Chapter 4

Window Utilization, Magnet Wire, and Insulation

Table of Contents

Window Utilization Factor, K_u

The window utilization factor is the amount of copper that appears in the window area of the transformer or inductor. The window utilization factor is influenced by five main factors:

1. Wire insulation, S_1.
2. Wire lay fill factor, layer or random wound, S_2.
3. Effective window area (or when using a toroid, the clearance hole for passage of the shuttle), S_3.
4. Insulation required for multiplayer windings, or between windings, S_4.
5. Workmanship, (quality).

These factors, multiplied together, will give a normalized window utilization of $K_u = 0.4$, as shown in Figure 4-1.

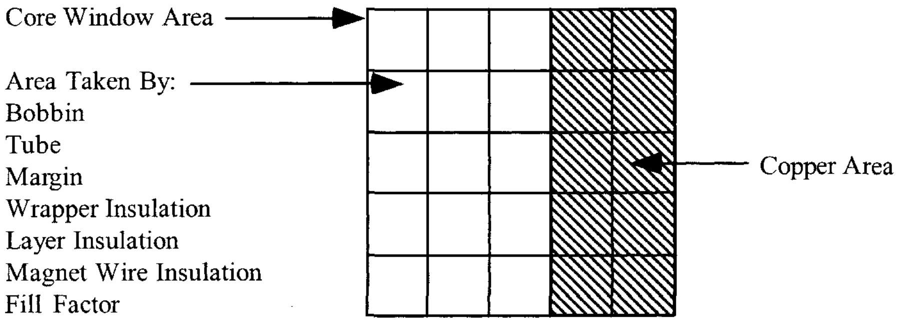


Figure 4-1. Window Area Occupied by Copper.

The window utilization factor, K_u, of the available core window is that space occupied by the winding (copper), and is calculated from areas S_1, S_2, S_3, and S_4:

$$K_u = S_1 S_2 S_3 S_4 \quad [4\text{-}1]$$

Where:

S_1 = conductor area/wire area

S_2 = wound area/usable window area

S_3 = usable window area/window area

S_4 = usable window area/usable window area + insulation

In which:

Conductor area, $A_{w(B)}$ = copper area.

Wire area, A_w = copper area + insulation area.

Wound area = number of turns x wire area of one turn.

Usable window area = available window area - residual area, that results from the particular winding technique used.

Window area = available window area.

Insulation area = area used for winding insulation.

S_1, Wire Insulation

In the design of high-current or low-current transformers, the ratio of the conductor area to the total wire area can vary from 0.941 to 0.673, depending on the wire size. In Figure 4-2, the thickness of the insulation has been exaggerated to show how the insulation impacts the overall area of the wire.

It can be seen, in Figure 4-2, that, by using multi-strands of fine wire to reduce the skin effect, it will have a significant impact on the window utilization factor, K_u. S_1 is not only dependent upon wire size, but it is also dependent upon insulation coating. Table 4-1 shows the ratio of bare magnet wire to the magnet wire with insulation for single, heavy, triple, and quad insulation. When designing low-current transformers, it is advisable to re-evaluate S_1 because of the increased amount of insulating material.

$$S_1 = \frac{A_{w(B)}}{A_w} \quad [4\text{-}2]$$

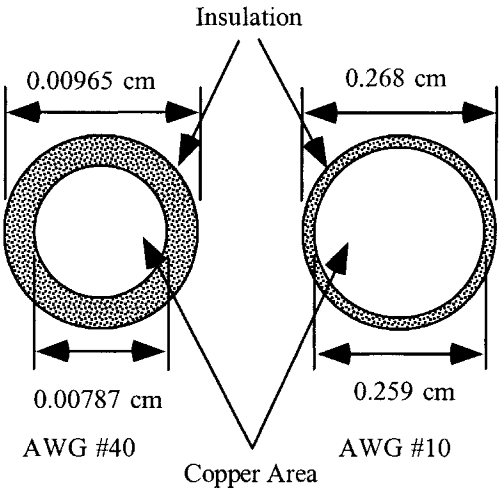


Figure 4-2. Comparing Insulation with Different Wire Gauges.

Table 4-1

Magnetic Wire Data (Nominal)					
Size AWG	Bare Area (cm^2)	Ratio Bare/Single	Ratio Bare/Heavy	Ratio Bare/Triple	Ratio Bare/Quad
10	0.1019	0.961	0.930	0.910	0.880
15	0.0571	0.939	0.899	0.867	0.826
20	0.0320	0.917	0.855	0.812	0.756
25	0.0179	0.878	0.793	0.733	0.662
30	0.0100	0.842	0.743	0.661	0.574
35	0.0056	0.815	0.698	0.588	0.502
40	0.0031	0.784	0.665	0.544	0.474

S_2, Fill Factor

S_2 is the fill factor, or the wire lay, for the usable window area. When winding a large number of turns tightly on a smooth surface, the winding length exceeds the calculated value from the wire diameter by 10 to 15%, depending on the wire gauge. See Figure 4-3. The wire lay is subjected to wire tension, and wire quality, such as continuous wire diameter and the winding technique depending on the skill of the operator. The wire lay factor relationship for various wire sizes for layer wound coils is shown in Table 4-2, and for random wound coils in Table 4-3. The Tables list the outside diameter for heavy film magnetic wire, 10 – 44 AWG.

Table 4-2

Wire Lay Factor For Layer Wound Coils			
AWG	Insulated Wire OD (inch)	Insulated Wire OD (cm)	Wire Lay Factor
10 to 25	0.1051 - 0.0199	0.2670 - 0.0505	0.90
26 to 30	0.0178 - 0.0116	0.0452 - 0.0294	0.89
31 to 35	0.0105 - 0.0067	0.0267 - 0.0170	0.88
36 to 38	0.0060 - 0.0049	0.0152 - 0.0124	0.87
39 to 40	0.0043 - 0.0038	0.0109 - 0.0096	0.86
41 to 44	0.0034 - 0.0025	0.00863 - 0.00635	0.85
Heavy film magnetic wire.			

Table 4-3

Wire Lay Factor For Random Wound Coils			
AWG	Insulated Wire OD (inch)	Insulated Wire OD (cm)	Wire Lay Factor
10 to 22	0.1051 - 0.0276	0.267 - 0.0701	0.90
23 to 39	0.0623 - 0.0109	0.0249 - 0.0043	0.85
40 to 44	0.0038 - 0.0025	0.0096 - 0.00635	0.75
Heavy film magnet wire.			

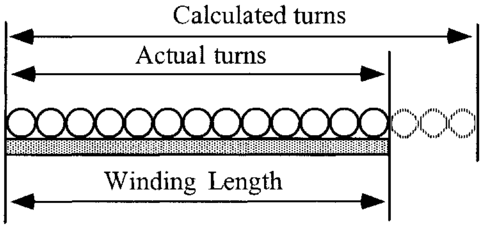


Figure 4-3. Capable Turns per Unit Length.

There are two ideal winding arrangements shown in Figure 4-4 and Figure 4-5. The square winding is shown in Figure 4-4 and the hexagonal winding is shown in Figure 4-5. The simplest form of winding is done by a coil being wound, turn-by-turn and layer-upon-layer, as shown in Figure 4-4. The square winding pattern has a theoretical fill factor of 0.785.

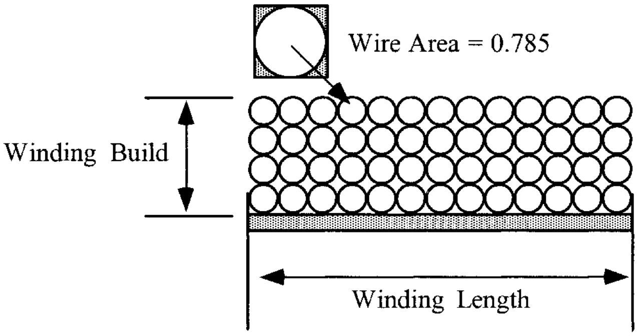


Figure 4-4. Theoretically, the Square Winding Pattern Fill Factor 0.785.

A seemingly, better fill factor can be achieved by using the hexagonal winding in Figure 4-5, compared to the square winding in Figure 4-4. In this type of winding, the individual wires do not lie exactly above each other, as in the square winding pattern. Instead, the wires lie in the grooves of the lower layer, as shown in Figure 4-5. This style of winding produces the tightest possible packing of the wire. The hexagonal style of winding will yield a theoretical fill factor of 0.907.

The fill factor, using the square winding pattern of 0.785, would be nearly impossible to achieve by hand winding without some layer insulation. Any layer insulation will reduce the fill factor even further. The fill factor, using the hexagonal winding pattern of 0.907, is just as hard to get. Hand winding, using the hexagonal technique, will result in the following: The first layer goes down with almost complete order. In the second layer, some disordering has occurred. With the third and fourth layer, disordering really sets in and the winding goes completely awry. This type of winding performs well with a small number of turns, but, with a large number of turns, it becomes randomly wound.

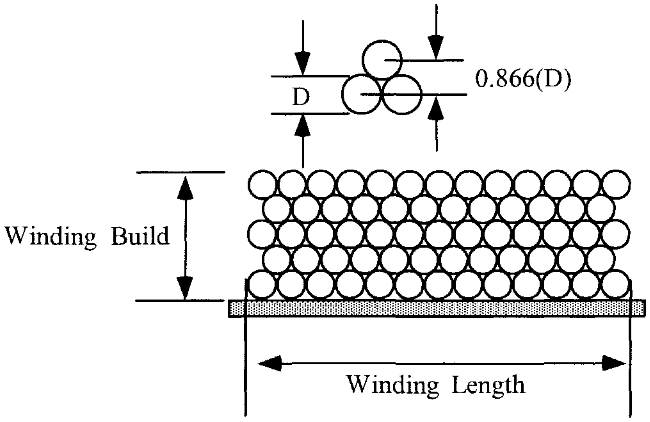


Figure 4-5. Theoretically, the Hexagonal Winding Pattern Fill Factor 0.907.

The ideal winding on a rectangular bobbin is shown in Figure 4-6. Then, when winding rectangular bobbins or tubes, the actual winding height in the region covered by the core will be greater than the calculated winding height or build due to the bowing of the windings. See Figure 4-7. The amount of bowing depends on the proportions of the winding and the height of the winding. Usually, the available winding build should be reduced by 15 to 20%, or 0.85x the winding build. When winding on a round bobbin or tube, this bowing effect is negligible.

The conclusion is, in comparing the square winding pattern used in the layer wound coil with its insulation with the hexagonal winding pattern and its awry winding pattern, both seem to have a fill factor of about 0.61. But there is always the hundred to one exception, such as, when a design happens to have the right bobbin, the right number of turns, and the right wire size. This normally only happens when the design is not critical.

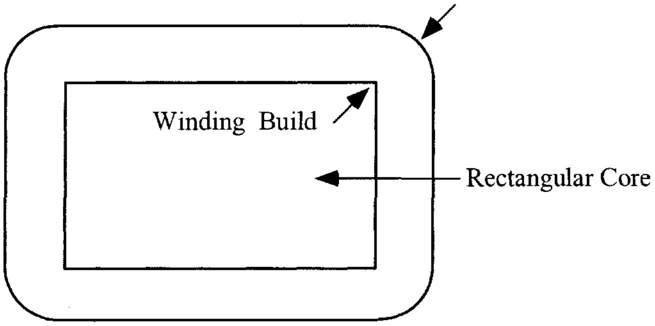


Figure 4-6. Ideal Winding on a Rectangular Bobbin.

To minimize this bowing effect and to insure a minimum build for either random or layer winding, the round bobbin, shown in Figure 4-8, will provide the most compact design. It can be seen, in Figure 4-8, that the round bobbin provides a uniform tension, all 360 degrees around the bobbin, for both layer and random windings. The other benefit, in using a round bobbin, is the reduction and minimizing of the leakage inductance caused from the bowing.

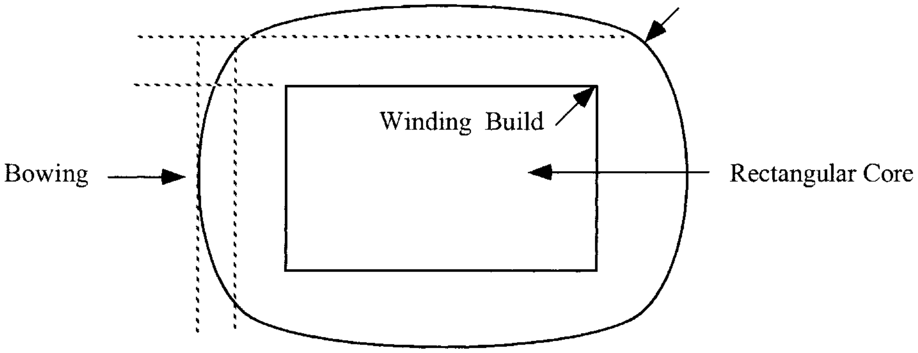


Figure 4-7. Bowing in Transformer Windings.

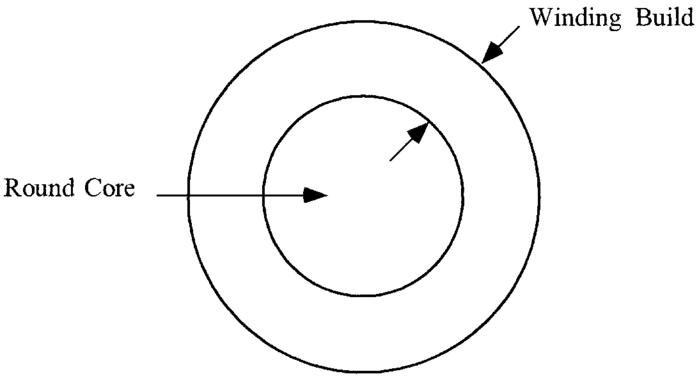


Figure 4-8. A Round Bobbin Insures Minimum Bowing.

S_3, Effective Window

The effective window, S_3, defines how much of the available window space may actually be used for the winding. The winding area available to the designer depends on the bobbin or tube configuration. Designing a layer winding that uses a tube will require a margin, as shown in Figure 4-9. The margin dimensions will vary with wire size. See Table 4-4. It can be seen, in Figure 4-9 and Table 4-4, how the margin reduces the effective window area. When transformers are constructed, using the layer winding technique, there is an industry standard for layer insulation thickness. This thickness is based on the diameter of the wire, as shown in Table 4-5.

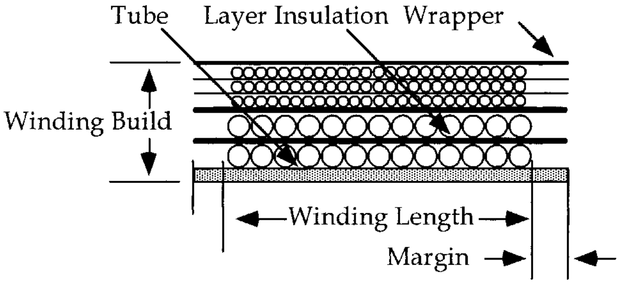


Figure 4-9. Transformer Windings with Margins.

Table 4-4

Winding Margins Versus AWG		
	Margin	
AWG	cm	inch
10-15	0.635	0.25
16-18	0.475	0.187
19-21	0.396	0.156
22-31	0.318	0.125
32-37	0.236	0.093
38-up	0.157	0.062

Table 4-5

Layer Insulation Thickness		
	Insulation Thickness	
AWG	cm	inch
10 - 16	0.02540	0.01000
17 - 19	0.01780	0.00700
20 - 21	0.01270	0.00500
22 - 23	0.00760	0.00300
24 - 27	0.00510	0.00200
28 - 33	0.00381	0.00150
34 - 41	0.00254	0.00100
42 - 46	0.00127	0.00050

A single bobbin design, as shown in Figure 4-10, offers an effective area, W_a, between 0.835 to 0.929 for laminations, and 0.55 to 0.75 for ferrites; a two bobbin configuration, as shown in Figure 4-11, offers an effective area, W_a, between 0.687 to 0.873 for the tape C cores.

The toroid is a little different. The term, S_3, defines how much of the available window space can actually be used for the winding. In order to wind the toroidal core, there has to be room to allow free passage of the shuttle. If half of the inside diameter is set aside for the shuttle, then, there will be 75% of the window area, (W_a), left for the design which is a good value for the effective window area factor, $S_3 = 0.75$, as shown in Figure 4-12. The toroid would fall into all of the above categories.

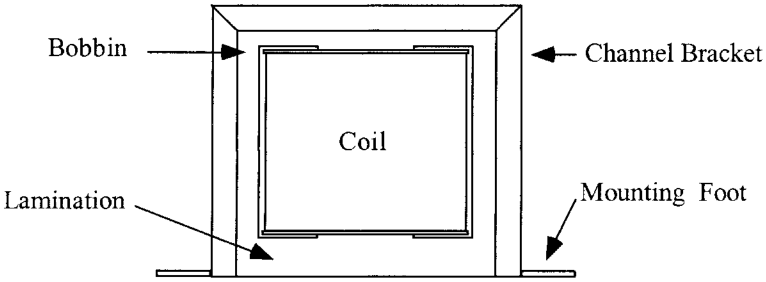


Figure 4-10. Transformer Construction with Single Bobbin.

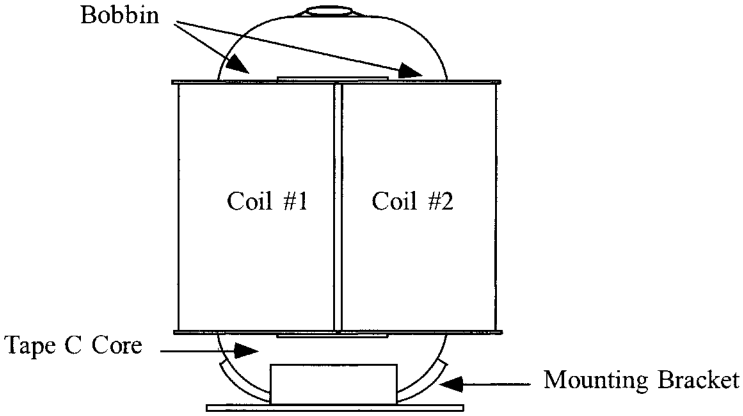
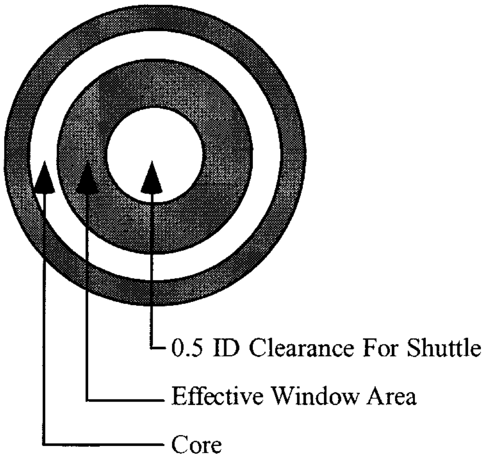


Figure 4-11. Transformer Construction with Dual Bobbins.



Effective Window area $W_{a(eff)} = (0.75)(\pi)(ID)^2/4$

Figure 4-12. Effective Winding Area of a Toroidal Core.

S_4, Insulation Factor

The insulation factor, S_4, defines how much of the usable window space is actually being used for insulation. If the transformer has multiple secondaries with significant amounts of insulation, S_4 should be reduced by 5 to 10% for each additional secondary winding, partly because of the added space occupied by insulation and partly because of the poorer space factor.

The insulation factor, S_4, is not taken into account in Figure 4-12. The insulation factor, S_4, is to be 1.0. The window utilization factor, K_u, is highly influenced by insulation factor, S_4, because of the rapid buildup of insulation in the toroid, as shown in Figure 4-13.

In Figure 4-13, it can be seen that the insulation buildup is greater on the inside, than on the outside. For example, in Figure 4-13, if 1.27 cm (1/2") wide tape was used with an overlap of 0.32 cm (1/8") on the outside diameter, the overlap thickness would be four times the thickness of the tape. It should be noted that the amount of overlap depends greatly on the size of the toroid and the required tape. In the design of toroidal components, and using the 0.5 ID remaining for passage of the shuttle, there is normally enough room for the wrapper.

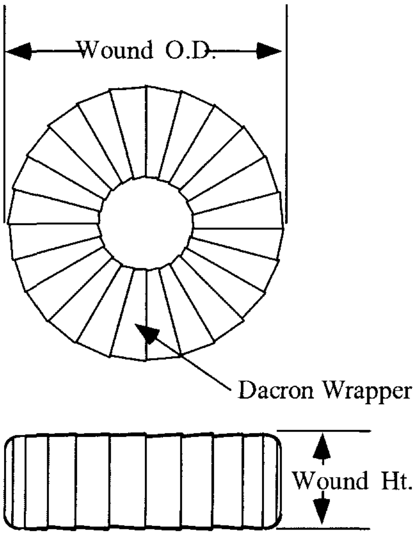


Figure 4-13. Wrapped Toroid.

Summary

The author hopes to have cleared up some of the mystery of how the window utilization factor, K_u, was derived and that the magic of 0.4 is now clear. All the different parts making up window utilization, have been explained, hopefully eliminating confusion and simplifying the complexity of the subject.

As stated at the beginning of this chapter, a good approximation for the window utilization factor is $K_u = 0.4$.

S_1 = conductor area/wire area = 0.855, #20 AWG

S_2 = wound area/usable window area = 0.61

S_3 = usable window area/window area = 0.75

S_4 = usable window area/usable window area + insulation = 1

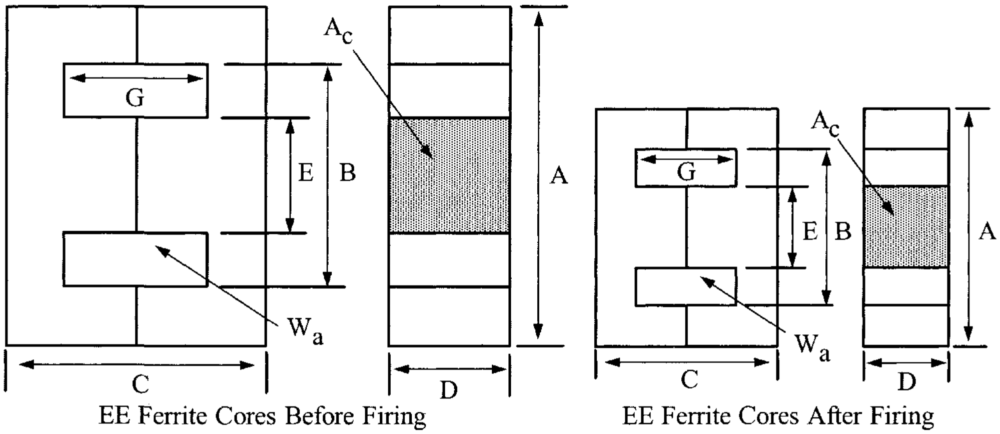
$$K_u = S_1 S_2 S_3 S_4$$
$$K_u = (0.855)(0.61)(0.75)(1.0) = 0.391 \approx 0.4 \qquad [4\text{-}3]$$

Being a very conservative number, it can be used in most designs. It is an important factor in all designs of magnetic components.

Window Utilization Factor, K_u for Bobbin Ferrites

In high frequency power electronics, the majority of the designs will use some kind of bobbin ferrite. The main reasons for using ferrites is its high frequency performance and cost. The window utilization factor, K_u, for bobbin ferrites is not as high as it is for iron alloy materials, such as laminations and C cores. Design engineers, who have been using bobbin ferrite materials, know the drawback in the window utilization factor, K_u. Once this problem is understood, then, the problem should go away.

Ferrite materials are fired in kilns like ceramic pottery. There is a certain amount of shrinkage after firing, and the amount varies from one manufacturer's process to another. The amount of shrinkage could vary as much as 15 to 30%, as shown in Figure 4-14. The ferrite manufacturers try to keep a tight control on the amount of shrinkage, because these cores must meet a dimensional tolerance after firing. Even though the shrinkage is under tight control, the tolerances on the end product are much larger than the iron alloy, stamped laminations. The end result is the bobbin has to slip on and meet all of the minimum and maximum dimensional tolerances.



EE Ferrite Cores Before Firing   EE Ferrite Cores After Firing

Figure 4-14. Ferrite EE Core Before and After Firing.

This dimensional tolerance has an impact on the winding area of the bobbin, clearly shown in Table 4-6. This smaller winding area reduces the power handling capability of the core. Operating at high frequency will also reduce the power handling capability of the core because of the skin effect. The skin effect requires the use of multistrands of fine wire in place of a large single strand. The selection of the correct wire size to minimize the skin effect at given frequency is shown in Equations [4-5] through [4-9]. Also shown is an example of the largest wire size that should be used when operating at 100kHz. Reevaluate the, K_u, Equation [4-3] so that it can operate at 100kHz, using a #26 wire, and using a cut ferrite core.

S_1 = conductor area/wire area = 0.79, #26 AWG

S_2 = wound area/usable window area = 0.61

S_3 = usable window area/window area = 0.6

S_4 = usable window area/usable window area + insulation = 1

$$K_u = S_1 S_2 S_3 S_4$$
$$K_u = (0.79)(0.61)(0.6)(1.0) = 0.289 \quad [4\text{-}4]$$

Table 4-6. Effective Window Area.

Effective Window Area			
Core	Window cm^2	Bobbin cm^2	Ratio B/W
RM-6	0.260	0.150	0.577
RM-8	0.456	0.303	0.664
RM-12	1.103	0.730	0.662
PQ-20/16	0.474	0.256	0.540
PQ-26/25	0.845	0.502	0.594
PQ-35/35	2.206	1.590	0.721
EFD-10	0.116	0.042	0.362
EFD-15	0.314	0.148	0.471
EFD-25	0.679	0.402	0.592
EC-35	1.571	0.971	0.618
EC-41	2.082	1.375	0.660
EC-70	6.177	4.650	0.753
Laminations			
EI-187	0.529	0.368	0.696
EI-375	1.512	1.170	0.774
EI-21	1.638	1.240	0.757

Circular mil and Square mil

There are engineers that use circular mils (CM)/amp or square mils/amp. This is the reciprocal current density. The norm is to use amps/cm^2, which is a true current density. There have been some requests to define circular mils and square mils. First, let's define a mil, which is .001 inch. Figure 4-15 shows the area of a square mil, and the area of a circular mil.

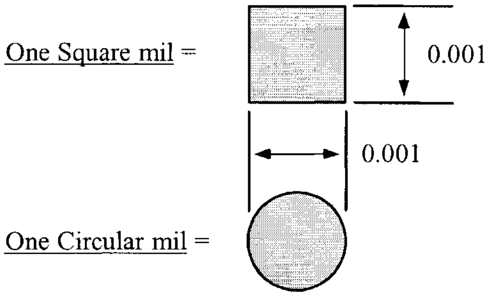


Figure 4-15. Comparing Circular-Mils and Square-Mils.

To convert Square mils to Circular mils , multiply by 1.2732.

To convert Circular mils to Square mils , multiply by 0.7854.

To convert Circular mils to Square centimeters , multiply by $5.066 \text{x} 10^{-6}$.

To convert Square mils to Square centimeters , multiply by $6.45 \text{x} 10^{-6}$

Note:

Designers have for many years used this rule of thumb:

$$500\text{CM/Amp} \approx 400\text{Amps/cm}^2$$
$$1000\text{CM/Amp} \approx 200\text{Amps/cm}^2$$

Magnet Wire

Standard magnet wire is available in three different materials, shown in Table 4-7. The most common is copper, but aluminum and silver are available. Aluminum magnet wire is one-third the weight of copper for the same size conductor and one-half the weight for the same conductivity. Aluminum magnet wire is a little more difficult to terminate, but it can be done. Silver magnet wire has the highest conductivity, easy to solder to, and weighs 20% more than copper.

Table 4-7

Magnet Wire Material Properties

Material	Symbol	Density grams/cm^3	Resistivity μΩ/cm	Weight Factor	Resistance Factor	Temperature Coefficient
Copper	Cu	8.89	1.72	1	1	0.00393
Silver	Ag	10.49	1.59	1.18	0.95	0.00380
Aluminum	Al	2.703	2.83	0.3	1.64	0.00410

Magnet Wire, Film Insulation

It is the design engineer's responsibility to ensure that the selected magnet wire used in the design is compatible with the environmental and design specification. The environmental specification will set the ambient temperature. The maximum operating temperature of the magnet wire is obtained by summing the maximum ambient temperature, plus the temperature rise of the magnetic component. After the maximum temperature has been obtained, see Table 4-8 for the Temperature Class. The magnet wire insulation guide listing in Table 4-7, is only a partial list from NEMA, Standard MW 1000.

The maximum operating temperature is the "Achilles Heel" to the magnet wire. Standard magnet wire is rated by temperature. The range is from 105°C to 220°C, as shown in Table 4-8. The insulation film of the magnet wire is on the surface of the copper wire. This insulation film is the most vulnerable to thermal overloads, so the selection of the insulation film is very critical for long life. When magnet wire is subjected to thermal overloads, or a high ambient temperature above its rated temperature, the life of the magnet wire is greatly reduced, as shown in Figures 4-16 and 4-17. The engineer must be very careful of hot spots so as not to degrade the service life of the magnetic component.

Table 4-8

Magnet Wire Insulation Guide

Temperature Class	Insulation Type	Dielectric Constant	NEMA Standard MW 1000
105°C	Polyurethane*	6.20	MW-2-C
105°C	Formvar	3.71	MW-15-C
130°C	Polyurethane-Nylon*	6.20	MW-28-C
155°C	Polyurethane-155	6.20	MW-79-C
180°C	Polyester Solderable*	3.95	MW-77-C
200°C	Polyester-amid-imide	4.55	MW-35-C
220°C	Polyimide (ML)	3.90	MW-16-C

*Solderable insulations.

Wire Table

Table 4-9 is the Wire Table for AWG, 10 to 44, heavy film wire. The bare wire areas are given in cm^2 in column 2, and the circular mils are given in column 3 for each wire size. The equivalent resistance in micro-ohms per centimeter ($\mu\Omega$/cm or 10^{-6} Ω/cm) is given in column 4 for each wire size. Columns 5 through 13 relate to heavy, insulated film coating. The weight of the magnet wire is found in column 13, in grams, per centimeter.

Table 4-10 provides the maximum outside diameter for magnet wire with single, heavy, triple, and quad film insulation. The dimensional data is in centimeters and inches, for AWG 10 through 44.

Table 4-9

Wire Table

AWG	Bare Area		Resistance	Heavy Synthetics								
			µΩ/cm	Area		Diameter		Turns-Per		Turns-Per		Weight
	$cm^2(10^{-3})$	cir-mil	20°C	$cm^2(10^{-3})$	cir-mil	cm	Inch	cm	Inch	cm^2	$Inch^2$	gm/cm
1	2	3	4	5	6	7	8	9	10	11	12	13
10	52.6100	10384.00	32.7	55.9000	11046.00	0.2670	0.105	3.9	10	11	69	0.46800
11	41.6800	8226.00	41.4	44.5000	8798.00	0.2380	0.094	4.4	11	13	90	0.37500
12	33.0800	6529.00	52.1	35.6400	7022.00	0.2130	0.084	4.9	12	17	108	0.29770
13	26.2600	5184.00	65.6	28.3600	5610.00	0.1900	0.075	5.5	13	21	136	0.23670
14	20.8200	4109.00	82.8	22.9500	4556.00	0.1710	0.068	6.0	15	26	169	0.18790
15	16.5100	3260.00	104.3	18.3700	3624.00	0.1530	0.060	6.8	17	33	211	0.14920
16	13.0700	2581.00	131.8	14.7300	2905.00	0.1370	0.054	7.3	19	41	263	0.11840
17	10.3900	2052.00	165.8	11.6800	2323.00	0.1220	0.048	8.2	21	51	331	0.09430
18	8.2280	1624.00	209.5	9.3260	1857.00	0.1090	0.043	9.1	23	64	415	0.07474
19	6.5310	1289.00	263.9	7.5390	1490.00	0.0980	0.039	10.2	26	80	515	0.05940
20	5.1880	1024.00	332.3	6.0650	1197.00	0.0879	0.035	11.4	29	99	638	0.04726
21	4.1160	812.30	418.9	4.8370	954.80	0.0785	0.031	12.8	32	124	800	0.03757
22	3.2430	640.10	531.4	3.8570	761.70	0.0701	0.028	14.3	36	156	1003	0.02965
23	2.5880	510.80	666.0	3.1350	620.00	0.0632	0.025	15.8	40	191	1234	0.02372
24	2.0470	404.00	842.1	2.5140	497.30	0.0566	0.022	17.6	45	239	1539	0.01884
25	1.6230	320.40	1062.0	2.0020	396.00	0.0505	0.020	19.8	50	300	1933	0.01498
26	1.2800	252.80	1345.0	1.6030	316.80	0.0452	0.018	22.1	56	374	2414	0.01185
27	1.0210	201.60	1687.0	1.3130	259.20	0.0409	0.016	24.4	62	457	2947	0.00945
28	0.8046	158.80	2142.0	1.0515	207.30	0.0366	0.014	27.3	69	571	3680	0.00747
29	0.6470	127.70	2664.0	0.8548	169.00	0.0330	0.013	30.3	77	702	4527	0.00602
30	0.5067	100.00	3402.0	0.6785	134.50	0.0294	0.012	33.9	86	884	5703	0.00472
31	0.4013	79.21	4294.0	0.5596	110.20	0.0267	0.011	37.5	95	1072	6914	0.00372
32	0.3242	64.00	5315.0	0.4559	90.25	0.0241	0.010	41.5	105	1316	8488	0.00305
33	0.2554	50.41	6748.0	0.3662	72.25	0.0216	0.009	46.3	118	1638	10565	0.00241
34	0.2011	39.69	8572.0	0.2863	56.25	0.0191	0.008	52.5	133	2095	13512	0.00189
35	0.1589	31.36	10849.0	0.2268	44.89	0.0170	0.007	58.8	149	2645	17060	0.00150
36	0.1266	25.00	13608.0	0.1813	36.00	0.0152	0.006	62.5	167	3309	21343	0.00119
37	0.1026	20.25	16801.0	0.1538	30.25	0.0140	0.006	71.6	182	3901	25161	0.00098
38	0.0811	16.00	21266.0	0.1207	24.01	0.0124	0.005	80.4	204	4971	32062	0.00077
39	0.0621	12.25	27775.0	0.0932	18.49	0.0109	0.004	91.6	233	6437	41518	0.00059
40	0.0487	9.61	35400.0	0.0723	14.44	0.0096	0.004	103.6	263	8298	53522	0.00046
41	0.0397	7.84	43405.0	0.0584	11.56	0.0086	0.003	115.7	294	10273	66260	0.00038
42	0.0317	6.25	54429.0	0.0456	9.00	0.0076	0.003	131.2	333	13163	84901	0.00030
43	0.0245	4.84	70308.0	0.0368	7.29	0.0069	0.003	145.8	370	16291	105076	0.00023
44	0.0202	4.00	85072.0	0.0316	6.25	0.0064	0.003	157.4	400	18957	122272	0.00020

Table 4-10

Dimensional Data for Film Insulated Magnetic Wire

Wire Size AWG	Maximum Diameter							
	Single-Insulation		Heavy-Insulation		Triple-Insulation		Quad-Insulation	
	Inches	Centimeters	Inches	Centimeters	Inches	Centimeters	Inches	Centimeters
10	0.1054	0.2677	0.1071	0.2720	0.1084	0.2753	0.1106	0.2809
11	0.9410	2.3901	0.0957	0.2431	0.0969	0.2461	0.0991	0.2517
12	0.0840	0.2134	0.0855	0.2172	0.0867	0.2202	0.0888	0.2256
13	0.0750	0.1905	0.0765	0.1943	0.0776	0.1971	0.0796	0.2022
14	0.0670	0.1702	0.0684	0.1737	0.0695	0.1765	0.0715	0.1816
15	0.0599	0.1521	0.0613	0.1557	0.0624	0.1585	0.0644	0.1636
16	0.0534	0.1356	0.0548	0.1392	0.0558	0.1417	0.0577	0.1466
17	0.0478	0.1214	0.0492	0.1250	0.0502	0.1275	0.0520	0.1321
18	0.0426	0.1082	0.0440	0.1118	0.0450	0.1143	0.0468	0.1189
19	0.0382	0.0970	0.0395	0.1003	0.0404	0.1026	0.0422	0.1072
20	0.0341	0.0866	0.0353	0.0897	0.0362	0.0919	0.0379	0.0963
21	0.0306	0.0777	0.0317	0.0805	0.0326	0.0828	0.0342	0.0869
22	0.0273	0.0693	0.0284	0.0721	0.0292	0.0742	0.0308	0.0782
23	0.0244	0.0620	0.0255	0.0648	0.0263	0.0668	0.0279	0.0709
24	0.0218	0.0554	0.0229	0.0582	0.0237	0.0602	0.2520	0.6401
25	0.0195	0.0495	0.0206	0.0523	0.0214	0.0544	0.0228	0.0579
26	0.0174	0.0442	0.0185	0.0470	0.0192	0.0488	0.0206	0.0523
27	0.0156	0.0396	0.0165	0.0419	0.0172	0.0437	0.0185	0.0470
28	0.0139	0.0353	0.0148	0.0376	0.0155	0.0394	0.0166	0.0422
29	0.0126	0.0320	0.0134	0.0340	0.0141	0.0358	0.0152	0.0386
30	0.0112	0.0284	0.0120	0.0305	0.0127	0.0323	0.0137	0.0348
31	0.0100	0.0254	0.0108	0.0274	0.0115	0.0292	0.0124	0.0315
32	0.0091	0.0231	0.0098	0.0249	0.0105	0.0267	0.0113	0.0287
33	0.0081	0.0206	0.0088	0.0224	0.0095	0.0241	0.0102	0.0259
34	0.0072	0.0183	0.0078	0.0198	0.0084	0.0213	0.0091	0.0231
35	0.0064	0.0163	0.0070	0.0178	0.0076	0.0193	0.0082	0.0208
36	0.0058	0.0147	0.0063	0.0160	0.0069	0.0175	0.0074	0.0188
37	0.0052	0.0132	0.0057	0.0145	0.0062	0.0157	0.0067	0.0170
38	0.0047	0.0119	0.0051	0.0130	0.0056	0.0142	0.0060	0.0152
39	0.0041	0.0104	0.0045	0.0114	0.0050	0.0127	0.0053	0.0135
40	0.0037	0.0094	0.0040	0.0102	0.0044	0.0112	0.0047	0.0119
41	0.0033	0.0084	0.0036	0.0091	0.0040	0.0102	0.0043	0.0109
42	0.0030	0.0076	0.0032	0.0081	0.0037	0.0094	0.0038	0.0097
43	0.0026	0.0066	0.0029	0.0074	0.0033	0.0084	0.0035	0.0089
44	0.0024	0.0061	0.0027	0.0069	0.0030	0.0076	0.0032	0.0081

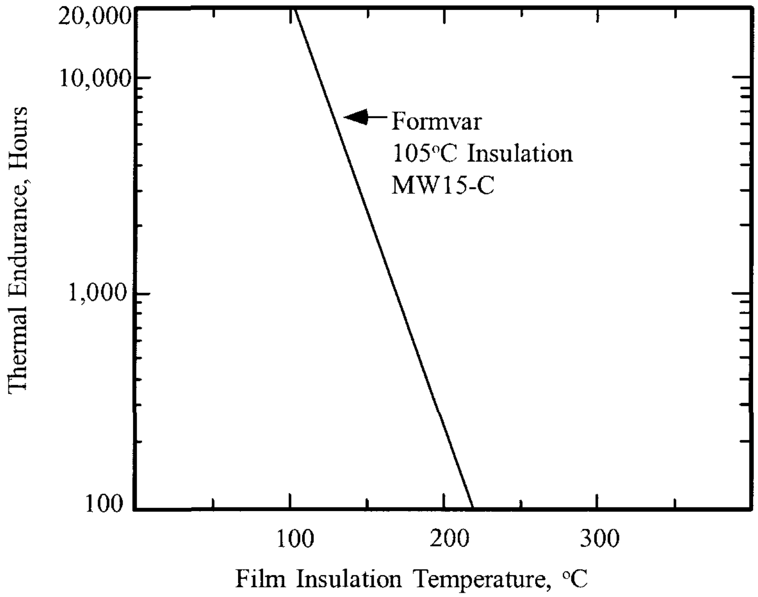


Figure 4-16. Thermal Endurance, for 105°C Formvar Insulation.

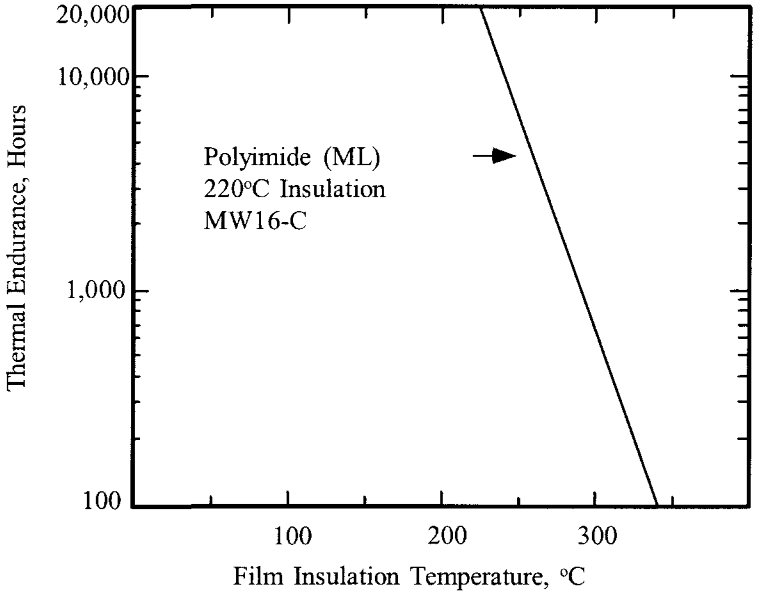


Figure 4-17. Thermal Endurance for 220°C Polyimide Insulation (ML).

Solderable Insulation

Solderable insulation is a special film insulation that is used on magnet wire in low cost, high volume applications. The magnet wire, with this solderable insulation, is wrapped around the terminal or pin, as shown in Figure 4-18. Then the terminal can be dip-soldered at the prescribed temperature without prior stripping. The ambient temperature range for this type of film insulation is 105°C to 180°C.

There are drawbacks in using some of the solderable insulation magnet wire. Prior to using, check your application with the wire manufacturer. Some solderable film insulation is not recommended where severe overloads may occur. Some solderable film insulations are susceptible to softening, due to prolonged exposure to strong solvents, such as alcohol, acetone, and methylethylketone.

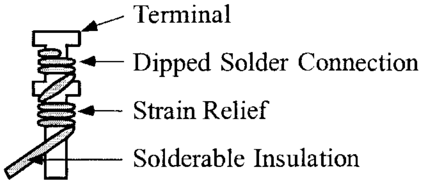


Figure 4-18. Solderable Insulation on a Dip Solder Terminal.

Bondable Magnet Wire

Bondable, magnet wires are a film-coated, copper or aluminum, with an additional coating of a thermoplastic adhesive. See Figure 4-19. They are used in applications where it is desirable to have the bonding agent, such as a solvent, which will hold the coil form until it is oven-baked. Most adhesive coatings can be softened with solvents or heat. If a coil is wound with an irregular shape, held in a form, and then raised to the appropriate temperature, the coil will retain its shape. Bondable magnet wires have applications such as armatures, field coils, and self-supporting coils.

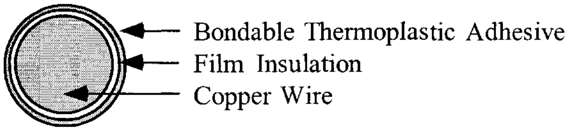


Figure 4-19. Typical Cross-Section of a Bondable Magnet Wire.

Base Film Insulation

All conventional film insulations may be adhesive-coated to achieve a bondable wire. However, care should be taken in selecting wires, which are insulated with high temperature films, since the adhesive coating may not withstand the equally high temperatures. See Table 4-11. The temperatures, in Table 4-11, are for reference only. It is wise to always check with the manufacturer for the latest in materials and application notes. The addition of the adhesive coating over the film insulation will result in an increase in the finished diameter, by the same magnitude, as if going from a single to a heavy insulation.

Table 4-11

Bondable Overcoats			
Type	Operating Temperature	Heat Activation Temperature	Solvents Activating Agents
Polyvinyl Butryal	105°C	120° - 140°C	Alcohol
Epoxy	130°C	130° - 150°C	Methylethylketone Acetone
Polyester	130°C	130° - 150°C	Methylethylketone
Nylon	155°C	180° - 220°C	None

Bonding Methods

Heat Bonding may be accomplished by the use of a temperature-controlled oven. Small components can use a controlled hot air blower to bond the wires. In either case, caution should be used when handling the coil while it is still hot, since deformation can take place.

Resistance Bonding is a method where a current is passed through the winding to achieve the desired bonding temperature. This method generates a very even, heat distribution resulting in a good bonding throughout the winding. Many coils can be resistance-bonded at the same time. The current required for one coil, will be the same current required when many are connected in series. Just solder the coils in series then adjust the applied voltage until the same current is reached.

Solvent Bonding is a method where the solvent activates the bonding material. This can be done, by passing the wire through a solvent-saturated felt pad or a light spray application. There are many activating solvents that can be used: denatured ethyl alcohol, isopropyl alcohol, methylethylketone and acetone. The solvents should always be checked on with the manufacturer for the latest in materials and application notes.

Miniature Square Magnet Wire

When product miniaturization calls for more copper in a given area, MWS Microsquare film, insulated magnet wire, allows the design of compact coils to deliver more power in less space. See Table 4-12. Microsquare magnet wire is available in both copper and aluminum. It is also available in a range of solderable and high temperature film insulation. A cross-section of a number 26, heavy build, microsquare magnet wire is shown in Figure 4-20.

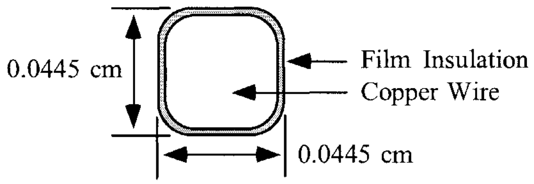


Figure 4-20. Cross-Section of a #26, Heavy, Microsquare Magnet Wire.

Table 4-12

Micro-Square Magnetic Wire (Nominal Dimension)								
Wire Size AWG	Bare Width cm	Bare Width Inch	Wire Area cm^2	Wire Area sq-mils	Copper Resistance Ω/cm	Aluminum Resistance Ω/cm	Single Width cm	Heavy Width cm
15	0.1450	0.0571	0.019614	3041	0.0000879	0.000144	0.1483	0.1514
16	0.1290	0.0508	0.015228	2361	0.0001132	0.000186	0.1323	0.1354
17	0.1151	0.0453	0.011816	1832	0.0001459	0.000239	0.1184	0.1212
18	0.1024	0.0403	0.009675	1500	0.0001782	0.000293	0.1054	0.1080
19	0.0912	0.0359	0.007514	1165	0.0002294	0.000377	0.0940	0.0968
20	0.0813	0.0320	0.006153	954	0.0002802	0.000460	0.0841	0.0866
21	0.0724	0.0285	0.004786	742	0.0003602	0.000591	0.0749	0.0772
22	0.0643	0.0253	0.003935	610	0.0004382	0.000719	0.0668	0.0688
23	0.0574	0.0226	0.003096	480	0.0005568	0.000914	0.0599	0.0620
24	0.0511	0.0201	0.002412	374	0.0007147	0.001173	0.0536	0.0556
25	0.0455	0.0179	0.002038	316	0.0008458	0.001388	0.0480	0.0498
26	0.0404	0.0159	0.001496	232	0.0011521	0.001891	0.0427	0.0445
27	0.0361	0.0142	0.001271	197	0.0013568	0.002227	0.0389	0.0409
28	0.0320	0.0126	0.001006	156	0.0017134	0.002813	0.0348	0.0366
29	0.0287	0.0113	0.000787	122	0.0021909	0.003596	0.0312	0.0330
30	0.0254	0.0100	0.000587	91	0.0029372	0.004822	0.0277	0.0295

Multistrand Wire and Skin Effect

Electronic equipment now operate at higher frequencies, and the predicted efficiency is altered, since the current carried by a conductor is distributed uniformly across the conductor, cross-section only, with direct current, and at low frequencies. The flux generated by the magnet wire is shown in Figure 4-21. There is a concentration of current near the wire surface at higher frequencies, which is termed the skin effect. This is the result of magnetic flux lines that generate eddy currents in the magnet wire, as shown in Figure 4-22.

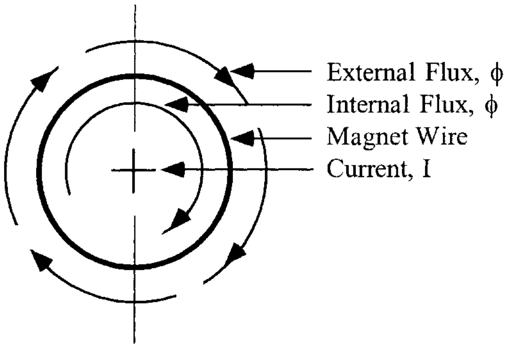
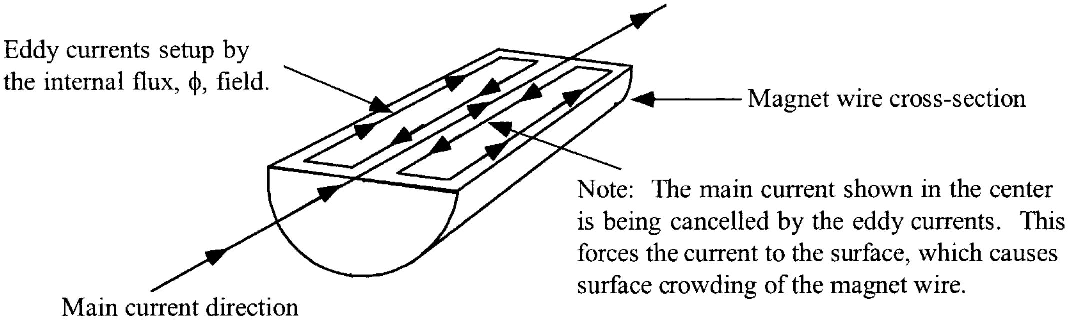


Figure 4-21. Flux Distribution in a Magnet Wire.



Note: The main current shown in the center is being cancelled by the eddy currents. This forces the current to the surface, which causes surface crowding of the magnet wire.

Figure 4-22. Eddy Currents Generated in a Magnet Wire.

Reduce Skin Effect in Transformers

Skin effect accounts for the fact that the ratio of effective alternating current resistance to direct current is greater than unity. The magnitude of this effect, at high frequency on conductivity, magnetic permeability, and inductance, is sufficient to require further evaluation of conductor size, during design. The skin depth is defined as the distance below the surface, where the current density has fallen to 1/ε or 37 percent of its value at the surface.

$$\epsilon = \left(\frac{6.62}{\sqrt{f}}\right)K, \quad [\text{cm}] \qquad [4\text{-}5]$$

ϵ, is the skin depth

f, is frequency in hertz

K, is equal to 1 for copper

When selecting the wire for high frequency, select a wire where the relationship between the ac resistance and the dc resistance is 1.

$$R_R = \frac{R_{ac}}{R_{dc}} = 1 \quad [4\text{-}6]$$

Using this approach, select the largest wire, operating at 100 kHz.

$$\epsilon = \left(\frac{6.62}{\sqrt{f}} \right) K, \quad [\text{cm}]$$

$$\epsilon = \left(\frac{6.62}{\sqrt{100,000}} \right) (1), \quad [\text{cm}] \quad [4\text{-}7]$$

$$\epsilon = 0.0209, \quad [\text{cm}]$$

The wire diameter is:

$$D_{AWG} = 2(\varepsilon), \quad [\text{cm}]$$

$$D_{AWG} = 2(0.0209), \quad [\text{cm}] \quad [4\text{-}8]$$

$$D_{AWG} = 0.0418, \quad [\text{cm}]$$

The bare wire area $A_{w(B)}$ is:

$$A_{w(B)} = \frac{\pi D_{AWG}^2}{4}, \quad [\text{cm}^2]$$

$$A_{w(B)} = \frac{(3.14)(0.0418)}{4}, \quad [\text{cm}^2] \quad [4\text{-}9]$$

$$A_{w(B)} = 0.00137, \quad [\text{cm}^2]$$

The wire size closest to this area of 0.00137 is AWG #26 with 0.00128 cm^2. (See Table 4-9).

Calculating Skin Effect in Inductors

Inductors have skin effect problems just like transformers. The skin effect depends on the amount of ac current ΔI in the inductor. The high frequency inductor current has two components: the dc current, I_{dc} and the ac current, ΔI. The dc current travels in the center of the conductor, and the ac travels on the surface of the conductor, as shown in Figure 4-23.

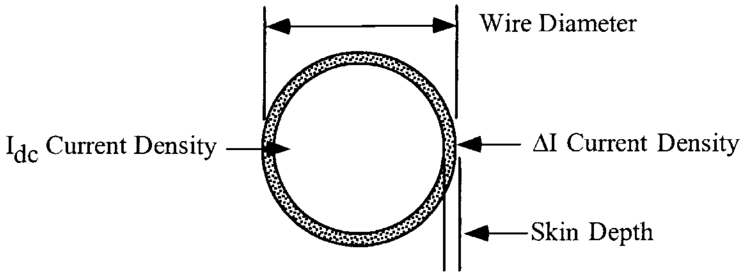


Figure 4-23. DC Inductor High Frequency Current Distribution.

The following procedure is used to calculate the high frequency current density, ΔI, while using Figure 4-23 as a reference.

The skin depth equation is:

$$\epsilon = \left(\frac{6.62}{\sqrt{f}}\right)K, \quad [\text{cm}] \quad [4\text{-}10]$$

Calculate the diameter of the copper conductor:

$$D_{AWG} = \sqrt{\frac{4\left(A_{w(B)}\right)}{\pi}}, \quad [\text{cm}] \quad [4\text{-}11]$$

Subtract two times the skin depth, ε from the diameter, D_{AWG}.

$$D_n = D_{AWG} - 2\varepsilon, \quad [\text{cm}] \quad [4\text{-}12]$$

Calculate the new wire area, A_n.

$$A_n = \frac{\pi\left(D_n\right)^2}{4}, \quad [\text{cm}^2] \quad [4\text{-}13]$$

The high frequency wire area, $A_{w(\Delta I)}$ is the difference between the wire area, $A_{w(B)}$ and the new area, A_n.

$$A_{w(\Delta I)} = A_{w(B)} - A_n, \quad [\text{cm}^2] \quad [4\text{-}14]$$

The ac current, ΔI in an inductor is a triangular waveform. The ΔI_{rms} current is:

$$\Delta I_{rms} = I_{pk}\sqrt{\frac{1}{3}}, \quad [\text{amps}] \quad [4\text{-}15]$$

Calculate the current density for the delta rms current, ΔI_{rms}.

$$J = \frac{\Delta I_{rms}}{A_{w(\Delta I)}}, \quad [\text{amps-per-cm}^2] \quad [4\text{-}16]$$

The delta rms current, ΔI_{rms} current density, J should be:

$$\Delta I_{rms} \text{ current density} \leq I_{dc} \text{ current density}$$

A graph of skin depth, as a function of frequency, is shown in Figure 4-24. The relationship of skin depth to AWG radius is shown in Figure 4-25, where $R_{ac}/R_{dc} = 1$ is plotted on a graph of AWG versus frequency.

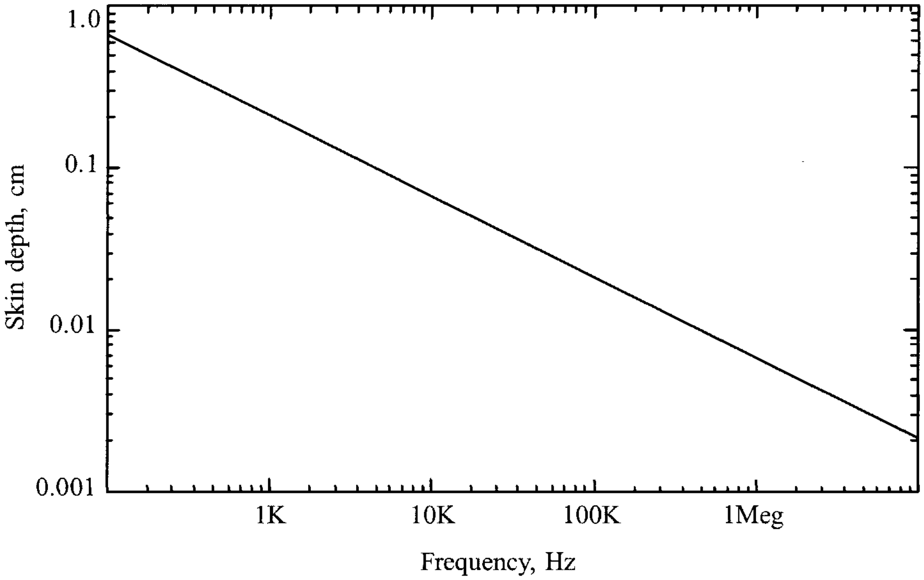


Figure 4-24. Skin Depth Versus Frequency.

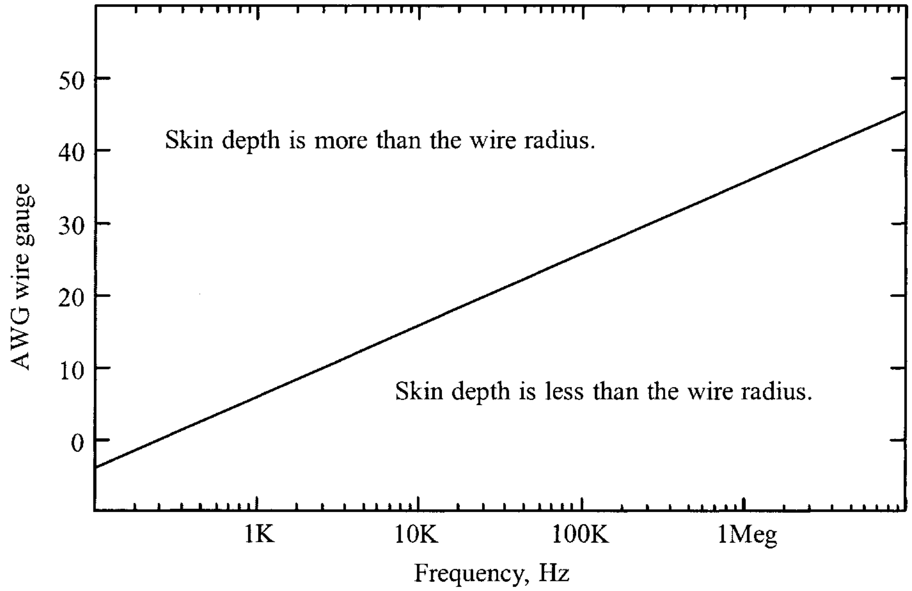


Figure 4-25. AWG Versus Frequency at Which Skin Depth Equals the Radius.

To illustrate how the AWG ac/dc resistance ratio changes with frequency, see Table 4-13. In Table 4-13, it can be seen that when a converter operates at 100 kHz, the largest wire that should be used is a number 26, with an ac/dc resistance ratio of 1.001.

Table 4-13

AWG ac/dc Resistance Ratio at Common Converter Frequencies									
		25 kHz		50 kHz		100 kHz		200 kHz	
AWG	$D_{(AWG)}$ cm	ε cm	$\frac{R_{ac}}{R_{dc}}$	ε cm	$\frac{R_{ac}}{R_{dc}}$	ε cm	$\frac{R_{ac}}{R_{dc}}$	ε cm	$\frac{R_{ac}}{R_{dc}}$
12	0.20309	0.041868	1.527	0.029606	2.007	0.020934	2.704	0.014802	3.699
14	0.16132	0.041868	1.300	0.029606	1.668	0.020934	2.214	0.014802	2.999
16	0.12814	0.041868	1.136	0.029606	1.407	0.020934	1.829	0.014802	2.447
18	0.10178	0.041868	1.032	0.029606	1.211	0.020934	1.530	0.014802	2.011
20	0.08085	0.041868	1.001	0.029606	1.077	0.020934	1.303	0.014802	1.672
22	0.06422	0.041868	1.000	0.029606	1.006	0.020934	1.137	0.014802	1.410
24	0.05101	0.041868	1.000	0.029606	1.000	0.020934	1.033	0.014802	1.214
26	0.04052	0.041868	1.000	0.029606	1.000	0.020934	1.001	0.014802	1.078
28	0.03219	0.041868	1.000	0.029606	1.000	0.020934	1.000	0.014802	1.006
30	0.02557	0.041868	1.000	0.029606	1.000	0.020934	1.000	0.014802	1.000

AWG Copper, skin depth is at 20°C.

Multistrand Litz Wire

The term litz wire is extracted from the German word, meaning woven wire. Litz wire is generally defined, as a wire constructed of individually, film insulated wires, braided together in a uniform pattern of twists and length of lay. This multistrand configuration minimizes the power losses, otherwise encountered, in a solid conductor, due to the skin effect. The minimum and maximum number of strand for standard litz wire is shown in Table 4-14. Magnet wire suppliers will supply larger, twisted magnet wire on request.

Table 4-14

Standard Litz Wire				
AWG	Minimum Strands	Approximate AWG	Maximum Strands	Approximate AWG
30	3	25	20	17.0
32	3	27	20	19.0
34	3	29	20	21.0
36	3	31	60	18.5
38	3	33	60	20.5
40	3	35	175	18.0
41	3	36	175	18.5
42	3	37	175	19.5
43	3	38	175	21.0
44	3	39	175	21.5
45	3	40	175	22.5
46	3	41	175	23.5
47	3	42	175	25.0
48	3	43	175	25.5

Proximity Effect

The operating frequency for power supplies is now in the range of 50 to 500 kHz. With it came along some new tasks for the engineer to address skin effect and proximity effect. They are quite similar in that they both generate eddy currents in the magnet wire. The eddy currents produced by these effects have the same solution, keeping the ratio of the ac resistance, R_{ac}, to the dc resistance, R_{dc} down:

$$R_R = \frac{R_{ac}}{R_{dc}} \quad [4\text{-}17]$$

The information provided here on proximity effect is taken from the five references provided at the end of this Chapter. The references are excellent, providing an in-depth analysis of the losses due to proximity effect, which is beyond the intent of this effort.

Proximity effect is caused by eddy currents induced in a wire due to the alternating magnetic field of other conductors in the vicinity. The flux generated by the magnet wire is shown in Figure 4-26. The eddy currents cause a distortion of the current density. This distortion is the result of magnetic flux lines that generate eddy currents in the magnet wire, therefore enhancing the main current, I, on one side and subtracting from the main current on the other, as shown in Figure 4-27. A magnet wire with its distorted current density is shown in Figure 4-28.

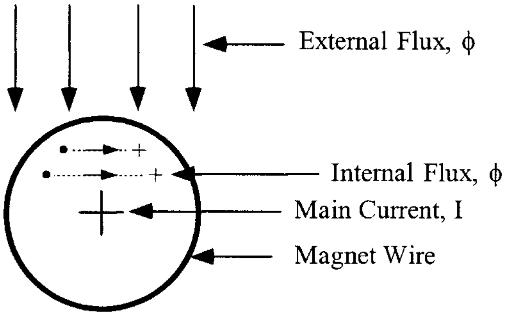
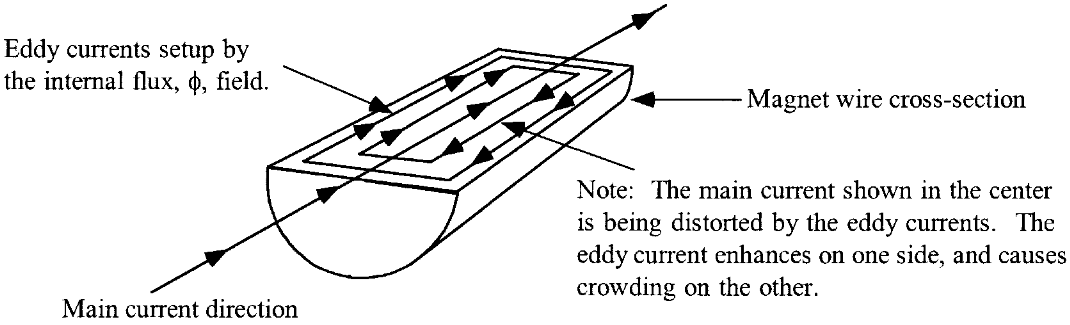


Figure 4-26. Flux Distribution in a Magnet Wire.



Note: The main current shown in the center is being distorted by the eddy currents. The eddy current enhances on one side, and causes crowding on the other.

Figure 4-27. Eddy Currents Generated in a Magnet Wire.

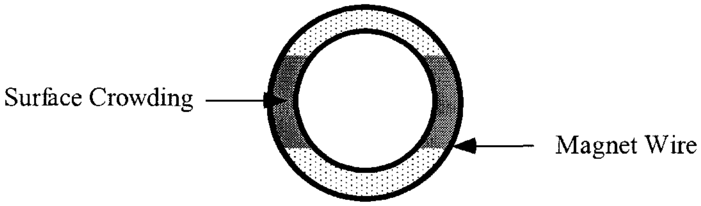


Figure 4-28. Magnet Wire, Showing Distorted Surface Crowding.

Proximity Effect in Transformers

Proximity effect has a minimum of impact on a transformer with a single layer secondary, as shown in Figure 4-29 along with its low frequency magneto-motive force (mmf) diagram. Keeping the proximity effect to a minimum requires the transformer to be designed with a minimum of layers. The selection of a core with a long narrow window will produce a design with a minimum of layers, in the same way as picking a core for a minimum of leakage inductance.

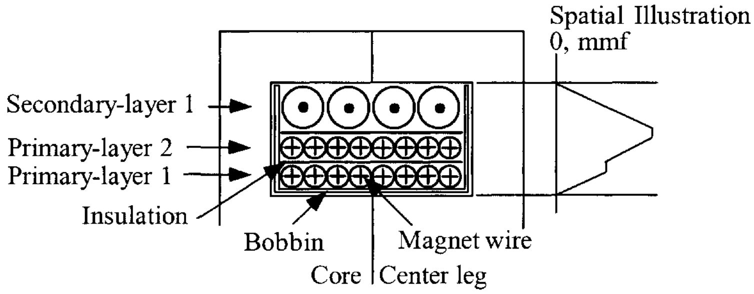


Figure 4-29. Simple Transformer Showing mmf.

Multiple Layer High Frequency Transformers and High Loss

The proximity effect is outlined for a transformer having a secondary with three layers, evenly spaced, as shown in Figure 4-30. A schematic diagram version of the transformer is shown in Figure 4-31, showing the different magneto-motive force (mmf = F_m) potentials. It is assumed that the high frequency penetration depth is 25%. The transformer has a 24 turn primary and a 24 turn secondary at 1 ampere. The transformer, A-T or magneto-motive force, (mmf) or F_m, is equal to 24.

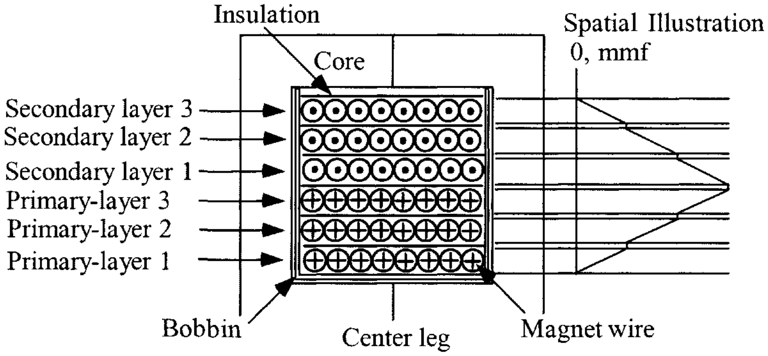


Figure 4-30. A Simple Transformer, Showing the Magneto-Motive Force, mmf.

$$F_m = NI, \quad \text{[magneto-motive force, mmf]}$$
$$\text{cgs}, F_m = 0.8NI, \quad \text{[magneto-motive force, mmf]} \qquad [4\text{-}18]$$

The schematic diagram as shown in Figure 4-31, is used as a guide to show how the proximity effect impacts the layer wound transformers. The load current, I_o, equals 1 amp, and the secondary will have three identical layers, with each layer having eight turns. Due to the skin effect or penetration depth, each wire uses only 25% of the available area. Therefore, the current will be crowded into 25% of the available copper wire.

To the right of S3, the mmf is 0. At the left of S3, $F_m = 8$ A-T.

1. The magnet field, ϕ_3 set up by the load current, I_o of 1 amp in layer S3 will generate a current, $1I_g$ in the winding layer, S2. It is in the opposite direction to the normal current flow and cancels the load current, I_o. The magneto-motive force, F_m, will generate 16 A-T or $I_c = 2$ amps to preserve the original load current, I_o, of 1 amp.
2. The magnet field, ϕ_2 set up by the load current, I_o, plus the difference between I_c and I_g in S2 will generate, $2I_g$, in the winding layer, S1. This is in the opposite direction to the normal current flow that cancels the load current, I_o, out. The magneto-motive force, F_m will generate, 24 A-T or $I_c = 3$ amps, to preserve the original load current, I_o, equals 1 amp.

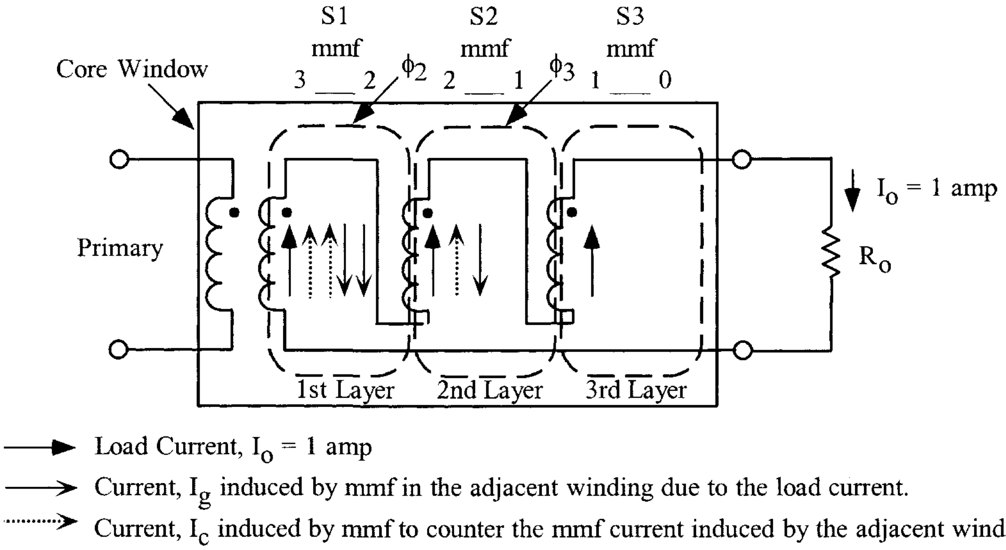


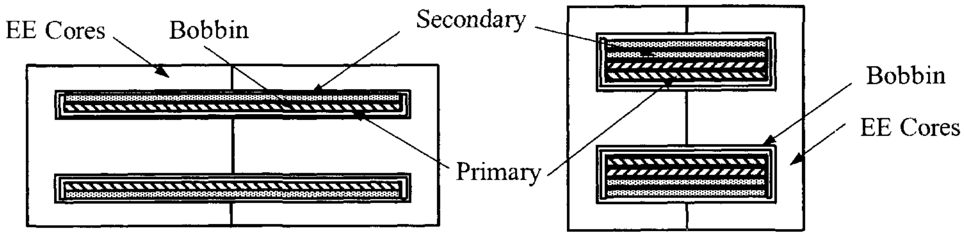
Figure 4-31. Transformer Schematic Diagram Showing mmf.

If the current in each layer is just the 1 amp, and limited in penetration, due to skin effect of only 25% of the conductor's thickness, the ac to dc resistance ratio, R_R, would be 4:1. The surface currents successive layers become much larger, as discussed above. The winding currents are tabulated in Table 4-15. The summation of the currents is given in Table 4-15. The current, I_g, is the adjacent winding induced current. The current, I_c, is the counter current induced by the magneto-motive force, mmf.

Table 4-15

Secondary Current Levels						
Winding	I_o	I_c	$I_o + I_c$	$I_o + I_c$	I_g	Total Wire Current
	amps	amps	amps	amps^2	amps	amps^2
S3	1	0	1	1	0	$(I_o + I_c)^2 = 1$
S2	1	1	2	4	1	$(I_o + I_c)^2 + (I_g)^2 = 5$
S1	1	2	3	9	2	$(I_o + I_c)^2 + (I_g)^2 = 13$

It can be seen, from the data in Table 4-15 that transformers with multiple layers operating at high frequency could be a real problem with proximity effect. The eddy current losses caused by the proximity effect go up exponentially as the number of layers. The selection of a core with a long winding length to a winding height ratio, will reduce the number of layers to a minimum, as shown in Figure 4-32.



Special Long Tongue EE Core. Standard EE Core Configuration

Figure 4-32. Comparing the Standard and the Special Long Tongue EE Cores.

Proximity Effect Using Dowell Curves

Dowell curves on proximity effect are shown in Figure 4-33. The vertical scale is, R_R, the ratio of R_{ac} to R_{dc}. The horizontal scale, K, is the ratio of the effective conductor height, or layer thickness, to the penetration depth, ε. On the right side of the curve it is labeled Number of Layers. These are segmented layers. Segmented layers are when the secondary is interleaved with the primary, then, each separation is a segment. The equation for K is:

$$K = \frac{h\sqrt{F_l}}{\varepsilon} \qquad [4\text{-}19]$$

$$h = 0.866 D_{AWG}$$

Where:

$$F_l = \frac{N D_{AWG}}{l_w} \qquad [4\text{-}20]$$

The variables in Equation 4-20 are described in Figure 4-34. It can be seen that if the number of turns, N, times the wire diameter, D_{AWG} are equal to the winding length, l_w, then, Equation 4-21 is simplified to:

$$K = \frac{h}{\varepsilon} \qquad [4\text{-}21]$$
$$h = 0.866 D_{AWG}$$

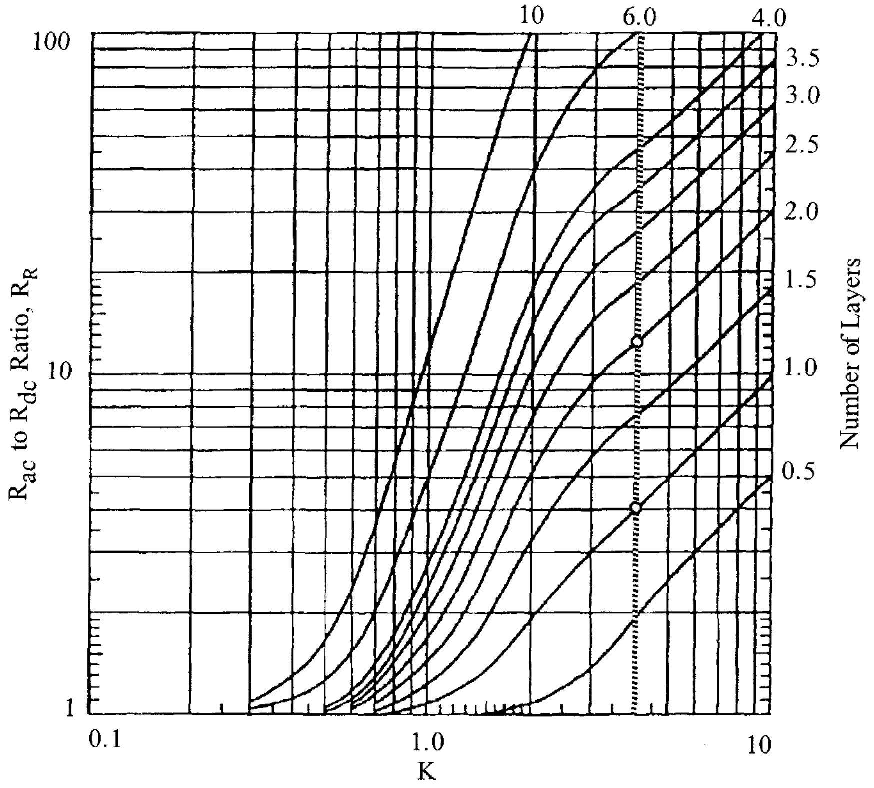


Figure 4-33. Ratio of ac/dc Resistance Due to Proximity Effect.

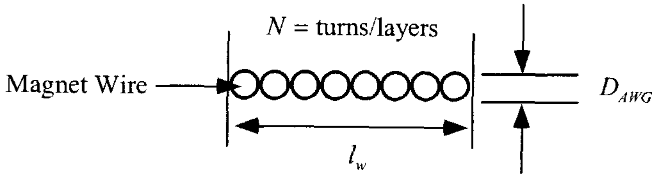


Figure 4-34. Winding Layer Parameters.

Using the Dowell curves as shown in Figure 4-33. Compare the loss ratio between the transformer in configuration A with two layers and transformer B that has the secondary interleaved with the primary, as shown in Figure 4-35. With a skin effect penetration depth of 25%, it will yield a, K, factor of 4. Both transformers, A and B, have the same A-T, but since the windings on transformer B are interleaved, it has only half the low frequency magneto-motive force (mmf).

There is a vertical dotted line shown in Figure 4-33, where K = 4. Follow the dotted line up to where it intersects 1 layer, then read the vertical column on the left, $R_R = 4$. Now follow the dotted line up to where it intersects 2 layer, then read the vertical column on the left, $R_R = 13$. Transformer B with its interleaved windings has a lower ac to dc resistance ratio, R_R, by a factor 3.25.

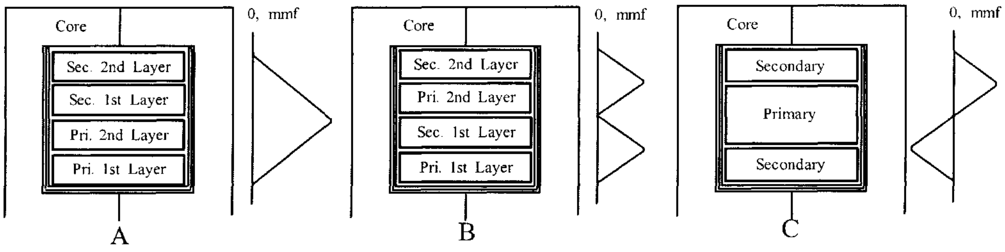


Figure 4-35. Transformers Wound with Different Primary and Secondary Configurations.

The proximity effect, with its exponentially losses tends to be the dominant conductor loss mechanism in high frequency magnetic components, particularly when windings are multi-layered.

Specialty Wire

There are a lot of new ideas out in the wire industry, if only the engineer had the time to evaluate these new concepts to build confidence and apply them.

Triple Insulated Wire

Transformers designed to meet the IEC/VDE safety specification requirements for creepage and clearance must adhere to one of the following specifications:

1. VDE0805 2. IEC950 3. EN60950 4. UL1950-3e 5. CSA 950-95

The engineer must be aware that one specification does not encompass all applications. For example, the IEC has specifications for office machines, data-processing equipment, electromedical equipment, appliances, and others.

Originally these IEC specifications were developed around linear 50 and 60 Hz transformers, and were not, always, conducive to optimal designs for high frequency, such as switching power transformers. The complexity of a standard, high frequency, switching type transformer, designed to the IEC/VDE safety specification, is shown in Figure 4-36. In any switching transformer, coupling has the highest priority because of the leakage flux.

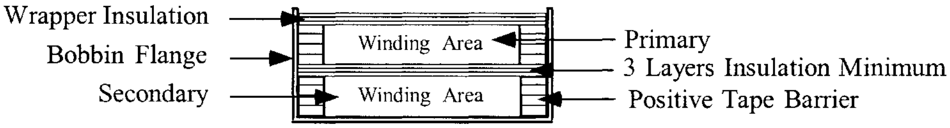


Figure 4-36. Bobbin Cross-Section Design to Meet IEC/VDE Specifications.

The triple, insulated wire was developed to meet the above specification and eliminate the need for three layers of insulating tape between primary and secondary. Also, the triple, insulated wire eliminates the need for the creepage margin, and now, the whole bobbin can be used for winding. This wire can also be used as hook-up wire, from the primary or secondary, to the circuits, without the use of sleeving or tubing.

The construction of the triple, insulated wire is shown in Figure 4-37. The temperature range for this type of wire is from 105°C to 180°C. The dimensions for triple, insulated wire are shown in Table 4-16, using a 0.002 inch coat per layer. Other thicknesses are available. The manufacturer, Rubadue Wire Company, is listed in the Reference section on page 4-41.

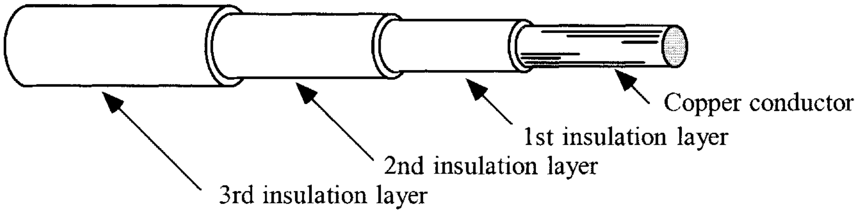


Figure 4-37. Triple, Insulated Wire Construction.

Triple Insulated Litz

High frequency litz wire, shown in Figure 4-38, is also available as a triple insulated wire from manufacturers. The insulation layers' thickness for litz wire comes in 0.002 and 0.003 inches.

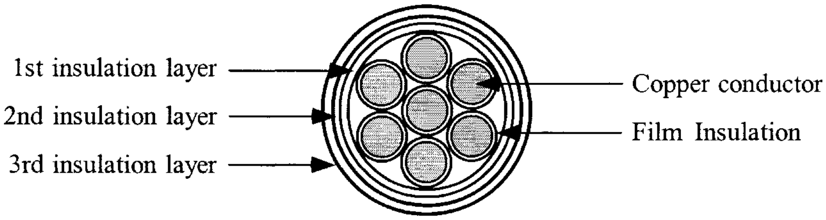


Figure 4-38. Triple, Insulated Litz Wire.

Table 4-16

Triple Insulated Wire (.002) Material						
	Bare Wire				With Insulation	
AWG	Area $cm^2(10^{-3})$	Diameter inch	Diameter mm	Resistance $\mu\Omega/cm$	Diameter inch	Diameter mm
16	13.0700	0.0508	1.2903	132	0.0628	1.5951
18	8.2280	0.0403	1.0236	166	0.0523	1.3284
19	6.5310	0.0359	0.9119	264	0.0479	1.2167
20	5.1880	0.0320	0.8128	332	0.0440	1.1176
21	4.1160	0.0285	0.7239	419	0.0405	1.0287
22	3.2430	0.0253	0.6426	531	0.0373	0.9474
23	2.5880	0.0226	0.5740	666	0.0346	0.8788
24	2.0470	0.0201	0.5105	842	0.0321	0.8153
25	1.6230	0.0179	0.4547	1062	0.0299	0.7595
26	1.2800	0.0159	0.4039	1345	0.0279	0.7087
27	1.0210	0.0142	0.3607	1687	0.0262	0.6655
28	0.8046	0.0126	0.3200	2142	0.0246	0.6248
29	0.6470	0.0113	0.2870	2664	0.0233	0.5918
30	0.5067	0.0100	0.2540	3402	0.0220	0.5588
32	0.3242	0.0080	0.2032	5315	0.0200	0.5080
34	0.2011	0.0063	0.1600	8572	0.0183	0.4648
36	0.1266	0.0050	0.1270	13608	0.0170	0.4318
38	0.0811	0.0040	0.1016	21266	0.0160	0.4064

Polyfilar Magnetic Wire

Poly or multiple strands of magnet wire, bonded together, can be used in many high frequency transformer and inductor applications. Round polyfilar magnet wire is shown in Figure 4-39, and square polyfilar is shown in Figure 4-40. Both can be used in place of foil in some applications. Polyfilar magnet wire can be used as a foil type winding, such as a low voltage, high current, or even a Faraday shield. The polyfilar, magnet wire strip width can be easily increased or decreased by adding or removing wires to provide the proper strip width to fit a bobbin. It is relatively easy to wind. Polyfilar wire has complete insulation, and it does not have the sharp edge problem that could cut insulation in the way foil does. It is not recommended to wind a transformer with polyfilar magnet wire in order to have an exact center tap, unless it is just a few turns, because of the penalty in capacitance. If the use of polyfilar is necessary, then use a magnet wire with a film insulation that has a low dielectric constant. See Table 4-8.

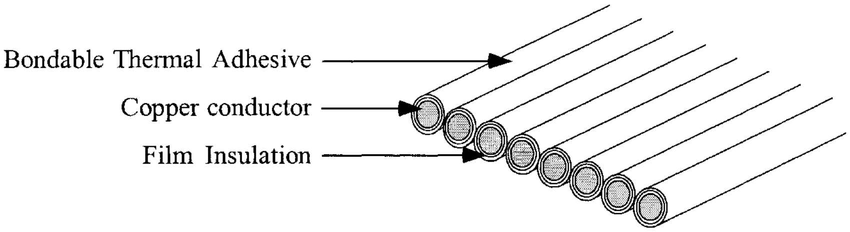


Figure 4-39. Polyfilar, Strip-Bonded, Round Magnet Wire.

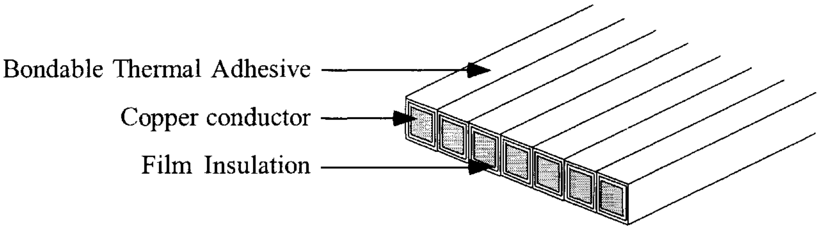


Figure 40. Polyfilar, Strip-Bonded, Square Magnet Wire.

Standard Foils

The biggest advantage for using foil over magnet wire is the fill factor. The design of a high current, high frequency, dc to dc converter is common place. The main reason for going to high frequency is the reduction in size. The power transformer is the largest component in the design. When designing high frequency transformers, the design equations relate to a very small transformer. When operating transformers at high frequencies, the skin effect becomes more and more dominate, and requires the use of smaller wire. If larger wire is required, because of the required current density, then, more parallel strands of wire will have to be used (litz wire). The use of small wire has a large effect on the fill factor.

When using foil, the gain in the fill factor is the biggest improvement over litz. To make a comparison, a litz design is shown in Figure 4-41, and a foil design is shown in Figure 4-42. In the litz design, there is a percentage of the winding area which cannot be used for the conductors. This lost area is made up of voids, space between the wires, and the insulation film on the wire. The foil wound coil, shown in Figure 4-42, can be designed to make optimum use of the available winding area. Each turn of the foil can extend, within limits, edge-to-edge of the bobbin or tube. The insulation required between layers is at a minimum, as long as the foil has been rolled to remove the sharp burr as shown in Figure 4-46.

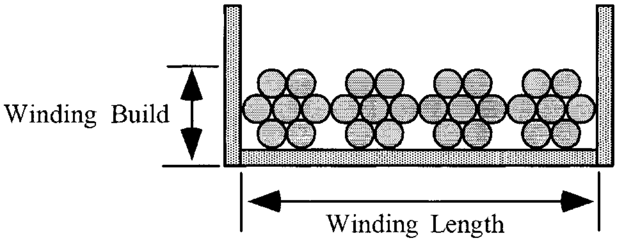


Figure 4-41. Layer Winding, Using Litz Magnet Wire.

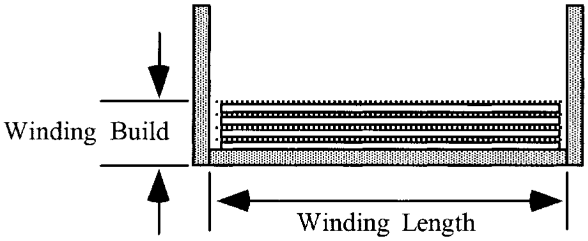


Figure 4-42. Layer Winding, Using Foil with Insulation.

The Use of Foils

Designing transformers and inductors, with foil, is a very laborious task, especially if the engineer only does it now and then. A monumental job, in itself, is finding out where to get the materials. Foil has its advantages, mainly, in high current, high frequency, and a high density environment.

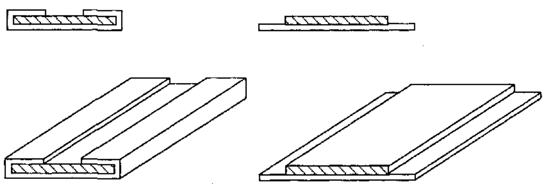
The window utilization factor, K_u, can be greater than 0.6, under the right conditions, without a lot of force. The standard foil materials used, by transformer engineers, are copper and aluminum. The engineer has a good selection of standard thicknesses as shown:

1.0 mil, 1.4 mil, 2.0 mil, 5.0 mil, and 10 mil

The engineer will find other thicknesses available, but standard thicknesses should be considered first. Be careful of using a nonstandard thickness. What you might be using could be from an overrun, and could create problems for you. Foil comes in standard widths, in inches, as shown:

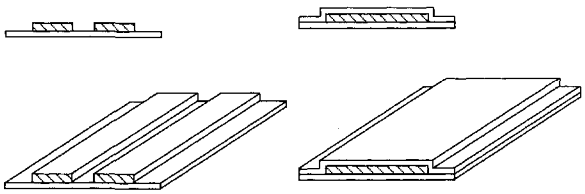
0.25, 0.375, 0.50, 0.625, 0.75, 1.0, 1.25, 1.50, 2.00, 2.50, 3.00, 4.00 (inches)

Standard widths are the widths that are most readily available. There are also different styles of pre-fab foils, as shown in Figures 4-43, 4-44, and 4-45.



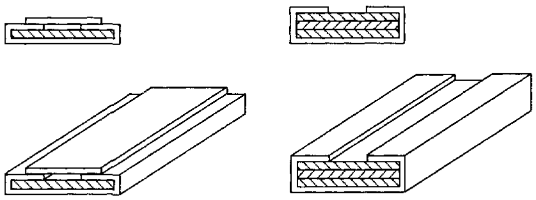
Cuffed Conductor Backed Conductor

Figure 4-43. Pre-fab Foils.



Backed Multiple Conductor Sandwiched Conductor

Figure 4-44. Pre-fab Foils.



Jacketed Conductor Jacketed Multiple Conductor

Figure 4-45. Pre-fab Foils.

Although special slitting is done all the time, there is normally a minimum buy. When slitting is done, special care must be attended to, with the sharp edges, as shown in Figure 4-46. The cut edge should be rolled after slitting it, at least two times, to remove the sharp burrs that could cut through the insulation. Therefore it is wise not to use insulation between layers of less than 1 mil.

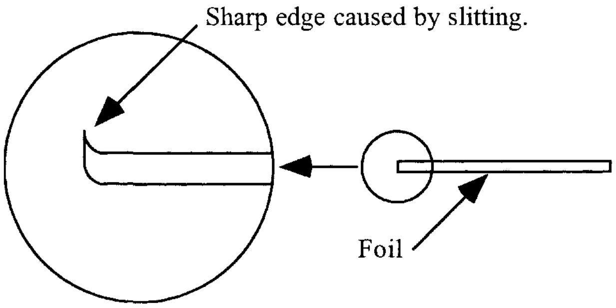


Figure 4-46. Foil with Sharp Edge Burrs after Slitting.

When winding transformers or inductors with foil, special care must be taken with lead finishing. One of the biggest problems about using foil is solder wicking. This wicking will puncture the insulation, resulting in a shorted turn. The normal insulation used for foil is very thin. Winding with foil, the coil is still subjected to bowing, only more so, as shown in Figure 4-7.

Foil used for winding transformers and inductors should be dead soft. There is another shortcoming about using foil, and that is, the inherit capacitance build-up, as shown in Figure 4-47.

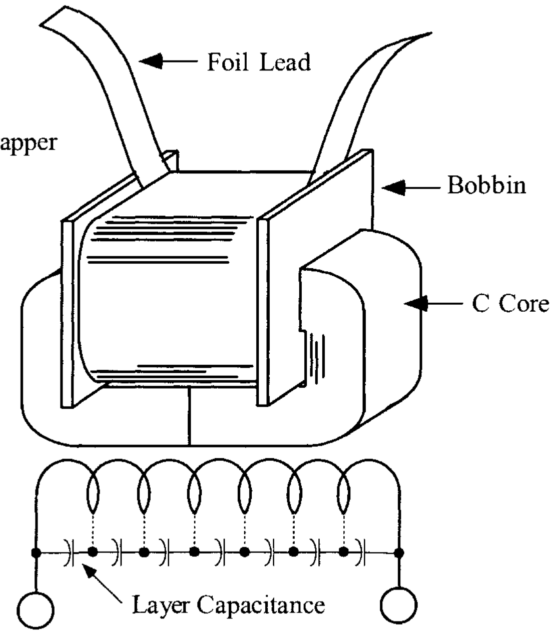


Figure 4-47. Foil Capacitance Equation.

The capacitance build-up is expressed:

$$C = 0.0885\left(\frac{K(N-1)(\mathrm{MLT})(G)}{d}\right), \quad [pfd] \quad [4\text{-}22]$$

K = Dielectric Constant

MLT = Mean Length Turn

N = Number of Turns

G = Foil Width, cm

d = Layer Insulation Thickness, cm

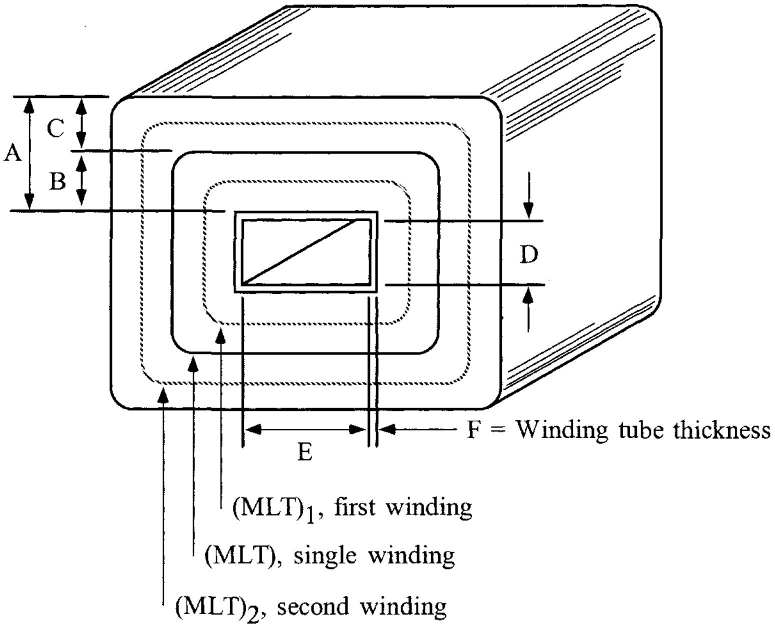
The dielectric constant K for different materials can be found in Table 4-17.

Table 4-17

Dielectric Constants	
Material	K
Kapton	3.2-3.5
Mylar	3-3.5
Kraft Paper	1.5-3.0
Fish Paper	1.5-3.0
Nomex	1.6-2.9

Calculating, MLT

The Mean Length Turn, (MLT), is required to calculate the winding resistance and weight for any given winding. The winding dimensions, relating to the Mean Length Turn, (MLT) for a tube or bobbin coil, are shown in Figure 4-48.



$$MLT = 2(D+2F)+2(E+2F)+\pi A, \quad \text{single winding}$$

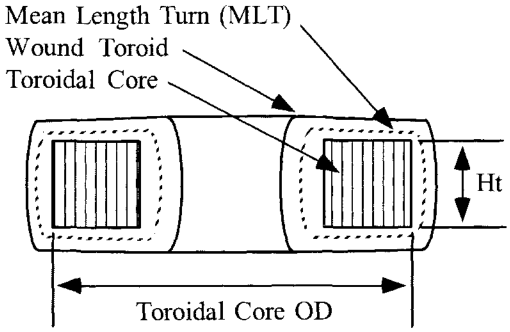
$$MLT_1 = 2(D+2F)+2(E+2F)+\pi B, \quad \text{first winding} \qquad [4\text{-}23]$$

$$MLT_2 = 2(D+2F)+2(E+2F)+\pi(2B+C), \quad \text{second winding}$$

Figure 4-48. Dimensions, Relating to the Winding Mean Length Turn, (MLT).

Calculating, MLT (toroid)

It is very difficult to calculate the Mean Length Turn (MLT) for a toroidal core that would satisfy all conditions. There are just too many ways to wind a toroid. If the toroid were designed to be wound by machine, then that would require a special clearance for a wire shuttle. If the toroid were designed to be hand-wound, the wound inside diameter would be different. The fabrication of a toroidal design is weighted heavily on the skill of the winder. A good approximation for a toroidal core, Mean Length Turn (MLT), is shown in Figure 4-49.



$$\text{MLT} = 0.8\left(OD + 2\left(Ht\right)\right), \quad \text{approximation} \quad [4\text{-}24]$$

Figure 4-49. Toroidal Mean Length Turn (MLT), is an Approximation.

Copper Resistance

The dc resistance calculation of a winding requires knowing the total length, l, of the conductor, the cross-sectional area, A_w, of the conductor, and the resistivity, ρ, of the conductor material. The value for the resistivity, ρ, in μΩ per cm for three different conductor materials can be found in Table 4-7.

$$R_{dc} = \left(\frac{\rho l}{A_w}\right), \quad [\Omega] \quad [4\text{-}20]$$

Copper Weight

The weight calculation of a winding requires knowing the total length, l, of the conductor, the cross-sectional area, A_w, of the conductor, and the density, λ, of the conductor material. The value for the density, λ, in grams per cm^3 for three different conductor materials, can be found in Table 4-7.

$$W_t = \lambda l A_w, \quad [\text{grams}] \quad [4\text{-}21]$$

Electrical Insulating Materials

The reliability and life span of a magnetic component depends on the stress level put upon the insulating materials. If the design or workmanship is not incorporated, then, insulation will not help you.

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9. MWS Wire Industries, "Wire Catalog," Revised June, 1992, 31200 Cedar Valley Drive, Westlake Village, CA 91362.

10. Alpha-Core Inc. (Special Foils), 915 Pembroke Street, Bridgeport, CT 06608 Phone: (203) 335 6805.

11. Industrial Dielectrics West, Inc., (Special Foils), 455 East 9th Street, San Bernardino, CA 92410 Phone: (909) 381 4734.

12. Rubadue Wire Company, Inc., (Triple Insulated Wire), 5150 E. LaPalma Avenue, Suite 108, Anaheim Hills, CA 92807 Phone: (714) 693 5512, Email: www.rubaduewire.com.