SECTION 2

ADVANCED PRACTICAL RADIO ENGINEERING

TECHNICAL ASSIGNMENT

POWER TRANSFORMERS

225 E

POWER TRANSFORMERS

FOREWORD

In a preceding assignment it was stated that inductive coupling is the most extensively used method of transferring electrical power from one circuit or device to another. An extension of that statement may be that the power transformer is the most commonly used application of inductive coupling.

Power may come into a radio station at 6,600 volts and by means of power transformer, be applied to the radio transmitter at 440 volts. Within the transmitter the voltage may be stepped down to 11 volts for the filaments of certain tubes, to 22 volts for the filaments of other tubes, and raised to 18,000 volts for application to the plate voltage rectifier, all by means of properly designed power transformers.

In an a.c. operated broadcast receiver a power transformer is employed to step the line voltage (usually 110) down to 2.5 volts or 6.3 volts (or to any other desired value) for operation of the tube heaters. Another winding—usually on the same transformer—steps the voltage up to perhaps 350 for application to the plate voltage rectifier.

You may never have to design a power transformer but every radio engineer (in fact, practically every radio-man) has to purchase, install and use power transformers. He must know what factors effect the operation of a transformer, determine its efficiency and suitability for a given application, etc. A *well-designed* power transformer probably is the most efficient component in an electrical system—a poorly designed, improperly selected or over-loaded transformer can seriously impair the operation of an electrical system.

At the CREI residence school, students use the formula given in this assignment to design, and then construct, power transformers. Losses, efficiency, etc. are then measured as a check on design accuracy. This assignment is highly practical and very important to every radio-man. *Study it carefully.*

E. H. Rietzke,
President.

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POWER TRANSFORMERS

SCOPE OF ASSIGNMENT

In every branch of radio the engineer must deal with power transformers, either large or small. In the broadcast receiver a transformer takes the line supply of (usually) 110 volts 60 cycles, and steps that voltage up to several hundred volts in one secondary winding to supply the anodes of the rectifier tube, and in other secondary windings the line voltage is stepped down to very low voltages for the filaments and heaters of the vacuum tubes. In a high power transmitter the plate voltages are ordinarily supplied by one or more high voltage rectifiers; in such an installation the line voltage, usually 220 or 440 volts, is stepped up to the desired high potential, possibly as high as 20,000 volts. The receiver transformer may supply a total of 40 or 50 watts; the high voltage transformer at the transmitter may supply 200 KW. The calculations for both are quite similar, and are not particularly difficult.

This assignment will take up in problem form the actual design of a transformer of medium size. The various equations used are all standard, and in most cases time and space will not be devoted to a discussion of the derivations. Where tables are used a sufficient range of figures will be listed so that the procedure may be applied to any ordinary size of transformer the engineer may have to design, either large or small. A review of the assignment on Magnetic Circuits will prove most helpful before studying this assignment.

Departing from the usual custom in the study of transformers, the transformer vectors will be considered only briefly in this assignment. Such vectors are taken up in most electrical engineering texts. A thorough discussion of this subject may be found in "Principles of Alternating Current Machinery" by Lawrence, (McGraw-Hill). The out-of-phase vector quantities—principally the reactive voltage due to leakage flux—and the IR drops in the transformer windings, greatly influence the design of a transformer. These quantities are very small, however, in proportion to the terminal voltages and do not show up on a vector unless greatly magnified. The effects will be discussed along with methods of minimizing the effects.

THEORY

FUNDAMENTAL CONSIDERATIONS.—The power transformer consists fundamentally of two windings, primary and secondary, wound around a common iron core, as shown in Fig. 1. Alternating current flowing in the primary winding produces a flux of continuously varying density in the iron core. This flux also links the secondary winding and induces a voltage across the secondary. As has been shown in a preceding assignment, if *all* the flux links both coils, the secondary terminal voltage as compared with the primary terminal voltage, will be a direct function of the turns ratio of the secondary turns to the primary turns.

This ideal condition could exist only if the secondary turns and primary turns actually occupied exactly the same space, which is obviously impossible. Since the two sets of windings do not occupy the same space, there is some *leakage flux* between the windings, as shown in Fig. 1. Before considering the effect of the leakage flux, let us briefly review the operation of the

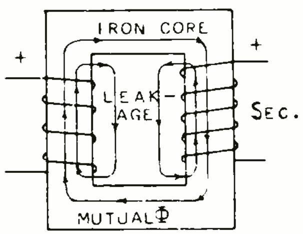

Fig. 1.—Schematic diagram of electrical and magnetic paths.

transformer. Consider the arrangement of the windings of Fig. 1 with the secondary for the instant open. Assume that $N_p = N_s$.

An alternating voltage is applied across the primary and current flows in the primary winding, this current being limited almost entirely by the inductive reactance of the primary since the resistance of the winding at no load is negligible as compared with the reactance. This current will establish exactly enough magnetic lines of induction in the iron core so that the induced voltage across the primary turns N_p equals the applied voltage, (neglecting the IR drop). Since the secondary turns N_s equal N_p, and since the flux through the iron core links both coils, then the voltage induced across the secondary will equal the voltage induced across the primary. Both the primary and secondary induced voltages will be opposite in polarity to the primary applied voltage and will be essentially equal to the amplitude of the applied voltage.

MAGNETIZING AND LOAD CURRENTS.— The current necessary to develop the mutual flux with the secondary open is called the *magnetizing current and this component of the primary current is essentially constant whether the secondary is loaded or open.*

When the secondary is connected to a load, current flows in the secondary winding. This current is opposite in direction to the primary current and its magnetic field is in such a direction as to oppose the field caused by the primary current-in other words the secondary current tends to reduce the core permeability or to demagnetize the iron. However the induced voltage across both primary and secondary *must* equal (almost) the applied voltage, regardless of secondary current, which means that the mutual flux in the iron cannot appreciably reduce. Thus the primary current must increase in proportion to the increase of secondary current in order to maintain the proper mutual flux. The entire operation of the transformer may be thought of as follows:

Regardless of load, the mutual flux is essentially constant. To maintain this flux with no load requires a certain fixed number of ampere turns and consequently a fixed magnetizing current. As a load is applied to the secondary, secondary current flows tending to demagnetize the iron. This is compensated for by a corresponding increase in primary current which tends to maintain the mutual flux at the original level. Thus the primary current must contain both components, magnetizing current and load current. The magnetizing current is small compared with the full load current. The IR drop in the transformer windings of a well designed transformer will be very small due to the low resistance of the windings, so from this point of view only, the regulation of such a transformer should be very good.

LEAKAGE FLUX.—The other factor which must be taken into consideration at this point is the leakage flux. Consider Fig. 1. The mutual flux flows through the iron and, as has been shown, is essentially constant regardless of load. A large part of the path of the leakage flux is through air. Also—and this is the important fact—*the leakage flux due to both primary and secondary currents is in the same direction in the space between the windings.*

As the secondary load current is increased, it tends to demagnetize the core, thus causing a corresponding increase in primary current. The secondary leakage flux does not tend to oppose the primary leakage flux—instead it adds to it. The mutual flux is essentially constant but the leakage flux is a direct function of the winding currents. The leakage flux thus sets up reactive voltages across the windings *which are not compensated for.* Also the leakage flux is out of phase with the mutual flux. The net result is a decrease of secondary terminal voltage with increased load and a certain phase shift between load current and voltage. This of course is manifest in the form of poor regulation.

It has been shown in an earlier assignment that the amount of flux produced by a given number of ampere turns is a function of the permeability of the medium and the cross-section of the space in which the flux can flow. So far as the leakage flux is concerned the path is largely through air, so $\mu = 1$ for any type of winding. Thus a reduction in the leakage flux must be accomplished by decreasing the effective cross-section of the path which is the space surrounding and between the coils. In the type of winding illustrated in Fig. 1 where the primary is placed on one leg of the core and the secondary on the other, the air space surrounding and between windings is of very large cross-section so that a large amount of leakage flux will be produced. This type of winding will form a relatively inefficient transformer having poor regulation.

Figs. 2 and 3 illustrate an arrangement of the windings on the core that greatly minimizes the

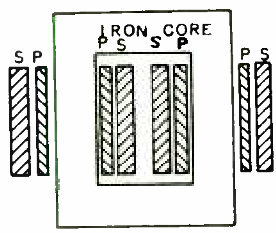

Fig. 2.—Cross-sectional view of transformer, showing iron core and primary and secondary windings.

leakage flux. Fig. 2 is a cross-section of core and windings; Fig. 3 is a top view of the same transformer. Both primary and secondary are split into two sections and half of each winding is placed on each leg of the core, one winding being placed immediately over the other. The space between windings is only that required for insulation, so that the cross-section area of the gap between windings in which leakage flux can be established is greatly reduced. This increases the

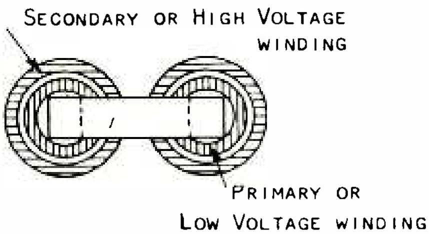

Fig. 3.—Top view of transformer.

reluctance of the path of the leakage flux and for given winding currents the leakage reactance will be greatly reduced. With such an arrangement the regulation will be considerably improved over the arrangement in Fig. 1.

VECTOR CONSIDERATIONS.—A brief consideration of the transformer vector will help to make the effect of leakage reactance clear. It should be understood that the small out-of-phase components are greatly exaggerated so as to be visible on the vector diagram, (Fig. 4). This of course exaggerates the angles between terminal and induced winding voltages. For simplicity it is assumed that the turns ratio is unity, that is, the primary and secondary windings have an equal number of turns.

In the vector E_p and E_s are the primary and secondary terminal voltages respectively. e_s and e_p shown to the right are equal and are the voltages *induced* into the secondary and primary windings respectively. These voltages are of the same polarity and are essentially opposite to the primary terminal voltage. Thus $-e_p$ is shown to the left as being almost in phase with the primary terminal voltage E_p.

The phase relation of the secondary current I_s with respect to E_s is shown by the angle θ and is determined by the power factor of the load. Since this current tends to demagnetize the iron, it must be compensated for in the primary by a component of equal magnitude i_2. In the primary must also flow a component of current i_1 which is the no-load magnetizing current. i_1 is slightly out of phase with the flux ϕ because it, in itself, consists of two components, the no-load magnetizing current and the component that supplies the no-load losses, the latter being mostly core loss. Thus the primary current I_p is the vector

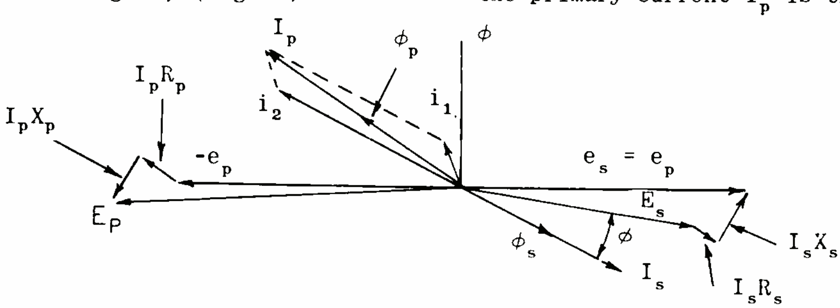

Fig. 4.—Vector diagram for the transformer.

sum of i_1 and i_2 and is somewhat larger than the secondary current.

To force the currents through the ohmic resistance of the primary and secondary respectively requires voltages I_pR_p and I_sR_s. These voltages are in phase with their respective currents.

To overcome the leakage reactances requires respectively I_pX_p and I_sX_s for the primary and secondary circuits. It is seen that the fluxes produced by the primary and secondary load currents, ϕ_p and ϕ_s, are in phase with their respective currents. Since the effect of leakage flux is entirely reactive, the reactive voltages, I_pX_p and I_sX_s, lead their respective currents by 90°. (This is the same as saying that the currents lag 90° behind the reactive voltages which is true because the reactance is inductive reactance.)

The combined effects of all these voltage components should be carefully noted. In the primary, the terminal line voltage must overcome three components of opposition, $-e_p$, I_pR_p, and I_pX_p, respectively the induced primary voltage, the IR drop in the primary winding, and the reactive drop due to primary leakage flux. In the secondary, the induced voltage which equals $-e_p$ in amplitude, must supply the vector sum of the terminal voltage E_s, the I_sR_s drop in the secondary winding, and the reactive drop I_sX_s due to secondary leakage flux.

It is apparent that the primary terminal voltage must be somewhat greater than the secondary induced voltage, and the secondary terminal voltage must be somewhat less than the secondary induced voltage. Therefore with unity turns ratio the secondary terminal voltage cannot equal the primary terminal voltage—and with any turns ratio the secondary terminal voltage cannot quite equal E_pN_s/N_p. However in a well designed transformer the undesired voltage components are extremely small in comparison to the desired terminal voltage and are easily compensated for. The difference is usually not more than 1 or 2 percent at full load.

TYPES OF TRANSFORMERS.—The two principal types of transformers are the core and shell types. The core type transformer is illustrated in Figs. 2 and 3. The shell type is shown in Figs. 5 and 6, Fig. 5 re-

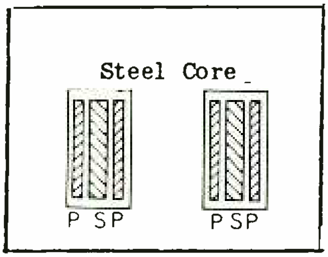

Fig. 5.—Cross section of shell-type transformer.

presenting a cross-section of core and windings and Fig. 6 representing

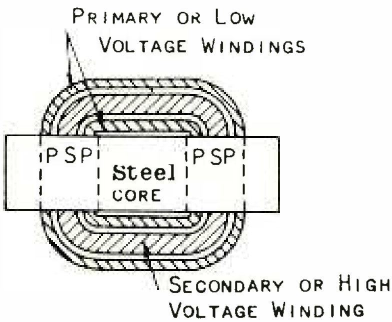

Fig. 6.—Top view of shell-type transformer.

a view from above. The core type is best adapted for high voltage low capacity transformers. This is because the most economical proportioning of material in the core type transformer requires a large number of turns and small cross-section of steel. The shell type, in which the steel largely surrounds the copper instead of vice versa as in the core type, is more economical for large capacity low voltage transformers because in this type economical construction requires large cross-section of steel and fewer turns. Power transformers supplying all the voltages for broadcast receivers are usually of the shell type. The shell type is usually more expensive to repair.

PRELIMINARY DESIGN CONSIDERATIONS

CORE CONSTRUCTION.—Modern high grade transformers are usually constructed with a core of silicon steel laminations. Several thicknesses of laminations may be found, two of the most commonly used being 14 mils, (.014 inch), and 20 mils (.02 inch), the latter being advisable only for silicon steel. Each lamination in some cases is coated on both sides with an insulating varnish, the thickness of the coating being in the order of 1 mil. Where the laminations are of silicon steel, the surface may be oxidized instead of varnished. This forms a very high resistance between laminations just as does the varnish and accomplishes the same results. The laminations are stacked to the required thickness of core and then tightly bolted or clamped together. Laminated cores must be used in all a-c machinery because in a solid steel core the eddy current losses would be prohibitive. Eddy currents are set up in the iron at right angles to the direction of the flux as it builds up through the core. In a large body of solid steel the conductivity would be very high and the eddy currents large, so that the power loss, I^2R, would also be extremely large. Where the core is made up of very thin laminations, each insulated from the other, the length of each conductor in which a voltage is induced is very short and the eddy current path around each lamination is of small area, so that the current is correspondingly reduced.

The use of silicon steel (usually not over 3 percent silicon) over ordinary transformer steel has several marked advantages. First, the resistance of silicon steel is much greater than that of ordinary steel so that eddy current loss is reduced. Second, as was shown in an earlier assignment, the permeability of silicon steel is higher, so that for a given field density fewer ampere turns are required. Third, the hysteresis loss in silicon steel is less than in ordinary steel. Ordinarily the increased efficiency obtained by the use of silicon steel more than compensates for its additional cost.

The core is built in sections so as to allow the coils to be wound and then placed over the core. The two ends of adjoining sections are interleaved and tightly bolted or clamped together. Such assembly leaves either two or four gaps, (depending upon whether the core is made up of two or four sections), of the thickness of the space between the adjacent sections of steel and in series in the magnetic circuit. Thus in a magnetic circuit calculation it is necessary to assume either two or four airgaps each having length of approximately .001 inch and area equal to the cross-section of the core.

The effect of the varnish or oxide on the laminations brings up another factor which must be considered. Assume the thickness of the lamination is .02 inch and the varnish on each side is .001 inch. Then the total thickness of the core in one dimension is approximately .9 iron and .1 varnish. Where the lamination has thickness of .014, for a given core dimension .875 is iron and .125 is varnish. Neglecting this factor would cause considerable error.

The core losses are due to eddy currents and hysteresis, both of which are functions of the flux density in the iron. It has been shown that the maximum amplitude of flux density is essentially constant whether the secondary is open or loaded, and regardless of the amount of the secondary loading. Thus the core losses are not a function of transformer load.

WINDINGS.—A transformer ordinarily has two windings, primary and secondary, but in special cases may have more than one secondary. Such a case is the power transformer of a modern broadcast receiver where individual secondaries are provided for filament, heater and plate supply circuits, a common primary winding and core being used. Such an arrangement does not cause any particular complications.

Either winding in a transformer may be used as a primary and either as a secondary, depending upon whether the voltage is to be stepped up or down. Thus a transformer designed to step a 2200 volt supply down to 220 volts will operate equally satisfactorily in stepping a 220 volt supply up to 2200 volts. In transformer work it is probably more accurate to speak of high voltage and low voltage windings rather than in terms of primary and secondary windings. However in most cases of transformers designed for use in radio apparatus the transformer will be built for a specific purpose and one winding will be arranged specifically to connect as a primary to a standard power circuit—110, 220 or 440 volts. In most cases in this discussion the terms primary and secondary will be used, but in the actual arrangement of the windings on the core the voltage will be specifically considered.

Since the mutual flux links both windings, the voltage across the secondary will equal the primary voltage times the turns ratio, $E_s = E_p N_s / N_p$. Neglecting the magnetizing component of primary current and the current component of power expended in heat in the primary winding, both of which are small compared with full load current, the secondary current will equal the primary current times the inverse turns ratio, $I_s = I_p N_p / N_s$. Thus considering only the load components of primary voltage and current, the primary power W_p equals the secondary power W_s,

$$W_p = W_s = E_p I_p = E_s I_s$$

$$= (E_p \frac{N_s}{N_p}) \quad (I_p \frac{N_p}{N_s})$$

The above relations will ordinarily be true within five percent, and in well designed transformers operating at full load, within two or three percent.

Unlike the core losses, the copper losses increase with load. The total copper loss is the sum of the I^2R losses in the primary and secondary windings.

$$I^2R = I_p^2R_p + I_s^2R_s$$

For given winding currents, as determined by the load, the larger the wire the less the copper loss. However an examination of Figs. 2, 3, 5 and 6 will show that if a larger size of wire is used the dimensions of the core must be increased. This increases the cost of the transformer and also increases the hysteresis loss which is a function of the volume of iron in the core, therefore counteracting to some extent the decreased copper loss. Thus to obtain reasonably good efficiency with economical construction, there must be established some relations between the various transformer dimensions.

If all the dimensions are made small, that is, if for a given rating the core is made small and operated at very high flux density, and the minimum size of wire that will carry the current is used, both core and copper losses will be large, and with the small dimensions the heat developed will not be radiated freely and the temperature rise of the transformer will be excessive. Thus the temperature rise sets one limit of design. Transformers are usually designed for temperature rise not to exceed 50° C at full load. This is also a function of the cooling system. Where the transformer is provided with oil, water, or air blast cooling so that the removal of heat does not depend entirely upon the surface dimensions, the core may be operated at higher flux density and the copper at higher current density than where a less efficient cooling system is used.

CORE LOSSES.—It is found in practice that a core loss of about one watt per pound of iron can be safely dissipated. In small 60 cycle transformers using ordinary transformer steel this allows an approximate maximum flux density of 40,000 lines/inch^2, with 60,000 lines/inch^2 for silicon steel. For large transformers these figures may be increased to 65,000 and 75,000 respectively. If the transformer is to be designed for 25 cycle operation these values may be increased about 15 percent.

The allowable current density in the windings is also a function of the cooling system. This is shown in the following table.

TABLE I

TYPE OF TRANSFORMER	CURRENT DENSITY IN AMPERES PER *SQUARE INCH.*	CURRENT DENSITY IN AMPERES PER *10^6 CIRCULAR MILS*
Poorly cooled	850 - 1200	670 - 940
Ordinary oil cooled, air blast, etc.	1100 - 1600	860 - 1260
Large, well cooled	1500 - 1900	1180 - 1490

COPPER LOSSES.—An example will make the term, "current density" clear. Suppose a cross-section of winding is taken such that the actual cross-section area of copper in that part of the winding is one square inch. Suppose the wire size is such that this total copper area is made up of 200 turns through which flow 4.5 amperes. The sum of all the currents flowing in this square inch of copper is equal to the current per turn times the number of turns— in this case 4.5 × 200 = 900 amperes per square inch = current density. If a larger wire is used such that one square inch of copper represents only 100 turns and the current per turn is increased to 9 amperes, the current density is still 900 amperes per square inch.

This factor is very important in transformer design. For example, it has been shown that the current in the secondary is an inverse function of the turns ratio. Therefore in a step-up transformer the secondary must have more turns than the primary, the ratio being equal to the voltage step-up factor, and the current will be decreased in proportion to the voltage increase. If the secondary voltage is 50 times as great as E_p, then $I_s = I_p/50$. If the secondary were wound with the same size wire as the primary, the secondary current being so small the current density would be *very* low. This would obviously be a very great waste of copper. Also with so much copper, the dimensions of the iron core would have to be unnecessarily large to accommodate the windings. Economically, this would be very poor design. Also, while the large secondary conductor would result in low secondary copper loss, the excessive volume of iron would result in excessive hysteresis loss. Thus there is no advantage in using wire that is larger than necessary to safely carry the full load currents without excessive temperature rise. The most satisfactory arrangement is to use a wire size such that the current density will fall within the limits as indicated above and will be essentially the same in both windings. This will result in substantially equal copper loss in the two windings. Then,

$$I_p^2 R_p = I_s^2 R_s$$

$$\frac{R_s}{R_p} = \frac{I_p^2}{I_s^2} = \left(\frac{I_p}{I_s}\right)^2 = \left(\frac{N_s}{N_p}\right)^2$$

From this equation, the ratio of the resistances of the secondary and primary windings should be a function of the square of the ratio of the number of turns. This assumes that the mean length per turn is the same in both windings, which may not be quite true. Another way of accomplishing the same result in design is to select a size of wire for the low voltage high current winding that has a circular mil area equal to that of the low current winding times the turns ratio. Or, in the case of a step-up transformer where the primary winding is first designed, the size of wire in the secondary winding should be such that its circular mil area is equal to that of the primary wire divided by the turns ratio. Of course in practice the size of wire having a cross-section area nearest to the calculated value will be used. These values are not particularly critical. If the current density is too great, the transformer will overheat on full load; if the current density at full load is considerably below allowable values, the construction cost will be excessive and the hysteresis loss will be greater than necessary, due to the excessive volume of iron.

There are some operating conditions under which it is desired that the operating temperature rise be quite low even though the cooling arrangement due to poor ventilation is not good. An example of such a case is the power transformer of a broadcast receiver where the receiver may be expected to operate at full load for hours at a time, and where the chassis of the receiver may be mounted in a small and poorly ventilated cabinet. In such a case the transformer should be designed for low hysteresis loss and with a low limit of current density to keep the copper loss low. In the arrangement of apparatus on the chassis, it is desirable to mount the power transformer on top where the heat will radiate upward away from the receiver components.

WINDING ARRANGEMENT.—The actual arrangement of the windings on the core will depend to a large extent on the type of transformer, voltages, etc. In general, to simplify the problem of insulation the low voltage winding is placed next to the iron core, with the high voltage winding placed over and insulated from the primary winding. With such an arrangement high voltage insulation is required only between the two windings, and not between a high voltage winding and an iron core. This arrangement on a core type transformer is shown in Figs. 2 and 3 where it is assumed that the primary is the low voltage winding—in other words, that it is a step-up transformer.

The arrangement of a step-up shell type transformer is shown in Figs. 5 and 6. Here again the primary is the low voltage winding. In this transformer the low voltage winding is split into two sections, one section on either side of the high voltage winding, so that the winding next to each part of the iron is a low voltage section.

PRIMARY WINDING.—In the actual calculations for the number of turns on each winding, the first consideration is the primary since it is the ampere turns in the primary that determine the flux in the core. Although the alternating current in the winding varies between zero and maximum values, the symbol ϕ in transformer calculations refers to *maximum* flux developed during the current cycle. In transformer design practice a relation, $C = \phi/N_pI_p$, is used. ϕ = maximum total flux in the core which is the product of the allowable flux density in lines/inch^2 times the cross-section area of the core in square inches; N_p and I_p are primary turns and effective full load current respectively. The proper value of C is a function of the type, capacity and voltage of the transformer, and the relative proportions of iron and copper. It is widely different for core and shell types as shown in the following table:

TABLE II

Cooling System	*Voltage*	*Value of C*	
		Core Type	*Shell Type*
Natural Draft	0 - 6000	55 - 70	500 - 700
	above 6000	70 - 75	500 - 700
Oil cooled	0 - 10,000	75 - 100	
	above 10,000	100 - 150	
Air Blast or	0 - 10,000	110 - 160	600 - 1000
water cooled	above 10,000	160 - 240	600 - 1000

It has been stated that the economical arrangement in a core type transformer calls for a large number of turns and small cross-section of core, and in a shell type transformer a smaller number of turns and a larger volume of iron. This is demonstrated in the given table. In a small transformer without artificial cooling C = 55 - 70 for the core type and 500 - 700 for the shell type, a difference of about 10 to 1. If both types of transformers are designed for the same voltage and power ratings, then at full load both will have the same primary current. It may also be assumed that the maximum flux density will be essentially the same in both. Then with I_p and flux density arbitrarily fixed, assume C is to be 60 for the core type and 600 for the shell type. As shown in Figs. 2 and 4, the amount of iron in the shell type will ordinarily be larger than in the core type. With a larger cross-section of iron for a given flux density, total maximum ϕ will be greater. Also the reluctance of the magnetic circuit will be lower than with the core type so that the specified flux density will be established with fewer ampere turns. But, the primary current at full load is fixed by the power rating of the transformer, so that the decrease of ampere-turns is obtained by a winding of fewer turns. Thus greater total flux ϕ and fewer ampere-turns, $N_p I_p$, results in a larger value of C. If the cross-section area of the iron, and hence the total flux for a given flux density, for the shell type is increased by $\sqrt{10}$ over that of given core type transformer, and the primary turns are decreased by $\sqrt{10}$, then C for the shell type as compared with the core type will be increased by 10.

$$C = \frac{\sqrt{10}\,\phi}{\frac{N_p}{\sqrt{10}} I_p} = \frac{\sqrt{10}\cdot\sqrt{10}\,\phi}{N_p I_p} = 10\,\frac{\phi}{N_p I_p}$$

The relation between the RMS value of primary voltage and the maximum value of ϕ is expressed by the following:

$$E_p = 4.44f \cdot N_p \cdot \phi \cdot 10^{-8} \quad (1)$$

Where E_p = RMS primary voltage, f = frequency in cycles per second, N_p = primary turns, ϕ = maximum value of flux in lines, 10^{-8} = a constant derived from the fact that 10^8 lines of force must be cut per second to induce 1 volt and 4.44 is a constant. The constant 4.44 is obtained from the mathematical proof, and will not be derived here. Note from Eq. (1) that the RMS value of the primary voltage is dependent on the product of N_p and ϕ. This product is sometimes referred to as the *number of linkages;* it represents the total amount of coupling of the flux with the primary coil. One can get the same value of induced voltage by increasing either N_p or ϕ and decreasing correspondingly the other quantity.

A further point to note is that the same flux, in threading through the turns of the secondary coil, induces a voltage in that coil, too. The magnitude of this secondary voltage is very simply found by substituting the secondary number of turns N_s for the primary number N_p in Eq. (1).

The determination of the proper number of primary turns is also influenced by another factor, the allowable *volts per turn*. This factor varies over quite wide limits with the power rating of the transformer, as is shown in the accompanying table. In smaller transformers still smaller ratios will ordinarily be used. In a transformer having a low power rating, the winding currents are relatively low and the I^2R loss in the windings, even if R is not extremely low, may not be excessive, so that a somewhat larger R, which represents of course a greater number of turns may be used with a smaller core. In the case of larger transformers the current is larger for a given voltage rating, and since the copper loss increases as I^2, it is desirable to make R as small as possible, which means fewer turns and a greater proportion of iron, keeping of course within the limits of C as specified. A low value of R also results in better regulation since the voltage drop in the winding is IR.

TABLE 3

KW rating *of transformer*	Allowable volts per *turn, core types*
10	2.5
20	3.5
50	5.5
100	7.0
200	9.0
500	13.0
1000	18.0

Thus it will be seen that the preliminary design problem in a transformer involves the determination of the number of primary turns and the cross-section area of the iron core, the latter being of course a direct function of the desired maximum flux density and the total number of lines of force required. The number of secondary turns is determined simply by multiplying the number of primary turns by the voltage ratio E_s/E_p. In the determination of the number of primary turns and core area that will satisfy the tables of C and the allowable volts per turn, and Eq. 1 for E_p, some arbitrary assumptions must be made and the preliminary calculations completed. If the result of the calculations is not satisfactory, other assumptions must be made and the calculations continued until the proper balance of factors is obtained. With the limits of the various factors as determined by commercial practice tabulated, the preliminary determinations are not difficult.

INSULATION.—Consideration must be given to the insulation of the windings. It has been shown that in practically all cases the voltage between adjacent turns on the same layer is low. In small transformers such as are used in low power radio apparatus the voltage per turn may be one volt or less. It is not high even in large transformers. Therefore cotton covered wire may be used or, in the case of quite small wire, enamel insulation is frequently used.

The maximum voltage between layers on any given winding should be kept below 400 volts. In small transformers empire cloth is frequently used between layers. The insulation between layers should extend beyond the windings to prevent creepage. Fuller board is commonly used as insulation between layers.

Between the low voltage winding and the core a layer of pressboard is ordinarily used. Pressboard may also be used between the primary and secondary windings if the voltage is not too high. In the case of a high voltage transformer a mica composition is ordinarily used as additional insulation between windings. Insulated bushings must be used where the terminals pass through the case. In all cases the insulation must be adequate to fully protect the windings under all operating conditions that may be encountered.

In testing the insulation of a transformer apply double the rated voltage per section for one minute at a frequency higher than normal, preferably double the operating frequency. Then apply 1.5 times the normal rated voltage for five minutes. All voltages should be applied and removed gradually.

RATING.—Before proceeding with the actual design of a transformer, the subject of transformer rating should be briefly discussed. Transformers are sometimes rated in kilowatt output capacity, KW. However it is possible that the actual load may have a very poor power factor so that with a given voltage the current may be very high in proportion to the actual watts dissipated in the load. Since the copper loss is a direct function of I^2R, it is desirable that the winding current does not exceed certain limits regardless of load power factor. Therefore transformers are more often rated in terms of kilovolt amperes, KVA, rather than in terms of KW. The KVA rating of, for example, 100 KVA simply means that the product of the current in amperes times the voltage in kilovolts should not exceed 100 regardless of the actual power expended in the load.

It is believed that a correlation of the various factors discussed can best be accomplished by working out a complete design of a medium size power transformer such as may be required for a comparatively low power radio transmitter.

TRANSFORMER DESIGN

NUMERICAL EXAMPLE.—It is desired to design a step-up transformer to supply high voltage to a rectifier plate supply of a broadcast transmitter. The transformer is to have a rating of 5 KVA, 60 cycle, 220 volt primary, 6600 volt secondary. It is to be an air cooled core type, the core to be built of silicon steel laminations .02" thick.

First make calculations for the primary turns and total flux.

At 5 KVA, full load, $I_p = \dfrac{VA}{E_p} = \dfrac{5000}{220}$

$= 22.72$ amperes.

From Table 3, try 2 volts per turns.

Then, primary turns, $N_p = \dfrac{220}{2} = 110$

$$E_p = 4.44f\, N_p\, \phi\, 10^{-8} \qquad (1)$$

$$\text{Max } \phi = \frac{E_p\, 10^8}{4.44f\, N_p}$$

$$= \frac{220 \times 10^8}{4.44 \times 60 \times 110} = 750{,}800 \text{ lines}$$

$$C = \frac{\phi}{I_p N_p} = \frac{750{,}800}{22.72 \times 110} = 300$$

Checking this with Table 2 for the core type transformer, it is seen that this is far too high. It is therefore necessary to select a smaller volts per turn ratio and repeat the calculations. Try 1 volt per turn.

Then, $N_p = \frac{220}{1} = 220$ turns.

$$\text{Max } \phi = \frac{220 \times 10^8}{4.44 \times 60 \times 220} = 375{,}400 \text{ lines}$$

$$C = \frac{375{,}400}{22.72 \times 220} = 75.$$

(From Table 2 this is very close to the limits specified and may be considered satisfactory.)

Secondary turns, $N_s = \frac{E_s}{E_p} N_p$

$$= \frac{6600}{220} \times 220 = 6600 \text{ turns.}$$

Note that the volts per turn figure is the same for both windings. N_s should be divisible by 4 for the core type. This allows the winding to be built in four sections and simplifies the mechanical arrangement.

CROSS-SECTION OF CORE, A. 5 KVA is a small transformer and the core is to be built of silicon steel. As has been previously shown, a flux density of 60,000 lines per square inch will be satisfactory. The total flux is 375,400 lines. Then,

$$A = \frac{\phi}{60{,}000} = \frac{375{,}400}{60{,}000}$$

$$= 6.25 \text{ square inches.}$$

In a core type transformer the cross-section of the core may be made square. However the laminations are insulated from each other with a coat of varnish about .001" thick on each side so that with .02" laminations about 10 percent of the total core material is varnish. Thus where d = the dimension of one side of the core, (see Fig. 7), the actual thickness of iron in one direction is approximately .9d, and the dimension of each side of the square core must be made a little larger to compensate for the varnish.

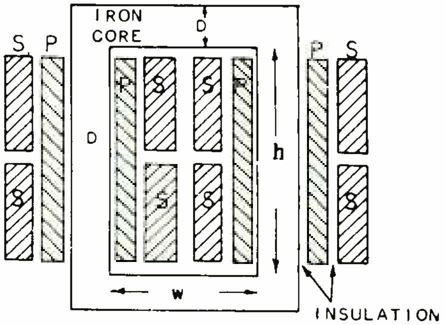

Fig. 7.—Arrangement of core, winding, and insulation.

$$A = 1.11 \times 6.25 = 6.93$$

$$D = \sqrt{6.93} = 2.64"$$

It is seen from Fig. 7 that after the cross-section of the core is determined it is necessary to calculate the other dimensions of the core. This is done by calculating the dimensions of the window hw which must contain a cross-section of the windings. It is first necessary to calculate the area of copper in the window. From this, by the use of a form factor as given in Table 4, the actual window dimensions may be determined.

DESIGN OF COILS.—It is obvious that the actual copper in the wind-

TABLE 4

TRANSFORMER SPACE FACTOR

POWER IN KW	CORE TYPE 0-10,000 Volts	CORE TYPE 10,000-33,000V	SHELL TYPE 0-2000V	SHELL TYPE 2000-10,000V
0 - 50	.22	.15		
50 - 1000	.33	.25	.40	.33

ings occupies only a portion of the window; other space is occupied by insulation; space must be allowed for air or oil circulation for cooling, etc. In fact Table 4 shows that in a transformer of the power and voltage rating under consideration, only .22 of the window is actually filled with copper. First, calculate the space occupied by the copper. This is a function of current density which will be called U. Call D the actual cross-section of copper in the window in square inches. From Table 1 it is found that for the type of transformer in question the current density U may be between 850 and 1200. U = 1000 should be a satisfactory value. Then,

$$D = \frac{N_pI_p + N_sI_s}{U} = \frac{2\,N_pI_p}{U}$$

(It has previously been shown that the ampere turns and current density should be very nearly equal in primary and secondary.)

$$N_p = 220$$

$$I_p = 22.72$$

$$D = \frac{2 \times 220 \times 22.72}{1000}$$

= 10 square inches of copper in window.

Since it is not possible to fill the entire window with copper, the form factor must be considered. As explained above and shown in Table 4, the form factor to use in this case is .22. Then the actual area of the window, hw, is

$$hw = \frac{D}{\text{Form factor}} = \frac{10}{.22}$$

= 45.4 square inches.

The dimensions of the window must be divided between height and width. This is done by first calculating the height. The ampere turns per inch length of the core is related to the heating of the transformer. Transformers are ordinarily rated at a maximum temperature rise 50°C at full load. Use the formula,

$$x = \frac{N_pI_p}{h}$$

where x = ampere turns per inch of core.

For natural cooled transformers, x = 500 - 750. Selecting an intermediate figure of 600,

$$h = \frac{N_pI_p}{x} = \frac{220 \times 22.72}{600} = 8.33''.$$

(oil cooled, x = 750-1260)
(water cooled, x = 1250-2000)

$$w = \frac{hw}{h} = \frac{45.4}{8.33} = 5.45''.$$

(In shell type transformers the practice is to make the dimensions of each window such that h is from 1.5 to 3 times w, and w is from .75 to 1.25 the width of the central iron core. Then the width of each leg of the iron core is one-half that of the center core.)

For minimum loss the current density in the primary should be the same as in the secondary, thus the square inches of copper cross-section should be equally divided, that is, 5 square inches for each. In the primary, the cross-section area of 220 turns is 5 square inches, and for one turn,

$$C.S. = \frac{5}{220} = .022 \text{ square inch}$$

Note that one inch equals 1,000 mils
= 22,000 square mils
= 22,000 × 1.273
= 28.006 circular mils (C.M.)

No. 6 wire has a cross-section area of 26,250 C.M. and No. 5 has a cross-section area of 33,102 C.M. By allowing a slightly greater current density, No. 6 may be used very satisfactorily.

The secondary winding contains 6600 turns. The cross-section area per turn is,

$$C.S. = \frac{5}{6600} = .000757 \text{ square inch.}$$

As a square conductor, one side is

$\sqrt{.000757} = .0275" = 27.5$ mils.

Cross-section area in square mils $= 27.5^2 = 757$ square mils.

Cross-section area in circular mils = 757 × 1.2732 = 963 C.M.

No. 20 wire with cross-section area of 1021.5 C.M. approaches this most closely and may be used very satisfactorily.

In the actual construction of the transformer the primary winding will be wound in two sections, 110 turns on each section, and the primary coils placed next to the core. A layer of pressboard is placed between the low voltage winding and the core. A layer of insulation will be placed over the primary winding and then the secondary windings will be wound in sections and placed over the primary windings. Mica insulation should be used between the primary and secondary windings since the secondary winding operates at quite high voltage. No. 6 wire winds about 6 turns per inch and the length of winding on the core may be a little more than 7 inches. Thus each section of the primary winding will consist of two and one-half layers.

The secondary winding should be wound in an even number of sections, one-half going over each core. No. 20 wire will wind about 30 turns per inch. On no one layer of a section should the voltage exceed 150 - 200 volts. The total length of the secondary winding on each core cannot exceed about 7 inches. (The total window is 8.33" high, and due to the voltage involved, the winding cannot fill up the entire length.) Thus a convenient secondary winding will be four sections, two sections per core, 100 turns per layer, each layer insulated from the other. With ordinary layer winding this will result in a maximum effective voltage between windings of 200 volts. (1 volt per turn.) With total secondary turns of 6600, total turns per section will be 6600/4 = 1650; with 100 turns per layer, each section will have 16.5 layers, each layer insulated from the other. Insulating spacers should be placed between the two sections on each core and between the secondary sections and the core end sections. The arrangement is shown in Fig. 7.

Before proceeding further, it is necessary to compute the dimension of the mean primary turn. The mean length of the primary turn is estimated on the assumption that the turns are square shaped. Referring to Fig. 7, page 14, it is seen that one side (1/4) of the mean square turn is the sum of the following items:

1/2 thickness of primary winding
Insulation between primary and core
Core dimension, D.
Insulation between primary and core
1/2 thickness of primary winding

Now, we must determine the thickness of the primary winding. Cooling of the primary is somewhat restricted and good insulation is essential; hence, double cotton covered (or single cotton covered enamel wire) should be used. (Enamel coating of wire increases the wire's diameter by 1 mil. Single cotton covering increases wire's diameter by 4 mils. Double cotton covering increases wire diameter by 8 mils.) Insulation between layers may be 20 mils each. The diameter of #6 wire is 162 mils, according to the wire table. However, double cotton covering adds 8 mils to the diameter, so diameter = 0.162 + .008 = 0.17". Three layers of wire are needed, separated by 20 mils, as specified above. The thickness of the primary is equal to:

$$3(0.17) + 2(.02) = 0.51 + .04 = 0.55"$$

One-half the thickness of the primary will therefore by 0.275".

Allowing 0.25" insulation between the core and the primary winding, the average dimension of a square primary turn will be:

1/2 thickness of primary winding = 0.275"
Insulation between primary and core = 0.25"
Core dimension, D = 2.64"
Insulation between primary and core = 0.25"
1/2 thickness of primary winding = 0.275"

The dimension of the mean primary turn is the sum of the above values, and is equal to 3.69". The length of the mean primary turn is four times that dimension, or 14.76". The length of the primary conductor is equal to N_p times the length of each turn. N_p was found to be 220 turns, so: 220 × 14.76" = 3247" or 270′ of number 6 wire will be required for the primary winding. The resistance of number 6 wire is 0.3951Ω/1000ft. (from the wire table). The resistance of the primary winding will be: 270 × .000395 or .1067 Ω. At full load, the copper loss in the primary is $I^2R = 22.72^2 \times .1067 \cong 55$ W. The secondary winding must be thoroughly insulated from the primary and a thickness of 0.25" should be allowed for this insulation. Since the maximum voltage across one layer should not exceed 150 to 200 volts this determines whether the secondary should be split into sections or not. Layers are wound first in one direction and then back in the other so that the voltage between layers is that of two layers at the maximum point. Splitting the secondary winding on each leg into two parts will improve the ventilation and permit the use of enamel wire. There is adequate window area to allow for the additional insulation between the two sections of each leg especially if enamel wire is used instead of D.C.C. wire.

Divide the secondary into four sections. Allow .25" between sections and at each end. The layers of wire should be separated by .01" insulation between layers.

The next step is to compute the thickness of the secondary winding. The diameter of number 20 wire is .03196". Add 1 mil (for enamel coating) to previous value. From our example problem 17 layers are necessary and 10 mils insulation should be allowed between layers or 16 pieces of insulation. The thickness of the secondary is: 17(.03296) + 16(.01) = 0.56032 + 0.16 = 0.72032" One-half the secondary thickness = 0.36".

The average dimension of a square secondary turn can be approximated as follows:

1/2 thickness of secondary winding = 0.36"
Insulation between windings = .25"
1/2 thickness of primary winding = .275"
Dimension of mean primary turn = 3.69"
1/2 thickness of primary winding = .275"
Insulation between windings = .25"
1/2 thickness of secondary winding = .36"

The dimension of the mean secondary turn is the sum of the above values, and is equal to 5.46". The length of the mean secondary turn is four times that dimension, or 21.84". The length of the secondary conductor is equal to N_s times the length of turn. N_s was previously determined as 6600 turns, so: 6600 × 21.84" = 144,200" or 12,000′ of number 20 wire will be required for the secondary winding.

The resistance of number 20 wire is 10.15 ohms/1000 ft. The resistance of the secondary winding will be 10.15 × 12 = 121.8 Ω.

$$I_s = \frac{I_p}{\text{turns ratio}} = \frac{22.72}{30} = .757\ \text{A}$$

The full-load power loss in the secondary is $I^2R = .757^2 \times 121.8$
$= 69.7\text{W}$

The copper loss in the secondary with this type of winding is somewhat greater than that of the primary because of the greater mean circumference per turn of the secondary winding, in this case 21.84" as compared with 14.76 inches. This is partly compensated for by the fact that in the primary the nearest smaller wire size to the calculated dimension is used and in the secondary the nearest larger size. This results in a somewhat greater current density in the primary winding than in the secondary winding. In a transformer having a larger core—that is, in a larger transformer—the primary and secondary copper losses would tend to be more nearly equal, particularly if the primary sections were arranged as in Fig. 6, on both sides of the secondary winding.

CALCULATIONS OF CORE LOSS.—The core hysteresis loss is calculated from Steinmentz' formula given in an earlier assignment on magnetic circuits:

$$W_h = \frac{KB^{1.6}}{10^7}\ \text{watt-second/cm}^3\text{/cycle.}$$

K for Silicon Steel = .001
B = 60,000 lines/inch^2
= 9300 Gausses.

$$W_h = \frac{.001 \times 9300^{1.6}}{10^7} = 2236 \times 10^{-7}$$

watt-second/cm^3/cycle.

In this transformer the core is uniform throughout and of square cross-section, the area of cross-section of the iron being 6.25 square inches or 40.3 cm^2. $6.25 \times (2.54)^2 = 40.3$ cm^2.

The height of the window is 8.33" so that the mean height of the core is 8.33" + 2.64" = 10.97". The width of the window is 5.45" so that the mean width of the core is 5.45" + 2.64" = 8.09". Thus the mean length of the iron core is 2(10.97" + 8.09") = 38.12" = 96.8 cm.

The volume of iron in the core is $40.3 \times 96.8 = 3900$ cm^3.

The hysteresis loss is
$W_h = 2236 \times 10^{-7} \times 3900 \times 60 = 52$ watts.

Eddy current core loss will be small because of the high electrical resistance of silicon steel. This loss can be calculated by the following formula:

$$W_{ec} = KV \times (T \times F \frac{B}{1000})^2 \times 10^{-5} \text{ watts.}$$

K = 1.5 for silicon steel (about 4 for ordinary steel).
V = Volume of core in cubic inches.
T = thickness of lamination—in this case .02 inch.
F = frequency in cycles.
B = flux density in lines per square inch.

V in inch^3 = $6.25 \times 38.12 = 238$ inch^3.
B = 60,000 lines/inch^2. Then,

$$W_{ec} = 1.5 \times 238 \times (.02 \times 60 \times \frac{60,000}{1000})^2 \times 10^{-5} = 18 \text{ watts}$$

The total core loss is
$W_h + W_{ec} = 52 + 18 = 70$ watts.

This loss is essentially constant whether the secondary is loaded or open.

Under full load the copper loss is,

$$W_p + W_s = 55 + 69.7 = 124.7 \text{ W}$$

Total transformer power loss = Copper Loss + Core Loss = 124.7 + 70 = 194.7 watts, = .1947 KW.
When working into a 5 KW load of unity power factor (resistive load), output 5 KW,
input = 5 KW + .1947 KW. = 5.1947 KW.
Full Load Efficiency

$$\frac{W(\text{output})}{W(\text{input})} = \frac{5}{5.1947} = 96.3 \text{ percent.}$$

At half load, that is, at half power output, the secondary and primary currents are each reduced to one-half of their respective full-load values, while the voltages remain unchanged. Since copper losses are I^2R losses, reducing the current to one-half decreases these losses to one-fourth of their full-load value. The core losses are unaffected because the flux density in the core tends to remain the same regardless of load.

At half load, the copper loss in this case will be equal to:

$$\frac{P_p + P_s}{4}$$

or, $\frac{55 + 69.7}{4} = \frac{124.7}{4} = 31.175$ W

The core loss is 70 W, as calculated previously. The total loss at half load = 70 + 31.175 = 101.175 W.

$$\text{Efficiency} = \frac{2.5 \text{ KW}}{2.601} = 96.2 \text{ percent}$$

It is interesting to note that the half load and full load efficiencies are practically identical in this case. It is not unusual to find the half load efficiency to be slightly higher than the full load efficiency in this transformer. This is due to the fact that the transformer loss is the sum of two components, the core loss which is fairly constant and the copper loss which decreases more rapidly than a decrease in power output. By variations of design it is possible to obtain maximum efficiency at various proportions of full load.

The efficiency will often be lower if the transformer is operated at less than full load because decreasing the load does not decrease the core losses. Somewhat lower efficiency will result if the power factor of the load is less than unity because then the current, and hence the copper losses, will be larger in proportion to the actual power delivered to the load.

A smaller or larger transformer, or a step-down transformer, may be designed by following the above procedure step by step.

To summarize a few of the important considerations in transformer design, the following is quoted in part from the catalog of one manufacturer of transformers for radio use, United Transformer Corp.

TEMPERATURE RISE.—A conservatively designed transformer should not have a temperature rise exceeding 40 to 55 Centigrade above ambient temperature. This is due to the danger of injury to the coil insulation when exposed to final temperatures of 85 degrees and above. It is not only the size of the transformer but also the efficiency as compared to the size, which controls the final temperature rise. Power transformers should employ the finest silicon steel and compact winding of high efficiency. To effect a high heat radiation coefficient all power components should be given a dull black finish.

EFFICIENCY.—As stated above, the temperature rise of a transformer is related with both efficiency and size. It is frequently assumed that a large transformer will be superior from the angle of loss, efficiency and heating, as compared to a smaller unit of equivalent rating. This is not true if large quantities of material are coupled with poor design. A large quantity of steel operated at the same flux density as a smaller quantity will result in an iron loss directly proportional to the bulk of the cores. Similarly, the larger bulk of copper used may have higher losses. Care should be taken in design to obtain the optimum ratios so that greatest efficiency and safety factor are obtained.

REGULATION.—The regulation of plate transformers (high voltage transformers for plate voltage rectifiers) is becoming an exceedingly important factor in modern amplifiers using class AB_2 or class B operation. A low temperature rise transformer will inherently have good regulation. In addition to this, the ratio of copper to steel in plate and power transformers should be such that the transformer resistance and leakage reactance are kept at a very low value. The regulation of all power transformers over 1000 watts should be better than 5 percent. The increase should be only slight in units below this power rating.

TYPES OF INSULATION.—The insulation used in power transformer equipment must have a high safety factor, taking into consideration the most severe conditions which may be encountered in service. As previously stated, temperature has a decided effect upon most insulating materials. To obviate this effect UTC uses mica almost exclusively at the points of high voltage stress in power equipment. This material while costly, is unequalled in dielectric strength, is practically unaffected by temperature, and is impervious to the injurious effects of the ozone caused by high voltage corona. Power equipment should be given a 24-hour vacuum-baking cycle with the coils thoroughly impregnated with a moisture-proof insulating varnish. In addition to the impregnating process, most smaller power components are poured in a complete enclosing casting with a high heat transfer insulating compound. Due to the large black surface obtained from the enclosing casting, these transformers will generally run cooler encased than as open units.

RESUME'

The student should now have a good knowledge of the factors involved in transformer design. He should be able to appreciate why all transformers are not alike and why more expensive transformers, if properly designed, should be worth the difference in price. The greatest efficiency that can be obtained at the desired load and temperature rise is a definite part of the design. Transformer design is a highly specialized field and although most students will probably not be required to design transformers, they should nevertheless understand the basic principles involved.

COPPER WIRE TABLE

Gauge No. B. & S.	Diam. in Mils	Circular Mil Area	Turns per Linear Inch: Enamel	S.S.C.	D.S.C. or S.C.C.	D.C.C.	Turns per Square Inch: S.C.C.	Enamel and S.S.C.	D.C.C.	Feet per Lb.: Pare	D.C.C.	Ohms per 1000 feet 20°C (68°F)	Pounds per 1000 feet	Diam. in mm.	Gauge No. B. & S.
0000	460.0	211,600	--	--	--	--	--	--	--	1.561	--	0.04901	640.5	11.68	0000
000	409.6	167,800	--	--	--	--	--	--	--	1.968	--	.06180	507.9	10.40	000
00	364.8	133,100	--	--	--	--	--	--	--	2.482	--	.07793	402.8	9.266	00
0	324.9	105,500	--	--	--	--	--	--	--	3.130	--	.09827	319.5	8.252	0
1	289.3	83,690	--	--	--	--	--	--	--	3.947	--	.1239	253.3	7.348	1
2	257.6	66,370	--	--	--	--	--	--	--	4.977	--	.1563	200.9	6.544	2
3	229.4	52,640	--	--	--	--	--	--	--	6.276	--	.1970	159.3	5.827	3
4	204.3	41,740	--	--	--	--	--	--	--	7.914	--	.2485	126.4	5.189	4
5	181.9	33,100	--	--	--	--	--	--	--	9.980	--	.3133	100.2	4.621	5
6	162.0	26,250	--	--	--	--	--	--	--	12.58	--	.3951	79.46	4.115	6
7	144.3	20,820	--	--	--	--	--	--	--	15.87	--	.4982	63.02	3.665	7
8	128.5	16,510	7.6	--	7.4	7.1	--	--	--	20.01	19.6	.6282	49.98	3.264	8
9	114.4	13,090	8.6	--	8.2	7.8	--	--	--	25.23	24.6	.7921	39.63	2.906	9
10	101.9	10,380	9.6	--	9.3	8.9	87.5	84.8	80.0	31.82	30.9	.9989	31.43	2.588	10
11	90.74	8,234	10.7	--	10.3	9.8	110	105	97.5	40.12	38.8	1.260	24.92	2.305	11
12	80.81	6,530	12.0	--	11.5	10.9	136	131	121	50.59	48.9	1.588	19.77	2.053	12
13	71.96	5,178	13.5	--	12.8	12.0	170	162	150	63.80	61.5	2.003	15.68	1.828	13
14	64.08	4,107	15.0	--	14.2	13.8	211	198	183	80.44	77.3	2.525	12.43	1.628	14
15	57.07	3,257	16.8	--	15.8	14.7	262	250	223	101.4	97.3	3.184	9.858	1.450	15
16	50.82	2,583	18.9	18.9	17.9	15.4	321	306	271	127.9	119	4.016	7.818	1.291	16
17	45.26	2,048	21.3	21.1	19.9	18.1	397	372	329	161.3	150	5.064	6.200	1.150	17
18	40.30	1,624	23.8	23.6	22.0	19.8	493	454	399	203.4	188	6.385	4.917	1.024	18
19	35.89	1,288	26.5	26.4	24.4	21.8	592	553	479	256.5	237	8.051	3.899	0.9116	19
20	31.96	1,022	29.7	29.4	27.0	23.6	775	725	625	323.4	298	10.15	3.092	.8118	20
21	28.46	810.1	33.1	32.7	29.8	26.0	940	895	754	407.8	370	12.80	2.452	.7230	21
22	25.35	642.4	37.0	36.5	34.1	30.0	1150	1070	910	514.2	461	16.14	1.945	.6438	22
23	22.57	509.5	41.3	40.6	37.6	31.6	1400	1300	1080	648.4	584	20.36	1.542	.5733	23
24	20.10	404.0	46.3	45.3	41.5	35.6	1700	1570	1260	817.7	745	25.67	1.223	.5106	24
25	17.90	320.4	51.7	50.4	45.8	38.6	2060	1910	1510	1031	903	32.37	0.9699	.4547	25
26	15.94	254.1	58.0	55.6	50.2	41.8	2500	2300	1750	1300	1118	40.81	.7692	.4049	26
27	14.20	201.5	64.9	61.5	55.0	45.0	3030	2780	2020	1639	1422	51.47	.6100	.3606	27
28	12.64	159.8	72.7	68.6	60.2	48.5	3670	3350	2310	2067	1749	64.90	.4837	.3211	28
29	11.26	126.7	81.6	74.8	65.4	51.8	4300	3900	2700	2607	2207	81.83	.3836	.2859	29
30	10.03	100.5	90.5	83.3	71.5	55.5	5040	4660	3020	3287	2534	103.2	.3042	.2546	30
31	8.928	79.70	101.	92.0	77.5	59.2	5920	5280	--	4145	2768	130.1	.2413	.2268	31
32	7.950	63.21	113.	101.	83.6	62.6	7060	6250	--	5227	3137	164.1	.1913	.2019	32
33	7.080	50.13	127.	110.	90.3	66.3	8120	7360	--	6591	4697	206.9	.1517	.1798	33
34	6.305	39.75	143.	120.	97.0	70.0	9600	8310	--	8310	6168	260.9	.1203	.1601	34
35	5.615	31.52	158.	132.	104.	73.5	10900	8700	--	10480	6737	329.0	.09542	.1426	35
36	5.000	25.00	175.	143.	111.	77.0	12200	10700	--	13210	7877	414.8	.07568	.1270	36
37	4.453	19.83	198.	154.	118.	80.3	--	--	--	16660	9309	523.1	.06001	.1131	37
38	3.965	15.72	224.	166.	126.	83.6	--	--	--	21010	10666	659.6	.04759	.1007	38
39	3.531	12.47	248.	181.	133.	86.6	--	--	--	26500	11907	831.8	.03774	.08969	39
40	3.145	9.89	282.	194.	140.	89.7	--	--	--	33410	14222	1049	.02993	.07987	40

POWER TRANSFORMERS

EXAMINATION

Slide rule calculations on this work are not only acceptable but are desirable to reduce time in computations, show all your work.

Design a power transformer to have the following characteristics: Rating, 1.5 KVA; primary line voltage 110; secondary terminal voltage 2500; frequency 60 cycles; use silicon transformer steel laminations .02" thick; core type.

Increase the core area 10 percent for insulation between laminations. For uniform results select 1000 amperes per square inch for current density, also use 600 for X. (The student can try other values for his own information but these are desirable for the problem being reasonably standard for most design purposes). The core volume should not include insulation for loss calculations.

Tabulate answers to the following questions on page two.

1. Total flux and value of C. (Check computations on these carefully).

2. Number of primary and secondary turns.

3. Core area and thickness including insulation.

4. Copper area and window area, also window dimensions.

5. Primary wire size, total wire length, length of each layer, number of layers, copper loss in primary, thickness of windings.

6. Secondary wire size, total wire length, length of each layer, number of layers, copper loss of secondary, thickness of windings.

7. Core volume, hysteresis loss, eddy current loss.

8. Total loss and transformer efficiency at full load.

9. Total loss and transformer efficiency at half load.

10. On separate sheet of paper draw a working set of diagrams full size or to scale, of the core and windings. Show all the essential dimensions for building the transformer from these drawings. See Fig. 7 for a start.

Tabulation of answers,

1.

2.

3.

4.

5.

6.

7.

8.

9.