Power Transformers—Designing and Rebuilding

● Under normal conditions there is little justification for the serviceman to utilize his time for winding or rebuilding power transformers, since complete transformers correctly designed by reliable manufacturers are available on open market for little more than the cost of the raw materials.

However under war conditions, transformers may be difficult or impossible to secure. Also, it is patriotic to conserve raw materials. The serviceman who understands the process of transformer designing can frequently effect a prompt repair on a damaged receiver, P.A. system, or other electronic device, whereas his competitor, lacking this knowledge, must either pass up the job or effect a delivery at a much later time.

Rebuilding Power Transformers

Transformer Failures—In general, reliable transformers are used in apparatus manufactured by recognized companies, and failure can usually be traced to causes other than faulty design.

The two most likely causes of transformer failure are:

1. Overload, usually caused by the failure of some associated component, such as a shorted rectifier tube, a defective filter condenser, etc., placing an abnormal load on one of the windings.
2. Moisture-absorption, causing either failure of insulation, or corrosion and opening of a winding.

In almost every case it is usually possible to salvage the primary and filament windings of the transformer so that the wire can be reused; although the salvage of the smaller gauge wire used in the high voltage secondary is more doubtful.

Space Factor—When endeavoring to rewind burned-out power transformers special attention should be given to space factor, since the home-built coil will generally have a greater physical size than the original equipment coil. If the original coil was a squeeze fit for the core window, it will be better to create a new transformer design, using a core of greater physical dimensions, than it would be to endeavor to duplicate the original which was probably wound with an automatic winding machine capable of producing a coil having little wasted space.

When salvaging wire from a defective or burned-out transformer it is an excellent idea to count the turns used on one winding, as this will indicate the number of turns per volt which can be employed for any subsequent winding which might be installed on the core. Thus if a transformer employs 22 turns on a 6.3 volt winding, a ratio of 3½ turns per volt may be used for any new windings it may be desired to install on this particular transformer core, provided that the frequency of the supply voltage remains the same.

Impregnation—After winding the coil, and anchoring the leads, the coil should be impregnated to make it impervious to moisture, so that corrosion or destructive electrolysis will not occur.

Before impregnation, the coil should be thoroughly heat-dried to drive out the moisture and to provide the maximum fluidity of the impregnant when the coil is dipped. The drying-out process can be accomplished by placing the coil in a common household oven heated to a temperature not exceeding 200 degrees F. for a sufficient length of time to permit the innermost parts of the coil to come up to oven temperature. Naturally, the larger the coil, the longer the heating time required.

Regular transformer varnishes are available, and in small quantities can usually be purchased from local motor repair shops. Some of these varnishes require baking for hardening, and details of the baking operation can be obtained from the supplier. Lacking these, a satisfactory job can be accomplished using ordinary clear varnish of good quality.

Audio transformer and choke coils are frequently impregnated with mixtures of beeswax and rosin, or beeswax, paraffine and rosin, since such mixtures do not get brittle when cold and possess a reasonable degree of fluidity when hot. However, wax impregnation is not ordinarily used for power transformer coils because the internally generated heat would cause softening.

Under no circumstances, attempt to use shellac as an impregnant. Shellac is a gum that is dissolved in alcohol, and almost always carries a percentage of water.

Transformer manufacturers employ vacuum impregnation, wherein the coils are submerged in the impregnant under a vacuum which releases any air trapped between the turns of the winding and which insures that the impregnant will reach the innermost portions of the coil.

However, for emergency, the following simple method has proven to be satisfactory. Immerse the coil vertically in a pail of varnish. Allow it to soak for a few minutes, then suspend it above the pail until the coil drains. Then repeat the process three or four times before hanging the coil up to dry.

In most cases it will be desirable to complete the winding of the coil before impregnating. If an attempt is made to impregnate the coil layer for layer as it is wound, it will be found that owing to the lubricating effect of the varnish, and turns will have an unpleasant tendency to slip off the ends of the coil.

In lieu of "spaghetti" or varnished cambric tubing, common shoe laces can be substituted for coil lead insulation, if the shoe lacings are coated with varnish and allowed to dry.

The shoe-lace substitution suggested in the preceding paragraph provides adequate insulation for low-voltage filament leads, and will serve as a mechanical protection for the finer wires of the primary and high voltage secondary. However, because of its coarse weave, no reliance should be placed on the shoe lacing as actual electrical insulation for the higher voltage wires.

How to Design Power Transformers

The information which follows will tell exactly how to proceed in designing small transformers. By making certain assumptions as outlined, the process becomes greatly simplified, and while it may be possible for a skilled transformer engineer to provide a somewhat more economical and compact design, the method presented will result in a satisfactorily performing transformer if the instructions are carefully followed.

The design of a reliable power transformer, having high efficiency, requires fairly elaborate calculations, and to take into account the d.c. which flows in a transformer secondary when a half-wave rectifier is used, some interesting equations have been derived.

A simple approximate-design method will be given, for the construction of single-phase low-powered transformers up to 180 volt-amp., or 180 watts for approximately unity power factors. This design is especially suited to transformers which supply a full-wave rectifier and filament energy to an a.c. powered radio receiver, three factors making it possible to secure a satisfactory transformer without complicated design methods, these factors being:

1. There is no urgent need for high efficiency. An 80 per cent efficient transformer which takes 60 watts to supply 48 output watts is fairly satisfactory, if it can radiate the heat which it generates.

2. These transformers are operated at a fairly constant load. This improves the maintenance of the various output voltages as each secondary winding will have a constant *IR* drop.

3. The load on the transformer secondary is nearly of unity power factor. The filament power load is essentially a resistance load, with unity power factor. The current supplied to the filter has slightly less than unity power factor, but this can be disregarded in low-powered transformers. The indirect heated receiving tubes, such as the 227 requires less than half as much d.c. power in their plate and grid circuits, as that which is needed to heat their cathodes. This would mean a unity power-factor heater supply and (assuming a series voltage divider) less than half as many additional watts for plate and grid supply, at a lower power factor. It is true that a power tube, such as 250 at its maximum rating, uses slightly over three times the wattage in its $B + C$ circuit than in its filament. It is rare, however, to have more than two power tubes in a receiver, and the assumption that the power factor of the secondary is unity is usually not over 20

per cent off. This means that the wire of the high-voltage secondary and of the primary should be increased to allow for this added current.

Small Transformer Details—Economy in a transformer is secured when the winding encloses a maximum of core area with a minimum of wire, and the magnetic path should be as short as possible.

The core form of a small transformer can be of several shapes, but it is usual to use standard punchings shaped like capital letter E's. As a rule, two punchings are used, one having longer legs than the other so that the magnetic circuit "breaks joints" in stacking the iron. Another convention usually followed in small transformers is the use of a single-winding form, all secondaries and primary being on the middle leg of the E core.

The spool form is usually an insulating tube, and side pieces may be fitted on which terminals are placed, or, if the coil is to be machine wound with interwoven cotton, the side pieces can be omitted, and flexible leads provided.

Ten Steps in Designing a Small Power Transformer—1. *Determine the Volts and Amperes Needed for Each Secondary.*

a. Find the total maximum secondary watts $= W_s = E_1I_1 + E_2I_2 + \cdots$ (where $E \times I$ refers to the wattage in each secondary winding)

b. Find the total watts needed for primary (W_p)
Assuming 90 per cent efficiency $W_p = W_s/0.9$. Where W_s = Secondary watts.

c. Find primary amperes assuming 90 per cent power factor

$$I_p = \frac{W_p}{E_p \times 0.9} = \frac{W_s}{0.81E_p}$$

where $E_p = 110$ volts, $I_p = W_s/89.1$ amp,

2. *Size of Wire.* Knowing the current for each winding, the wire size is determined by the circular mils per ampere which it is desired to use. A safe rule is to use 1,000 cir. mils per ampere for transformers under 50 watts, and 1,500 cir. mils per ampere for higher powers—however, most commercial designs use 800 cir. mils per ampere.

3. *Core Considerations.* A curve showing core areas for different powers is Figure "A" which shows the area for 40 watts to be 1 sq. in., 70 watts, 1.5 sq. in., 120 watts, 2 sq. in. The area of the core is the same as the inside dimensions of the spool, making a 10 per cent allowance for stacking; for example, a spool 1 by 2 in. inside would enclose 2 sq. in., but, allowing for a 10 per cent loss, only 90 per cent or $0.9 \times 2 = 1.8$ sq. in. is the net core area. The core area is needed to determine the turns per volt.

4. *Core-Loss and Induction.* The flux density at which the core is to be worked determines the iron (core) loss. Figure "B" gives several curves of different core materials, watts per pound being plotted against flux densities in kilolines per square inch. Sixty-five kilolines per square inch is an average value of the induction. The making of a curve such as Figure "B" depends largely on experimental data, not directly on a theoretical basis. For this reason, no definite value of the core loss can be given; it depends on the quality of core material which is available. Standard core material generally has a power loss of .86 watts per pound. It should be noted that better and better core material is constantly being made, having lower loss per pound, so that the use of higher flux densities is becoming possible. Up to 85 kilolines is not uncommon, but unusual for this application. The core loss increases with frequency, a typical curve being Figure "C."

5. *Induced-voltage Equation, Turns per Volt.* The elementary definition, that 10^8 magnetic lines cut, per second, will induce one volt pressure, is the basis of the equation

$$E = \frac{BANf}{10^8} \times 4.44$$

where E is the voltage, A the area of the core, B the flux density in the same units as A, f the cycles per second, and N the number of turns. A more useful working equation for small power transformers is obtained by solving for N/E in turns per volt:

$$\frac{N}{E} = \frac{10^8}{BAf4.44}$$

Figure "D" is an alignment chart of this equation. The left column is B the flux density, in both kilolines per square inch and kilogausses (kilolines per square centimeter the center column is the net core area in both square inches and square centimeters, the right column giving the turns per volt for both 25 and 60 cycles per second.

Using a flux density of 65 kilolines per square inch and the net core area mentioned in step 3 (1.8 sq. in.), the turns per volt for 60 cycles are found to be 3.1 turns per volt. Thus for each volt on the transformer, there must be 3.1 turns. It is customary to change the turns per volt to an even number so that the proper center taps can be made. In this case, by using 4 turns per volt, with the same core area, the induction will be lower, with a corresponding lower core loss. It is also quite possible, and sometimes advisable, to change the core area so that an even number of turns per volt is given. For example, by increasing the core area to 2.8 sq. in. 2 turns per volt could be used, or decreased to 1.4 sq. in. so that 4 turns per volt would be used. The reason for desiring the even numbers of turns per volt is to

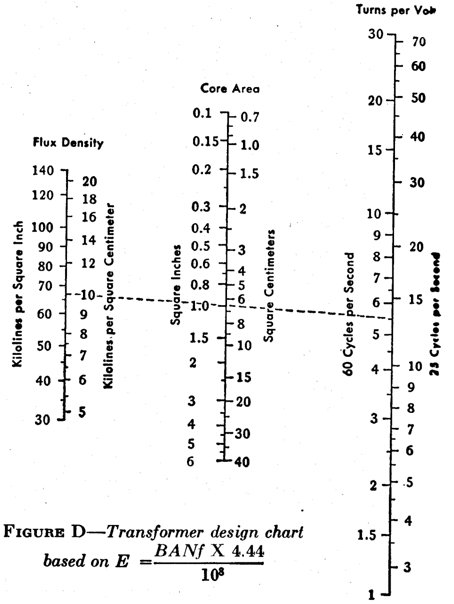

Figure D—*Transformer design chart based on* $E = \frac{BANf \times 4.44}{10^8}$

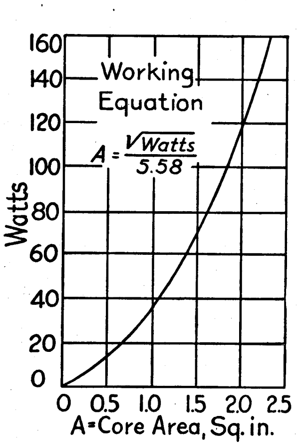

Figure A—*Small power transformer core area as a function of watts.*

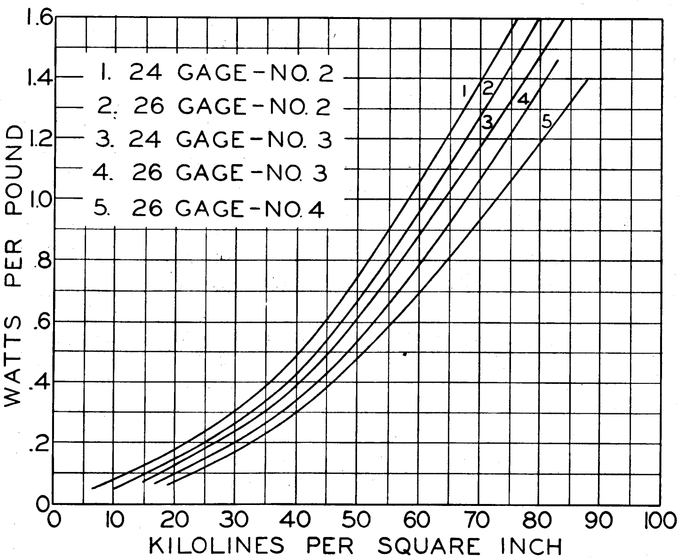

Figure B—*Core-loss curves Armco Radio grades (60 cycles).*

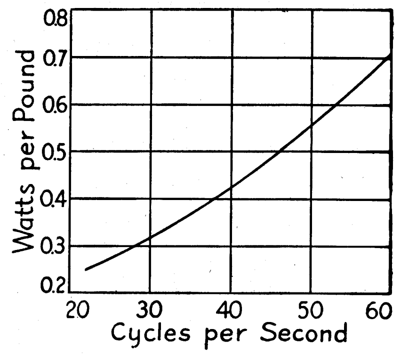

Figure C—*Core-loss* vs. *frequency* $B = 10{,}000$.

supply the 1/2-volt steps for receiving tubes, such as 7 1/2 volts, which would require an integral number of turns when the turns per volt are used.

The voltage drop in the transformer winding should be mentioned here. For instance, the load voltage at a tube filament is lower than the no-load voltage by the amount of *IR* drop in the winding and the connecting wires to the tube. Thus, it may be that to secure 7 1/2 volts at the tube filament, the transformer no-load voltage will have to be 8. In this case, any integral number of turns per volt, either odd or even, will suit the design.

6. *Turns for Each Winding.* In step 1 the desired voltages were given, E_1, E_2, etc. Using the value of turns per volt in step 5, the total turns for each winding are found. For example, with 4 turns per volt, a 110-volt winding should have 4 × 110 = 440 turns.

7. *Winding Space Required.* From the total turns for each winding, and the wire size, the total area of winding space is calculated. Different wires and insulations have definite turns per square inch. The method of insulation, however, may have these values vary by factors of as much as three to one. That is, a 900-turn coil wound in layers with enamel wire may take up one square inch of cross-section area. By interleaving thin insulating paper between layers, only 600 turns can be wound in a square-inch area; and by using a certain size of cotton interwoven between turns, only 400 turns can be wound in a square inch. Thus, the space of winding depends to a large degree on the kind and thickness of insulation. Double cotton-covered wire takes up considerably more space than enameled wire. Yet, if the extra-needed insulating space for the interlayer protection is considered, the space ratio may not be so great.

After adding up the winding space of all the windings the area should be compared with that of the core. If the winding will go in the core space, this part of the design is finished.

If the wires will not go in the available space, the winding may be redesigned, or the core area increased. Using thinner coverings for wire, fewer secondaries or fewer circular mils per ampere will decrease the space needed for the wire. A larger iron size or a thicker stack of the same sized iron will increase the core area and allow a smaller number of turns per volt, thus decreasing the cross section of the winding.

8. *Copper Loss.*

a. Find the length of the mean (average) turns in feet.

b. Find the length of each winding in feet by multiplying the number of turns by the mean turn length.

c. From the following wire table find the ohms per 1,000 feet for the size wire used, and then from 8-*b* the actual ohms for this length.

d. Multiply the current squared for each winding by the ohms for that winding.

e. Add the I^2R's for each winding to get the copper loss L_1.

9. *Core Loss.* The core loss in watts L_2 is found from the weight of the core and flux density and kind of core used in step 4. A useful factor is that 4 per cent silicon steel weighs 0.27 lb. per cubic inch.

10. *The approximate percentage efficiency is*

$$\frac{W_s \times 100}{W_s + L_1 + L_2},$$

W_s being the secondary watts (see step 1).

NOTE: If step 10 shows about 90 percent efficiency, the design is complete. If much less than 90 percent, step 1*a* must be modified, a new, larger value of *Ip* being used in finding a larger primary wire. This will not change the efficiency, but will prevent overloading the primary winding due to its carrying a greater current than that for which it was designed. It is desirable, as a rule, to keep the efficiency above 90 percent, and this can be done by reducing L_1 and L_2, by using larger wires, or larger cores.

Copper Wire Table

Gauge No. B. & S.	Diam. in Mils[1]	Circular Mil Area	Turns per Linear Inch[2]				Turns per Square Inch[2]			Feet per Lb.		Ohms per 1000 ft. 25° C.	Correct Capacity at 1500 C.M. per Amp.[3]	Diam. in mm.
			Enamel	S.S.C.	D.S.C. or S.C.C.	D.C.C.	S.C.C.	Enamel	D.C.C.	Bare	D.C.C.			
1	289.3	82690	—	—	—	—	—	—	—	3.947	—	.1264	55.7	7.348
2	257.6	66370	—	—	—	—	—	—	—	4.977	—	.1593	44.1	6.544
3	229.4	52640	—	—	—	—	—	—	—	6.276	—	.2009	35.0	5.827
4	204.3	41740	—	—	—	—	—	—	—	7.914	—	.2533	27.7	5.189
5	181.9	33100	—	—	—	—	—	—	—	9.980	—	.3195	22.0	4.621
6	162.0	26250	—	—	—	—	—	—	—	12.58	—	.4028	17.5	4.115
7	144.3	20820	—	—	—	—	—	—	—	15.87	—	.5080	13.8	3.665
8	128.5	16510	7.6	—	7.4	7.1	—	—	—	20.01	19.6	.6405	11.0	3.264
9	114.4	13090	8.6	—	8.2	7.8	—	—	—	25.23	24.6	.8077	8.7	2.906
10	101.9	10380	9.6	—	9.3	8.9	87.5	84.8	80.0	31.82	30.9	1.018	6.9	2.588
11	90.74	8234	10.7	—	10.3	9.8	110	105	97.5	40.12	38.8	1.284	5.5	2.305
12	80.81	6530	12.0	—	11.5	10.9	136	131	121	50.59	48.9	1.619	4.4	2.053
13	71.96	5178	13.5	—	12.8	12.0	170	162	150	63.80	61.5	2.042	3.5	1.828
14	64.08	4107	15.0	—	14.2	13.8	211	198	183	80.44	77.3	2.575	2.7	1.628
15	57.07	3257	16.8	—	15.8	14.7	262	250	223	101.4	97.3	3.247	2.2	1.450
16	50.82	2583	18.9	18.9	17.9	16.4	321	306	271	127.9	119	4.094	1.7	1.291
17	45.26	2048	21.2	21.2	19.9	18.1	397	372	329	161.3	150	5.163	1.3	1.150
18	40.30	1624	23.6	23.6	22.0	19.8	493	454	399	203.4	188	6.510	1.1	1.024
19	35.89	1288	26.4	26.4	24.4	21.8	592	553	479	256.5	237	8.210	.86	.9116
20	31.96	1022	29.4	29.4	27.0	23.8	775	725	625	323.4	298	10.35	.68	.8118
21	28.46	810.1	33.1	32.7	29.8	26.0	940	895	754	407.8	370	13.05	.54	.7230
22	25.35	642.4	37.0	36.5	34.1	30.0	1150	1070	910	514.2	461	16.46	.43	.6438
23	22.57	509.5	41.3	40.6	37.6	31.6	1400	1300	1080	648.4	584	20.76	.34	.5733
24	20.10	404.0	46.3	45.3	41.5	35.6	1700	1570	1260	817.7	745	26.17	.27	.5106
25	17.90	320.4	51.7	50.4	45.6	38.6	2060	1910	1510	1031	903	33.00	.21	.4547
26	15.94	254.1	58.0	55.6	50.2	41.8	2500	2300	1750	1300	1118	41.62	.17	.4049
27	14.20	201.5	64.9	61.5	55.0	45.0	3030	2780	2020	1639	1422	52.48	.13	.3606
28	12.64	159.8	72.7	68.6	60.2	48.5	3670	3350	2310	2067	1759	66.17	.11	.3211
29	11.26	126.7	81.6	74.8	65.4	51.8	4300	3900	2700	2607	2207	83.44	.084	.2859
30	10.03	100.5	90.5	83.3	71.5	55.5	5040	4660	3020	3287	2534	105.2	.067	.2546
31	8.928	79.70	101.	92.0	77.5	59.2	5920	5280	—	4145	2768	132.7	.053	.2268
32	7.950	63.21	113.	101.	83.6	62.6	7060	6250	—	5227	3137	167.3	.042	.2019
33	7.080	50.13	127.	110.	90.3	66.3	8120	7360	—	6591	4697	211.0	.033	.1798
34	6.305	39.75	143.	120.	97.0	70.0	9600	8310	—	8310	6168	266.0	.026	.1601
35	5.615	31.52	158.	132.	104.	73.5	10900	8700	—	10480	6737	335.0	.021	.1426
36	5.000	25.00	175.	143.	111.	77.0	12200	10700	—	13210	7877	423.0	.017	.1270
37	4.453	19.83	198.	154.	118.	80.3	—	—	—	16660	9309	533.4	.013	.1131
38	3.965	15.72	224.	166.	126.	83.6	—	—	—	21010	10666	672.6	.010	.1007
39	3.531	12.47	248.	181.	133.	86.6	—	—	—	26500	11907	848.1	.008	.0897
40	3.145	9.88	282.	194.	140.	89.7	—	—	—	33410	14222	1069	.006	.0799

[1] A mil is 1/1000 (one thousandth) of an inch.

[2] The figures given are approximate only, since the thickness of the insulation varies with different manufacturers.

[3] The current-carrying capacity at 1000 C.M. per ampere is equal to the circular-mil area (Column 3) divided by 1000.