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Transformer Design Tradeoffs

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PREFACE

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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 of a transformer, cm^2
A_w	wire area, cm^2
AWG	American Wire Gauge
B_m	flux density, teslas
E	voltage
η	efficiency
f	frequency, Hz
I	current, amps
I_o	load current, amps
I_p	primary current, amps
I_s	secondary current, amps
J	current density, $amps/cm^2$
J_p	primary current density, $amps/cm^2$
J_s	secondary 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_m	magnetic path, cm
ℓ	linear dimension, cm
MLT	mean length turn, cm
N	turns
P	power, watts
P_{cu}	copper loss, watts
P_{fe}	core loss, watts
P_{in}	input power, watts
P_o	output power, watts
Ψ	watts/unit area, cm

LIST OF SYMBOLS (cont)

P_p	primary loss, watts
P_s	secondary loss, watts
P_Σ	total loss (core and copper), watts
P_t	apparent power, watts
R	resistance, ohms
R_E	equivalent core-loss (shunt) resistance, ohms
R_{cu}	copper resistance, ohms
Reg (%)	transformer regulation in percent
R_o	load resistance, ohms
R_p	primary resistance, ohms
R_s	secondary resistance, ohms
R_t	total 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	teslas
V_o	load voltage, volts
Vol	volume, cm^3
W_a	window area, cm^2
W_t	weight, grams

ABSTRACT

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 unit to the less familiar metric equivalents. Material is presented to assist in this transition in the field of transformer design and fabrication.

The conversion process in power electronics requires the use of transformer components which frequently are the heaviest and bulkiest items in the conversion circuit. They also have a significant effect upon the overall performance and efficiency of the system. Accordingly, the design of such transformers has an important effect on overall system weight, power-inversion efficiency, and cost.

For years manufacturers have rated their cores with a number that represents its relative power-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."

The author has developed a coordination between the A_p numbers and current density J for a given regulation and temperature rise. The area product A_p is a dimension to the fourth power, whereas volume is a dimension to the third power and surface area A_t is a dimension to the second power. 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 transformer design. They also make it possible to design transformers of small bulk and volume or to optimize efficiency.

INTRODUCTION

The conversion process in power electronics requires the use of transformers, components which frequently are the heaviest and bulkiest item in the conversion circuits. They also have a significant effect upon the overall performance and efficiency of the system. Accordingly, the design of such transformers has an important influence on overall system weight, power conversion efficiency and cost. Because of the interdependence and interaction of parameters, judicious design tradeoffs are necessary to achieve optimization.

The information presented herein explains the reasons for making such tradeoffs as a guide for making them intelligently.

Manufacturers have for years assigned numeric codes to their cores which represent the relative power 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 transformer cores and several other important parameters which must be considered in transformer 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 regulation and 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 transformer design. They make it possible to design transformers 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 transformers 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.

One of the basic steps in transformer design is the selection of the proper core material. To aid in the selection of cores a comparison of five common core materials is presented which illustrates their influence on overall transformer efficiency and weight. The designer should also be aware of the cost difference between core materials of the nickel steel families and the silicon steel family. In many instances, the author has found it possible to achieve suitable designs using low cost, silicon steel C-cores when the proper design tradeoffs are made.

THE DESIGN PROBLEM, GENERALLY

The designer is faced with a set of constraints which must be observed in the design of any transformer. One of these is the output power, P_o, (operating voltage multiplied by maximum current demand) which the secondary winding must be capable of delivering to the load within specified regulation limits. Another relates to minimum efficiency of operation which is dependent upon the maximum power loss which can be allowed in the transformer. Still another defines the maximum permissible temperature rise for the transformer when used in its intended environment having a defined ambient temperature range.

Other constraints relate to volume occupied by the transformer and particularly in aerospace applications, weight, since weight minimization is an important goal in the design of space flight electronics. Lastly, cost effectiveness is often an important consideration.

Depending upon application, certain of these constraints will dominate. Parameters affecting others may then be traded off as necessary to achieve the most desirable design. It is not possible to optimize all parameters in a single design because of the interaction and interdependence of parameters.

For example, if volume and weight are of great significance, reductions in both often can be effected by operating the transformer at a higher frequency but at a penalty in efficiency. When the frequency cannot be raised, reduction in weight and volume may still be possible by selecting a more efficient core material, but at a penalty of increased cost. Judicious tradeoffs thus must be effected to achieve the design goals.

A flow chart showing the interrelation and interaction of the various design factors which must be taken into consideration is shown in Figure 1.

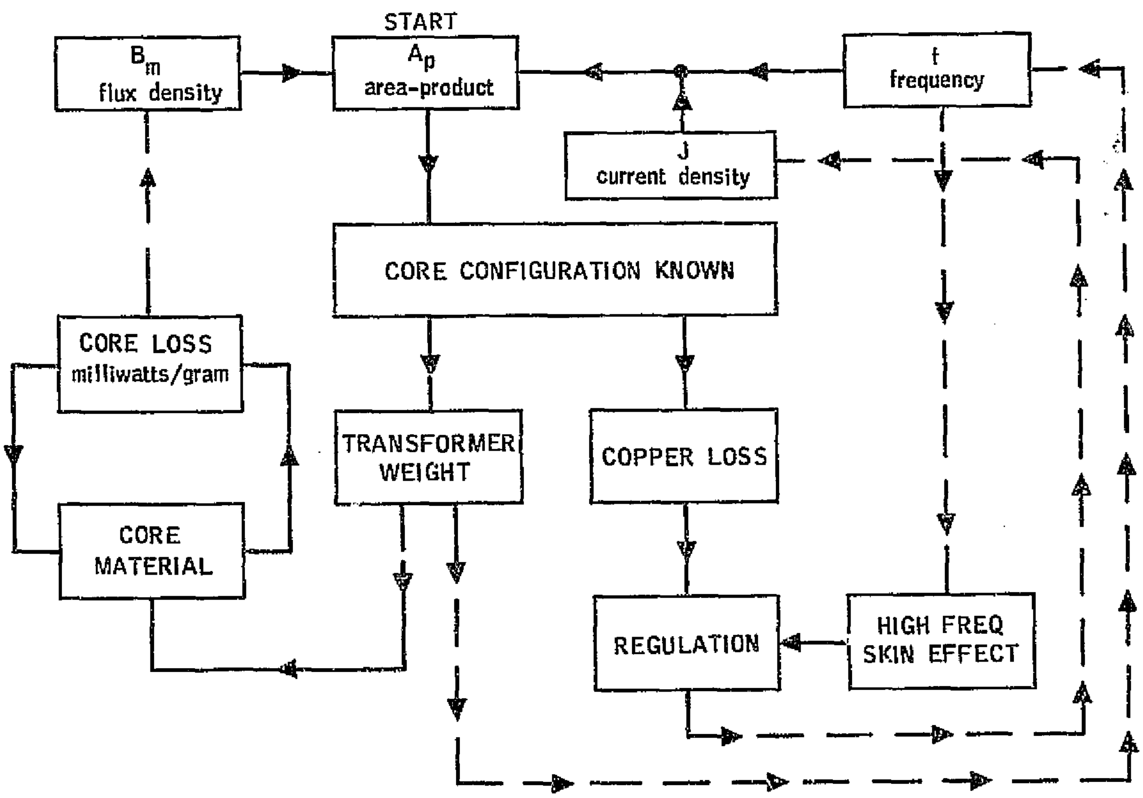

Fig. 1. Transformer Design Factors Flow Chart

Various transformer 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 transformer 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 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:

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

Figure 2 shows in outline form a C-core type transformer 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.

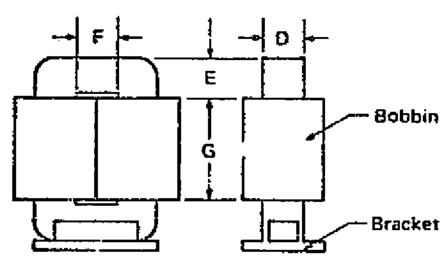

Fig. 2. C-Core Transformer

*Reference 1.

RELATIONSHIP OF A_p TO TRANSFORMER POWER HANDLING CAPABILITY

According to the newly developed approach, the power handling capability of a core is related to its area product by an equation which may be stated as:

$$A_p = \left(\frac{P_t \times 10^4}{K\, B_m\, f\, K_u\, K_j}\right)^{1.16} \qquad (2)$$

K_j = CURRENT DENSITY COEFFICIENT
323 FOR 25°C RISE
468 FOR 50°C RISE

K_u = WINDOW UTILIZATION FACTOR
0.4 IN MOST CASES

f = FREQUENCY, Hz

B_m = FLUX DENSITY, TESLA

K = WAVEFORM COEFFICIENT
4.0 SQUARE WAVE
4.44 SINE WAVE

P_t = APPARENT POWER
PRIMARY PLUS SECONDARY

From the above it can be seen that factors such as flux density, frequency of operation, 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 transformer 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 D (page 36).

OUTPUT POWER VS INPUT POWER VS APPARENT POWER CAPABILITY

Output power (P_o) is of greatest interest to the user. To the transformer designer it is the apparent power (P_t) which is associated with the geometry of the transformer that is of greater importance. Assume, for the sake of simplicity, the core of an isolation transformer has but two windings in the window area (W_a), a primary and a secondary. Also assume that the window area (W_a) is divided up in proportion to the power handling capability of the windings using equal current density. The primary winding handles P_{in} and the secondary handles P_o to the load. Since the power transformer has to be designed to accommodate the primary P_{in} and secondary P_o, then:

$$P_t = P_{in} + P_o$$

$$P_t = \frac{P_o}{\eta} + P_o \qquad (3)$$

The designer must be concerned with the apparent power handling capability, P_t, of the transformer core and windings. P_t may vary by a factor ranging from 2 to 2.828 times the input power, P_{in}, depending upon the configuration of the circuit in which the transformer is used because of the different RMS current levels in the windings during operation. If the current wave shape in the rectifier transformer becomes interrupted its effective RMS value changes. Transformer size, thus, is not only affected by the load demand but, also, by the different copper (winding) losses incurred in the various circuit arrangements.

For example, for a load of one watt, compare the power handling capabilities required (neglecting transformer and diode losses so that ($P_{in} = P_o$) for the full-wave bridge circuit of Figure 3, the full-wave center-tapped secondary circuit of Figure 4, and the push-pull center-tapped full-wave circuit in Figure 5.

For the circuit shown in Figure 3,

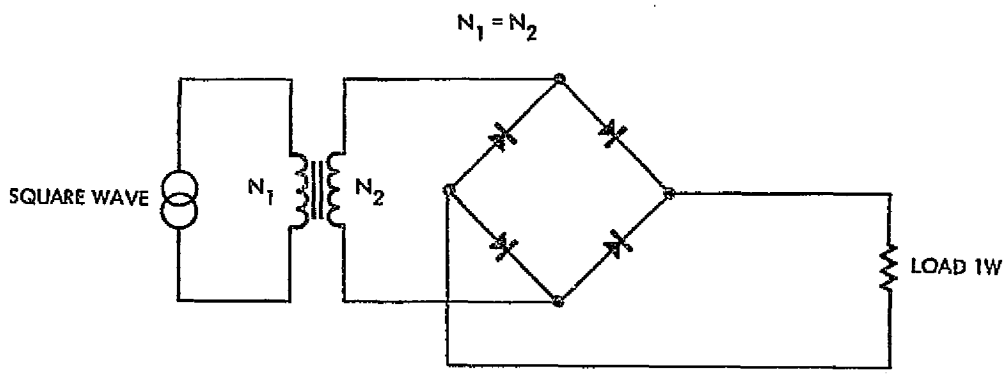

Fig. 3. Full Wave Bridge Circuit

the total apparent power P_t is 2 watts, as may be seen from:

$$P_t = \overbrace{(I_{N1}\ E_{N1})}^{P_{in}} + \overbrace{(I_{N2}\ E_{N2})}^{P_o} \qquad (4)$$

$$P_t = 2\ P_{in}$$

in which I_{N1} and I_{N2} are the currents associated with the primary and secondary windings, respectively, and E_{N1} and E_{N2} are the voltages across the primary and secondary windings, respectively.

The circuit shown in Figure 4

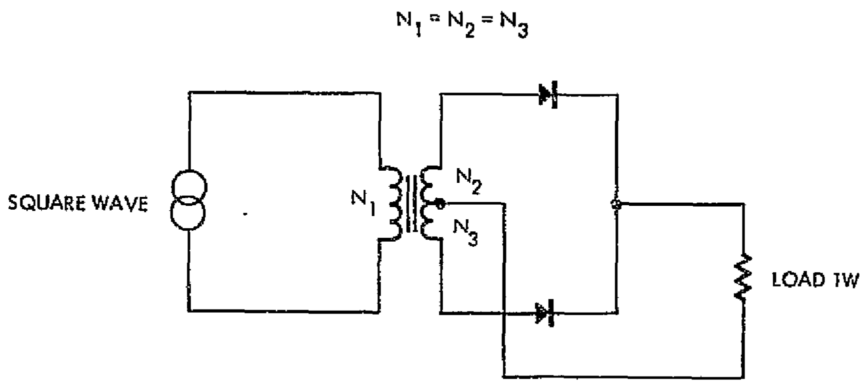

Fig. 4. Full Wave Center Tapped Circuit

requires an increase of 20.7% in P_t due to the increased RMS rating because of the interrupted current flowing in that winding.

$$P_t = (I_{N1}\ E_{N1}) + \left[(0.707 I_{N2}\ E_{N2}) + (0.707 I_{N3}\ E_{N3})\right] \tag{5}$$

$$P_t = P_{in} + 0.707\ P_{in} + 0.707\ P_{in} = 2.414\ P_{in}$$

and for the circuit shown in Figure 5

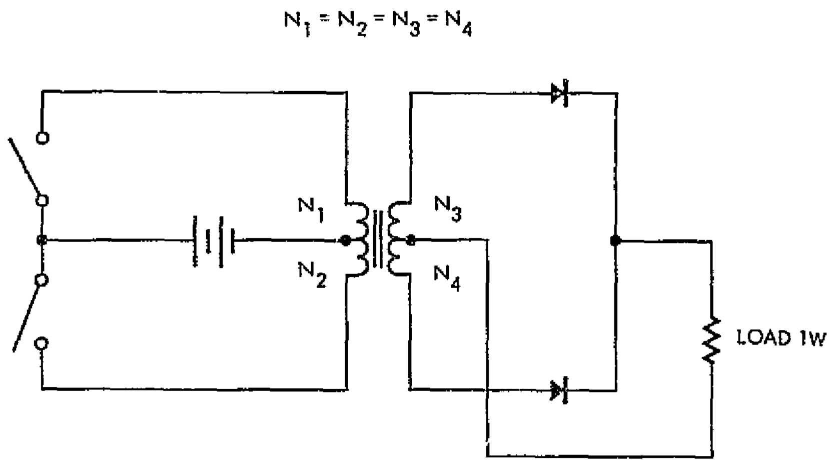

Fig. 5. Pushpull Full Wave Center Tapped Circuit

which is typical of a dc to dc converter, requires a P_t increase to 2.828 because of the interrupted current flowing in the primary and secondary windings

$$\text{since} \qquad N_1 = N_2 = N_3 = N_4 \quad ,$$

$$P_t = \left[(0.707 I_{N1}\ E_{N1}) + (0.707 I_{N2}\ E_{N2})\right] + \left[(0.707 I_{N3}\ E_{N3}) + (0.707 I_{N4}\ E_{N4})\right] \quad (6)$$

$$P_t = 0.707\ P_{in} + 0.707\ P_{in} + 0.707\ P_{in} + 0.707\ P_{in} = 2.828\ P_{in}$$

Thus the circuit configuration in which the transformer is to be used must be considered by the designer when sizing the transformer.

Rather than discuss the various methods previously used by designers, the author believes it will be more useful to consider typical design problems and to work out solutions using the approach based upon the newly formulated relationships.

A SPECIFIC DESIGN PROBLEM AS AN EXAMPLE

Assume a specification for a transformer design as shown in Figure 4 (page 7) requiring:

E_o (output voltage) = 10 volts

I_o (output current) = 2.0 amps

E_{in} (input voltage) = 50 volts

*Operating frequency (f) = 2500 Hz (square wave)

Maximum temperature rise = 25°C

**Transformer efficiency = 95%.

Assuming the bridge rectifier of Figure 3, and using the efficiency constraint of 95%, the apparent power handled by the transformer is calculated (from equation (3)) to be: (1.0 volt diode drop (V_d) assumed).

Insert values

$$P_t = \frac{P_o}{\eta} + P_o \tag{3}$$

$$P_t = I_o (E_o + V_d) \times (\frac{1}{\eta} + 1)$$

$$P_t = \frac{24}{0.95} + 24 = 49.3 \text{ watts}$$

This value determines the apparent power handling capability of the core needed for the transformer. A suitable core selection is made by using the area product listings in the catalogs describing the many C-core configurations (sizes and shapes) available from the various suppliers.

*For high frequency skin effect, see Appendix J (page 57).
**For transformer regulation as a function of efficiency, see Appendix E (page 39).

Core Selection

Applying the data from the example to equation (2):

$$A_p = \left(\frac{49.3 \times 10^4}{(4)(0.3)*(2500)(0.4)(323)}\right)^{1.16} = 1.32 \text{ cm}^4$$

After the A_p has been determined, the geometry of the transformer can be evaluated as described in Appendix G for weight, Appendix C for surface area and Appendix H for volume, and appropriate changes made, if required. Having established the configuration, it is then necessary to determine the core material to complete core selection. Material selection requires consideration of efficiency constraint which is 0.95 in the example. The total transformer losses are

$$P_\Sigma = \frac{P_o}{\eta} - P_o \qquad (7)$$

Inserting values:

$$P_\Sigma = \frac{24}{0.95} - 24 = 1.26 \text{ watts}$$

Maximum efficiency is realized when the copper (winding) losses are equal to the iron (core) losses (see Appendix B, page 27) which is expressed as

$$P_{cu} = P_{fe} \quad \text{, and therefore}$$

$$P_{cu} = \frac{P_\Sigma}{2} \qquad \text{and thus}$$

$$P_{cu} = 0.63 = P_{fe}$$

Referring to Table 1, column 3 (pages 11 and 12), the AL-124 core with a A_p of 1.44 cm^4 is closest to the 1.32 cm^4 A_p calculated above.

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*This is an arbitrary figure developed through years of experience. It can be scaled upwardly for comparison of materials with higher flux density.

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Table 1. 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	$I = \sqrt{\frac{W}{\Omega}}$	ΔT 25°C $J = \frac{amps}{cm^2}$	Ω @ 75° C	P_Σ	$I = \sqrt{\frac{W}{\Omega}}$	ΔT 50°C $J = \frac{amps}{cm^2}$	Total Weight	Volume cm^3	A_c cm^2
1	AL-2	20.9	0.2[illegible]	3.55	662 30	8.93	0.127	0.187	370	9.81	1.46	0.273	528	23.33	7.14	0.265
2	AL-3	23.9	0.410	4.18	662 30	10.5	0.717	0.18[illegible]	365	11.5	1.67	0.269	522	31.18	8.92	0.410
3	AL-5	33.6	0.767	4.59	946 30	16.5	1.01	0.174	345	18.1	2.35	0.255	493	51.8	14.06	0.539
4	AL-6	37.5	1.011	5.23	946 30	18.8	1.13	0.1[illegible]	341	20.6	2.63	0.253	489	65.1	16.88	0.716
5	AL-124	45.3	1.44	5.50	1317 30	27.5	1.36	0.157	310	30.2	3.17	0.229	443	80.8	22.50	0.716
6	AL-8	63.4	2.51	5.74	221 20	0.482	1.90	1.404	271	0.529	4.44	2.05	395	127.85	35.66	0.806
7	AL-9	69.0	3.0[illegible]	6.38	221 20	0.535	2.07	1.39	268	0.587	4.83	2.03	391	155.8	41.62	1.077
8	AL-10	74.5	3.85	7.01	221 20	0.588	2.24	1.38	266	0.646	5.22	2.01	387	183.2	47.55	1.342
9	AL-12	87.0	4.57	7.09	278 20	0.748	2.61	1.32	255	0.821	6.09	1.93	371	204.2	61.38	1.26
10	AL-13[illegible]	93.7	5.1[illegible]	7.36	325 20	0.908	2.81	1.24	240	0.997	6.56	1.81	345	227.0	69.63	1.26
11	AL-78	98.1	6.[illegible]	7.01	312 20	0.831	2.94	1.33	256	0.912	6.87	1.94	374	258.0	62.83	1.34
12	AL-18	118	7.92	7.61	510 20	1.47	3.55	1.10	211	1.61	8.26	1.60	308	321.0	[illegible].79	1.45
13	AL-15	120	9.07	8.05	386 20	1.18	3.58	1.23	237	1.30	8.40	1.79	346	352.0	94.43	1.80
14	AL-16	127	10.8	8.89	386 20	1.30	3.80	1.20	233	1.43	8.89	1.76	340	397.0	104.95	2.15
15	AL-17	142	14.4	10.3	386 20	1.51	4.25	1.185	228	1.66	9.94	1.73	333	502.0	124.94	2.87
16	AL-19	159	18.	10.8	511 20	2.10	4.77	1.065	205	2.31	11.1	1.55	299	589.0	155.44	2.87
17	AL-20	182	22.6	11.5	511 20	2.23	5.46	1.106	213	2.45	12.7	1.61	310	715.0	187.08	3.58
18	AL-22	202	28.0	11.5	637 20	2.78	6.05	1.043	201	3.05	14.1	1.52	293	835.0	212.04	3.58
19	AL-23	220	34.9	12.7	637 20	3.07	6.60	1.036	200	3.37	15.4	1.51	291	994.0	244.67	4.48
20	AL-24	245	40.0	12.0	946 20	4.32	7.35	0.922	178	4.74	17.1	1.35	259	1090.0	280.91	3.58

copper loss = iron loss

Definitions for Table 1

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 two bobbins 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 equal to $2\ P_{cu}$
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 transformer surface area, total loss is equal to $2\ P_{cu}$
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. Transformer volume calculated from Figure H1
16. Core effective cross-section

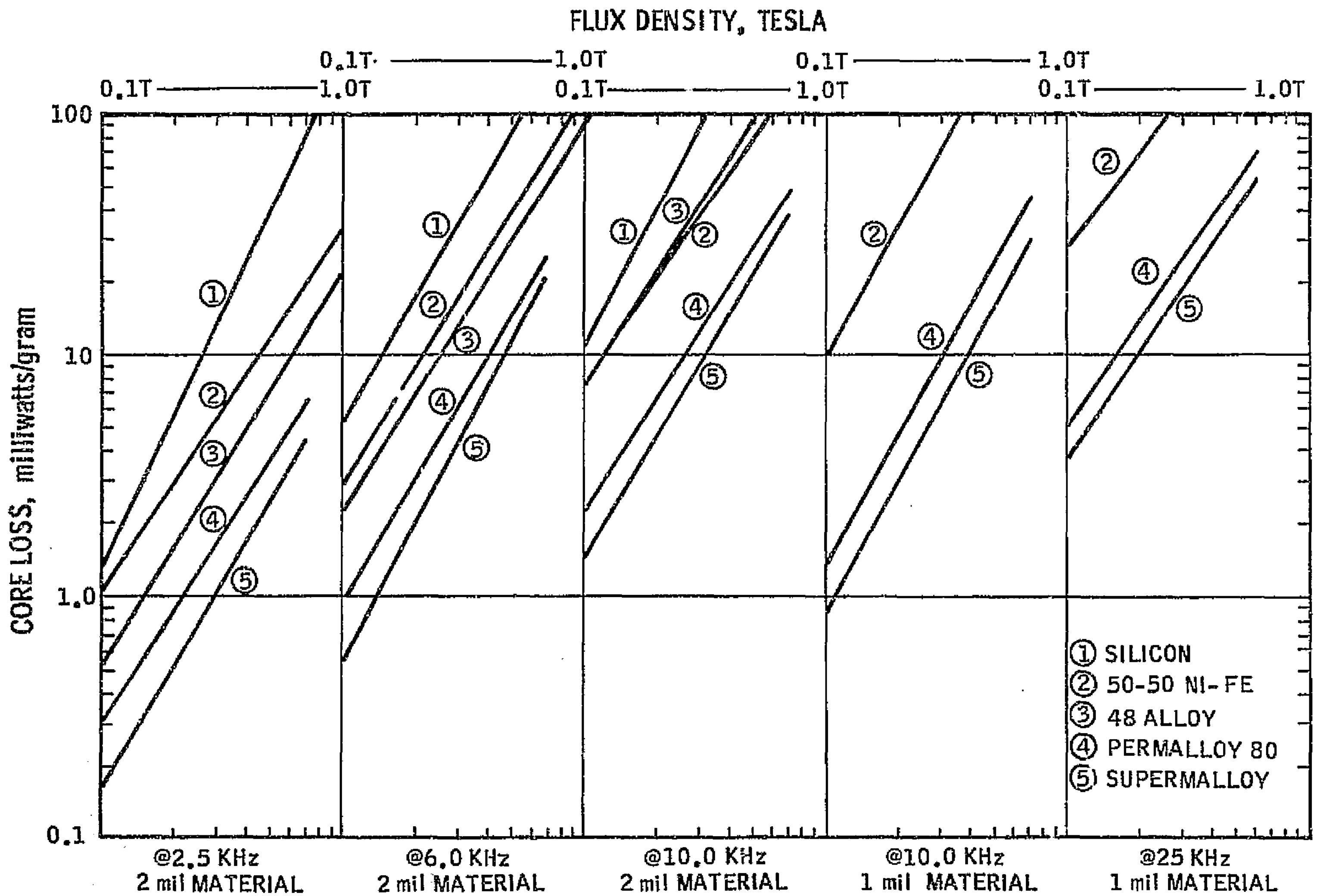


Fig. 6. Magnetic Material Comparison at a Constant Frequency

Referring to column 14, the weight of the core is 46.6 grams. The core loss in milliwatts per gram is obtained from

$$\frac{0.63 \text{ watts}}{46.6 \text{ grams}} = 0.0135 \text{ which converts to}$$

13.5 milliwatts/gram.

The efficiency of various silicon and nickel steels for various high frequencies and flux density is shown in the graphs of Figure 6*. Reading from the 2.5 KHz frequency curve for a flux density of 0.3 tesla, the loss per gram is about 12 milliwatts per gram, which for 46.6 grams is a total core loss of 560 milliwatts which permits use of a silicon steel core material.

Winding Parameters

The power loss in the winding can now be accurately determined. First it is necessary to calculate the number of turns in the primary and secondary. The number of primary turns is calculated from the Faraday law which states:

$$N = \frac{E \times 10^4}{4 B_m A_c f} \tag{8}$$

Inserting values from the data:

$$N = \frac{50 \times 10^4}{(4)(0.3)(0.716)(2500)} = 233 \text{ turn (primary)}$$

*These curves are for sine waves but are substantially the same for square waves.

(The core cross-section value A_c is obtained from Table 1 (pages 11 and 12).)

The secondary turns are calculated from:

$$\frac{\text{Primary turns}}{\text{Voltage}} = \frac{233}{50} = 4.7 \text{ turns per volt}$$

Since the specified load voltage is 10 volts plus two diode drops, $4.7 \times 12 = 57$ turns (secondary).

Current Density and Wire Size

The relationship between the area product A_p and current density is:

$$J = K_j A_p^{-0.14} \tag{9}$$

in which K_j is a constant which has a value of 323 for a 25°C rise and a value of 468 for a 50°C rise. Derivation is shown in Appendix D (page 36).

Inserting values:

$$J = (323)(1.44)^{-0.14} = 307 \text{ amp/cm}^2$$

The primary winding current will be:

$$\frac{\text{input power}}{\text{input voltage}} = \frac{25.2}{50.0} = 0.50 \text{ amp}$$

The wire size for the primary is:

$$\frac{0.50}{307} = 0.00162 \text{ cm}^2$$

From the wire table, page 45, No. 25 wire has a diameter of 0.001623 cm^2 and is therefore suitable.

The wire size for the secondary is:

$$\frac{2.0}{307} = .00651 \text{ cm}^2$$

From the wire table, page 45, No. 19 wire has a diameter of 0.00653 cm^2 and is therefore suitable.

The power loss in the windings then can be calculated. The resistance of a winding is the mean length turn in cm multiplied by the resistance in microhms per cm and the total number of turns, or:

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

For the primary winding:

$$R = 5.5 \times 0.00106 \times 233 = 1.36\,\Omega$$

For the secondary winding:

$$R = 5.5 \times 0.000264 \times 57 = 0.0827\Omega$$

Since power loss is: $P = I^2R$ (11)

Copper loss in the primary is $(0.50)^2 \times 1.36$ or 0.340 watt. In the secondary, the loss is $(2.0)^2 \times 0.0827$ or 0.331. The total loss in the windings is 0.671 watt. Since the power loss in the core is 0.560 watt, the total power loss in the transformer will be 1.23 watts, which will meet the required efficiency parameter.

Another Design Problem As An Example

Assume a specification for a transformer design as shown in Figure 4 in which:

E_o = 56.0 volts after a diode drop 1.0 volt

P_o = 100 watts to the load

E_{IN} = 200 volts

*Operating frequency = 10 KHz (square wave)

Maximum temperature rise = 25°C

**Transformer efficiency = 98%

Because of the diode drop, the actual output power of the transformer is 101.8 watts. Since Figure 4 shows a center tapped secondary, P_t is 20.7% greater than in the first example because of the increased RMS rating as explained in equation (5). Thus

$$P_t = \left(\frac{P_o}{\eta} + P_o\right) \times 1.207$$

Inserting values:

$$P_t = \left(\frac{101.8}{0.98} + 101.8\right) \times 1.207 = 248 \text{ watts}$$

The proper core is obtained from the area product using equation (2).

Inserting values:

$$A_p = \left(\frac{248 \times 10^4}{(4.0)(0.3)(10^4)(0.4)(323)}\right)^{1.14} = 1.71 \text{ cm}^4$$

*For high frequency skin effect, see Appendix J (page 57).
**For transformer regulation as a function of efficiency, see Appendix E (page 39).

After the A_p has been determined, the geometry of the transformer can be evaluated as described in the first example, (page 10), and appropriate changes made, if desired. Having established the configuration, it is then necessary to determine the core material to complete core selection. Material selection requires consideration of efficiency constraint which is 0.98 in the example.

The transformer losses are, from equation (7)

$$P_\Sigma = \frac{P_o}{\eta} - P_o$$

Inserting values:

$$P_\Sigma = \frac{101.8}{0.98} - 101.8 = 2.08 \text{ watts}$$

Again maximum efficiency is realized when the copper (winding) losses are equal to the iron (core) losses which is expressed as:

$$P_{cu} = P_{fe} \quad \text{, and therefore}$$

$$P_{cu} = \frac{P_\Sigma}{2} \quad \text{and thus}$$

$$P_{cu} = 1.04 = P_{fe}$$

Referring to Table 1, column 3 (pages 11 and 12), the AL-8 core with an A_p of 2.31 is closest to the 1.71 cm^4 A_p caluclated above. Referring to column 14, the weight of the core is 66.6 grams. The core loss in milliwatts per gram is obtained from

$$\frac{1.04 \text{ watts}}{66.6 \text{ grams}} = 0.0156 \text{ which converts to}$$

15.6 milliwatts/gram.

Knowing the core loss in milliwatts/grams, the designer refers to the graphs of Figure 6 (page 13). Reading from the curve for the 10 KHz frequency of operation which is specified, it appears that for a flux density of 0.3 tesla, the material that comes closest to 15.6 milliwatts per gram is Permalloy 80 which is approximately 12 milliwatts per gram. When nickel steel is used, Table 12 (page 55) in Appendix I provides a weight correction factor. The weight of 66.6 is increased to 76.5 to give a total core loss of 918 milliwatts.

Winding Parameters

The power loss in the winding can then be determined. First it is necessary to calculate the number of turns in the primary and secondary. The number of primary turns is calculated from the Faraday law equation (8) which states:

$$N = \frac{E \times 10^4}{4B_m A_c f}$$

Inserting values from the data:

$$N = \frac{200 \times 10^4}{(4)(0.3)(0.806)(10^4)} = 207 \text{ turns (primary)}$$

(The core cross-section value A_c is obtained from Table 1, pages 11 and 12).

The secondary turns are calculated from:

$$\frac{\text{primary turns}}{\text{voltage}} = \frac{207}{200} = 1.035 \text{ turns per volt}$$

Since the specified secondary voltage is 57, $1.035 \times 57 = 59$ turns each side of center tap.

Current Density and Wire Size

The relationship between the area product A_p and current density from equation (9) is:

$$J = K_j A_p^{-0.14}$$

in which K_j is a constant which has a value of 323 for a 25°C rise and a value of 468 for a 50°C rise. Derivation is shown in Appendix D (page 36).

Inserting values:

$$J = (323)(2.31)^{-0.14} = 287 \text{ amp/cm}^2$$

the primary winding current will be:

$$\frac{\text{input power}}{\text{input voltage}} = \frac{104}{200} = 0.52 \text{ amp.}$$

The wire size for the primary is:

$$\frac{0.52}{285} = 0.00181 \text{ cm}^2$$

From the wire table, (page 45), No. 25 wire has a diameter of 0.001623 cm^2. The rule is that when the calculated wire size does not fall close to those listed in the table, the next smallest size should be selected.

The wire size for the secondary is:

$$\frac{\text{output current } (0.707)}{287} = \frac{1.79 \times (0.707)}{287} = 0.0044 \text{ cm}^2$$

From the wire table, No. 21 wire has a diameter of 0.00411 cm^2 and is therefore suitable.

The power loss in the winding then can be calculated. From equation (10), (page 16):

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

for the primary winding:

$$R = 5.74 \times 0.001062 \times 207 = 1.26\,\Omega$$

for the secondary winding:

$$R = 5.74 \times 0.000419 \times 59 = 0.142\,\Omega$$

since power loss is:

$$P = I^2R$$

Copper loss in the primary is $(0.52)^2 \times 1.26$ or 0.341 watts. In the secondary, the loss is $(1.79 \times 0.707)^2 \times 0.142 \times 2 = 0.455$ watts. The total loss in the winding is 0.796 watts. Since the power loss in the core is 0.918 watts, the total power loss in the transformer will be 1.714 watts, which will meet the required efficiency parameter.

The author has put in Appendix K the area product A_p relationships between volume, surface area, current density, and weight for pot core, tape wound cores (toroids), power cores, laminations, and C cores. 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.

REFERENCES

1. McLyman, C., "Design Parameters of Toroidal and Bobbin Magnetics. Technical Memorandum 33-651, Pages 12-15 Jet Propulsion Laboratory, Pasadena, Ca.

2. Blume, L. F., Transformer Engineering, John Wiley & Sons's, Inc., New York, N.Y. 1938. Pages 272-282

3. Terman, F. E., Radio Engineers Handbook, McGraw-Hill Book Co., Inc., New York 1943. Pages 28-37

APPENDIX A

TRANSFORMER POWER HANDLING CAPABILITY

The power handling capability of a transformer can be related to its A_p quantity (which is actually its W_aA_c product where W_a is the available core window area in cm^2 and A_c is the effective cross-sectional area of the core in cm^2), as follows.

A form of the Faraday law of electromagnetic induction much used by transformer designers states:

$$E = K\, B_m\, A_c\, N\, f \times 10^{-4} \tag{A1}$$

(The constant K is taken at 4 for square wave and at 4.44 for sine wave operation.)

It is convenient to restate this expression as:

$$N\, A_c = \frac{E \times 10^4}{4\, B_m\, f} \tag{A2}$$

for the following manipulation.

By definition the window utilization factor is:

$$K_u = \frac{N\, A_w}{W_a} \tag{A3}$$

and this may be restated as:

$$N = \frac{K_u\, W_a}{A_w} \tag{A4}$$

If both sides of the equation are multiplied by A_c, then:

$$N A_c = \frac{K_u W_a A_c}{A_w} \qquad \text{(A5)}$$

From equation (A2):

$$\frac{K_u W_a A_c}{A_w} = \frac{E \times 10^4}{4 B_m f} \qquad \text{(A6)}$$

Solving for $W_a A_c$:

$$W_a A_c = \frac{E A_w \times 10^4}{4 B_m f K_u} \qquad \text{(A7)}$$

By definition, current density J = amp/cm^2 which may also be stated:

$$J = \frac{I}{A_w} \qquad \text{(A8)}$$

which may also be stated as:

$$A_w = \frac{I}{J} \qquad \text{(A9)}$$

It will be remembered that transformer efficiency is defined as:

$$\eta = \frac{P_o}{P_{in}} \quad \text{and} \quad P_{in} = E I \qquad \text{(A10)}$$

Rewriting equation (A7) as:

$$EA_w = 4B_{mf} K_u W_a A_c 10^{-4} = \frac{EI}{J} \qquad \text{(A11)}$$

and since:

$$\frac{EI}{J} = \frac{P_{in}}{J} = \frac{P_o}{J\eta} \tag{A12}$$

then:

$$W_aA_c\Big|_{total} = W_aA_c\Big|_{Primary} + W_aA_c\Big|_{Secondary}$$

$$W_aA_c\Big|_{total} = \frac{P_o \times 10^4}{J\, 4B_m f K_u} + \frac{P_o \times 10^4}{4B_m f K_u J} = \frac{P_o \times 10^4}{4B_m f K_u J}(1/\eta + 1) \tag{A13}$$

and since

$$P_t = \frac{P_o}{\eta} + P_o \tag{A14}$$

then

$$W_aA_c = \frac{P_t \times 10^4}{4B_m f K_u J} \tag{A15}$$

which may also be stated as applied in Appendix D (page 36) Transformer Current Density as:

$$A_p = \frac{P_t \times 10^4}{4\, B_m\, f\, J\, K_u} \tag{A16}$$

APPENDIX B

TRANSFORMER EFFICIENCY

The efficiency rating of a transformer is a measure of the effectiveness of the design. Efficiency is defined as the ratio of the output power P_o to the input power P_{in}. The difference between the P_o and the P_{in} is due to losses. The total power loss in a transformer is made up of fixed losses in the core and quadratic losses in the windings or copper. Thus

$$P_{\Sigma} = P_{fe} + P_{cu} \tag{B1}$$

where P_{fe} represents the core loss and P_{cu} represents the copper loss.

Maximum efficiency is achieved when the fixed loss is equal to the quadratic loss as shown by the equations on page 28. Transformer loss versus output load current is shown in Figure B1, below.

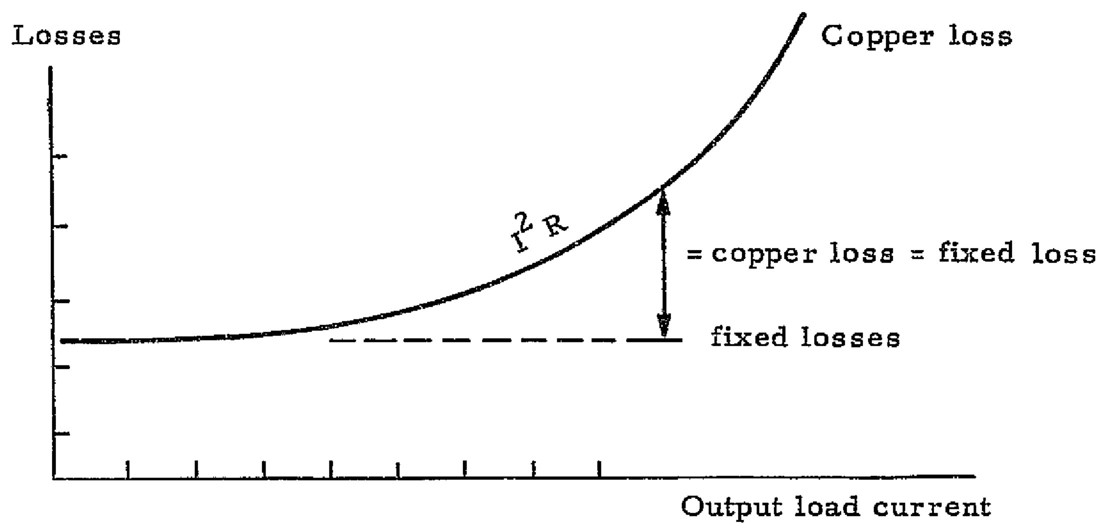


Fig. B1. Transformer Loss Versus Output Load Current

The copper loss increases as the square of the output power multiplied by a constant K which is thus:

$$P_{cu} = KP_o^2 \tag{B2}$$

which may be rewritten as

$$P_{\Sigma} = P_{fe} + K\,P_o^2 \tag{B3}$$

Since

$$P_{in} = P_o + P_{\Sigma} \quad ,$$

and the efficiency is

$$\eta = \frac{P_o}{P_o + P_{\Sigma}}$$

then:

$$\eta = \frac{P_o}{P_o + P_{fe} + KP_o^2} = \frac{P_o}{P_{fe} + P_o + KP_o^2}$$

and, differentiating with respect to P_o:

$$\frac{d\eta}{dP_o} = -P_o\left[P_{fe} + P_o + KP_o^2\right]^{-2} (1 + 2\,KP_o)$$

$$+ \left[P_{fe} + P_o + KP_o^2\right] = 0 \text{ for max } \eta$$

$$-P_o(1 + 2\,KP_o) + \left(P_{fe} + P_o + KP_o^2\right) = 0$$

$$-P_o - 2KP_o^2 + P_{fe} + P_o + KP_o^2 = 0$$

$$\therefore\; P_{fe} = KP_o^2 = P_{cu} \tag{B4}$$

APPENDIX C

RELATIONSHIP OF A_p TO CONTROL OF TEMPERATURE RISE

Temperature Rise

Not all of the P_{in} input power to the transformer is delivered to the load as the P_o. Some of the input power is converted to heat by hysteresis and eddy currents induced in the core material, and by the resistance of the windings. The first is a fixed loss arising from core excitation and is termed "core loss." The second is a variable loss in the windings which is related to the current demand of the load and thus varies as I^2R. This is termed the quadratic or copper loss.

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 transformer by a combination of radiation and convection, and thus is dependent upon the total exposed surface area of the core and windings.

Ideally, maximum efficiency is achieved when the fixed and quadratic losses are equal. Thus:

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

and

$$P_{cu} = \frac{P_{\Sigma}}{2} \tag{C2}$$

When the copper loss in the primary winding is equal to the copper loss in the secondary, the current density in the primary is the same as the current density in the secondary:

$$\frac{P_p}{R_p} = \frac{P_s}{R_s} \tag{C3}$$

and

$$\frac{P_\Sigma}{R_t} = \frac{2P_p}{R_p/2} = \frac{4P_p}{R_p} = (2I_p)^2 \qquad \text{(C4)}$$

then:

$$J_p = \frac{I_p}{W_a/2} = \frac{2I_p}{W_a} = J_s = J \qquad \text{(C5)}$$

Calculation of Temperature Rise

Temperature rise in a transformer 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:

$$P_\Sigma = P_{fe} + P_{cu} \qquad \text{(C6)}$$

and the assumption that thermal energy is dissipated throughout the surface area of the core and winding assembly.

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:

$$W_r = K\epsilon\,(T2^4 - T1^4) \qquad \text{(C7)}$$

in which

W_r = watts per square inch of surface

$K = 3.68 \times 10^{-11}$

*Reference No. 2

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:

$$W_c = KF\theta^{\eta}\sqrt{p} \tag{C8}$$

in which:

W_c = watts loss per square inch

K = 1.4×10^{-3}

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

θ = temperature rise, degrees C

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),

$$W = 3.68 \times 10^{-11}\ \epsilon(T2^4 - T1^4) + 1.4 \times 10^{-3}\ F\theta^{1.25}\sqrt{p} \tag{C9}$$

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 C1 below. It is based on equation (C9)

*Reference No. 2

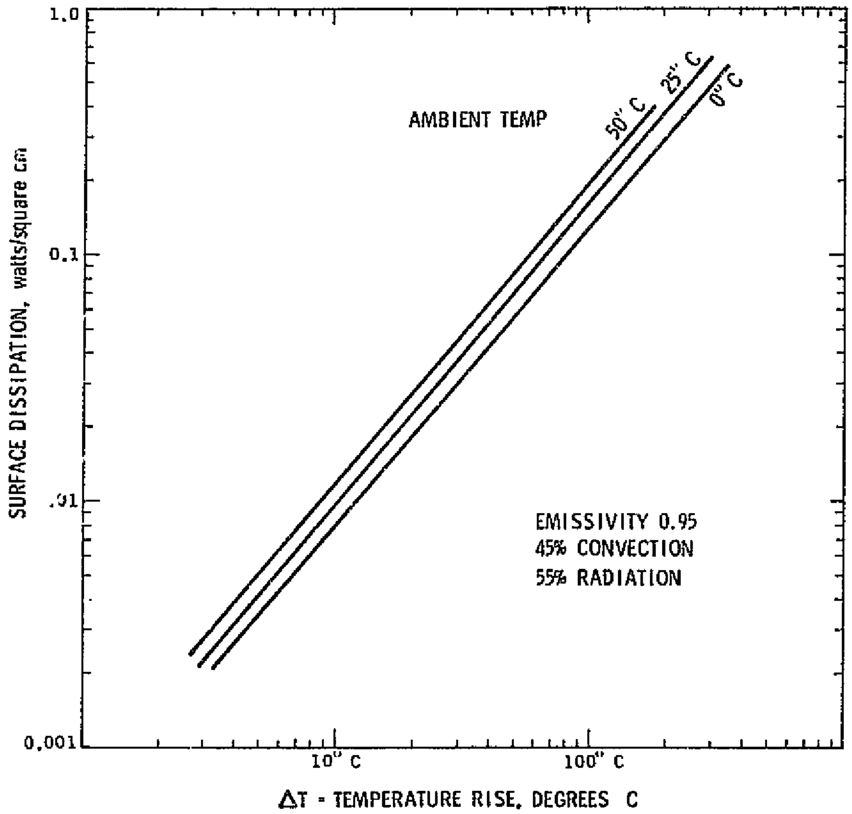


Fig. C1. Temperature Rise Versus Surface Dissipation

relying on data obtained from Reference 2 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:

$$A_t = \frac{P_\Sigma}{\Psi} \tag{C10}$$

in which Ψ is the power density or the average power lost per unit area of the heat dissipating surface of the transformer and P_{Σ} is the total power lost or dissipated.

Surface area A_t of a transformer can be related to the area product A_p of a C-core transformer. The straightline logarithmic relationship shown in Figure C2 below, has been plotted from the data shown in Table 1 (pages 11 and 12).

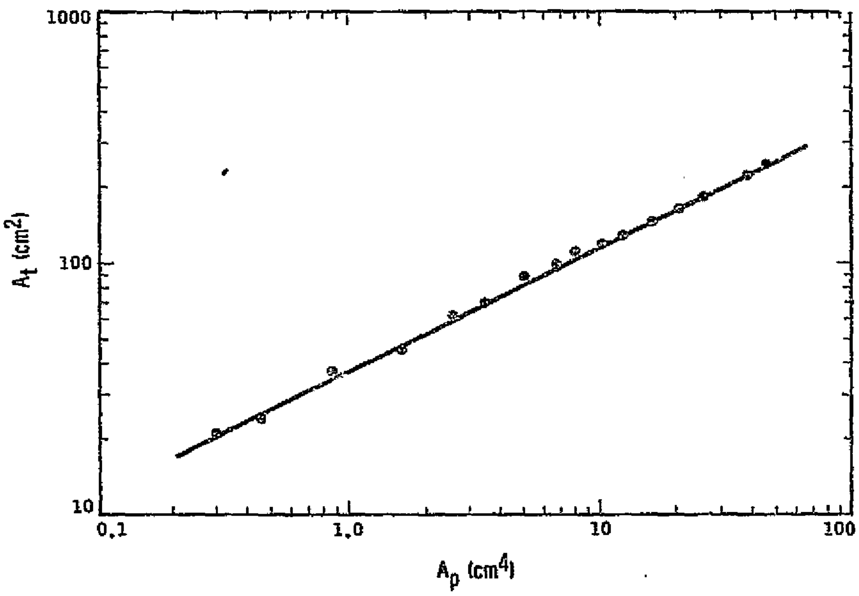
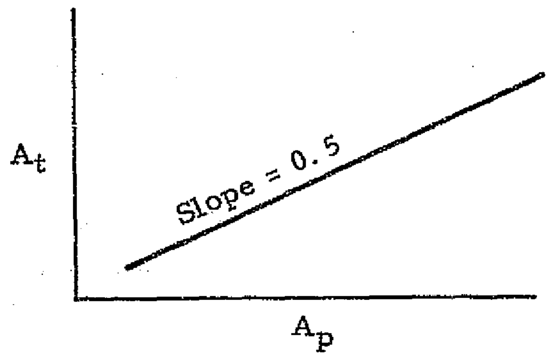


Fig. C2. Surface Area Versus Area Product A_p

The relationship is obtained from the conventional slope relationship:

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

according to:



in which the subscripts denote the extremes of the values in each column.

From this it appears that:

$$A_t = K_s(A_p)^{0.5} = \frac{P_\Sigma}{\Psi} \tag{C11}$$

and that (from Fig. C1)

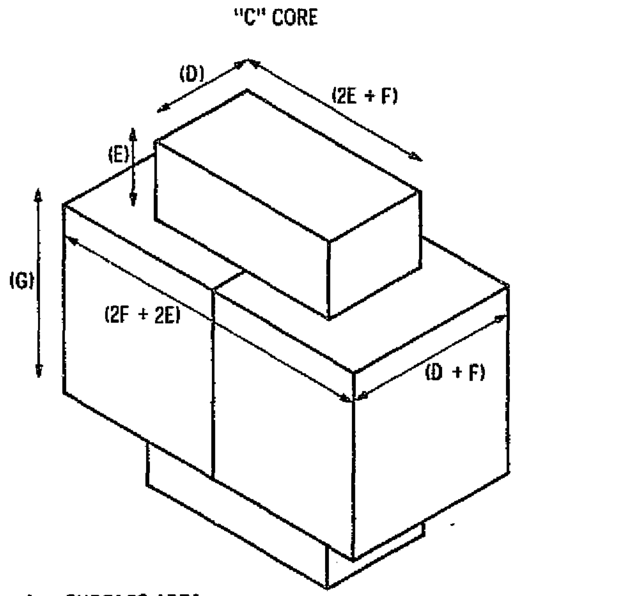
$$\Psi = 0.03 \text{ W/cm}^2 \text{ @ } 25°\text{C rise}$$

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

in which the constant K_s has been derived empirically by averaging the data presented in Table 1 (pages 11 and 12) columns 2 and 3. Column 3 was increased to account for the gross area of the iron and K_s therefore is 39.2.

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

Table 1 (pages 11 and 12) 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 Figures C3 and C4 below, which derive from the geometry of the core and windings of C-type core transformers as fabricated to industry standards.



A_t = SURFACE AREA

$A_t = 4E\ (2E+F) + (ED)\ 4 + 2\ (D+F)\ (G) + 2\ (2F+2E)\ (G) + 2\ (D+F)\ (2F+2E)$

Fig. C3. Surface Area Calculation

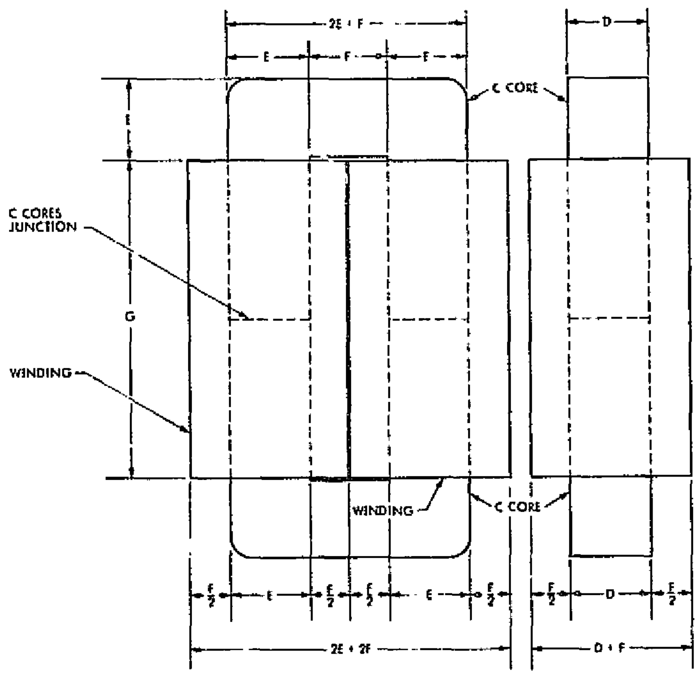


Fig. C4. Industrial Description

APPENDIX D

TRANSFORMER CURRENT DENSITY

Current density J of a transformer can be related to the surface area A_t of a C-core transformer for a given temperature rise. The straightline logarithmic relationship shown in Figure D1 below, has been plotted from the data shown in Table 1 (pages 11 and 12).

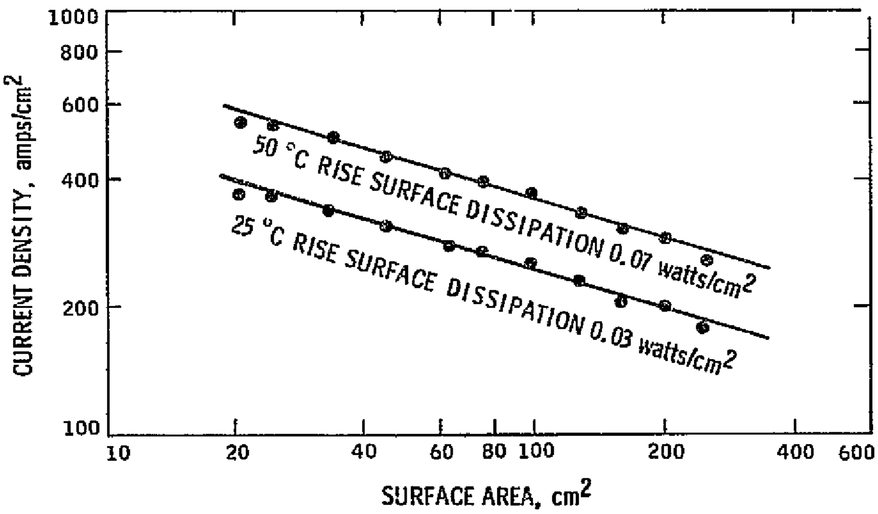
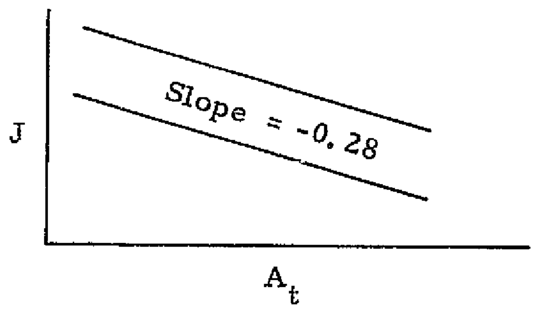


Fig. D1. Current Density Versus Surface Area for a 25°C and 50°C Rise

The relationship is obtained from the conventional slope relationship:

$$\text{Slope} = \frac{\text{Log } J_1/J_2}{\text{Log } A_t^1/A_t^2}$$

according to:



The relationship is:

$$J = K_l A_t^{-0.28} \tag{D1}$$

in which K_l is a constant which is calculated to be 776 for a 25°C temperature rise and 1120 for a 50° temperature rise.

The relationship of current density J to the area product A_p for a given temperature rise can be derived as follows.

The surface area A_t relation to the area product A_p derived in equation C11 of Appendic C, states:

$$A_t = K_s (A_p)^{0.5} \tag{D2}$$

Combining the equations D1 and D2

$$A_t^{-0.28} = \frac{J}{K_l} = (K_s A_p^{0.5})^{-0.28}$$

$$J = K_l (K_s A_p^{0.5})^{-0.28}$$

$$J = K_l K_s^{-0.28} A_p^{-0.14}$$

$$K_j = K_l (K_s)^{(-0.28)}$$

$$J = K_j A_p^{-0.14} \tag{D3}$$

where:

K_j for 25°C rise is 323 and K_j for 50° rise is 468 from the data of Table 1 (pages 11 and 12) in columns 3 and 6 and 3 and 10. This expression may now be inserted in equation (A16) from Appendix A which is:

$$A_p = \frac{P_t \times 10^4}{4 B_m f J K_u}$$

yielding:

$$A_p = \frac{P_t \times 10^4}{4 B_m f K_u \left(K_j A_P^{-0.14}\right)}$$

$$A_p^{0.86} = \frac{P_t \times 10^4}{4 B_m f K_u K_j}$$

$$A_p = \left(\frac{P_t \times 10^4}{4 B_m f K_u K_j}\right)^{1.16} \qquad \text{(D4)}$$

Figure D2 utilizes the efficiency rating in watts loss in terms of two different, but commonly used allowable temperature rises for the transformer over ambient temperature. The data presented are used as bases for indicating the needed transformer surface area A_t (in cm^2).

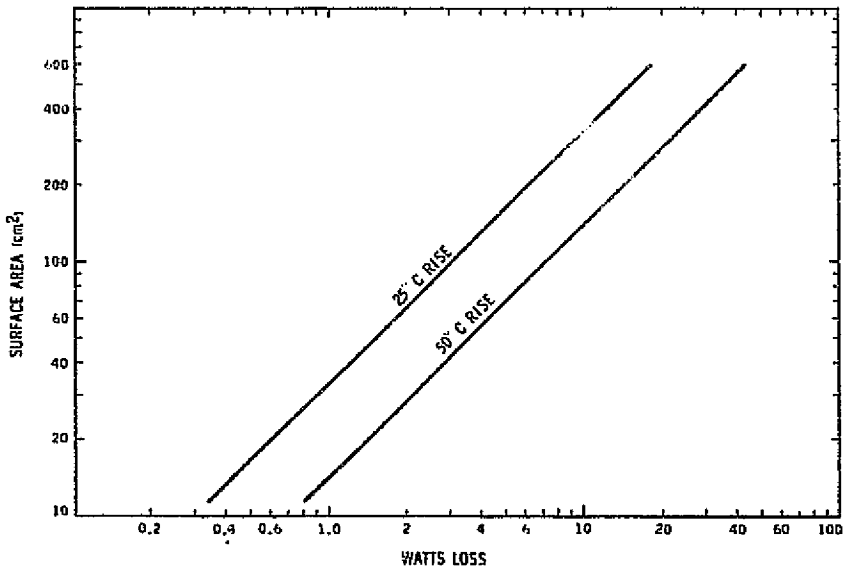


Fig. D2. Surface Area Versus Total Watt Loss for a 25°C and 50°C Rise

APPENDIX E

REGULATION AS A FUNCTION OF EFFICIENCY

The size of a transformer usually is determined either by a temperature rise limit, or by allowable voltage regulation, assuming that size and weight are to be minimized.

Figure E1 below shows circuit diagram of a transformer with one secondary.

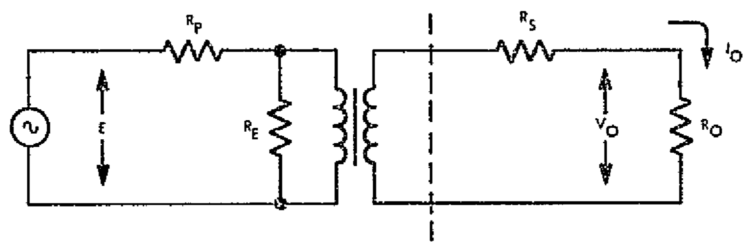


Fig. E1. Transformer Circuit Diagram

The analytical equivalent is shown in Figure E2.

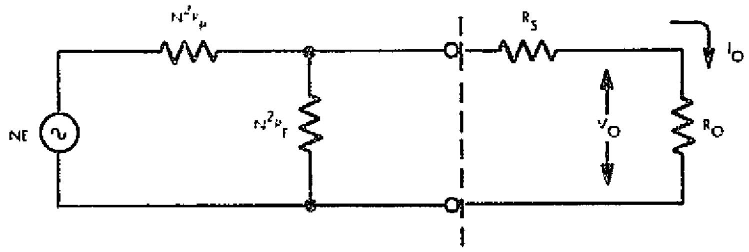


Fig. E2. Transformer Analytical Equivalent

This assumes that distributed capacitance in the secondary can be neglected because the secondary voltage is not excessive. Also the winding geometry is designed to limit the leakage inductance to a level low enough to be neglected under most operating conditions.

Transformer voltage regulation can be expressed as:

$$\mathrm{Reg}\ (\%) = \frac{V_o\ (\mathrm{N.\,L.}) - V_o\ (\mathrm{F.\,L.})}{V_o\ (\mathrm{N.\,L.})} \times 100 \qquad \text{(E1)}$$

in which V_o (N. L.) is the no load voltage and V_o (F. L.) is the full load voltage.

The output voltage computed using Figure E1 is:

$$V_o = \frac{R_o}{R_o + R_s} \; \frac{(N^2R_p) \parallel (N^2R_E) \parallel (R_o + R_s)}{N^2R_p} \; NE \qquad \text{(E2)}$$

For the usual condition of

$$N^2R_E \gg N^2R_p \parallel (R_o + R_s),$$

V_o simplifies to

$$V_o = V_o(\mathrm{F.\,L.}) = \frac{R_o}{R_o + (N^2R_p + R_s)} \; NE \qquad \text{(E3)}$$

For equal window areas allocated for the primary and secondary windings, it can be shown that $N^2R_p = R_s$.

For simplicity

Let $$R_{cu} \equiv N^2R_p + R_s = 2R_s$$

At no load (N. L.) R_o approaches infinity, therefore:

$$V_o\ (\mathrm{N.\,L.}) = NE \qquad \text{(E4)}$$

$$\text{Reg}\ (\%) = \frac{NE - \dfrac{R_o}{R_o + R_{cu}}\, NE}{NE} \times 100 \tag{E5}$$

$$= \left(1 - \frac{R_o}{R_o + R_{cu}}\right) \times 100 \tag{E6}$$

$$= \frac{R_{cu}}{R_o + R_{cu}} \times 100 \tag{E7}$$

Thus it appears that regulation is independent of the transformer turns ratio.

Regulation as a function of copper loss, multiply the equation E7 by I_o^2

$$\text{Reg}\ (\%) = \frac{I_o^2\, R_{cu}}{I_o^2\, (R_o + R_{cu})} \times 100 \tag{E8}$$

then

$$\text{Reg}\ (\%) = \frac{P_{cu}}{P_o + P_{cu}} \times 100 \tag{E9}$$

$$P_{in} = P_{cu} + P_{fe} + P_o \tag{E10}$$

Regulation as a function of efficiency

$$\frac{P_o}{P_{in}} = \frac{P_o}{P_{cu} + P_{fe} + P_o} = \eta \tag{E11}$$

By definition

$$P_{cu} = P_{fe}$$

Solving for $P_{cu} + P_{fe}$

$$\frac{P_o(1-\eta)}{\eta} = P_o\left(\frac{1}{\eta} - 1\right) = P_{cu} + P_{fe} = 2\,P_{cu} \tag{E12}$$

$$\frac{\text{Reg }(\%)}{100} = \frac{1}{1 + \frac{P_o}{P_{cu}}} = \frac{1}{1 + \frac{2}{1/\eta - 1}} = \frac{1-\eta}{1+\eta} \tag{E13}$$

$$\text{Reg }(\%) = \frac{1-\eta}{1+\eta} \times 100 \tag{E14}$$

Efficiency as a function of regulation, multiply both sides of the equation by $(1+\eta)$:

$$\text{Reg }(\%) + \eta\,\text{Reg }(\%) = 100 - \eta 100 \tag{E15}$$

solve for η

$$\eta\,100 + \eta\,\text{Reg }(\%) = 100 - \text{Reg }(\%) \tag{E16}$$

$$\eta\,(100 + \text{Reg }(\%) = 100 - \text{Reg }(\%) \tag{E17}$$

$$\eta = \frac{100 - \text{Reg }(\%)}{100 + \text{Reg }(\%)} \tag{E18}$$

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

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

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

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

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

in which

conductor area = copper area

wire area = copper area + insulation area

wound area = number of turns x wire area of one turn

usable window are = 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, page 44 may be used for calculating some typical values such as for AWG 10, AWG 20, AWG 30 and AWG 40.

Table F1. Wire Table

Awg Wire Size	Bare Area		Resistance	Heavy Synthetics								
	cm^{2}10^{-3} (footnote b)	CIR-MIL[a]	$\frac{10^{-6}\,\Omega}{\text{cm at }20°\text{C}}$	Area		Diameter		Turns-Per		Turns-Per		Weight
				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	4.16	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. 1).

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

TEMPERATURE CORRECTION FACTORS

The values shown in Fig. 1 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) x ζ

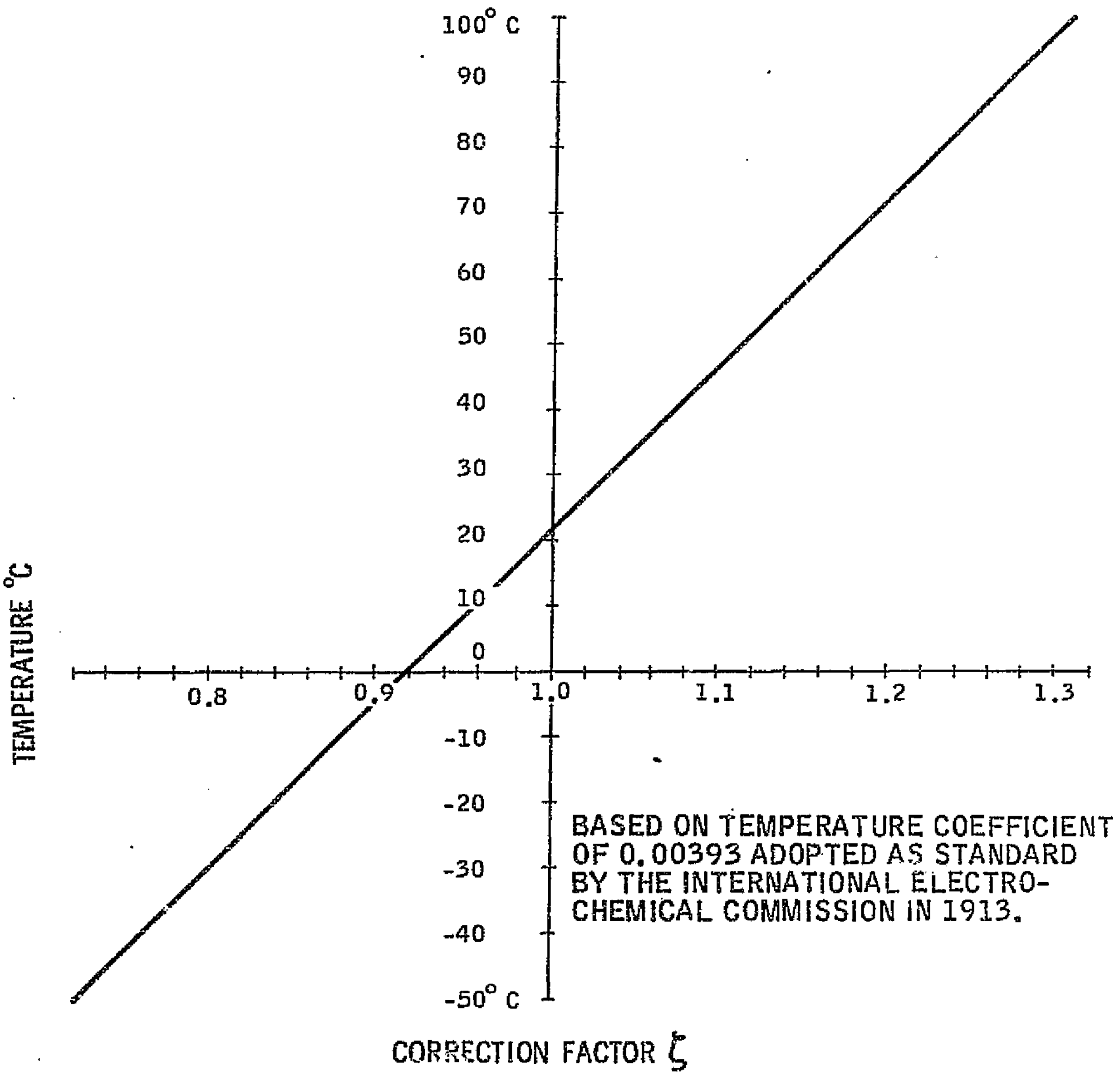


Fig. F1. Resistance Correction Factor (ζ, Zeta) for wire temperature between -50° and 100°C

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

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

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

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

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

Thus:

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

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

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

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

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 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, $S_1 \times S_2 \times S_3 \times S_4 = 0.855 \times 0.060 \times 0.75 \times 1.0 = 0.385$, which is very close to 0.4.

This may be stated somewhat differently as:

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

APPENDIX G

TRANSFORMER WEIGHT

The total weight W_t of a transformer can be related to the area product A_p. The straightline logarithmic relationship shown in Figure G1 below, has been calculated from the data shown in Table 1 (pages 11 and 12).

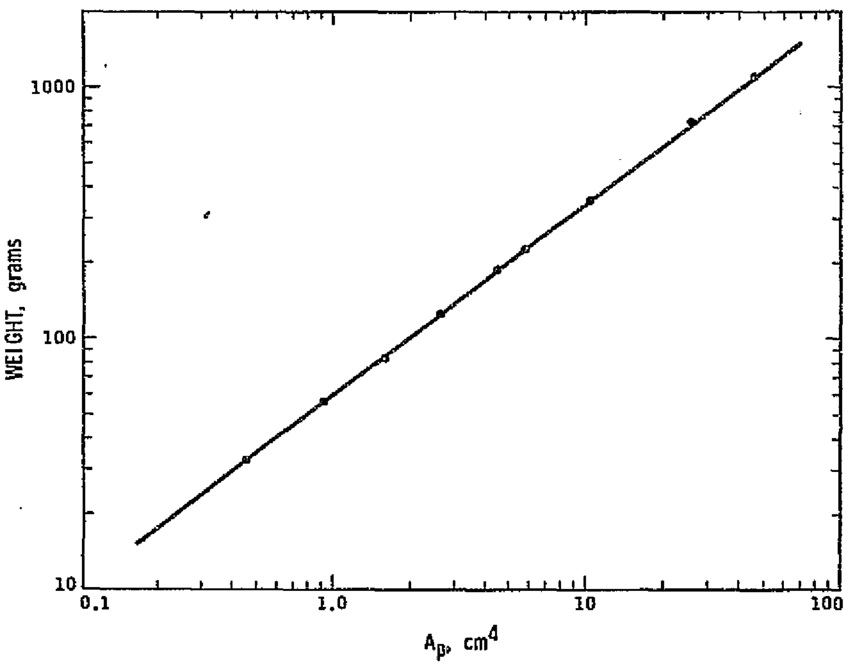


Fig. G1. Transformer Total W_t Versus Area Product A_p

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 and 15 for weight, and column 3 for area product.

The relationship is:

$$W_t = K_w A_p^{0.75} \tag{G1}$$

in which the constant K_w has been derived empirically by averaging the data presented in columns 3, 14 and 15 of Table 1 (pages 11 and 12) and is 66.6.

Table I2 (page 55) shows how weight varies as a function of selected different magnetic materials used for transformer C-cores. Magnetic materials for C-cores are discussed in Appendix I (page 54).

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:

$$W_t = K_1 \ell^3 \tag{G2}$$

$$A_p = K_2 \ell^4 \tag{G3}$$

$$\ell^4 = \frac{A_p}{K_2} \tag{G4}$$

$$\ell = \left(\frac{A_p}{K_2}\right)^{0.25} \tag{G5}$$

$$\ell^3 = \left[\left(\frac{A_p}{K_2}\right)^{0.25}\right]^3 = \left(\frac{A_p}{K_2}\right)^{0.75} \quad \text{(G6)}$$

$$W_t = K_1\left(\frac{A_p}{K_2}\right)^{0.75} \quad \text{(G7)}$$

$$K_w = \frac{K_1}{K_2^{0.75}} \quad \text{(G8)}$$

$$W_t = K_w A_p^{0.75} \quad \text{(G9)}$$

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

APPENDIX H

TRANSFORMER VOLUME

The volume of a transformer can be related to the area product A_p of a C-core transformer, treating the volume as shown in Figure H1 below as a solid cube quantity without subtraction of anything for the core window.

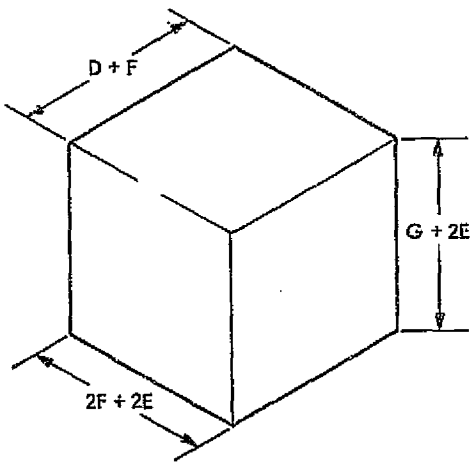


Fig. H1. C-Core Volume

The straight-line logarithmic relationship plotted in Figure H2 below, has been calculated from data in Table 1, using the data shown in Figure H1 above.

The relationship is obtained from the conventional slope relationship:

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

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:

$$\text{Vol.} = K_v A_p^{0.75} \qquad \text{(H1)}$$

in which K_v is a constant related to core configuration. It is 17.9 for a C-core, which has been derived by averaging the values in Table 1.

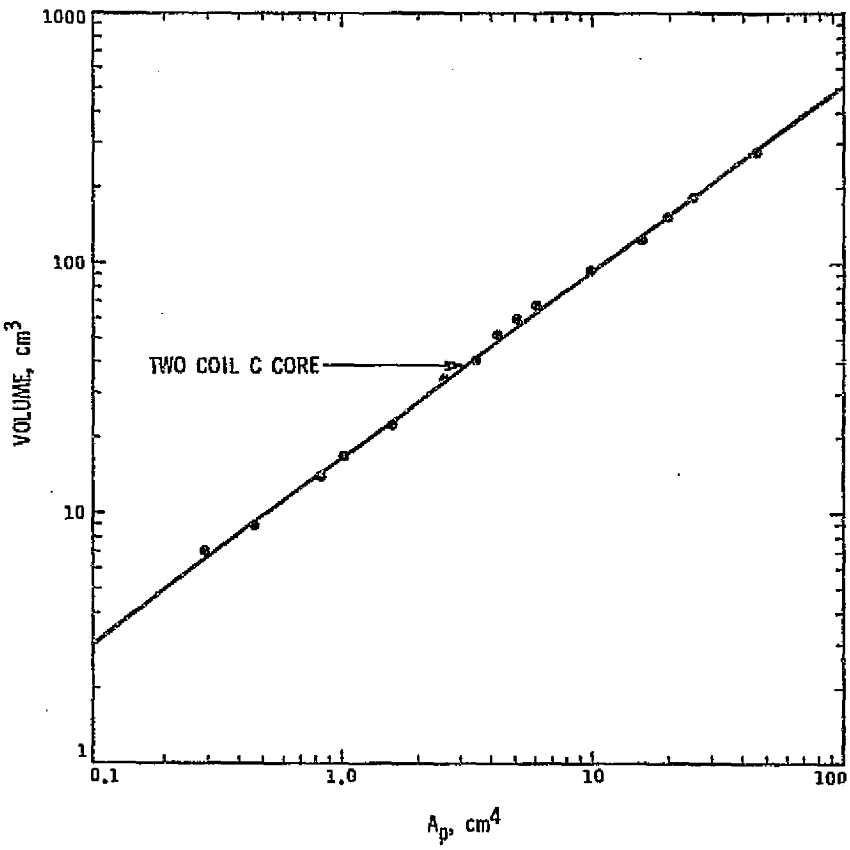


Fig. H2. Transformer Volume Versus Area Product A_p

APPENDIX I

MAGNETIC CORE MATERIAL TRADEOFF

The relationships between area product A_p and certain parameters are associated only with such geometric properties as surface area and volume, weight, and the factors affecting temperature rise such as current density. A_p has no relevance to the magnetic core materials used, but since the designer often must make tradeoffs between such goals as efficiency and size which are influenced by core material selection, some useful data is presented below.

In the many articles written about inverter and converter transformer design, recommendations with respect to choice of core material usually are a compromise selection of material characteristics such as those tabulated in Table I1, and graphically displayed in Figure I1. The selected data are typical of commercially available core materials suitable for the mentioned applications.

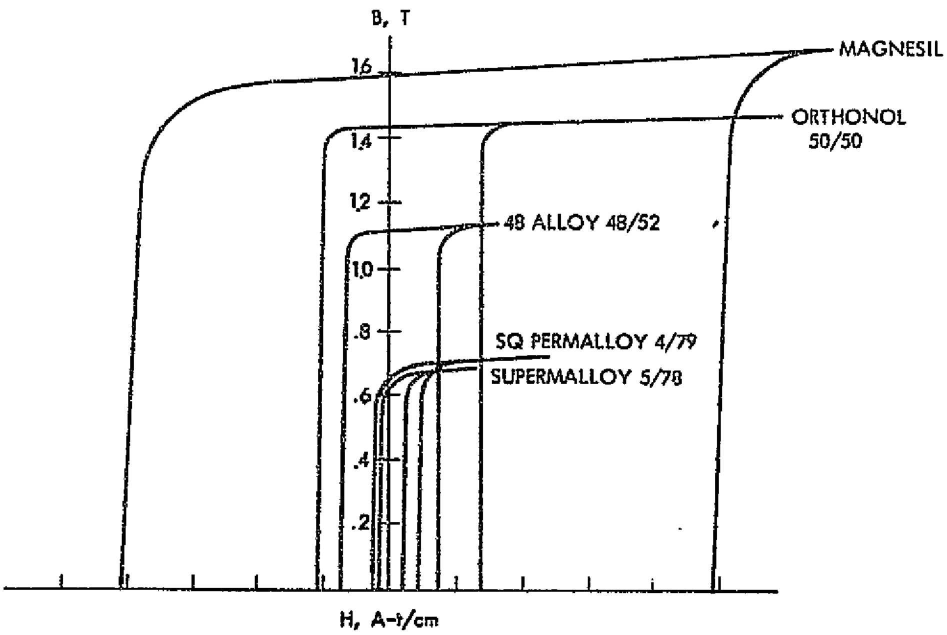


Fig. I1. The Typical d.c. B-H Loops of Magnetic Material

Table I1. Magnetic core material characteristics

Trade names	Composition	Saturated flux density, T[1]	DC coercive force, amp-turn/cm	Squareness ratio	Material density, g/cm^3	Loss factor at 3 kHz and 0.5 T, W/kg
Magnesil Silectron Microsil Supersil	3% Si 97% Fe	1.5-1.8	0.5-0.75	0.85-1.0	7.63	33.1
Deltamax Orthonol 49 Sq. Mu	50% Ni 50% Fe	1.4-1.6	0.125-0.25	0.94-1.0	8.24	17.66
Allegheny 4750 48 Alloy Carpenter 49	48% Ni 52% Fe	1.15-1.4	0.062-0.187	0.80-0.92	8.19	11.03
4-79 Permalloy Sq. Permalloy 80 Sq. Mu 79	79% Ni 17% Fe 4% Mo	0.66-0.82	0.025-0.05	0.80-1.0	8.73	5.51
Supermalloy	78% Ni 17% Fe 5% Mo	0.65-0.82	0.0037-0.01	0.40-0.70	8.76	3.75

[1] 1 T = 10^4 G

[2] 1 g/cm^3 = 0.036 lb/in.^{3}

Table I2. Core material characteristics

Material	Density	Factor*
Magnesil	7.63	1.000
Supermender	8.15	1.066
48 Alloy	8.19	1.073
Orthonol	8.24	1.079
Sq Permalloy	8.73	1.144
Supermalloy	8.77	1.148

*Weight factor.

As can be seen, the material which provides the highest flux density, silicon, produces the smallest component size. If size is the most important consideration, this would determine the choice of materials. On the other hand, the type 78 SUPERMALLOY material (see the 5/78 curve in Figure 11), has the lowest flux density and this material would result in the largest size transformer. However, this material has the lowest coercive force and lowest core loss of any of the available materials. These factors might well be decisive in other applications.

Inverter transformer design usually is aimed at achieving the smallest size with the highest efficiency, and with adequate performance for the widest range of environmental conditions. Unfortunately, the material which produces the smallest size has the lowest efficiency, and conversely, the highest efficiency materials result in the largest size. Thus tradeoffs must be made between the allowable transformer size and the minimum tolerable efficiency. Choice of core material is thus based upon achieving the best characteristic for the most critical or important design parameter, with acceptable compromises on all other parameters.

Fortunately, there is such a wide choice of core sizes available (Table 1, pages 11 and 12, lists only 20 out of more than 200 commercially available), that relative proportions of iron and copper can be varied without changing the A_p area product.*

*However, at frequencies above about 20 kHz, eddy current losses are so much greater than hysteresis losses that it is necessary to use very thin (1 and 2 mil) strip cores.

APPENDIX J

SKIN EFFECT

Skin Effect

It is now common practice to operate dc-to-dc converters at frequencies up to 50 kHz. At higher frequencies, skin effect alters the predicted efficiency since the current carried by a conductor is distributed uniformly across the conductor cross-section only at dc and at low frequencies. The concentration of current near the wire surface at higher frequencies is termed the skin effect. This is the result of magnetic flux lines which circle only part of the conductor. Those portions of the cross section which are circled by the largest number of flux lines exhibit greater reactance.

Skin effect accounts for the fact that the effective alternating current resistance to direct current ratio is greater than unity*. The magnitudes of the effects due to increased frequency on conductivity, magnetic permeability and inductance are sufficient to require further consideration of the size of the conductor. The depth of the skin effect is expressed by:

$$\text{depth (cm)} = 6.61/f^{1/2}) \, K \qquad \text{(J1)}$$

in which K is a constant according to the relationship:

$$K = [(1/\mu r) \, \rho/\rho c]^{1/2} \qquad \text{(J2)}$$

in which:

μr = relative permeability of conductor material ($\mu r = 1$ for copper and other nonmagnetic materials)

ρ = resistivity of conductor material at any temperature

ρc = resistivity of copper at 20°C = 1.724 microhm-centimeter

K = unity for copper

*Reference 3.

Figures J1 and J2 below show respectively, skin depth as a function of frequency according to equation (J2) above, and as related to the AWG radius, or as $R_{ac}/R_{dc} = 1$ versus frequency.*

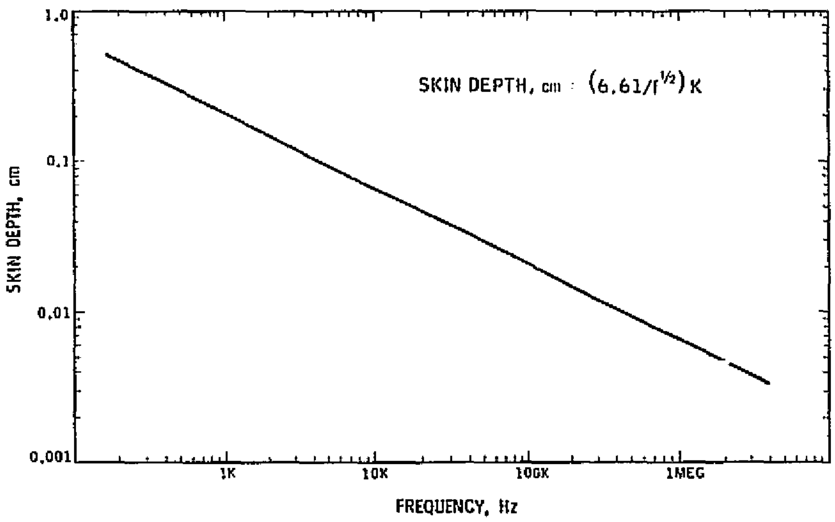


Fig. J1. Skin Depth Versus Frequency

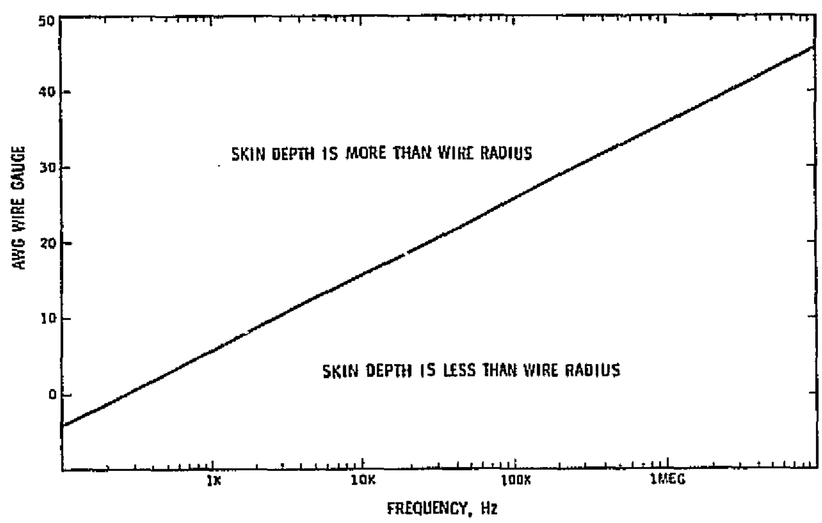


Fig. J2. Skin Depth Equal to AWG Radius Versus Frequency

*The data presented is for sine wave excitation. The author could not find any data for square wave excitation.

APPENDIX K

AREA PRODUCT A_p RELATIONSHIP

There is a unique relationship between the "Area Product", A_p characteristic number for transformer cores and several other important parameters which must be considered in transformer design.

The power handling capability of a transformer can be related to its A_p quantity (which is actually its $W_a A_c$ product where W_a is the available core window area in cm^2 and A_c is the effective cross-sectional area of the core in cm^2).

These relationships can now be used as new tools to simplify and standardize the process of transformer design. They make it possible to design transformers of smaller bulk and volume or to optimize efficiency.

Table K1 was developed using the least-squares curve fit from the data obtained in Tables K2 through K6. The area product A_p relationships with volume, surface area, current density, and weight for tape wound cores, C type core, powder cores, laminations and pot core are found in Figures K1 through K20.

Table K1. Transformer Configuration Constants

	K_j 25°C	K_j 50°C	η	K_s	K_w	K_v
Pot cores	433	632	-0.17	33.8	48.0	14.5
Powder cores	290	423	-0.12	32.5	58.8	13.1
Lamination	366	534	-0.12	41.3	68.2	19.7
C type cores	323	468	-0.14	39.2	66.6	17.9
Tape wound cores	250	365	-0.13	50.9	82.3	25.0

$$J = K_j A_p^{(\eta)} \qquad A_t = K_s A_p^{0.50}$$

$$W_t = K_w A_p^{0.75} \qquad Vol = K_v A_p^{0.75}$$

Table K2. Powder Cores 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	$I = \sqrt{\frac{W}{\Omega}}$	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	55051	7.19	0.0437	2.12	86 25	0.215	0.216	0.706	435	0.236	0.503	1.03	635	5.81	1.39	0.113
2	55121	12.3	0.137	2.71	160 25	0.513	0.369	0.599	369	0.563	0.861	0.874	538	13.3	3.11	0.196
3	55848	17.3	0.259	2.95	257 25	0.897	0.519	0.537	344	0.985	1.211	0.783	502	21.3	5.07	0.232
4	55059	21.9	0.466	3.39	316 25	1.27	0.657	0.508	314	1.39	1.533	0.742	458	32.3	7.28	0.327
5	55894	30.8	1.021	4.51	351 25	1.87	0.924	0.496	306	2.06	2.16	0.724	447	59.4	12.4	0.639
6	55586	48.6	1.821	4.39	902 25	4.69	1.46	0.394	244	5.15	3.40	0.574	355	94.9	23.3	0.458
7	55071	44.7	1.966	4.77	656 25	3.70	1.34	0.425	263	4.07	3.13	0.620	383	94.4	21.0	0.666
8	55076	51.6	2.46	4.88	815 25	4.71	1.55	0.405	250	5.17	3.61	0.590	365	113.0	25.7	0.670
9	55083	66.8	4.57	6.02	959 25	6.84	2.00	0.382	236	7.50	4.68	0.558	345	178.0	39.1	1.06
10	55090	89.4	6.19	6.65	1372 25	10.8	2.68	0.352	225	11.8	6.26	0.513	329	271.0	59.5	1.32
11	55439	86.9	8.48	7.48	959 25	8.49	2.60	0.391	250	9.32	6.08	0.571	365	291.0	58.1	1.95
12	55716	100.0	9.38	6.54	1684 25	13.0	3.00	0.339	217	14.3	7.00	0.494	317	303.0	69.0	1.24
13	55110	124.0	13.66	7.09	2125 25	17.8	3.72	0.322	206	19.6	8.68	0.470	301	405.0	93.4	1.44

copper loss = iron loss

Definitions for Table K2

Information given is listed by column as:

1. Manufacturer part number
2. Surface area calculated from Figure K21
3. Area product effective iron area times window area
4. Mean length turn
5. Total number of turns and wire size 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 equal to 2 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 transformer surface area, total loss is equal to 2 P_{cu}
12. Current calculated from column 10 and 11
13. Current density calculated from column 5 and 12
14. Effective core weight for silicon plus copper weight
15. Transformer volume calculated from Figure K24
16. Core effective cross-section

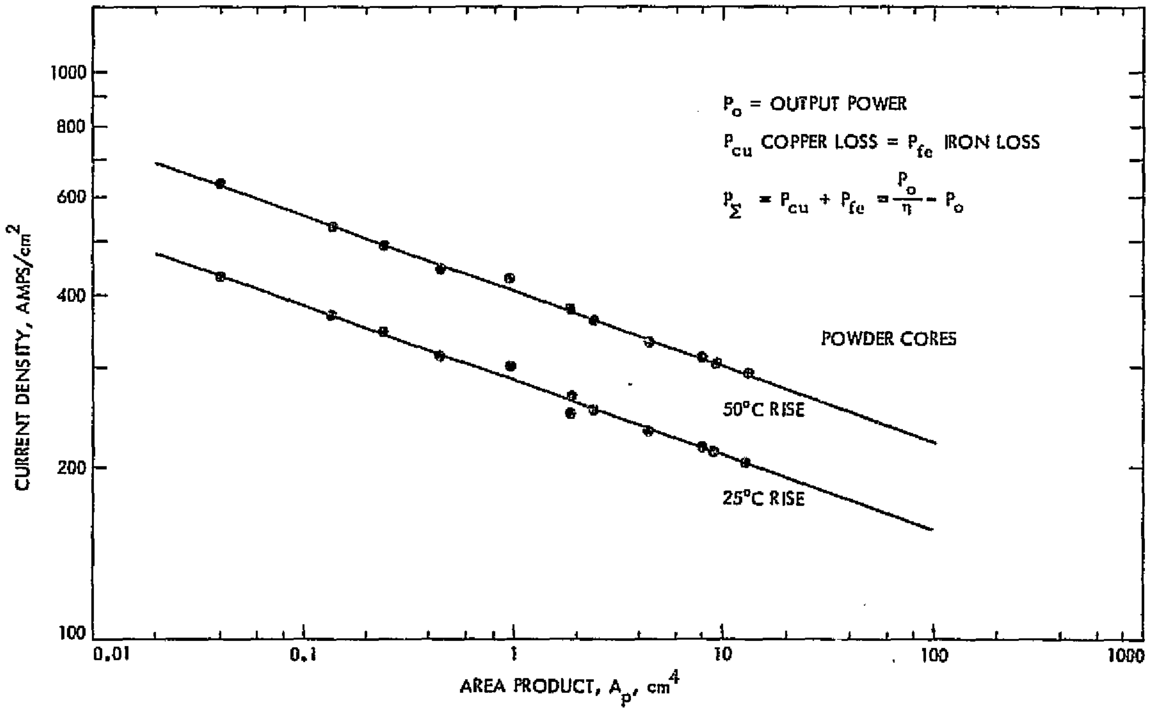


Fig. K1. Current Density Versus Area Product A_p for a 25°C and 50°C Rise for Powder Cores

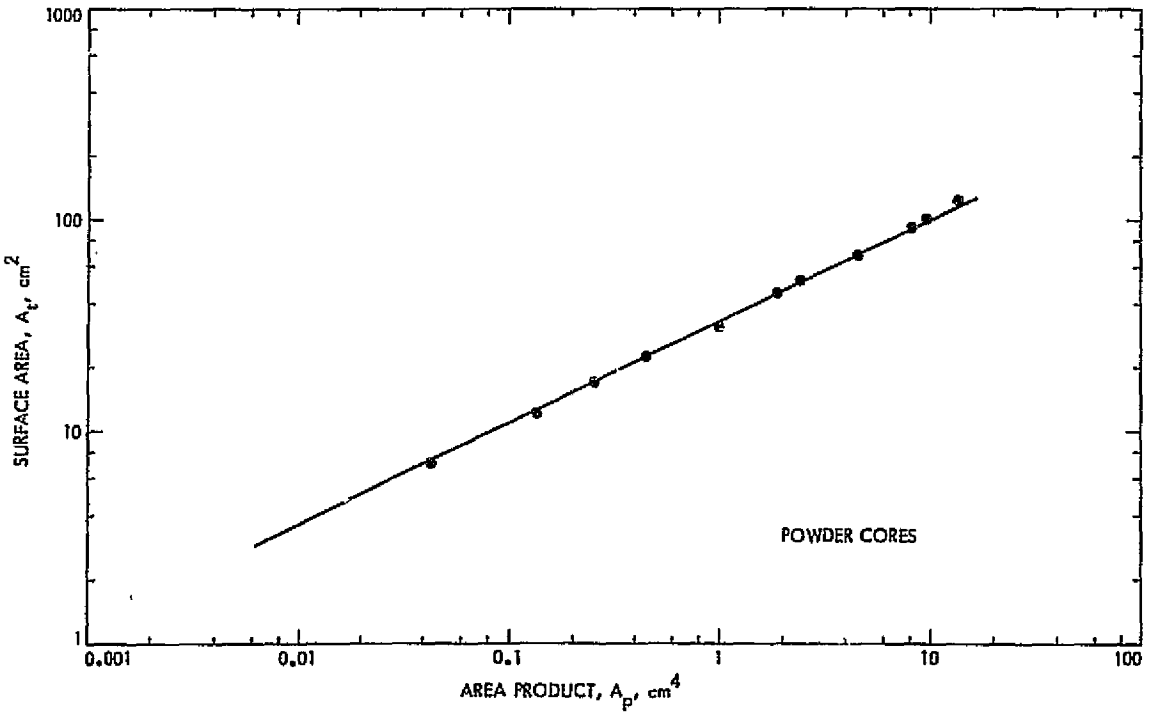


Fig. K2. Surface Area Versus Area Product A_p for Powder Cores

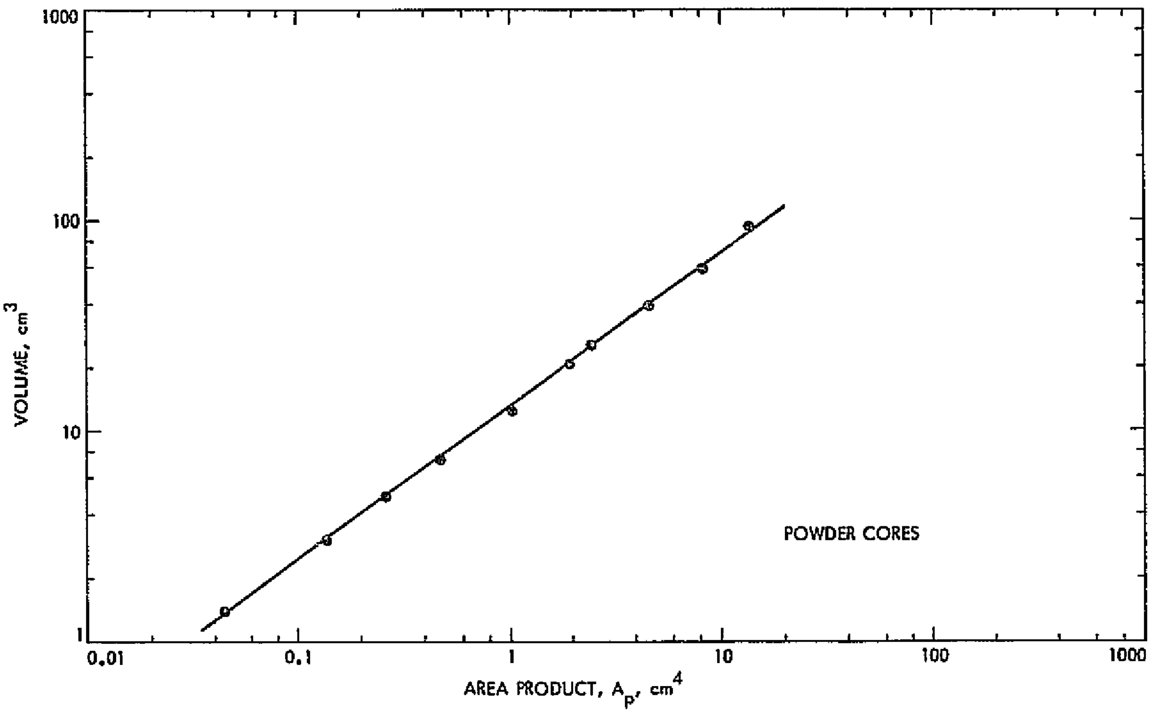


Fig. K3. Volume Versus Area Product A_p for Powder Cores

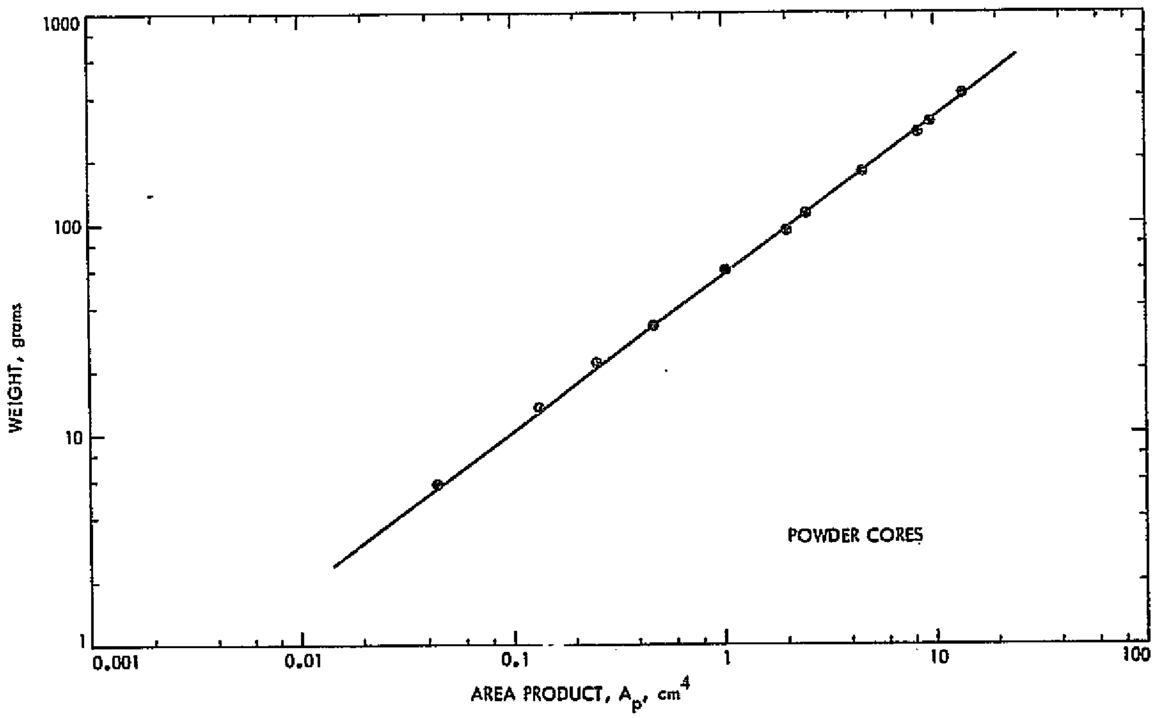


Fig. K4. Total Weight Versus Area Product A_p for Powder Cores

Table K3. Pot cores 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	$I = \sqrt{\frac{W}{\Omega}}$	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	9 x 5	2.93	0.0065	1.85	25 30	0.175	0.098	0.529	1044	0.192	0.230	0.774	1527	1.12	0.367	0.10
2	11 x 7	4.35	0.0152	2.2	37 30	0.309	0.130	0.458	904	0.339	0.304	0.670	1322	2.08	0.662	0.16
3	14 x 8	6.96	0.0393	2.8	74 30	0.787	0.208	0.363	716	0.864	0.487	0.531	1048	4.18	1.35	0.25
4	18 x 11	11.3	0.114	3.56	143 30	1.934	0.339	0.296	584	2.12	0.791	0.432	853	8.37	2.78	0.43
5	22 x 13	17.0	0.246	4.4	207 30	3.46	0.510	0.271	535	3.80	1.190	0.396	782	17.3	5.17	0.63
6	26 x 16	23.9	0.498	5.2	96 25	0.592	0.717	0.778	479	0.650	1.67	1.13	696	28.5	8.65	0.94
7	30 x 19	32.8	1.016	6.0	144 25	1.024	0.984	0.693	427	1.12	2.30	1.01	622	48.9	13.9	1.36
8	36 x 22	44.8	2.01	7.3	189 25	1.636	1.34	0.639	394	1.79	3.14	0.937	577	77.8	22.0	2.01
9	47 x 28	76.0	5.62	9.3	345 25	3.81	2.28	0.547	337	4.18	5.32	0.790	492	173.0	48.6	3.12
10	59 x 36	122.0	13.4	12.0	608 25	8.65	3.66	0.459	283	9.50	8.54	0.670	413	379.0	98.3	4.85

copper loss = iron loss

Definition for Table K3

Information given is listed by column as:

1. Manufacturer part number
2. Surface area calculated from Figure K21
3. Area product effective iron area times window area
4. Mean length turn
5. Total number of turns and wire size 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 equal to 2 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 transformer surface area, total loss is equal to 2 P_{cu}
12. Current calculated from column 10 and 11
13. Current density calculated from column 5 and 12
14. Effective core weight for silicon plus copper weight
15. Transformer volume calculated from Figure K24
16. Core effective cross-section

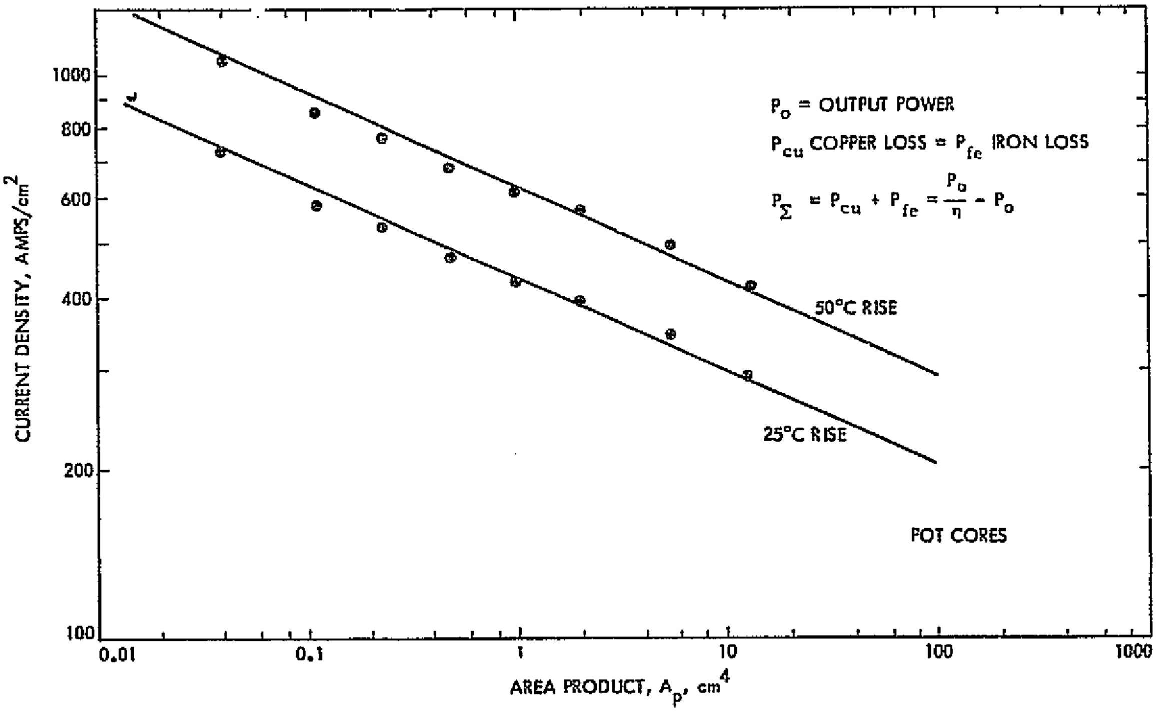


Fig. K5. Current Density Versus Area Product A_p for a 25°C and 50°C Rise for Pot Cores

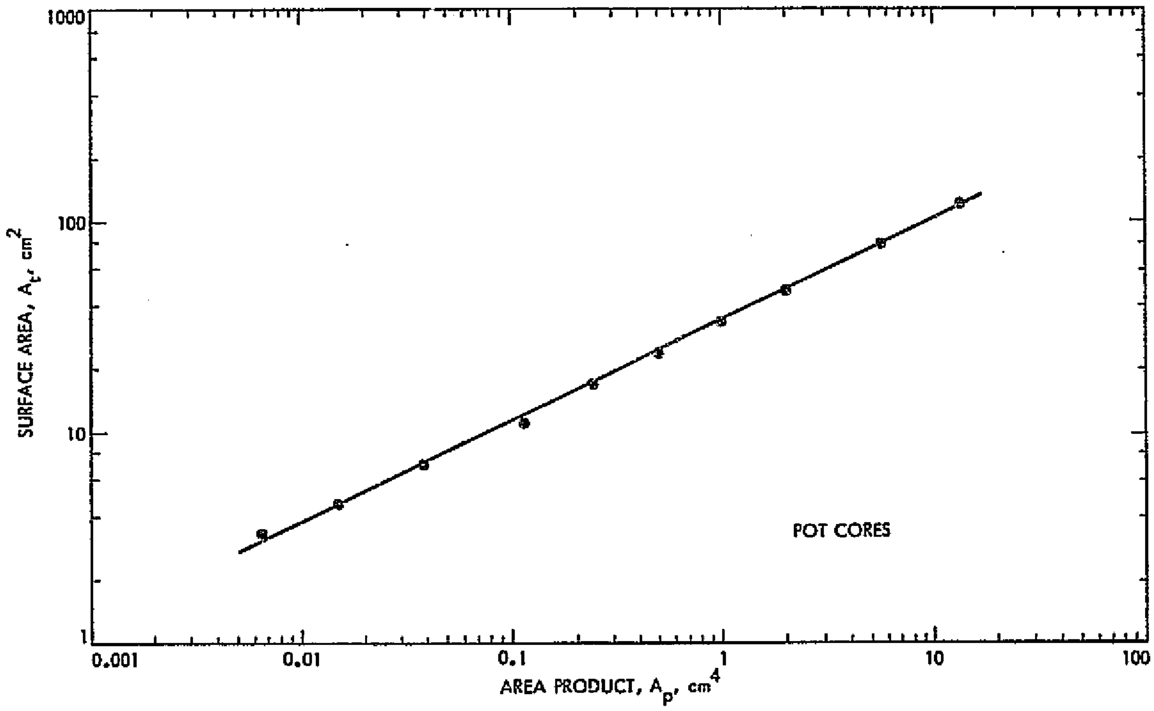


Fig. K6. Surface Area Versus Area Product A_p for Pot Cores

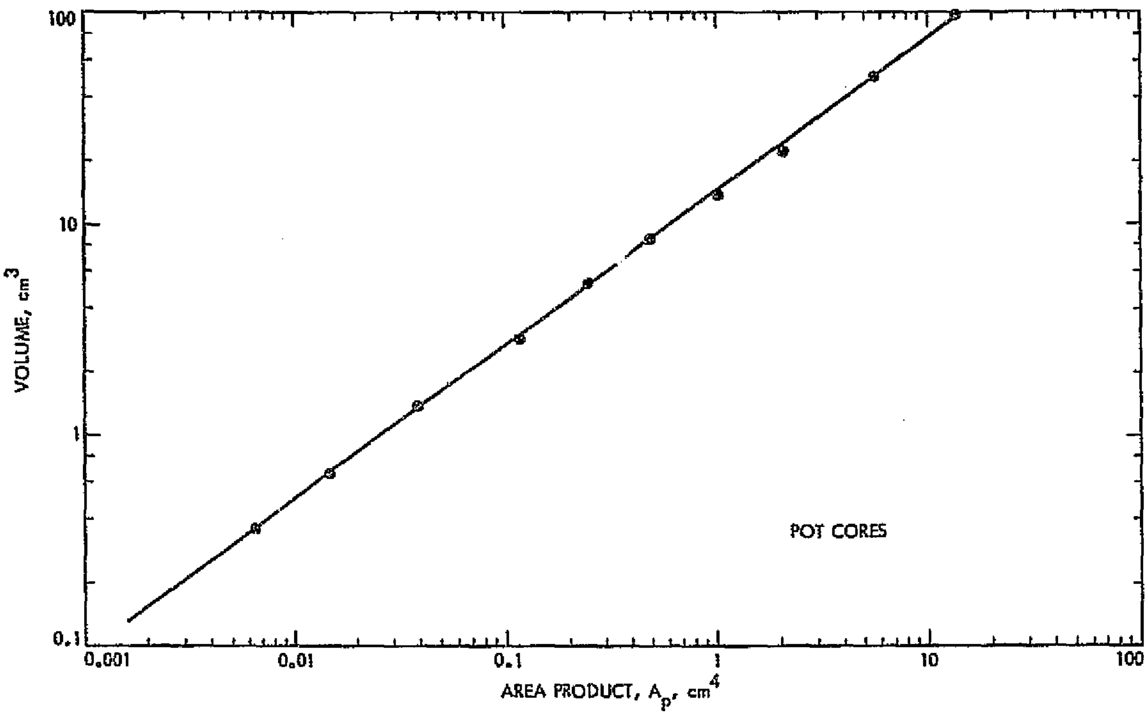


Fig. K7. Volume Versus Area Product A_p for Pot Cores

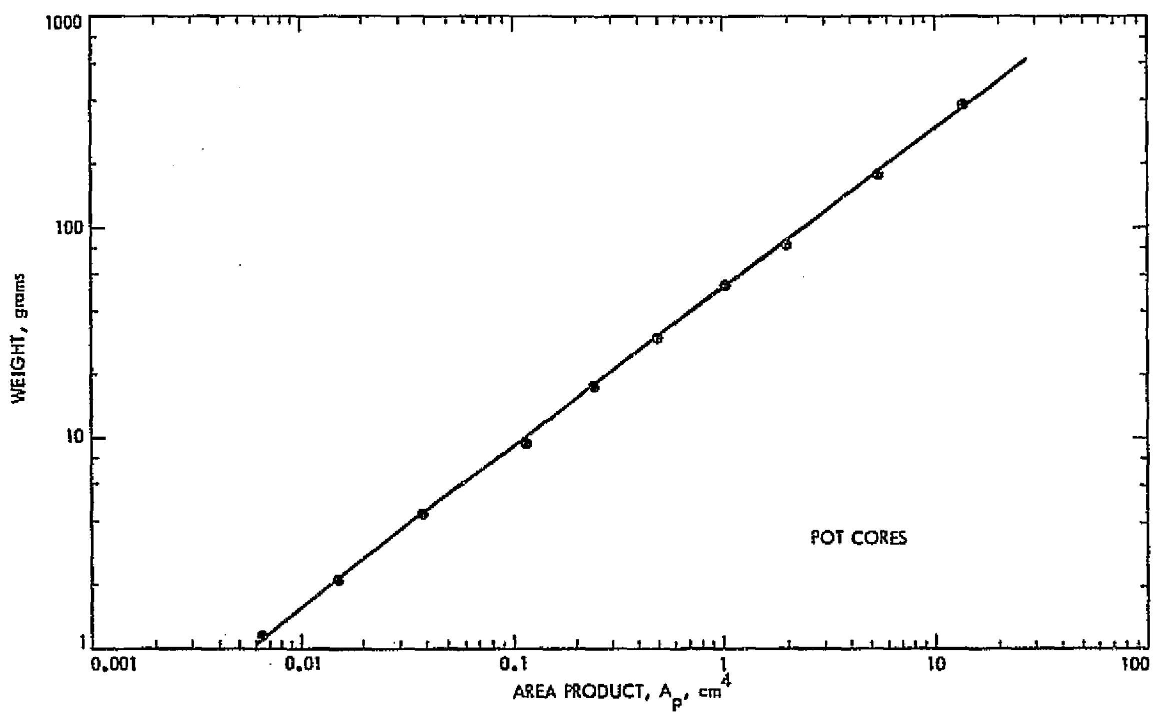


Fig. K8. Total Weight Versus Area Product A_p for Pot Cores

Table K4. Laminations 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	$I = \sqrt{\frac{W}{\Omega}}$	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	EE-3031	4.11	0.0090	1.72	90 30	0.58	0.123	0.323	638	0.645	0.288	0.472	932	2.04	0.651	0.056
2	EE-2829	6.63	0.0254	2.33	147 30	1.30	0.199	0.276	546	1.43	0.464	0.403	795	3.78	1.35	0.101
3	EI-187	14.4	0.120	3.20	314 30	3.82	0.432	0.237	469	4.19	1.01	0.347	685	10.2	4.34	0.225
4	EE-2425	23.8	0.325	5.08	498 30	9.61	0.714	0.192	380	10.5	1.67	0.281	555	24.6	9.22	0.403
5	EE-2627	40.6	1.01	5.79	245 25	1.68	1.22	0.602	371	1.85	2.84	0.876	540	61.3	19.1	0.907
6	EI-375	47.7	1.38	6.30	350 25	2.62	1.43	0.522	322	2.87	3.34	0.762	470	74.4	25.3	0.907
7	EI-50	57.7	1.95	7.09	263 25	2.21	1.73	0.625	385	2.43	4.04	0.912	562	124.0	36.8	1.61
8	EI-21	66.0	2.62	7.57	372 25	3.34	1.98	0.544	335	3.66	4.62	0.793	489	140.0	39.2	1.61
9	EI-625	90.0	4.76	8.84	503 25	5.27	2.70	0.505	312	5.79	6.30	0.737	455	223.0	60.0	2.52
10	EI-75	130.0	9.87	10.6	211 20	0.826	3.90	1.54	296	0.906	9.10	2.24	432	417.0	104.0	3.63
11	EI-87	176.0	18.3	12.3	296 20	1.34	5.28	1.40	270	1.48	12.3	2.04	393	616.0	164.0	4.94
12	EI-100	230.0	31.2	14.5	386 20	2.07	6.90	1.29	249	2.27	16.1	1.88	363	953.0	246.0	6.45
13	EI-112	292.0	49.9	16.0	492 20	2.91	8.76	1.23	237	3.19	20.4	1.79	344	1370.0	350.0	8.16
14	EI-125	361.0	76.3	17.7	625 20	4.09	10.8	1.15	222	4.49	25.3	1.68	324	1870.0	481.0	10.08
15	EI-138	432.0	112.0	19.5	740 20	5.33	13.0	1.10	213	5.85	30.2	1.61	310	2560.0	629.0	12.19
16	EI-150	518.0	158.0	21.2	893 20	6.99	15.5	1.05	203	7.67	36.3	1.54	296	3360.0	829.0	14.51
17	EI-175	704.0	292.0	24.7	1080 20	9.85	21.1	1.034	199	10.8	49.3	1.51	291	5180.0	1312.0	19.75
18	EI-36	778.0	361.0	26.5	1701 20	16.6	23.3	0.836	161	18.3	54.5	1.22	235	5930.0	1654.0	17.03
19	EI-19	1093.0	668.0	31.7	2886 20	33.8	32.8	0.696	134	37.1	76.5	1.015	196	8694.0	2875.0	19.75

copper loss = iron loss

Definitions for Table K4

Information given is listed by column as:

1. Manufacturer part number
2. Surface area calculated from Figure K22
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 one 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 equal to 2 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 transformer surface area, total loss is equal to 2 P_{cu}
12. Current calculated from column 10 and 11
13. Current density calculated from column 5 and 12
14. Effective core weight for silicon plus copper weight
15. Transformer volume calculated from Figure K25
16. Core effective cross-section

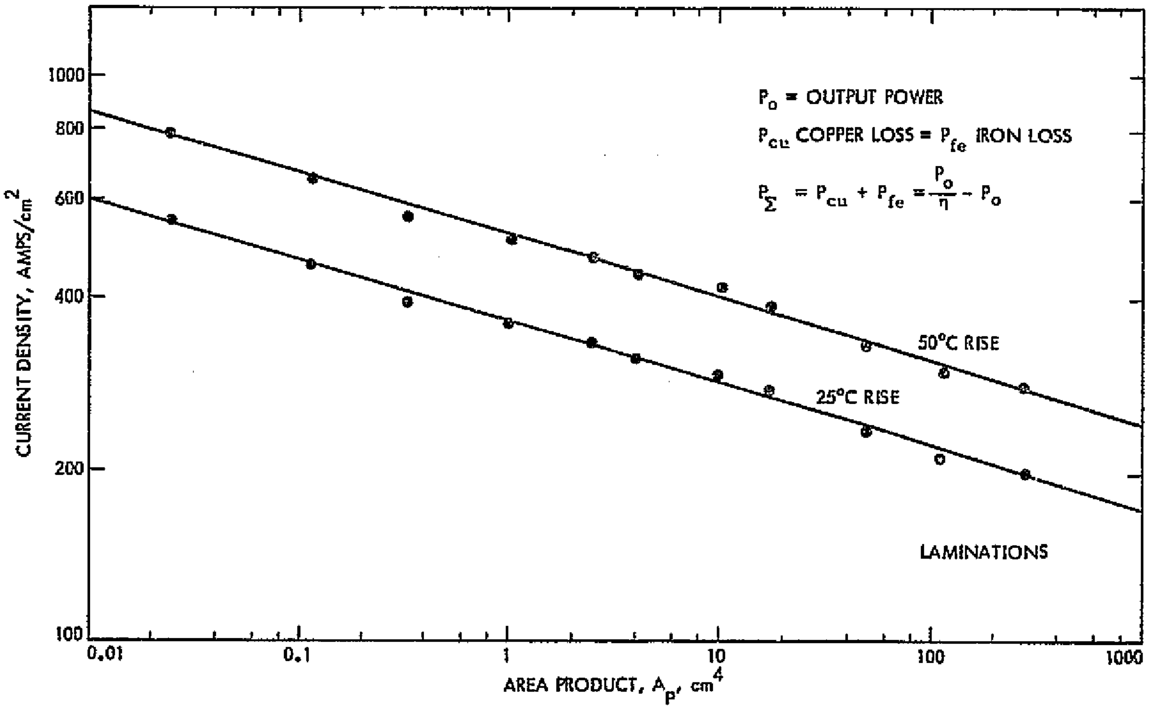


Fig. K9. Current Density Versus Area Product A_p for 25°C and 50°C Rise for Laminations

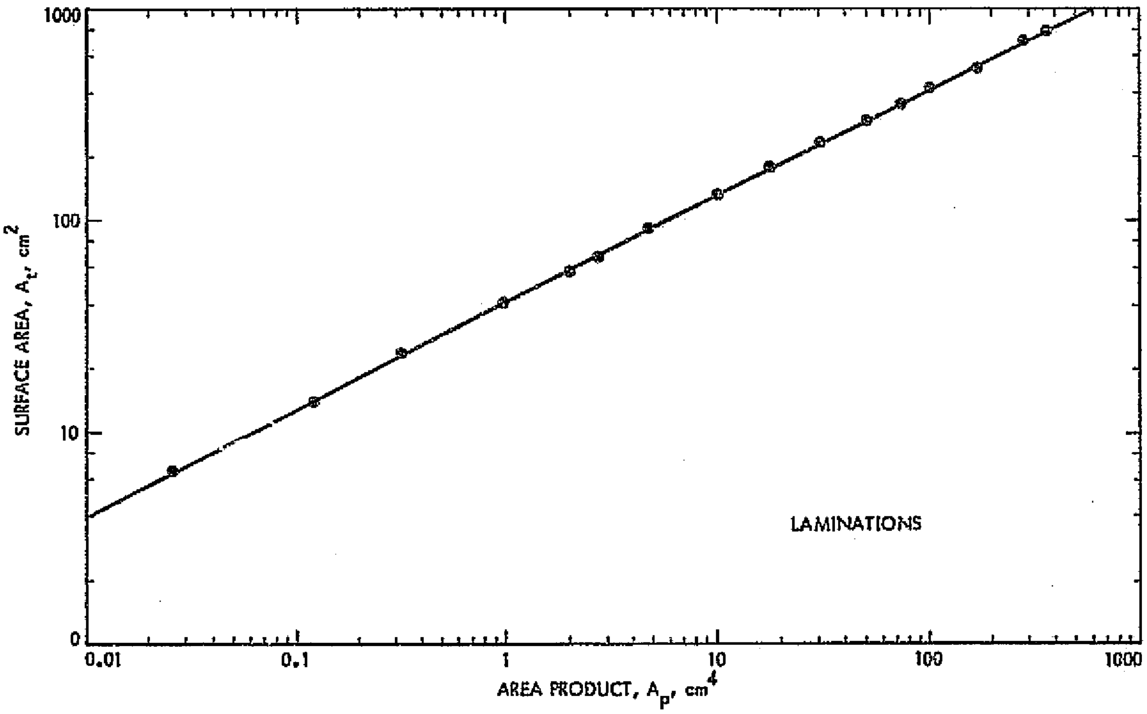


Fig. K10. Surface Area Versus Area Product A_p for Laminations

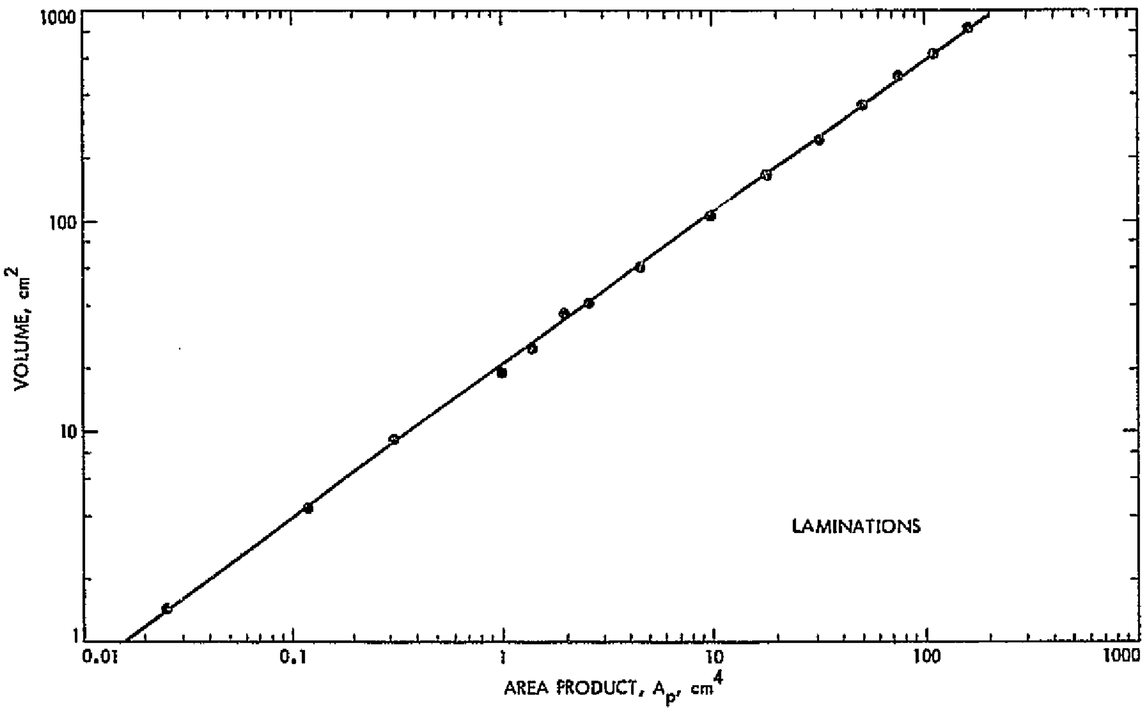


Fig. K11. Volume Versus Area Product A_p for Laminations

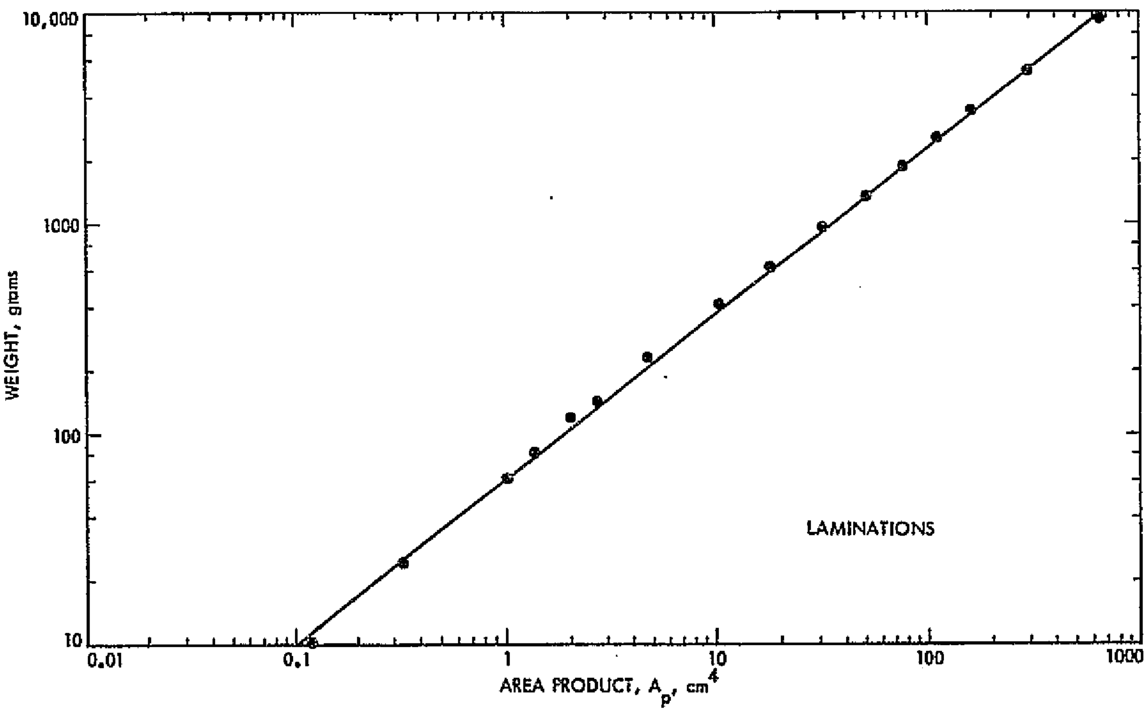


Fig. K12. Total Weight Versus Area Product A_p for Laminations

Table K5. 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	$I = \sqrt{\frac{W}{\Omega}}$	ΔT 25°C $J = \frac{amps}{cm^2}$	Ω @ 75° C	P_Σ	$I = \sqrt{\frac{W}{\Omega}}$	ΔT 50°C $J = \frac{amps}{cm^2}$	Total Weight	Volume cm^3	A_c cm^2
1	AL-2	20.9	0.265	3.55	662	30	8.93	0.627	0.187	370	9.81	1.46	0.273	528	23.33	7.14	0.265
2	AL-3	23.9	0.410	4.18	662	30	10.5	0.717	0.186	365	11.5	1.67	0.269	522	31.18	8.92	0.410
3	AL-5	33.6	0.767	4.59	946	30	16.5	1.01	0.174	345	18.1	2.35	0.255	493	51.8	14.06	0.539
4	AL-6	37.5	1.011	5.23	946	30	18.8	1.13	0.172	341	20.6	2.63	0.253	489	65.1	16.88	0.716
5	AL-124	45.3	1.44	5.50	1317	30	27.5	1.36	0.157	310	30.2	3.17	0.229	443	80.8	22.50	0.716
6	AL-8	63.4	2.51	5.74	221	20	0.482	1.90	1.404	271	0.529	4.44	2.05	395	127.85	35.66	0.806
7	AL-9	69.0	3.09	6.38	221	20	0.535	2.07	1.39	268	0.587	4.83	2.03	391	155.8	41.62	1.077
8	AL-10	74.5	3.85	7.01	221	20	0.588	2.24	1.38	266	0.646	5.22	2.01	387	183.2	47.55	1.342
9	AL-12	87.0	4.57	7.09	278	20	0.748	2.61	1.32	255	0.821	6.09	1.93	371	204.2	61.38	1.26
10	AL-135	93.7	5.14	7.36	325	20	0.908	2.81	1.24	240	0.997	6.56	1.81	345	227.0	69.63	1.26
11	AL-78	98.1	6.07	7.01	312	20	0.831	2.94	1.33	256	0.912	6.87	1.94	374	258.0	62.83	1.34
12	AL-18	118	7.92	7.61	510	20	1.47	3.55	1.10	211	1.61	8.26	1.60	308	321.0	94.79	1.25
13	AL-15	120	9.07	8.05	386	20	1.18	3.58	1.23	237	1.30	8.40	1.79	346	352.0	94.43	1.80
14	AL-16	127	10.8	8.89	386	20	1.30	3.80	1.20	233	1.43	8.89	1.76	340	397.0	104.95	2.15
15	AL-17	142	14.4	10.3	386	20	1.51	4.25	1.185	228	1.66	9.94	1.73	333	502.0	124.94	2.87
16	AL-19	159	18.	10.8	511	20	2.10	4.77	1.065	205	2.31	11.1	1.55	299	589.0	155.44	2.87
17	AL-20	182	22.	11.5	511	20	2.23	5.46	1.106	213	2.45	12.7	1.61	310	715.0	187.08	3.58
18	AL-22	202	28.0	11.5	637	20	2.78	6.05	1.043	201	3.05	14.1	1.52	293	835.0	212.04	3.58
19	AL-23	220	34.9	12.7	637	20	3.07	6.60	1.036	200	3.37	15.4	1.51	291	994.0	244.67	4.48
20	AL-24	245	40.0	12.0	948	20	4.32	7.35	0.922	178	4.74	17.1	1.35	259	1090.0	280.91	3.58

copper loss = iron loss

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Definitions for Table K5

Information given is listed by column as:

1. Manufacturer part number
2. Surface area calculated from Figure K23
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 two bobbins 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 equal to 2 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 transformer surface area, total loss is equal to 2 P_{cu}
12. Current calculated from column 10 and 11
13. Current density calculated from column 5 and 12
14. Effective core weight for silicon plus copper weight
15. Transformer volume calculated from Figure K26
16. Core effective cross-section

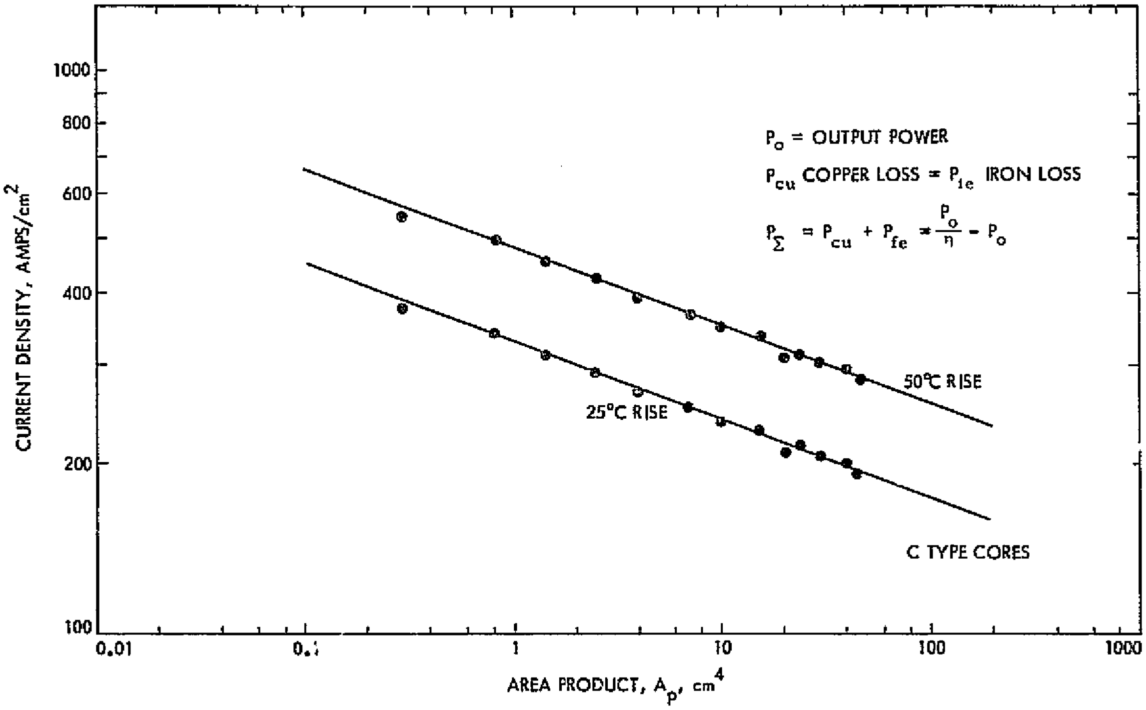

Fig. K13. Current Density Versus Area Product A_p for 25°C and 50°C Rise for C-Type Cores

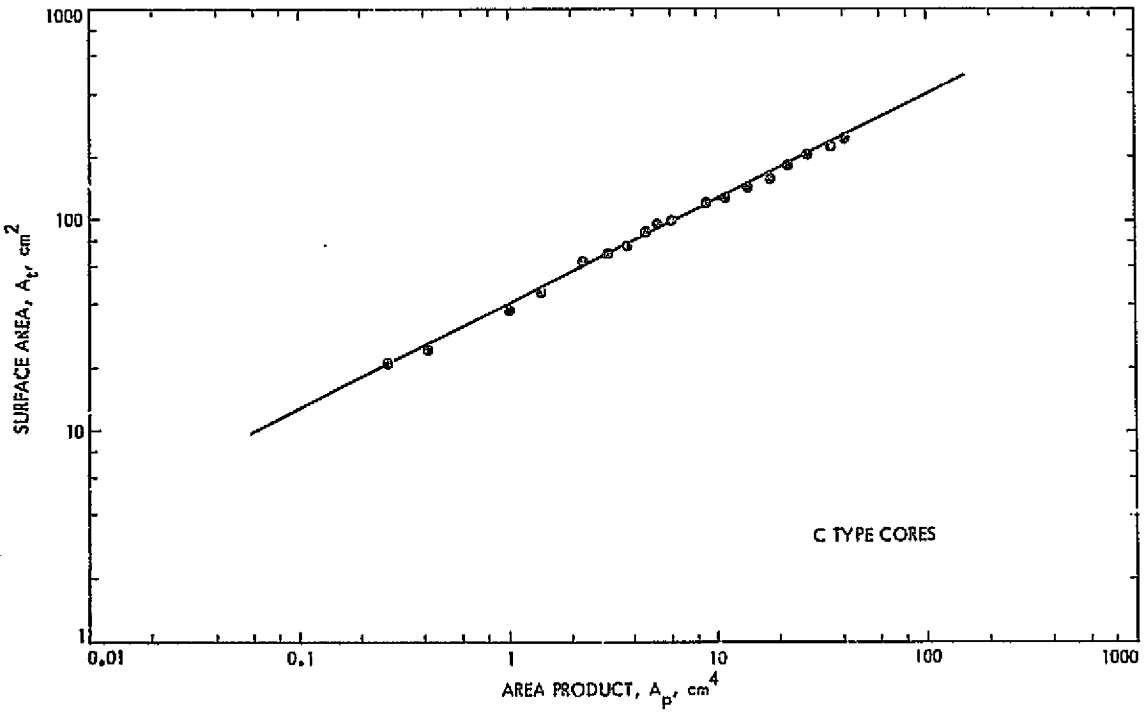

Fig. K14. Surface Area Versus Area Product A_p for C-Type Cores

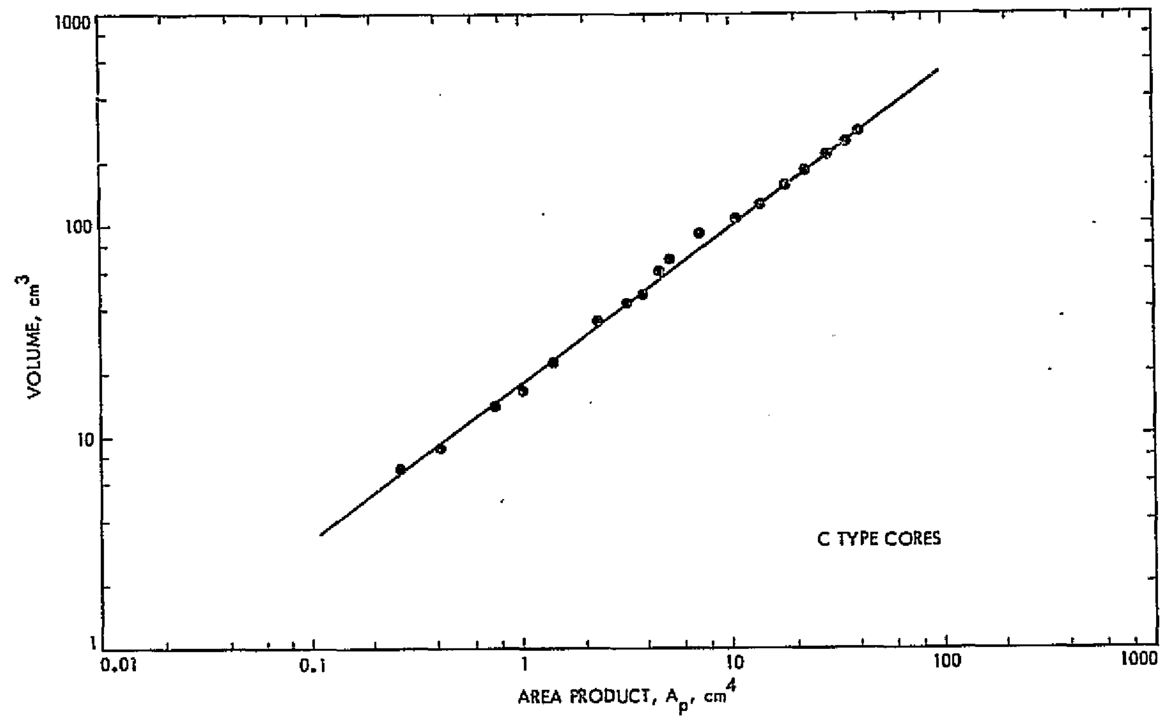

Fig. K15. Volume Versus Area Product A_p for C-Type Cores

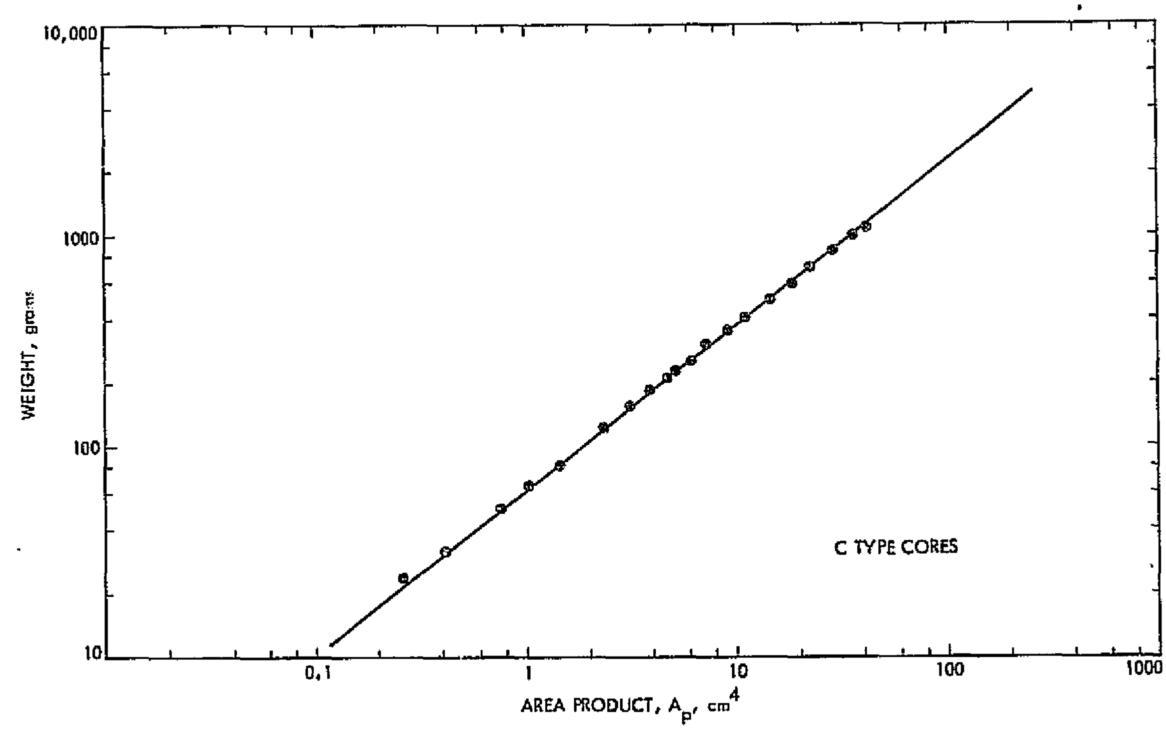

Fig. K16. Total Weight Versus Area Product A_p for C-Type Cores

Table K6. Tape wound 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	$I = \sqrt{\frac{W}{\Omega}}$	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	52402	7.26	0.0100	2.05	302 30	2.35	0.218	0.215	425	2.58	0.508	0.313	619	3.75	1.42	0.022
2	52153	8.29	0.0196	2.22	302 30	2.54	0.249	0.221	436	2.80	0.580	0.322	636	4.60	1.71	0.053
3	52107	11.1	0.0201	2.21	606 30	5.09	0.333	0.180	357	5.59	0.777	0.263	520	7.64	2.63	0.022
4	52403	13.5	0.0267	2.30	621 30	5.43	0.405	0.193	381	5.96	0.945	0.281	556	10.4	3.48	0.022
5	52057	17.4	0.0659	2.53	1017 30	9.78	0.522	0.163	322	10.7	1.22	0.238	471	15.1	4.98	0.043
6	52000	15.2	0.0787	2.70	606 30	6.22	0.456	0.191	378	6.82	1.06	0.278	550	11.7	3.99	0.086
7	52063	20.7	0.132	2.85	1017 30	11.0	0.621	0.167	331	12.1	1.45	0.244	483	18.9	6.20	0.086
8	52002	21.8	0.144	2.88	1114 30	12.2	0.654	0.163	323	13.4	1.53	0.239	472	20.6	6.72	0.086
9	52007	27.6	0.380	3.87	982 30	14.4	0.828	0.169	334	15.8	1.93	0.246	487	32.2	9.84	0.257
10	52167	31.5	0.516	4.23	1000 30	16.1	0.945	0.171	338	17.6	2.21	0.250	494	39.9	11.9	0.343
11	52094	30.4	0.592	4.47	1017 30	17.3	0.912	0.162	321	19.0	2.13	0.237	468	42.8	12.2	0.386
12	52004	46.1	0.725	4.02	315 20	0.469	1.38	1.20	234	0.515	3.23	1.77	341	70.2	21.3	0.171
13	52032	56.5	1.46	4.65	315 20	0.543	1.69	1.25	240	0.596	3.95	1.82	351	93.5	27.8	0.343
14	52026	61.0	2.18	5.28	315 20	0.616	1.83	1.22	235	0.676	4.27	1.77	342	116.0	32.8	0.514
15	52038	65.9	2.91	5.97	315 20	0.697	1.98	1.19	230	0.765	4.61	1.74	334	139.0	38.3	0.686
16	52035	88.9	4.68	6.33	505 20	1.19	2.67	1.06	204	1.3	6.22	1.55	298	210.0	59.0	0.686
17	52055	116.0	6.81	6.76	737 20	1.85	3.48	0.970	187	2.0	8.12	1.42	273	303.0	86.4	0.686
18	52012	110.0	9.35	8.88	505 20	1.66	3.30	0.996	192	1.82	7.70	1.45	280	378.0	87.4	1.371
19	52017	179.0	12.5	7.51	698 17	0.97	5.37	1.66	160	1.065	12.5	2.33	274	562.0	163.0	0.686
20	52031	256.0	19.8	8.23	1114 17	1.70	7.68	1.50	145	1.86	17.9	2.19	211	931.0	272.0	0.686
21	52103	220.0	24.5	8.77	688 17	1.12	6.60	1.72	165	1.23	15.4	2.51	241	741.0	212.0	1.371
22	52128	304.0	39.4	9.49	1104 17	1.94	9.12	1.53	147	2.13	21.3	2.24	215	1182.0	341.0	1.371
23	52022	256.0	49.1	11.3	688 17	1.44	7.68	1.63	157	1.58	17.9	2.38	229	1106.0	291.0	2.742
24	52042	347.0	78.7	12.0	1104 17	2.45	10.4	1.45	140	2.69	24.3	2.12	204	1681.0	453.0	2.742
25	52100	422.0	145.0	15.4	1089 17	3.11	12.7	1.43	138	3.41	29.5	2.08	200	2459.0	633.0	5.142
26	52112	378.0	510.0	20.3	2871 17	10.8	26.3	1.1	106	11.8	61.5	1.61	155	7100.0	1891.0	6.855
27	[illegible]	1014.0	813.0	22.2	2856 17	11.7	24.4	1.02	98.1	12.9	71.0	1.66	159	8891.0	2299.0	10.968

copper loss = iron loss

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Definitions for Table K6

Information given is listed by column as:

1. Manufacturer part number
2. Surface area calculated from Figure K21
3. Area product effective iron area times window area
4. Mean length turn
5. Total number of turns and wire size 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 equal to 2 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 transformer surface area, total loss is equal to 2 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. Transformer volume calculated from Figure K24
16. Core effective cross-section

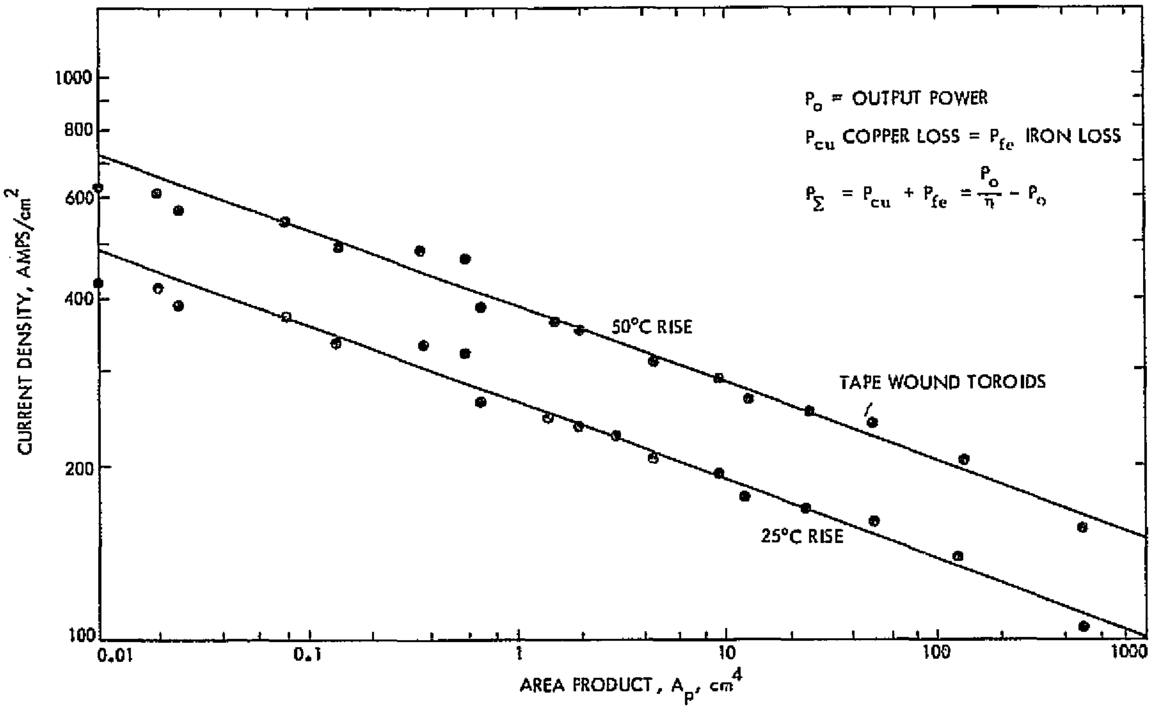

Fig. K17. Current Density Versus Area Product A_p for 25°C and 50°C Rise for Tape-Wound Toroids

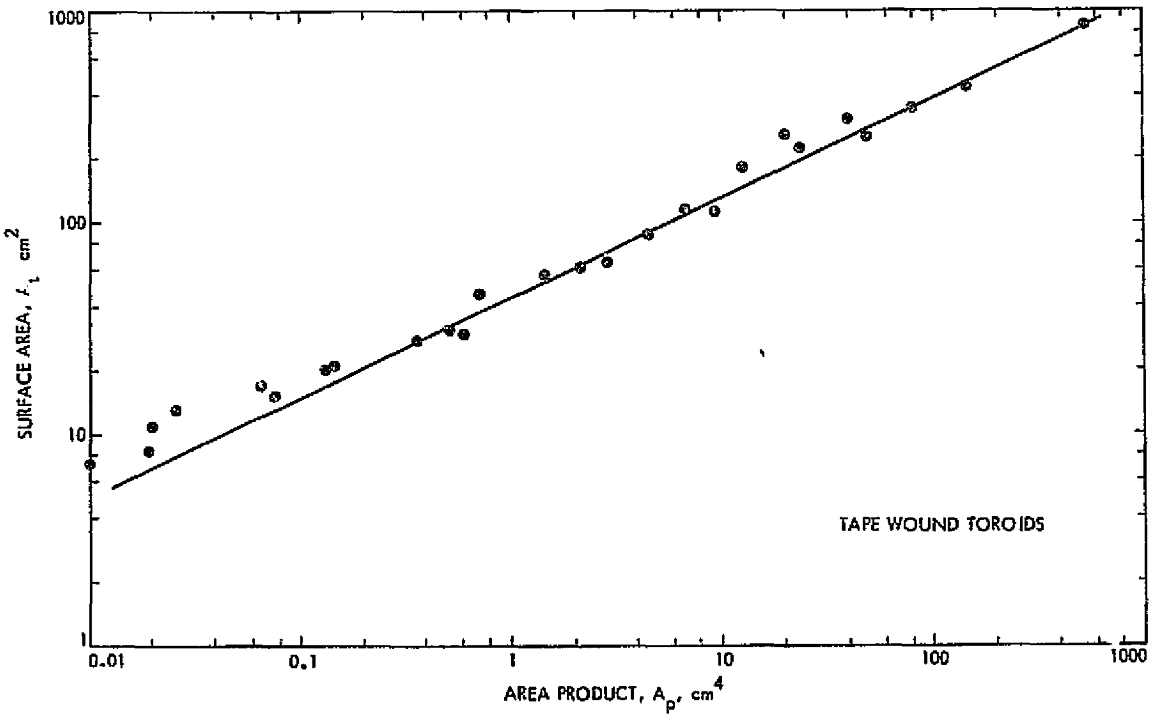

Fig. K18. Surface Area Versus Area Product A_p for Tape-Wound Toroids

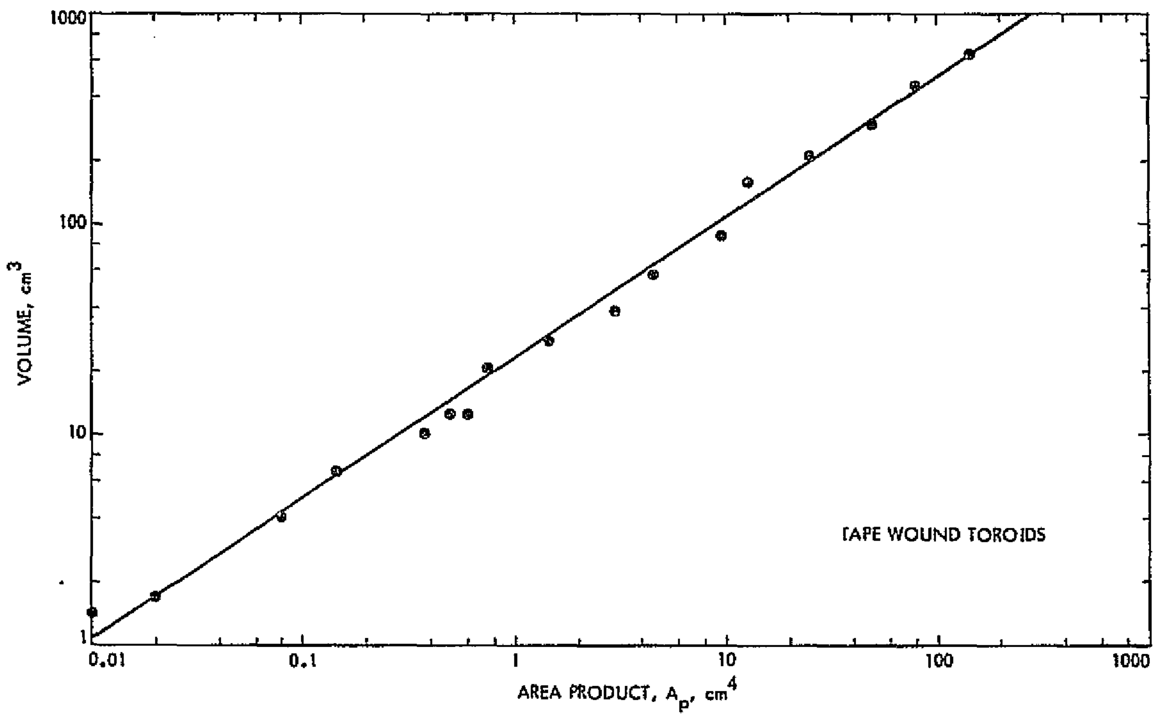

Fig. K19. Volume Versus Area Product A_p for Tape-Wound Toroids

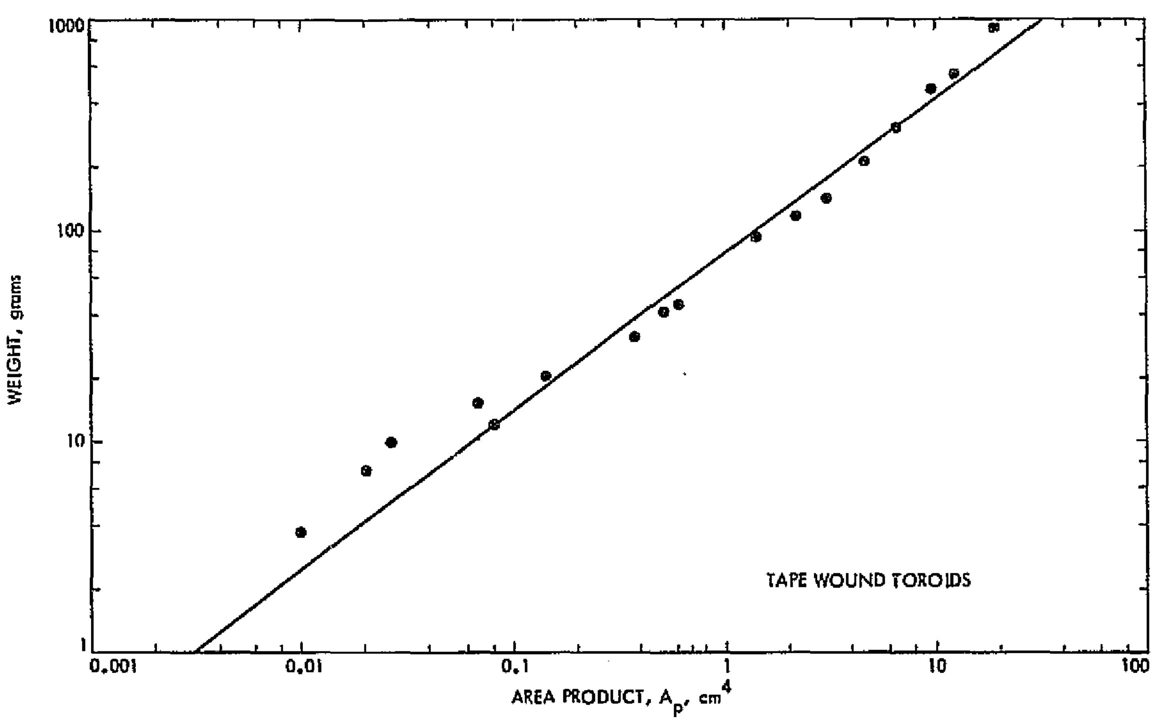

Fig. K20. Total Weight Versus Area Product A_p for Tape-Wound Toroids

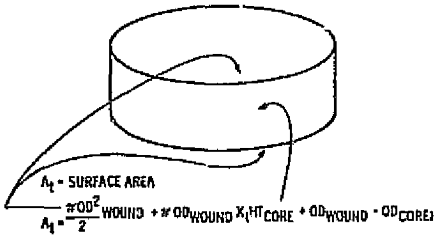

Fig. K21. Tape Wound Core, Power Cores, and Pot Cores Surface Area A_t

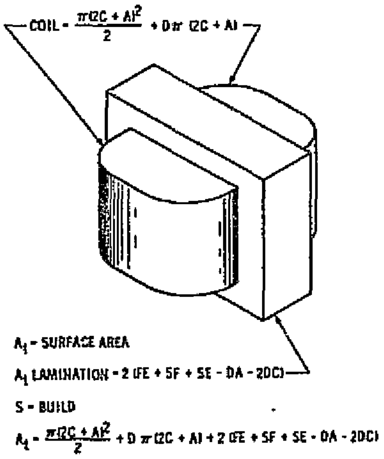

Fig. K22. Lamination Surface Area A_t

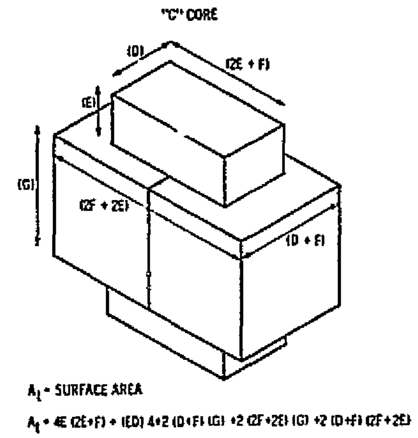

Fig. K23. C Core Surface Area A_t

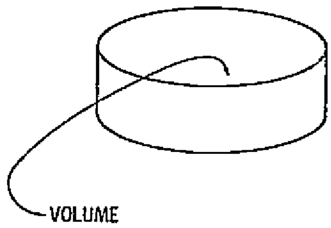

Fig. K24. Tape wound core, Powder Core, and Pot Cores

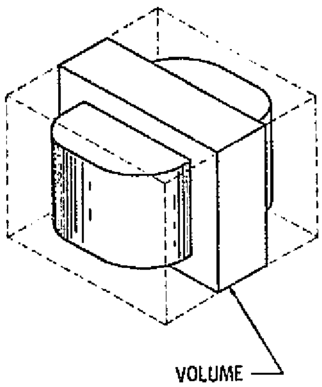

Fig. K25. Laminations

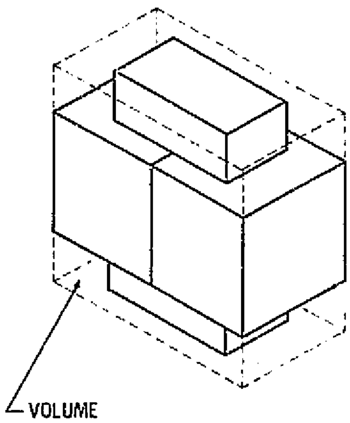

Fig. K26. C Type Cores

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