Spacecraft Transformer and Inductor Design

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National Aeronautics and Space Administration
Jet Propulsion Laboratory
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PREFACE

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ABSTRACT

The conversion process in spacecraft power electronics requires the use of magnetic components which frequently are the heaviest and bulkiest items in the conversion circuit. They also have a significant effect upon the performance, weight, cost, and efficiency of the power system.

This handbook contains eight chapters, which pertain to magnetic material selection, transformer and inductor design tradeoffs, transformer design, iron core dc inductor design, toroidal powder core inductor design, window utilization factors, regulation, and temperature rise. Relationships are given which simplify and standardize the design of transformers and the analysis of the circuits in which they are used.

The interactions of the various design parameters are also presented in simplified form so that tradeoffs and optimizations may easily be made.
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LIST OF SYMBOLS

\( \alpha \)  regulation, \%  
\( A_c \)  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\(^2\)  
\( A_{w(B)} \)  bare 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  
\( B_s \)  flux density to saturate  
\( \text{cir-mil} \)  area of a circle whose diameter = 0.001 inches  
\( D \)  lamination tongue width, cm  
\( E \)  voltage  
\( \text{Eng} \)  energy, watt seconds  
\( \eta \)  efficiency  
\( f \)  frequency, Hz  
\( F \)  fringing flux factor  
\( G \)  window height, cm  
\( H \)  magnetizing force ampturns/cm  
\( H_s \)  magnetizing force to saturate  
\( I \)  current, amps  
\( I_o \)  load current, amps  
\( I_p \)  primary current, amps
LIST OF SYMBOLS (contd)

\( l_s \) 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

\( K_e \) electrical coefficient

\( K_g \) geometry coefficient

\( K_l \) gap loss coefficient

\( K_j \) current density coefficient

\( K_p \) area product 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

\( m \) meter

MLT mean length turn, cm

\( \mu_\Delta \) effective permeability

\( \mu_m \) core material permeability

\( \mu_o \) absolute permeability

\( \mu_r \) relative permeability
LIST OF SYMBOLS (contd)

\( N \)  \( \text{turns} \)

\( P \)  \( \text{power, watts} \)

\( \phi \)  \( \text{flux webers} \)

\( P_{cu} \)  \( \text{copper loss, watts} \)

\( P_{fe} \)  \( \text{core loss, watts} \)

\( P_{in} \)  \( \text{input power, watts} \)

\( P_o \)  \( \text{output power, watts} \)

\( \psi \)  \( \text{heat flux density, watts/cm}^2 \)

\( P_p \)  \( \text{primary loss, watts} \)

\( P_s \)  \( \text{secondary loss, watts} \)

\( P_\Sigma \)  \( \text{total loss (core and copper), watts} \)

\( P_t \)  \( \text{apparent power, watts} \)

\( R \)  \( \text{resistance, ohms} \)

\( \rho \)  \( \text{resistivity} \)

\( R_E \)  \( \text{equivalent core-loss (shunt) resistance, ohms} \)

\( R_{cu} \)  \( \text{copper resistance, ohms} \)

\( R_o \)  \( \text{load resistance, ohms} \)

\( R_p \)  \( \text{primary resistance, ohms} \)

\( R_s \)  \( \text{secondary resistance, ohms} \)

\( R_t \)  \( \text{total resistance, ohms} \)

\( S_1 \)  \( \text{conductor area/wire area} \)

\( S_2 \)  \( \text{wound area/usable window} \)

\( S_3 \)  \( \text{usable window area/window area} \)
LIST OF SYMBOLS (contd)

- $S_4$: usable window area/usable window area + insulation area
- $T$: flux density, teslas
- $V_o$: load voltage, volts
- $Vol$: volume, cm$^3$
- $W_a$: window area, cm$^2$
- $W_t$: weight, grams
- $\varsigma$: zeta resistance correction factor for temperature
A. INTRODUCTION

Transformers used in static inverters, converters and transformer-rectifier (T-R) supplies intended for spacecraft power applications are usually of square loop tape toroidal design. The design of reliable, efficient, and lightweight devices for this use has been seriously hampered by the lack of engineering data describing the behavior of both the commonly used and the more exotic core materials with higher frequency square wave excitation.

A program has been carried out at JPL to develop this data from measurements of the dynamic B-H loop characteristics of the different tape core materials presently available from various industry sources. Cores were procured in both toroidal and "C" forms and were tested in both upgapped (uncut) and gapped (cut) configurations. The following describes the results of this investigation.

B. TYPICAL OPERATION

Transformers used for inverters, converters, and T-R supplies operate from the spacecraft power bus, which could be dc or ac. In some power applications, a commonly used circuit is a driven transistor switch arrangement such as that shown in Fig. 1-1.

Fig. 1-1. Typical driven transistor inverter
One important consideration affecting the design of suitable transformers is that care must be taken to ensure that operation involves balanced drive to the transformer primary. In the absence of balanced drive, a net dc current will flow in the transformer primary, which causes the core to saturate easily during alternate half-cycles. A saturated core cannot support the applied voltage, and, because of lowered transformer impedance, the current flowing in a switching transistor is limited mainly by its beta. The resulting high current, in conjunction with the transformer leakage inductance, results in a high voltage spike during the switching sequence that could be destructive to the transistors. To provide balanced drive, it is necessary to exactly match the transistors for \( V_{CE} \) (SAT) and beta, and this is not always sufficiently effective. Also, exact matching of the transistors is a major problem in the practical sense.

C. MATERIAL CHARACTERISTICS

Many available core materials approximate the ideal square loop characteristic illustrated by the B-H curve shown in Fig. 1-2.

![Ideal square B-H loop](image)

Fig. 1-2. Ideal square B-H loop

Representative dc B-H loops for commonly available core materials are shown in Fig. 1-3. Other characteristics are tabulated in Table 1-1.

Many articles have been written about inverter and converter transformer design. Usually, the author's recommendation represents a compromise among material characteristics such as those tabulated in
Fig. 1-3. The typical dc B-H loops of magnetic materials

Table 1-1. Magnetic core material characteristics

<table>
<thead>
<tr>
<th>Trade names</th>
<th>Composition</th>
<th>Saturated flux density, B (tesla)</th>
<th>DC coercive force, amp-turn/cm</th>
<th>Squareness ratio</th>
<th>Material density, g/cm³</th>
<th>Loss factor at 3 kHz and 0.5 T, W/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesil Siletron</td>
<td>3% Si 97% Fe</td>
<td>1.5-1.8</td>
<td>0.5-0.75</td>
<td>0.85-1.0</td>
<td>7.63</td>
<td>33.1</td>
</tr>
<tr>
<td>Microsil Supersil</td>
<td>50% Ni 50% Fe</td>
<td>1.4-1.6</td>
<td>0.125-0.25</td>
<td>0.94-1.0</td>
<td>8.24</td>
<td>17.66</td>
</tr>
<tr>
<td>Deltamax Orthonol</td>
<td>49% Ni 52% Fe</td>
<td>1.15-1.4</td>
<td>0.062-0.187</td>
<td>0.80-0.92</td>
<td>8.19</td>
<td>11.03</td>
</tr>
<tr>
<td>4750 48 Alloy</td>
<td>79% Ni 17% Fe</td>
<td>0.66-0.82</td>
<td>0.025-0.05</td>
<td>0.80-1.0</td>
<td>8.73</td>
<td>5.51</td>
</tr>
<tr>
<td>Carpenter 49</td>
<td>78% Ni 17% Fe</td>
<td>0.65-0.82</td>
<td>0.0037-0.01</td>
<td>0.40-0.70</td>
<td>8.76</td>
<td>3.75</td>
</tr>
</tbody>
</table>

1 T = 10⁴ Gauss

2 g/cm³ = 0.036 lb/in.³
Table 1-1 and displayed in Fig. 1-3. These data are typical of commercially available core materials that are suitable for the particular application.

As can be seen, the material that provides the highest flux density (silicon) would result in smallest component size, and this would influence the choice, if size were the most important consideration. The type 78 material (see the 78% curve in Fig. 1-3) has the lowest flux density. This results in the largest size transformer, but, on the other hand, this material has the lowest coercive force and the lowest core loss of any core material available.

Usually, inverter transformer design is aimed at the smallest size, with the highest efficiency, and adequate performance under the widest range of environmental conditions. Unfortunately, the core material that can produce the smallest size has the lowest efficiency. The highest efficiency materials result in the largest size. Thus the transformer designer must make tradeoffs between allowable transformer size and the minimum efficiency that can be tolerated. The choice of core material will then be based upon achieving the best characteristic on the most critical or important design parameter, and acceptable compromises on the other parameters.

Based upon analysis of a number of designs, most engineers select size rather than efficiency as the most important criteria and select an intermediate loss factor core material for their transformers. Consequently, square loop 50-50 nickel-iron has become the most popular material.

D. CORE SATURATION DEFINITION

To standardize the definition of saturation, several unique points on the B-H loop are defined as shown in Fig. 1-4.

The straight line through \((H_o, 0)\) and \((H_s, B_s)\) may be written as:

\[
B = \left( \frac{dB}{dH} \right) (H - H_o)
\]

(1-1)
The line through \((0, B_s)\) and \((H_s, B_s)\) has essentially zero slope and may be written as:

\[
B = B_s = B_s
\]  \hspace{1cm} (1-2)

Equations (1) and (2) together defined "saturation" conditions as follows:

\[
B_s = \left( \frac{dB}{dH} \right) (H_s - H_0)
\]  \hspace{1cm} (1-3)

Solving Eq. (1-3) for \(H_s\),

\[
H_s = H_0 + \frac{B_s}{\mu_0}
\]  \hspace{1cm} (1-4)

where

\[
\mu_0 = \frac{dB}{dH}
\]

by definition.

1-6
Saturation occurs by definition is when the peak exciting current is twice the average exciting current as shown in Fig. 1-5. Analytically this means that:

\[ H_{pk} = 2H_s \]  \hspace{1cm} (1-5)

Solving Eq. (1-1) for \( H_1 \), we obtain

\[ H_1 = H_o + \frac{B_1}{\mu_o} \]  \hspace{1cm} (1-6)

To obtain the presaturation dc margin (\( \Delta H \)), Eq. (1-4) is subtracted from Eq. (1-3):

\[ \Delta H = H_s - H_1 = \frac{B_s - B_1}{\mu_o} \]  \hspace{1cm} (1-7)

The actual unbalanced dc current must be limited to:

\[ I_{dc} \leq \frac{\Delta H L_m}{N} \text{ (amperes)} \]  \hspace{1cm} (1-8)

where

\[ N = \text{TURNS} \]
\[ L_m = \text{mean magnetic length} \]
Combining Eqs. (1-7) and (1-8) gives

\[ I_{dc} \leq \frac{(B_s - B_l) H_m}{\mu_0 N} \]  

(1-9)

As mentioned earlier, in an effort to prevent core saturation, the switching transistors are matched for beta and \( V_{CE}^{(SAT)} \) characteristics. The effect of core saturation using an uncut or ungapped core is shown in Fig. 1-6, which illustrates the effect on the B-H loop when traversed with a dc bias. Figure 1-7 shows typical B-H loops of 50-50 nickel-iron excited from an ac source with progressively reduced excitation; the vertical scale is 0.4 T/cm. It can be noted that the minor loop remains at one extreme position within the B-H major loop after reduction of excitation. The unfortunate effect of this random minor loop positioning is that when conduction again begins in the transformer winding after shutdown, the flux swing could begin from the extreme, and not from the normal zero axis. The effect of this is to drive the core into saturation with the production of spikes that can destroy transistors.

Fig. 1-6. B-H loop with dc bias

Fig. 1-7. Typical square loop material with ac excitation
E. THE TEST SETUP

A test fixture, schematically indicated in Fig. 1-8, was built to effect comparison of dynamic B-H loop characteristics of various core materials. Cores were fabricated from various core materials in the basic core configuration designated No. 52029 for toroidal cores manufactured by Magnetics, Inc. The materials used were those most likely to be of interest to designers of inverter or converter transformers. Test conditions are listed in Table 1-2.

![Diagram of Dynamic B-H loop test fixture](image)

**Fig. 1-8. Dynamic B-H loop test fixture**

<table>
<thead>
<tr>
<th>Core type</th>
<th>Material</th>
<th>$B_m$, T</th>
<th>$N_T$</th>
<th>Frequency, kHz</th>
<th>$l_m$, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>52029 (2A)</td>
<td>Orthonol</td>
<td>1.45</td>
<td>54</td>
<td>2.4</td>
<td>9.47</td>
</tr>
<tr>
<td>52029 (2D)</td>
<td>Sq. Permalloy</td>
<td>0.75</td>
<td>54</td>
<td>2.4</td>
<td>9.47</td>
</tr>
<tr>
<td>52029 (2F)</td>
<td>Supermalloy</td>
<td>0.75</td>
<td>54</td>
<td>2.4</td>
<td>9.47</td>
</tr>
<tr>
<td>52029 (2H)</td>
<td>48-Alloy</td>
<td>1.15</td>
<td>54</td>
<td>2.4</td>
<td>9.47</td>
</tr>
<tr>
<td>52029 (2H)</td>
<td>Magnesil</td>
<td>1.6</td>
<td>54</td>
<td>2.4</td>
<td>9.47</td>
</tr>
</tbody>
</table>
Winding data was derived from the following:

$$N = \frac{V \cdot 10^4}{4.0 \cdot B_m \cdot f \cdot A_c}$$

(1-10)

The test transformer represented in Fig. 1-9 consists of 54-turn primary and secondary windings, with square wave excitation on the primary. Normally switch S1 is open. With switch S1 closed, the secondary current is rectified by the diode to produce a dc bias in the secondary winding.

![Diagram of transformer setup with S1 switch](image)

Fig. 1-9. Implementing dc unbalance

Cores were fabricated from each of the materials by winding a ribbon of the same thickness on a mandrel of a given diameter. Ribbon termination was effected by welding in the conventional manner. The cores were vacuum impregnated, baked, and finished as usual.

Figures 1-10 through 1-14 show the dynamic B-H loops obtained for the different core materials designated therein.

![Curve diagram](image)

Vert = 0.5 T/cm  
Horiz = 100 mA/cm  

Fig. 1-10. Magnesil (K) B-H loop
Fig. 1-11. Orthonol (A) B-H loop

Fig. 1-12. 48 Alloy (H) B-H loop

Fig. 1-13. Sq. Permalloy (P) B-H loop
Fig. 1-14. Supermalloy (F) B-H loop

VERT = 0.2 T/cm
HORIZ = 10 mA/cm

Fig. 1-15. Composite 52029 (2K), (A), (H), (P), and (F) B-H loops

VERT = 0.5 T/cm
HORIZ = 50 mA/cm

Figure 1-15 shows a composite of all the B-H loops. In each of these, switch S1 was in the open position so that there was no dc bias applied to the core and windings.

The photographs designated Figures 1-16 through 1-20 show the dynamic B-H loop patterns obtained for the designated core materials when the test conditions included a sequence in which switch S1 was open, then closed, and then opened. It is apparent from this data that with a small amount of dc bias, the minor dynamic B-H loop can traverse the major B-H loop from saturation to saturation. In Figs. 1-16 to 1-20, note that after the dc bias had been removed, the minor B-H loops remained shifted to one side or the other. Because of the ac coupling of the integrator to
the oscilloscope, the photographs do not present a complete picture of what really happens during the flux swing.

![Graph of Magnesil (K) B-H loop with and without dc bias](image1)

**VERT = 0.3 T/cm**  
**HORIZ = 200 mA/cm**

**Fig. 1-16.** Magnesil (K) B-H loop with and without dc bias

![Graph of Orthonol (A) B-H loop with and without dc bias](image2)

**VERT = 0.2 T/cm**  
**HORIZ = 100 mA/cm**

**Fig. 1-17.** Orthonol (A) B-H loop with and without dc bias

*Preceding page blank*
Fig. 1-18. 48 Alloy (H) B-H loop with and without dc bias

VERT = 0.2 T/cm
HORIZ = 50 mA/cm

Fig. 1-19. Sq. Permalloy (P) B-H loop with and without dc bias

VERT = 0.1 T/cm
HORIZ = 20 mA/cm

Fig. 1-20. Supermalloy (F) B-H loop with and without dc bias

VERT = 0.1 T/cm
HORIZ = 20 mA/cm
F. CORE SATURATION THEORY

The domain theory of the nature of magnetism is based on the assumption that all magnetic materials consist of individual molecular magnets. These minute magnets are capable of movement within the material. When a magnetic material is in its unmagnetized state, the individual magnetic particles are arranged at random, and effectively neutralize each other. An example of this is shown in Fig. 1-21, where the tiny magnetic particles are arranged in a disorganized manner. The north poles are represented by the darkened ends of the magnetic particles. When a material is magnetized, the individual particles are aligned or oriented in a definite direction (Fig. 1-22).

![Fig. 1-21. Unmagnetized material](image1) ![Fig. 1-22. Magnetized material](image2)

The degree of magnetization of a material depends on the degree of alignment of the particles. The external magnetizing force can continue up to the point of saturation, that is, the point at which essentially all of the domains are lined up in the same direction.

In a typical toroid core, the effective air gap is less than $10^{-6}$ cm. Such a gap is negligible in comparison to the ratio of mean length to permeability. If the toroid were subjected to a strong magnetic field (enough to saturate), essentially all of the domains would line up in the same direction.
If suddenly the field were removed at $B_m$, the domains would remain lined up and be magnetized along that axis. The amount of flux density that remains is called residual flux or $B_r$. The result of this effect was shown earlier in Figs. 1-16 to 1-20.

G. AIR GAP

An air gap introduced into the core has a powerful demagnetizing effect, resulting in "shearing over" of the hysteresis loop and a considerable decrease in permeability of high-permeability materials. The dc excitation follows the same pattern. However, the core bias is considerably less affected by the introduction of a small air gap than the magnetization characteristics. The magnitude of the air gap effect also depends on the length of the mean magnetic path and on the characteristics of the uncut core. For the same air gap, the decrease in permeability will be less with a greater magnetic flux path but more pronounced in a low coercive force, high-permeability core.

H. EFFECT OF GAPPING

Figure 1-23 shows a comparison of a typical toroid core $B$-$H$ loop without and with a gap. The gap increases the effective length of the magnetic path. When voltage $E$ is impressed across primary winding $N_1$ of a transformer, the resulting current $i_m$ will be small because of the highly inductive circuit shown in Fig. 1-24. For a particular size core, maximum inductance occurs when the air gap is minimum.

When $S_1$ is closed, an unbalanced dc current flows in the $N_2$ turns and the core is subjected to a dc magnetizing force, resulting in a flux density that may be expressed as

$$B_{dc} = \frac{0.4\pi N I_{dc} \times 10^{-4}}{l_g + \frac{1}{l_m}} \quad \text{[teslas]} \quad (1-11)$$
Fig. 1-23. Air gap increases the effective length of the magnetic path

Fig. 1-24. Implementing dc unbalance

In converter and inverter design, this is augmented by the ac flux swing, which is:

\[ B_{ac} = \frac{E \cdot 10^4}{K \cdot f \cdot A_c \cdot N} \]  \hspace{1cm} \text{[teslas]} (1-12)

If the sum of \( B_{dc} \) and \( B_{ac} \) shifts operation above the maximum operating flux density of the core material, the incremental permeability (\( \mu_{ac} \)) is reduced. This lowers the impedance and increases the flow of magnetizing
current \( i_m \). This can be remedied by introducing an air gap into the core assembly, which effects a decrease in dc magnetization in the core. However, the amount of air gap that can be incorporated has a practical limitation since the air gap lowers impedance, which results in increased magnetizing current \( i_m \) which is inductive. The resultant voltage spikes produced by such currents apply a high stress to the switching transistors, and may cause failure. This can be minimized by tight control of lapping and etching of the gap to keep the gap to a minimum.

From Fig. 1-23, it can be seen that the B-H curves depict maximum flux density \( B_m \) and residual flux \( B_r \) for ungapped and gapped cores, and that the useful flux swing is designated \( \Delta B \), which is the difference between them. It will be noted in Fig. 1-23a that \( B_r \) approaches \( B_m \), but that in Fig. 1-23b there is a much greater \( \Delta B \) between them. In either case, when excitation voltage is removed at the peak of the excursion of the B-H loop, flux falls to the \( B_r \) point. It is apparent that introducing an air gap then reduces \( B_r \) to a lower level, and increases the useful flux density. Thus insertion of an air gap in the core eliminates, or reduces markedly, the voltage spikes produced by the leakage inductance due to the transformer saturation.

Two types of core configurations were investigated in the ungapped and gapped states. Figure 1-23 shows the type of toroidal core that was cut

![Fig. 1-25. Typical cut toroid](image-url)
and Fig. 1-26 shows the type of C core that was cut. Toroidal cores as conventionally fabricated are virtually gapless. To increase the gap, the cores were physically cut in half and the cut edges were lapped, acid etched to remove cut debris, and banded to form the cores. A minimum air gap on the order of less than 25 μm was established.

Fig. 1-26. Typical cut "C" core

As will be noted from Figs. 1-27 to 1-31, which show the B-H loops of the uncut and cut cores, the results obtained indicated that the effect of gapping was the same for both the C-cores and the toroidal cores subjected to testing. It will be noted however, that gapping of the toroidal cores produced a lowered squareness characteristic for the B-H loop as shown in Table 1-3; this data was obtained from Figs. 1-27 to 1-31. Also, from Figs. 1-27 to 1-31, ΔH was extracted as shown in Fig. 1-32 and tabulated in Table 1-4.

![Graph](image-url)

**Fig. 1-27.** Magnesil 52029 (2K) B-H loop. (a) uncut and (b) cut
Fig. 1.28. Orthonol 52029 (2A) B-H loop, (a) uncut and (b) cut

Fig. 1.29. 48 Alloy 52029 (2H) B-H loop, (a) uncut and (b) cut

Fig. 1.30. Sq. Permalloy 52029 (2D) B-H loop, (a) uncut and (b) cut
Fig. 1-31. Supermalloy 52029 (2F) B-H loop, (a) uncut and (b) cut

Fig. 1-32. Defining ΔH and ΔH_{OP}

Table 1-3. Comparing $B_r/B_m$ on uncut and cut cores

<table>
<thead>
<tr>
<th>Code</th>
<th>Material</th>
<th>Uncut $B_r/B_m$</th>
<th>Cut $B_r/B_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>Orthonol</td>
<td>0.96</td>
<td>0.62</td>
</tr>
<tr>
<td>(D)</td>
<td>Mo-Permalloy</td>
<td>0.86</td>
<td>0.21</td>
</tr>
<tr>
<td>(K)</td>
<td>Magnesil</td>
<td>0.93</td>
<td>0.22</td>
</tr>
<tr>
<td>(F)</td>
<td>Supermalloy</td>
<td>0.81</td>
<td>0.24</td>
</tr>
<tr>
<td>(H)</td>
<td>48 Alloy</td>
<td>0.83</td>
<td>0.30</td>
</tr>
</tbody>
</table>
A direct comparison of cut and uncut cores was made electrically by means of two different test circuits. The magnetic material used in this branch of the test was Orthonol. The operating frequency was 2.4 kHz, and the flux density was 0.6 T. The first test circuit, shown in Fig. 1-33, was a driven inverter operating into a 30 W load, with the transistors operating into and out of saturation. Drive was applied continuously. S1 controls the supply voltage to Q1 and Q2.

<table>
<thead>
<tr>
<th>Material</th>
<th>$B_m$ (tesla)</th>
<th>$B_{ac}$ (tesla)</th>
<th>$B_{dc}$ (tesla)</th>
<th>$\Delta H_{OP}$</th>
<th>$\Delta H$</th>
<th>$\Delta H_{OP}$</th>
<th>$\Delta H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orthonal</td>
<td>1.44</td>
<td>1.15</td>
<td>0.288</td>
<td>0.0125</td>
<td>0.0</td>
<td>0.895</td>
<td>0.178</td>
</tr>
<tr>
<td>48 Alloy</td>
<td>1.12</td>
<td>0.89</td>
<td>0.224</td>
<td>0.0250</td>
<td>0.0</td>
<td>1.60</td>
<td>0.350</td>
</tr>
<tr>
<td>Sq. Permalloy</td>
<td>0.73</td>
<td>0.58</td>
<td>0.146</td>
<td>0.01</td>
<td>0.005</td>
<td>0.983</td>
<td>0.178</td>
</tr>
<tr>
<td>Supermalloy</td>
<td>0.68</td>
<td>0.58</td>
<td>0.136</td>
<td>0.0175</td>
<td>0.005</td>
<td>0.491</td>
<td>0.224</td>
</tr>
<tr>
<td>Magnesil</td>
<td>1.54</td>
<td>1.23</td>
<td>0.31</td>
<td>0.075</td>
<td>0.025</td>
<td>7.15</td>
<td>1.78</td>
</tr>
</tbody>
</table>

Fig. 1-33. Inverter inrush current measurement
With switch S1 closed, transistor Q1 was turned on and allowed to saturate. This applied \( E-V_C(SAT) \) across the transformer winding. Switch S1 was then opened. The flux in transformer T2 then dropped to the residual flux density \( B_r \). Switch S1 was closed again. This was done several times in succession to catch the flux in an additive direction.

Figures 1-34 and 1-35 show the inrush current measured at the center tap of T2.

![Fig. 1-34. Typical inrush of an uncut core in a driven inverter](image)

![Fig. 1-35. Typical inrush current of a cut core in a driven inverter](image)

It will be noted in Fig. 1-34 that the uncut core saturated and that inrush current was limited only by circuit resistance and transistor beta. It can be noted in Fig. 1-35 that saturation did not occur in the case of the cut core. The high inrush current and transistor stress was thus virtually eliminated.
The second test circuit arrangement is shown in Fig. 1-36. The purpose of this test was to excite a transformer and measure the inrush current using a current probe. A square wave power oscillator was used to excite transformer T2. Switch S1 was opened and closed several times to catch the flux in an additive direction. Figures 1-37 and 1-38 show inrush current for a cut and uncut core respectively.

Fig. 1-36. T-R supply current measurement

Fig. 1-37. Typical inrush current of an uncut core operating from an ac source

Fig. 1-38. Typical inrush current of a cut core in a T-R
A small amount of air gap, less than 25 μm, has a powerful effect on the demagnetizing force and this gap has little effect on core loss. This small amount of air gap decreases the residual magnetism by "shearing over" the hysteresis loop. This eliminated the problem of the core tending to remain saturated.

A typical example showing the merit of the cut core was in the checkout of a Mariner spacecraft. During the checkout of a prototype science package, a large (8 A, 200 μs) turn-on transient was observed. The normal running current was 0.06 A, and was fused with a parallel-redundant 1/8-A fuse as required by the Mariner Mars 1971 design philosophy. With this 8-A inrush current, the 1/8-A fuses were easily blown. This did not happen on every turn-on, but only when the core would "latch up" in the wrong direction for turn-on. Upon inspection, the transformer turned out to be a 50-50 Ni-Fe toroid. The design was changed from a toroidal core to a cut-core with a 25-μm air gap. The new design was completely successful in eliminating the 8-A turn-on transient.

I. A NEW CORE CONFIGURATION

A new configuration has been developed for transformers which combines the protective feature of a gapped core with the much lower magnetizing current requirement of an uncut core. The uncut core functions under normal operating conditions, and the cut core takes over during abnormal conditions to prevent high switching transients and their potentially destructive effect on the transistors.

This configuration is a composite of cut and uncut cores assembled together in concentric relationship, with the uncut core nested within the cut core. The uncut core has high permeability and thus requires a very small magnetizing current. On the other hand, the cut core has a low permeability and thus requires a much higher magnetization current.

The uncut core is designed to operate at a flux density which is sufficient for normal operation of the converter. The uncut core may saturate under the abnormal conditions previously described. The cut core then takes over and supports the applied voltage so that excessive current does not flow. In a
sense it acts like a ballast resistor in some circuits to limit current flow to a safe level.

The photographs designated Figures 1-39 and 1-40 show the magnetization curves for a composite core of the same material, at two different flux densities. The much lower $B_r$ characteristics of the composite as compared to the uncut core is readily apparent.

The desired features of the composite core can be obtained more economically by utilizing different materials for the cut and uncut portions of the core. It was found that when the design required high nickel (4/79) the cut portion could be low nickel (50/50) and because low nickel has twice the flux density as high nickel the core was made 66 percent high nickel and 33 percent low nickel.

![Fig. 1-39. The uncut core excited at 0.2 T/cm](image1)

![Fig. 1-40. Both cores cut and uncut excited at 0.2 T/cm](image2)

The photograph designated Figure 1-41 shows a cut core at the right and an uncut core at the left. Both have been impregnated to bond the ribbon layers together. The photograph designated Figure 1-42 shows in the lower portion, a cut core assembled by banding together with a smaller uncut core. The O.D. of the latter has been trimmed to fit within the I.D. of the cut core by peeling a wrap or two of the ribbon steel. The upper view shows an assembly of the nested cores.

In order to provide uniformity of characteristics for the gapped cores, a gap dimension of 50 $\mu$m is recommended so that variations produced by thermal cycling will not affect this gap greatly. This is now obtained by inserting a sheet of paper or film material between the core ends during banding. Then the composite core is placed in the aluminum box and sealed.
This same protective feature can be accomplished in transformers with laminationed cores. When laminations are stacked by interleaving them one by one, the result will be minimum air gap as shown in Figure 1-43 by the squareness of the B-H loop. Shearing over of the B-H loop or decreasing the residual flux is shown in the next Figure 1-44 and is accomplished by butt stacking half of lamination in the core cross section which introduces a small amount of air gap.
Table 1-5 compiles a list of composite cores manufactured by Magnetics Inc., alongside their standard dimensional equivalent cores. Also included in Table 1-5 is the cores' area product $A_p$, which is described in Chapter 2.

**Table 1-5. Composite cores**

<table>
<thead>
<tr>
<th>Composite</th>
<th>Standard</th>
<th>$A_p$, cm$^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>01605-2D</td>
<td>52000</td>
<td>0.0728</td>
</tr>
<tr>
<td>01754-2D</td>
<td>52002</td>
<td>0.144</td>
</tr>
<tr>
<td>01755-2D</td>
<td>52076</td>
<td>0.285</td>
</tr>
<tr>
<td>01609-2D</td>
<td>52061</td>
<td>0.389</td>
</tr>
<tr>
<td>01756-2D</td>
<td>52106</td>
<td>0.439</td>
</tr>
<tr>
<td>01606-2D</td>
<td>52094</td>
<td>0.603</td>
</tr>
<tr>
<td>01757-2D</td>
<td>52029</td>
<td>1.090</td>
</tr>
<tr>
<td>01758-2D</td>
<td>52032</td>
<td>1.455</td>
</tr>
<tr>
<td>01607-2D</td>
<td>52026</td>
<td>2.180</td>
</tr>
<tr>
<td>01759-2D</td>
<td>52038</td>
<td>2.910</td>
</tr>
<tr>
<td>01608-2D</td>
<td>52035</td>
<td>4.676</td>
</tr>
<tr>
<td>01623-2D</td>
<td>52425</td>
<td>5.255</td>
</tr>
<tr>
<td>01624-2D</td>
<td>52169</td>
<td>7.13</td>
</tr>
</tbody>
</table>

$A_c = 66\%$ Square Permalloy 4/79.

$A_c = 33\%$ Orthonol 50/50.

$lg = 2$ mil Kaption.
Fig. 1-43. Stack 1 x 1

Fig. 1-44. Stack one half 1 x 1 and one half butt stack
J. SUMMARY

Low-loss tape-wound toroidal core materials that have a very square hysteresis characteristic (B-H loop) have been used extensively in the design of spacecraft transformers. Due to the squareness of the B-H loops of these materials, transformers designed with them tend to saturate quite easily. As a result, large voltage and current spikes, which cause undue stress on the electronic circuitry, can occur. Saturation occurs when there is any unbalance in the ac drive to the transformer, or when any dc excitation exists. Also, due to the square characteristic, a high residual flux state \( B_r \) may remain when excitation is removed. Reapplication of excitation in the same direction may cause deep saturation and an extremely large current spike, limited only by source impedance and transformer winding resistance, can result. This can produce catastrophic failure.

By introducing a small (less than 25-\( \mu \)m) air gap into the core, the problems described above can be avoided and, at the same time, the low-loss properties of the materials retained. The air gap has the effect of "shearing over" the B-H loop of the material such that the residual flux state is low and the margin between operating flux density and saturation flux density is high. The air gap thus has a powerful demagnetizing effect upon the square loop materials. Properly designed transformers using "cut" toroid or "C-core" square loop materials will not saturate upon turn-on and can tolerate a certain amount of unbalanced drive or dc excitation.

It should be emphasized, however, that because of the nature of the material and the small size of the gap, extreme care and control must be taken in performing the gapping operation, otherwise the desired shearing effect will not be achieved and the low-loss properties will be lost. The cores must be very carefully cut, lapped, and etched to provide smooth, residue-free surfaces. Reassembly must be performed with equal care.
BIBLIOGRAPHY


CHAPTER II

TRANSFORMER DESIGN TRADEOFFS
A. INTRODUCTION

Manufacturers have for years assigned numeric codes to their cores; these codes represent the power-handling ability. This method assigns to each core a number which is the product of its window area \(W_a\) and core cross section area \(A_C\) and is called "Area Product," \(A_p\).

These numbers are used by core suppliers to summarize dimensional and electrical properties in their catalogs. They are available for laminations, C-cores, pot cores, powder cores, and toroidal tape-wound cores.

The author has developed additional 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 lighter weight and smaller volume or to optimize efficiency without going through a cut and try design procedure. 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, the area product \(A_p\) is treated extensively. A great deal of other information is also 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.
B. THE AREA PRODUCT $A_p$ AND ITS RELATIONSHIPS

The $A_p$ of a 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

$$A_p = W_a A_c \quad [\text{cm}^4]$$

Figures 2-1 - 2-5 show in outline form five transformer core types that are typical of those shown in the catalogs of suppliers.

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.

Table 2-1 was developed using the least-squares curve fit from the data obtained in Tables 2-2 through 2-7. The area product $A_p$ relationships with volume, surface area, current density, and weight for pot cores, powder cores, laminations, C-cores, and tape-wound cores will be presented in detail in the following paragraphs.

<table>
<thead>
<tr>
<th>Core</th>
<th>Losses</th>
<th>$K_{ij}$ (25°C)</th>
<th>$K_{ij}$ (50°C)</th>
<th>$(x)$</th>
<th>$K_s$</th>
<th>$K_w$</th>
<th>$K_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pot core</td>
<td>$P_{cu} = P_{fe}$</td>
<td>433</td>
<td>632</td>
<td>-0.17</td>
<td>33.8</td>
<td>48.0</td>
<td>14.5</td>
</tr>
<tr>
<td>Powder core</td>
<td>$P_{cu} &gt;&gt; P_{fe}$</td>
<td>403</td>
<td>590</td>
<td>-0.12</td>
<td>32.5</td>
<td>58.8</td>
<td>13.1</td>
</tr>
<tr>
<td>Lamination</td>
<td>$P_{cu} = P_{fe}$</td>
<td>366</td>
<td>534</td>
<td>-0.12</td>
<td>41.3</td>
<td>68.2</td>
<td>19.7</td>
</tr>
<tr>
<td>C-core</td>
<td>$P_{cu} = P_{fe}$</td>
<td>323</td>
<td>468</td>
<td>-0.14</td>
<td>39.2</td>
<td>66.6</td>
<td>17.9</td>
</tr>
<tr>
<td>Single-coil</td>
<td>$P_{cu} &gt;&gt; P_{fe}$</td>
<td>395</td>
<td>569</td>
<td>-0.14</td>
<td>44.5</td>
<td>76.6</td>
<td>25.6</td>
</tr>
<tr>
<td>Tape-wound core</td>
<td>$P_{cu} = P_{fe}$</td>
<td>250</td>
<td>365</td>
<td>-0.13</td>
<td>50.9</td>
<td>82.3</td>
<td>25.0</td>
</tr>
</tbody>
</table>

$J = K_j A_p^{(x)}$

$A_t = K_s A_p^{0.50}$

$W_t = K_w A_p^{0.75}$

$\text{Vol} = K_v A_p^{0.75}$

2-4
Fig. 2-1. C-core

Fig. 2-2. EI lamination

Fig. 2-3. Pot core

Fig. 2-4. Tape-wound toroidal core

Fig. 2-5. Powder core
Definitions for Table 2-2

Information given is listed by column as:

1. Manufacturer part number
2. Surface area calculated from Figure 2-22
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 7-2 for a $\Delta T$ 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 7-2 for a $\Delta T$ of 50°C with a room ambient of 25°C surface dissipation times the transformer 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 for silicon plus copper weight in grams
15. Transformer volume calculated from Figure 2-6
16. $C$: Effective cross-section
### Table 2-2. Powder core characteristics

<table>
<thead>
<tr>
<th>Core</th>
<th>N</th>
<th>AWG</th>
<th>D @ 50°C</th>
<th>Pz</th>
<th>ΔT 25°C</th>
<th>D @ 75°C</th>
<th>Pz</th>
<th>ΔT 50°C</th>
<th>J = 1/cm²</th>
<th>Weight</th>
<th>Volume</th>
<th>A₀</th>
<th>cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>55051</td>
<td>7.19</td>
<td>0.0437</td>
<td>2.12</td>
<td>86</td>
<td>25</td>
<td>0.215</td>
<td>0.216</td>
<td>1.60</td>
<td>617</td>
<td>0.536</td>
<td>1.46</td>
<td>999</td>
</tr>
<tr>
<td>2</td>
<td>55121</td>
<td>12.3</td>
<td>0.137</td>
<td>2.71</td>
<td>160</td>
<td>25</td>
<td>0.513</td>
<td>0.369</td>
<td>0.848</td>
<td>522</td>
<td>0.163</td>
<td>1.23</td>
<td>762</td>
</tr>
<tr>
<td>3</td>
<td>55048</td>
<td>17.3</td>
<td>0.235</td>
<td>2.95</td>
<td>257</td>
<td>25</td>
<td>0.897</td>
<td>0.519</td>
<td>0.761</td>
<td>469</td>
<td>0.185</td>
<td>1.211</td>
<td>683</td>
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<tr>
<td>4</td>
<td>55059</td>
<td>21.9</td>
<td>0.444</td>
<td>3.29</td>
<td>376</td>
<td>25</td>
<td>1.27</td>
<td>0.657</td>
<td>0.719</td>
<td>443</td>
<td>1.39</td>
<td>1.533</td>
<td>647</td>
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<td>5</td>
<td>55954</td>
<td>30.0</td>
<td>1.021</td>
<td>1.51</td>
<td>351</td>
<td>25</td>
<td>1.87</td>
<td>0.924</td>
<td>0.705</td>
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(Δ) Copper loss, iron loss
Definitions for Table 2-3

Information given is listed by column as:

1. Manufacturer part number
2. Surface area calculated from Figure 2-22
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 7-2 for a $\Delta T$ 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 7-2 for a $\Delta T$ 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 in grams
15. Transformer volume calculated from Figure 2-6
16. Core effective cross-section
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<td>AWG</td>
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<td>\Delta T 25°C</td>
<td>J = I/cm²</td>
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Copper loss = Iron loss
Definitions for Table 2-4

Information given is listed by column as:

1. Manufacturer part number
2. Surface area calculated from Figure 2-23
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 $50^\circ C$
7. Watts loss is based on Figure 7-2 for a $\Delta T$ of $25^\circ C$ with a room ambient of $25^\circ C$ 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 $75^\circ C$
11. Watts loss is based on Figure 7-2 for a $\Delta T$ of $50^\circ C$ with a room ambient of $25^\circ C$ 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 in grams
15. Transformer volume calculated from Figure 2-7
16. Core effective cross-section (thickness, 0.014) square stack
| Core    | A \(_1\) cm\(^2\) | A \(_p\) cm\(^2\) | MLT cm | N/0.0089 | P_L | 1 \(\sqrt{W/G}\) | \(\Delta T\) 5°C | 1 \(\sqrt{W/G}\) | \(\Delta T\) 75°C | 1 \(\sqrt{W/G}\) | Weight \(l_{Cu}\) | Volume cm\(^3\) | A \(_e\) cm\(^2\) |
|---------|-----------------|-----------------|--------|----------|-----|----------------|-------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------|
| EE-3931 | 4.11            | 0.0089          | 1.72   | 90       | 30  | 0.58           | 0.123             | 0.323            | 638            | 0.045        | 0.288          | 0.472          | 932            | 1.02        | 1.02  |
| EE-2829 | 6.63            | 0.0228          | 2.33   | 147      | 30  | 1.30           | 0.199             | 0.276            | 546            | 1.43         | 0.464          | 0.403          | 795            | 2.1    | 1.59 |
| El-187  | 14.4            | 0.196           | 3.20   | 314      | 30  | 3.82           | 0.432             | 0.237            | 469            | 4.19         | 1.01           | 0.347          | 635            | 7.09    | 3.08 |
| EE-2425 | 23.8            | 0.293           | 5.08   | 499      | 30  | 9.61           | 0.714             | 0.192            | 380            | 16.5        | 1.67           | 0.281          | 555            | 15.6  | 9.06 |
| EE-2627 | 40.6            | 0.906           | 5.79   | 245      | 25  | 1.68           | 1.12              | 0.602            | 371            | 1.85         | 2.84           | 0.876          | 540            | 45.4  | 15.6 |
| El-375  | 47.7            | 1.23            | 6.30   | 350      | 25  | 2.62           | 1.43              | 0.526            | 322            | 2.87         | 3.34           | 0.762          | 470            | 49.7  | 21.7 |
| El-50   | 57.7            | 1.75            | 7.09   | 263      | 25  | 2.21           | 1.73              | 0.645            | 385            | 2.43         | 4.04           | 0.912          | 962            | 90.6  | 31.7 |
| El-21   | 66.0            | 2.16            | 7.97   | 372      | 25  | 3.34           | 1.98              | 0.544            | 335            | 3.66         | 4.62           | 0.793          | 489            | 49.3  | 41.0 |
| El-625  | 90.0            | 4.29            | 8.84   | 503      | 25  | 5.27           | 2.70              | 0.505            | 312            | 5.79         | 6.30           | 0.737          | 455            | 159    | 44.4 |
| El-75   | 130.0           | 8.09            | 10.6   | 211      | 20  | 0.826          | 3.90              | 1.54             | 296            | 0.906        | 9.10           | 2.24           | 432            | 112    | 105 |
| El-87   | 176.0           | 16.5            | 12.3   | 294      | 20  | 1.34           | 5.28              | 1.40             | 270            | 1.48         | 12.3          | 2.04           | 393            | 841    | 135 |
| El-100  | 230.0           | 28.1            | 14.5   | 386      | 20  | 2.07           | 6.90              | 1.29             | 249            | 2.27         | 16.1          | 1.88           | 363            | 712    | 241 |
| El-112  | 252.0           | 44.9            | 16.0   | 492      | 20  | 2.91           | 8.76              | 1.23             | 237            | 3.19         | 20.4          | 1.79           | 344            | 102    | 142 |
| El-125  | 361.0           | 68.7            | 17.7   | 645      | 20  | 4.09           | 10.8              | 1.15             | 222            | 4.49         | 25.3          | 1.68           | 324            | 1411   | 460 |
| El-138  | 432.0           | 107.0           | 19.5   | 740      | 20  | 5.33           | 13.0              | 1.10             | 213            | 5.85         | 30.2          | 1.61           | 310            | 1890   | 640 |
| El-150  | 518.0           | 141.0           | 21.2   | 893      | 20  | 6.99           | 15.5              | 1.05             | 203            | 7.67         | 76.3          | 1.54           | 296            | 2457   | 706 |
| El-175  | 704.0           | 261.0           | 24.7   | 1083     | 20  | 9.85           | 21.1              | 1.034            | 199            | 10.8         | 49.3          | 1.51           | 291            | 3575   | 2355 |
| El-36   | 778.0           | 324.0           | 26.5   | 1701     | 20  | 16.6           | 23.3              | 0.836            | 161            | 18.3         | 54.5          | 1.22           | 235            | 3706   | 1273 |
| El-19   | 1093.0          | 609.0           | 31.7   | 2886     | 20  | 33.8           | 32.8              | 0.696            | 134            | 37.1         | 76.5          | 1.015          | 196            | 4889   | 1805 |

* Copper loss + iron loss*
Definitions for Table 2-5

Information given is listed by column as:

1. Manufacturer part number
2. Surface area calculated from Figure 2-24
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 7-2 for a $\Delta T$ of 25°C with a room ambient of 25°C surface dissipation times the transformer surface area, total loss is equal to $2P_{cu}$
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 7-2 for a $\Delta T$ of 50°C with a room ambient of 25°C surface dissipation times the transformer surface area, total loss is equal to $2P_{cu}$
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 in grams
15. Transformer volume calculated from Figure 2-8
16. Core effective cross-section
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Table 2-5. C-core characteristics

| Copper loss = Iron loss |
Definitions for Table 2-6

Information given is listed by column as:

1. Manufacturer part number
2. Surface area calculated from Figure 2-25
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 7-2 for a $\Delta T$ 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 7-2 for a $\Delta T$ 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 in grams
15. Inductor volume calculated from Figure 2-9
16. Core effective cross-section
Table 2-6. Single-coil C-core characteristics

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<th>$P_\Sigma$</th>
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<th>$\Delta T 25^\circ C$</th>
<th>$J @ 1/cm^2$</th>
<th>$P_\Sigma$</th>
<th>$\frac{\sqrt{V}}{D}$</th>
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<th>$J @ 1/cm^2$</th>
<th>Weight Cu</th>
<th>Volume cm$^3$</th>
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Definitions for Table 2-7

Information given is listed by column as:

1. Manufacturer part number
2. Surface area calculated from Figure 2-22
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 7-2 for a $\Delta T$ of 25°C with a room ambient of 25°C surface dissipation times the transformer surface area, total loss is equal to $2P_{cu}$
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 7-2 for a $\Delta T$ of 50°C with a room ambient of 25°C surface dissipation times the transformer surface area, total loss is equal to $2P_{cu}$
12. Current calculated from column 10 and 11
13. Current density calculated from column 5 and 12
14. Effective core weight plus copper weight in grams
15. Transformer volume calculated from Figure 2-6
16. Core effective cross-section
Table 2-7. Tape-wound core characteristics

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<th>N/A</th>
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<th>$\Delta T \text{ \circ C} \cdot f \cdot 10^{-4} \text{ cm}^2$</th>
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<td>2.37</td>
<td>1.81</td>
<td>2.24</td>
<td>2.19</td>
<td>0.490</td>
<td>0.88</td>
<td>1.58</td>
<td>0.88</td>
<td>0.632</td>
<td>0.632</td>
</tr>
<tr>
<td>12</td>
<td>24094</td>
<td>1.33</td>
<td>2.37</td>
<td>1.81</td>
<td>2.24</td>
<td>2.19</td>
<td>0.490</td>
<td>0.88</td>
<td>1.58</td>
<td>0.88</td>
<td>0.633</td>
<td>0.633</td>
</tr>
<tr>
<td>13</td>
<td>24094</td>
<td>1.33</td>
<td>2.37</td>
<td>1.81</td>
<td>2.24</td>
<td>2.19</td>
<td>0.490</td>
<td>0.88</td>
<td>1.58</td>
<td>0.88</td>
<td>0.634</td>
<td>0.634</td>
</tr>
<tr>
<td>14</td>
<td>24094</td>
<td>1.33</td>
<td>2.37</td>
<td>1.81</td>
<td>2.24</td>
<td>2.19</td>
<td>0.490</td>
<td>0.88</td>
<td>1.58</td>
<td>0.88</td>
<td>0.635</td>
<td>0.635</td>
</tr>
<tr>
<td>15</td>
<td>24094</td>
<td>1.33</td>
<td>2.37</td>
<td>1.81</td>
<td>2.24</td>
<td>2.19</td>
<td>0.490</td>
<td>0.88</td>
<td>1.58</td>
<td>0.88</td>
<td>0.636</td>
<td>0.636</td>
</tr>
<tr>
<td>16</td>
<td>24094</td>
<td>1.33</td>
<td>2.37</td>
<td>1.81</td>
<td>2.24</td>
<td>2.19</td>
<td>0.490</td>
<td>0.88</td>
<td>1.58</td>
<td>0.88</td>
<td>0.637</td>
<td>0.637</td>
</tr>
</tbody>
</table>

* copper loss = iron loss
C. TRANSFORMER VOLUME

The volume of a transformer can be related to the area product $A_p$ of a transformer, treating the volume as shown in Figures 2-6 through 2-9 below as solid quantity without subtraction of anything for the core window. Derivation of the relationship is according to the following: volume varies in accordance with the cube of any linear dimension $l$ (designated $l^3$ below), where area product $A_p$ varies as the fourth power:

$$\text{Vol} = K_1 l^3$$  \hspace{1cm} (2-1)

$$A_p = K_2 l^4$$  \hspace{1cm} (2-2)

$$l^4 = \frac{A_p}{K_2}$$  \hspace{1cm} (2-3)

$$l = \left(\frac{A_p}{K_2}\right)^{0.25}$$  \hspace{1cm} (2-4)

$$l^3 = \left[\left(\frac{A_p}{K_2}\right)^{0.25}\right]^3 = \left(\frac{A_p}{K_2}\right)^{0.75}$$  \hspace{1cm} (2-5)

$$\text{Vol} = K_1 \left(\frac{A_p}{K_2}\right)^{0.75}$$  \hspace{1cm} (2-6)
Fig. 2-6. Tape-wound core, powder core, and pot core volume

Fig. 2-7. EI Lamination core volume

Fig. 2-8. C-core volume

Fig. 2-9. Single-coil C-core volume
The volume/area product relationship is

$$\text{Vol} = K_v A_p^{0.75}$$

in which $K_v$ is a constant related to core configuration, these values are given in Table 2-8. This constant was obtained by averaging the values in Tables 2-2 through 2-7, column 15.

The relationship between volume and area product $A_p$ for various core types is given in Figures 2-10 through 2-15. It was obtained from the data shown in Tables 2-2 through 2-7, in which the Vol and $A_p$ values are shown in columns 15 for volume, and column 3 for area product.

<table>
<thead>
<tr>
<th>Core type</th>
<th>$K_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pot core</td>
<td>14.5</td>
</tr>
<tr>
<td>Powder core</td>
<td>13.1</td>
</tr>
<tr>
<td>Lamination</td>
<td>19.7</td>
</tr>
<tr>
<td>C-core</td>
<td>17.9</td>
</tr>
<tr>
<td>Single-coil C-core</td>
<td>25.6</td>
</tr>
<tr>
<td>Tape-wound core</td>
<td>25.0</td>
</tr>
</tbody>
</table>

Table 2-8. Constant $K_v$.
Fig. 2-10. Volume versus area product $A_p$ for pot cores

Fig. 2-11. Volume versus area product $A_p$ for powder cores
Fig. 2-12. Volume versus area product $A_p$ for laminations

Fig. 2-13. Volume versus area product $A_p$ for C-cores
Fig. 2-14. Volume versus area product $A_p$ for single-coil C-cores

Fig. 2-15. Volume versus area product $A_p$ for tape-wound toroids
IV. TRANSFORMER WEIGHT

The total weight $W_t$ of a transformer can be related to the area product $A_p$. Derivation of the relationship is according to the following: weight $W_t$ varies in accordance with the cube of any linear dimension $\ell$ (designated $\ell^3$ below), whereas area product $A_p$ varies as the fourth power:

$$W_t = K_3 \ell^3$$  \hspace{1cm} (2-9)

$$A_p = K_2 \ell^4$$  \hspace{1cm} (2-10)

$$\ell^4 = \frac{A_p}{K_2}$$  \hspace{1cm} (2-11)

$$\ell = \left( \frac{A_p}{K_2} \right)^{0.25}$$  \hspace{1cm} (2-12)

$$\ell^3 = \left[ \left( \frac{A_p}{K_2} \right)^{0.25} \right]^3 = \left( \frac{A_p}{K_2} \right)^{0.75}$$  \hspace{1cm} (2-13)

$$W_t = K_3 \left( \frac{A_p}{K_2} \right)^{0.75}$$  \hspace{1cm} (2-14)

$$K_w = \frac{K_3}{K_2^{0.75}}$$  \hspace{1cm} (2-15)

$$W_t = K_w A_p^{0.75}$$  \hspace{1cm} (2-16)

The weight/area product relationship

$$W_t = K_w A_p^{0.75}$$  \hspace{1cm} 2-24
in which \( K_w \) is a constant related to core configuration, is shown in Table 2-9, which has been derived by averaging the values in Tables 2-2 through 2-7, column 14.

The relationship between weight and area product \( A_p \) for various core types is given in Figures 2-16 through 2-21. It was obtained from the data shown in Tables 2-2 through 2-7, in which the \( W_t \) and \( A_p \) values are shown in column 14 for weight, and column 3 for area product.

Table 2-9. Constant \( K_w \)

<table>
<thead>
<tr>
<th>Core type</th>
<th>( K_w )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pot core</td>
<td>48.0</td>
</tr>
<tr>
<td>Powder core</td>
<td>58.8</td>
</tr>
<tr>
<td>Lamination</td>
<td>68.2</td>
</tr>
<tr>
<td>C-core</td>
<td>66.6</td>
</tr>
<tr>
<td>Single-coil C-core</td>
<td>76.6</td>
</tr>
<tr>
<td>Tape-wound core</td>
<td>82.3</td>
</tr>
</tbody>
</table>

Fig. 2-16. Total weight versus area product \( A_p \) for pot cores
Fig. 2-17. Total weight versus area product $A_p^r$ for powder cores

Fig. 2-18. Total weight versus area product $A_p^r$ for laminations
Fig. 2-19. Total weight versus area product $A_p$ for C-cores

Fig. 2-20. Total weight versus area product $A_p$ for single-coil C-cores
Fig. 2-21. Total weight versus area product $A_p$ for tape-wound toroids

E. TRANSFORMER SURFACE AREA

The surface area $A_t$ of a transformer can be related to the area product $A_p$ of a transformer treating the surface area as shown in Figures 2-22 through 2-25. Derivation of the relationships is in accordance with the square of any linear dimension $l$ (designated $l^2$ below), where area product varies as the fourth power:

$$A_t = K_4 l^2$$  \hspace{1cm} (2-17)
Fig. 2-22. Tape-wound core, powder core, and pot core surface area $A_t$

$A_t = \text{SURFACE AREA}$

$A_t = \frac{\pi d^2}{2} \text{WOUND} + \pi d_{\text{WOUND}} X_{\text{HIT, CORE}} + \frac{d_{\text{WOUND}}}{2} \text{OD, CORE}$

Fig. 2-23. EI lamination surface area $A_t$

$A_t = \text{SURFACE AREA}$

$A_t\text{ LAMINATION} = 2 \text{ (FE + SF + SE - DA - 2DC)}$

$S = \text{BUILD}$

$A_t = \frac{\pi (2C + A)^2}{2} + D \pi (2C + A) + 2 (\text{FE + SF + SE - DA - 2DC})$

Fig. 2-24. C-core surface area $A_t$

$A_t = \text{SURFACE AREA}$

$A_t = 4E(2E+F) + 16D + 2(D+F)(G) + 2(2F+2E)(G) + 2(D+F)(2F+2E)$

Fig. 2-25. Single-coil C-core surface area $A_t$

$A_t = 2(E+F) + (D+2F) + (G+2E)(D+2F)-3EF$
The surface area/area product relationship

\[ A_p = K_2 t^4 \]  \hspace{1cm} (2-18)

\[ t^4 = \frac{A_p}{K_2} \]  \hspace{1cm} (2-19)

\[ t = \left(\frac{A_p}{K_2}\right)^{0.25} \]  \hspace{1cm} (2-20)

\[ t^2 = \left[\left(\frac{A_p}{K_2}\right)^{0.25}\right]^2 \]  \hspace{1cm} (2-21)

\[ t^2 = \left(\frac{A_p}{K_2}\right)^{0.5} \]  \hspace{1cm} (2-22)

\[ A_t = K_4 \left(\frac{A_p}{K_2}\right)^{0.5} \]  \hspace{1cm} (2-23)

\[ K_s = \frac{K_4}{K_2^{0.5}} \]  \hspace{1cm} (2-24)

\[ A_t = K_s A_p^{0.5} \]  \hspace{1cm} (2-25)

The surface area/area product relationship

\[ A_t = K_s A_p^{0.5} \]

in which \( K_s \) is a constant related to core configuration is shown in Table 2-10, which has been derived by averaging the values in Tables 2-2 through 2-7, column 2.
Table 2-10. Constant $K_B$

<table>
<thead>
<tr>
<th>Core type</th>
<th>$K_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pot core</td>
<td>33.8</td>
</tr>
<tr>
<td>Powder core</td>
<td>32.5</td>
</tr>
<tr>
<td>Lamination</td>
<td>41.3</td>
</tr>
<tr>
<td>C-core</td>
<td>39.2</td>
</tr>
<tr>
<td>Single-coil C-core</td>
<td>44.5</td>
</tr>
<tr>
<td>Tape-wound core</td>
<td>50.9</td>
</tr>
</tbody>
</table>

The relationship between surface area and area product $A_p$ for various core types is given in Figures 2-26 through 2-31. It was obtained from the data shown in Tables 2-2 through 2-7, in which the $A_t$ and $A_p$ values are shown in columns 2 for surface area, and column 3 for area product.

![Graph showing surface area versus area product $A_p$ for pot cores](image-url)
Fig. 2-27. Surface area versus area product $A_p$ for powder cores

Fig. 2-28. Surface area versus area product $A_p$ for laminations
Fig. 2-29. Surface area versus area product $A_p$ for C-cores

Fig. 2-30. Surface area versus area product $A_p$ for single-coil C-cores
Fig. 2-31. Surface area versus area product $A_p$ for tape-wound toroids

F. TRANSFORMER CURRENT DENSITY

Current density $J$ of a transformer can be related to the area product $A_p$ of a transformer for a given temperature rise.

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

$$A_t = K_s A_p^{0.5} \quad (2-26)$$

$$P_{cu} = I^2 R \quad (2-27)$$

$$I = A_w^{1/3} \quad \text{ORIGINAL PAGE IS OF POOR QUALITY} \quad (2-28)$$

2-34
\[ \therefore P_{cu} = A_w^2 J^2 R \] (2-29)

\[ R = \frac{MLT}{A_w} N_\rho \] (2-30)

\[ \therefore P_{cu} = A_w^2 J^2 \frac{MLT}{A_w} N_\rho \] (2-31)

\[ \frac{\gamma_{cu}}{MLT} = A_w J^2 N_\rho \] (2-32)

Since MLT has a dimension of length

\[ MLT = K_5 A_p^{0.25} \] (2-33)

\[ P_{cu} = A_w J^2 K_5 A_p^{0.25} N_\rho \] (2-34)

\[ A_w N = K_6 W_a - K_3 A_p^{0.5} \] (2-35)

\[ P_{cu} = K_6 A_p^{0.5} K_5 A_p^{0.25} J^2 \] (2-36)

\[ K_7 = K_6 K_5 \rho \] (2-37)

Assuming the core loss is the same as the copper loss for optimized transformer operation (See Chapter 7).

\[ P_{cu} = K_7 A_p^{0.75} J^2 - P_{fc} \] (2-38)

\[ P_{\Sigma} = P_{cu} + P_{fc} \] (2-39)

\[ \Delta T = K_8 \frac{P_{\Sigma}}{A_k} \] (2-40)
\[ \Delta T = \frac{2K_8 K_7^2 A_p^{0.75}}{K_s A_p^{0.5}} \]  
(2-41)

\[ K_9 = \frac{2K_8 K_7}{K_s} \]  
(2-42)

\[ \Delta T = K_9 J^2 A_p^{0.25} \]  
(2-43)

\[ J^2 = \frac{\Delta T}{K_9 A_p^{0.25}} \]  
(2-44)

\[ K_{10} = \frac{\Delta T}{K_9} \]  
(2-45)

\[ J^2 = K_{10} A_p^{0.25} \]  
(2-46)

\[ J = K_j A_p^{-0.125} \]  
(2-47)

The current density/area product relationship

\[ J = K_j A_p^{-0.125} \]

in which \( K_j \) is a constant related to core configuration, is shown in Table 2-11, which has been derived by averaging the values in Tables 2-2 through 2-7, columns 9 and 13.

*This is the theoretical value for current density/area product relationship. The empirical values for different core configuration are found in Table 2-1.*
Table 2-11. Constant $K_j$

<table>
<thead>
<tr>
<th>Core type</th>
<th>$K_j(\Delta 25^\circ)$</th>
<th>$K_j(\Delta 50^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pot core</td>
<td>433</td>
<td>632</td>
</tr>
<tr>
<td>Powder core</td>
<td>403</td>
<td>590</td>
</tr>
<tr>
<td>Lamination</td>
<td>366</td>
<td>534</td>
</tr>
<tr>
<td>C-type core</td>
<td>322</td>
<td>468</td>
</tr>
<tr>
<td>Single-coil C-core</td>
<td>395</td>
<td>569</td>
</tr>
<tr>
<td>Tape-wound core</td>
<td>250</td>
<td>365</td>
</tr>
</tbody>
</table>

The relationship between current density and area product $A_p$ for a temperature rise of 25°C and 50°C is given in Figures 2-32 through 2-37. It was obtained from the data shown in Tables 2-2 through 2-7, in which the $J$ and $A_p$ values are shown in columns 9 and 13 for current density, and column 3 for area product.

![Graph](image_url)  

Fig. 2-32. Current density versus area product $A_p$ for a 25°C and 50°C rise for pot cores
Fig. 2-33. Current density versus area product $A_p$ for a 25°C and 50°C rise for powder cores.

Fig. 2-34. Current density versus area product $A_p$ for 25°C and 50°C rise for laminations.
Fig. 2-35. Current density versus area product \( A_p \) for 25°C and 50°C rise for C-cores.

\[
p_o = \text{OUTPUT POWER} \\
p_{\text{cu}} = \text{COPPER LOSS} = p_{\text{fe}} \text{ IRON LOSS} \\
p_{\Sigma} = p_{\text{cu}} + p_{\text{fe}} = n - p_o
\]

Fig. 2-36. Current density versus area product \( A_p \) for a 25°C and 50°C rise for single-coil C-cores.
Fig. 2-37. Current density versus area product $A_p$ for 25°C and 50°C rise for tape-wound toroids.
CHAPTER III

POWER TRANSFORMER DESIGN
A. 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 tradeoffs are necessary to achieve design optimization.

B. 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 a specified temperature environment.

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 always 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 3-1.

![Transformer Flow Chart](image)

**Fig. 3-1.** 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 will work 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.
C. 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:

$$A_p = \left( \frac{P_t \times 10^4}{KB_{m} f w K_j} \right)^{0.16} \text{ [cm}^4\text{]} \quad (3-1)$$

where

- $K$ = waveform coefficient
  - 4.0 square wave
  - 4.43 sine wave
- $B_m$ = flux density, tesla
- $f$ = frequency, Hz
- $K_u$ = window utilization factor (see Chapter 6)
- $K_j$ = current density coefficient (see Chapter 2)
- $P_t$ = 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 Chapter 2. The derivation for area product $A_p$ is set forth in detail at the end of this chapter Appendix 3.A.

D. 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:

\[
P_t = P_{in} + P_o
\]  \hspace{1cm} (3-2)

\[
P_{in} = \frac{P_o}{\eta}
\]  \hspace{1cm} (3-3)

\[
P_t = \frac{P_o}{\eta} + P_o
\]  \hspace{1cm} (3-4)

\[
P_i = P_o\left(\frac{1}{\eta} + 1\right)
\]  \hspace{1cm} (3-5)

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 type of circuit in which the transformer is used. If the current in the rectifier transformer becomes interrupted, its effective RMS value changes. Transformer size, thus, is not only determined by the load demand but, also, by application because of the different copper losses incurred due to current waveform (see Chapter 7, Fig. 7-20).

For example, for a load of one watt, compare the power handling capabilities required for each winding (neglecting transformer and diode losses so that \(P_{in} = P_o\)) for the full-wave bridge circuit of Fig. 3-2, the full-wave center-tapped secondary circuit of Fig. 3-3, and the push-pull center-tapped full-wave circuit in Fig. 3-4, where all windings have the same number of turns \(N\).
The total apparent power $P_t$ for the circuit shown in Fig. 3-2 is 2 watts. This is shown in the following equation:

\[
P_t = (I_{N1} E_{N1}) + (I_{N2} E_{N2})
\]

(3-6)

\[
P_t = 2P_{in}
\]

(3-7)

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.

Fig. 3-3. Full-wave, center-tapped circuit
The total power $P_t$ for the circuit shown in Fig. 3-3 increased 20.7% due to the distorted waveform of the interrupted current flowing in the secondary winding. This is shown in the following equation:

$$P_t = (I_{N1} E_{N1}) + \left[ (0.707I_{N2} E_{N2}) + (0.707I_{N3} E_{N3}) \right] \tag{3-8}$$

$$P_t = P_{in} + 0.707 P_{in} + 0.707 P_{in} = 2.414 P_{in} \tag{3-9}$$

Rewriting equation 3-5 to incorporate the RMS rating,

$$P_t = P_o \left( \frac{1}{\eta} + \sqrt{2} \right) \tag{3-10}$$

Fig. 3-4. Push-pull, full-wave, center-tapped circuit

The total power $P_t$ for the circuit shown in Figure 3-4, which is typical of a dc to dc converter, increases to 2.828 times $P_{in}$ because of the interrupted current flowing in both the primary and secondary windings since
Again,

\[ P_t = \left[ 0.707I_{N1} E_{N1} \right] + \left[ 0.707I_{N2} E_{N2} \right] + \left[ 0.707I_{N3} E_{N3} \right] + \left[ 0.707I_{N4} E_{N4} \right] \]  \hspace{1cm} (3-11)

\[ P_t = 0.707 P_{in} + 0.707 P_{in} + 0.707 P_{in} + 0.707 P_{in} = 2.828 P_{in} \] \hspace{1cm} (3-12)

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 used by transformer 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.

E. A 2.5-kHz TRANSFORMER DESIGN PROBL. AS AN EXAMPLE

Assume a specification for a transformer design as shown in Fig. 3-2, requiring the following:

1. \( E_o' \) 10 volts
2. \( I_o \) 2.0 amperes
3. \( E_{in} \) 50 volts
4. \( f \), 2500 Hz (square wave)
5. Maximum temperature rise, 25°C
6. Transformer efficiency, 95%

Assuming the bridge rectifier of Fig. 3-2 and using the efficiency const. int of 95%:
Definitions for Table 3-1

Information given is listed by column as:

1. Manufacturer part number
2. Surface area calculated from Chapter 2, Fig. 2-24
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 Fig. 7-2 for a $\Delta T$ 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 Fig. 7-2 for a $\Delta T$ 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 in grams
15. Copper weight in grams
16. Transformer volume calculated from Chapter 2, Fig. 2-8
17. Core effective cross-section
## Table 3-1. C-core characteristics

<table>
<thead>
<tr>
<th>1</th>
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Notes: Copper loss = iron loss
Fig. 3-5. Magnetic material comparison at a constant frequency
**Step No. 1.** Calculate the apparent power $P_t$ from equation 3-5, allowing for 1.0 volt diode drop ($V_d$) assumed:

$$P_t = P_o \left( \frac{1}{\eta} + 1 \right)$$

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

$$P_t = 2 (10 + 2) \left( \frac{1}{0.95} + 1 \right)$$

$$P_t \approx 49.3 \text{ [watts]}$$

**Step No. 2.** Calculate the area product $A_p$ from equation 3-1:

$$A_p = \left( \frac{P_t \times 10^4}{KB_{mKuK_j}} \right)^{1.16}$$

Assuming

$K = 4.0$

$B_m = 0.3 \text{ [tesla]}$

$K_u = 0.4 \text{ (Chapter 6)}$

$K_j = 323 \text{ (Chapter 2)}$

$$A_p = \left( \frac{(49.3) \times 10^4}{(4.0)(0.3)(2500)(0.4)(323)} \right)^{1.16}$$

or

$$A_p = 1.32 \text{ [cm}^4\text{]}$$

After the $A_p$ has been determined, the geometry of the transformer can be evaluated as described in Chapter 2 for weight, for surface area, and 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.

Step No. 3. Select a C-core from Table 3-1 with a value of $A_p$ closest to the one calculated.

AL-124 with an $A_p = 1.44 \text{ [cm}^4\text{]}$

Step No. 4. Calculate the total transformer losses $P_\Sigma$:

$$P_\Sigma = \frac{P_0}{\eta} - P_0 \quad \text{[watts]}$$

$$P_\Sigma = \frac{24}{0.95} - 24$$

$$P_\Sigma = 1.74 \quad \text{[watts]}$$

Maximum efficiency is realized when the copper (winding) losses are equal to the iron (core) losses (see Chapter 7):

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

and therefore

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

and thus

$$P_{cu} = \frac{1.26}{2}$$

$$P_{cu} = 0.63 = P_{fe}$$
Step No. 5. Select the core weight from Table 3-1, column 14, then calculate the core loss in milliwatts per gram:

\[ P_{lw} \times 10^3 = \text{milliwatts/g} \]

\[ \frac{0.64}{46.6} \times 10^3 = \text{milliwatts/g} \]

13.5 milliwatts/g

Step No. 6. Select the proper magnetic material in Fig. 3-5, reading from the 2.5 kHz frequency curve for a flux density of 0.3 tesla. The magnetic material that comes closest to 13.5 milliwatts per gram is silicon steel, with approximately 12 milliwatts per gram. With a weight of 46.6 grams, the total core loss is 560 milliwatts, which meets the requirement of the design.

Step No. 7. Calculate the number of primary turns using Faraday's l.w., equation 3.A-1.

\[ N_p = \frac{E \times 10^4}{4 \varphi B A_c r} \]

The iron cross section \( A_c \) is found in Table 3-1, column 17:

\[ A_c = 0.716 \quad \text{[cm}^2) \]

Thus

\[ N_p = \frac{(50) \times 10^4}{(4)(0.3)(0.716)(2500)} \]

*See Appendix 3.A, at the end of Chapter 3.
or

\[ N_p = 233 \text{ turns (primary)} \]

**Step No. 8.** Calculate the current density \( J \) from equation 3.17:

\[ J = K_j A_p^{-0.14} \]

(The value for \( K_j \) is found in Table 2-1.)

\[ J = (323)(1,32)^{-0.14} \]

\[ J = 307 \quad \left[A/cm^2\right] \]

**Step No. 9.** Calculate the primary current \( I_p \) and wire size \( A_w \):

\[ I_p = \frac{P_t}{2 L_p} \quad \left[A\right] \]

\[ I_p = \frac{(49,3)}{(2)(50)} \]

\[ I_p = 0.493 \quad \left[A\right] \]

The bare wire size \( A_{w(B)} \) for the primary is

\[ A_{w(B)} = \frac{I_p}{J} \]

\[ A_{w(B)} = \frac{0.493}{307} \quad \left[A/cm^2\right] \]

\[ A_{w(B)} = 0.001606 \quad \left[A/cm^2\right] \]
Step No. 10. Select the wire area $A_w$ in Table 6-1 for equivalent (AWG) wire size, column A.

AWG No. 25 = 0.001623 \text{ cm}^2

The rule is that when the calculated wire size does not fall close to those listed in the table, the next smaller size should be selected.

Step No. 11. Calculate the resistance of the primary winding, using Table 6-1, column C, and Table 3-1, column 4, for the MLT:

$$R_p = \text{MLT} \times N \times (\text{column C}) \times \zeta \times 10^{-6} \text{ [\Omega]}$$

$$R_p = (5.5)(233)(1062)(1.098) \times 10^{-6}$$

$$R_p = 1.49 \text{ [\Omega]}$$

Step No. 12. Calculate the primary copper loss $P_{cu}$:

$$P_{cu} = I_p^2 R_p$$

$$P_{cu} = (0.493)^2 (1.49)$$

$$P_{cu} = 0.362 \text{ [watts]}$$

Step No. 13. Calculate the secondary turns:

$$N_s = \frac{N}{E_p} (E_s)$$

$$E_s = \phi + 2 V_d$$

$$N_s = \frac{233}{(50)^2} (12)$$

$$N_s = 56$$
Step No. 14. Calculate the wire size $A_w(B)$ for the secondary winding:

$$A_w(B) = \frac{I_s}{J}$$

$$A_w(B) = \frac{(2)}{(307)}$$

$$A_w(B) = 0.00651 \text{ cm}^2$$

Step No. 15. Select the wire area $A_w$ in Table 6-1 for equivalent (AWG) wire size, column A:

AWG No. 19 = 0.00653 \text{ cm}^2

The rule is that when the calculated wire size does not fall close to those listed in the table, the next smaller size should be selected.

Step No. 16. Calculate the resistance of the secondary winding, using Table 6-1, column C, and Table 3-1, column 4, for the MLT.

$$R_s = \text{MLT} \times N \times (\text{column C}) \times \xi \times 10^{-6} \Omega$$

$$R_s = (5.5)(56)(264)(1.098) \times 10^{-6}$$

$$R_s = 0.0893 \Omega$$

Step No. 17. Calculate the secondary copper loss $P_{cu}$:

$$P_{cu} = I_s^2 R_s$$

$$P_{cu} = (2.0)^2 (0.0813)$$

$$P_{cu} = 0.357 \text{ watts}$$
Step No. 18. Summarize the losses and compare with the total losses $P_\Sigma$:

- Primary $P_{cu} = 0.362$ [watts]
- Secondary $P_{cu} = 0.357$ [watts]
- Core $P_{fc} = 0.560$ [watts]
- Total $P_\Sigma = 1.279$ [watts]

The total power loss in the transformer is 1.279 watts, which will effectively meet the required 95% efficiency.

From Chapter 7, the surface area $A_t$ required to dissipate waste heat (expressed as watts loss per unit area) is:

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

where

$$\psi = 0.03 \text{ W/cm}^2 \text{ at } 25^\circ \text{C rise}$$

Referring to Table 3-1, column 1, for the AL-124 size core, the surface area $A_t$ is 45.3 cm$^2$:

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

and thus

$$\psi = \frac{1.279}{45.3}$$
which will produce the required temperature rise.

F. A 10-kHz TRANSFORMER DESIGN PROBLEM AS AN EXAMPLE

Assume a specification for a transformer design, as shown in Fig. 3-3, requiring the following:

1. $E_o$, 56 volts
2. $I_o$, 1.79 amperes
3. $E_{in}$, 200 volts
4. $f$, 10 kHz (square wave)
5. Maximum temperature rise, 25°C
6. Transformer efficiency, 98%

assuming the full-wave, center-tapped rectifier of Fig. 3-3 and using the efficiency constraint of 98%.

Step No. 1. Calculate the apparent power $P_t$ from equation 3-10, allowing for 1.0 volt diode drop ($V_d$) assumed:

$$F_t = \left( \frac{1}{\eta} + \sqrt{2} \right)$$

$$P_t = I_o (E_o + V_d) \times \left( \frac{1}{\eta} + \sqrt{2} \right)$$

$$P_t = 1.79 (56 + 1) \times \left( \frac{1}{0.98} + 1.41 \right)$$

$$P_t = 248 \text{ [watts]}$$
Step No. 2. Calculate the area product $A_p$ from equation 3-1:

$$A_p = \left( \frac{P_t \times 10^4}{K B_n f K_u K_j} \right)^{1.16} \quad [\text{cm}^4]$$

assuming

$$K = 4.0$$
$$B_m = 0.3 \quad [\text{tesla}]$$
$$K_u = 0.4 \text{ (Chapter 6)}$$
$$K_j = 323 \text{ (Chapter 2)}$$

$$A_p = \left( \frac{248 \times 10^4}{(4.0)(0.3)(10^4)(0.4)(323)} \right)^{1.16}$$

or

$$A_p = 1.72 \quad [\text{cm}^4]$$

after the $A_p$ has been determined, the geometry of the transformer can be evaluated as described in Chapter 2 for weight, for surface area, and 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.

Step No. 3. Select a C-core from Table 3-1 with a value of $A_p$ closest to the one calculated:

AL-8 with an $A_p = 2.31 \quad [\text{cm}^4]$
Step No. 4. Calculate the total transformer losses $P_\Sigma$:

$$P_\Sigma = \frac{P_o}{\eta} - P_o \quad \text{[watts]}$$

$$P_\Sigma = \left( \frac{102}{0.98} \right) - (102)$$

$$P_\Sigma = 2.08 \quad \text{[watts]}$$

Maximum efficiency is realized when the copper (winding) losses are equal to the iron (core) losses (see Chapter 7) which is expressed as

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

and therefore

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

and thus

$$P_{cu} = \frac{2.08}{2}$$

$$P_{cu} = 1.04 \quad \text{[watts]}$$

Step No. 5. Select the core weight from Table 3-1, Column 14, then calculate the core loss in milliwatts per gram:

$AL-8$ $W_t = 66.6$ grams

$$\frac{P_{fe}}{W_t} \times 10^3 = \text{milliwatts/g}$$

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Step No. 6. Select the proper magnetic material in Fig. 3-5, reading from the 10-kHz frequency curve with a density of 0.3 tesla. The magnetic material that comes closest to 15.6 milliwatts per gram is Permalloy 80, with approximately 12 milliwatts per gram. When nickel steel is used, Table 7-1 provides a weight correction factor.

The weight from Table 3-1 is multiplied by the weight correction factor:

\[
66.6 \times 1.144 = 76.2 \text{ [grams]}
\]

With a weight of 76.2 grams the total core loss is

\[
12 \times 76.2 \times 10^{-3} = 0.914 \text{ [watts]}
\]

Step No. 7. Calculate the number of primary turns using Faraday's law, equation 3. A-1:

\[
N_p = \frac{E_p \times 10^4}{4BmAc^2}
\]

The iron cross section \(A_c\) is found in Table 3-1, column 17:

\[
A_c = 0.606 \text{ [cm}^2\text{]}
\]

\[
N_p = \frac{(200) \times 10^4}{(4)(0.0)(0.806)10^4}
\]

\[
N_p = 207 \text{ turns (primary)}
\]
Step No. 8. Calculate the current density \( J \) from equation 3. A-17:

\[
J = K_j A^{-0.14}
\]

The value for \( K_j \) is found in Table 2-1:

\[
J = (323)(2.31)^{-0.14}
\]

\[
J = 287 \quad [\text{A/cm}^2]
\]

Step No. 9. Calculate the primary current \( I_p \) and wire size \( A_w \):

\[
I_p = \frac{I_o (E_o + V_d)}{E_p \eta} \quad [\text{A}]
\]

\[
I_p = 1.79 \frac{(56 + 1)}{(200)(0.98)}
\]

\[
I_p = 0.520 \quad [\text{A}]
\]

The bare wire size for the primary is

\[
A_w(B) = \frac{I_p}{J} \quad [\text{cm}^2]
\]

\[
A_w(B) = \frac{0.520}{287}
\]

\[
A_w(B) = 0.00181 \quad [\text{cm}^2]
\]

Step No. 10. Select the wire area \( A_w(B) \) in Table 6-1 for equivalent (AWG) wire size, column A:

AWG No. 25 = 0.001623 \quad [\text{cm}^2]

The rule is that when the calculated wire size does not fall close to those listed in the table, the next smaller size should be selected.
Step No. 11. Calculate the resistance of the primary winding, using Table 6-1, column C, and Table 3-1, column 4, for the MLT:

\[ R_p = \text{MLT} \times N \times (\text{column C}) \times \xi \times 10^{-6} \quad [\Omega] \]

\[ R_p = (5.74)(207)(1062)(1.098) \times 10^{-6} \]

\[ R_p = 1.38 \quad [\Omega] \]

Step No. 12. Calculate the primary copper loss \( P_{cu} \):

\[ P_{cu} = I_p^2 R_p \quad [\text{watts}] \]

\[ P_{cu} = (0.520)^2 (1.38) \]

\[ P_{cu} = 0.373 \quad [\text{watts}] \]

Step No. 13. Calculate the secondary turns:

\[ N_s = \frac{N}{E_p} (E_s) \]

\[ E_s = 56 + 1 \ V_d \]

\[ N_s = \frac{(207)}{(200)} (57) \]

\[ N_s = 59 \text{ turns secondary} \]
Step No. 14. Calculate the wire size $A_{w(B)}$ for the secondary winding (see equation 3-8):

\[
A_{w(B)} = \frac{I_o (0.707)}{J} \quad [\text{cm}^2]
\]

\[
A_{w(B)} = 1.79 (0.707) = 1.25 \quad [\text{cm}^2]
\]

\[
A_{w(B)} = 0.0044 \quad [\text{cm}^2]
\]

Step No. 15. Select the bare wire area $A_{w(B)}$ in Table 6-1 for equivalent (AWG) wire size, column A:

AWG No. 21 = 0.00411

[cm²]

The rule is that when the calculated wire size does not fall close to those listed in the table, the next smaller size should be selected.

Step No. 16. Calculate the resistance of the secondary winding, using Table 6-1, column C, and Table 3-1, column 4, for the MLT:

\[
R_s = \text{MLT} \times N \times (\text{column C}) \times \xi \times 10^{-6}
\]

\[
R_s = (5.74)(59)(419)(1.098) \times 10^{-6}
\]

\[
R_s = 0.156 \quad [\Omega]
\]

Step No. 17. Calculate the total secondary copper loss $P_{cu}$, $N_2$ plus $N_3$ (see Fig. 3-3):

\[
P_{cu} = (I_o \times 0.707)^2 R_s + (I_o \times 0.707)^2 R_s \quad [\text{watts}]
\]
Step No. 18. Summarize the losses and compare with the total losses $P_\Sigma$: 

- Primary $P_{Cu} = 0.373$ [watts]
- Secondary $P_{Cu} = 0.499$ [watts]
- Core $P_{fc} = 1.07$ [watts]
- Total $P_\Sigma = 1.942$ [watts]

The total power loss in the transformer is 1.942 watts, which will meet the required 98% efficiency.

From Chapter 7, the surface area $A_t$ required to dissipate waste heat (expressed as watts loss per unit area) is

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

where

$$\psi = 0.03 \text{ W/cm}^2 \text{ at } 25^\circ \text{C rise}$$

Referring to Table 3-1, column 1, for the AL-8 size core, the surface area $A_t$ is 63.4 cm$^2$:

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

$$\psi = \frac{1.942}{63.4}$$

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$$P_{Cu} = 2 (1.79 \times 0.707)^2 0.156$$

$$P_{Cu} = 0.499$$ [watts]
\[ \psi = 0.0306 \, \text{[W/cm}^2\text{]} \]

which will produce the required temperature rise.

REFERENCES


APPENDIX 3. A
TRANSFORMER POWER HANDLING CAPABILITY

The power handling capability of a transformer can be related to \( A_p \), a quantity (which is the \( W_a A_c \) 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\(^2\)), as follows.

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

\[
E = KB_m A_c N f \times 10^{-4} \quad \text{(3, A-1)}
\]

(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:

\[
N A_c = \frac{E \times 10^4}{4 B_m f} \quad \text{(3, A-2)}
\]

for the following manipulation.

By definition the window utilization factor is:

\[
K_w = \frac{N A_w}{W_a} \quad \text{(3, A-3)}
\]

and this may be restated as:

\[
N = \frac{K_w W_a}{A_w} \quad \text{(3, A-4)}
\]
If both sides of the equation are multiplied by $A_c$, then:

$$N A_c = \frac{K_u W_a A_c}{A_w} \quad (3, \text{A-5})$$

From equation 3.A-2:

$$K_u W_a A_c = \frac{E \times 10^4}{4 B_m f} \quad (3, \text{A-6})$$

Solving for $W_a A_c$:

$$W_a A_c = \frac{E A_w \times 10^4}{4 B_m f K_u} \quad (3, \text{A-7})$$

By definition, current density $J = \text{amp/cm}^2$ which may also be stated:

$$J = \frac{I}{A_w} \quad (3, \text{A-8})$$

which may also be stated as:

$$A_w = \frac{I}{J} \quad (3, \text{A-9})$$

It will be remembered that transformer efficiency is defined as:

$$\eta = \frac{P_o}{P_{in}} \quad \text{and} \quad P_{in} = EI \quad (3, \text{A-10})$$

Rewriting equation 3.A-7 as:

$$EA_w = 4B_m fK_u W_a A_c 10^{-4} \times \frac{EI}{J} \quad (3, \text{A-11})$$
and since:

$$\frac{E_l}{J} = \frac{P_{in}}{J} = \frac{P_o}{J \eta} \quad (3, A-12)$$

then:

$$\begin{align*}
W_a A_c |_{total} &= W_a A_c |_{Primary} + W_a A_c |_{Secondary} \\
&= \frac{P_o \times 10^4}{\eta J} \frac{4BmK_u}{4BmK_u J} + \frac{P_o \times 10^4}{4BmK_u} (1/\eta + 1) \quad (3, A-13)
\end{align*}$$

and since

$$P_t = \frac{P_o}{\eta} + P_o \quad (3, A-14)$$

then

$$W_a A_c = \frac{P_t \times 10^4}{4BmK_u J} \quad (3, A-15)$$

and

$$A_p = \frac{P_t \times 10^4}{4BmK_u} \quad (3, A-16)$$

Combining the equation from Table 2-1,

$$J = K_j A_p^{-0.14} \quad (3, A-17)$$
yielding

\[ A_p = \frac{P_t \times 10^4}{4 B_m f K u (K_j A_p^{-0.14})} \]  \hspace{1cm} (3. A-18)

\[ A_p^{0.86} = \frac{P_t \times 10^4}{4 B_m f K u K_j} \]  \hspace{1cm} (3. A-19)

\[ A_p = \left( \frac{P_t \times 10^4}{4 B_m f K u K_j} \right)^{1.16} \]  \hspace{1cm} \left[ cm^4 \right] \hspace{1cm} (3. A-20)
CHAPTER IV

SIMPLIFIED CUT CORE INDUCTOR DESIGN
A. INTRODUCTION

Designers have used various approaches in arriving at suitable inductor designs. For example, in many cases a rule of thumb used for dealing with current density is that a good working level is 1000 circular mils per ampere. This is satisfactory in many instances; however, the wire size used to meet this requirement may produce a heavier and bulkier inductor than desired or required. The information presented herein will make it possible to avoid the use of this and other rules of thumb and to develop a more economical and a better design.

B. CORE MATERIAL

Designers have routinely tended to specify moly permalloy powder core materials for filter inductors used in high frequency power converters and pulse-width modulated (PWM) switched regulators because of the availability of manufacturers' literature containing tables, graphs and examples which simplify the design task. Use of these cores may not result in an inductor design optimized for size and weight. For example as shown in Figure 4-1, 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 the original inductance at 1.2 tesla.

There are significant advantages to be gained by the use of C cores and cut toroids fabricated from grain-oriented silicon steel, despite such disadvantages as the need for banding and gapping materials, banding tools, mounting brackets and winding mandrels.

See Reference 1.
Grain-oriented silicon steels provide greater flexibility in the design of high frequency inductors because the air gap can be adjusted to any desired length and because the relative permeability is high even at high 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 on the other hand have useful flux density capabilities to only about 0.3 tesla.

C. 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 the equation which may be stated as follows:
\[ A_p^w = \left( \frac{2(Eng) \times 10^4}{B_m K_u K_j} \right)^{1.16} \text{ [cm}^4\text{]} \] (4-1)

\[ K_j = \text{current density coefficient} \]
(See Chapter 2.)

\[ K_u = \text{window utilization factor} \]
(See Chapter 6.)

\[ B_m = \text{flux density, tesla} \]

\[ Eng = \text{energy, watt seconds} \]

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 Chapter 2.

**D. FUNDAMENTAL CONSIDERATIONS**

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

1. Desired inductance
2. Direct current
3. Alternating current \( \Delta I \)
4. Power loss and temperature rise

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 4-1 as follows.

---

Deviation is set forth in detail in Appendix 4. A at the end of this chapter.
Table 4-1. Magnetic material

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Flux Density (tesla)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesil</td>
<td>3% Si, 97% Fe</td>
</tr>
<tr>
<td>Orthonol</td>
<td>50% Ni, 50% Fe</td>
</tr>
<tr>
<td>48 Alloy</td>
<td>48% Ni, 50% Fe</td>
</tr>
<tr>
<td>Permalloy</td>
<td>79% Ni, 17% Fe, 4% Mo</td>
</tr>
</tbody>
</table>

It should be remembered that maximum flux density depends upon $B_{dc} + B_{ac}$ in manner shown in Figure 4-2.

![Figure 4-2](image)

Fig. 4-2. Flux density versus $I_{dc} + \Delta I$

\[ B_{1-\alpha x} = B_{dc} + B_{ac} \] [tesla]

\[ B_{dc} = \frac{0.4\pi NI_{dc} \times 10^{-4}}{1g + \frac{1m}{\mu r}} \] [tesla] \hspace{1cm} (4-2)

\[ B_{ac} = \frac{0.4\pi N \Delta I}{2} \times 10^{-4} \] [tesla] \hspace{1cm} (4-3)
Combining Eqs. (4-2) and (4-3),

$$B_{\text{max}} = \frac{0.4\pi NI_{\text{dc}} \times 10^{-4}}{1 + \frac{m}{g \mu_r}} + \frac{0.4\pi N \Delta I}{2} \times 10^{-4} \quad \text{[tesla]} \quad (4-4)$$

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

$$L = \frac{0.4\pi N^2 A_c \times 10^{-8}}{1 + \frac{m}{g \mu_r}} \quad \text{[henry]} \quad (4-5)$$

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 ($l_m/\mu_r$).

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

$$L = \frac{0.4\pi N^2 A_c \times 10^{-8}}{l_g} \quad \text{[henry]} \quad (4-6)$$

Final determination of the air gap size 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 4-6. Fringing flux is a larger percentage of the total for larger gaps. The fringing flux factor is:

\[ F' = \left(1 + \frac{1}{\sqrt{\frac{G}{A_c}}} \log_e \frac{2G}{g}\right) \tag{4-7} \]

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

Equation (4-7) is plotted in Figure 4-3 below.

![Figure 4-3](image)

**Fig. 4-3.** Increase of reactor inductance with flux fringing at the gap.

Inductance \( L \) computed in equation (4-6) does not include the effect of fringing flux. The value of inductance \( L' \) corrected for fringing flux is:

\[ L' = \frac{0.4\pi N^2 A_c F \times 10^{-8}}{\log_e \frac{2G}{g}} \text{ [henry]} \tag{4-8} \]

*See Reference 2.*
Effective permeability may be calculated from the following expression:

$$\mu_{\Delta} = \frac{\mu_m}{1 + \frac{g}{l_m} \mu_m}$$

$$\mu_m = \text{core material permeability}$$

Curves which have been plotted for values of $\frac{g}{l_m}$ from 0 to 0.005 are shown in Figure 4-4.

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 4-5.

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

\[
\frac{L I^2}{2} = \text{Energy} \quad \text{[watt seconds]} \quad (4-10)
\]

Fig. 4-5. Minimum design permeability

and

\[
A_p = \left( \frac{2(\text{Eng}) \times 10^4}{B_m K_u K_j} \right)^{1.16} \quad \text{[cm}^4\text{]} \quad (4-11)
\]

in which:

- \( B_m \) = maximum flux density \((B_{dc} + B_{ac})\)
- \( K_u = 0.4 \) (Chapter 6)
- \( K_j = \) (See Chapter 2)
- \( \text{Eng} = \) energy, watt seconds
E. 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 (4-10):

\[
\text{Eng} = \frac{L_i^2}{2} \quad (4-12)
\]

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

\[
\text{Eng} = 0.030 \quad \text{[watt seconds]}
\]

**Step No. 2.** Calculate the area product \( A_p \) from equation (4-1):

\[
A_p = \left( \frac{2(\text{Eng}) \times 10^4}{B_m K_u K_j} \right)^{1.16} \quad \text{[cm}^4]\]

\[
A_p = \left( \frac{2(0.03) \times 10^4}{(1.2)(0.4)(395)} \right)^{1.16} = 3.80 \quad \text{[cm}^4]\]

A core which has an area product closest to the calculated value is the AL-10 which is described in Table 2-6, Chapter 2, and Appendix 4B. That size core has an area product \( A_p \) of 3.85 cm\(^4\) (\( A_c = 1.34 \text{ eff. cm}^2 \) and \( W_a = 2.87 \text{ cm}^2 \)).

After the \( A_p \) has been determined, the geometry of the inductor can be evaluated as described in Chapter 2 for weight, surface area, volume, and appropriate changes made, if required.
Step No. 3. Determine the current density from:

\[ J = K_j A_p^{-0.14} \]  \hspace{1cm} (4-13)^{*}

\[ J = 395(3.80)^{-0.14} = 328 \text{ amps/cm}^2 \]

Step No. 4. Determine the wire size from:

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

Wire size = \( \frac{2}{328} = 0.00609 \) \hspace{1cm} [cm^2]

Select the wire size from Table 6-1, column A, Chapter 6. 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 closest wire size to 0.00609 is AWG No. 20

Area = 0.005188 (bare) \hspace{1cm} [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 6-1, Chapter 6, column J.

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

\[ 2.58 \times 98.9 = 255 \]

Total number of turns = 255

*Derivation of equation (4-13) is shown in Chapter 2.
Step No. 6. The air gap dimension is determined from equation (4-6) by solving for $l_g$ as follows:

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

(4-14)

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

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

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:

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

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 4-3 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 4. B-8 shows a $G$ value of 3.015 cm. Therefore:

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

and accordingly

$$\frac{G}{\sqrt{A_c}} = \frac{3.015}{1.16} = 2.60$$
The fringing flux factor $F$ from Figure 4-3 may be stated:

$$F = 1.28$$

The recalculatd number of turns can be determined by rewriting equation 4-8:

$$N = \sqrt{\frac{1.8}{0.4\pi A_c F \times 10^{-6}}}$$

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 (4-4)

$$B_{max} = \frac{0.4\pi N(I_{dc} + \frac{\Delta I}{2})}{1} \times 10^{-4} \quad [\text{tesla}]$$

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

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

**Step No. 8.** Calculate core loss. This may be determined from Figure 4-6, in conjunction with the equation below:

$$B_{ac} = \frac{0.4\pi N \frac{\Delta I}{2}}{1} \times 10^{-4} \quad [\text{tesla}]$$
The ac core loss for this value can be found by reference to the graph shown in Figure 4-6 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 4.B-8 for the AL-10 size core, the weight of the core is 110 grams. The core loss in milliwatts per gram is obtained from:

\[
P_{fe} = (2.1)(110) = 230 \quad \text{[milliwatts]}
\]

**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 4.B-8 for the AL-10 size core for the mean length per turn (MLT) and the wire table (Chapter 6) for the resistance of No. 20 wire then:

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

\[
R = 8.33 \times 226 \times 332 \times 1.098 \times 10^{-6}
\]

\[
R = 0.686 \quad [\Omega]
\]

Since power loss is \( P_{cu} = I^2R \),

\[
P_{cu} = (2)^2(0.625) = 2.75 \quad \text{[watts]}
\]

\[
P_{\Sigma} = P_{cu} + P_{fe}
\]
From Chapter 7 the surface area $A_t$ required to dissipate waste heat (expressed as watts loss per unit area) is:

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

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

Referring to Table 4.B-8 for the AL-10 size core, the surface area $A_t$ is 79.39 cm$^2$.

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

$$\Psi = \frac{2.90}{79.39} = 0.0365 [\text{W/cm}^2]$$

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 with a resistance of 0.600 ohms at 25$^\circ$C and a resistance of 0.647 $\Omega$ at 45$^\circ$C.)

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 of the 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 4.B which contains 20 tables and 22 figures. The index has been prepared to make it possible for the designer to readily locate specific information.
Fig. 4-6. Design curves showing maximum core loss for 2 mil silicon "C" cores
APPENDIX 4-A

LINEAR REACTOR DESIGN WITH AN IRON CORE

After calculating the inductance and dc current, select the proper size core with a given $L_1^2/2$. The energy handling capability of an inductor can be determined by its area product $A_p$ of which, $W_a$ is the available core window area in cm$^2$ and $A_c$ is the core effective cross sectional area cm$^2$. The $W_a A_c$ or area product $A_p$ relationship is obtained by solving $E = LdI/dt$ as follows:

\[ E = L \frac{dI}{dt} = N \frac{d\phi}{dt} \quad (4. A-1) \]

\[ L = N \frac{d\phi}{dI} \quad (4. A-2) \]

\[ \phi = B_m A_c \quad (4. A-3) \]

\[ B_m = \frac{\mu_0 N I}{l \frac{m}{g} + \mu_r} \quad (4. A-4) \]

\[ \phi = \frac{\mu_0 N I A_c}{l \frac{m}{g} + \mu_r} \quad (4. A-5) \]

\[ \frac{d\phi}{dI} = \frac{\mu_0 N A_c}{l \frac{m}{g} + \mu_r} \quad (4. A-6) \]

\[ L = N \frac{d\phi}{dI} = \frac{\mu_0 N^2 A_c}{l \frac{m}{g} + \mu_r} \quad (4. A-7) \]

Symbols marked with a prime (such as $H'$) are mks (meter kilogram second) units.
77-35

\[ \text{Energy} = \frac{1}{2} LI^2 = \frac{\mu_0 N^2 A_c' I^2}{2 \left( \frac{l_g' + \frac{1}{\mu_r}}{l_g' + \frac{m}{\mu_r}} \right)} \]  

(4. A-8)

If \( B_m \) is specified,

\[ 1 = \frac{B_m \left( \frac{l_g' + \frac{1}{\mu_r}}{\mu_0 N} \right)}{l_g' + \frac{m}{\mu_r}} \]  

(4. A-9)

\[ \text{Eng} = \frac{\mu_0 N^2 A_c'}{2 \left( \frac{l_g' + \frac{m}{\mu_r}}{\mu_0 N} \right)^2} \]  

(4. A-10)

\[ \text{Eng} = \frac{B_m^2 \left( \frac{l_g' + \frac{1}{\mu_r}}{\mu_0} \right) A_c'}{2 \mu_0} \]  

(4. A-11)

\[ I = \frac{K_u W_a' J'}{N} = \frac{B_m \left( \frac{l_g' + \frac{1}{\mu_r}}{\mu_0 N} \right)}{\mu_0} \]  

(4. A-12)

Solving for \( \left( \frac{l_g' + \frac{m}{\mu_r}}{l_g' + \frac{1}{\mu_r}} \right) \)

\[ \left( \frac{l_g' + \frac{1}{\mu_r}}{l_g' + \frac{m}{\mu_r}} \right) = \frac{\mu_0 K_u W_a' J'}{B_m} \]  

(4. A-13)
Substituting into the energy equation

\[
\text{Eng} = \frac{B_m^2 \left( \frac{\mu_0 K_u W_a J'}{B_m} \right) A_c'}{2\mu_0} \quad (4. A-14)
\]

\[
\text{Eng} = \frac{B_m^2 A_c'}{2\mu_0} \times \frac{\mu_0 K_u W_a J'}{B_m} \quad (4. A-15)
\]

\[
\text{Eng} = \frac{B_m K_u W_a A_c J'}{2} \quad (4. A-16)
\]

let

\[
W_a = \text{window area, cm}^2
\]
\[
A_c = \text{core area, cm}^2
\]
\[
J = \text{current density, amps/cm}^2
\]
\[
H = \text{magnetizing force, amp turn/cm}
\]
\[
l_g = \text{air gap, cm}
\]
\[
l_m = \text{magnetic path length, cm}
\]
\[
W_a' = W_a \times 10^{-4}
\]
\[
A_c' = A_c \times 10^{-4}
\]
\[
J' = J \times 10^4
\]
\[
l_m' = l_m \times 10^{-2}
\]
\[
l_g' = l_g \times 10^{-2}
\]
\[
H' = H \times 10^2
\]
Substituting into the energy equation

\[
\text{Eng} = \frac{W A B}{2\frac{\text{JK}}{m_u}} \times 10^{-4}
\]

(4. A-17)

Solving for \( A_p = W_a A_c \)

\[
A_p = \frac{2(\text{Eng})}{B^m \text{JK}_u} \times 10^4
\]

(4. A-18)

Combining equation from Table 2-1.

\[
J = K_j A_p^{-0.14}
\]

(4. A-19)

yielding:

\[
A_p = \frac{2(\text{Eng}) \times 10^4}{K_u B^m (K_j A_p^{-0.14})}
\]

(4. A-20)

\[
A_p^{0.86} = \frac{2(\text{Eng}) \times 10^4}{K_u B^m K_j}
\]

(4. A-21)

\[
A_p = \left( \frac{2(\text{Eng}) \times 10^4}{K_u B^m K_j} \right)^{1.16} \text{[cm}^4\text{]}
\]

(4. A-22)
APPENDIX 4.B

C CORE AND BOBBIN MAGNETIC AND DIMENSIONAL SPECIFICATION

A. Definitions for Tables 4.B-1 through 4.B-20

Tables 4.B-1 through 4.B-20* show magnetic and dimensional specifications for twenty C cores. The information 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 $W_a$ gross
6. Iron area $A_c$ effective
7. Mean magnetic path length $l_m$
8. Core weight of silicon steel multiplied by the stacking factor
9. Copper weight single bobbin
10. Mean length turn
11. Ratio of C dimension divided by the square root of the iron area ($A_t$)
12. Ratio of the $W_a$ (eff)/$W_a$
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 4.B-1 through 4.B-20 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 3, 4.

**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 4.B-1. "C" core AL-2**

<table>
<thead>
<tr>
<th></th>
<th>ENGLISH</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt. Wt.</td>
<td>0.0023</td>
<td>0.269</td>
</tr>
<tr>
<td>Wt. Wt.</td>
<td>0.146</td>
<td>1.000</td>
</tr>
<tr>
<td>As (effective)</td>
<td>0.041</td>
<td>0.264</td>
</tr>
<tr>
<td>im</td>
<td>2.73</td>
<td>6.071</td>
</tr>
<tr>
<td>CORE Wt.</td>
<td>0.022</td>
<td>0.127</td>
</tr>
<tr>
<td>COPPER Wt.</td>
<td>0.371</td>
<td>18.87</td>
</tr>
<tr>
<td>* M.M. FULL WOUND</td>
<td>1.76</td>
<td>4.47</td>
</tr>
<tr>
<td>G' Y'AZ</td>
<td>3.08</td>
<td></td>
</tr>
<tr>
<td>Wt. (effective As)</td>
<td>0.038</td>
<td></td>
</tr>
<tr>
<td>A'f</td>
<td>3.00</td>
<td>24.56</td>
</tr>
<tr>
<td>D</td>
<td>0.246</td>
<td>0.035</td>
</tr>
<tr>
<td>L</td>
<td>0.146</td>
<td>0.034</td>
</tr>
<tr>
<td>r</td>
<td>0.269</td>
<td>0.036</td>
</tr>
<tr>
<td>G</td>
<td>0.026</td>
<td>0.031</td>
</tr>
<tr>
<td>BRACKET WIREMARK METALS</td>
<td>0.0410.03</td>
<td></td>
</tr>
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</table>

**Fig. 4.B-1. Wiregraph for "C" core AL-2**
Table 4.B-2, "C" core AL-3

<table>
<thead>
<tr>
<th>&quot;C&quot; CORE</th>
<th>ENGLISH</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wa/As</td>
<td>0.0088 in²</td>
<td>0.410 cm²</td>
</tr>
<tr>
<td>Wa</td>
<td>0.100 in³</td>
<td>1.006 cm³</td>
</tr>
<tr>
<td>As (effective)</td>
<td>0.003 in²</td>
<td>0.409 cm²</td>
</tr>
<tr>
<td>L</td>
<td>2.233 m</td>
<td>5.971 cm</td>
</tr>
<tr>
<td>CORE WGT</td>
<td>0.034 lb</td>
<td>0.1872 g</td>
</tr>
<tr>
<td>COPPER WGT</td>
<td>0.002 lb</td>
<td>19.25 g</td>
</tr>
<tr>
<td>* WLT FULLWINDED</td>
<td>2.91 in</td>
<td>7.3 cm</td>
</tr>
<tr>
<td>G/CGS</td>
<td>0.035</td>
<td></td>
</tr>
<tr>
<td>&quot;A&quot; effective A</td>
<td>6.27 in²</td>
<td>2.508 cm²</td>
</tr>
<tr>
<td>D</td>
<td>0.795 in</td>
<td>0.0932 cm</td>
</tr>
<tr>
<td>C</td>
<td>0.187 in</td>
<td>0.474 cm</td>
</tr>
<tr>
<td>F</td>
<td>1.360 in</td>
<td>0.365 cm</td>
</tr>
<tr>
<td>G</td>
<td>0.286 in</td>
<td>1.557 cm</td>
</tr>
<tr>
<td>BOBBIN</td>
<td>COREX ELECTRONICS * 4.3</td>
<td></td>
</tr>
<tr>
<td>LENGTH</td>
<td>0.580 in</td>
<td>1.47 cm</td>
</tr>
<tr>
<td>BUILD</td>
<td>0.229 in</td>
<td>0.571 cm</td>
</tr>
<tr>
<td>* Fa (effective)</td>
<td>0.100 in²</td>
<td>0.401 cm²</td>
</tr>
<tr>
<td>BRACKET</td>
<td>HALLMARK METALS * 0.016002</td>
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</table>

Fig. 4.B-2. Wiregraph for "C" core AL-3
Table 4.B-3. "C" core AL-5

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<tr>
<th>&quot;C&quot; CORE</th>
<th>ENGLISH</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire / Ac</td>
<td>0.018 in^2</td>
<td>0.03 cm^2</td>
</tr>
<tr>
<td>Wire</td>
<td>0.219 in^2</td>
<td>1.62 cm^2</td>
</tr>
<tr>
<td>Ac (effective)</td>
<td>0.032 in</td>
<td>0.82 cm</td>
</tr>
<tr>
<td>Im</td>
<td>2.013 in</td>
<td>7.6 cm</td>
</tr>
<tr>
<td>CORE WT</td>
<td>0.087 lb</td>
<td>39.6 grams</td>
</tr>
<tr>
<td>Copper WT</td>
<td>0.0843 lb</td>
<td>39.2 grams</td>
</tr>
<tr>
<td>* HLT FULLWOUND</td>
<td>2.13 in</td>
<td>5.43 cm</td>
</tr>
<tr>
<td>G/YAR</td>
<td>1.048</td>
<td></td>
</tr>
<tr>
<td>Wa (effective) / Wa</td>
<td>8.843</td>
<td></td>
</tr>
<tr>
<td>At</td>
<td>5.80 in^2</td>
<td>14.1 cm^2</td>
</tr>
<tr>
<td>D</td>
<td>0.375 in</td>
<td>0.96 cm</td>
</tr>
<tr>
<td>C</td>
<td>0.250 in</td>
<td>0.64 cm</td>
</tr>
<tr>
<td>F</td>
<td>0.210 in</td>
<td>0.53 cm</td>
</tr>
<tr>
<td>G</td>
<td>0.156 in</td>
<td>0.39 cm</td>
</tr>
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<td>BOBBIN</td>
<td>DORCO ELECTRONICS = 4-L-6</td>
<td></td>
</tr>
<tr>
<td>LENGTH</td>
<td>0.800 in</td>
<td>11.8 cm</td>
</tr>
<tr>
<td>RISE</td>
<td>0.225 in</td>
<td>0.57 cm</td>
</tr>
<tr>
<td>* Wa (effective)</td>
<td>0.148 in^2</td>
<td>1.90 cm^2</td>
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<tr>
<td>BRACKET</td>
<td>HALLMARK METALS = DF-012-04</td>
<td></td>
</tr>
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</table>

Fig. 4.B-3. Wiregraph for "C" core AL-5
Table 4.B-4. "C" core AL-6

<table>
<thead>
<tr>
<th>&quot;C&quot; CORE</th>
<th>AL-6</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wa/Ac</td>
<td>6.04</td>
<td>1.02</td>
</tr>
<tr>
<td>Wa x Ac</td>
<td>0.216</td>
<td>0.28</td>
</tr>
<tr>
<td>Wa</td>
<td>0.216</td>
<td>0.28</td>
</tr>
<tr>
<td>Ae (effective)</td>
<td>0.011</td>
<td>0.014</td>
</tr>
<tr>
<td>la</td>
<td>2.033</td>
<td>41.4</td>
</tr>
<tr>
<td>CORE WT</td>
<td>0.091</td>
<td>41.4</td>
</tr>
<tr>
<td>COPPER WT</td>
<td>0.019</td>
<td>22.8</td>
</tr>
</tbody>
</table>

* MLT FULLWOUND 2.38 m / 2.03 cm

<table>
<thead>
<tr>
<th>Wa (effective)</th>
<th>Wa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ae</td>
<td>4.59</td>
</tr>
<tr>
<td>D</td>
<td>0.039</td>
</tr>
<tr>
<td>E</td>
<td>0.010</td>
</tr>
<tr>
<td>F</td>
<td>0.023</td>
</tr>
<tr>
<td>G</td>
<td>0.076</td>
</tr>
</tbody>
</table>

RUBBIN: C-REEL ELECTRONICS - 5.6
LENGTH: 0.032 m / 2.11 cm
BUILD: 0.275 m / 0.071 cm

* Wa (effective) 0.166 m / 1.20 cm

Fig. 4.B-4. Wiregraph for "C" core AL-6

Fig. 4.B-4. Wiregraph for "C" core AL-6
Table 4. B-5. "C" core AL-124

<table>
<thead>
<tr>
<th>&quot;C&quot; CORE</th>
<th>AL-124</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wx/hx</td>
<td>2.60</td>
<td></td>
</tr>
<tr>
<td>We x Ax</td>
<td>0.0347</td>
<td>1.44</td>
</tr>
<tr>
<td>We</td>
<td>0.313</td>
<td>2.82</td>
</tr>
<tr>
<td>Ac (effective)</td>
<td>0.111</td>
<td>0.218</td>
</tr>
<tr>
<td>ln</td>
<td>1.368</td>
<td>6.00</td>
</tr>
<tr>
<td>CORE WT</td>
<td>0.103</td>
<td>39.7</td>
</tr>
<tr>
<td>COPPER WT</td>
<td>0.175</td>
<td>62.1</td>
</tr>
<tr>
<td>* MOLT FULLWOUND</td>
<td>2.56</td>
<td>9.58</td>
</tr>
<tr>
<td>G/Vae</td>
<td>2.07</td>
<td></td>
</tr>
<tr>
<td>Wx/BH(ferrite)</td>
<td>0.016</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0.03</td>
<td>0.78</td>
</tr>
<tr>
<td>D</td>
<td>0.260</td>
<td>1.32</td>
</tr>
<tr>
<td>E</td>
<td>0.200</td>
<td>0.838</td>
</tr>
<tr>
<td>F</td>
<td>0.215</td>
<td>0.718</td>
</tr>
<tr>
<td>t</td>
<td>1.00</td>
<td>2.44</td>
</tr>
<tr>
<td>BOBBIN</td>
<td>DORCO ELECTRONICS # 14-124</td>
<td></td>
</tr>
<tr>
<td>LENGTH</td>
<td>0.316</td>
<td>25.3</td>
</tr>
<tr>
<td>BUDG</td>
<td>0.194</td>
<td>0.721</td>
</tr>
<tr>
<td>&quot;Wx(BH)effective</td>
<td>0.025</td>
<td>1.17</td>
</tr>
<tr>
<td>BRACKET</td>
<td>HALLMARK METALS # 88-013-04</td>
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Fig. 4. B-5. Wiregraph for "C" core AL-124
Table 4. B-6. "C" core AL-8

<table>
<thead>
<tr>
<th>&quot;C&quot; CORE</th>
<th>AL-8</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wa/Ac</td>
<td>0.008 in&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.21 cm&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Wa x Ac</td>
<td>0.048 in&lt;sup&gt;3&lt;/sup&gt;</td>
<td>0.28 cm&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Ac (effective)</td>
<td>0.120 in&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.30 cm&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>t</td>
<td>1.108 in</td>
<td>2.8 cm</td>
</tr>
<tr>
<td>Coercive</td>
<td>0.141 lb</td>
<td>63.19 dynes</td>
</tr>
<tr>
<td>Copper WT</td>
<td>0.190 lb</td>
<td>81.7 dynes</td>
</tr>
<tr>
<td>* MLT FULLY HODD</td>
<td>3.17 lb</td>
<td>7.00 cm</td>
</tr>
<tr>
<td>&quot;G&quot;/&quot;V&quot;2</td>
<td>3.36</td>
<td></td>
</tr>
<tr>
<td>Wa (effective)/Wa</td>
<td>0.898</td>
<td></td>
</tr>
<tr>
<td>A&lt;sub&gt;T&lt;/sub&gt;</td>
<td>11.25 in&lt;sup&gt;2&lt;/sup&gt;</td>
<td>28.8 cm&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>D</td>
<td>0.575 in</td>
<td>0.557 cm</td>
</tr>
<tr>
<td>E</td>
<td>0.575 in</td>
<td>0.557 cm</td>
</tr>
<tr>
<td>F</td>
<td>0.575 in</td>
<td>0.557 cm</td>
</tr>
<tr>
<td>Q</td>
<td>1.187 in</td>
<td>3.015 cm</td>
</tr>
<tr>
<td>DODGER</td>
<td>DODGER ELECTRONICS</td>
<td>1.4</td>
</tr>
<tr>
<td>LENGTH</td>
<td>1.142 in</td>
<td>2.9 cm</td>
</tr>
<tr>
<td>BUILD</td>
<td>0.199 in</td>
<td>0.494 cm</td>
</tr>
<tr>
<td>* Wa (effective)</td>
<td>0.199 in&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.494 cm&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>BRACKET</td>
<td>HALLMARK METALS</td>
<td>3010230</td>
</tr>
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</table>

Fig. 4. B-6. Wiregraph for "C" core AL-8
Table 4.B-7. "C" core AL-9

<table>
<thead>
<tr>
<th>&quot;C&quot; CORE</th>
<th>ENGLISH</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wa/Hz</td>
<td></td>
<td>237</td>
</tr>
<tr>
<td>Wa x Ae</td>
<td>0.074 in²</td>
<td>0.99 cm²</td>
</tr>
<tr>
<td>Wa</td>
<td>0.446 in²</td>
<td>2.439 cm²</td>
</tr>
<tr>
<td>Ae (effective)</td>
<td>0.187 in²</td>
<td>1.972 cm²</td>
</tr>
<tr>
<td>ln</td>
<td>4.198 in</td>
<td>10.66 cm</td>
</tr>
<tr>
<td>CORE WT</td>
<td>0.197 lb</td>
<td>89.2 grams</td>
</tr>
<tr>
<td>COPPER WT</td>
<td>0.190 lb</td>
<td>80.0 grams</td>
</tr>
<tr>
<td>* WLT FULLWOUND</td>
<td>3.02 in</td>
<td>7.69 cm</td>
</tr>
<tr>
<td>G / VAC</td>
<td></td>
<td>2.00</td>
</tr>
</tbody>
</table>

| Wa (effective) | 0.898 in² | 28.30 cm² |
| A               | 12.16 in²  | 30.30 cm²  |
| D               | 0.500 in   | 1.27 cm    |
| C               | 0.376 in   | 0.952 cm   |
| F               | 0.376 in   | 0.952 cm   |
| G               | 1.197 in   | 3.015 cm   |
| BOBBIN         | DORCO ELECTRONICS #1-9 |
| LENGTH         | 1.143 in   | 2.90 cm    |
| GUILD          | 0.360 in   | 0.999 cm   |
| * Wa (effective) | 0.369 in² | 2.978 cm²  |
| BRACKET        | HALLMARK METALS #0810206 |

Fig. 4.B-7. Wiregraph for "C" core AL-9
Table 4.B-8. "C" core AL-10

<table>
<thead>
<tr>
<th>CORE</th>
<th>AL-10</th>
<th>ENGLISH</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>We/Ar</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>We x Ac</td>
<td>0.092 in²</td>
<td>3.89 cm²</td>
<td></td>
</tr>
<tr>
<td>We</td>
<td>0.445 in²</td>
<td>2.812 cm²</td>
<td></td>
</tr>
<tr>
<td>Ac (effective)</td>
<td>0.208 in</td>
<td>1.342 cm</td>
<td></td>
</tr>
<tr>
<td>In</td>
<td>4.168 in</td>
<td>10.60 cm</td>
<td></td>
</tr>
<tr>
<td>CORE WT</td>
<td>0.243 lb</td>
<td>0.110</td>
<td></td>
</tr>
<tr>
<td>COPPER WT</td>
<td>0.213 lb</td>
<td>0.094</td>
<td></td>
</tr>
<tr>
<td>* W.L. FULLBOUND</td>
<td>3.37 lb</td>
<td>0.530</td>
<td></td>
</tr>
<tr>
<td>D/4Ac</td>
<td>2.601</td>
<td></td>
<td></td>
</tr>
<tr>
<td>We (effective)</td>
<td>0.098</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>10.01 in²</td>
<td>63.6 cm²</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>0.526 in</td>
<td>1.327 cm</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.375 in</td>
<td>0.952 cm</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.376 in</td>
<td>0.952 cm</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>1.167 in</td>
<td>3.019 cm</td>
<td></td>
</tr>
<tr>
<td>BOGDEE</td>
<td>DODGE ELECTRONICS *-AL-10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LENGTH</td>
<td>1.242 in</td>
<td>3.15 cm</td>
<td></td>
</tr>
<tr>
<td>BUELD</td>
<td>0.350 in</td>
<td>0.889 cm</td>
<td></td>
</tr>
<tr>
<td>*We (effective)</td>
<td>0.392 in²</td>
<td>2.518 cm²</td>
<td></td>
</tr>
<tr>
<td>BRACKET</td>
<td>HALVAR METALS *-6.01092.96</td>
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<td></td>
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</table>

Fig. 4.B-8. Wiregraph for "C" core AL-10
Table 4.B-9. "C" core AL-12

<table>
<thead>
<tr>
<th>&quot;C&quot; CORE</th>
<th>ENGLISH</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ws/Wac</td>
<td>0.108 in²</td>
<td>180 cm²</td>
</tr>
<tr>
<td>Wa</td>
<td>0.864 in²</td>
<td>146 cm²</td>
</tr>
<tr>
<td>A (effective)</td>
<td>0.185 in²</td>
<td>31 cm²</td>
</tr>
<tr>
<td>rm</td>
<td>4.923 in</td>
<td>12.5 cm</td>
</tr>
<tr>
<td>CORE WT</td>
<td>0.244 lb</td>
<td>110 g</td>
</tr>
<tr>
<td>COPPER WT</td>
<td>0.795 lb</td>
<td>137 g</td>
</tr>
<tr>
<td>* MLT FULLWOUND</td>
<td>3.94 in</td>
<td>10 cm</td>
</tr>
<tr>
<td>G/VAC</td>
<td>2.95</td>
<td></td>
</tr>
<tr>
<td>Wa (effective)</td>
<td>0.091 in²</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4.B-9. Wiregraph for "C" core AL-12

![Wiregraph for "C" core AL-12](image)
Table 4.B-10. "C" core AL-135

<table>
<thead>
<tr>
<th>C&quot; CORE</th>
<th>AL 135</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wa (lbs)</td>
<td>2.91</td>
<td></td>
</tr>
<tr>
<td>Wa x Ac</td>
<td>0.122</td>
<td>0.14</td>
</tr>
<tr>
<td>Wa</td>
<td>0.033</td>
<td>0.007</td>
</tr>
<tr>
<td>Ac (effective)</td>
<td>0.196</td>
<td></td>
</tr>
<tr>
<td>h</td>
<td>6.064</td>
<td>15.3</td>
</tr>
<tr>
<td>CORE WT</td>
<td>0.251</td>
<td>114</td>
</tr>
<tr>
<td>COPPER P/F</td>
<td>0.312</td>
<td></td>
</tr>
<tr>
<td>*MTL FULLROUND</td>
<td>3/4&quot;</td>
<td></td>
</tr>
<tr>
<td>G/M&quot;</td>
<td>2.56</td>
<td></td>
</tr>
<tr>
<td>Wa (effective)/We</td>
<td>0.016</td>
<td></td>
</tr>
<tr>
<td>A_y</td>
<td>12.05</td>
<td>110</td>
</tr>
<tr>
<td>D</td>
<td>0.660</td>
<td>1.71</td>
</tr>
<tr>
<td>E</td>
<td>0.437</td>
<td>1.11</td>
</tr>
<tr>
<td>F</td>
<td>0.562</td>
<td>1.47</td>
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<tr>
<td>G</td>
<td>0.126</td>
<td>2.867</td>
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<tr>
<td>ORIGIN</td>
<td>DURCO ELECTRONICS</td>
<td>1-1/12</td>
</tr>
<tr>
<td>LENGTH</td>
<td>1.08</td>
<td>2.79</td>
</tr>
<tr>
<td>BUILD</td>
<td>0.532</td>
<td>1.38</td>
</tr>
<tr>
<td>*Wa (effective)</td>
<td>0.579</td>
<td>2.87</td>
</tr>
<tr>
<td>HBRACKET</td>
<td>HALLMARK METALS</td>
<td>08147507</td>
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</table>

Fig. 4.B-10. Wiregraph for "C" core AL-135
Table 4.B-11. "C" core AL-78

<table>
<thead>
<tr>
<th>&quot;C&quot; CORE</th>
<th>AL-78</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>W x A x</td>
<td>0.146</td>
<td>5.27</td>
</tr>
<tr>
<td>W x A x</td>
<td>0.106</td>
<td>4.03</td>
</tr>
<tr>
<td>A x (effective)</td>
<td>0.036</td>
<td>1.34</td>
</tr>
<tr>
<td>h x</td>
<td>0.881</td>
<td>14.58</td>
</tr>
<tr>
<td>CORE WT</td>
<td>0.342</td>
<td>164</td>
</tr>
<tr>
<td>COPPER WT</td>
<td>0.331</td>
<td>159</td>
</tr>
<tr>
<td>* MNT FULLWOUND</td>
<td>3.21</td>
<td>8.15</td>
</tr>
<tr>
<td>D x V x F</td>
<td>0.098</td>
<td></td>
</tr>
<tr>
<td>A x</td>
<td>18.93</td>
<td>109.6</td>
</tr>
<tr>
<td>D</td>
<td>0.700</td>
<td>2.33</td>
</tr>
<tr>
<td>E</td>
<td>0.310</td>
<td>0.705</td>
</tr>
<tr>
<td>F</td>
<td>0.310</td>
<td>0.795</td>
</tr>
<tr>
<td>G</td>
<td>2.250</td>
<td>5.715</td>
</tr>
<tr>
<td>BOBBIN</td>
<td>DURCO ELECTRONICS * 1-L-78</td>
<td></td>
</tr>
<tr>
<td>LENGTH</td>
<td>2.205</td>
<td>5.60</td>
</tr>
<tr>
<td>BUILD</td>
<td>0.288</td>
<td>0.731</td>
</tr>
<tr>
<td>* WW (effective)</td>
<td>0.035</td>
<td>4.10</td>
</tr>
<tr>
<td>BRACKET</td>
<td>HALLMARK METALS * 01251506</td>
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Fig. 4.B-11. Wiregraph for "C" core AL-78
Fig. 4.B-12. Wiregraph for "C" core AL-18
Table 4. B-13. "C" core AL-15

<table>
<thead>
<tr>
<th>&quot;C&quot; CONC</th>
<th>AL-15</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wx/Ac</td>
<td>0.218</td>
<td>0.07</td>
</tr>
<tr>
<td>W x Ac</td>
<td>0.218</td>
<td>0.07</td>
</tr>
<tr>
<td>Ac (effective)</td>
<td>0.279</td>
<td>1.00</td>
</tr>
<tr>
<td>Im</td>
<td>6.508</td>
<td>14.2</td>
</tr>
<tr>
<td>Core WT</td>
<td>0.638</td>
<td>1.87</td>
</tr>
<tr>
<td>Copper WT</td>
<td>0.448</td>
<td>2.63</td>
</tr>
<tr>
<td>* MTL FULL-WOUND</td>
<td>2.87</td>
<td>12.08</td>
</tr>
<tr>
<td>C/Vac</td>
<td>2.59</td>
<td></td>
</tr>
<tr>
<td>Wx (effective)/Wx</td>
<td>0.681</td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>1.07</td>
<td>135.9</td>
</tr>
<tr>
<td>D</td>
<td>0.422</td>
<td>1.087</td>
</tr>
<tr>
<td>b</td>
<td>0.409</td>
<td>1.07</td>
</tr>
<tr>
<td>F</td>
<td>0.500</td>
<td>1.27</td>
</tr>
<tr>
<td>G</td>
<td>1.562</td>
<td>3.987</td>
</tr>
<tr>
<td>Bobbin</td>
<td>EORCO ELECTRONICS + F-15</td>
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</tr>
<tr>
<td>Length</td>
<td>1.497</td>
<td>3.80</td>
</tr>
<tr>
<td>Build</td>
<td>0.495</td>
<td>1.26</td>
</tr>
<tr>
<td>* Wx (effective)</td>
<td>0.696</td>
<td>1.49</td>
</tr>
<tr>
<td>Bracket</td>
<td>HAULMARK METALS + 010-108-01</td>
<td></td>
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Fig. 4. B-13. Wiregraph for "C" core AL-15
Table 4. B-14. "C" core AL-16

<table>
<thead>
<tr>
<th>&quot;C&quot; CORE</th>
<th>AL-16</th>
<th>ENGLISH</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt/ft2</td>
<td>7.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wt x Αc</td>
<td>0.39</td>
<td>10.9</td>
<td>4.29</td>
</tr>
<tr>
<td>Wt</td>
<td>3.78</td>
<td>4.03</td>
<td></td>
</tr>
<tr>
<td>Ac (effective)</td>
<td>0.036</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>lb</td>
<td>0.566</td>
<td>14.2</td>
<td></td>
</tr>
<tr>
<td>KG CORE</td>
<td>9.91</td>
<td>222</td>
<td>grains</td>
</tr>
<tr>
<td>COPPER WT</td>
<td>0.675</td>
<td>116</td>
<td>grains</td>
</tr>
<tr>
<td>* MLT FULLWOUND</td>
<td>4.22</td>
<td>10.72</td>
<td></td>
</tr>
<tr>
<td>G/YAa</td>
<td>2.70</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We (effective) Nm

| A    | 22.21 | 143.3 cm² |
| D    | 0.750 | 1.906 cm   |
| E    | 0.500 | 1.27 cm    |
| F    | 0.500 | 1.27 cm    |
| G    | 1.503 | 3.907 cm    |

BOSKIN DORCO ELECTRONICS # 1-1-16

LENGTH | 1.697 | 3.30 cm |
SHAFT  | 0.865 | 2.2 cm   |
* Wt (effective) | 0.090 | 4.45 cm² |

BRACKET HALLMARK METALS + 013-108-08

Fig. 4. B-14. Wiregraph for "C" core AL-16
Table 4.B-15. "C" core AL-17

<table>
<thead>
<tr>
<th>&quot;C&quot; CORE</th>
<th>AL-17</th>
<th>ENGLISH</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire/Ac</td>
<td>0.35</td>
<td>in²</td>
<td>144 cm²</td>
</tr>
<tr>
<td>W x A</td>
<td>0.781</td>
<td>in²</td>
<td>5.037 cm²</td>
</tr>
<tr>
<td>A (effective)</td>
<td>0.669</td>
<td>in²</td>
<td>3.919 cm²</td>
</tr>
<tr>
<td>H</td>
<td>5.988</td>
<td>in</td>
<td>15.2 cm</td>
</tr>
<tr>
<td>Coax wt</td>
<td>0.693</td>
<td>lb</td>
<td>314 grams</td>
</tr>
<tr>
<td>Copper wt</td>
<td>0.633</td>
<td>lb</td>
<td>241 grams</td>
</tr>
</tbody>
</table>

* MLT FULLWOUND: 4.72 oz, 121.9 oz

G/VAC: 2.242

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔT</td>
<td>24.5</td>
</tr>
<tr>
<td>D</td>
<td>1.030</td>
</tr>
<tr>
<td>E</td>
<td>0.500</td>
</tr>
<tr>
<td>F</td>
<td>0.500</td>
</tr>
<tr>
<td>G</td>
<td>1.562</td>
</tr>
</tbody>
</table>

DORCO ELECTRONICS: D-15-17

LENGTH: 1.497 in, 2.99 cm
BUILD: 0.405 in, 1.02 cm
* Wa (effective): 0.616 in², 4.05 cm²

BRACKET: HALLMARK METALS: 10-1050-08

---

![Wiregraph for "C" core AL-17](image)

Fig. 4.B-15. Wiregraph for "C" core AL-17

4-36
Table 4.B-16. "C" core AL-19

<table>
<thead>
<tr>
<th>&quot;C&quot; CORE</th>
<th>AL-19</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wa/Hz</td>
<td>0.416</td>
<td>0.018</td>
</tr>
<tr>
<td>Wa x Ac</td>
<td>0.077</td>
<td>0.003</td>
</tr>
<tr>
<td>Ac (effective)</td>
<td>0.445</td>
<td>0.017</td>
</tr>
<tr>
<td>ln</td>
<td>6.039</td>
<td>16.8</td>
</tr>
<tr>
<td>CORE WT</td>
<td>0.724</td>
<td>328</td>
</tr>
<tr>
<td>COPPER WT</td>
<td>0.721</td>
<td>332</td>
</tr>
<tr>
<td>MLY PULLWOUND</td>
<td>5.11</td>
<td>12.08</td>
</tr>
<tr>
<td>G/VA</td>
<td>2.34</td>
<td></td>
</tr>
</tbody>
</table>

| Wa (effective)/Wa | 0.403 |
| A+ | 20.2 | 182 |
| D  | 1.000 | 2.54 |
| E  | 0.600 | 1.57 |
| F  | 0.626 | 1.66 |
| G  | 1.562 | 3.95 |
| DOBBIN | CORCO ELECTRONICS | 1.1-19 |
| LENGTH | 1.497 | 3.82 |
| GUILD | 0.709 | 1.81 |
| # Wa (effective) | 0.863 | 2.20 |
| BRACKET | HALLMARK METALS | 10-110.0 |

Fig. 4.B-16. Wiregraph for "C" core AL-19
Table 4.B-17. "C" core AL-20

<table>
<thead>
<tr>
<th>&quot;C&quot; CORE</th>
<th>AL-20</th>
<th>MG TRUC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire/Ac</td>
<td>0.043</td>
<td>0.068</td>
</tr>
<tr>
<td>Wire</td>
<td>0.931</td>
<td>0.931</td>
</tr>
<tr>
<td>Ac (effective)</td>
<td>0.016</td>
<td>0.398</td>
</tr>
<tr>
<td>in</td>
<td>9.228</td>
<td>15.8</td>
</tr>
<tr>
<td>CORE WT</td>
<td>0.185</td>
<td>437</td>
</tr>
<tr>
<td>COPPER WT</td>
<td>0.767</td>
<td>168</td>
</tr>
<tr>
<td>* NLT FULLWOUND</td>
<td>5.26</td>
<td>12.62</td>
</tr>
<tr>
<td>G/V/VAC</td>
<td></td>
<td>2.09</td>
</tr>
<tr>
<td>We (effective)/Vs</td>
<td>31.7</td>
<td>31.7</td>
</tr>
<tr>
<td>D</td>
<td>1.020</td>
<td>2.04</td>
</tr>
<tr>
<td>E</td>
<td>0.925</td>
<td>1.587</td>
</tr>
<tr>
<td>F</td>
<td>0.512</td>
<td>1.587</td>
</tr>
<tr>
<td>C</td>
<td>0.583</td>
<td>3.957</td>
</tr>
<tr>
<td>ROBBIN GAGE ELECTRONICS</td>
<td>0.1-30</td>
<td></td>
</tr>
<tr>
<td>LENGTH</td>
<td>1.497</td>
<td>3.064</td>
</tr>
<tr>
<td>BUILD</td>
<td>0.500</td>
<td>1.498</td>
</tr>
<tr>
<td>* Vs (effective)</td>
<td>0.897</td>
<td>5.99</td>
</tr>
<tr>
<td>BRACKET HALLMARK METALS</td>
<td>1014-008</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4.B-17. Wiregraph for "C" core AL-20
Table 4.B-18. "C" core AL-22

<table>
<thead>
<tr>
<th>&quot;C&quot; CORE</th>
<th>AL-22</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wb/Hz</td>
<td>0.852</td>
<td>26.0</td>
</tr>
<tr>
<td>Wb x Hz</td>
<td>0.305</td>
<td>1.08</td>
</tr>
<tr>
<td>&quot;A&quot; (effective)</td>
<td>0.595</td>
<td>2.04</td>
</tr>
<tr>
<td>d</td>
<td>0.976</td>
<td>12.2</td>
</tr>
<tr>
<td>CORE WT</td>
<td>1.08 lb</td>
<td>480 g</td>
</tr>
<tr>
<td>COPPER WT</td>
<td>0.051 lb</td>
<td>235 g</td>
</tr>
<tr>
<td>MIL. T. FULLWINDING</td>
<td>0.36 in</td>
<td>9.17 mm</td>
</tr>
<tr>
<td>G/1000</td>
<td>2.59</td>
<td></td>
</tr>
<tr>
<td>Wire (effective)</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>Ay</td>
<td>35.3 in²</td>
<td>226 cm²</td>
</tr>
<tr>
<td>D</td>
<td>1.002 in</td>
<td>2.54 cm</td>
</tr>
<tr>
<td>C</td>
<td>0.867 in</td>
<td>2.19 cm</td>
</tr>
<tr>
<td>R</td>
<td>0.295 in</td>
<td>0.75 cm</td>
</tr>
<tr>
<td>G</td>
<td>1.037 in</td>
<td>2.62 cm</td>
</tr>
<tr>
<td>BOBBIN</td>
<td>DORCO-EL ELEKTRONIKS</td>
<td>1.42</td>
</tr>
<tr>
<td>LENGTH</td>
<td>1.872 in</td>
<td>4.75 cm</td>
</tr>
<tr>
<td>BUILD</td>
<td>0.560 in</td>
<td>1.42 cm</td>
</tr>
<tr>
<td>*Wire (effective)</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>BRACKET</td>
<td>HALMARK METALS</td>
<td>0.114</td>
</tr>
</tbody>
</table>

![Diagram of "C" core AL-22](image)

Fig. 4.B-18. Wiregraph for "C" core AL-22
Table 4, B-19. "C" core AL-23

<table>
<thead>
<tr>
<th>COIL</th>
<th>&quot;ENGLISH&quot;</th>
<th>&quot;METRIC&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.841</td>
<td>26.05</td>
</tr>
<tr>
<td>B</td>
<td>1.21</td>
<td>3.88</td>
</tr>
<tr>
<td>C</td>
<td>0.056</td>
<td>0.04</td>
</tr>
<tr>
<td>D</td>
<td>1.085</td>
<td>0.35</td>
</tr>
<tr>
<td>E</td>
<td>0.925</td>
<td>0.97</td>
</tr>
<tr>
<td>F</td>
<td>1.017</td>
<td>1.46</td>
</tr>
<tr>
<td>G</td>
<td>1.050</td>
<td>1.40</td>
</tr>
</tbody>
</table>

**, MELT FULLWOUND, 5.96 m, 14.80 cm**

**GryVac, 2.27**

**Wax Insulated Wax, 6.017**

**A**

**D**

**E**

**F**

**G**

**BRACKET, HALLMARK METALS, 18-119-003**

**Fig. 4, B-19. Wiregraph for "C" core AL-23**
Table 4. B-20. "C" core AL-24

<table>
<thead>
<tr>
<th>&quot;C&quot; CORE</th>
<th>AL-24</th>
<th>FT THICK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire No.</td>
<td>0.092</td>
<td>2.77</td>
</tr>
<tr>
<td>Wire x AC</td>
<td>40.0</td>
<td></td>
</tr>
<tr>
<td>WA</td>
<td>1.72</td>
<td>11.10</td>
</tr>
<tr>
<td>Ac (effective)</td>
<td>0.556</td>
<td>2.58 cm²</td>
</tr>
<tr>
<td>AL</td>
<td>7.871</td>
<td>70.3 cm²</td>
</tr>
<tr>
<td>CORE WT</td>
<td>1.220</td>
<td>55.7 kg</td>
</tr>
<tr>
<td>COPPER WT</td>
<td>1.581</td>
<td>68.0 kg</td>
</tr>
<tr>
<td>* MLI FOLLOWING</td>
<td>5.75</td>
<td>1.02 cm²</td>
</tr>
<tr>
<td>G/VAC</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>WA (effective)</td>
<td>0.029</td>
<td></td>
</tr>
<tr>
<td>wt.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>436</td>
<td>28.6 cm²</td>
</tr>
<tr>
<td>E</td>
<td>1.00</td>
<td>2.54 cm</td>
</tr>
<tr>
<td>F</td>
<td>0.675</td>
<td>1.547 cm</td>
</tr>
<tr>
<td>G</td>
<td>0.750</td>
<td>1.005 cm</td>
</tr>
<tr>
<td>H</td>
<td>2.912</td>
<td>5.931 cm</td>
</tr>
<tr>
<td>BOBBIN SGH IM ELECTRONICS</td>
<td>1 L-24</td>
<td></td>
</tr>
<tr>
<td>LENGTH</td>
<td>2.248</td>
<td>3.702 cm</td>
</tr>
<tr>
<td>BUILD</td>
<td>0.716</td>
<td>1.816 cm</td>
</tr>
<tr>
<td>* WA (effective)</td>
<td>1.007</td>
<td>10.072 cm²</td>
</tr>
<tr>
<td>BRACKET</td>
<td>HALLMARK METALS</td>
<td>10.000 cm²</td>
</tr>
</tbody>
</table>

Fig. 4. B-20. Wiregraph for "C" core AL-24
Fig. 4.B-21. Graph for inductance, capacitance, and reactance
Fig. 4. B-22. Area product vs energy $\frac{L^2}{2}$

$A_p = \left( \frac{2(E_{mc} \times 10^4)}{B_{m}' K_u K_j} \right)$

$B_{m}' = 1.2$ (tesla)
$K_u = 0.4$
$K_j = 395$
REFERENCES


CHAPTER V
TOROIDAL POWDER CORE SELECTION
WITH dc CURRENT
A. INTRODUCTION

Inductors which carry direct current are used frequently in a wide variety of ground, air, and space applications. Selection of the best magnetic core for an inductor frequently involves a trial-and-error type of calculation.

The design of an inductor also frequently involves consideration of the effect of its magnetic field on other devices near where it is placed. This is especially true in the design of high-current inductors for converters and switching regulators used in spacecraft, which may also employ sensitive magnetic field detectors. For this type of design problem it is frequently imperative that a toroidal core be used. The magnetic flux in a moly-permalloy toroid (core) can be contained inside the core more readily than in a lamination or C type core, as the winding covers the core along the whole magnetic path length.

The author has developed a simplified method of designing optimum dc carrying inductors with moly-permalloy powder cores. This method allows the correct core permeability to be determined without relying on trial and error.

B. RELATIONSHIP OF $A_p$ TO INDUCTOR'S ENERGY HANDLING CAPABILITY

According to the newly developed approach, the energy-handling capability of a core is related to its area product $A_p$:

$$A_p = \left( \frac{2(\text{Eng}) \times 10^4}{BmKuK_j} \right)^{1.14} \quad [\text{cm}^4] \quad (5-1)$$

where:

$K_j = \text{current density coefficient} \ (\text{see Chapter 2})$

$K_u = \text{window utilization factor} \ (\text{see Chapter 6})$

$B_m = \text{flux density, tesla}$

$\text{Eng} = \text{energy, watt seconds}$
From the above, it can be seen that factors such as flux density, window utilization factor \( K_u \) (which defines the maximum space that 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 losses. Derivation is set forth in detail in Chapter 2. The energy-handling capability of a core is derived from

\[
\text{Eng} = \frac{L^2}{2} \quad \text{[watt second]} \quad (5-2)
\]

III. FUNDAMENTAL CONSIDERATIONS

The design of a linear reactor depends upon four related factors:

1. Desired inductance
2. Direct current
3. Alternating current \( \Delta I \)
4. Power loss and temperature rise

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 permeability chosen dictates the maximum dc flux density which can be tolerated for a given design. Permeability values for different powder cores are shown in Table 5-1.

Table 5-1. Different powder core permeabilities

<table>
<thead>
<tr>
<th>Permeability</th>
<th>Amp turn/cm with dc bias</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( L &lt; 80% )</td>
</tr>
<tr>
<td>14</td>
<td>253</td>
</tr>
<tr>
<td>36</td>
<td>140</td>
</tr>
<tr>
<td>60</td>
<td>56</td>
</tr>
<tr>
<td>125</td>
<td>28</td>
</tr>
<tr>
<td>147</td>
<td>23</td>
</tr>
<tr>
<td>160</td>
<td>20</td>
</tr>
<tr>
<td>173</td>
<td>19</td>
</tr>
<tr>
<td>200</td>
<td>16</td>
</tr>
<tr>
<td>300</td>
<td>11</td>
</tr>
<tr>
<td>555</td>
<td>4</td>
</tr>
</tbody>
</table>
If an inductance is to be constant with increasing direct current, there must be a negligible drop in inductance over the operating current range. The maximum $H$, then, is an indication of a core's capability. In terms of ampere-turns and mean magnetic path length $l_m$,

$$H = \frac{NI}{l_m} \quad [\text{amp turn/cm}] \quad (5-3)$$

$$NI = 0.8 Hl_m \quad [\text{amp turn}] \quad (5-4)$$

Inductance decreases with increasing flux density and magnetizing force for various materials of different values of permeability $\mu_{\Delta}$. The selection of the correct permeability for a given design is made using equation 5-4 after solving for the area product $A_p^*:

$$\mu_{\Delta} = \frac{B_m l_m \times 10^4}{0.4\pi W_{\text{f}} K_u}$$ \quad (5-5)$$

It should be remembered that maximum flux density depends upon $B_{dc} + B_{ac}$ in the manner shown in Fig. 5-1.

$$B_m = B_{dc} + B_{ac} \quad [\text{tesla}] \quad (5-6)$$

$$B_{dc} = \frac{0.4\pi NI_{dc} \times 10^{-4}}{l_m} \frac{1}{\mu_{\Delta}} \quad [\text{tesla}] \quad (5-7)$$

Derivation is set forth in detail in Appendix 5.A at the end of this Chapter.
Combining Eqs. (5-7) and (5-8),

\[ B_m = \frac{0.4\pi N \frac{\Delta I}{2} \times 10^{-4}}{\frac{1}{m}} \]

\[ + \frac{0.4\pi N \frac{\Delta I}{2} \times 10^{-4}}{\frac{1}{\mu \Delta}} \]  

Fig. 5-1. Flux density versus \( I_{dc} + \Delta I \)

Moly-permalloy powder cores operating with a dc bias of 0.3 tesla have only about 80% of their original inductance, with very rapid falloff at higher densities as shown in Fig. 5-2.

The flux density for the initial design for moly-permalloy powder cores should be limited to 0.2 tesla maximum for \( B_{dc} \) plus \( B_{ac} \).

The losses in a moly-permalloy inductor due to ac flux density are very low compared to the steady state dc copper loss. It is then assumed that the majority of the losses are copper:

\[ P_{cu} >> P_{fe} \]  

(5-10)
D. A SPECIFIED PROBLEM AS AN EXAMPLE

For a typical design example, assume the following:

1. Inductance 0.0015 henry
2. dc current 2 amperes
3. 25°C rise

The procedure would be as shown below.

Step No. 1. Calculate the energy-handling capability from equation 5-2:

\[
\text{Energy} = \frac{LI^2}{2} \quad \text{[watt second]}
\]

\[
\text{Energy} = \frac{0.0015 \times 2^2}{2} = 0.003 \quad \text{[watt second]}
\]
Step No. 2. Calculate the area product $A_p$ from equation 5-1:

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

$$B_m = 0.2 \text{[tesla]}$$

$$K_u = 0.4$$

$$K_j = 403$$

$$A_p = \left( \frac{2(0.003) \times 10^4}{(0.2)(0.4)(403)} \right)^{1.14} \text{[cm}^4\text{]}$$

or

$$A_p = 2.03 \text{[cm}^4\text{]}$$

After the $A_p$ has been determined, the geometry of the inductor can be evaluated as described in Chapter 2 for weight, for surface area, and for volume, and appropriate changes made, if required.

Step No. 3. Select a powder core from Table 2-2 with a value of $A_p$ closest to the one calculated:

55071 with an $A_p = 1.966 \text{[cm}^4\text{]}$

For more information, see Table 5.B-6.

Step No. 4. Calculate the current density $J$ from equation 5.A-19:

$$J = K_j A_p^{-0.12} \text{[A/cm]}$$
The value for $K_j$ is found in Table 2-1:

$$J = (403) (1.966)^{-0.12}$$

$$J = 372 \quad [\text{A/cm}]$$

**Step No. 5.** Calculate the permeability of the core required from equation 5.A-24:

$$\mu_{\Delta} = \frac{B_m l_m \times 10^4}{0.4\pi W_a J K_u}$$

(see Table 5.B-6.)

$$\mu_{\Delta} = \frac{(0.2) (8.15) \times 10^4}{(1.25) (2.93) (372) (0.4)}$$

$$\mu_{\Delta} = 38$$

From the manufacturer's catalog, the core that has the same size but has a permeability closer to the one calculated is the core 55550, with a permeability of 26. This particular core has 28 millihenry per 1000 turns.

**Step No. 6.** Calculate the number of turns required for 1.5 millihenry.

$$N = 1000 \sqrt{\frac{L}{L_{1000}}}$$

$L = \text{inductance}$

$L_{1000} = \text{inductance at 1000 turns}$

$$N = 1000 \sqrt{\frac{1.5}{28}}$$

$$N = 231$$
Step No. 7. Calculate the bare wire size $A_{w(B)}$:

$$A_{w(B)} = \frac{I}{J} \quad [cm^2]$$

$$A_{w(B)} = \frac{2.0}{372} \quad [cm^2]$$

$$A_{w(B)} = 0.00537 \quad [cm^2]$$

Step No. 8. Select the wire area $A_w$ in Table 6-1 for equivalent (AWG) wire size, column A:

AWG No. 20 = 0.005188

Step No. 9. Calculate the resistance of the winding, using Table 1-1, column C, and Table 2-2, column 4, for the MLT:

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

$$R = (4.77)(231)(332)(1.098) \times 10^{-6} \quad [\Omega]$$

$$R = 0.402 \quad [\Omega]$$

Step No. 10. Calculate the copper loss:

$$P_{cu} = I^2 R \quad [\text{watts}]$$

$$P_{cu} = (2)^2 (0.402)$$

$$P_{cu} = 1.608 \quad [\text{watts}]$$

From chapter 7, the surface area $A_t$ required to dissipate waste heat (expressed as watts loss per unit area) is:
Referring to Table 2-2, column 2, for the 55071 size core, the surface area $A_t$ is 44.7 cm$^2$.

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

$$\psi = \frac{1.608}{44.7}$$

$$\psi = 0.036 \text{ [W/cm}^2\text{]}$$

which will produce the required temperature rise.

(In a test sample made to prove out this example, the measured inductance was found to be 0.0015 hy with a resistance of 0.36 ohms at 25°C and 0.388 ohms at 45°C.)
BIBLIOGRAPHY


Smith, G. D., Designing Toroidal Inductors with dc Bias. NASA Technical Note D-2320, Goddard Space Flight Center, Greenbelt, Md.

APPENDIX 5. A
TOROID POWDER CORE SELECTION WITH DC CURRENT

After calculating the inductance and dc current, select the proper permeability and size of powder core with a given $L_1^2/2$. The energy-handling capability of an inductor can be determined by its $A_p$ product, of which $W_a$ is the available core window area in cm$^2$ and $A_c$ is the core effective cross sectional area in cm$^2$. The $W_a A_c$ or area product $A_p$ relationship is obtained by solving $E = LdI/dt$ as follows:

\[ E = L \frac{dI}{dt} = N \frac{d\Phi}{dt} \]  (5. A-1)

\[ L = N \frac{d\Phi}{dI} \]  (5. A-2)

\[ \Phi = B_m A'_c \]  (5. A-3)

\[ B_m = \mu_\Delta \mu_0 H = \frac{\mu_\Delta \mu_0 NI}{I_m} \]  (5. A-4)

\[ \Phi = \frac{\mu_\Delta \mu_0 NI A'_c}{I_m} \]  (5. A-5)

\[ \frac{d\Phi}{dI} = \frac{\mu_\Delta \mu_0 N A'_c}{I_m} \]  (5. A-6)

\[ L = N \frac{d\Phi}{dI} = \frac{\mu_\Delta \mu_0 N^2 A'_c}{I_m} \]  (5. A-7)

\[ \text{Energy} = \frac{L I_1^2}{2} = \frac{\mu_r \mu_0 N^2 A'_c I^2_1}{I_m} \]  (5. A-8)

*Primes indicate measurements in the mks system.
If \( B_m \) is specified,

\[
I = \frac{B_m l_m}{\mu_\Delta \mu_o N} \tag{5. A-9}
\]

\[
\text{Eng} = \frac{\mu_\Delta \mu_o N^2 A'_c}{2 l'_m} \left( \frac{B_m l_m}{\mu_\Delta \mu_o N} \right)^2 \tag{5. A-10}
\]

Reducing to

\[
\text{Eng} = \frac{B_m l'_m A'_c}{2 \mu_\Delta \mu_o} \text{ [watt seconds]} \tag{5. A-11}
\]

\[
I = \frac{K_u W'_a J'}{N} = \frac{B_m l'_m}{\mu_\Delta \mu_o N} \tag{5. A-12}
\]

Solving for \( \mu_\Delta \mu_o \)

\[
\mu_\Delta \mu_o = \frac{B_m l'_m}{K_u W'_a J'} \tag{5. A-13}
\]

Substituting into the energy equation,

\[
\text{Eng} = \frac{B_m^2 l'_m A'_c}{2} \cdot \frac{K_u W'_a J'}{B_m l'_m} = \frac{W'_a A'_c B_m J' K_u}{2} \tag{5. A-14}
\]
let

\[ l_1' = l_1 \times 10^{-2} \]
\[ W_1' = W_1 \times 10^{-4} \]
\[ A_1' = A_1 \times 10^{-4} \]
\[ J' = J \times 10^4 \]

Substituting into the energy equation,

\[ \text{Eng} = \frac{W_a A_c B_m J K_u}{2} \times 10^{-4} \]  \hspace{1cm} (5.A-15)

Solving for \( W_a A_c \),

\[ W_a A_c = \frac{2 \text{Eng} \times 10^4}{K_u B_m J} \]  \hspace{1cm} (5.A-16)

and since the area product is

\[ A_p = W_a A_c \]  \hspace{1cm} (5.A-17)

then

\[ A_p = \frac{2 \text{Energy} \times 10^4}{K_u B_m J} \]  \hspace{1cm} (5.A-18)

Combining the equation from Table 2-1,

\[ J = K_j A_p^{-0.12} \]  \hspace{1cm} (5.A-19)
yielding

\[ A_p = \frac{2 \text{(Energy)} \times 10^4}{K_u B_m (K_j A_p^{-0.12})} \]  

(5. A-20)

\[ A_p^{0.88} = \frac{2 \text{(Energy)} \times 10^4}{K_u B_m K_j} \]  

(: .-21)

\[ A_p = \left( \frac{2 \text{(Energy)} \times 10^4}{K_u B_m K_j} \right)^{1.14} \left[ \text{cm}^4 \right] \]  

(5. A-22)

After the core size has been determined, the next step is to pick the right permeability for that core size. This is done by solving for \( \mu_\Delta \) in equation 5. A-13.

\[ \mu_\Delta = \frac{B_m 1_m \times 10^{-2}}{\mu_o \frac{W_a}{J K_u}} \]  

(5. A-23)

for \( \mu_o = 4\pi \times 10^{-7} \)

\[ \mu_\Delta = \frac{B_m 1_m \times 10^4}{0.4\pi W_a J K_u} \]  

(5. A-24)
APPENDIX 5. B

MAGNETIC AND DIMENSIONAL SPECIFICATIONS FOR 13 COMMONLY USED MOLY-PERMALLOY CORES

The following remarks apply to each of Tables 5. B-1 to 5. B-13, the data in which was compiled from manufacturers' data.

1. Total weight is core weight plus wire weight assuming AWG 20
2. Maximum OD of wound core with residual hole = 1/2 ID
3. M.L.T. (mean length/turn) full wound toroid
4. Effective window area \( W_{\text{a(\text{eff})}} = \frac{3\pi r^2}{4} \)

Graphs (Figs. 5. B-1 to 5. B-13) relate to the 13 different core sizes. The graphs show resistance, number of turns, inductance and wire size for a window utilization factor of 0.40, and are based on a permeability of 60. To convert for other permeability values, the appropriate inductance multiplication factors listed should be used. The information appearing in the tables and on the figures will enable the engineer to arrive at a close approximation for breadboarding purposes.
### Table 5.B-1. Dimensional specifications for Magnetic Inc 55051-A2, Arnold Engineering A-051027-2

<table>
<thead>
<tr>
<th></th>
<th>ENGLISH</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>W x A</td>
<td>0.00404 in²</td>
<td>0.00012 cm²</td>
</tr>
<tr>
<td>OD</td>
<td>0.510 in</td>
<td>1.294 cm</td>
</tr>
<tr>
<td>ID</td>
<td>0.227 in</td>
<td>0.577 cm</td>
</tr>
<tr>
<td>HT</td>
<td>0.217 in</td>
<td>0.542 cm</td>
</tr>
<tr>
<td>Window Area</td>
<td>0.015 x 10⁴ cur·mil</td>
<td>0.157 cm²</td>
</tr>
<tr>
<td>Effective Area</td>
<td>0.0161 in²</td>
<td>0.161 cm²</td>
</tr>
<tr>
<td>Cross Section</td>
<td>1.229 in</td>
<td>3.12 cm</td>
</tr>
<tr>
<td>Path Length</td>
<td>1.096 in</td>
<td>2.78 cm</td>
</tr>
<tr>
<td>Core Height</td>
<td>0.0966 lb</td>
<td>44.2 grams</td>
</tr>
<tr>
<td>Total Weight</td>
<td>0.010 lb</td>
<td>4.535 grams</td>
</tr>
<tr>
<td>Wound OD Min</td>
<td>0.541 in</td>
<td>1.37 cm</td>
</tr>
<tr>
<td>MFL</td>
<td>0.0904 in²</td>
<td>2.16 cm²</td>
</tr>
<tr>
<td>Surface Area</td>
<td>1.918 in²</td>
<td>5.02 cm²</td>
</tr>
<tr>
<td>Permeability</td>
<td>68</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 5.B-1. Wire and inductance graph for Core 55051-A2**

<table>
<thead>
<tr>
<th></th>
<th>ENGLISH</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>W x A</td>
<td>0.077 in</td>
<td>1.97 cm</td>
</tr>
<tr>
<td>W x A</td>
<td>0.115 in</td>
<td>2.92 cm</td>
</tr>
<tr>
<td>OD</td>
<td>0.080 in</td>
<td>2.04 cm</td>
</tr>
<tr>
<td>ID</td>
<td>0.075 in</td>
<td>1.91 cm</td>
</tr>
<tr>
<td>HT</td>
<td>0.080 in</td>
<td>2.04 cm</td>
</tr>
<tr>
<td>W x WINDOW AREA</td>
<td>0.115 in</td>
<td>2.92 cm</td>
</tr>
<tr>
<td>W x EFFECTIVE</td>
<td>0.082 in</td>
<td>2.08 cm</td>
</tr>
<tr>
<td>A x PATH LENGTH</td>
<td>0.115 in</td>
<td>2.92 cm</td>
</tr>
<tr>
<td>CORE WEIGHT</td>
<td>0.014 lb</td>
<td>6.5 g</td>
</tr>
<tr>
<td>TOTAL WEIGHT</td>
<td>0.025 lb</td>
<td>11.7 g</td>
</tr>
<tr>
<td>WOUND OD MIN</td>
<td>0.75 in</td>
<td>1.92 cm</td>
</tr>
<tr>
<td>MLT</td>
<td>1.05 in</td>
<td>2.67 cm</td>
</tr>
<tr>
<td>A x SURFACE AREA</td>
<td>1.762 in2</td>
<td>4.5 cm2</td>
</tr>
</tbody>
</table>

\[ \mu_{125} \times L = 2.08 \times 60 \]
\[ \mu_{160} \times L = 2.47 \times 60 \]
\[ \mu_{200} \times L = 3.23 \times 60 \]
\[ \mu_{550} \times L = 9.07 \times 60 \]

![Diagram of Core 55121-A2 with wire and inductance graph]

Fig. 5. B-2. Wire and inductance graph for Core 55121-A2

<table>
<thead>
<tr>
<th></th>
<th>ENGLISH</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wa Ac</td>
<td>4.91</td>
<td></td>
</tr>
<tr>
<td>Wa x Ac</td>
<td>0.005 lb-in^2</td>
<td>0.264 cm^2</td>
</tr>
<tr>
<td>OD</td>
<td>0.819 in</td>
<td>2.07 cm</td>
</tr>
<tr>
<td>ID</td>
<td>0.47 in</td>
<td>1.19 cm</td>
</tr>
<tr>
<td>HT</td>
<td>0.280 in</td>
<td>0.711 cm</td>
</tr>
<tr>
<td>Wa WINDOW AREA</td>
<td>0.47 x 10^9</td>
<td>1.14 cm^2</td>
</tr>
<tr>
<td>Wa EFFECTIVE</td>
<td>0.1124 lb</td>
<td>0.956 cm^2</td>
</tr>
<tr>
<td>Ac CROSS SECTION</td>
<td>0.045 in</td>
<td>0.212 cm</td>
</tr>
<tr>
<td>Tt PATH LENGTH</td>
<td>2.91 in</td>
<td>7.4 cm</td>
</tr>
<tr>
<td>CORE WEIGHT</td>
<td>0.02 lb</td>
<td>9.1 grams</td>
</tr>
<tr>
<td>TOTAL WEIGHT</td>
<td>0.044 lb</td>
<td>18.6 grams</td>
</tr>
<tr>
<td>WOUND G.D MIN</td>
<td>0.425 in</td>
<td>2.3 cm</td>
</tr>
<tr>
<td>MLT</td>
<td>1.166 in</td>
<td>2.97 cm</td>
</tr>
<tr>
<td>AN = SURFACE AREA</td>
<td>2.848 in^2</td>
<td>15.89 cm^2</td>
</tr>
<tr>
<td>PERMEABILITY</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>( \mu ) 125</td>
<td>2.06 x 10^6</td>
<td>( \mu ) 60</td>
</tr>
<tr>
<td>( \mu ) 160</td>
<td>2.67 x 10^6</td>
<td>( \mu ) 60</td>
</tr>
<tr>
<td>( \mu ) 200</td>
<td>3.33 x 10^6</td>
<td>( \mu ) 50</td>
</tr>
<tr>
<td>( \mu ) 550</td>
<td>5.17 x 10^6</td>
<td>( \mu ) 60</td>
</tr>
</tbody>
</table>

Fig. 5. B-3. Wire and inductance graph for Core 55848-A2
Table 5. B-4. Dimensional specifications for Magnetic Inc 55594-A2, Arnold Engineering A-059043-2

<table>
<thead>
<tr>
<th></th>
<th>ENGLISH</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wd/2Ac</td>
<td>4, 10</td>
<td></td>
</tr>
<tr>
<td>Wd x Ac</td>
<td>6.0713 in³</td>
<td>0.460 cm³</td>
</tr>
<tr>
<td>OD</td>
<td>6.939 in</td>
<td>2.036 cm</td>
</tr>
<tr>
<td>ID</td>
<td>6.527 in</td>
<td>1.629 cm</td>
</tr>
<tr>
<td>Ht</td>
<td>6.110 in</td>
<td>0.826 cm</td>
</tr>
<tr>
<td>Wa : WINDOW AREA</td>
<td>0.52 x 10⁶ CIR-MIL</td>
<td>1.407 cm²</td>
</tr>
<tr>
<td>Wa : EFFECTIVE</td>
<td>0.054 in²</td>
<td>1.056 cm²</td>
</tr>
<tr>
<td>Ac : CROSS SECTION</td>
<td>0.0597 in²</td>
<td>0.0127 cm²</td>
</tr>
<tr>
<td>ln : PATH LENGTH</td>
<td>2.23 in</td>
<td>5.67 cm</td>
</tr>
<tr>
<td>CORE WEIGHT</td>
<td>0.021 lb</td>
<td>15.0 g</td>
</tr>
<tr>
<td>TOTAL WEIGHT</td>
<td>0.0716 lb</td>
<td>32.5 g</td>
</tr>
<tr>
<td>WOUND QD MIN</td>
<td>1.035 in</td>
<td>2.61 cm</td>
</tr>
<tr>
<td>MLT</td>
<td>1.356 in</td>
<td>1.45 cm</td>
</tr>
<tr>
<td>A_s : SURFACE AREA</td>
<td>3.103 in²</td>
<td>20.019 cm²</td>
</tr>
<tr>
<td>PERMEABILITY</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>( \mu ) 125</td>
<td>2.08 x L ( \mu ) 60</td>
<td></td>
</tr>
<tr>
<td>( \mu ) 150</td>
<td>2.67 x L ( \mu ) 60</td>
<td></td>
</tr>
<tr>
<td>( \mu ) 200</td>
<td>3.23 x L ( \mu ) 60</td>
<td></td>
</tr>
<tr>
<td>( \mu ) 500</td>
<td>9.17 x L ( \mu ) 60</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5. B-4. Wire and inductance graph for Core 55059-A2
Table 5. B-5. Dimensional specifications for Magnetic Inc 55059-A2, Arnold Engineering A-894075-2

<table>
<thead>
<tr>
<th></th>
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<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wa x Hc</td>
<td>0.0219 in³</td>
<td>0.097 cm³</td>
</tr>
<tr>
<td>OD</td>
<td>1.090 in</td>
<td>2.77 cm</td>
</tr>
<tr>
<td>ID</td>
<td>0.555 in</td>
<td>1.41 cm</td>
</tr>
<tr>
<td>Ht</td>
<td>0.472 in</td>
<td>1.20 cm</td>
</tr>
<tr>
<td>Wa WINDOW AREA</td>
<td>0.13 x 10⁶ CHIL-MIL</td>
<td>1.41 cm²</td>
</tr>
<tr>
<td>Wa - EFFECTIVE</td>
<td>0.1814 in²</td>
<td>1.17 cm²</td>
</tr>
<tr>
<td>Ac CROSS SECTION</td>
<td>0.099 in²</td>
<td>0.634 cm²</td>
</tr>
<tr>
<td>hm PATH LENGTH</td>
<td>2.50 in</td>
<td>6.35 cm</td>
</tr>
<tr>
<td>CORE WEIGHT</td>
<td>0.077 lb</td>
<td>35 grams</td>
</tr>
<tr>
<td>TOTAL WEIGHT</td>
<td>0.132 lb</td>
<td>60 grams</td>
</tr>
<tr>
<td>WOUND OD MIN</td>
<td>1.191 in</td>
<td>3.00 cm</td>
</tr>
<tr>
<td>MLT</td>
<td>1.84 in</td>
<td>4.67 cm</td>
</tr>
<tr>
<td>Aₜ SURFACE AREA</td>
<td>4.38 in²</td>
<td>28.32 cm²</td>
</tr>
<tr>
<td>PERMEABILITY</td>
<td></td>
<td>60 μₑm²</td>
</tr>
<tr>
<td>μ 125</td>
<td>2.08 x L = μ 60</td>
<td></td>
</tr>
<tr>
<td>μ 160</td>
<td>2.67 x L = μ 60</td>
<td></td>
</tr>
<tr>
<td>μ 200</td>
<td>3.33 x L = μ 60</td>
<td></td>
</tr>
<tr>
<td>μ 550</td>
<td>9.17 x L = μ 60</td>
<td></td>
</tr>
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</table>

Fig. 5. B-5. Wire and inductance graph for Core 55894-A2
Table 5. B-6. Dimensional specifications for Magnetic Inc 55071-A2, Arnold Engineering A-291061-2

<table>
<thead>
<tr>
<th>ENGLISH</th>
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<tr>
<td>WA x Ac</td>
<td>0.9448 in³</td>
</tr>
<tr>
<td>OD</td>
<td>1.312 in</td>
</tr>
<tr>
<td>ID</td>
<td>0.760 in</td>
</tr>
<tr>
<td>HT</td>
<td>0.457 in</td>
</tr>
<tr>
<td>W x WINDOW AREA</td>
<td>0.58 x 10⁶ CIR-MIL</td>
</tr>
<tr>
<td>W x EFFECTIVE</td>
<td>0.120 in²</td>
</tr>
<tr>
<td>Ac x CROSS SECTION</td>
<td>0.1032 in²</td>
</tr>
<tr>
<td>Im x PATH LENGTH</td>
<td>3.21 in</td>
</tr>
<tr>
<td>CORE WEIGHT</td>
<td>0.101 lb</td>
</tr>
<tr>
<td>TOTAL WEIGHT</td>
<td>0.198 lb</td>
</tr>
<tr>
<td>WOUND OD MIN</td>
<td>1.486 in</td>
</tr>
<tr>
<td>MLT</td>
<td>1.85 in</td>
</tr>
<tr>
<td>A x SURFACE AREA</td>
<td>4.389 in²</td>
</tr>
<tr>
<td>PERMEABILITY</td>
<td>60</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\mu 125 & = 2.08 \times L = M 60 \\
\mu 160 & = 2.67 \times L = M 60 \\
\mu 200 & = 3.33 \times L = M 60 \\
\mu 550 & = 9.17 \times L = M 60
\end{align*}
\]

Fig. 5. B-6. Wire and inductance graph for Core 55071-A2
Table 5, B-7. Dimensional specifications for Magnetic Inc 55586-A2, Arnold Engineering A-345038-2

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<thead>
<tr>
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<th>METRIC</th>
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<tbody>
<tr>
<td>Wa/Ae</td>
<td>0.044 in²</td>
<td>1.032 cm²</td>
</tr>
<tr>
<td>Wa x Ae</td>
<td>0.382 in²</td>
<td>0.983 cm²</td>
</tr>
<tr>
<td>HT</td>
<td>0.387 in</td>
<td>0.983 cm</td>
</tr>
<tr>
<td>Wa = WINDOW AREA</td>
<td>0.79 x 10⁻⁶</td>
<td>4.09 cm²</td>
</tr>
<tr>
<td>Wa = EFFECTIVE</td>
<td>0.4644 in²</td>
<td>1.099 cm²</td>
</tr>
<tr>
<td>Ac = CROSS SECTION</td>
<td>0.0714 in²</td>
<td>0.458 cm²</td>
</tr>
<tr>
<td>In = PATH LENGTH</td>
<td>3.51 in</td>
<td>8.9 cm</td>
</tr>
<tr>
<td>CORE WEIGHT</td>
<td>0.075 lb</td>
<td>34 grams</td>
</tr>
<tr>
<td>TOTAL WEIGHT</td>
<td>0.133 lb</td>
<td>87.4 grams</td>
</tr>
<tr>
<td>WOUND OD MIN</td>
<td>1.58 in</td>
<td>-0.62 cm</td>
</tr>
<tr>
<td>ULT</td>
<td>1.70 in</td>
<td>-1.12 cm</td>
</tr>
<tr>
<td>AΣ = SURFACE AREA</td>
<td>6.85 in²</td>
<td>44.24 cm²</td>
</tr>
<tr>
<td>PERMEABILITY</td>
<td></td>
<td>60</td>
</tr>
</tbody>
</table>

\[ \mu_{125} = 2.08 \times L = \mu_{60} \]
\[ \mu_{160} = 2.67 \times L = \mu_{60} \]
\[ \mu_{200} = 3.33 \times L = \mu_{60} \]
\[ \mu_{550} = 9.17 \times L = \mu_{60} \]

Fig. 5, B-7. Wire and inductance graph for Core 55586-A2

<table>
<thead>
<tr>
<th>Dimension</th>
<th>English</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>W x A</td>
<td>0.9486</td>
<td>2.44</td>
</tr>
<tr>
<td>W x A</td>
<td>0.9486</td>
<td>2.44</td>
</tr>
<tr>
<td>OD</td>
<td>1.44</td>
<td>3.66</td>
</tr>
<tr>
<td>ID</td>
<td>0.840</td>
<td>2.15</td>
</tr>
<tr>
<td>HT</td>
<td>0.444</td>
<td>1.17</td>
</tr>
<tr>
<td>W x A x HT</td>
<td>0.72 x 15</td>
<td>1.92 cm²</td>
</tr>
<tr>
<td>W x A x EFFECTIVE</td>
<td>0.422</td>
<td>1.07</td>
</tr>
<tr>
<td>A x CROSS SECTION</td>
<td>0.1095</td>
<td>0.670</td>
</tr>
<tr>
<td>Ln x PATH LENGTH</td>
<td>3.54</td>
<td>8.98</td>
</tr>
<tr>
<td>CORE WEIGHT</td>
<td>0.112</td>
<td>51</td>
</tr>
<tr>
<td>TOTAL WEIGHT</td>
<td>0.219</td>
<td>104.4</td>
</tr>
<tr>
<td>WOUND OD MIN</td>
<td>1.62</td>
<td>4.13</td>
</tr>
<tr>
<td>MLT</td>
<td>1.91</td>
<td>4.88</td>
</tr>
<tr>
<td>A_s x SURFACE AREA</td>
<td>7.271</td>
<td>46.91</td>
</tr>
<tr>
<td>PERMEABILITY</td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>$\mu$ 125</td>
<td></td>
<td>2.08 x L + $\mu$ 60</td>
</tr>
<tr>
<td>$\mu$ 160</td>
<td></td>
<td>2.07 x L + $\mu$ 60</td>
</tr>
<tr>
<td>$\mu$ 200</td>
<td></td>
<td>3.33 x L + $\mu$ 60</td>
</tr>
<tr>
<td>$\mu$ 550</td>
<td></td>
<td>9.17 x L + $\mu$ 60</td>
</tr>
</tbody>
</table>

Fig. 5. B-8. Wire and inductance graph for Core 55076-A2
Table 5, B-9. Dimensional specifications for Magnetic Inc 55083-A2, Arnold Engineering A-083081-2

<table>
<thead>
<tr>
<th></th>
<th>ENGLISH</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wa-Ae</td>
<td>4.92</td>
<td></td>
</tr>
<tr>
<td>Wa x Ac</td>
<td>0.106 m^3</td>
<td>4.14 cm^3</td>
</tr>
<tr>
<td>OD</td>
<td>1.602 in</td>
<td>4.07 cm</td>
</tr>
<tr>
<td>ID</td>
<td>0.918 in</td>
<td>2.33 cm</td>
</tr>
<tr>
<td>HT</td>
<td>0.004 in</td>
<td>0.10 cm</td>
</tr>
<tr>
<td>Wa WINDOW AREA</td>
<td>0.84 x 10^6 CIR-MIL</td>
<td>4.27 cm^2</td>
</tr>
<tr>
<td>Wa EFFECTIVE</td>
<td>0.490 in^2</td>
<td>3.108 cm^2</td>
</tr>
<tr>
<td>Ac CROSS SECTION</td>
<td>0.164 in^2</td>
<td>1.05 cm^2</td>
</tr>
<tr>
<td>Im PATH LENGTH</td>
<td>1.88 in</td>
<td>4.78 cm</td>
</tr>
<tr>
<td>CORE WEIGHT</td>
<td>0.14 lb</td>
<td>0.063 kg</td>
</tr>
<tr>
<td>TOTAL WEIGHT</td>
<td>0.188 lb</td>
<td>0.085 kg</td>
</tr>
<tr>
<td>WOUND OD MIN</td>
<td>1.27 in</td>
<td>3.23 cm</td>
</tr>
<tr>
<td>MLT</td>
<td>5.16 in</td>
<td>13.1 cm</td>
</tr>
<tr>
<td>$A_1^*$ SURFACE AREA</td>
<td>0.07 m^2</td>
<td>0.084 cm^2</td>
</tr>
<tr>
<td>PERMEABILITY</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>$\mu$ 125</td>
<td>2.08 x $L$ x $\mu$ 60</td>
<td></td>
</tr>
<tr>
<td>$\mu$ 160</td>
<td>2.67 x $L$ x $\mu$ 60</td>
<td></td>
</tr>
<tr>
<td>$\mu$ 200</td>
<td>3.23 x $L$ x $\mu$ 60</td>
<td></td>
</tr>
<tr>
<td>$\mu$ 550</td>
<td>9.17 x $L$ x $\mu$ 60</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5, B-9. Wire and inductance graph for Core 55083-A2
Table 5. B-10. Dimensional specifications for Magnetic Inc 55439-A2, Arnold Engineering A-759135-2

<table>
<thead>
<tr>
<th>ENGLISH</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wa x A1</td>
<td>0.200 in²</td>
</tr>
<tr>
<td>OD</td>
<td>1.875 in</td>
</tr>
<tr>
<td>ID</td>
<td>0.916 in</td>
</tr>
<tr>
<td>HT</td>
<td>0.700 in</td>
</tr>
<tr>
<td>Wa WINDOW AREA</td>
<td>0,84 x 10⁶ OHM-MIL</td>
</tr>
<tr>
<td>Wa - EFFECTIVE</td>
<td>0,460 in²</td>
</tr>
<tr>
<td>Ac CROSS SECTION</td>
<td>0,162 in²</td>
</tr>
<tr>
<td>ln PATH LENGTH</td>
<td>4.21 in</td>
</tr>
<tr>
<td>CORE WEIGHT</td>
<td>0.14 lb</td>
</tr>
<tr>
<td>TOTAL WEIGHT</td>
<td>0.43 lb</td>
</tr>
<tr>
<td>WOUND GO SIM</td>
<td>3.94 in</td>
</tr>
<tr>
<td>LLT</td>
<td>1.00 in</td>
</tr>
<tr>
<td>A_s SURFACE AREA</td>
<td>12.10 in²</td>
</tr>
<tr>
<td>PERMEABILITY</td>
<td>60</td>
</tr>
<tr>
<td>$\mu$ 125</td>
<td>2.08 x L = $\mu$ 60</td>
</tr>
<tr>
<td>$\mu$ 160</td>
<td>2.67 x L = $\mu$ 60</td>
</tr>
<tr>
<td>$\mu$ 200</td>
<td>3.33 x L = $\mu$ 60</td>
</tr>
<tr>
<td>$\mu$ 550</td>
<td>7.17 x L = $\mu$ 60</td>
</tr>
</tbody>
</table>

Fig. 5. B-10. Wire and inductance graph for Core 55439-A2

<table>
<thead>
<tr>
<th>ENGLISH</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wa/Ac</td>
<td>0.528 in^2</td>
</tr>
<tr>
<td>Wa x Ac</td>
<td>3.334 in</td>
</tr>
<tr>
<td>OD</td>
<td>1.168 in</td>
</tr>
<tr>
<td>ID</td>
<td>0.585 in</td>
</tr>
<tr>
<td>HT</td>
<td>1.1 x 10^6 CIR-MIL</td>
</tr>
<tr>
<td>Wa WINDOW AREA</td>
<td>1.121 in^2</td>
</tr>
<tr>
<td>Wa EFFECTIVE</td>
<td>0.623 in^2</td>
</tr>
<tr>
<td>Ac CROSS SECTION</td>
<td>2.57 in</td>
</tr>
<tr>
<td>Ln PATH LENGTH</td>
<td>5.61 in</td>
</tr>
<tr>
<td>CORE WEIGHT</td>
<td>0.188 lb</td>
</tr>
<tr>
<td>TOTAL WEIGHT</td>
<td>0.264 lb</td>
</tr>
<tr>
<td>WOUND OD MIN</td>
<td>2.75 in</td>
</tr>
<tr>
<td>MLT</td>
<td>5.61 in</td>
</tr>
<tr>
<td>A1 SURFACE AREA</td>
<td>17.42 in^2</td>
</tr>
</tbody>
</table>

PERMEABILITY

- \( \mu 125 \), 2.08 x L + M 60
- \( \mu 160 \), 2.47 x L + M 60
- \( \mu 215 \), 3.33 x L + M 60
- \( \mu 550 \), 9.17 x L + M 60

Fig. 5. B-11. Wire and inductance graph for Core 55110-A2
Table 5, B-12. Dimensional specifications for Magnetic Inc 55716-A2, Arnold Engineering A-106073-2

<table>
<thead>
<tr>
<th>English</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_{in}$</td>
<td>0.224 in$^3$ = 1.28 cm$^3$</td>
</tr>
<tr>
<td>$W_{out}$</td>
<td>2.015 in = 5.17 cm</td>
</tr>
<tr>
<td>ID</td>
<td>1.218 in = 3.10 cm</td>
</tr>
<tr>
<td>HT</td>
<td>0.065 in = 1.65 mm</td>
</tr>
<tr>
<td>$W_{win}$ WINDOW AREA</td>
<td>1.14 x 10^3 CM$^2$ CM$^2$</td>
</tr>
<tr>
<td>$W_{eff}$ EFFECTIVE</td>
<td>0.874 in$^2$ = 5.62 cm$^2$</td>
</tr>
<tr>
<td>$A_{cs}$ CROSS SECTION</td>
<td>0.192 in$^2$ = 1.24 cm$^2$</td>
</tr>
<tr>
<td>$l_{p}$ PATH LENGTH</td>
<td>6.02 in = 15.2 cm</td>
</tr>
<tr>
<td>CORE WEIGHT</td>
<td>0.291 lb = 135 grams</td>
</tr>
<tr>
<td>TOTAL WEIGHT</td>
<td>0.642 lb = 290 grams</td>
</tr>
<tr>
<td>WOUND OD MIN</td>
<td>2.26 in = 5.73 cm</td>
</tr>
<tr>
<td>$T_{1}$ T</td>
<td>2.54 in = 6.5 cm</td>
</tr>
<tr>
<td>$A_{a}$ SURFACE AREA</td>
<td>14.15 in$^2$ = 91.32 cm$^2$</td>
</tr>
<tr>
<td>PERMEABILITY</td>
<td>60</td>
</tr>
</tbody>
</table>

| $\mu$ 125 | $2.08 \times L = \mu 60$ |
| $\mu$ 160 | $2.67 \times L = \mu 60$ |
| $\mu$ 200 | $3.33 \times L = \mu 60$ |
| $\mu$ 550 | $9.17 \times L = \mu 60$ |

Fig. 5, B-12. Wire and inductance graph for Core 55716-A2

<table>
<thead>
<tr>
<th></th>
<th>ENGLISH</th>
<th>METRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wm/Ac</td>
<td>4.57</td>
<td>4.57</td>
</tr>
<tr>
<td>Wm x Ac</td>
<td>0.194 m²</td>
<td>64.9 cm²</td>
</tr>
<tr>
<td>OD</td>
<td>1.875 in</td>
<td>4.76 cm</td>
</tr>
<tr>
<td>ID</td>
<td>1.098 in</td>
<td>2.79 cm</td>
</tr>
<tr>
<td>HT</td>
<td>0.615 in</td>
<td>1.56 cm</td>
</tr>
<tr>
<td>Wm x WINDOW AREA</td>
<td>3.33 x 10⁶ G/M MIL</td>
<td>4.11 cm²</td>
</tr>
<tr>
<td>Wm = EFFECTIVE</td>
<td>0.210 m²</td>
<td>4.59 cm²</td>
</tr>
<tr>
<td>Ac = CROSS SECTION</td>
<td>0.265 m²</td>
<td>1.17 cm²</td>
</tr>
<tr>
<td>ln = PATH LENGTH</td>
<td>4.48 in</td>
<td>11.4 cm</td>
</tr>
<tr>
<td>CORE WEIGHT</td>
<td>0.284 lb</td>
<td>130 grams</td>
</tr>
<tr>
<td>TOTAL WEIGHT</td>
<td>0.588 lb</td>
<td>267 grams</td>
</tr>
<tr>
<td>WOUND OD MIN</td>
<td>2.16 in</td>
<td>5.44 cm</td>
</tr>
<tr>
<td>MLT</td>
<td>2.62 in</td>
<td>6.66 cm</td>
</tr>
<tr>
<td>A₀ = SURFACE AREA</td>
<td>12.64 m²</td>
<td>115.5 cm²</td>
</tr>
<tr>
<td>PERMEABILITY</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>µ 125</td>
<td>2.08 x L = µ 60</td>
<td></td>
</tr>
<tr>
<td>µ 160</td>
<td>2.67 x L = µ 60</td>
<td></td>
</tr>
<tr>
<td>µ 200</td>
<td>3.35 x L = µ 60</td>
<td></td>
</tr>
<tr>
<td>µ 550</td>
<td>9.17 x L = µ 60</td>
<td></td>
</tr>
</tbody>
</table>

![Diagram of core dimensions](image)

**Fig. 5. B-13. Wire and inductance graph for Core 55090-A2**
CHAPTER VI

WINDOW UTILIZATION FACTOR $K_u$
A. INTRODUCTION

The window utilization factor is the amount of copper that appears in the window area of the transformer or inductor. The window utilization factor is influenced by 4 different factors: (1) wire insulation, (2) wire lay (fill factor), (3) bobbin area (or, when using a toroid, the clearance hole for passage of the shuttle), and (4) insulation required for multilayer windings or between windings. In the design of high-current or low-current transformers, the ratio of conductor area over total wire area can vary from 0.941 to 0.673, depending on the wire size. The wire lay or fill factor can vary from 0.7 to 0.55, depending on the winding technique. The amount and the type of insulation are dependent on the voltage.

B. 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 $S_4$:

$$K_u = S_1 \times S_2 \times S_3 \times S_4 \quad (6-1)$$

where

$$S_1 = \frac{\text{conductor area}}{\text{wire area}}$$
$$S_2 = \frac{\text{wound area}}{\text{usable window area}}$$
$$S_3 = \frac{\text{usable window area}}{\text{window area}}$$
$$S_4 = \frac{\text{usable window area}}{\text{usable window area} + \text{insulation area}}$$

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 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 6-1
may be used for calculating some typical values such as for AWG 10, AWG 20,
AWG 30 and AWG 40.

Thus:

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

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

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

$$\text{AWG 40} = \frac{0.0485 \text{ cm}^2}{0.0723 \text{ cm}^2} = 0.673.$$

When designing low-current transformers, it is advisable to reevaluate
$S_1$ because of the increased amount of insulation.

$S_2$ 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 area 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, varia-
tions 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 area $W_a$
between 0.835 to 0.929 while a two bobbin configuration offers an effective area $W_a$
between 0.687 to 0.872. A good value to use for both configurations is 0.75.
When designing with a pot core, \( S_3 \) has to be reduced because the effective \( W_a \) varies between 0.55 and 0.71.

The term \( S_4 \) 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 \( S_4 \) should be reduced by 10% for each additional secondary winding because of the added space occupied by insulation and partly due to poorer space factor.

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:

\[
0.4 = \frac{A_w}{A_w^{\text{Bare}}} \times \frac{W_a^{\text{eff}}}{W_a} \times \frac{\text{Fill Factor}}{\text{Insulation Factor}}
\]

\[
\left( \frac{S_1}{S_2} \right) \left( \frac{S_3}{S_4} \right)
\]

C. CONVERSION DATA FOR WIRE SIZES FROM #10 TO #44

Columns A and B in Table 6-1 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 microhm/cm or \( 10^{-6} \text{\Omega/cm} \) in wire length for each wire size. 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/cm.

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

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

For resistance correction factor \( \zeta \) (Zeta) for higher and lower temperature, see Figure 6-1.
### Table 6-1: Wire Table

<table>
<thead>
<tr>
<th>#</th>
<th>Wire Size</th>
<th>Area (cm²/cm)</th>
<th>Resistance (Ω·cm)</th>
<th>Density</th>
<th>Area (cm²)</th>
<th>Diameter (cm)</th>
<th>Thickness (inch)</th>
<th>Density (cm²/σ)</th>
<th>Weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>102.8</td>
<td>52.6</td>
<td>1028</td>
<td>0.051</td>
<td>1028</td>
<td>0.105</td>
<td>0.016</td>
<td>0.091</td>
<td>0.091</td>
</tr>
<tr>
<td>11</td>
<td>205.6</td>
<td>101.6</td>
<td>2056</td>
<td>0.051</td>
<td>2056</td>
<td>0.210</td>
<td>0.036</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>12</td>
<td>308.4</td>
<td>50.0</td>
<td>3084</td>
<td>0.051</td>
<td>3084</td>
<td>0.315</td>
<td>0.054</td>
<td>0.315</td>
<td>0.315</td>
</tr>
<tr>
<td>13</td>
<td>411.2</td>
<td>20.6</td>
<td>4112</td>
<td>0.051</td>
<td>4112</td>
<td>0.420</td>
<td>0.076</td>
<td>0.420</td>
<td>0.420</td>
</tr>
<tr>
<td>14</td>
<td>514.0</td>
<td>10.0</td>
<td>5140</td>
<td>0.051</td>
<td>5140</td>
<td>0.525</td>
<td>0.098</td>
<td>0.525</td>
<td>0.525</td>
</tr>
<tr>
<td>15</td>
<td>616.8</td>
<td>5.0</td>
<td>6168</td>
<td>0.051</td>
<td>6168</td>
<td>0.630</td>
<td>0.120</td>
<td>0.630</td>
<td>0.630</td>
</tr>
<tr>
<td>16</td>
<td>719.6</td>
<td>2.5</td>
<td>7196</td>
<td>0.051</td>
<td>7196</td>
<td>0.735</td>
<td>0.144</td>
<td>0.735</td>
<td>0.735</td>
</tr>
<tr>
<td>17</td>
<td>822.4</td>
<td>1.0</td>
<td>8224</td>
<td>0.051</td>
<td>8224</td>
<td>0.840</td>
<td>0.166</td>
<td>0.840</td>
<td>0.840</td>
</tr>
<tr>
<td>18</td>
<td>925.2</td>
<td>0.5</td>
<td>9252</td>
<td>0.051</td>
<td>9252</td>
<td>0.945</td>
<td>0.188</td>
<td>0.945</td>
<td>0.945</td>
</tr>
<tr>
<td>19</td>
<td>1028.0</td>
<td>0.25</td>
<td>10280</td>
<td>0.051</td>
<td>10280</td>
<td>1.050</td>
<td>0.210</td>
<td>1.050</td>
<td>1.050</td>
</tr>
<tr>
<td>20</td>
<td>1130.8</td>
<td>0.1</td>
<td>11308</td>
<td>0.051</td>
<td>11308</td>
<td>1.155</td>
<td>0.231</td>
<td>1.155</td>
<td>1.155</td>
</tr>
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<td>15420</td>
<td>0.051</td>
<td>15420</td>
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<td>0.318</td>
<td>1.575</td>
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<td>0.051</td>
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<td>0.051</td>
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<td>0.362</td>
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<td>20560</td>
<td>2.100</td>
<td>0.428</td>
<td>2.100</td>
<td>2.100</td>
</tr>
</tbody>
</table>

**Notes:**
- *This data from REA Magnetic Wire Data (Ref. 1).*
- *This notation means the entry in the column must be multiplied by 10⁻³.
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

\[ W_t = (MLT) \times (N) \times (\text{Column L}) \quad \text{[grams]} \]
Turns per square inch and turns per square cm are based on 60% wire fill factor. Mean length/turn for a given winding may be calculated with the aid of Fig. 6-2. Figure 6-3 shows a transformer being constructed using layer insulation. When a transformer is being built in this way, Table 6-2 and 6-3 will help the designer find the correct insulation thickness and margin for the appropriate wire size.

D. TEMPERATURE CORRECTION FACTORS

The resistance values given in Table 6-1 are based upon a temperature of 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 6-1 by the appropriate correction factor shown on the graph. Thus, Corrected Resistance = Ω/cm (at 20°C) × ζ.

E. WINDOW UTILIZATION FACTOR FOR A TOROID

The toroidal magnetic component has found wide use in industry and aerospace because of its high frequency capability. The high frequency capability of the toroid is due to its high ratio of window area over core cross section and its ability to accommodate different strip thickness in its boxed configuration. Tape strip thickness is an important consideration in selecting cores. Eddy-current losses in the core can be reduced at higher frequencies by use of thinner strip stock. The high ratio of window area over core cross section insures the minimum of iron and large winding area to minimize the flux density and core loss.

The magnetic flux in the tape wound toroid can be contained inside the core more readily than in lamination or C type core as the winding covers the core along the whole magnetics path length which gives lower electromagnetic interference.

The toroid does not give a smooth A-p relationship as lamination, C core, powder cores and pot cores with respect to volume, weight, surface area and current density as can be seen in Chapter 2. This is because the actual core is always embedded in a case having a wall thickness which has no fixed relation to the actual core and becomes relatively large the smaller the actual core
COMPUTATION OF MEAN TURN LENGTH

\[ (MLT)_1 = 2(r+2J) + 2(s+2J) + \pi a_1 \]
\[ (MLT)_2 = 2(r+2J) + 2(s+2J) + \pi (a_1 + a_2) \]
OR
\[ (MLT)_2 = (MLT)_1 + (a_1 + a_2 + 2c) \]
OR
\[ (MLT)_n = 2(r+2J) + 2(s+2J) + \pi \left[ 2(a_1 + a_2 + \ldots + a_{n-1} + a_n) \right] \]

WHERE:
- \( a_1 = \text{BUILD OF WINDING #1} \)
- \( a_2 = \text{BUILD OF WINDING #2} \)
- \( a_n = \text{BUILD OF WINDING #n} \)
- \( c = \text{THICKNESS OF INSULATION BETWEEN } a_1 \text{ & } a_2 \)

Fig. 6-2. Computation of mean turn length
Fig. 6-3. Layer insulated coil

Table 6-2. Layer insulation vs AWG

<table>
<thead>
<tr>
<th>AWG</th>
<th>Insulation thickness (cm)</th>
<th>Insulation thickness (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-16</td>
<td>0.0254</td>
<td>0.01</td>
</tr>
<tr>
<td>17-19</td>
<td>0.0178</td>
<td>0.007</td>
</tr>
<tr>
<td>20-21</td>
<td>0.0127</td>
<td>0.005</td>
</tr>
<tr>
<td>22-23</td>
<td>0.0076</td>
<td>0.003</td>
</tr>
<tr>
<td>24-27</td>
<td>0.0051</td>
<td>0.002</td>
</tr>
<tr>
<td>28-33</td>
<td>0.00381</td>
<td>0.0015</td>
</tr>
<tr>
<td>34-41</td>
<td>0.00254</td>
<td>0.001</td>
</tr>
<tr>
<td>42-46</td>
<td>0.6 .127</td>
<td>0.0005</td>
</tr>
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</table>
Table 6-3. Margin vs AWG

<table>
<thead>
<tr>
<th>AWG</th>
<th>Margin cm</th>
<th>Margin inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-15</td>
<td>0.635</td>
<td>0.250</td>
</tr>
<tr>
<td>16-18</td>
<td>0.475</td>
<td>0.187</td>
</tr>
<tr>
<td>19-21</td>
<td>0.396</td>
<td>0.156</td>
</tr>
<tr>
<td>22-31</td>
<td>0.318</td>
<td>0.125</td>
</tr>
<tr>
<td>32-37</td>
<td>0.236</td>
<td>0.093</td>
</tr>
<tr>
<td>38</td>
<td>0.157</td>
<td>0.062</td>
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</tbody>
</table>

cross section is. The available window area inside the case, therefore, is not a fixed percentage of the window area of the uncased core.

Design Manual TWC-300 of MAGNETICS, Inc. indicates that random wound cores can be produced with fill factors as high as 0.7, but that progressive sector wound cores can be produced with fill factors of only up to 0.55. As a typical working value for copper wire with a heavy synthetic film insulation, a ratio of 0.60 may be used safely. Figure 6-4 is based upon a fill factor ratio of 0.60 for wire sizes 14 through 42 with 0.5 I.D. remaining.

The term usable window cm\(^2\)/window cm\(^2\) \((S_3)\) defines how much of the available window space may actually be used for the winding. Figure 6-5 is based on the assumption that the inside diameter (ID) of the wound core is one-half that of the bare core, i.e., \(S_3 = 0.75\) (to allow free passage of the shuttle).

Insulation factor \((S4)\) in Figure 6-4 is 1.0; this does not take into account any insulation. The window utilization factor \((K_u)\) is highly influenced by the insulation factor \((S4)\) because of the rapid build-up of insulation in a toroid as shown in Figure 6-6.

It can be seen in Figure 6-6 the insulation build-up is greater on the inside than on the outside. For an example in Figure 6-6 if 1.27 cm wide tape was to be used with an overlap of 0.32 cm on the O.D., the overlap thickness
Figure 6-4. Toroid inside diameter versus turns
Figure 6-5. Effective winding area of a toroid

\[ \text{Effective Window Area} = \frac{\pi \cdot (\text{I.D.)}^2}{4} \]

\[ \text{I.D. of Toroid Core} \]
\[ \text{O.D.} \]

\[ \text{Clearance for Passage of Shuttle} \]
\[ \text{I.D.} \]

Figure 6-6. Wrap toroid
would be four times the thickness of the tape. It will be noted that the amount of overlap will depend greatly on the size of the toroid. As the toroid window gets smaller the overlap increases. There is a way to minimize the build on a wrapped toroid and that is to use periphery insulation as shown in Figure 6-7. The use of periphery insulation minimizes the inside diameter overlay as shown in Figure 6-8.

Figure 6-7. Periphery insulation

Figure 6-8. Minimizing toroidal inside build
When a design requires a multitude of windings, all of which have to be insulated, then the insulation factor \((S_4)\) becomes very important in the window utilization factor \((K_u)\). For example, a low current toroidal transformer with insulation has a significant influence on the window utilization factor as shown below:

\[
S_1 = \#40 \text{ AWG} \quad K_u = S_1 \times S_2 \times S_3 \times S_4
\]

\[
K_u = 0.673 \times 0.60 \times 0.75 \times 0.80
\]

\[
K_u = 0.242.
\]

Table 6-4 was generated as an aid for the engineer; it is a listing of 29 A.I.E.E. preferred tape-wound toroidal cores with metric dimension. The power handling capability is listed in the last column under \(A_p\) product.
### Table 6-4. A.I.E.E. preferred tape-wound toroidal cores

<table>
<thead>
<tr>
<th>Mag Inc</th>
<th>Arnold</th>
<th>(A_e (\text{cm}^2))</th>
<th>(W_e (\text{cm}^2))</th>
<th>(D (\text{D} \text{cm}))</th>
<th>(OD (\text{OD} \text{cm}))</th>
<th>(HR (\text{cm}))</th>
<th>(l_m (\text{cm}))</th>
<th>(\text{(3) Core Wt (grams)})</th>
<th>(A_p (\text{cm}^4))</th>
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</thead>
<tbody>
<tr>
<td>52056</td>
<td>RT9043</td>
<td>0.043</td>
<td>0.915</td>
<td>1.079</td>
<td>1.778</td>
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<td>4.49</td>
<td>1.67</td>
<td>0.0393</td>
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<td>3.73</td>
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<td>0.711</td>
<td>6.40</td>
<td>10.9</td>
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(1) Cross-sectional area calculated for 2 mil (0.002 in.) material
(2) Dimensions listed are sizes of aluminum boxed cores (not coated)
(3) 0.002 mil thickness and high nickel material

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CHAPTER VII

TRANSFORMER - INDUCTOR

EFFICIENCY, REGULATION, AND TEMPERATURE RISE
A. INTRODUCTION

Transformer efficiency, regulation, and temperature rise are all interrelated. Not all of the input power to the transformer is delivered to the load. The difference between the input power and output power is converted into heat. This power loss can be broken down into two components: core loss and copper loss. The core loss is a fixed loss, and the copper loss is a variable loss which is related to the current demand of the load. Copper loss goes up by the square of the current and is termed quadratic loss. Maximum efficiency is achieved when the fixed loss is equal to the quadratic at rated load. Transformer regulation is the copper loss $P_{cu}$ divided by the output power $P_o$.

B. TRANSFORMER EFFICIENCY

The efficiency of a transformer is a good way to measure 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 determined by the fixed losses in the core and the quadratic losses in the windings or copper. Thus

$$P_{\Sigma} = P_{fe} + P_{cu} \quad (7-1)$$

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

Maximum efficiency is achieved when the fixed loss is made equal to the quadratic loss as shown by equation 7-11. Transformer loss versus output load current is shown in Figure 7-1.

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

$$P_{cu} = KP_o^2 \quad (7-2)$$
Fig. 7-1. Transformer loss versus output load current

which may be rewritten as

$$P_{\Sigma} = P_{fe} + KP_{o}^2$$  \hspace{1cm} (7-3)

Since

$$P_{in} = P_{o} + P_{\Sigma}$$  \hspace{1cm} (7-4)

and the efficiency is

$$\eta = \frac{P_{o}}{P_{o} + P_{\Sigma}}$$  \hspace{1cm} (7-5)

then

$$\eta = \frac{P_{o}}{P_{o} + P_{fe} + KP_{o}^2} = \frac{P_{o}}{P_{fe} + P_{o} + KP_{o}^2}$$  \hspace{1cm} (7-6)
and, differentiating with respect to $P_o$:

$$\frac{d\eta}{dP_o} = -P_o\left[P_{fe} + P_o + KP_o^2\right]^{-2}(1 + 2 KP_o)$$  \hspace{1cm} (7-7)

$$+ \left[P_{fe} + P_o + KP_o^2\right] = 0 \text{ for max } \eta$$  \hspace{1cm} (7-8)

$$-P_o (1 + 2 KP_o) + \left(P_{fe} + P_o + KP_o^2\right) = 0$$  \hspace{1cm} (7-9)

$$-P_o - 2KP_o^2 + P_{fe} + P_o + KP_o^2 = 0$$  \hspace{1cm} (7-10)

$$\therefore P_{fe} = KP_o^2 = P_{cu}$$  \hspace{1cm} (7-11)

C. RELATIONSHIP OF $P_o$ TO CONTROL OF TEMPERATURE RISE

1. 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 heat generated 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. This heat is dissipated from the exposed surfaces of the transformer by a combination of radiation and convection. The dissipation is therefore 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:

$$P_\Sigma = P_{fe} + P_{cu} \quad (7-12)$$

and

$$P_{cu} = \frac{P_\Sigma}{2} \quad (7-13)$$

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:

$$\frac{P_p}{R_p} = \frac{P_s}{R_s} \quad (7-14)$$

and

$$\frac{P_\Sigma}{R_t} = \frac{2P_p}{R_p/2} = \frac{4P_p}{R_p} = (2I_p)^2 \quad (7-15)$$

Then

$$J_p = \frac{I_p}{W_a/2} = \frac{2I_p}{W_a} = J_s = J \quad (7-16)$$

2. **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:

\[ P_\Sigma = P_{fe} + P_{cu} \]  \hspace{1cm} (7-17)

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

Transfer of heat by thermal \textit{radiation} occurs when a body is raised to a temperature above its surroundings and emits radiant energy in the form of waves. In accordance with the Stefan-Boltzmann law,\footnote{Reference 2, Chapter 3.} this may be expressed as:

\[ W_r = K_r \epsilon (T_2^4 - T_1^4) \]  \hspace{1cm} (7-18)

in which

- \( W_r \) = watts per square centimeter of surface
- \( K_r = 5.70 \times 10^{-12} \text{ W cm}^{-2} \text{ } \left( ^0\text{K}\right)^{-4} \)
- \( \epsilon \) = emissivity factor
- \( T_2 \) = hot body temperature in degrees kelvin
- \( T_1 \) = ambient or surrounding temperature in degrees kelvin

Transfer of heat by \textit{convection} occurs when a body is hotter than the surrounding medium, which usually is air. The layer of air in contact with the hot body which is heated by conduction expands, and rises, taking the absorbed heat with it. The next layer, being colder, replaces the risen layer, and in turn on being heated also rises. This continues as long as the air or medium surrounding the body is at a lower temperature. The transfer of heat by convection is stated mathematically as:

\[ W_c = K_c F_\theta^\theta \sqrt{p} \]  \hspace{1cm} (7-19)
in which:

\[ W_c = \text{watts loss per square centimeter} \]
\[ K_c = 2.17 \times 10^{-4} \]
\[ F = \text{air friction factor (unity for a vertical surface)} \]
\[ \theta = \text{temperature rise, degrees C} \]
\[ p = \text{relative barometric pressure (unity at sea level)} \]
\[ \eta = \text{exponential value ranging from 1.0 to 1.25, depending on the shape and position of the surface being cooled.} \]

The total heat dissipated from a plane vertical surface is expressed by the sum of equations 7-18 and 7-19:

\[ W = 5.70 \times 10^{-12} \varepsilon (T_2^4 - T_1^4) + 1.4 \times 10^{-3} F \theta^{1.25} \sqrt{p} \] (7-20)

3. Temperature Rise Versus Surface Area Dissipation

The temperature rise which may be expected for various levels of power loss is shown in the monograph of Figure 7-2 below. It is based on equation 7-20 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 temperature of 25°C, at sea level. Power loss (heat dissipation) is expressed in watts/cm² 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.

*See References in Chapter 3.
4. **Surface Area Required for Heat Dissipation**

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

$$A_t = \frac{P_e}{\psi}$$

in which $\psi$ is the power density or the average power dissipated per unit area from the surface of the transformer and $P_e$ 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 transformer. The straightline logarithmic relationship shown in Figure 7-3 below has been plotted from the data shown in Table 2-5, Chapter 2.
From this, the following relationship evolves:

\[ A_t = K_s (A_p)^{0.5} = \frac{P_s}{\psi} \quad (7-22) \]

and (from Fig. 7-2)

\[ \psi = 0.03 \text{ W/cm}^2 \text{ at } 25^\circ\text{C rise} \quad (7-23) \]

\[ \psi = 0.07 \text{ W/cm}^2 \text{ at } 50^\circ\text{C rise} \quad (7-24) \]

Figure 7-4 utilizes the efficiency rating in watts dissipated in terms of two different, but commonly allowable temperature rises for the transformer over ambient temperature. The data presented are used as bases for determining the needed transformer surface area \( A_t \) (in cm\(^2\)).
D. REGULATION AS A FUNCTION OF EFFICIENCY

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

Figure 7-5 shows the circuit diagram of a transformer with one secondary. Note that \( \alpha = \) regulation (%).

![Transformer circuit diagram](image)

Fig. 7-5. Transformer circuit diagram
The analytical equivalent is shown in Figure 7-6.

![Transformer analytical equivalent](image)

**Fig. 7-6. Transformer analytical equivalent**

This assumes that distributed capacitance in the secondary can be neglected because the frequency and secondary voltage are not excessively high. 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 now be expressed as:

\[
\alpha = \left( \frac{V_o(N_s L_s) - V_o(F_s L_s)}{V_o(N_s L_s)} \right) \times 100
\]  \hspace{1cm} (7-25)

in which \(V_o(N_s L_s)\) is the no load voltage and \(V_o(F_s L_s)\) is the full load voltage.

The output voltage computed using Figure 7-5 is:

\[
V_o = \frac{R_p}{R_o + R_s} \left( \frac{N^2 R_p}{N^2 R_E} \right) \left( \frac{1}{R_o + R_s} \right) \]  \hspace{1cm} (7-26)

For the usual condition of

\[N^2 R_E \gg N^2 R_p \parallel (R_o + R_s)\]
For equal window areas allocated for the primary and secondary windings, it can be shown that $N^2 R_p = R_s$.

For simplicity, let

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

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

$$ V_o (N.L.) = NE $$

$$ \alpha = \frac{1}{R_o + R_{cu}} \times 100 $$

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

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

This shows that regulation is independent of the transformer turns ratio.

For regulation as a function of copper loss, multiply equation 7-31 by $I_o^2$:

$$ \alpha = \frac{I_o^2 R_{cu}}{I_o^2 (R_o + R_{cu})} \times 100 $$

7-35
then

\[ \alpha = \frac{P_{cu}}{P_o + P_{cu}} \times 100 \]  
(7-33)

\[ P_{in} = P_{cu} + P_{fe} + P_o \]  
(7-34)

For regulation as a function of efficiency,

\[ \frac{P_o}{P_{in}} = \frac{P_o}{P_{cu} + P_{fe} + P_o} = \eta \]  
(7-35)

By definition

\[ P_{cu} = P_{fe} \]  
(7-36)

Solving for \( P_{cu} + P_{fe} \)

\[ \frac{P_o(1 - \eta)}{\eta} = P_o \left( \frac{1}{\eta} - 1 \right) = P_{cu} + P_{fe} = 2P_{cu} \]  
(7-37)

\[ \frac{\alpha}{100} = \frac{1 - \eta}{1 + \frac{P_o}{P_{cu}}} = \frac{1}{1 + \frac{1/\eta - 1}{2}} = \frac{1 - \eta}{1 + \eta} \]  
(7-38)

\[ \alpha = \frac{1 - \eta}{1 + \eta} \times 100 \]  
(7-39)

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

\[ \alpha + \eta \alpha = 100 - \eta \times 100 \]  
(7-40)
Solve for $\eta$

$$\eta 100 + \eta \alpha = 100 - \alpha$$  \hspace{0.5cm} (7-41)

$$\eta (100 + \alpha) = 100 - \alpha$$  \hspace{0.5cm} (7-42)

$$\eta = \frac{100 - \alpha}{100 + \alpha}$$  \hspace{0.5cm} (7-43)

E. DESIGNING FOR A GIVEN REGULATION

1. Transformers

Although most transformers are designed for a given temperature rise, they can also be designed for a given regulation. The regulation and power-handling ability of a core is related to two constants:

$$VA = K_g K_e \alpha$$  \hspace{0.5cm} (7-44)

$$\alpha = \text{Regulation} \%$$

The constant $K_g$ is determined by the core geometry which may be related by the following equation:

$$K_g = \frac{W_a A_c^2}{\text{MLT}}$$  \hspace{0.5cm} (7-45)

The constant $K_e$ is determined by the magnetic and electric operating conditions which may be related by the following equation:

$$K_e = 0.145 K_f^2 B_m^2 \times 10^{-4}$$  \hspace{0.5cm} (7-46)

The derivation of the relationship for $K_g$ and $K_e$ is given at the end of this chapter.
The area product $A_p$ can be related to the core geometry $K_g$ in the following equation:

$$A_p = K_p K_g^{0.8} \quad (7-47)$$

The derivation is given in detail at the end of this chapter.

Rewriting equation 7-44,

$$K_g = \frac{VA}{K_e \sigma} \quad (7-48)$$

$$A_p = K_p \left( \frac{VA}{K_e \sigma} \right)^{0.8} \quad (7-49)$$

Figure 7-7 shows how area product $A_p$ varies as a function of regulation, in percent.

Fig. 7-7. Area product versus regulation
Figure 7-8 shows how weight $W_t$ varies as a function of regulation, in percent.

Fig. 7-8. Weight versus regulation

2. **Inductors**

Inductors, like transformers, are designed for a given temperature rise. They can also be designed for a given regulation. The regulation and energy handling ability of a core is related to two constants:

$$ (\text{Energy})^2 = K_g K_e \alpha $$

$$ \alpha = \text{Regulation (\%)} $$
The constant $K_g$ is determined by the core geometry:

\[ K_g = \frac{W_s A_c^2 K_u}{MLT} \]  

(7-51)

The constant $K_e$ is determined by the magnetic and electric operating conditions:

\[ K_e = \omega 1.145 P_o B_{dc}^2 \times 10^{-4} \]  

(7-52)

The derivation of the specific functions for $K_g$ and $K_e$ is given at the end of this chapter.

3. Transformer Design Example I

For a typical design example, assume an isolation transformer with the following specifications:

(1) 115 volts
(2) 1.0 amperes
(3) Sine wave
(4) Frequency 60 Hz
(5) Regulation $\leq 2\%$

The procedure would then be as follows:

**Step No. 1.** Calculate the output power:

\[ P_o = VA \]
\[ P_o = (115)(1.0) \]
\[ P_o = 115 \text{ [watts]} \]
Step No. 2. Calculate the electrical conditions from equation 7-46:

\[ K_e = 0.145 K^2 f^2 B^2_m \times 10^{-4} \]

\[ \begin{align*}
K &= 4.44 \\
f &= 60 \quad [\text{Hz}] \\
B &= 1.2 \quad [\text{tesla}] \\
K_e &= 0.145(4.44)^2(60)^2(1.2)^2 \times 10^{-4} \\
K_e &= 1.53
\end{align*} \]

Step No. 3. Calculate the core geometry from equation 7-44:

\[ K_g = \frac{VA}{K_e \alpha} \]

\[ 
K_g = \frac{115}{(1.53)(2.0)} \\
K_g = 37.6
\]

Step No. 4. Select a lamination from Table 7.B-2 with a value \( K_g \) closest to the one calculated:

EI - 150 with a \( K_g = 35.3 \)

Step No. 5. Calculate the number of primary turns using Faraday’s law, equation 3.A-1:

\[ N = \frac{E_p \times 10^4}{4.44 A_c \frac{B_m}{f}} \]
The iron cross section $A_c$ is found in Table 7.B-2:

$$A_c = 13.1 \text{ cm}^2$$

$$N = \frac{115 \times 10^4}{4.44(13.1)(1.2)(60)}$$

$$N = 275 \text{ turns}$$

**Step No. 6.** Calculate the effective window area $W_{a(\text{eff})}$:

$$W_{a(\text{eff})} = W_a S_3$$

A typical value for $S_3$ is 0.75, as shown in Chapter 6.

Select the window area $W_a$ from Table 7.B-2 for EI 150:

$$W_{a(\text{eff})} = (10.9)(0.75)$$

$$W_{a(\text{eff})} = 8.175 \text{ cm}^2$$

**Step No. 7.** Calculate the primary winding area:

Primary winding area $= \frac{W_{a(\text{eff})}}{2}$

Primary winding area $= \frac{8.175}{2}$

Primary winding area $= 4.09 \text{ cm}^2$
**Step No. 8.** Calculate the wire area $A_w$ with insulation, using a fill factor $S_2$ of 0.6:

$$A_w = \frac{W_{a\text{ (pri)}}}{N} \times S_2$$

$$A_w = \frac{(4.09)(0.6)}{275}$$

$$A_w = 0.00892 \text{ cm}^2$$

**Step No. 9.** Select the wire area $A_w$ with insulation in Table 6-1 for equivalent (AWG) wire size column D:

AWG No. 18 = 0.009326 \text{ cm}^2

The rule is that when the calculated wire size does not fall close to those listed in the table, the next smaller size should be selected.

**Step No. 10.** Calculate the resistance of the winding using Table 6-1, column C, and Table 7.B-2 for the MLT:

$$R = \text{MLT} \times N \times (\text{column C}) \times 10^{-6}$$

$$R_p = (21.2)(275)(209.5) \times 10^{-6}$$

$$R_p = 1.22 \text{ [\Omega]}$$

$$R_p = R_s$$

$$R_t = 2 R_p$$

$$R_t = 2 (1.22) \text{ [\Omega]}$$

$$R_t = 2.44 \text{ [\Omega]}$$

77-35

7-20
Step No. 11. Calculate the copper loss $P_{cu}$ and the regulation:

$$P_{cu} = I^2 R_t$$

$$P_{cu} = (1)^2 (2.44)$$

$$P_{cu} = 2.44 \text{ [watts]}$$

$$\alpha = \frac{P_{cu}}{P_o} \times 100$$

$$\alpha = \frac{2.44}{115} \times 100$$

$$\alpha = 2.12 \%$$

4. Transformer Design Example II

For a typical design example, assume a filament transformer using a C core:

(1) 120 volt input
(2) 400 Hz
(3) Sine wave
(4) 6.3 volt output
(5) 5.0 ampere output
(6) Regulation $\alpha$ 1.0%

The procedure would then be as follows:

Step No. 1. Calculate the output power:

$$P_o = VA$$

$$P_o = (6.3)(5)$$

$$P_o = 31.5 \text{ [watts]}$$
Step No. 2. Calculate the electrical conditions from equation 7-46:

\[ K_e = 0.145 K^2 f^2 B_m^2 \times 10^{-4} \]

\[ K = 4.44 \] \[ f = 400 \] \[ B = 1.2 \] \[ [Hz] \] \[ [tesla] \]

\[ K_e = (0.145)(4.44)^2(400)^2(1.2)^2 \times 10^{-4} \]

\[ K_e = 65.8 \]

Step No. 3. Calculate the core geometry from equation 7-44:

\[ K_g = \frac{VA}{K_e^2} \]

\[ K_g = \frac{31.5}{(65.8)(1)} \]

\[ K_g = 0.479 \]

Step No. 4. Select a C core from Table 7.B-1 with a value \( K_g \) closest to the one calculated:

AL-18 with a \( K_g = 0.530 \)

Step No. 5. Calculate the number of primary turns using Faraday's law, equation 3.A-1,

\[ N = \frac{E_p \times 10^4}{4.44 A_c B_m f} \]

The iron cross section \( A_c \) is found in Table 7.B-1:

\[ A_c = 1.257 \] \[ [cm^2] \]
Step No. 6. Calculate the effective window area $W_{a\text{ (eff)}}$:

$$W_{a\text{ (eff)}} = W_a S_3$$

A typical value for $S_3$ is 0.75 as shown in Chapter 6. Select the window area $W_a$ from Table 7.B-1 for AL-18:

$$W_{a\text{ (eff)}} = (6.3)(0.75)$$

$$W_{a\text{ (eff)}} = 4.72 \text{ cm}^2$$

Step No. 7. Calculate primary winding area:

Primary winding area = Secondary winding area

$$\text{Primary winding area} = \frac{W_{a\text{ (eff)}}}{2}$$

$$\text{Primary winding area} = \frac{4.72}{2}$$

$$\text{Primary winding area} = 2.36 \text{ cm}^2$$

Step No. 8. Calculate the wire area $A_w$ with insulation using a fill factor $S_2$ of 0.6:

$$A_w = \frac{W_{a\text{ (pri)}} S_2}{N}$$

$$A_w = \frac{(2.36)(0.6)}{448}$$

$$A_w = 0.00316 \text{ cm}^2$$
**Step No. 9.** Select the wire area $A_w$ with insulation in Table 6-1 for equivalent (AWG) wire size, column D:

$$AWG\ No.\ 23 = 0.003135\ [cm^2]$$

The rule is that when the calculated wire size does not fall close to those listed in the table, the next smaller size should be selected.

**Step No. 10.** Calculate the resistance of the primary winding, using Table 6-1, column C, and Table 7.B-1 for the MLT:

$$R_p = MLT \times N \times (\text{column C}) \times 10^{-6}$$

$$R_p = (7.51)(448)(666) \times 10^{-6}$$

$$R_p = 2.24\ \Omega$$

**Step No. 11.** Calculate the primary copper loss $P_{cu}$:

$$I_p = \frac{V/\sqrt{3}}{E_p}$$

$$I_p = \frac{32}{120} = 0.263\ \text{[A]}$$

$$P_{cu} = I_p^2 R_p$$

$$P_{cu} = (0.263)^2(2.24)$$

$$P_{cu} = 0.155\ \text{[watts]}$$
**Step No. 12.** Calculate the secondary turns:

\[ N_s = \frac{N_p}{E_p} (E_s) \]

\[ N_s = \frac{448}{120} (6.3) \]

\[ N_s = 24 \]

**Step No. 13.** Calculate the secondary wire area \( A_w \) with insulation using a fill factor \( S_2 \) of 0.6:

\[ A_w = \frac{W_a(\text{sec}) S_2}{N} \]

\[ A_w = \frac{(2.36)(0.6)}{24} \]

\[ A_w = 0.059 \text{ [cm}^2\text{]} \]

**Step No. 14.** Select the secondary wire area \( A_w \) with insulation in Table 6-1 for equivalent (AWG) wire size, column D:

\[ \text{AWG No. 10} = 0.0559 \text{ [cm}^2\text{]} \]

The rule is that when the calculated wire size does not fall close to those listed in the table, the next smaller size should be selected.
Step No. 15. Calculate the resistance of the secondary winding using Table 6-1, column C, and Table 7. B-1 for the MLT:

\[ R_s = \text{MLT} \times N \times (\text{column C}) \times 10^{-6} \]

\[ R_s = (7.51)(24)(32.7) \times 10^{-6} \]

\[ R_s = 0.0059 \quad [\Omega] \]

Step No. 16. Calculate the copper loss \( P_{cu} \):

\[ P_{cu} = I_s^2 R_s \]

\[ P_{cu} = (5)^2 (0.0059) \]

\[ P_{cu} = 0.148 \quad [\text{watts}] \]

Step No. 17. Calculate the regulation:

\[ \alpha = \left( \frac{P_e + P_s}{P_o} \right) \times 100 \]

\[ \alpha = \left( \frac{0.155 + 0.148}{31.5} \right) \times 100 \]

\[ \alpha = 0.962 \quad [\%] \]

5. Inductor Design Example

For a typical design example, assume:

(1) Inductance = 0.05 henry

(2) Output power \( P_o = 200 \text{ watts} \)
(:, Output current \( I_o = 2.0 \text{ amperes} \)
(4) Regulation \( \alpha = 1\% \)

The procedure would then be as follows:

**Step No. 1.** Calculate the energy involved from equation 7, B-16:

\[
\text{Energy} = \frac{L I_o^2}{2}
\]

\[
\text{Energy} = \frac{0.05(2.0)^2}{2}
\]

\[
\text{Energy} = 0.10 \quad \text{[watt seconds]}
\]

**Step No. 2.** Calculate the electrical conditions from equation 7-52:

\[
K_e = 0.145 P_o B_{dc}^2 \times 10^{-4}
\]

\[
P_o = 200 \quad \text{[watts]}
\]

\[
B_{dc} = 1.2 \quad \text{[tesla]}
\]

\[
K_e = 0.145(200)(1.2)^2 \times 10^{-4}
\]

\[
K_e = 0.00418
\]
Step No. 3. Calculate the core geometry from equations 7-50:

\[ K_g = \frac{(\text{Energy})^2}{K_e \alpha} \]

\[ K_g = \frac{(0.1)^2}{(0.00418)(1)} \]

\[ K_g = 2.39 \]

Step No. 4. Select a C core from Table 7.B-1 with a value \( K_g \) closest to the one calculated:

AL-20 with \( K_g = 2.32 \)

Also select the area product \( A_p \) for this C core from Table 2-6:

\[ A_p = 22.6 \text{ cm}^4 \]

Step No. 5. Calculate the current density from area product equation 4.A-18:

\[ J = \frac{2 \times (\text{Energy}) \times 10^4}{B_m \ K_u A_p} \]

Insert values, \( K_u = 0.4 \),

\[ J = \frac{2 \times (0.1) \times 10^4}{(1.2)(0.4)(22.6)} \]

\[ J = 184 \text{ A/cm}^2 \]
Step No. 6. Determine the bare wire size \( A_w \): 

\[
A_w(B) = \frac{I_d}{J} = \frac{2.0}{184}
\]

\[
A_w(B) = 0.0108 \ [\text{cm}^2]
\]

Step No. 7. Select an AWG wire size from Table 6-1, column A. The rule is that when the calculated wire size does not fall close to those listed in the table, the next smaller size should be selected.

AWG 17 = 0.01038 \ [\text{cm}^2]

Step No. 8. Calculate the effective window area \( W_a(\text{eff}) \):

\[
W_a(\text{eff}) = W_a S_3
\]

A typical value for \( S_3 \) is 0.75, as shown in Chapter 6.

Select the window area \( W_a \) from Table 7.8-1 for an AL-20:

\[
W_a(\text{eff}) = (6.30)(0.75)
\]

\[
W_a(\text{eff}) = 4.72 \ [\text{cm}^2]
\]

Step No. 9. Select the wire area with insulation for a No. 17 in Table 6-1, column D:

\[
A_w \text{ with insulation} = 0.01168 \ [\text{cm}^2]
\]
Step No. 10. Calculate the number of turns using a fill factor $S_2$ of 0.6:

$$N = \frac{W_a(\text{eff}) S_2}{A_w}$$

$$N = \frac{(4.72)(0.6)}{(0.91158)}$$

$$N = 242$$

Step No. 11. Calculate the gap from the inductance equation 4-6:

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

The iron cross section $A_c$ is found in Table 7.B-1:

$$A_c = 3.58$$

$$l_g = \frac{1.26(242)^2(3.58) \times 10^{-8}}{(0.05)}$$

$$l_g = 0.0528$$

Step No. 12. Calculate the amount of fringing flux from equation 4-7 (the value for $G$ is found in Table 4.B-17):

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

$$F = \left(1 + \frac{(0.0528)}{\sqrt{3.58}} \log_e \frac{2(3.967)}{0.0528}\right)$$

$$F = 1.14$$
After finding the fringing flux $F$, insert it into equation 4-8, rearrange, and solve for the correct number of turns:

$$N = \sqrt{\frac{1}{0.4\pi A_c F \times 10^{-8}}}$$

$$N = \sqrt{\frac{(0.0528)(0.05)}{(1.26)(3.58)(1.14) \times 10^{-8}}}$$

$$N = 226$$

**Step No. 13.** Calculate the resistance of the winding, using wire Table 6-1, column C and Table 7.B-1 for the MLT:

$$R = \text{MLT} \times N \times (\text{column C}) \times 10^{-6}$$

$$R = (13.62)(226)(165.8) \times 10^{-6}$$

$$R = 0.51 \Omega$$

**Step No. 14.** Calculate the power loss in the winding:

$$P_{cu} = I_o^2 R$$

$$P_{cu} = (2)^2(0.51)$$

$$P_{cu} = 2.04 \text{ watts}$$
Step No. 15. Calculate the regulation from equation 7, B-23:

\[ \alpha = \frac{P_{\text{cu}}}{P_o} \times 100 \]

\[ \alpha = \frac{2.04}{200} \times 100 \]

\[ \alpha = 1.02 \text{ [%]} \]

Step No. 16. Calculate the flux density for \( B_{\text{dc}} \) from equation 7, B-7:

\[ B_{\text{dc}} = \frac{0.4\pi N I_{\text{dc}} \times 10^{-4}}{1g} \]

\[ B_{\text{dc}} = \frac{(1.26)(226)(2.0) \times 10^{-4}}{(0.0528)} \]

\[ B_{\text{dc}} = 1.08 \text{ [tesla]} \]

(In a test sample made to verify this example, the measured inductance was found to be 0.047 henry and the resistance was 0.45 ohms.)

F. 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, however the designer often must make tradeoffs between such goals as efficiency and size which are influenced by core material selection.
Usually in articles written about inverter and converter transformer design, recommendations with respect to choice of core material are a compromise of material characteristics such as those tabulated in Table 7-1, and graphically displayed in Figure 7-9. The characteristics shown here are those typical of commercially available core materials. As can be seen, the core material which provides the highest flux density is supermendur. It also produces the smallest component size. If size is the most important consideration, this should determine the choice of materials. On the other hand, the type 78 supermalloy material (see the 5/78 curve in Figure 7-9), 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.

Table 7-1. Magnetic core material characteristics

<table>
<thead>
<tr>
<th>TRADE NAMES</th>
<th>COMPOSITION</th>
<th>( \ast ) SATURATED FLUX DENSITY, Tolls</th>
<th>DC COERCIVE FORCE, AMP\textsc{-}TURN/CM</th>
<th>SQUARENESS RATIO</th>
<th>( \ast \ast ) MATERIAL DENSITY, ( g/cm^3 )</th>
<th>CURIE TEMPERATURE, ( {\text{K}} )</th>
<th>WEIGHT FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supermendur</td>
<td>49% Co</td>
<td>1.9-2.2</td>
<td>0.18-0.44</td>
<td>0.90-1.0</td>
<td>8.15</td>
<td>930</td>
<td>1.066</td>
</tr>
<tr>
<td>Permendur</td>
<td>49% Fe</td>
<td>25 Y</td>
<td>1.5-1.8</td>
<td>0.85-0.75</td>
<td>7.63</td>
<td>750</td>
<td>1.00</td>
</tr>
<tr>
<td>Magnesil</td>
<td>3% Si</td>
<td>97% Fe</td>
<td>1.4-1.6</td>
<td>0.94-1.0</td>
<td>8.24</td>
<td>500</td>
<td>1.079</td>
</tr>
<tr>
<td>Sillectron</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microwell</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superell</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deltamax</td>
<td>50% Ni</td>
<td>50% Fe</td>
<td>1.15-1.4</td>
<td>0.062-0.187</td>
<td>0.80-0.92</td>
<td>8.19</td>
<td>480</td>
</tr>
<tr>
<td>Orthomol 49 Sq Mm</td>
<td>48% Ni</td>
<td>52% Fe</td>
<td>0.66-0.82</td>
<td>0.80-1.0</td>
<td>8.73</td>
<td>460</td>
<td>1.144</td>
</tr>
<tr>
<td>Allegheny 4750</td>
<td>48% Ni</td>
<td>52% Fe</td>
<td>0.80-0.92</td>
<td>0.80-1.0</td>
<td>8.76</td>
<td>400</td>
<td>1.148</td>
</tr>
<tr>
<td>4-79 Permalloy</td>
<td>25% Ni</td>
<td>75% Fe</td>
<td>0.65-0.82</td>
<td>0.40-0.70</td>
<td>8.76</td>
<td>400</td>
<td>1.148</td>
</tr>
<tr>
<td>Supermalloy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferites F</td>
<td>Mn</td>
<td></td>
<td>0.45-0.50</td>
<td>0.25</td>
<td>4.6</td>
<td>250</td>
<td>0.629</td>
</tr>
<tr>
<td>N27</td>
<td>Zn</td>
<td></td>
<td>0.25</td>
<td>0.30-0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3CB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( \ast \) Tolls = 10^4 Gauss
\( \ast \ast \) g/cm\(^3\) = 0.036 lb/in\(^3\)
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. Figures 7-10 through 7-17 compare the core loss of different magnetic materials as a function of flux density, frequency and material thickness.
Fig. 7-10. Design curves showing maximum core loss for 2 mil silicon
Fig. 7-11. Design curves showing maximum core loss for 12 mil silicon.
Fig. 7-12. Design curves showing maximum core loss for 2 mil supermendor
Fig. 7-13. Design curves showing maximum core loss for 4 mil supermendor
Fig. 7-14. Design curves showing maximum core loss for 2 mil 50% Ni, 50% Fe
Fig. 7-15. Design curves showing maximum core loss for 2 mil 48% Ni, 52% Fe
Fig. 7-16. Design curves showing maximum core losses for 2 mil 30% Ni, 20% Fe
Fig. 7-17. Design curves showing maximum core loss for ferrite
Fortunately, there is such a large choice of core sizes available (Tables 2-2 through 2-7 list only a few of the different cores that are commercially available), that relative proportions of iron and copper can be varied over a wide range without changing the $A_p$ area product.*

G. SKIN EFFECT

It is now common practice to operate dc-to-dc converters at frequencies up to 50 kHz. At the 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 these effects at high frequency on conductivity, magnetic permeability and inductance are sufficient to require further evaluation of conductor size during design. The depth of the skin effect is expressed by:

$$\text{depth (cm)} = (6.61/\tau^{1/2}) K$$  \hspace{1cm} (7-53)

in which $K$ is a constant according to the relationship:

$$K = [(1/\mu x) \rho / \rho c]^{1/2}$$  \hspace{1cm} (7-54)

*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.
in which:

\[ \mu_r = \text{relative permeability of conductor material (}\mu_r = 1 \text{ for copper and other nonmagnetic materials)} \]

\[ \rho = \text{resistivity of conductor material at any temperature} \]

\[ c = \text{resistivity of copper at } 20^\circ \text{C} = 1.724 \text{ microhm-centimeter} \]

\[ K = \text{unity for copper} \]

Figures 7-18 and 7-19 below show respectively, skin depth as a function of frequency according to equation 7-53 above, and as related to the AWG radius, or as \( R_{ac}/R_{dc} = 1 \) versus frequency.*

Fig. 7-18. Skin depth versus frequency

*The data presented is for sine wave excitation. The author could not find any data for square wave excitation.
Fig. 7-19. Skin depth equal to AWG radius versus frequency

Figure 7-20 shows how the RMS values change with different waveshapes.
Fig. 7-20. Common waveshapes, RMS values
77-35

REFERENCE

Although most transformers are designed for a given temperature rise, they can also be designed for a given regulation. The regulation and power-handling ability of a core is related to two constants:

\[ VA = K_g K_e \alpha \]  
\[ \alpha = \text{Regulation (\%)} \]  

The constant \( K_g \) is determined by the core geometry:

\[ K_g = f (A_c, W_a, MLT) \]  

The constant \( K_e \) is determined by the magnetic and electric operating conditions:

\[ K_e = f (f, B_m) \]  

The derivation of the specific functions for \( K_g \) and \( K_e \) is as follows: first assume two-winding transformers with equal primary and secondary regulation, schematically shown in Figure 7.A-1. The primary winding has a resistance \( R_p \) ohms, and the secondary winding has a resistance \( R_s \) ohms:

\[ \alpha = \frac{\Delta E_p}{E_p} \times 100 + \frac{\Delta E_s}{E_s} \times 100 \]  
\[ \Delta E_p = R_p I_p \]  
\[ \Delta E_s = R_s I_s \]
Multiply the numerator and denominator by $E_p$:

$$
\alpha = 200 \frac{R_p I_p}{E_p} \left( \frac{E_p}{E_p} \right) \quad (7.A-8)
$$

$$
\alpha = 200 \frac{R_p \text{VA}}{E_p^2} \quad (7.A-9)
$$

From the resistivity formula, it is easily shown that

$$
R_p = \frac{\text{MLT} N_p^2}{W_a K_p} \rho \quad (7.A-10)
$$

$$
\rho = 1.724 \times 10^{-6} \text{ ohms} \cdot \text{cm}
$$

$K_p =$ window utilization factor (primary)
Faraday's law expressed in metric units is

\[ E_p = K_fN A_c B_m \times 10^{-4} \]  \hspace{1cm} (7.A-11)

where

\[ \begin{align*}
K &= 4.0 \text{ square wave} \\
K &= 4.44 \text{ sine wave}
\end{align*} \]

Substituting equation 7.4-10 and 7.A-11 for \( R_p \) and \( E_p \) in equation 7.A-12,

\[ VA = \frac{E_p^2}{200 R_p} \times \alpha \]  \hspace{1cm} (7.A-12)

\[ VA = \frac{(K_fN A_c B_m \times 10^{-4})(K_fN A_c B_m \times 10^{-4})}{200 \times \frac{\text{MLT}}{W_a K_p}} \times \alpha \]  \hspace{1cm} (7.A-13)

\[ VA = \frac{K_f^2 A_c^2 B_m^2 W_a K_p \rho \times 10^{-10}}{\text{MLT}} \times \alpha \]  \hspace{1cm} (7.A-14)

Inserting \( 1.724 \times 10^{-6} \) for \( \rho \)

\[ VA = \frac{0.29 K_f^2 A_c^2 B_m^2 W_a K_p \times 10^{-4}}{\text{MLT}} \times \alpha \]  \hspace{1cm} (7.A-15)

Let

\[ K_e = 0.29 K_f^2 B_m \times 10^{-4} \]  \hspace{1cm} (7.A-16)
and

\[ K_g = \frac{W_a K_p A_c^2}{MLT} \quad [\text{cm}^5] \quad (7.A-17) \]

The total transformer window utilization factor is then

\[ K_p + K_g = K_u \quad (7.A-18) \]

and equations 7.A-15 and 7.A-16 change to

\[ K_e = 0.145 K_{T B m}^2 \times 10^{-4} \quad (7.A-19) \]

and

\[ K_g = \frac{W_a K_u A_c^2}{MLT} \quad [\text{cm}^5] \quad (7.A-20) \]

Coefficient \( K_u \) values for C cores, lamination, pot cores, powder cores, and tape-wound cores are shown in Tables 7.B-1 through 7.B-5.

Regulation of a transformer is related to the copper loss as shown in equation 7.A-21:

\[ \alpha = \frac{P_{cu}}{P_o} \times 100 \quad [%] \quad (7.A-21) \]

The copper loss in a transformer is related to the RMS current (see Chapter 3, Power Transformer Design; also see Fig. 7-20).
Many transformers such as those used in DC-AC and DC-AC power supplies and for full wave rectifiers do not have 100% duty cycles in all windings. Proper selection of wire size based on duty cycle is, of course, necessary. The following multipliers will convert these types to a VA rating based on 100% duty cycle in all windings.

<table>
<thead>
<tr>
<th>PRIMARY DUTY CYCLE</th>
<th>SEC. DUTY CYCLE</th>
<th>MULTIPLY REQUIRED VA BY</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>50%</td>
<td>1.41</td>
</tr>
<tr>
<td>50%</td>
<td>100%</td>
<td>1.41</td>
</tr>
<tr>
<td>50%</td>
<td>50%</td>
<td>1.82</td>
</tr>
</tbody>
</table>
APPENDIX 7. B

INDUCTORS DESIGNED FOR A GIVEN REGULATION

Inductors, like transformers, are designed for a given temperature rise. They can also be designed for a given regulation. The regulation and energy-handling ability of a core is related to two constants:

\[
(Energy)^2 = K_g K_e \alpha
\]

\[
\alpha = \text{Regulation} \ (\%)
\]  \hspace{1cm} (7. B-1)

The constant \( K_g \) is determined by the core geometry:

\[
K_g = f (A_c, W_a, \text{MLT})
\]  \hspace{1cm} (7. B-2)

The constant \( K_e \) is determined by the magnetic and electric operating conditions:

\[
K_e = f (P_o, B_m)
\]  \hspace{1cm} (7. B-3)

The derivation of the specific functions for \( K_g \) and \( K_e \) is as follows for the circuit shown in Fig. 7. B-1:

![Fig. 7. B-1. Output inductor](image)
Inductance is equal to

\[ L = \frac{0.4 \pi N^2 A_c \times 10^{-8}}{I_{dc}} \text{ [henry]} \]  \hspace{2cm} (7, B-6)

Flux density is equal to

\[ B_{dc} = \frac{0.4 \pi N I_{dc} \times 10^{-4}}{I_{dc}} \text{ [tesla]} \]  \hspace{2cm} (7, B-7)

Combining the two equations,

\[ \frac{L}{B_{dc}} = \frac{NA_c \times 10^{-4}}{I_{dc}} \]  \hspace{2cm} (7, B-8)

Solving for N,

\[ N = \frac{LI_{dc} \times 10^4}{B_{dc} A_c} \]  \hspace{2cm} (7, B-9)

Since the resistance equation is

\[ R = \frac{\rho N^2 MLT}{K_w W_a} \text{ [\Omega]} \]  \hspace{2cm} (7, B-10)
and the regulation equation is

\[ \alpha = \frac{I_{dc}}{V_o} \frac{R}{X} \times 10^2 \quad \text{[\%]} \] (7. B-11)

Inserting the resistance equation (7. B-11) gives

\[ \alpha = \frac{I_{dc}}{V_o} \times \frac{\rho N^2}{K_u W_a} \times 10^2 \] (7. B-12)

\[ N^2 = \left( \frac{L I_{dc}}{B_{dc} A_c} \right)^2 \times 10^8 \] (7. B-13)

\[ \alpha = \frac{I_{dc}}{V_o} \frac{MLT \rho}{I_u W_a} \times \left( \frac{L I_{dc}}{R_{dc} A_c} \right)^2 \times 10^{10} \] (7. B-14)

\[ \alpha = \frac{I_{dc}}{V_o} \frac{MLT \rho (L I_{dc})^2}{K_u W_a B_{dc}^2 A_c^2} \times 10^{10} \] (7. B-15)

Energy = \frac{L I_{dc}^2}{2} \quad \text{[watts seconds]} \] (7. B-16)

Multiplying the equation by \( \frac{I_{dc}}{I_{dc}} \) and combining,

\[ \alpha = \frac{\left( \frac{L I_{dc}^2}{2} \frac{\rho MLT}{V_o} \times 10^{10} \right)}{K_u W_a A_c^2 B_{dc}^2} \] (7. B-17)
which reduces to

\[ \alpha = \frac{(2 \text{ Energy})^2}{P_o B_{dc}^2} \cdot \frac{\rhoMLS}{K_u W_a A_c^2} \times 10^{10} \quad (7.\text{B-18}) \]

\[ \rho = 1.724 \times 10^{-6} \text{ ohms} \cdot \text{ cm} \]

\[ \alpha \approx 6.89 \frac{(\text{Energy})^2}{P_o B_{dc}^2} \cdot \frac{\MLS}{K_u W_a A_c^2} \times 10^4 \quad (7.\text{B-19}) \]

Solving for energy,

\[ (\text{Energy})^2 = 0.145 \frac{P_o B_{dc}^2}{K_u W_a A_c^2} \frac{K_u W_a A_c^2}{\MLS} \times 10^{-4} \alpha \quad (7.\text{B-20}) \]

\[ K_g = \frac{K_u W_a A_c^2}{\MLS} \quad \left[ \text{cm}^5 \right] \quad (7.\text{B-21}) \]

Coefficient \( K_g \) values for C cores, lamination, pot cores, powder cores, and tape-wound cores are shown in Tables 7.\text{B.1} through 7.\text{B.5}.

\[ K_e = 0.145 \frac{P_o B_{dc}^2}{10^{-4}} \quad (7.\text{B-22}) \]

\[ \alpha = \frac{P_{\text{cu}}}{P_o} \times 100 \quad \left[ \% \right] \quad (7.\text{B-23}) \]

The regulation of an inductor is related to the copper loss, as shown in equation 7.\text{B-24}:

\[ \alpha = \frac{P_{\text{cu}}}{P_o} \times 100 \quad \left[ \% \right] \quad (7.\text{B-24}) \]
The copper loss in an inductor is related to the RMS current. The RMS current in a down regulator, as shown in Figure 7.B-1, is always equal to or less than $I_0$:

$$I_{\text{RMS}} \leq I_0$$

(7.B-25)
Table 7. B-1. Coefficient $K_g$ for C cores

<table>
<thead>
<tr>
<th>Core</th>
<th>$10^{-3} K_g$</th>
<th>$W_a$ cm$^2$</th>
<th>$A_c$ cm$^2$</th>
<th>MLT, cm</th>
<th>G, cm</th>
<th>D, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL-2</td>
<td>6.27</td>
<td>1.006</td>
<td>0.264</td>
<td>4.47</td>
<td>1.587</td>
<td>0.635</td>
</tr>
<tr>
<td>AL-3</td>
<td>14.4</td>
<td>1.006</td>
<td>0.406</td>
<td>5.10</td>
<td>1.587</td>
<td>0.952</td>
</tr>
<tr>
<td>AL-5</td>
<td>30.5</td>
<td>1.423</td>
<td>0.539</td>
<td>5.42</td>
<td>2.22</td>
<td>0.952</td>
</tr>
<tr>
<td>AL-6</td>
<td>47.8</td>
<td>1.413</td>
<td>0.716</td>
<td>6.06</td>
<td>2.22</td>
<td>1.27</td>
</tr>
<tr>
<td>AL-124</td>
<td>63.1</td>
<td>2.02</td>
<td>0.716</td>
<td>6.56</td>
<td>2.54</td>
<td>1.27</td>
</tr>
<tr>
<td>AL-8</td>
<td>106</td>
<td>2.87</td>
<td>0.806</td>
<td>7.06</td>
<td>3.015</td>
<td>0.952</td>
</tr>
<tr>
<td>AL-9</td>
<td>173</td>
<td>2.87</td>
<td>1.077</td>
<td>7.69</td>
<td>3.015</td>
<td>1.27</td>
</tr>
<tr>
<td>AL-10</td>
<td>248</td>
<td>2.87</td>
<td>1.342</td>
<td>8.33</td>
<td>3.015</td>
<td>1.587</td>
</tr>
<tr>
<td>AL-12</td>
<td>256</td>
<td>3.63</td>
<td>1.260</td>
<td>9.00</td>
<td>2.857</td>
<td>1.27</td>
</tr>
<tr>
<td>AL-135</td>
<td>273</td>
<td>4.083</td>
<td>1.260</td>
<td>9.50</td>
<td>2.857</td>
<td>1.27</td>
</tr>
<tr>
<td>AL-78</td>
<td>399</td>
<td>4.53</td>
<td>1.340</td>
<td>8.15</td>
<td>5.715</td>
<td>1.91</td>
</tr>
<tr>
<td>AL-18</td>
<td>530</td>
<td>6.36</td>
<td>1.257</td>
<td>7.51</td>
<td>3.927</td>
<td>1.27</td>
</tr>
<tr>
<td>AL-15</td>
<td>648</td>
<td>5.037</td>
<td>1.80</td>
<td>10.08</td>
<td>3.967</td>
<td>1.587</td>
</tr>
<tr>
<td>AL-16</td>
<td>869</td>
<td>5.037</td>
<td>2.15</td>
<td>10.72</td>
<td>3.967</td>
<td>1.905</td>
</tr>
<tr>
<td>AL-17</td>
<td>1380</td>
<td>5.037</td>
<td>2.87</td>
<td>11.99</td>
<td>3.967</td>
<td>2.54</td>
</tr>
<tr>
<td>AL-19</td>
<td>1600</td>
<td>6.30</td>
<td>2.87</td>
<td>12.98</td>
<td>3.967</td>
<td>2.54</td>
</tr>
<tr>
<td>AL-20</td>
<td>2370</td>
<td>6.30</td>
<td>3.58</td>
<td>13.62</td>
<td>3.967</td>
<td>2.54</td>
</tr>
<tr>
<td>AL-22</td>
<td>2940</td>
<td>7.804</td>
<td>3.58</td>
<td>13.62</td>
<td>4.92</td>
<td>2.54</td>
</tr>
<tr>
<td>AL-23</td>
<td>4210</td>
<td>7.804</td>
<td>4.48</td>
<td>14.98</td>
<td>4.92</td>
<td>3.175</td>
</tr>
<tr>
<td>AL-24</td>
<td>3910</td>
<td>11.16</td>
<td>3.58</td>
<td>14.62</td>
<td>5.875</td>
<td>2.54</td>
</tr>
</tbody>
</table>

$^a$Where $K_u = 0.4$. 

7-58
Table 7. B-2. Coefficient $K_g$ for laminations$^a$

<table>
<thead>
<tr>
<th>Core</th>
<th>$10^{-3} K_g$</th>
<th>$W_{a'}$ cm$^2$</th>
<th>$A_{c'}$ cm$^2$</th>
<th>MLT, cm</th>
<th>G, cm</th>
<th>D, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>EE 3031</td>
<td>0.103</td>
<td>0.176</td>
<td>0.0502</td>
<td>1.72</td>
<td>0.714</td>
<td>0.239</td>
</tr>
<tr>
<td>EE 2829</td>
<td>0.356</td>
<td>0.252</td>
<td>0.0907</td>
<td>2.33</td>
<td>0.792</td>
<td>0.318</td>
</tr>
<tr>
<td>EE 187</td>
<td>2.75</td>
<td>0.530</td>
<td>0.204</td>
<td>3.20</td>
<td>1.113</td>
<td>0.478</td>
</tr>
<tr>
<td>EE 2425</td>
<td>8.37</td>
<td>0.807</td>
<td>0.363</td>
<td>5.08</td>
<td>1.27</td>
<td>0.635</td>
</tr>
<tr>
<td>EE 2627</td>
<td>51.1</td>
<td>1.11</td>
<td>0.816</td>
<td>5.79</td>
<td>1.748</td>
<td>0.953</td>
</tr>
<tr>
<td>EI 375</td>
<td>63.8</td>
<td>1.51</td>
<td>0.816</td>
<td>6.30</td>
<td>1.905</td>
<td>0.953</td>
</tr>
<tr>
<td>EI 50</td>
<td>144</td>
<td>1.21</td>
<td>1.45</td>
<td>7.09</td>
<td>1.91</td>
<td>1.27</td>
</tr>
<tr>
<td>EI 21</td>
<td>181</td>
<td>1.63</td>
<td>1.45</td>
<td>7.57</td>
<td>2.06</td>
<td>1.27</td>
</tr>
<tr>
<td>EI 625</td>
<td>441</td>
<td>1.89</td>
<td>2.27</td>
<td>8.84</td>
<td>2.38</td>
<td>1.59</td>
</tr>
<tr>
<td>EI 75</td>
<td>1100</td>
<td>2.72</td>
<td>3.27</td>
<td>10.6</td>
<td>2.86</td>
<td>1.91</td>
</tr>
<tr>
<td>EI 87</td>
<td>2390</td>
<td>3.71</td>
<td>4.45</td>
<td>12.3</td>
<td>3.33</td>
<td>2.22</td>
</tr>
<tr>
<td>EI 100</td>
<td>4500</td>
<td>4.83</td>
<td>5.81</td>
<td>14.5</td>
<td>3.81</td>
<td>2.54</td>
</tr>
<tr>
<td>EI 112</td>
<td>8240</td>
<td>6.12</td>
<td>7.34</td>
<td>16.0</td>
<td>4.28</td>
<td>2.86</td>
</tr>
<tr>
<td>EI 125</td>
<td>14100</td>
<td>7.57</td>
<td>9.07</td>
<td>17.7</td>
<td>4.76</td>
<td>3.18</td>
</tr>
<tr>
<td>EI 138</td>
<td>25400</td>
<td>9.20</td>
<td>11.6</td>
<td>19.5</td>
<td>5.24</td>
<td>3.49</td>
</tr>
<tr>
<td>EI 150</td>
<td>35300</td>
<td>10.9</td>
<td>13.1</td>
<td>21.2</td>
<td>5.72</td>
<td>3.81</td>
</tr>
<tr>
<td>EI 175</td>
<td>75900</td>
<td>14.8</td>
<td>17.8</td>
<td>24.7</td>
<td>6.67</td>
<td>4.45</td>
</tr>
<tr>
<td>EI 36</td>
<td>74900</td>
<td>21.2</td>
<td>15.3</td>
<td>26.5</td>
<td>6.67</td>
<td>4.13</td>
</tr>
<tr>
<td>EI 19</td>
<td>135000</td>
<td>33.8</td>
<td>17.8</td>
<td>31.7</td>
<td>7.62</td>
<td>4.45</td>
</tr>
</tbody>
</table>

$^a$Where $K_u = 0.4$.  

7-59
Table 7, B-3. Coefficient $K_g$ for pot cores\(^a\)

<table>
<thead>
<tr>
<th>Core</th>
<th>$10^{-3}K_g$</th>
<th>$W_a$, cm(^2)</th>
<th>$A_c$, cm(^2)</th>
<th>MLT, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 x 5</td>
<td>0.109</td>
<td>0.065</td>
<td>0.10</td>
<td>1.85</td>
</tr>
<tr>
<td>11 x 7</td>
<td>0.343</td>
<td>0.095</td>
<td>0.16</td>
<td>2.2</td>
</tr>
<tr>
<td>14 x 8</td>
<td>1.09</td>
<td>0.157</td>
<td>0.25</td>
<td>2.6</td>
</tr>
<tr>
<td>18 x 11</td>
<td>4.28</td>
<td>0.266</td>
<td>0.43</td>
<td>3.56</td>
</tr>
<tr>
<td>22 x 13</td>
<td>10.9</td>
<td>0.390</td>
<td>0.63</td>
<td>4.4</td>
</tr>
<tr>
<td>26 x 16</td>
<td>27.9</td>
<td>0.530</td>
<td>0.93</td>
<td>5.2</td>
</tr>
<tr>
<td>30 x 19</td>
<td>71.6</td>
<td>0.747</td>
<td>1.5</td>
<td>6.0</td>
</tr>
<tr>
<td>36 x 22</td>
<td>171</td>
<td>1.00</td>
<td>2.6</td>
<td>7.3</td>
</tr>
<tr>
<td>47 x 28</td>
<td>584</td>
<td>1.80</td>
<td>3.12</td>
<td>9.3</td>
</tr>
<tr>
<td>59 x 36</td>
<td>1683</td>
<td>2.77</td>
<td>4.85</td>
<td>12.0</td>
</tr>
</tbody>
</table>

\(^a\)Where $K_u = 0.31$. 
Table 7. B-4. Coefficient $K_g$ for powder core$^a$

<table>
<thead>
<tr>
<th>Core</th>
<th>$10^{-3} K_g$</th>
<th>$w_a$, cm$^2$</th>
<th>$A_c$, cm$^2$</th>
<th>MLT, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>55051</td>
<td>0.901</td>
<td>0.381</td>
<td>0.113</td>
<td>2.16</td>
</tr>
<tr>
<td>55121</td>
<td>4.00</td>
<td>0.713</td>
<td>0.196</td>
<td>2.74</td>
</tr>
<tr>
<td>55848</td>
<td>8.26</td>
<td>1.14</td>
<td>0.232</td>
<td>2.97</td>
</tr>
<tr>
<td>55059</td>
<td>17.4</td>
<td>1.407</td>
<td>0.327</td>
<td>3.45</td>
</tr>
<tr>
<td>55894</td>
<td>55.3</td>
<td>1.561</td>
<td>0.639</td>
<td>4.61</td>
</tr>
<tr>
<td>55586</td>
<td>77.7</td>
<td>4.00</td>
<td>0.458</td>
<td>4.32</td>
</tr>
<tr>
<td>55071</td>
<td>108</td>
<td>2.93</td>
<td>0.666</td>
<td>4.80</td>
</tr>
<tr>
<td>55076</td>
<td>13.4</td>
<td>3.64</td>
<td>0.670</td>
<td>4.88</td>
</tr>
<tr>
<td>55083</td>
<td>316</td>
<td>4.27</td>
<td>1.060</td>
<td>6.07</td>
</tr>
<tr>
<td>55090</td>
<td>639</td>
<td>6.11</td>
<td>1.32</td>
<td>6.66</td>
</tr>
<tr>
<td>55439</td>
<td>852</td>
<td>4.27</td>
<td>1.95</td>
<td>7.62</td>
</tr>
<tr>
<td>55716</td>
<td>712</td>
<td>7.52</td>
<td>1.24</td>
<td>6.50</td>
</tr>
<tr>
<td>55110</td>
<td>1123</td>
<td>9.48</td>
<td>1.44</td>
<td>7.00</td>
</tr>
</tbody>
</table>

$^a$Where $K_u = 0.4$. 

77-35
Table 7. B-5. Coefficient $K_g$ for tape-wound toroids$^a$

<table>
<thead>
<tr>
<th>Core</th>
<th>$10^3$ Kg</th>
<th>$W_a$, cm$^2$</th>
<th>$A_c$, cm$^2$</th>
<th>MLT, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>52402</td>
<td>0.0472</td>
<td>0.502</td>
<td>0.022</td>
<td>2.06</td>
</tr>
<tr>
<td>52153</td>
<td>0.254</td>
<td>0.502</td>
<td>0.053</td>
<td>2.22</td>
</tr>
<tr>
<td>52107</td>
<td>0.0860</td>
<td>0.982</td>
<td>0.022</td>
<td>2.21</td>
</tr>
<tr>
<td>52403</td>
<td>0.107</td>
<td>1.28</td>
<td>0.022</td>
<td>2.30</td>
</tr>
<tr>
<td>52057</td>
<td>0.456</td>
<td>1.56</td>
<td>0.043</td>
<td>2.53</td>
</tr>
<tr>
<td>52000</td>
<td>1.07</td>
<td>0.982</td>
<td>0.086</td>
<td>2.70</td>
</tr>
<tr>
<td>52063</td>
<td>1.62</td>
<td>1.56</td>
<td>0.086</td>
<td>2.85</td>
</tr>
<tr>
<td>52002</td>
<td>1.81</td>
<td>1.76</td>
<td>0.086</td>
<td>2.88</td>
</tr>
<tr>
<td>52007</td>
<td>10.6</td>
<td>1.56</td>
<td>0.257</td>
<td>3.87</td>
</tr>
<tr>
<td>52167</td>
<td>17.4</td>
<td>1.56</td>
<td>0.343</td>
<td>4.23</td>
</tr>
<tr>
<td>52094</td>
<td>20.8</td>
<td>1.56</td>
<td>0.386</td>
<td>4.47</td>
</tr>
<tr>
<td>52004</td>
<td>12.7</td>
<td>4.38</td>
<td>0.171</td>
<td>4.02</td>
</tr>
<tr>
<td>52032</td>
<td>44.3</td>
<td>4.38</td>
<td>0.343</td>
<td>4.65</td>
</tr>
<tr>
<td>52026</td>
<td>87.7</td>
<td>4.38</td>
<td>0.514</td>
<td>5.28</td>
</tr>
<tr>
<td>52038</td>
<td>138</td>
<td>4.38</td>
<td>0.686</td>
<td>5.97</td>
</tr>
<tr>
<td>52035</td>
<td>203</td>
<td>6.816</td>
<td>0.686</td>
<td>6.33</td>
</tr>
<tr>
<td>52055</td>
<td>276</td>
<td>9.93</td>
<td>0.686</td>
<td>6.76</td>
</tr>
<tr>
<td>52012</td>
<td>587</td>
<td>6.94</td>
<td>1.371</td>
<td>8.88</td>
</tr>
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<td>52017</td>
<td>459</td>
<td>18.3</td>
<td>0.686</td>
<td>7.51</td>
</tr>
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<td>52031</td>
<td>668</td>
<td>29.2</td>
<td>0.686</td>
<td>8.23</td>
</tr>
<tr>
<td>52103</td>
<td>1570</td>
<td>18.3</td>
<td>1.371</td>
<td>8.77</td>
</tr>
<tr>
<td>52128</td>
<td>2220</td>
<td>28.0</td>
<td>1.371</td>
<td>9.49</td>
</tr>
<tr>
<td>52022</td>
<td>4870</td>
<td>18.3</td>
<td>2.742</td>
<td>11.30</td>
</tr>
<tr>
<td>52042</td>
<td>6790</td>
<td>27.1</td>
<td>2.742</td>
<td>12.0</td>
</tr>
<tr>
<td>52100</td>
<td>18600</td>
<td>27.1</td>
<td>5.142</td>
<td>15.4</td>
</tr>
<tr>
<td>52112</td>
<td>68100</td>
<td>73.6</td>
<td>6.855</td>
<td>20.3</td>
</tr>
<tr>
<td>52426</td>
<td>159000</td>
<td>73.6</td>
<td>10.968</td>
<td>22.2</td>
</tr>
</tbody>
</table>

$^a$ Where $K_u = 0.4$. 
APPENDIX 7.C
TRANSFORMER AREA PRODUCT AND GEOMETRY

The geometry $K_g$ of a transformer, which can be related to the area product $A_p$, is derived in Chapter 7 and is shown here in equation 7.C-1. Derivation of the relationship is according to the following: Geometry $K_g$ varies in accordance with the fifth power of any linear dimension $l$ (designated $l^5$ below), whereas area product $A_p$ varies as the fourth power:

$$K_g = \frac{W_a A_e^2 K_u}{MLT} \quad (7.C-1)$$

$$K_g = K_{10} l^5 \quad (7.C-2)$$

$$A_p = K_2 l^4 \quad (7.C-3)$$

$$l = \left(\frac{K_g}{K_{10}}\right)^{0.20} \quad (7.C-4)$$

$$l^4 = \left[\left(\frac{K_g}{K_{10}}\right)^{0.20}\right]^4 = \left(\frac{K_g}{K_{10}}\right)^{0.8} \quad (7.C-5)$$

$$A_p = K_2 \left(\frac{K_g}{K_{10}}\right)^{0.8} \quad (7.C-6)$$

$$K_p = \frac{K_2}{K_{10}^{0.8}} \quad (7.C-7)$$

$$A_p = K_p K_g^{0.8} \quad (7.C-8)$$
The area product/geometry relationship is

\[ A_p = K_p K_g^{0.8} \]

in which \( K_p \) is a constant related to core configuration, shown in Table 7, C-1, which has been derived by averaging the values in Tables 2-2 through 2-7 (see Chapter 2) and Tables 7, B-1 through 7, B-5.

The relationship between area product \( A_p \) and core geometry is given in Figures 7, C-1 through 7, C-5. It was obtained from the data shown in Tables 2-2 through 2-7 for area product \( A_p \) and Tables 7, B-1 through 7, B-5 for \( K_g \).

Table 7, C-1. Constant \( K_p \) relationship

<table>
<thead>
<tr>
<th>Core type</th>
<th>( K_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pot cover</td>
<td>8.87</td>
</tr>
<tr>
<td>Powder cores</td>
<td>11.8</td>
</tr>
<tr>
<td>Lamination</td>
<td>8.3</td>
</tr>
<tr>
<td>G cores</td>
<td>12.5</td>
</tr>
<tr>
<td>Tape-wound cores</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 7.C-1. Area product versus core geometry for pot cores

Fig. 7.C-2. Area product versus core geometry for powder cores
Fig. 7.C-3. Area product versus core geometry for C cores

Fig. 7.C-4. Area product versus core geometry for laminations
Fig. 7.C-5, Area product versus core geometry for tape-wound toroids
Chapter VIII

INDUCTOR DESIGN WITH NO DC FLUX
A. INTRODUCTION

The design of an ac inductor is quite similar to designing a transformer. If there is no dc flux in the core the design calculations are straightforward.

The apparent power $P_t$ of an inductor is the VA of the inductor; that is, the excitation voltage and the current through the inductor:

$$P_t = VA$$  \hspace{1cm} (8-1)

B. RELATIONSHIP OF $A_p$ TO INDUCTOR VOLT-AMPERE CAPABILITY

According to the newly developed approach, the volt-ampere capability of a core is related to its area product $A_p$ by an equation which may be stated as follows:

$$A_p = \left( \frac{VA \times 10^4}{4.44 B_m f K_U K_j} \right)^{1.14}$$  \hspace{1cm} (8-2)

$K_j = \text{current density coefficient (see Chapter 2)}$

$K_U = \text{window utilization factor (see Chapter 6)}$

$f = \text{frequency, Hz}$

$B_m = \text{flux density, tesla}$

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 Chapter 2.
B. FUNDAMENTAL CONSIDERATIONS

The design of a linear inductor depends upon four related factors:

1. Desired inductance
2. Applied Voltage
3. Frequency
4. Operating flux density

With these requirements established, the designer must determine the maximum values for $B_{ac}$ which will not produce magnetic saturation, and make tradeoffs which will yield the highest inductance for a given volume. The core material selected determines the maximum flux density that can be tolerated for a given design. Magnetic saturation values for different core materials are given in Table 4-1.

The number of turns is calculated from the Faraday law, which states:

$$N = \frac{E \times 10^4}{4.44 \frac{B_{m}}{f} A_{c}} \quad (8-3)$$

The inductance of an iron-core inductor having an air gap may be expressed as

$$L = \frac{0.4 \pi N^2 A_{c} \times 10^{-8}}{1 \frac{m}{g} + \frac{m}{\mu_{r}}} \quad \text{[henry]} \quad (8-4)$$

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 ($l_{m}/\mu_{r}$).

When the core air gap ($l_g$) is large compared to relative permeability ($l_{m}/\mu_{r}$), because of the high relative permeability ($\mu_{r}$), variations in $\mu_{r}$ do not substantially effect the total effective magnetic path length or the inductance.
The inductance equation then reduces to:

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

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 make the effective air gap shorter than its physical dimension.

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 (8-5). Fringing flux is a larger percentage of the total for larger gaps. The fringing flux factor is:

\[
F = \left( 1 + \frac{l_g}{\sqrt{A_c}} \log_e \frac{2G}{l_g} \right)
\]

where \( G \) is a dimension defined in Chapter 2. (Equation 8-6 is also valid for laminations; this equation is plotted in Figure 4-3).

Inductance \( L \) computed in equation (8-5) does not include the effect of fringing flux. The value of inductance \( L' \) corrected for fringing flux is:

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

The losses in an ac inductor are made up of three components:

1. Copper loss, \( P_{cu} \)
2. Iron loss, \( P_{fe} \)
3. Gap loss, \( P_g \)

The copper loss and iron loss have been previously discussed. Gap loss\(^*\) is independent of core strip thickness and permeability. Maximum efficiency

\(^*\) Reference
is reached in an inductor, as in a transformer, when the copper loss $P_{cu}$ and the iron loss $P_{fe}$ are equal but only when the core gap is zero. The loss does not occur in the air gap itself, but is caused by magnetic flux fringing around the gap and re-entering the core in a direction of high loss. As the air gap increases, the flux across it fringes more and more, and some of the fringing flux strikes the core perpendicular to the laminations and sets up eddy currents which cause additional loss. Distribution of fringing flux is also affected by other aspects of core geometry, the proximity of coil turns to the core, and whether there are turns on both legs. Accurate prediction of gap loss depends on the amount of fringing flux. For laminated cores it can be estimated from

$$P_g = K_l 2D_{l} l_{g} f B_{m}^{2}$$  \[\text{watts}\]  (8-8)

\begin{align*}
K_l &= 0.0388 \\
D &= \text{lamination tongue width, cm} \\
l_{g} &= \text{gap length, cm} \\
f &= \text{frequency, Hz} \\
B_{m} &= \text{flux density, tesla}
\end{align*}

The fringing flux is around the gap and re-entering the core in a direction of high loss as shown in Figure 8-1.
D. DESIGN EXAMPLE

For a typical design example, assume:

(1) Constructed with laminations
(2) Applied voltage, 115 V
(3) Frequency, 60 Hz
(4) Alternating current, 0.5 amps
(5) 25°C rise

The design procedure would then be as follows:

Step No. 1. Calculate the apparent power \( P_t \) from equation 8-1:

\[
P_t = VA
\]

\[
P_t = (115)(0.5)
\]

\[
P_t = 57.5
\]

Step No. 2. Calculate the area product \( A_p \) from equation 8-2:

\[
A_p = \left( \frac{VA \times 10^4}{4.44 B_m f K_u K_j} \right)^{1.14}
\]

\[
B_m = 1.2 \text{ tesla}
\]

\[
K_u = 0.4 \text{ (see Chapter 6)}
\]

\[
K_j = 366 \text{ (see Chapter 2)}
\]

\[
A_p = \left( \frac{57.5 \times 10^4}{4.44 (1.2)(60)(0.4)(366)} \right)^{1.14}
\]

\[
A_p = 17.4
\]
Step No. 3. Select a size of lamination from Table 2-4 with a value $A_p$ closest to the one calculated.

El-87 with an $A_p = 16.5$

Step No. 4. Calculate the number of turns using Faraday's law, equation 8-3:

$$N = \frac{E \times 10^4}{4.44 B_m f A_c}$$

The iron cross-section $A_c$ is found in Table 2-4:

$$A_c = 4.45 \text{ [cm}^2\text{]}$$

$$N = \frac{115 \times 10^4}{(4.44)(1.2)(60)(4.45)}$$

$$N = 808 \text{ [turns]}$$

Step No. 5. Calculate the impedance:

$$X_L = \frac{E}{I}$$

$$X_L = \frac{115}{0.5}$$

$$X_L = 230 \text{ [\Omega]}$$
Step No. 6. Calculate the inductance:

\[ L = \frac{X_L}{2\pi f} \]

\[ L = \frac{230}{(6.28)(60)} \]

\[ L = 0.610 \text{ [henry]} \]

Step No. 7. Calculate the air gap from the inductance, equation 8-5:

\[ l_g = \frac{0.4\pi N^2 A_c \times 10^{-8}}{L} \text{ [cm]} \]

\[ l_g = \frac{(1.26)(808)^2(4.45)(10^{-8})}{0.610} \]

\[ l_g = 0.060 \text{ [cm]} \]

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

\[ cn \times 393.7 = \text{mils (inch system)} \]

Substituting values:

\[ 0.060 \times 393.7 = 23.6 \text{ [mils]} \]

When designing inductors using lamination, it is common to place the gapping material along the mating surface between the E and I. When this method of gapping is used, only half of the material is required. In this case a 10 mil and a 2 mil thickness were used.
Step No. 8. Calculate the amount of fringing flux from equation 8-6; the value for \( G \) is found in Table 7-B2:

\[
F = \left(1 + \frac{\log_{10} \frac{2G}{l}}{\log_{10} \frac{A}{l}}\right)
\]

\[
F = \left(1 + \frac{0.060}{\log_{10} \frac{2(3.33)}{0.060}}\right)
\]

\[
F = 1.13
\]

After finding the fringing flux \( F \), insert it into equation 8-7, rearrange and solve for the correct number of turns:

\[
N = \sqrt{\frac{1}{g} \frac{L}{\sqrt{0.4 \pi A_c F \times 10^{-8}}}}
\]

\[
N = \sqrt{\frac{(0.060)(0.610)}{(1.26)(4.45)(1.13) \times 10^{-8}}}
\]

\[
N = 760
\]

The design should be checked to verify that the reduction in turns does not cause saturation of the core.

Step No. 9. Calculate the current density using Table 2-1:

\[
J = K_j A_p \cdot 0.12
\]

\[
J = (366)(16.5)^{-0.12}
\]

\[
J = 261 \text{ [amps/cm}^2\text{]}
\]
Step No. 10. Determine the bare wire size $A_{w(E)}$

\[ A_{w(B)} = \frac{I}{J} \]

\[ A_{w(B)} = \frac{0.5}{26} \]

\[ A_{w(B)} = 0.00192 \text{ [cm}^2\]\n
Step No. 11. Select an AWG wire size from Table 6-1, column A.

AWG No. 24 = 0.00205 \text{ [cm}^2\]

The rule is that when the calculated wire size does not fall close to those listed in the table, the next smaller size should be selected.

Step No. 12. Calculate the resistance of the winding using Table 6-1, column C, and Table 2-4 for the MLT:

\[ R = \text{MLT} \times N \times (\text{column C}) \times \zeta \times 10^{-6} \]

\[ R = (12.3)(760)(842.1)(1.098) \times 10^{-6} \]

\[ R = 8.64 \text{ [\Omega]} \]

Step No. 13. Calculate the power loss in the winding:

\[ P_{cu} = I^2 R \]

\[ P_{cu} = (0.5)^2 (8.64) \]

\[ P_{cu} = 2.16 \text{ [watts]} \]
From the core loss curves (Figure 7-10), 12 mil silicon at a flux density of 1.2 tesla has a core loss of approximately 1.0 milliwatts per gram. The lamination EI-87 has a weight of 481 grams:

\[ P_{fe} = (0.001)(481) \]

\[ P_{fe} = 0.481 \text{ [watts]} \]

**Step No. 14.** Calculate the gap loss from equation 8-8; the value of \( D \) is found in Table 7-B-2:

\[ P_g = K_1 2D f B_m^2 \text{ [watts]} \]

\[ P_g = (0.0388)(4.44)(4.060)(1.2)^2 \]

\[ P_g = 0.894 \text{ [watts]} \]

**Step No. 15.** Calculate the combined losses, copper, iron, and gap:

\[ P_\Sigma = P_{cu} + P_{fe} + P_g \]

\[ P_\Sigma = 2.16 + 0.481 + 0.894 \]

\[ P_\Sigma = 3.53 \text{ [watts]} \]

In a test sample made to verify these example calculations, the measured inductance was found to be 0.592 henry with a current 0.515 ampere at 115 volt, 60 Hz, and the inductor had a coil resistance of 8.08 ohms.
REFERENCES