An Outline Method Of Transformer Design   Jim Tregellas November 2012

 The best way to understand how a transformer might be designed for use in a one off electronic project is to follow through a simple design example. The design process which follows does not create a transformer which is optimum for mass production, but it will go fairly close. Modern computer programs are available (not cheap), and these can run through the successive optimization routine which is necessary to squeeze the last few per cent out of the copper and iron (and price) if mass production of a particular design is desired. Similarly, the technique outlined assumes the use of ordinary wasteless E and I laminations made from standard 4% silicon iron (non grain oriented electrical steel or NGOES) to form the transformer core, and ignores the use of C cores, grain oriented steel (GOES), high temperature winding wires and bobbins, and other special materials and techniques which result in a smaller but not necessarily cheaper transformer. Note that this description also largely ignores the fine technical details necessary to obtain type approval of a transformer assembly from the regulatory authorities. To ensure safety, YOU must make a comprehensive study of the applicable electrical and safety standards in your country, before you attempt any formal design. The design example proposed is as follows…………

"Design a regulated power supply powered from 240 VAC, which produces a 5 volt 1 amp. output and uses a 7805 regulator".

In the transformer design process we will have to answer 5 basic questions. These are………..

  (a) What transformer volt amp rating is required?
  (b) What core area is required?
  (c) How many turns are required on each winding?
  (d) What wire diameter is to be used on each winding?
  (e) Will the windings and insulation required fit the available window area?

What transformer volt amp rating is required?

To answer this question we will first have to design the power supply and will use the following circuit
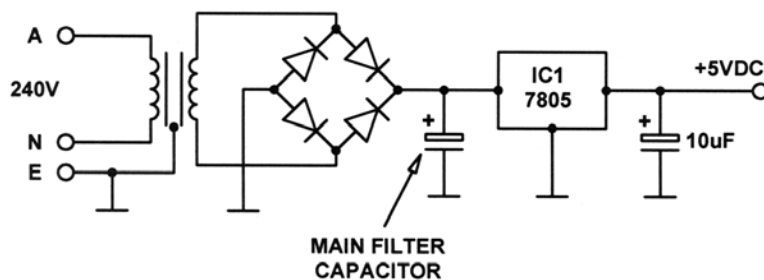
Required transformer peak output voltage
Output required   5V
Regulator drop out voltage from 7805 data   2V
Ripple voltage   2V   (see Appendix 1)
Allowance for 10% low mains voltage   1V
Rectifier forward drop 2 x 0.8V   1.6 V

12.6V

The RMS secondary voltage is thus 0.707 x 12.6 = 8.91V   say 9 volts RMS <u>at full load.</u>

and the VA rating is {12.6- (Vripple/2)} x 1 amp.= {12.6 – 1} x 1= 11.6VA

The transformer RMS secondary current is 11.6/9 = 1.3 amp

And the primary current is 11.6/240 = 48.3 mA

The filter capacitor required is $\dfrac{1 \times 10^{-2}}{2}$ = 5000uF (use 4700uF and see Appendix 1)

What Core Area is Required?

Having calculated the VA rating as 11.6VA, the core area is calculated from the empirical relationship

$$A = 116\sqrt{VA} \quad \text{or} \quad VA = (A/116)^2$$ where   A is the core cross sectional area in square mm
VA is the transformer VA rating

This empirical relationship is based on the amount of copper which can be jammed into the window of a standard wasteless lamination (see Appendix 2). For simple transformers with only one primary and secondary winding, this relationship is relatively accurate, and may actually underestimate the core capacity by up to 10%. For complex transformers with many separate windings and much interwinding insulation, it may overestimate the core capacity by up to 300%.

For our example $A = 116\sqrt{11.6}$
=395 mm^2 or roughly 20 x 20 mm for the centre leg.
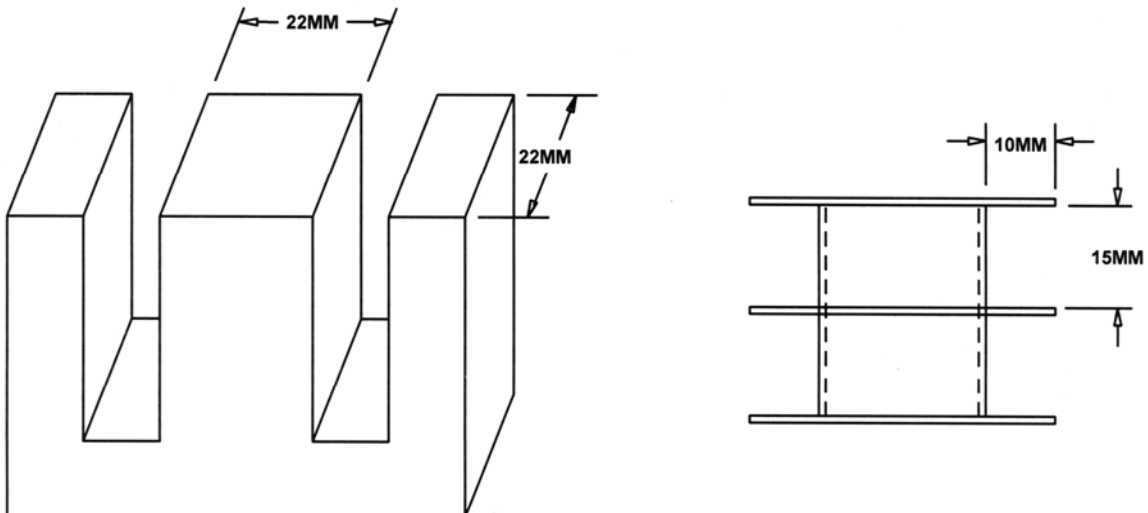
Now a standard core and bobbin assembly are available with the above dimensions which we will use.
Core cross sectional area = 22 x 22 = 484 mm^2

Window area (each side) = 10 x 15 = 150 mm^2
How many turns are required on each winding?

This is simply calculated from the universal transformer equation

$$N = \frac{10^8 E}{444 n f B A}$$

where   N is the number of turns
     f is the frequency in Hz (normally 50Hz)
     B is the core flux density in Tesla
     A is the core cross sectional area in mm^2
     n is the core stacking factor
     E is the rms winding voltage

A few words on a couple of terms in this equation –

Flux density B. As the transformer grows larger, its volume increases faster than its surface area, and so to avoid overheating, the core flux density must be reduced to decrease core losses/ kilogram of iron. For large transformers (above 300VA), the core flux density used should probably lie between 1.1 and 1.2 Tesla. For transformers from say 30-300VA use 1.15- 1.25 Tesla, and for units smaller than 30VA use 1.2-1.3 Tesla or even more if the unit is very small. Where leakage flux is important (hi fi amps, electronic instruments) use 0.8 – 1.0 Tesla to stay in the linear portion of the BH curve. The object of the exercise is to make the core and copper losses about equal for maximum efficiency, but this is not always possible. Grain oriented cores can be run at slightly higher flux densities.

Core stacking factor n This actually describes what part of the core is solid iron (as opposed to the oxide on each lamination which is placed there to reduce eddy current losses). For most common laminations, this figure is about 0.95 (95%).

For our example the turns per volt are $\dfrac{10^8}{444 \; x \; 0.95 \; x \; 50 \; x \; 1.2 \; x \; 484}$ = 8.164 T/V

For the 240 volt primary there are thus 8.164 x 240 = 1959 turns
 Obviously there will be resistive losses in the transformer which cause the secondary output voltage to drop from its no load figure when under full load. To compensate for this drop we must multiply the secondary voltage by a fiddle factor, and the following are typical.

30VA	1.10 (known as 10% voltage regulation)
100VA	1.06
300VA	1.02

The no load secondary voltage required is thus 1.1 x 8.91 = 9.8V RMS
and the secondary turns are therefore 9.8 x 8.164 = 80 turns

These figures can be much refined if one is prepared to go to the extra trouble of calculating the mean length/turn and multiplying by the number of turns to get a total winding length for both primary and secondary. The resistance of each winding can then be calculated using data from the wire tables, and after referring the secondary resistance back to the primary (or vice versa), an accurate figure for regulation can be obtained and the secondary turns corrected appropriately.

What Wire Size?

The size of wire used governs the temperature rise which occurs in the finished transformer due to the resistive losses in the wire. The following current densities give temperature rises of <40C above ambient temperature and are a good starting point.

For < 30VA transformers	3.4 amps/mm^2 or 2200 amps/inch^2
For 30- 150VA	2.8 amps/mm^2 or 1800 amps/inch^2
For >150VA	2.3 amps/mm^2 or 1500 amps/inch^2

Obviously to minimize heating and improve regulation, the largest wire size possible should be used and in all cases the objective is to fill the bobbin space available. The figures just given therefore only dictate the <u>minimum</u> wire size that should be used.

In our example the primary current was 48.3mA, and secondary current was 1.3 amp.

For the primary we will therefore need a cross sectional area of $\dfrac{0.0483}{3.4}$ square mm of copper.

Thus $\pi r^2 = \dfrac{0.0483}{3.4}$ and the wire radius comes out at 0.0672 mm, or 0.134 mm diameter.

Doing the same sum for the secondary current of 1.3 amps produces a wire diameter of 0.77mm. The nearest wire sizes for the primary are 0.16, 0.18, and 0.20 mm. For the secondary, the nearest sizes are 0.8, 0.85, and 0.9 mm. We will try the 0.2 mm and 0.9mm wires to see if they fit the available window areas in the bobbin.

Will the wire and insulation fit the bobbin?

To answer this question we need four pieces of data.
   (a) The wire diameter
   (b) The number of turns
   (c) The method of winding
   (d) The window area

The method of winding used for most transformers is scramble winding (as opposed to layered winding where each layer of wire is separated by a layer of insulation).

To calculate the window area needed, we add 0.02mm to the wire diameter (to account for the thickness of a single layer of enamel insulation), square this number (because a circular wire occupies a square shape in the winding cross section), multiply this figure by 1.2 (to account for included air spaces in the winding) and then multiply by the number of turns.

So for the primary:

Area = (0.22^2) x 1959 x 1.2 = 113.79 mm^2

We can use the heavy wire with room to spare as the available window area is 150 mm^2

and for the secondary:

Area = (0.92^2) x 80 x 1.2 = 81.25 mm^2

Again the heavier wire fits.

The finished design is thus

Primary   240V   1959 turns of 0.2mm diameter copper

Secondary 9V   80 turns of 0.9mm diameter copper
Note that the use of much heavier wire than actually required significantly boosts the amount of power this assembly can handle. It is thus not surprising that this particular core forms the basis for winding a very popular transformer which features a 15V RMS 1 amp multi-tap secondary winding (15VA rating).

Insulation

Providing safe insulation on a transformer is something of an art form. The comments and diagrams in this section are simply suggestions as to how this desirable result may be achieved, and comprehensive testing must be done on each transformer to ensure safety and electrical requirements are actually met. However, here are a few observations which may make the path to the goal rather easier………☺

Winding wire

A large number of different insulating lacquers are used to coat winding wire, and winding wire is generally supplied with single or double lacquer overcoats. From a transformer design point of view, three properties of winding wire are of interest, these being the maximum safe operating temperature (developed in the hot spot in the centre of a winding), the breakdown voltage of the insulating lacquer film, and the number of pinhole defects which may occur in the film.
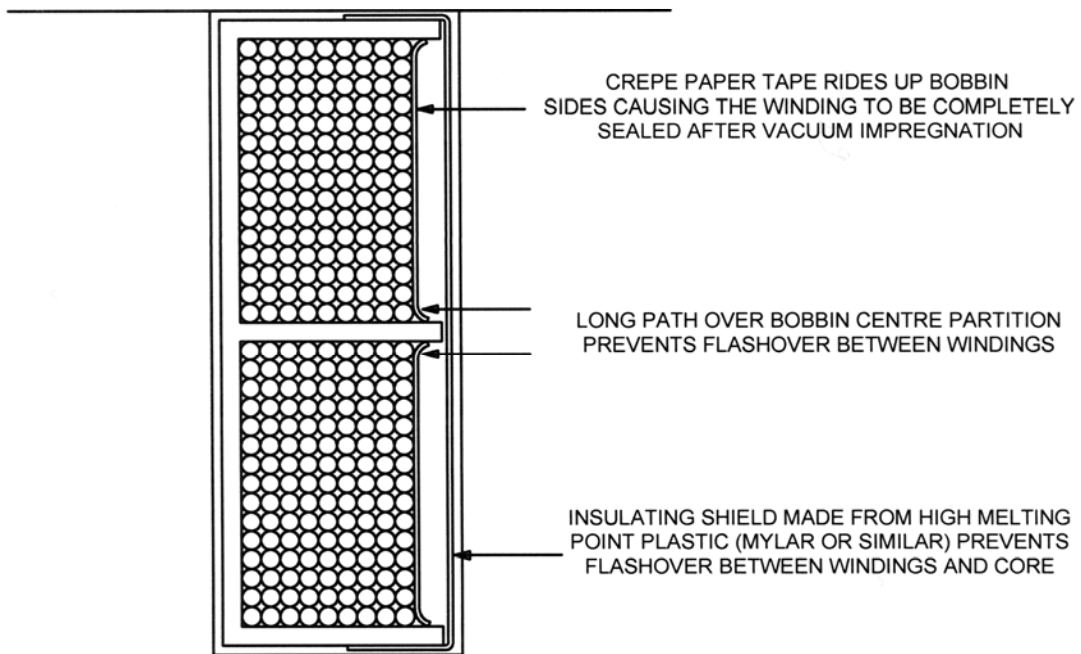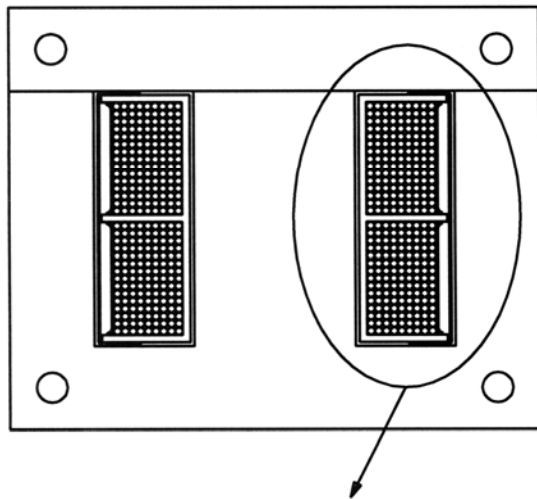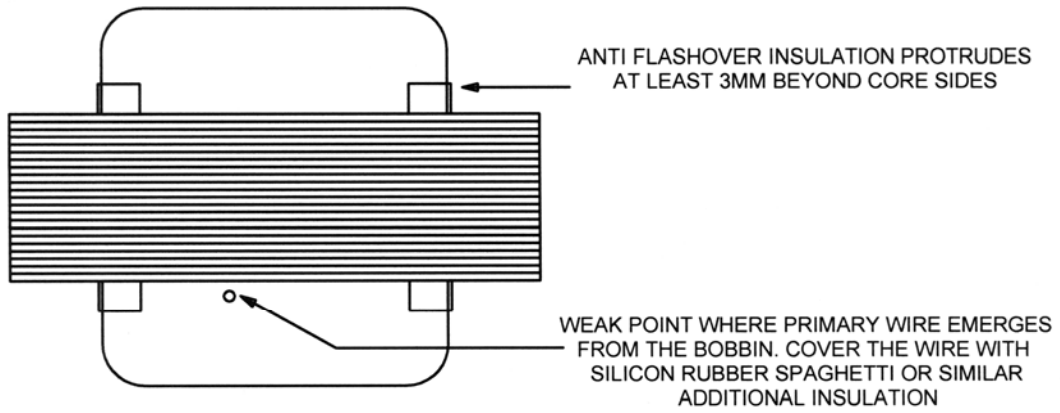The film breakdown voltage is a complex function of wire diameter, and increases as the wire diameter increases, but even for the smallest singly coated wires 0.03mm diameter, the breakdown voltage is a minimum of 200 volts. So for 2 wires in contact, ignoring pinholes in the film, this figure becomes 400 volts. Taking pinholes into account and possible abuse to the film during winding, a safe working figure in a scramble wound winding is thus about 100 volts per layer. Note that in a high voltage scramble wound winding, the thickness of the winding should be built up evenly to prevent the possibility of turns near the start and end from lying next to one another, causing winding breakdown. In a very high voltage winding it is probably sensible to break it down into 200 volt sections, each comprehensively insulated from the next section with high quality electrical tape.
The problem of excessive hot spot temperature rise should not arise if the quite conservative current densities cited earlier in this article are used. This is true even if low temperature wire insulation such as polyurethane is used. This self fluxing wire is great, allowing the winding ends to be easily tinned by dipping them into a solder pot. No stripping is required, and the wire is safe for use at winding temperatures up to 120C. Usually this sort of insulation has the colour of raspberry jam and is marketed under names such as Solderite. However, if temperature rise is of concern, it can be measured by using the change in resistance method detailed in the literature.
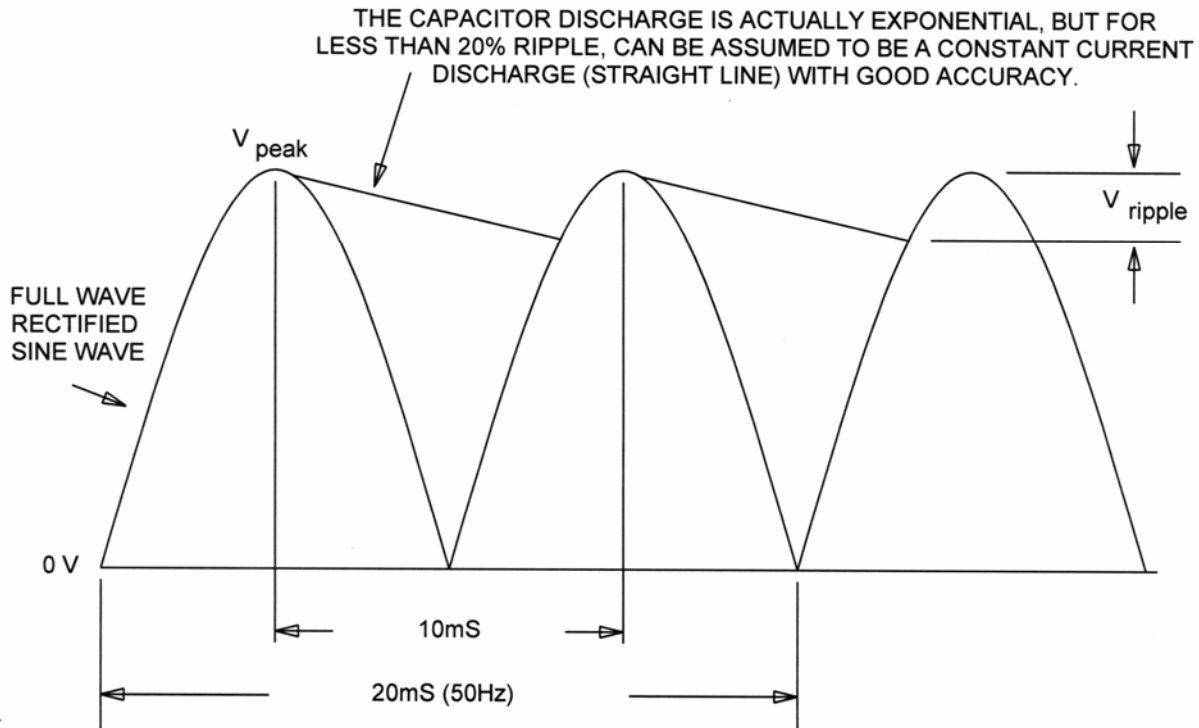
Insulation materials

Air is by far the worst insulator likely to be encountered, with a breakdown voltage of about 30KV/cm or 75KV/inch. As transformer tests normally involve applying at least 3KV RMS between windings, and between each winding and core, the minimum air gap existing between a bare uninsulated winding or termination and anything else metallic should be at least 1.5mm, with 3mm being desirable.
No low melting point plastic should ever be used (eg polyester) in a transformer because under mechanical stress, these plastics flow, eventually leaving no insulation at all. Australian standards demand that if unfilled nylon or similar bobbins are used, two C shaped pieces of elephant hide must be placed on the central partition of the bobbin, in case the transformer should become overhot under gross overload. This prevents the primary and secondary windings coming into contact if the bobbin melts. Glass filled bobbins are infinitely superior in this regard and not much more costly.

ANTI FLASHOVER INSULATION PROTRUDES AT LEAST 3MM BEYOND CORE SIDES

WEAK POINT WHERE PRIMARY WIRE EMERGES FROM THE BOBBIN. COVER THE WIRE WITH SILICON RUBBER SPAGHETTI OR SIMILAR ADDITIONAL INSULATION

CREPE PAPER TAPE RIDES UP BOBBIN SIDES CAUSING THE WINDING TO BE COMPLETELY SEALED AFTER VACUUM IMPREGNATION

LONG PATH OVER BOBBIN CENTRE PARTITION PREVENTS FLASHOVER BETWEEN WINDINGS

INSULATING SHIELD MADE FROM HIGH MELTING POINT PLASTIC (MYLAR OR SIMILAR) PREVENTS FLASHOVER BETWEEN WINDINGS AND CORE

Appendix 1- Selecting the Main Filter Capacitor in a DC Power Supply

THE CAPACITOR DISCHARGE IS ACTUALLY EXPONENTIAL, BUT FOR LESS THAN 20% RIPPLE, CAN BE ASSUMED TO BE A CONSTANT CURRENT DISCHARGE (STRAIGHT LINE) WITH GOOD ACCURACY.

V_{peak}

V_{ripple}

FULL WAVE RECTIFIED SINE WAVE

0 V

10mS

20mS (50Hz)

These days, dc power supplies most commonly use a capacitive filter to smooth their output voltage, with choke input and pi section filters now being rarely used. If the capacitor discharge is assumed to be constant current, then the following simple equations for capacitors can be used.

$q = It$ and $q=CV$ and hence $CV =It$ OR

$C= It/V$ where V is the ripple voltage required
I is the supply dc output current
T is the discharge time

To calculate the capacitor required, assume the discharge time is either the full 10 milliseconds of a half cycle (full wave rectification) or 20 milliseconds (half wave rectification). Depending on the actual ripple percentage chosen, this assumption will cause the capacitor value to be around 10 – 20% bigger than required, which is no bad thing as electrolytic capacitors normally have wide offset tolerances. Capacitors are typically manufactured with a -10% +50% tolerance on their value.

The ripple percentage chosen (100 Vripple/ Vpeak) should lie between 5 and 25%, with 10% being a good design compromise. Using ripple percentages of less than 5% is rarely done and generally is poor design practice because all of the energy supplied to the power supply load during the capacitor discharge time, has to be delivered in a very short pulse at the peak of the half cycle. This creates huge peak currents which in turn badly stress the transformer, rectifiers, and storage capacitor, creating considerable amounts of heating.

Appendix 2- Wasteless Laminations
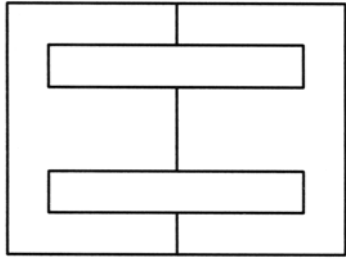
LAMINATION STAMPING PATTERN
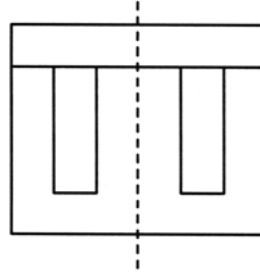
FINISHED TRANSFORMER CORE
(NOTE THE TWO IDENTICAL MAGNETIC
CIRCUITS OF CONSTANT CROSS SECTION
SIDE BY SIDE)

Most mass produced transformers being manufactured these days use wasteless laminations to form their magnetic core. There is no waste because two "I" laminations are stamped from the windows of two "E" laminations, completely using all the metal in the strip from which they are punched. This production method results in a pair of laminations of fixed proportions.

Working across the width of the E lamination in the second diagram, these proportions are

Left and right hand leg, both windows, and bottom of the E   1 unit

Centre leg   2 units

Because of these relationships, the "I" lamination ends up being 6 units long and 1 unit wide. This in turn forces the "E" to be 4 units high and have 2 windows 3 x 1 unit. The assembled transformer thus ends up with proportions of 5 units high and 6 units wide.

Knowledge of these relationships is very handy when designing a transformer, but even more useful if a transformer is to be rewound. The cross sectional area of the core has to be known in order to determine the turns/volt which will be used, but the width of the centre leg usually cannot be measured accurately because it is buried under the bobbin and/or a whole lot of insulation/wire. Fortunately, all that is necessary to obtain the width of the centre leg is to measure the total width of the "E" and then divide by 3. This figure is then multiplied by the thickness of the lamination stack to get the core cross sectional area.

APPENDIX 3
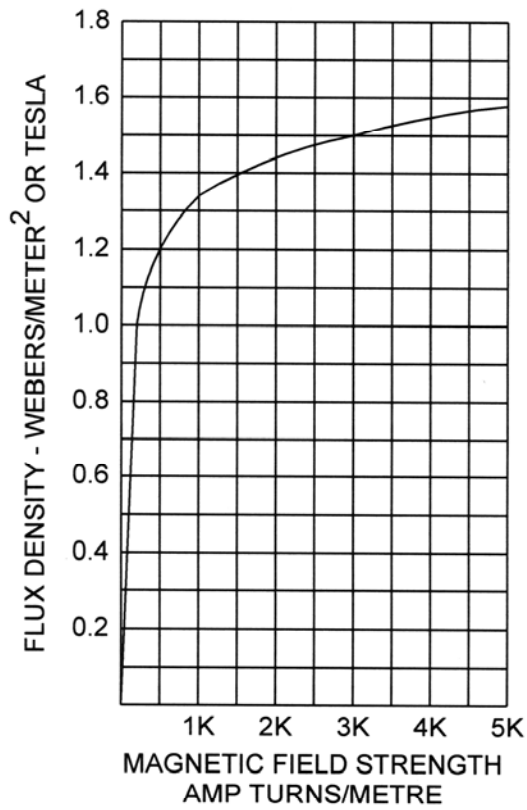
TYPICAL BH CURVE FOR
NON GRAIN ORIENTED
4% SILICON IRON FOR
TRANSFORMERS

Core Area		Power Rating	Core Area		Power Rating
Inch^2	mm^2	watts	inch^2	mm^2	watts
0.5	323	8	2.5	1613	195
0.75	484	18	3.0	1935	280
1.0	645	31	3.5	2258	381
1.25	806	49	4.0	2581	500
1.5	968	70	5.0	3226	780
2.0	1290	125	6.0	3871	1120