

Chapter 4

Window Utilization, Magnet Wire, and Insulation

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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 torrid, 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.

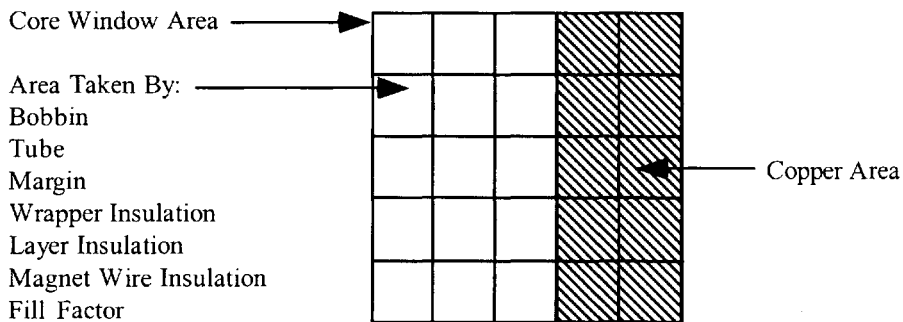


Figure 4-1. Window Area Occupied by Copper.

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

$$K_u = S_1 \times S_2 \times S_3 \times S_4$$

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.

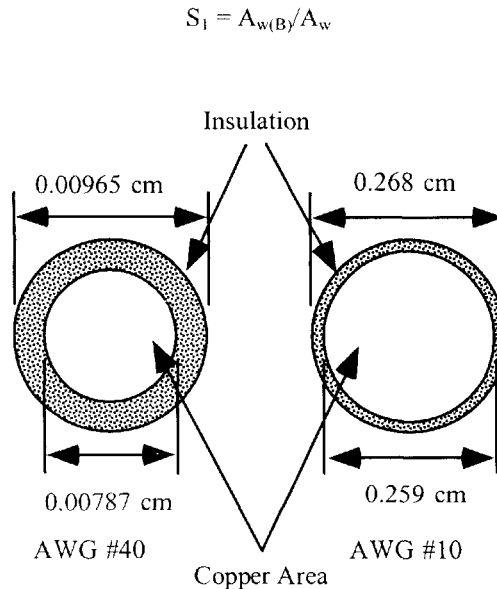


Figure 4-2. Comparing Insulation with Different Wire Gauges.

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 |

S₂, Fill Factor

S₂ 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 is shown in Table 4-2, for layer wound coils, and in Table 4-3, for random wound coils. 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. | | | |

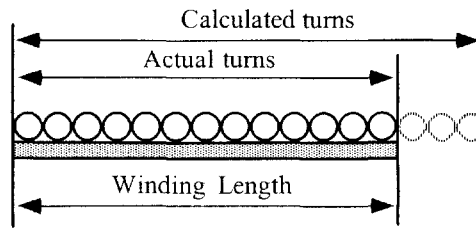


Figure 4-3. Capable Turns per Unit Length.

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.

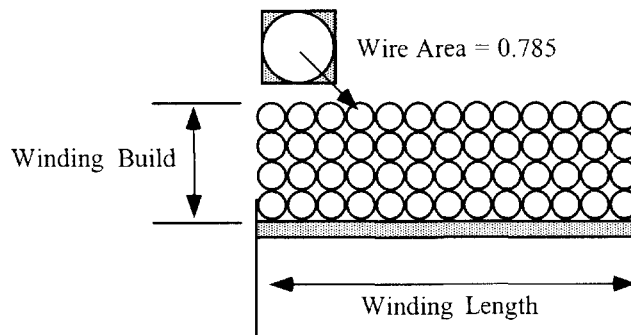


Figure 4-4. Theoretically, the Square Winding Pattern Fill Factor 0.785.

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

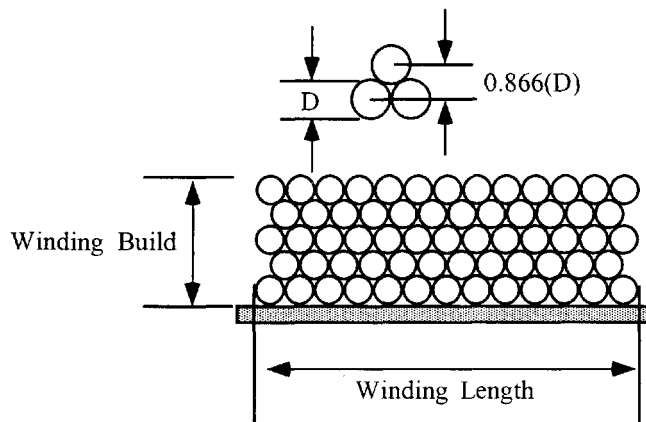


Figure 4-5. Theoretically, the Hexagonal Winding Pattern Fill Factor 0.907.

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.

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.

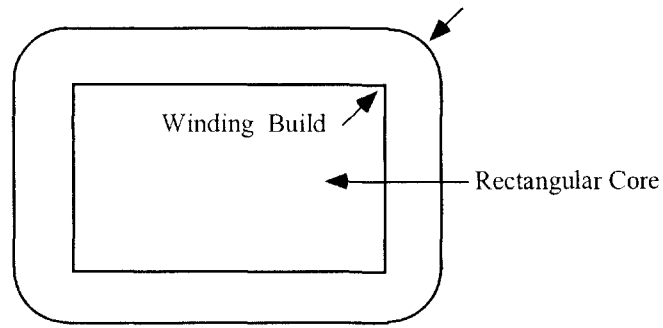


Figure 4-6. Ideal Winding on a Rectangular Bobbin.

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 reducing and minimizing of the leakage inductance caused from the bowing.

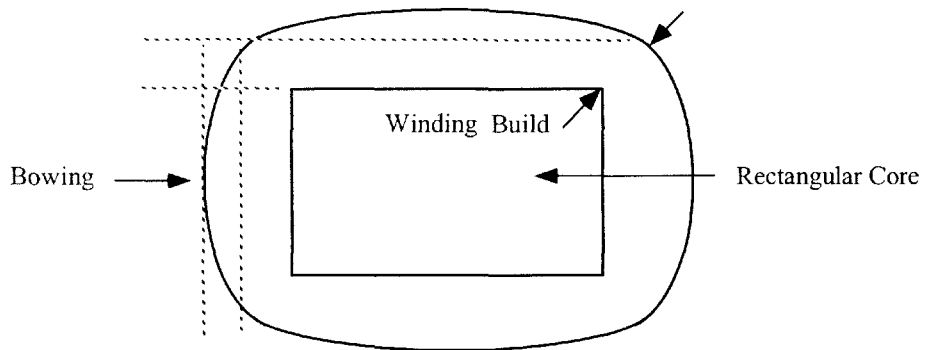


Figure 4-7. Bowing in Transformer Windings.

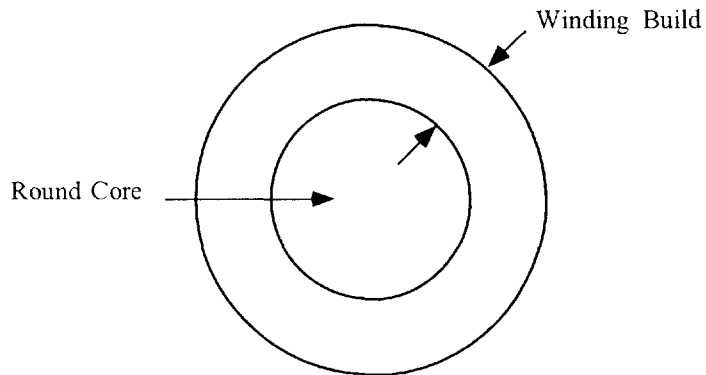


Figure 4-8. A Round Bobbin Insures Minimum Bowing.

S₃, Effective Window

The effective window, S₃, 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.

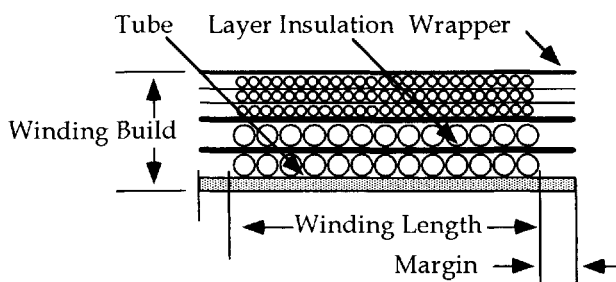


Figure 4-9. Transformer Windings with Margins.

Table 4-4

| Winding Margins Versus AWG | | |
|----------------------------|--------|-------|
| AWG | Margin | |
| | 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 | | |
|----------------------------|----------------------|---------|
| AWG | Insulation Thickness | |
| | 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, while 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.

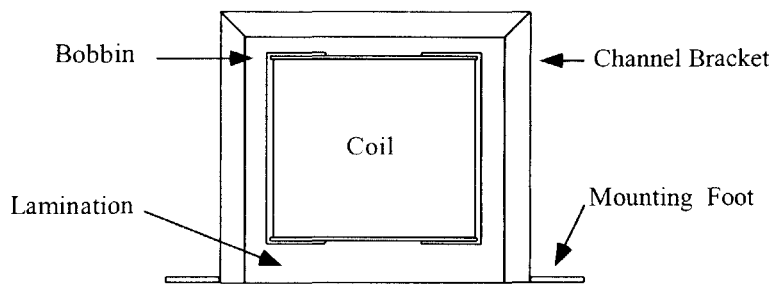


Figure 4-10. Transformer Construction with Single Bobbin.

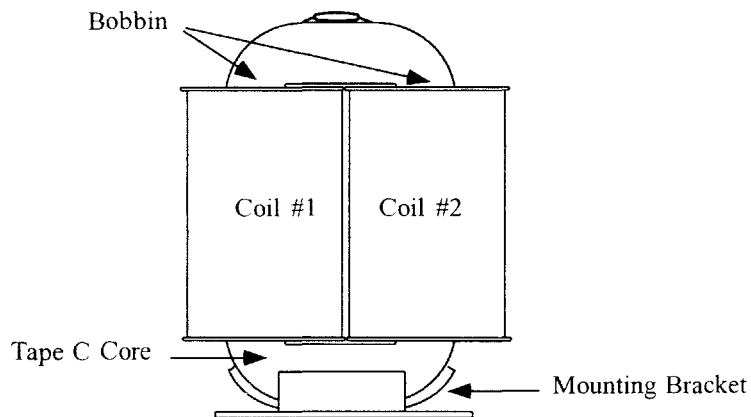
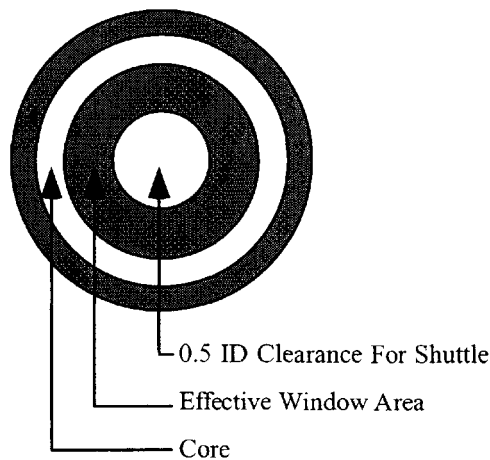


Figure 4-11. Transformer Construction with Dual Bobbins.



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

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

S₄, Insulation Factor

The insulation factor, S₄, 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, S₄ 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, S₄, is not taken into account in Figure 4-12. The insulation factor, S₄, is to be 1.0. The window utilization factor, K_w, is highly influenced by insulation factor, S₄, 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.

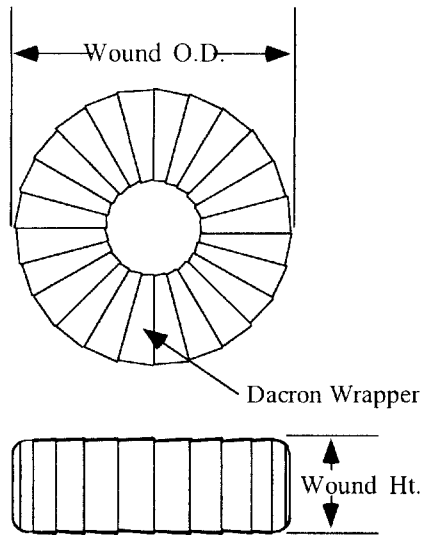


Figure 4-13. Wrapped Toroid.

Circular mil and Square mil

There are engineers that use circular mils/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 of all, let's define a mil, which is .001 inch. Figure 4-14 shows the area of a square mil, and the area of a circular mil.

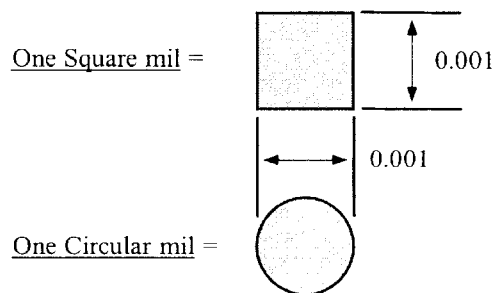


Figure 4-14. Comparing Circular-Mils and Square-Mils.

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 5.066×10^{-6} .

To convert Square mils to Square centimeters , multiply by 6.45×10^{-6}

Summary

I hope I have cleared up some of the mystery of how the window utilization factor, K_u , was derived. I hope the magic of 0.4 is now clear. I have tried to bring together all of the different parts that make up the window utilization and then, explain each one. I hope I have simplified for you the complexity of the window utilization factor. I hope I have not confused you more.

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

$$S_1 = \text{conductor area/wire area} = 0.855, \text{ \#20 AWG}$$

$$S_2 = \text{wound area/usable window area} = 0.61$$

$$S_3 = \text{usable window area/window area} = 0.75$$

$$S_4 = \text{usable window area/usable window area + insulation} = 1$$

$$K_u = S_1 S_2 S_3 S_4$$

$$K_u = (0.855)(0.61)(0.75)(1.0) = 0.391 \approx 0.4$$

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

Magnet Wire

Standard magnet wire is available in three different materials, as shown in Table 4-6. 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 4-6

| 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 then see Table 4-7 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 4-7. 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 4-15 and 4-16. The engineer must be very careful of hot spots so as not to degrade the service life of the magnetic component.

Table 4-7

| 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 4-8 is the wire table for AWG, 10 to 44, heavy film wire. The bare wire area is given in cm², in column 2, and the circular mils is given in column 3 for each wire size. The equivalent resistance in micro-ohms per centimeter ($\mu\Omega/\text{cm}$ or $10^{-6} \Omega/\text{cm}$ and in wire length 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 4-9 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 4-8

| Wire Table | | | | | | | | | | | | |
|------------|------------------------|----------|---|------------------------|----------|----------|-------|-----------|------|---------------|-----------------|---------|
| AWG | Bare Area | | Resistance $\mu\Omega/\text{cm}$ 20°C | Heavy Synthetics | | | | | | | | |
| | | | | Area | | Diameter | | Turns-Per | | Turns-Per | | Weight |
| | $\text{cm}^2(10^{-3})$ | cir-mil | | $\text{cm}^2(10^{-3})$ | 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 4-9

| 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 | 0.0941 | 0.2390 | 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 |

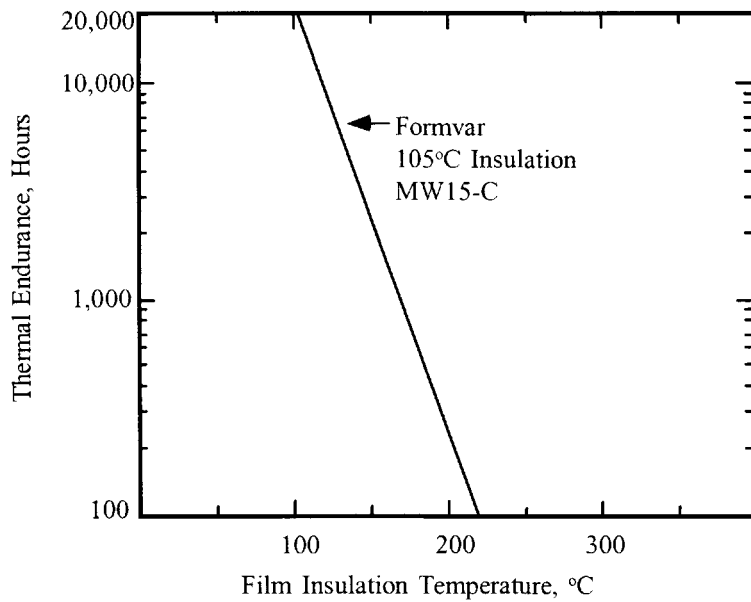


Figure 4-15. Thermal Endurance, for 105°C Formvar Insulation.

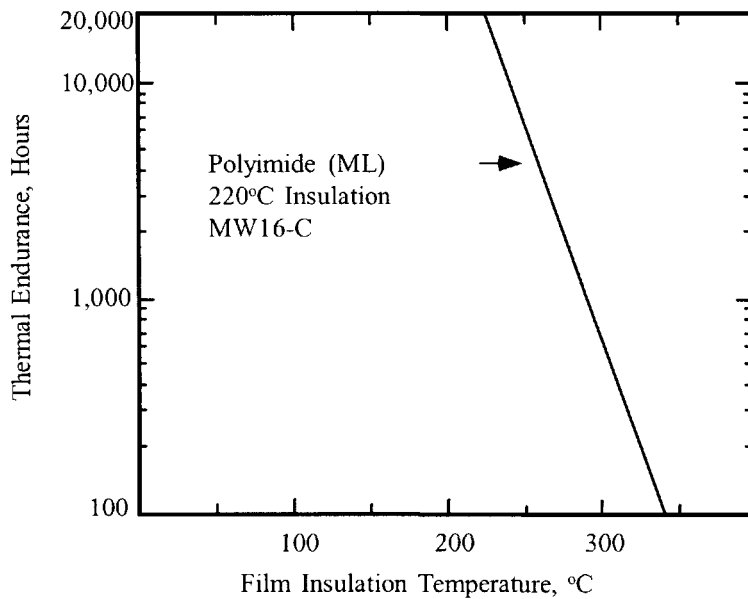


Figure 4-16. Thermal Endurance for 220°C Polyimide Insulation (ML).

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 4-17. 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.

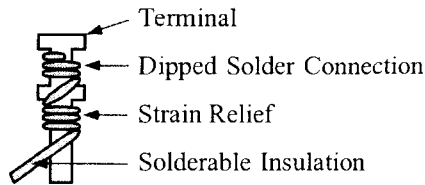


Figure 4-17. Solderable Insulation on a Dip Solder Terminal.

Bondable Magnet Wire

Bondable, magnet wires are a film-coated, copper or aluminum, with an additional coating of a thermoplastic adhesive. See Figure 4-18. 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.

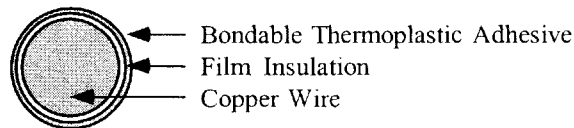


Figure 4-18. Typical Cross-Section of a Bondable Magnet Wire.

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 4-10. The temperatures in Table 4-10 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 4-10

| 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 design of compact coils that deliver more power in less space. See Table 4-11. 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 4-19.

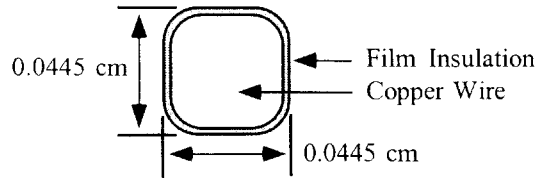


Figure 4-19. Cross-Section of a 26, Heavy, Microsquare Magnet Wire.

Table 4-11

| 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 are now operating 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 4-20. 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 4-21.

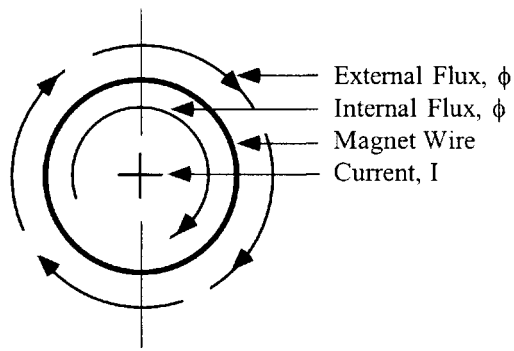


Figure 4-20. Flux Distribution in a Magnet Wire.

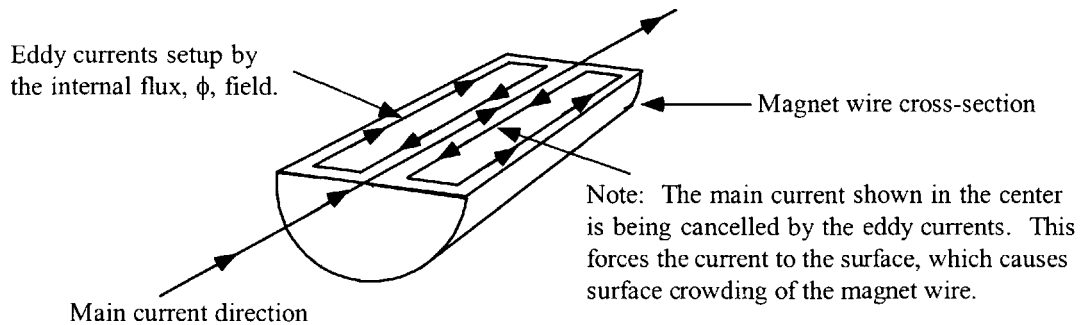


Figure 4-21. Eddy Currents Generated in a Magnet Wire.

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 $1/e$ or 37 percent of its value at the surface.

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

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, so that the relationship between the ac resistance and the dc resistance is 1.

$$\frac{R_{ac}}{R_{dc}} = 1$$

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

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

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

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

Then, the wire diameter is:

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

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

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

Then, the bare wire area $A_{w(B)}$ is:

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

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

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

A graph of skin depth, as a function of frequency, is shown in Figure 4-22. The relationship of skin depth to AWG radius is shown in Figure 4-23, where $R_{ac}/R_{dc}=1$ is plotted on a graph of AWG versus frequency.

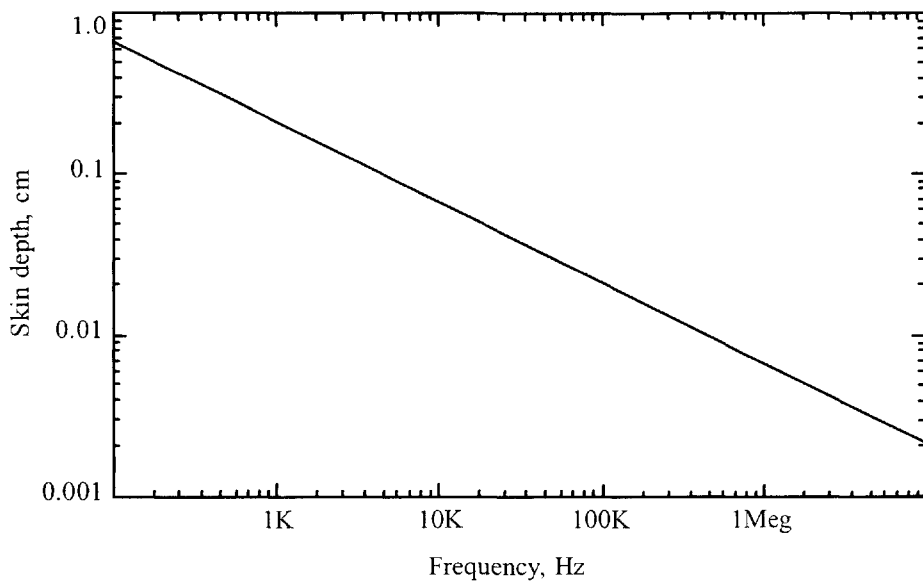


Figure 4-22. Skin Depth Versus Frequency.

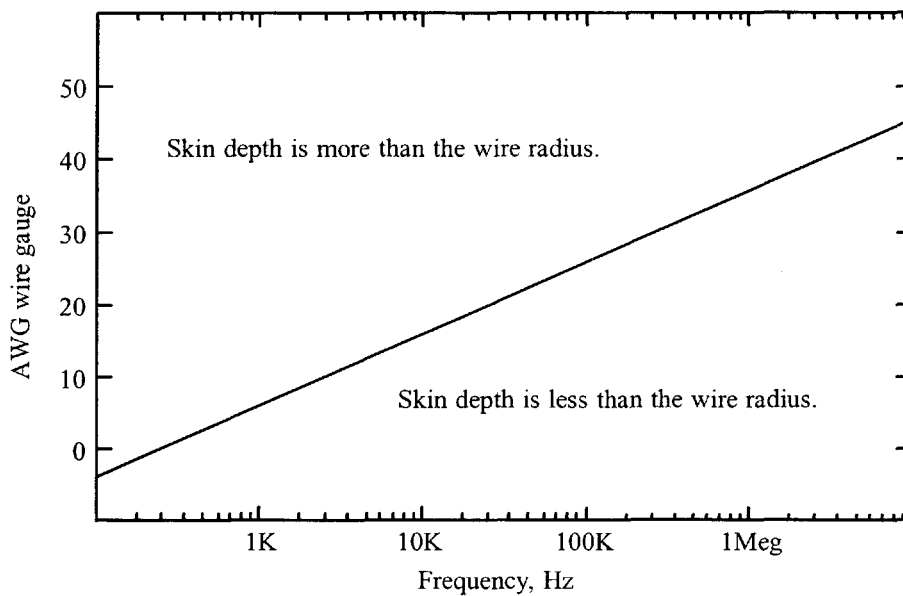


Figure 4-23. AWG Versus Frequency at Which Skin Depth Equals the Radius.

To illustrate how the AWG, ac/dc resistance ratio changes with frequency, see Table 4-12.

Table 4-12

| AWG ac/dc Resistance Ratio at Common Converter Frequencies | | | | | | | | | |
|--|-------------------|------------------|-------------------------|------------------|-------------------------|------------------|-------------------------|------------------|-------------------------|
| AWG | $D_{(AWG)}$ cm | 25 kHz | | 50 kHz | | 100 kHz | | 200 kHz | |
| | | 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

In Table 4-12, 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.

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 4-13. Magnet wire suppliers will supply larger, twisted magnet wire on request.

Table 4-13

| 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 |

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 4-24. In any switching transformer, coupling has the highest priority because of the leakage flux.

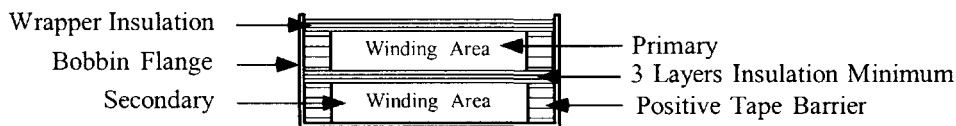


Figure 4-24. Bobbin Cross-Section Design to Meet IEC/VDE Specifications.

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 4-25. 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 4-14, 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 4-34.

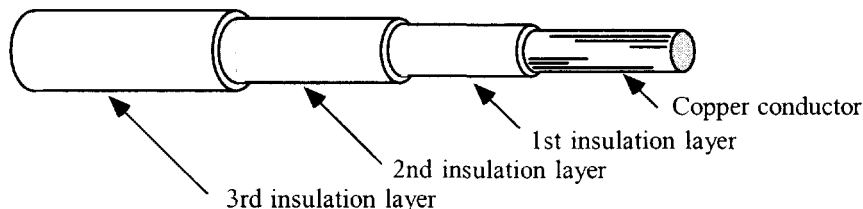


Figure 4-25. Triple, Insulated Wire Construction.

Table 4-14

| Triple Insulated Wire (.002) Material | | | | | | |
|---------------------------------------|--------------------------------|------------------|----------------|-------------------------------------|------------------|----------------|
| AWG | Bare Wire | | | | With Insulation | |
| | Area $\text{cm}^2(10^{-3})$ | Diameter inch | Diameter mm | Resistance $\mu\Omega/\text{cm}$ | 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 |

Triple Insulated Litz

High frequency litz wire, shown in Figure 4-26, is also available, triple insulated wire from manufacturers. The insulation, layers' thickness for litz wire comes in 0.002 and 0.003 inches.

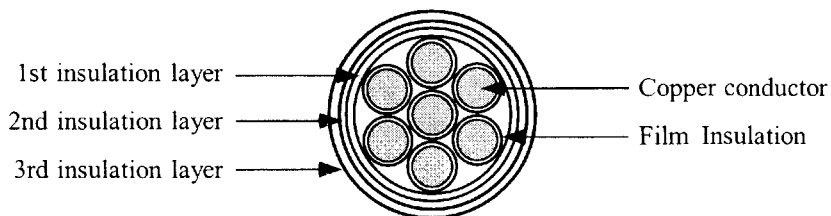


Figure 4-26. Triple, Insulated Litz Wire.

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 4-27, and square polyfilar is shown in Figure 28. 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 4-7.

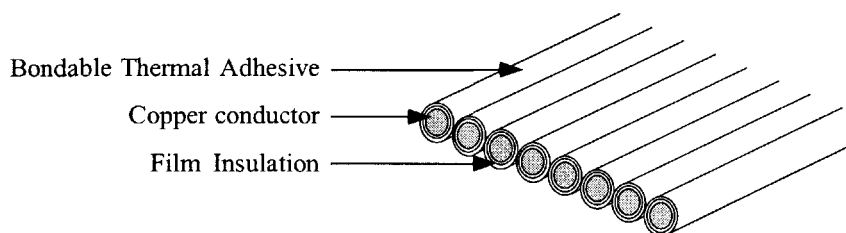


Figure 4-27. Polyfilar, Strip-Bonded, Round Magnet Wire.

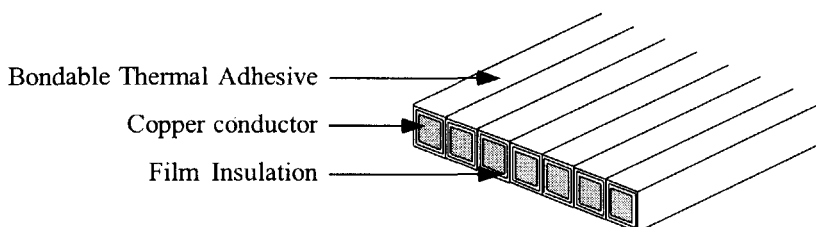


Figure 28. Polyfilar, Strip-Bonded, Square Magnet Wire.

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 4-29, and a foil design is shown in Figure 4-30. 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 4-35 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.

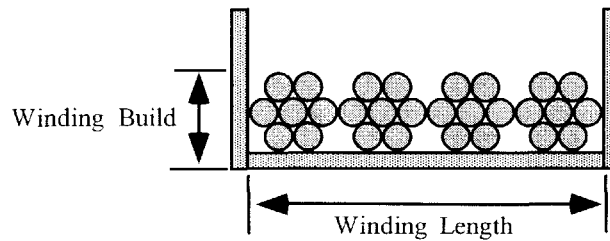


Figure 4-29. Layer Winding, Using Litz Magnet Wire.

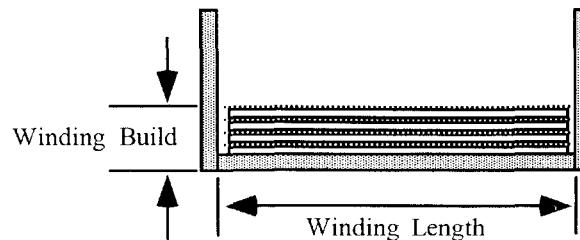


Figure 4-30. Layer Winding, Using Foil with Insulation.

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 4-31, 4-32, and 4-33.

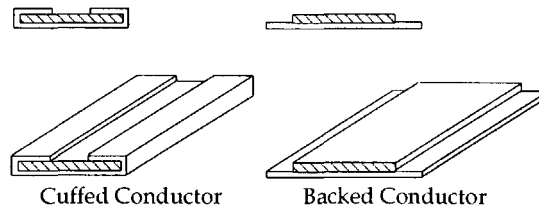


Figure 4-31. Pre-fab Foils.

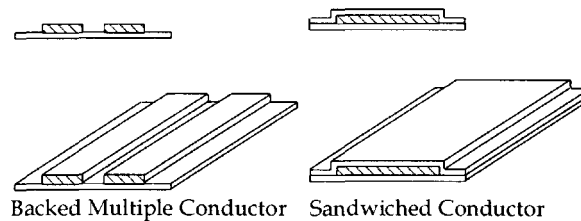


Figure 4-32. Pre-fab Foils.

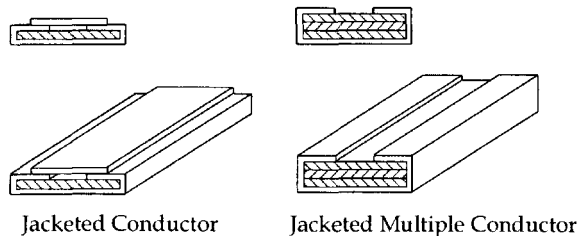


Figure 4-33. Pre-fab Foils.

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 4-34. The cut edge should be

rolled after slitting it, at least two times, to remove the sharp burrs that could cut through the insulation. It is wise, not to use insulation between layers of less than 1 mil.

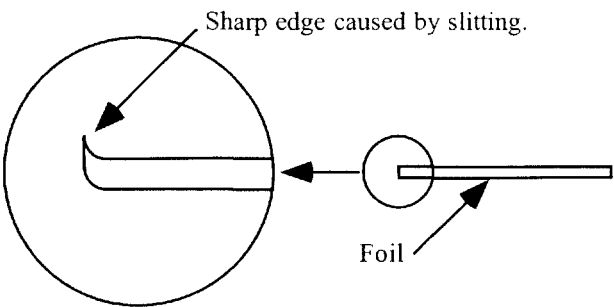


Figure 4-34. Foil with Sharp Edge Burrs after Slitting.

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 4-35.

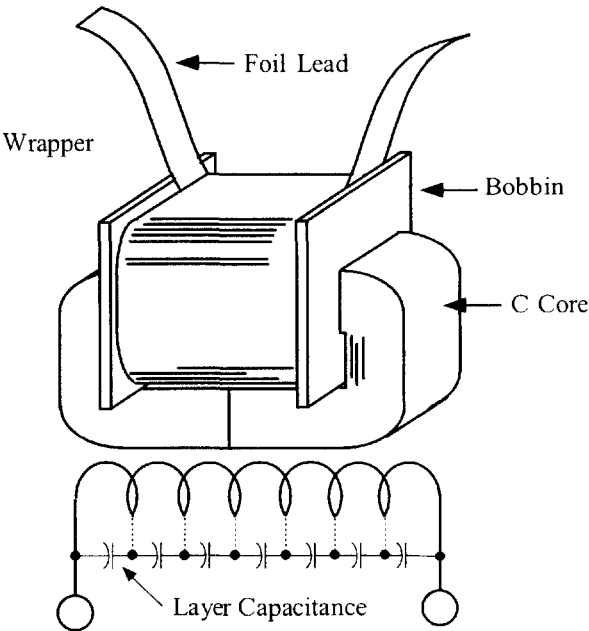


Figure 4-35. Foil Capacitance Equation.

The capacitance build up is expressed:

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

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 4-15.

Table 4-15

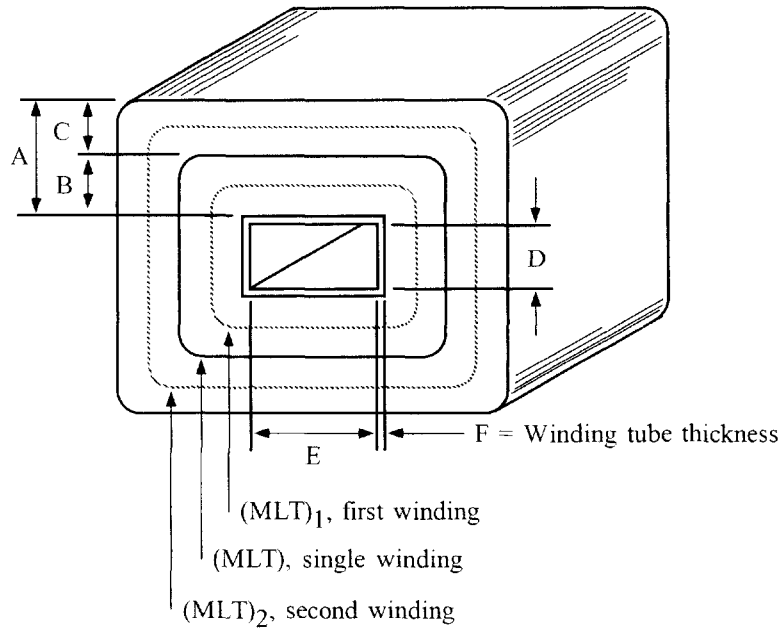
| Dielectric Constants | |
|----------------------|---------|
| Material | K |
| Kapton | 3.2-3.5 |
| Mylar | 3-3.5 |
| Kraft Paper | 1.5-3.0 |
| Fish Paper | 1.5-3.0 |
| Nomex | 1.6-2.9 |

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 4-36.

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, then, 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 4-37.

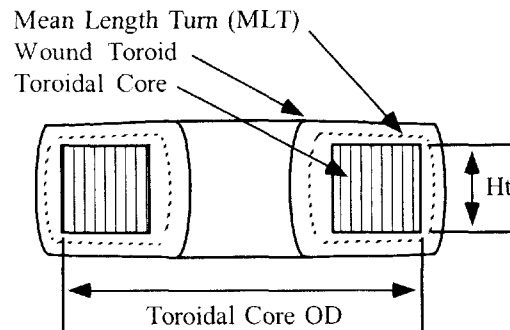


$$MLT = 2(D + 2F) + 2(E + 2F) + \pi A, \quad \text{single winding}$$

$$MLT_1 = 2(D + 2F) + 2(E + 2F) + \pi B, \quad \text{first winding}$$

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

Figure 4-36. Dimensions, Relating to the Winding Mean Length Turn, (MLT).



$$MLT = 0.8(OD + 2(Ht)), \quad \text{approximation}$$

Figure 4-37. 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 $\mu\Omega$ per cm for three different conductor materials can be found in Table 4-7.

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

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.

$$W_f = \lambda l A_w, \quad [\text{grams}]$$

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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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.