb	553 grams
COPPER WT	1.501 lb	680 grams
* MLT FULLWOUND	5.75 in	14.62 cm
$G/\sqrt{Ac}$		3.10
Wa (effective) /Wa		0.929
A_T	43.6 in^2	281.6 cm^2
D	1.000 in	2.54 cm
E	0.625 in	1.587 cm
F	0.750 in	1.905 cm
G	2.313 in	5.875 cm
BOBBIN	DORCO ELECTRONICS # 1-L-24	
LENGTH	2.248 in	5.709 cm
BUILD	0.715 in	1.816 cm
* Wa (effective)	1.607 in^2	10.37 cm^2
BRACKET	HALLMARK METALS # 10-200-010	



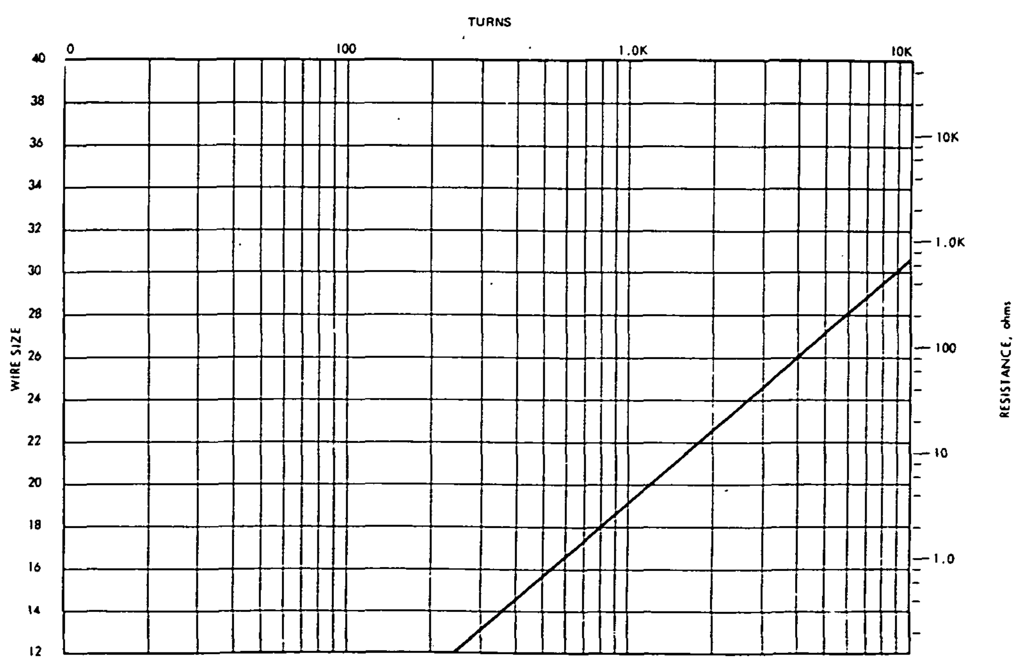
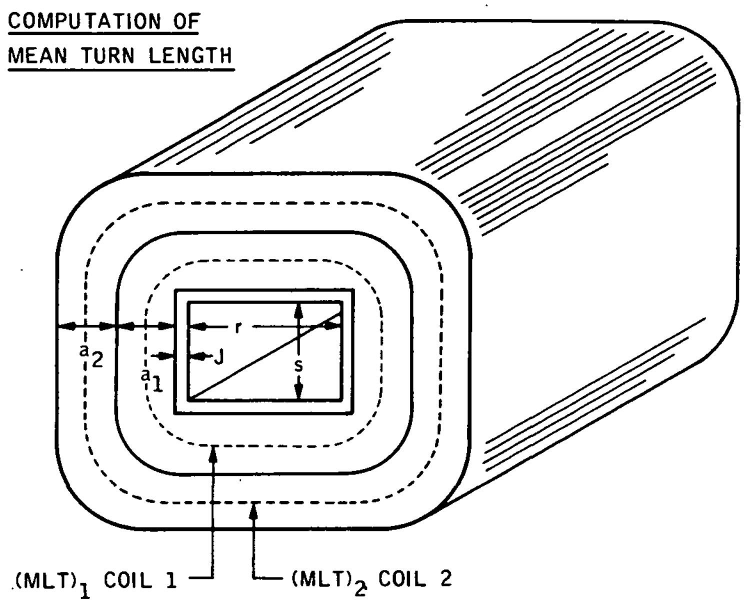


Fig. G20. Wiregraph for "C" core AL-24



$$(MLT)_1 = 2(r+2J) + 2(s+2J) + \pi a_1$$

$$(MLT)_2 = 2(r+2J) + 2(s+2J) + \pi(2a_1+a_2)$$

OR

$$(MLT)_2 = (MLT)_1 + \quad (a_1+a_2+2c)$$

OR

$$(MLT)_n = 2(r+2J) + 2(s+2J) + \pi \left[2(a_1+a_2+\ldots+a_{n-1}) + a_n\right]$$

WHERE:

a_1 = BUILD OF WINDING #1
a_2 = BUILD OF WINDING #2
a_n = BUILD OF WINDING #n
c = THICKNESS OF INSULATION BETWEEN a_1 & a_2

Fig. G21. Computation of mean turn length

Table G22. Conversion factors

Area	
To convert	Multiply By
Circular Mils to Square Inches	7.854×10^{-7}
Circular Mils to Square Mils	7.854×10^{-1}
Circular Mils to Square Millimeters	5.066×10^{-4}
Square Centimeters to Square Inches	1.55×10^{-1}
Square Feet to Square Meters	9.29×10^{-2}
Square Inches to Circular Mils	1.273×10^{6}
Square Inches to Square Centimeters	6.4516
Square Inches to Square Millimeters	6.4516×10^{2}
Square Inches to Square Mils	1.000×10^{6}
Square Meters to Square Feet	1.0764×10^{1}
Square Millimeters to Square Inches	1.55×10^{-3}
Square Millimeters to Circular Mils	1.973×10^{3}
Square Mils to Circular Mils	1.2732
Square Mils to Square Inches	1.00×10^{-6}
Length	
Centimeters to Inches	3.937×10^{-1}
Centimeters to Feet	3.281×10^{-2}
Feet to Centimeters	3.048×10^{1}
Feet to Meters	3.048×10^{-1}
Inches to Centimeters	2.54
Inches to Meters	2.54×10^{-2}
Inches to Millimeters	2.54×10^{1}
Inches to Mils	1.00×10^{3}
Kilometers to Miles	6.214×10^{-1}
Meters to Feet	3.2808
Meters to Inches	3.937×10^{1}
Meters to Yards	1.0936
Miles to Kilometers	1.6039

Table G22 (contd)

Length (contd)	
To convert	Multiply By
Millimeters to Inches	3.937×10^{-2}
Millimeters to Mils	3.937×10^{1}
Mils to Inches	1.00×10^{-3}
Mils to Millimeters	2.54×10^{-2}
Yards to Meters	9.144×10^{-1}
Weight (wt)	
Ounces to Pounds	6.25×10^{-2}
Ounces to Grams	$2.8349 \quad 10^{1}$
Pounds to Ounces	1.6×10^{1}
Pounds to Grams	4.5359×10^{2}
Grams to Ounces	3.527×10^{-2}
Grams to Pounds	2.205×10^{-3}

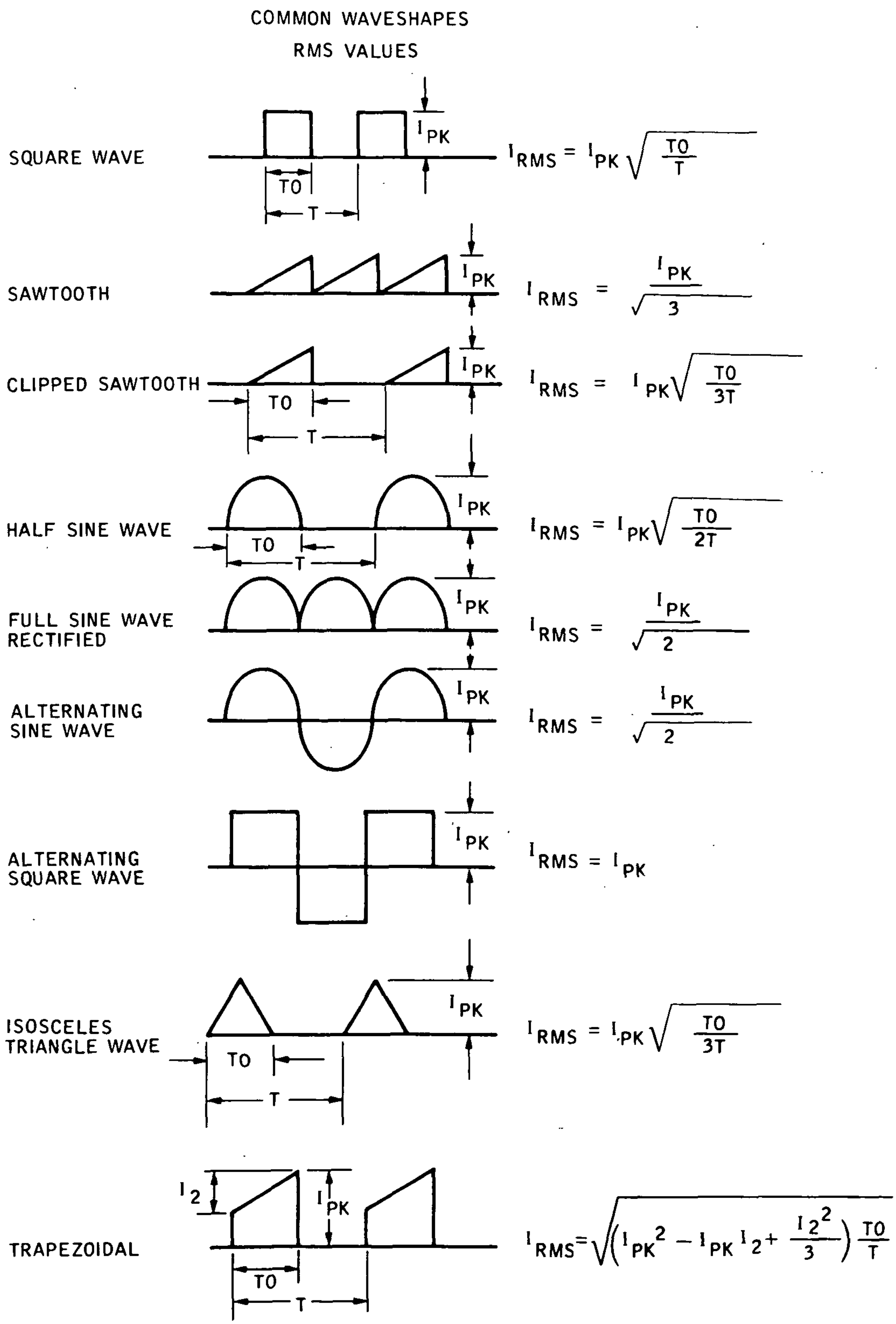


Figure G22. Common waveshapes RMS values

Table G23. Calculated and measured inductance using various gap lengths

Core	A_c (cm^2)	l_m (cm)	N	l_g (cm)	$G/\sqrt{A_c}$	L mh Calculate	L′ mh Measured	$F = \frac{L'}{L}$	l_g/G
AL-8	0.806	10.66	236	0.0508	3.36	11.1	11.8	1.06	0.0168
AL-8	0.806	10.66	236	0.305	3.36	1.855	3.5	1.89	0.10
AL-124	0.716	8.4	76	0.101	3.00	0.437	0.673	1.42	0.04
AL-124	0.716	8.4	76	0.305	3.00	0.170	0.320	1.88	0.12
AL-18	1.257	14.34	320	0.457	3.502	3.54	6.63	1.87	0.116
AL-18	1.257	14.34	320	1.067	3.502	1.51	4.54	3.00	0.272
AL-22	3.58	17.2	74	0.711	2.598	0.347	0.665	1.92	0.144
AL-22	3.58	17.2	74	0.203	2.598	1.216	1.740	1.43	0.04

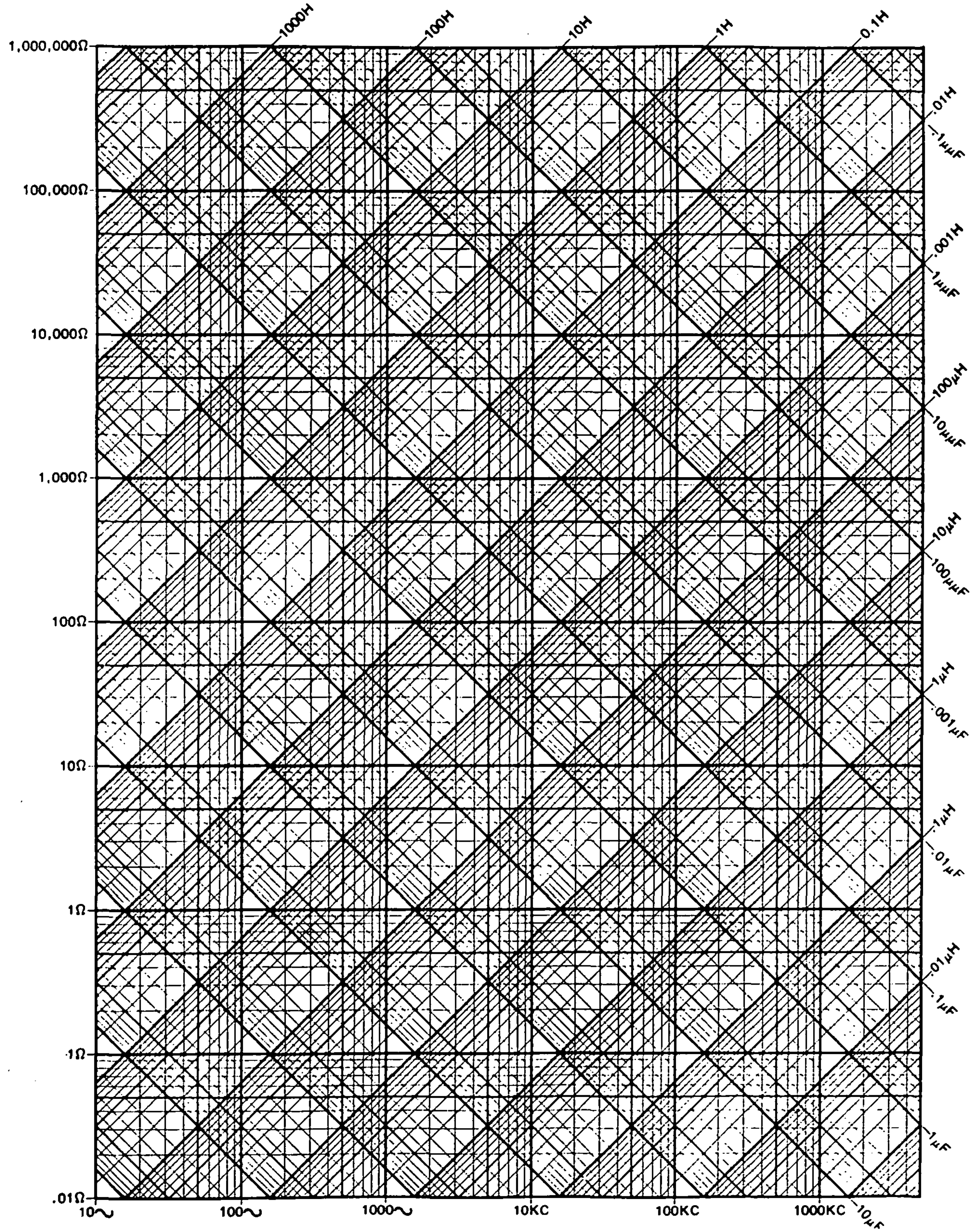


Fig. G23. Graph for inductance, capacitance, and reactance

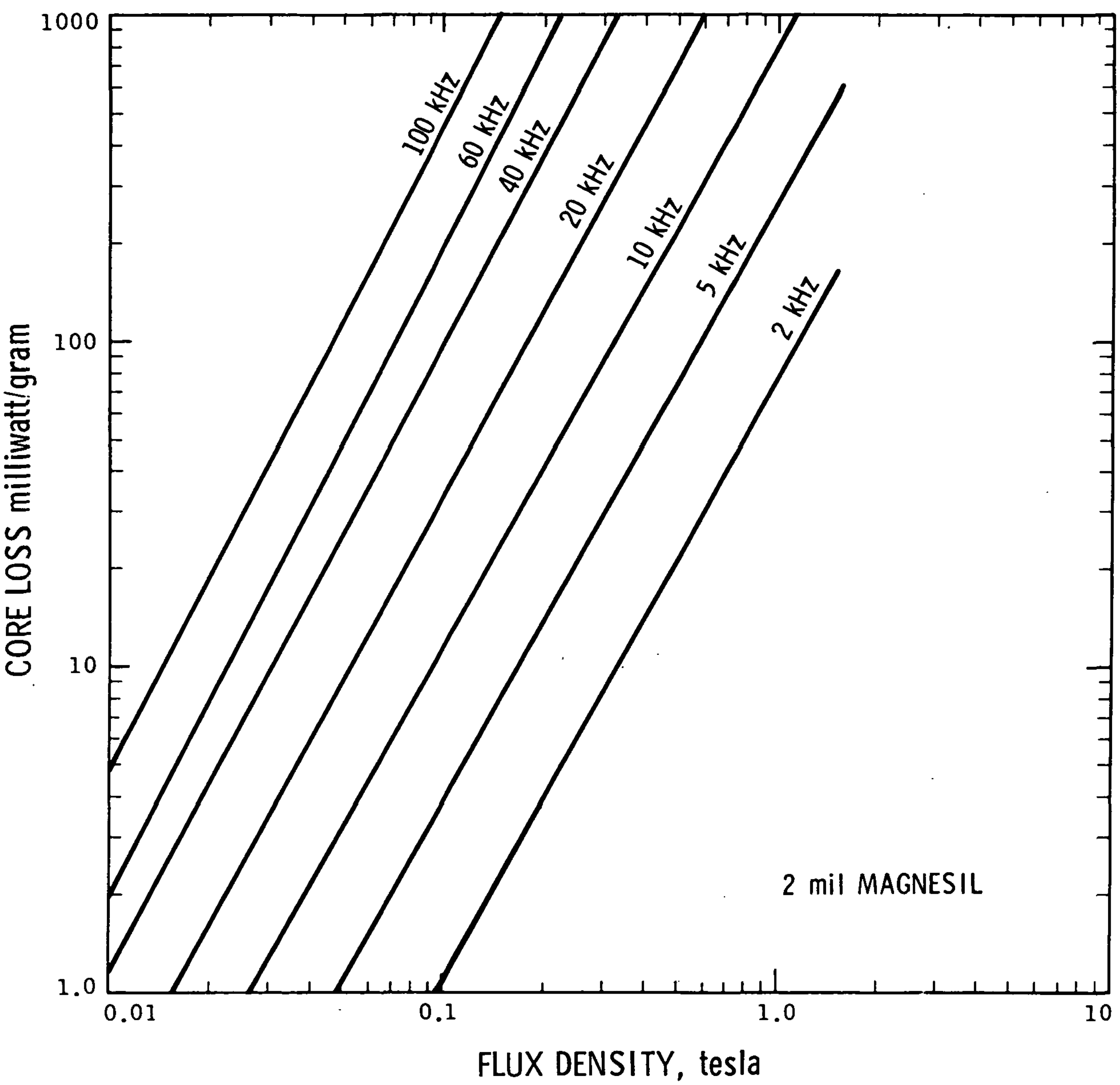


Fig. G24. Design curves showing maximum core loss for 2 mil silicon "C" cores

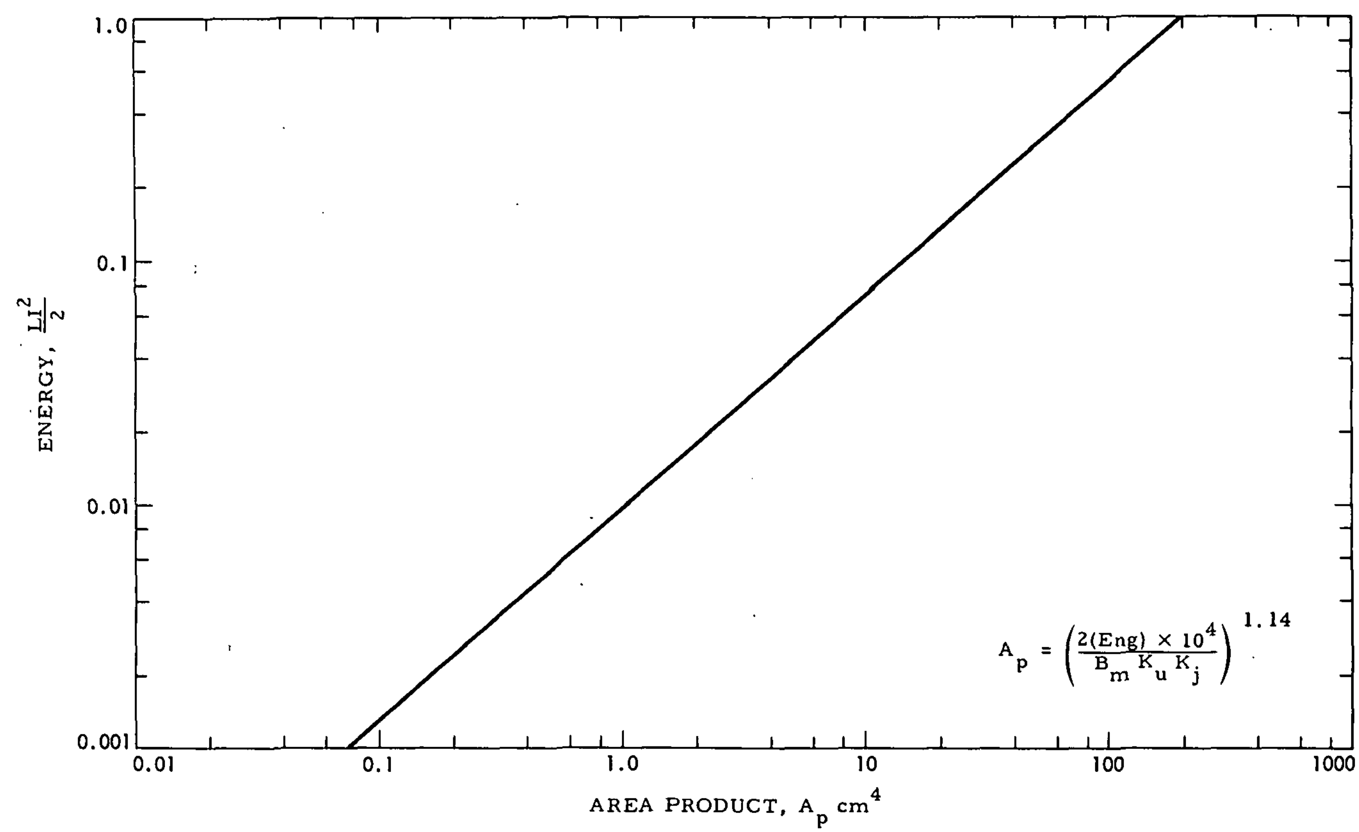


Fig. G25. Area product vs energy $\frac{LI^2}{2}$

B_m = 1.2 (tesla)
K_u = 0.4
K_j = 395

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TECHNICAL REPORT STANDARD TITLE PAGE

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16. Abstract

Although filter inductor designers have routinely tended to specify moly permalloy powder cores for use in high frequency power converters and pulse-width modulated switching regulators, there are significant advantages in specifying C cores and cut toroids fabricated from grain oriented silicon steels which should not be overlooked. Such steel cores can develop flux densities of 1.6 tesla, with useful linearity to 1.2 tesla, whereas moly permalloy cores carrying d.c. current have useful flux density capabilities only to about 0.3 tesla. The use of silicon steel cores thus makes it possible to design more compact cores, and therefore inductors of reduced volume, or conversely to provide greater load capacity in inductors of a given volume.

For years manufacturers have rated their cores with a number that represents its relative energy-handling ability. This method assigns to each core a number which is the product of its window and core cross-section area, and is called "Area Product A_p." The author has developed a correlation between the A_p numbers and current density J for a given temperature rise. Also, the author has developed straight-line relationships for A_p and Volume, A_p and surface area A_t and, A_p and weight. These relationships can now be used as new tools to simplify and standardize the process of inductor design.

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16. Abstract

They also make it possible to design inductors of small bulk and volume or to optimize efficiency.

The adoption by NASA of the metric system for dimensioning to replace the long-used English units imposes a requirement on the U.S. transformer designer to convert from the familiar units to the less familiar metric equivalents. Material is presented to assist in that transition in the field of transformer design and fabrication.

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