

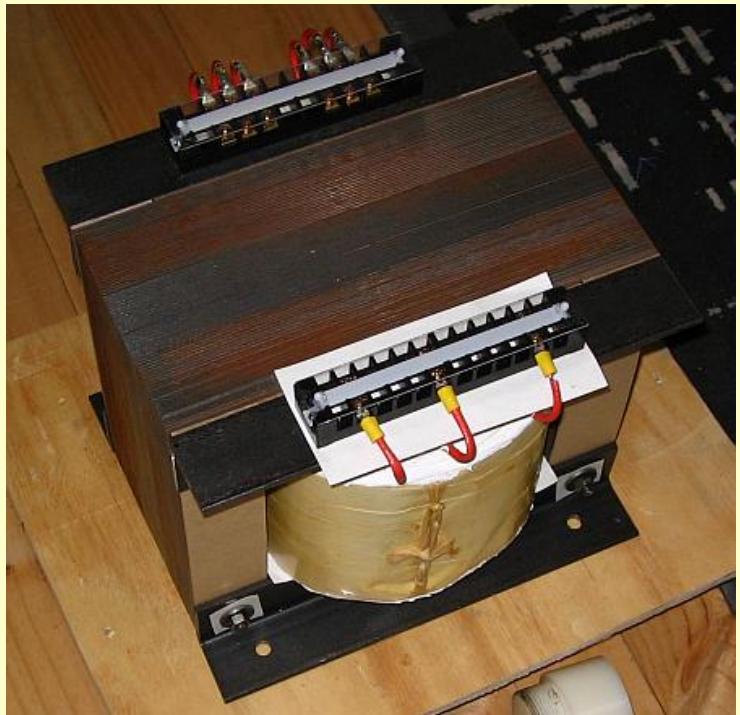
# Practical transformer winding

In the good old times it was a matter of fact that every electronic hobbyist or technician would wind himself any power transformers he needed, and rewind any that burned out. Unfortunately, nowadays transformer winding is fast becoming a lost art, and I have seen many people despair about where to find some very specific transformer, or pull their hair out about the cost of having one professionally wound to specifications.

Since I started in electronics, as a 12 year old boy, I have always wound my own transformers. I started using the basic, but useful instructions provided in The Radio Amateur's Handbook of the time, and later I came to better understand how transformers work, which enabled me to optimize a given transformer for the intended application.

Following a request by many readers of my web site, I've added this page, which is complementary to the previously published [Transformers and coils](#). You should first read (and understand!) that page, before trying to design any transformer. Then come to this more practically-oriented page, to learn some tricks and hints about the design process, and about hands-on winding.

This page addresses mainly single-phase power transformers in the power range from about 1 watt to 10,000 watts, operating at line frequencies, but much of what's described here can be applied to a wide range of other transformers too.



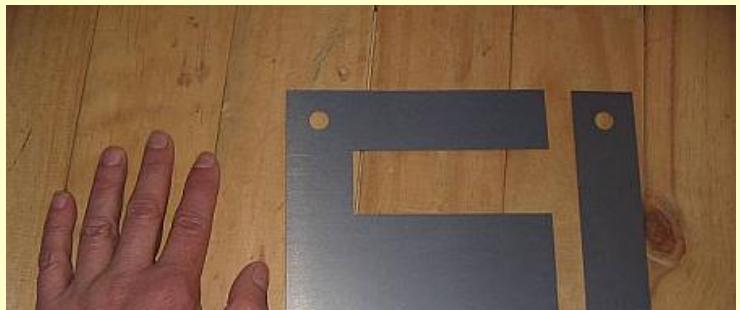
Let's start with the materials. To make a typical transformer, you need the iron laminations for the core, enameled copper wire of several different diameters for the windings, a bobbin (or some material to make one), insulating material to apply between wire layers, between windings, around the whole winding assembly, and on exposed wires, and in most cases it's also a good idea to use an impregnation varnish.

The photo here shows several stacks of iron E-I laminations, two coils of wire (with cardboard protecting the wire from damage), one roll of thick, stiff Pressspan, another roll of NMN laminate (we will soon see what that is), two small bundles of spaghetti for wire protection, and a can of transformer varnish. Add to this some glue, cotton straps, ropes, adhesive tape, terminals, bolts, angle iron, and other small material, and that's it.

All these materials are sold by companies specializing in transformers and parts for transformers. Enameled wire is also sold by many other distributors, but is usually cheapest at the places that sell it together with the other materials. You will have to dig into the phone book or some other directory to find these companies, since they don't usually have a shiny nice store in the downtown shopping mall!

Transformer iron is an alloy of iron with silicon and some other minor components. It's characterized by a relatively high permeability, very high saturation flux density, relatively low hysteresis loss, and relatively high specific resistance. This latter factor, along with the practice of using the material in thin, insulated sheets, reduces the power losses produced by eddy currents.

The most common shape of these sheets is shown at right. It's the classic "economy E-I" shape. Why it's



called E-I should be pretty obvious when looking at the photo! But the explanation for "economy" might be a bit more elusive: It's because at the exact proportions shown in the photo, the I's are nothing else than the cutouts to make the windows in the E's, when two E's are cut facing each other! This allows stamping E's and I's out of a large steel sheet, without any wasting of material, except for the little round bits cut out of the bolt holes. By the way, small laminations often don't have such bolt holes, and such cores are held together by clamps instead of bolts, or even welded.



The lamination in the photo is a large one, as the comparison with my hand shows. It's an E80 (the center leg is 80mm wide), typically used for transformers in the 3 to 10 kilowatt range!

In any E-I lamination you are likely to encounter, the center leg is twice as wide as each of the other parts. This is because the entire magnetic flux has to go through the center leg, but then splits up, with one half of the flux returning through each of the side legs. If you ever come across a lamination that has all three legs of the same width, then you are looking at a lamination intended for three phase transformers!

Such an economy E-I lamination like shown here has completely fixed proportions, beyond the rule above, that stem from the need to cut the I out of the winding window of two E's facing each other: If the center leg is 2 units wide, then the window is 1 x 3 units, the total E is 6 x 4 units, the I is 1 x 6 units, and so on.



Not all laminations follow the "economy" proportions, though. Here is an example of a lamination that comes in one piece, instead of being divided into an E and an I, and that has the windows proportionally much larger than the E-I lamination shown above. Such a lamination is a bit more expensive to make, because the steel cut from the windows is wasted, unless the manufacturer can find some other use for it. But being able to accommodate a much large winding assembly, it has some advantages in certain cases.

These "non-economy" laminations were quite usual in Europe, many years ago, but nowadays copper is so much more expensive than steel, that transformers are usually designed to use more steel and less copper. And for that goal, the economy lamination is very well suited. So you won't very often come across a lamination like this, unless you are restoring antique equipment.

The laminations should be thin, and reasonably well insulated from each other, to reduce eddy currents to an insignificant value. Typical thicknesses vary from 0.2 to 0.5mm, but higher frequency transformers (audio) use much thinner ones, while extremely large transformers might use slightly thicker ones.

The insulation is often applied at the factory that makes the big rolls of steel sheet, even before stamping the E's and I's. Different kinds of insulation are used: A thin oxide layer, a thin layer of enamel, or any of several chemical processes. Antique transformers sometimes even used very thin paper!



When I was young, patient and overly eager to do things right, I painted each and every E and I for my transformers, using diluted transformer varnish, to make a thin, nice layer. The photo shows the steel for a 200 watt transformer, drying. Later, getting old and lazy, I noticed that the layer of rust on old, recycled laminations is more than enough insulation, and that the very thin and imperfect insulation that comes on new laminations is enough too, even if it takes only a light scratch with the multimeter's test probe to puncture it and get through to the steel. We don't need perfect insulation between the sheets! We only need enough

resistance to reduce eddy currents to a low level.

Transformer steel is not all born alike. Manufacturers will provide data sheets about their products (often on their web sites), where you can see what they offer. There are usually many grades, with vastly different loss characteristics. At a given flux density and frequency, a good material might have ten times less loss than a cheap material! So it pays to look, investigate, and decide intelligently what to buy. Thinner sheets normally have lower loss, and the rest of the secret lies in the exact alloy. In any case, you need to know what material you have, to be able to make a meaningful transformer design!

Some transformer steel is grain-oriented. That means that when rolling the steel sheets, a process is used to align the crystalline grains in the direction of the rolling. This kind of material has particularly good behavior when the magnetic flux is aligned with the direction in which the sheet was rolled, but is worse than standard material in the perpendicular direction. Such grain-oriented material is ideal for toroidal cores, which are made by coiling up a long strip of steel, but is not a large improvement for E-I laminations, because in these a significant portion of the material has to work with the flux perpendicular to the rolling direction.



Enamelled copper wire comes in many different diameters, and with several different kinds of enamel. The diameters vary from less than that of a hair, to about that of a child's finger. Different standards exist for the wire diameter. A very common one is *American Wire Gauge*, shortened to AWG, which is used in much of the world. Britain has its own standard, and in many countries the wire is specified simply by its diameter in millimeters.

Thick wires usually are coated with a sort of enamel that is very tough, an excellent insulator, highly heat-resistant, highly resistant to solvents, and that clings to copper even better than dirt does to children! This enamel is usually yellowish clear, so that the wire coated in it looks mostly copper-colored, but many exceptions exist. To solder the ends of these wires, it's necessary to scrape off the enamel, using a sharp knife or similar tool. This procedure would be too difficult with a thin, fragile

wire, so that these thin wires are instead covered with an enamel that has most of the same characteristics of the other one, except the heat resistance: It will melt and turn into solder flux at a temperature a common soldering iron easily achieves! This allows easily soldering these wires, without previously stripping them. But transformers using this latter kind of wire enamel cannot survive temperatures as high as those using only the former kind of wire enamel. The red wire on the right side in this photo has this kind of enamel. But be careful with colors! The clear wire on the extreme left side also has solderable enamel, while the dark violet one in the middle is of the non-melting variety!

The thickness of the enamel layer depends on the wire thickness, the manufacturer, and can sometimes be chosen: Some manufacturers will offer the wire with several different thicknesses of enamel. In any case, the diameter specified by a certain AWG number refers to the copper diameter, so that the complete wire, with enamel, will be slightly thicker than what the AWG standard tells!

Here is a [wire table for AWG wire](#). It shows the AWG number, the diameter in millimeters excluding the enamel, the approximate typical total diameter including the enamel (but this varies somewhat), the cross sectional copper area in square millimeters, the area of the square of window space occupied by that wire in a transformer (including the enamel, of course), the current carrying capacity at a typical, average value of current density, the resistance in ohms per meter, and finally how many meters of that wire come in one kilogram, because enamelled wire is usually bought by weight, not length.

This table has wires from AWG #1 to #40, and for the thickest ones I didn't calculate all data. But you should be aware that there are wires exceeding this range! The thinnest I have ever used was #46. It breaks when you blow at it! The photo here shows a #39 wire lying on a #7 wire. The hairy thing below is my floor carpet. Note that even this #39 wire is not much thicker than the hairs of this carpet!



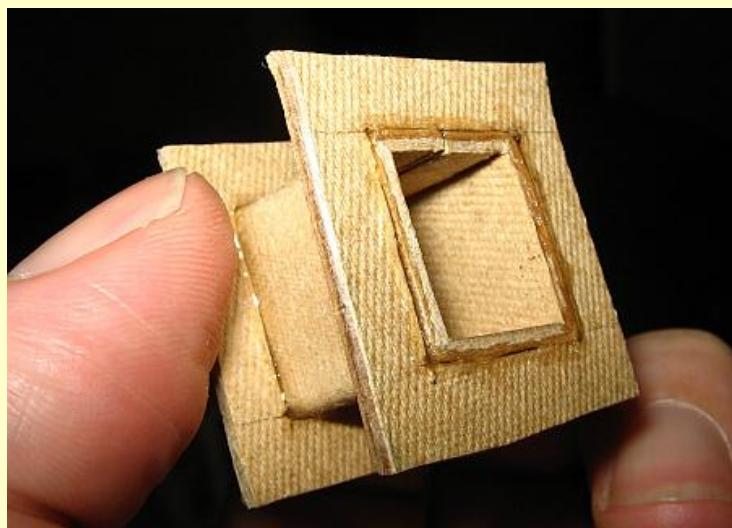
It's interesting to note that every three AWG numbers, the cross sectional area exactly doubles. Any deviation from this in my table is due to approximation errors.



Modern transformers of small to moderate size are usually wound on plastic bobbins. Here you can see simple ones. Some bobbins have pins or terminals molded into them, others have one or two divisions. Some don't have the slits for terminals, which the ones shown here do have.

Typically for a given size of E-I laminations, bobbins will be available in two or three sizes, accomodating different numbers of steel sheets. So you can vary the amount of steel in your transformer not only by choosing the lamination size, but also the height of the lamination stack!

Here is a little transformer using a divided (or split) bobbin. This is very practical, because it completely separates the primary from the secondary winding, making it much easier to achieve the degree of insulation required for safety. More about that later.



If you cannot find a plastic bobbin in the proper size, don't despair! Bobbins can be easily made from materials such as strong cardboard, or Pressspan, which is nothing else than a particularly strong cardboard.

The bobbin shown here was made from 1.5mm thick Pressspan, which is really too thick for this small bobbin, but I had nothing better on hand. The pieces are cut to size using a sharp knife (X-acto or the like), and glued together with cyanoacrylate adhesive (instant bonder). The clever structural design of this super high tech bobbin holds it together perfectly while the glue sets!

You must make the inner dimensions of the bobbin core a tad larger than the transformer center leg, but JUST a tad, no more, unless you want to waste valuable winding space! The sides can be made

pretty tight to the size of the laminations, because if they don't fit at the end, they are easily enough cut or filed down, even after the winding has been made. But the length of the bobbin must be smaller than the window length of the core, by as much as 2 or 3%, plus any tolerances of your manufacture! Because it is critically important that the E's and I's can touch each other properly, without being kept separated by a bobbin that deformed during winding, and grew!

Be sure to at least break the corners as shown here, or even better, round them off. Otherwise the wire is guaranteed to tangle at the sharp corners during winding, and a wire loop sticking out of the

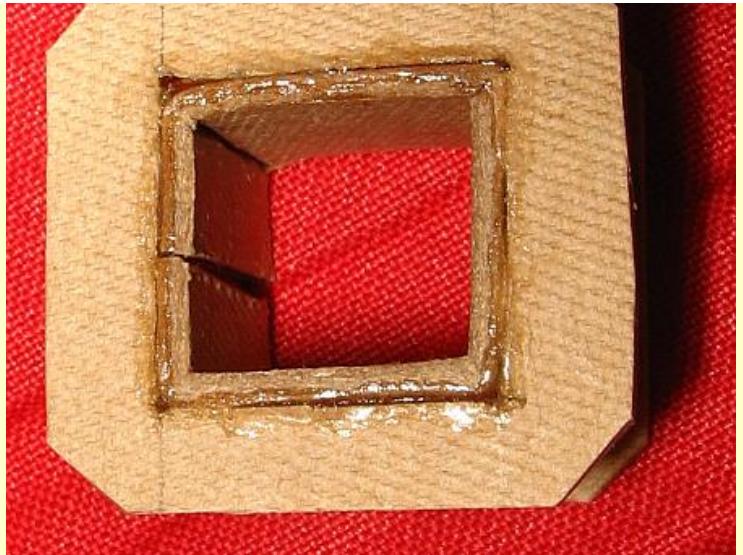


completed winding can ruin the whole thing!

Note that the junction of the bobbin's center piece is placed in the middle of one side, and not in a corner. It's next to impossible to produce a reasonably symmetrical and precise bobbin when placing the junction in a corner.

If the material is thin compared to the bobbin size, the junction should be made by overlapping the material. Of course, the overlapped junction is always placed on one side that will end up outside the core window, so that the added bulk has little detrimental effect.

To bend this thick material in reasonably clean right angles, my technique is to use a sharp knife to cut out a 90 degree wedge from the inside, along each bend line, leaving only the outer third of the material intact. After that admittedly cruel treatment, the Presspan eagerly bends to my will.



Most antique transformers, and many of the larger modern ones, don't use a real complete bobbin. Instead, they use only the center former, and no sides at all! It takes some tricks and practice to wind a transformer like this without having the whole thing come apart many times over during winding, but for people who have acquired enough practice, it's faster than making a real bobbin!

Further down, I will show you a trick to make this kind of transformer, with high quality.

Note in this photo how the Argentinian maker of this transformer (back in 1931!) used insulating material of several different thicknesses for the bobbin center, the interlayer insulation, the interwinding insulation, and the terminal support.

You might ask why any insulation material is required at all, if the wire is insulated by its enamel layer! Well, the enamel is very thin, and easily scratched. It might survive as much as a few thousand volts, but it might also break down with a lot less! It depends on type, condition, thickness, temperature, and other factors. So, wherever the voltage can exceed a few tens of volts, some additional insulation needs to be used. Specially between the primary and secondary, safety regulations ask for an insulation good for at least

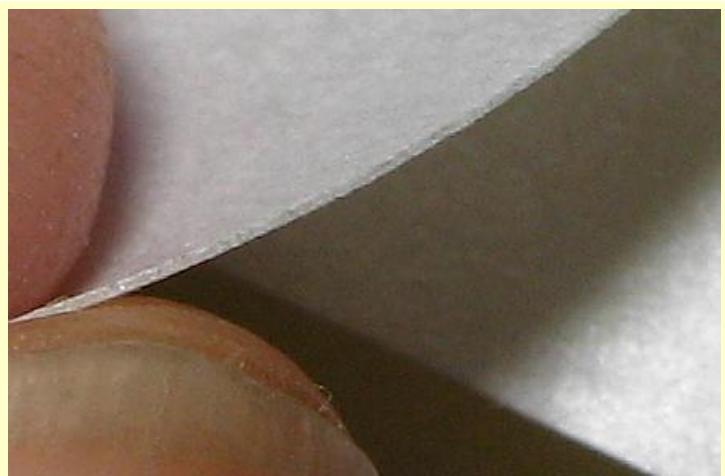
4000 volts, to avoid electrocuting somebody when there is a lightning transient on the AC power network.

In antique transformers, the most usual insulating material was paper, impregnated with something like beeswax, tar or the like. This impregnation had several purposes: Mainly, it would seal the pores of the paper, making it a really good insulator, while without the impregnation it would only insulate as well as the same thickness of air! But in addition, it kept moisture out, it helped stick the thin wires in place during winding, and it improved the thermal conductivity of the completed winding assembly.

It was also quite sticky, dirty, messy and gross.

Modern insulating materials are far superior. Plastic sheets such as Mylar provide excellent dielectric strength and have no pores, so they require no impregnation to realize their high degree of insulation. Nomex instead, with its fibrous structure, behaves like paper, but both Nomex and Mylar are much better than paper at surviving high temperatures! This is a key characteristic of insulating materials: The temperature class. It's coded with a letter. Paper would have an A or B rating, telling that it is fine for temperatures not much above that of boiling water. Different plastic insulation materials instead are routinely available in classes as high as F, G or even H! They can safely run much hotter than paper can.

The photo shows an NMN insulating sheet. This is a sandwich of a Mylar sheet embedded between two layers of Nomex. The Nomex will eagerly soak up and distribute the impregnation varnish (or the oil, in an oil-immersed transformer), while the Mylar will provide safe insulation even in places that for any reason stayed dry! I love this material. It's thermal class G, if I remember right.



Insulation materials come not only in many different variants, and temperature classes, but of course also in many different thicknesses. You choose the proper thickness so that it has enough dielectric strength and mechanical strength, without taking up an undue portion of your valuable window space!

Despite all modern materials, good old paper and cardboard is still used sometimes. Mostly in its form known by the German word Pressspan, which means "compressed chips", and is simply a very dense paper or cardboard.

It's very good practice to soak a completed transformer in some impregnation varnish. It will form fillets around wires, papers, and anything else. It will improve the insulation, make the transformer highly moisture-proof, glue everything together so that nothing can rattle, come loose, or chafe through, it will improve thermal transfer, and so on.

Varnish comes in several thermal classes, just like the insulation material, and also it comes in variants that dry at high temperature, or at room temperature. My experience is that no varnish ever fully dries at room temperature, and when you start using the transformer and it warms up, the varnish inside will start drying, and stink! So, it's necessary to apply heat anyway, regardless of what sort of varnish you use.

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Now that you have turned into a person very knowledgeable about transformer materials, let's turn to those pesky questions such as "how many turns do I have to wind?" or "what wire size?" or "how much power will I get?"

There are three typical situations:

1. You need to repair/rewind a transformer that burned out.
2. You want to rewind an existing transformer, to produce the voltages and currents you need, which are different from the original ones. A variation of this case is when you want a certain voltage, at the highest current that transformer can provide.
3. You have fixed specifications, want to design a transformer to optimally meet them, and you will buy the core and all other materials.

Let's start with the first case. You MUST find out why that transformer failed! A correctly designed, correctly built and correctly used transformer is, for all practical ends, eternal. If it failed, there is a reason. If you know that the transformer was shorted, overloaded for a long while, exposed to intense lightning transients, thrown into water, gnawed through by rats, exposed to corrosive substances, or anything like that, then your best approach is to unwind it, count the turns, measure the wire sizes, and rewind it exactly as it was originally made.

The photo shows an antique speaker field coil, mounted in my winding machine. I unwind coils by pulling off the wire while having the thing spin in the machine, so that the turns counter in the machine will do the pesky job of keeping count. The problem, as illustrated here, is often that thin wires won't come off nicely! They are stuck in place, and will break, then entire chunks of wire will come off all together. This often makes it hard to accurately count the turns.



In such cases you might simply estimate how many turns you didn't count. Or you can collect all the pieces of wire you removed, weigh them, calculate the amount of wire from there, and calculate the turns number from it. Or, instead of unwinding the coil, cut it with a knife or better a Dremel tool, remove it in one block, measure the cross sectional area of the entire winding, then remove a little piece of wire to measure the diameter, and finally calculate the number of turns from this. Any of these methods will usually be precise enough for non-demanding applications, and none of it will be precise enough when you need anything critical.

By the way, do you know how to precisely measure the diameter of a thin wire, when you don't have a micrometer screw? Simple: You wind 10 or 20 or even more turns tightly on a former (such as a screwdriver stem), measure the length of the coil with a common ruler, then divide by the number of turns to get the wire diameter. It's highly accurate. Sometimes it's even better than using a micrometer screw, which can flatten the wire if you apply too much torque!

But there are cases when you have a burned transformer, and no good reason why it burned. It might have been a manufacturing defect, a huge transient, an overload that went undetected, but maybe - the Gods of Electromagnetics forbid - that transformer might have been misdesigned! In that case, painstakingly rewinding it with the same wire gauges and turn numbers as original, will only produce a transformer that will fail again. So, if you don't know why a transformer failed, redo the design, and compare your results with what the manufacturer did! Many manufacturers are cheapskates, and use substandard transformers, in the hope that most clients will never use them intensively enough to blow them up! This sends you straight to the section about the third case, further down this page!

In the second case, when you want to rewind an existing transformer for new output values, very often the transformer will already have a properly wound and healthy primary winding. In such a case, keep it! There is no point in unwinding and rewinding the primary, if it is fine. The calculation work for such a transformer is quite simple: Before taking it apart, measure the voltage delivered by the secondary. Disassemble it, unwind the secondary, counting the turns, and calculate the number of turns per volt from this. Calculate the new number of turns you need for your desired voltage. Calculate what's the largest wire size that will comfortably fit in the available space. Get the wire, wind it, and assemble the transformer. The power rating will be the same as before, and this allows you to calculate the current you can safely draw, at your new voltage.

And if you also want a new primary, well, do the same as above, but unwind and re-wind all windings, according to the value of turns per volt you found out!



Do you know what you can do with all that wire you remove from old transformers? Well, a super trendy wig, like the one shown here, modelled by my sister, is sure to catch everybody's attention! Otherwise, there isn't really much use for such wire. It comes out totally kinked, stretched, broken, scraped, with varnish, wax or tar sticking to it. Don't even dream about ever re-using it in any other transformer!

OK, now it's time to really start designing a transformer. Because this is what you have to do in case 3, which is essentially creating a transformer from scratch. I hope you are still fresh and aware of everything you learned in [Transformers and coils](#), because you will need it here to understand what's going on.

The design process starts with guessing the size of core you need, for the power you want. If you are experienced in electronics, you will be able to make a reasonably close first guess. Otherwise, use the data given by core manufacturers to get this first guess.

The core chosen will have a certain cross sectional area, and will have a certain window area. The two multiplied are the "area product", which can be

related to the approximate power capability, with a reasonably simple, but nonlinear curve. This curve also depends on the quality of the core material, and several other factors.

The next step is calculating how many turns per volt you need on this core. To this end, you have to decide how much flux density you will put through your core, and then you can apply the equations from [Transformers and coils](#). The optimal flux density might be anything from 0.8 to 1.6 Tesla, and sometimes even outside this range! General rules of thumb are these:

- Larger transformers use lower flux densities.
- Better core material uses higher flux densities.

- Transformers that are always energized, but rarely used at full power, use lower flux densities.
  - Likewise, transformers that work at full power whenever energized, use very high flux density.
  - Forced air cooled transformers use higher flux density.
  - Oil-immersed transformers use even higher flux density!
  - Higher flux density produces better voltage regulation.
  - Lower flux density produces less base loss.
  - Lower flux density is less likely to produce humming noise, and magnetic stray fields.
  - Lower flux density produces lower iron loss, but higher copper loss.

I have seen many text books giving design equations that result in a flux density of 1 Tesla in each and every transformer you calculate by them, like if that were a sacred rule! If you come across any such book, BURN IT! It's nonsense! While 1 Tesla indeed tends to produce a workable transformer in most cases, in at least 70% of all situations it's far enough from the optimal value to warrant some effort toward optimization! Specially in small transformers, and in those using the better core materials.

So, I suggest to start with a value chosen from the rules above, and then calculate the transformer based on this value, analyzing the losses, heating, voltage drop, efficiency, and so on. Then change the flux density, by 10 or 20%, and re-do all the calculations. You will see what I mean! There is a clear optimum value for flux density in each particular case, and this value is very often sufficiently removed from 1 Tesla to make you wonder why some book authors still copy that "magic number" from other, long gone authors! Most likely they have no idea about the matter they are copying.

That said, sometimes I do wind my transformers for 1 Tesla, because there are cases when this is really a good value!

The loss calculation isn't very hard: The manufacturers of transformer steel specify the loss of their products, as a certain amount of watts per unit of volume or weight, under certain conditions of frequency and flux density. And the better of these data sheets also contain curves, or give equations, to calculate the loss under different conditions. That's about the iron loss. The total loss of the transformer also includes the copper loss, which is caused simply by the current flowing through the resistance of the wire. For a given flux density you get a certain number of turns per volt, this allows you to calculate the total turns in each winding. Dividing the available window cross section between these wires, insulation, bobbin, and inevitably wasted space, you get the wire cross sections. From the dimensions of the core, you can then calculate the total wire length, from this and the cross sections you calculate the resistances of the windings, and from that and the currents you calculate the power loss. It's easy!

What? You are banging your head against the wall? Come on! Don't cry! I have prepared an Excel sheet for you, which takes care of these calculations! It's really too time consuming to do all this math step by step, every time. Click on the screenshot at right to get the Excel file, and then play with it as you continue reading.

In this sheet, you enter your data in the green area, and watch what happens in the orange one. The first three values you have to enter are the ones that specify the core. First is the center leg width of the lamination used, in millimeters. The 100mm width given in the example is a pretty large lamination. You will typically use values between 12 and 50mm. The sheet is based on the proportions of the economy E-I core, so that you don't need to enter any other dimensions of the lamination. If you happen to be using a lamination that has different proportions than the economy E-I, you should still enter the width of the center leg, but later by increasing wire size beyond that calculated by the

| Transformer calculation sheet, by Manfred Mornhinweg |          |   |          |                               |                     |                               |
|--|----------|---|----------|-------------------------------|---------------------|-------------------------------|
| Input data:  | Iron:    | Center leg mm:  | 100      | Design decisions:             | Flux Density T:     | 0.4                           |
|  |          | Stack height mm:  | 150      |                               | mm <sup>2</sup> /A: | 64                            |
|  |          | Loss W/kg@11.50Hz   | 2        |                               | Fill factor:        | 84                            |
|  |          | Primary V:  | 230      |                               | Temperature rise K: | 70                            |
|  |          | Secondary no-load V:                                      | 2000     | Prices:                       |                     |                               |
|  |          | Frequency Hz:   | 50       |                               | Iron \$/kg          | 3.2                           |
|  |          |   |          |                               | Copper \$/kg        | 18                            |
| Output data:   |          | Cross section mm <sup>2</sup> :                           | 15000    | Window area mm <sup>2</sup> : | 7500                | Copper area mm <sup>2</sup> : |
|  |          | TURNS per Volt:   | 0.3003   | Avg. turn length mm:          | 657.0796            | 3000                          |
| Primary turns:                                       | 69.06907 | Length m:   | 45.38388 | mm <sup>2</sup> :             | 21.71739            | Ampere:                       |
| Secondary turns:                                     | 600.6006 | Length m:   | 394.6424 | mm <sup>2</sup> :             | 2.4975              | Ampere:                       |
| Input power VA:                                      | 9990     |   |          | Iron loss W:                  | 138.6               |                               |
| Power loss %:  | 2.96957  |   |          | Copper loss W:                | 157.6991            |                               |
| Voltage drop %:                                      | 1.57857  |   |          | Total loss W:                 | 295.2991            |                               |
| Loaded Vout:   | 1968.429 |   |          | Surface area m <sup>2</sup> : | 0.3154              |                               |
| Iron weight kg:                                      | 69.3     | Required thermal transfer coefficient W/m <sup>2</sup> K: |          |                               |                     |                               |
| Copper weight kg:                                    | 17.60316 | 13.42056  |          |                               |                     |                               |
| Cost \$:   | 503.4106 | 7 is easy to get<br>Convection cooling up to 12           |          |                               |                     |                               |
| Cost €:  | 360.2024 | Strong fan up to 30                                       |          |                               |                     |                               |

The second value you have to enter about the core is the stack height, also expressed in millimeters. This is simply the height of the stack of E's, well compressed. This sheet does not allow you to enter the stacking factor, which tells how much of the stack is actually steel. There's always some little space used by insulation, and even wasted space due to imperfect

compression. But the effect of this is small enough to ignore, as long as you compress the stack well enough!

Good stack heights to use are from the same as the center leg width, to close to twice that. Often you have the choice to use a certain lamination, stacked as high as the center leg is wide, or use the next smaller lamination, stacked much higher, with both options producing the same output. It pays to simulate both options, optimize each, and compare the efficiency, voltage drop, weight, and cost! The differences can be profound.

And the third value is the loss factor of the steel material. This must be taken from the datasheet provided by the manufacturer of the lamination. My sheet expects this loss factor to be expressed in watts per kilogram of material, at a flux density of 1 tesla and a frequency of 50 hertz. Many data sheets include the value in this exact form, but those published by US companies might instead express the loss factor in an eclectic mixture of metric, CGS and Imperial units! If that's what you have, you will need to convert the value into its fully metric equivalent. You might want to modify the spreadsheet to do that.

The value of 2 W/kg @ 1T and 50Hz is pretty representative for modern low cost laminations. A modern ultra low loss material might be a lot better, while an antique or ultra-cheap material might be significantly worse.

The next three values in that column are pretty obvious: You have to indicate the primary and secondary voltages, and the frequency of operation. The secondary voltage refers to the open circuit (no load) voltage. And the frequency will usually be either 50 or 60 Hertz. If you enter a frequency far away from this, it's quite possible that the loss calculated for the material will be rather imprecise, so use this sheet with caution if you need to design a transformer for a very different frequency.

In the right hand column, you have four values which are design decisions which you can vary somewhat. The first is the all-important flux density. Just try varying that value, and watch how things change in the orange output area! Specially, see what happens with the iron loss. I have already given guidelines about what flux density to use. Use them and see what happens in your case, when you change it.

The next is the amount of copper cross section you will allow for each ampere of current in the windings. Reasonable values are about 0.25 mm<sup>2</sup>/A for very small transformers, increasing to 0.5 for large ones. 0.35 is typical for medium sized transformers (50 to 300 watts or so). When you adjust this value, the design of the transformer doesn't really change, but the sheet will calculate a new set of currents, power, voltage drop, efficiency and loss. With this parameter, you basically are telling the sheet how much you will stress a particular transformer.

The fill factor expresses how much of the lamination's window will actually be filled with copper. It can never be very high, because a lot of that area gets inevitably filled out with the bobbin, the wire's lacquer, the air around the round wire, the insulation between layers, between windings, and some space is always lost due to sloppy winding, even if you are careful! The value of 0.4 used in this example has proven in practice to be achievable without much trouble. If you wind very carefully, and minimize the amount of space devoted to insulation, you should be able to get up to 0.5. But don't push this number too much, or you will end up with a transformer design that you cannot actually wind! On the contrary, if you have never before wound a transformer, and will do so by hand, in a ragged, ugly winding, it might be a good idea to design the transformer with an even lower fill factor, such as 0.3, to make sure you will be able to fit all the turns! Of course, using a lower fill factor means simply using thinner wire, and this means that at a given amount of loss and heating, you get less current.

The fill factor can be pushed beyond 0.5 when you wind a transformer with square wire (instead of round), or with copper tape separated by thin layers of insulation. But square wire is hard to find and a hassle to wind properly, and tape winding is acceptably easy only for transformers that have rather few turns. This is often the case with high frequency transformers used in switching power supplies, but not at line frequencies.

The temperature rise defines how many Kelvins (same as degrees Celsius in this case) hotter than the surrounding air and objects you want your transformer to run. You need to carefully choose this value, according to the highest ambient temperature (inside the equipment!) at which your transformer will have to work, also taking into account the highest temperature your wire, insulation material, varnish, glue, etc, can survive. And what's most difficult, you will also need to estimate the thermal gradient from the innermost wire turns (the hottest ones) to the transformer's surface! Calculating all this can be quite hard, and I can't give you simplified equations for it. Maybe you can find them elsewhere. The value of 70 Kelvins which I used in the example design is relatively high. This is so because this transformer would work in open air, not inside a housing, where the ambient temperature is never above 25 degrees Celsius; also, I used class G or higher insulating material, wire and varnish throughout; and finally, this transformer was carefully impregnated with varnish, giving it a reasonably good thermal conductivity between winding layers.

If your transformer will not be impregnated, or use class A or B insulation material (paper), or run inside a cabinet that can be hot, then you will need to use a lower value for allowed temperature rise than my 70 Kelvins!

Finally, you can enter your local and current prices for enameled copper wire and transformer steel laminations, to have the sheet calculate the cost of these main materials for your transformer. All the additional cost, for the bobbin, insulation material, terminals, bolts and so on, is usually small compared to the copper and steel cost. The most expensive item is usually the wire, by far.

The first two lines of the orange output area of my spreadsheet show some basic results for that transformer: The cross

sectional area of the magnetic core and of the winding window, also the total copper area (after applying the fill factor), the turns per volt constant that will be valid for all windings on this transformer, and the average length of one turn, which is calculated as the average between the length of a wire that goes around the center leg touching it, and one that goes around the entire winding package, touching the outer legs.

Then you have a line for the primary winding and one for the secondary. Each of these lines tells you the number of turns, the length of the wire need to wind it, the copper cross sectional area of the wire, and the nominal current that will flow at full rating. The number of turns isn't rounded off, so you will have to do that, because you can't wind a fraction of a turn. You can fiddle with your voltage data to get the sheet to show round numbers of turns. The wire length is based on the length of the average turn, so this will be correct only if you wind the primary and secondary side-by-side, on a split bobbin. If instead you wind the secondary on top of the primary, you will need less wire than calculated for the primary, and more than calculated for the secondary. Anyway, these lengths are not very useful in practice, because wire is bought by weight, not length. The main situation where they are useful is when you have to wind a transformer with several thin wires in parallel, because these are much easier to bend than one thick wire. In such a situation, it's great to know how long the total winding is, so that you can cut the strands and twist them together, before you start winding.

The remainder of the orange output area is divided into two columns. The left one shows some important performance data of the transformer: There is the input power, expressed in voltamperes, which is really more correct than watts. The value calculated by the sheet does not include the magnetizing current; Calculating it would need additional information about the core. But in medium to larger transformers, at least, the magnetizing current tends to be small enough to be ignored.

Then comes the percentual power loss of the transformer, at full load. This includes both the iron loss and copper loss. The output power is of course the input power minus this loss.

Then we can see the voltage drop at full load. The value is calculated only from the resistances of the windings. Any additional loss caused by imperfect coupling between the windings is not considered here. So, if you use a poor core or winding technique, that results in bad coupling, you should expect a somewhat higher voltage drop. Just for user convenience, the sheet also calculates the output voltage under full load, which is based on the voltage drop calculated above.

Below comes the weight of iron laminations and copper wire used in the transformer. This has several purposes. One is knowing how heavy the beast will be, of course. The other is knowing how much material you have to buy! If you use side-by-side winding of the primary and secondary, you need to buy one half the calculated copper wire of each size (plus some extra, of course, to be on the safe side). If instead you wind the secondary over the primary, you need a little less than half of that weight of the primary wire, and a little more than half that weight of the secondary.

And then, the sheet will calculate the total cost for laminations and wire, and also divide this by the power, to give the cost per watt for your transformer, which is a good figure of merit which you might want to optimize. Even while this calculation doesn't include the cost for insulating material and other odds and ends, it's still a good reference.

The right side column of this area is about thermal matters. These tell whether your transformer will survive, so don't take them lightly! The sheet calculates the power loss in the iron, in the copper, and adds them to get the total power loss. Copper loss is calculated at ambient temperature, though. When the wire heats up, its resistance increases, and so its loss increases too! For this reason, take the calculated value with a small grain of salt. The same is true for the voltage drop and efficiency calculations!

You need to be aware of the fact that the iron loss is essentially constant, regardless of the load placed on the transformer, except for a little effect caused by voltage drop in the windings reducing available magnetizing voltage, which causes a slight **decrease** in core loss when the load gets **higher**! The loss in the wire instead increases with the square of the current taken from the transformer, and the value calculated by the sheet is for the full rated current.

This gives you some big help in optimizing a transformer design. For example, a transformer that will spend lots of time plugged in, but idling or loafing along at low load, will see very little copper loss, but the iron loss will be there all the time. So, you should design that transformer with a relatively low flux density, resulting in low core loss, accepting a higher copper loss instead, by setting a smaller value of copper cross section per ampere. After all, most of the time the rated design current won't be present, so that the very high copper loss resulting in the calculation will be present only very rarely, for short times! Transformers used in radio communication equipment, in audio amplifiers, and many other uses, are best designed in this way.

The opposite case happens with transformers that are energized only briefly, but run at full output power whenever energized. Examples of such use are microwave ovens and spot welders. In such a transformer, iron loss always happens at the same time as copper loss, and you can optimize the transformer to get the lowest total loss, regardless of how it distributes between the iron and the copper. Even more, you might intentionally place more loss into the core than the windings, based on the fact that the core is less prone to be damaged by heat, has more thermal mass, and that the short operation time won't allow the peak heat to distribute through the transformer! And then, such a transformer that operates only for short times can be designed to have a really huge loss, because it will have time to cool off between uses! These things are what makes microwave oven transformers that deliver 800 watts be as small as a 200 watt transformer intended for continuous service at low rate, and run at a flux density of 2 teslas or even more!

The heat produced by a transformer has to be dissipated to the surrounding air. The spreadsheet calculates the approximate total surface area of the transformer, and finally calculates a required thermal transfer coefficient, which expresses how much power the transformer needs to dissipate per unit of surface it has, and per temperature rise allowed. This coefficient tells you how difficult it will be to keep this transformer cool enough to survive! The violet area below this coefficient includes referential values (not calculated by the sheet) which you can use to try judging whether your transformer will be OK, when you have it in a tight area, in a more open area, cooled by a fan, or immersed in oil. I have my doubts about these values, specially about the value for the oil-immersed transformer, so please take these with a big grain of salt, and let me know if you have any further, better, or more reliable data.

Anyway, my transformers designed for a coefficient of around 12 have all survived so far, even while getting quite hot at full load, so this value can't be too far from the truth.

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A typical design sequence using this spreadsheet would be to first enter the tentative core size and loss, the required voltages and frequency, then start with something like 1 tesla and  $0.35\text{mm}^2/\text{A}$ , leaving the fill factor at 0.4 and setting the temperature rise according to your transformer's materials and environment. Then you can observe the power and current it would operate at, and the losses, efficiency, voltage drop, and also you would get the thermal transfer coefficient which you can compare to the table to gain an idea of whether the transformer will survive. You can then tweak the flux density and current density, trying to get the characteristics into the range you need, without exceeding the thermal possibilities. If you just can't find a combination that provides what you need, you will have to try with a larger (or lower loss) core. Then you might want to explore several different core sizes, optimizing each, and watch the cost, finally settling for the design that best provides what you need, at the lowest possible cost, while staying in the survivable thermal range.

This work with the spreadsheet is only the first step, though. When you have arrived at a good design using the sheet, you need to tweak it to make it buildable with real, available material! For example, you cannot get wire in any desired diameter. The sheet doesn't know that; It might ask you for a wire measuring 1.2345 square millimeters, or anything else. It's **your** job to see what wire you can actually buy, or maybe what wire you happen to have in stock, and adapt the design. The AWG standard is quite finely stepped, so you don't need to change the design very much to adapt it to standard AWG sizes. But I have heard that in the US many stores only sell the even numbered AWG sizes of wire! That's odd (pardon the pun), since even down here in less developed Chile I can easily buy all AWG sizes, even and odd. If you are limited to even sizes only, you will have to make bigger compromises.

A good approximation technique is to round the wire size to the nearest AWG size, or if the values calculated fall just in the middle between AWG sizes, you might want to use the next thicker wire for the primary, and the next smaller wire for the secondary. That way the final losses and the amount of space required will be almost exactly the same as calculated by the sheet.

If your transformer uses lots of turns of thin wire, you are about ready to start winding at this point. But if it uses a winding that has few turns of a thick wire, you should check how well (or how poorly) that wire fits in an integer number of layers, considering the width of the bobbin, and about 5% of lost space due to the wire not being perfectly straight. The problem is this: If the sheet calculates you need 48 turns of a certain wire size, and it happens that you can fit only 15 turns per layer, then you will end up with three complete layers, plus one additional layer in which you have just three turns! So the total height taken up in the window by those 48 turns will be as much as 4 complete layers, that could have 60 turns! Consequently, the winding might end up too high, and won't fit the window! Then you cannot assemble the core, and you have to unwind that winding, throw the wire away, get new (thinner) wire, do it again... you get the idea. Try to avoid such frustration!

When you are in the situation just described, it would be wise to try the next smaller wire size. It's very likely that this smaller wire size would accommodate 16 turns per layer, thus allowing you to wind the 48 turns in three nice, clean, complete layers, and using up a little bit less space than calculated by the sheet. This can in turn allow you to use the next larger wire size for the other winding, which will almost completely compensate for the higher loss and voltage drop of the smaller wire you used for the 48 turns!

Putting it in short words, you have to pick the best wire sizes for your transformer so that their cross sections are close enough to the calculated values, but still allow a good, space-saving distribution on the bobbin and thus inside the window area of the core.

Sometimes you might end up with a high current transformer requiring a very thick wire. Such a wire is very stiff! If the bobbin is small, you might not be able to bend that thick wire tightly enough around the corners of the bobbin. The result would be a huge loss of space, and the completed winding wouldn't fit in the window, making it unusable. To work around this problem, you can replace one thick wire by a bundle of seven wires, each of which is one third as thick as the single wire. Such a seven wire bundle twists very nicely into a round cable, and is more than 20 times as flexible as the single thick wire! It costs only very slightly more money, and performs great. So, this is the way to go when you have a need for such thick high current conductors. It's good to know that an AWG number 10 units higher is roughly one third the diameter. So, if you would need a #7 wire and this is too thick to wind comfortably, you can use 7 strands of #17, lightly twisted together.

Sometimes instead of using one thick wire you will also find it convenient to wind with two or three thinner wires in parallel, without twisting them. This technique can significantly ease the distribution of a winding in entire layers.

Another hint: Most transformers use some thin and some thick wire. For transformers that have the windings on top of each other (instead of side-by-side), I suggest to **always** first wind the windings that use the thin wire, then the ones using thicker wires, regardless of which will be primary and secondary. This allows to wind the stiffer wire on the outside, where the bending radius required is a lot larger and thus less demanding. Whether the primary is under or over the secondary has no significant effect on performance.

You might have noticed that my spreadsheet only considers transformers that have a single primary and a single secondary. But many transformers use several secondaries, and some use two or more primaries! In such cases you will have to do some more work manually. You should use the sheet to calculate the transformer, simulating only the main secondary, tweaking it for the total power, and then manually reduce the wire size of that secondary proportionally to the percentage of the total transformer power this secondary will have to deliver. Then you can add the other windings, calculating their turns number from the turns per volt calculated by the sheet, and the wire size from the current they have to carry, and the  $\text{mm}^2/\text{A}$  you selected.

Or if you have two equal secondaries (or two equal primaries!), you can let the sheet calculate a single secondary (or primary) of twice the voltage. That will produce the correct number of total turns and wire sizes. You only have to remember to cut the wire after having wound half of the turns, bring it out, start again and wind the second half!

You might have noticed that I didn't assign additional wire cross section to the primary, to account for the magnetizing current. The reason is that the magnetizing current is normally much smaller than the main current, and on top of that, the magnetizing current is 90 degrees out of phase with the main current! The vectorial sum of the main and magnetizing currents is so little higher than the main current alone, that there is usually no need to consider the difference.

You might also miss any discussion of core saturation. The problem is that's quite hard to discuss saturation of silicon steel cores, because they just don't saturate at a well defined level of flux density! Instead, the saturation is quite gradual: It might start at a level as low as 0.5 tesla, become more noticeable at 1 tesla, then the curve bends further, but even at 2 tesla there might be a significant amount of permeability left! The effect of this is that with increasing flux density, the magnetizing current increases more sharply, but it would be really hard to reach a level where the saturation makes the transformer stop working. So, the most important consideration about flux density is the sharply increasing core loss. Only when you are using very high flux density, would it be a good idea to allow some additional cross section for the primary wire, to accomodate the larger magnetizing current.

Enough calculations. Let's go to winding!

Very often, winding a transformer for a hobbyist will start with unwinding an old, burned one! The photo shows part of the guts of a Heathkit tube tester from the 1950's, which was given to me in damaged but restorable condition by my friend Renato Menare. Its power transformer worked, but got extremely hot in just one minute of operation, and started smelling burned after two minutes.

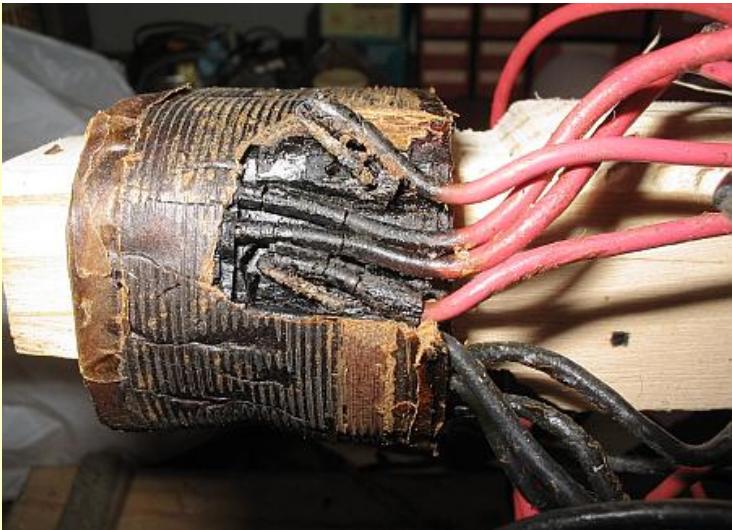
After restoring the tube tester, without touching the transformer, I used it for about a year, switching it on only for a minute at a time to test one tube, and then letting it cool off. But eventually the inevitable happened: The transformer burned out, filling my home with smoke.

Such a tube tester transformer is one of the worst nightmares any transformer maker can get: It has two secondaries, each of which has a huge number of taps to provide all the different filament and plate voltages needed by any of the thousands of different tubes around in the 1950s! It takes patience to rewind such a thing. Every few turns you have to install a tap!



The first step is removing the transformer from the circuit, unsoldering all wires and taking notes which wire goes where. The fact that may wires are the same color doesn't help. Then, the core has to be disassembled. To do that, you first remove the bolts, then push a sharp knife between the first and second lamination, prying them apart to break any glue or varnish or rust between them, then grab the lamination with flat pliers and wiggle it out. Depending on how much the core was compressed during manufacture, this can be quite hard to do, and one or two laminations might be damaged in the process. That's not the end of the world, the transformer should later work even with one or two laminations less. Usually, after removing the first few, the others come out easily. Sometimes each lamination needs a little help with the knife to come loose, while in other transformers the core falls apart on its own as soon as compression is relieved.

Once the winding assembly has been freed of the



core, it is mounted on a suitable wooden core in the winding machine. Then the windings are carefully unwound, letting the turns counter of the winding machine do its job. You should take notes on the number of turns of each winding, between each tap and the next, and anything else you find worthwhile noting down. Shooting pictures with a digital camera can also be very helpful, should you later suddenly get doubts about where each tap connection should be located!

You should also save the wire, so you can measure its diameter and find out what sizes of wire you need to buy.

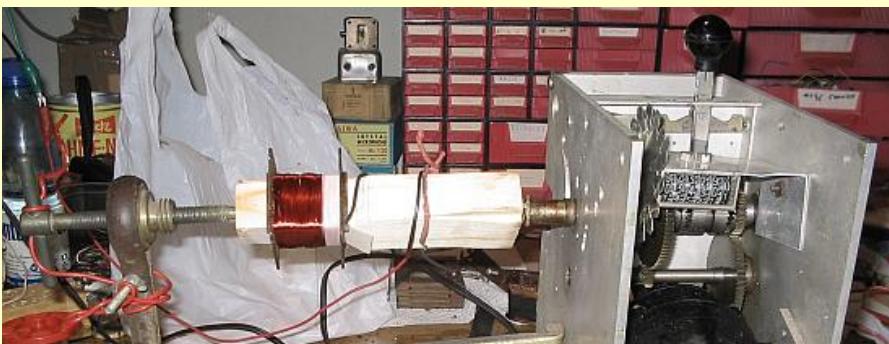
As the layers of wire and paper come off, things usually turn darker and ever darker! This is because transformers work hottest at the inside. This picture shows severely carbonized insulation, both the paper

and on the connection wires. Probably the paper slowly carbonized, becoming slightly conductive, causing further loss, further heating, until the beast failed for good. This is the problem of paper insulation!

When I was done unwinding this transformer, I found that even the cardboard winding core was totally carbonized, crumbly and definitely unusable. I was left with the heap of burned, charcoal-like insulation shown here, kilometers of thin, crumbly, burned copper wire, burned pieces of hookup wire, these photos, and a piece of paper where I had written down wire sizes and turn numbers.

Don't do such a job in your parent's bedroom, because as you can see, it's messy! Even the kitchen might not be the best place to do it. Neither mothers nor wifes tend to like this sort of transformer autopsy!

When not even the bobbin is usable, you will need to make a new one, or find one that fits. I was lucky this time, and found one in my junk box (aka treasure chest) that just fit this core, and even had side walls! It's a great thing that core sizes are standarized, even if several different standards exist...



It's probably high time to introduce my transformer winding machine. Here you can see it in all its glory, somewhat obscured by the messy background (my workbench). Amateur radio friend Enrique Villanueva, CE5FSB, gave me this machine when I was still a schoolboy. That was many years ago, Enrique is no longer in this world, but I remember him every time I wind a transformer! He was a



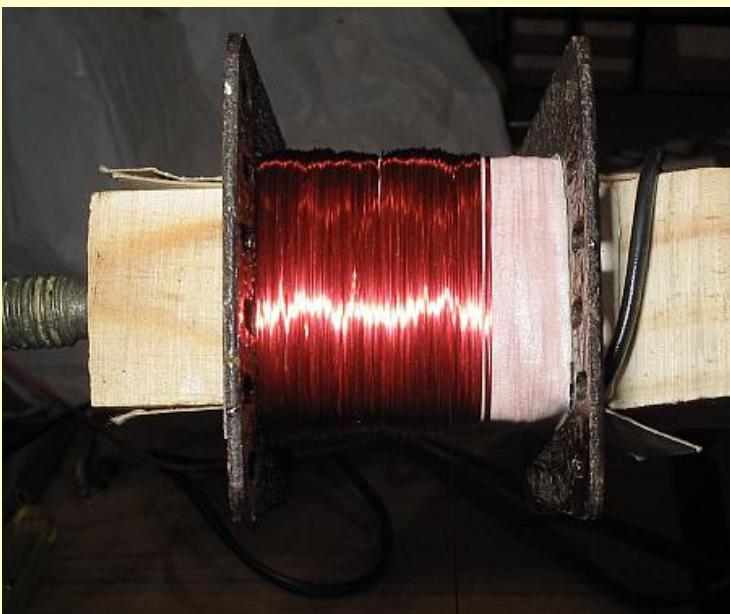
true gentleman, and always helpful.

This machine is simply a motor and switchable two-speed gearbox with central neutral position, that drives a three-pronged thorn, opposed to which is an adjustable centering screw. It's quite handmade, but does the job well. The fast speed is about 120 rpm, and the slow one is about 15 rpm.

I added a turns counter to it. It didn't have one when I got it. This turns counter came from a surplus store, out of a broken gas meter. It advances 4 counts per revolution, so I coupled it to the machine's drive shaft via a 4:1 speed reduction, getting exactly one count per turn. To make this coupling, I made two gears! One was cut from the lid of a coffee can, has 16 teeth, and is visible in the picture. The other one was made from a piece of wire, has 4 wire loops acting as teeth, and is hidden in the photo. It's crude, but was cheap and has worked well for about 30 years now! I can hardly even try to calculate how many transformers I have wound with this machine!

When winding a transformer, you need to have the wire unwind straight and cleanly from the spool on which it's sold. If you simply stand the spool on the ground, the wire will twist while unwinding, curl up, and kink. At that point, you can throw it away and start anew! So, don't. Instead, you need to fashion some device that allows the spool to rotate, letting the wire unwind without kinking. This photo shows one of the methods I often use: A screwdriver, serving as axle, held in a vise.

Sometimes I'm too lazy to set up the vise. In those cases I simply hold that same screwdriver between my knees while winding the transformer!



Here you can see the junk box bobbin, made from Pertinax, mounted on a wooden core in my winding machine, and with part of the primary winding already wound.

There are several styles for winding transformers. The highest quality one is to painstakingly lay the windings out in neat, perfect, orderly layers, with every turn of wire placed precisely next to its neighbor, in close contact, and never crossing over. Each layer is separated from the next by a sheet of thin insulation material, cut precisely to the width of the bobbin, and to such a length that it will overlap a bit. This overlap is placed at either of the outside sides of the bobbin, not on the sides that will end up in the core's window. Such a winding is gorgeously beautiful to look at, produces an excellent fill factor, but is very time consuming to make. I tend to use that technique when winding few turns of thick wire, but not when winding many turns of thin wire. One time only I wound a 78,000 turn high voltage transformer in that way, because no other technique

would do, but I almost turned crazy, and never repeated that feat.

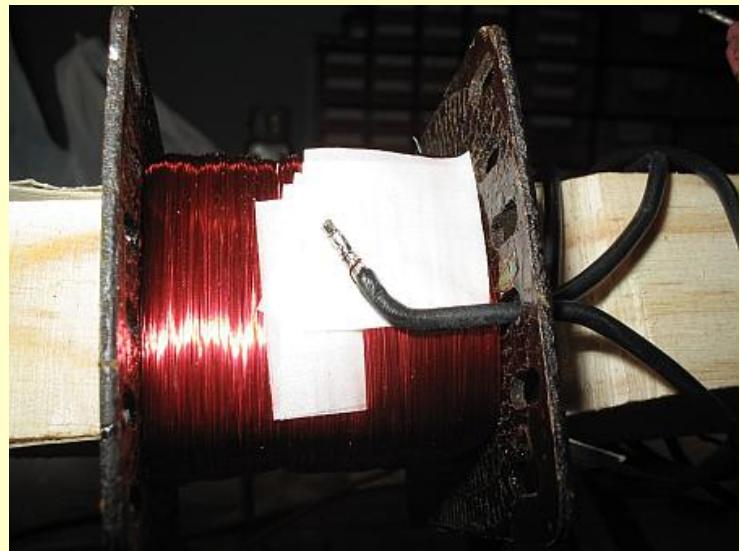
Modern small split bobbin transformers are normally wound in a very untidy way: The operator at the factory simply lets the machine run, and fill the bobbin section with wire, letting it build up wherever it wants to. There are no layers, no insulation between layers, it looks poor, is less reliable, the fill factor is less good but still acceptable, and it's fast and cheap to do.

The winding shown in this photo, instead, is a hybrid of both techniques. The winding is split up into just a few layers, two or three or so, but each layer is wound thick, with the wire turns actually building up on each other. I let the machine run and guide the wire to let it slowly fill the layer from one side to the other (never going forth and back several times!), letting the windings build up to the desired height, about two millimeters or six wire diameters in this case. When that ugly layer is complete, I apply a coating of self adhesive tape as insulation, and then wind the next layer. It's almost as quick to do as a totally wild winding, but significantly more reliable.

A word about tapes: Transformer parts stores sell self-adhesive mylar tape, usually yellow, in several thicknesses and widths. This is a good material, and you should use it. But I often don't have it on hand, and use alternative materials. Vinyl insulating tape can be pressed into service, but isn't great, because it gets very soft when hot, and the wires can press through it. Much better, even if you don't believe that, is painter's masking tape! It has just about the optimal elasticity, is thin, cheap, comes in several widths, holds up well when hot, and looks pretty good on transformers for antique equipment, on which any plastic tape would look out of place! Masking tape is what I used for this transformer.

A question many newcomers have is how to handle the ends and taps of windings. When the wire is rather thick and robust, you can simply let the end stick out of the bobbin! In that case it's good practice to protect that wire by a piece of spaghetti (I don't mean an Italian noodle, but a piece of plastic or fiber hose that looks much like it). It should ideally be only slightly thicker than the wire. You slip it over the wire, and anchor it in the winding assembly, with adhesive tape and the pressure of the windings. It will protect the wire from chafing, and provide additional insulation at places where the wire might pass very close to other wires or to the core.

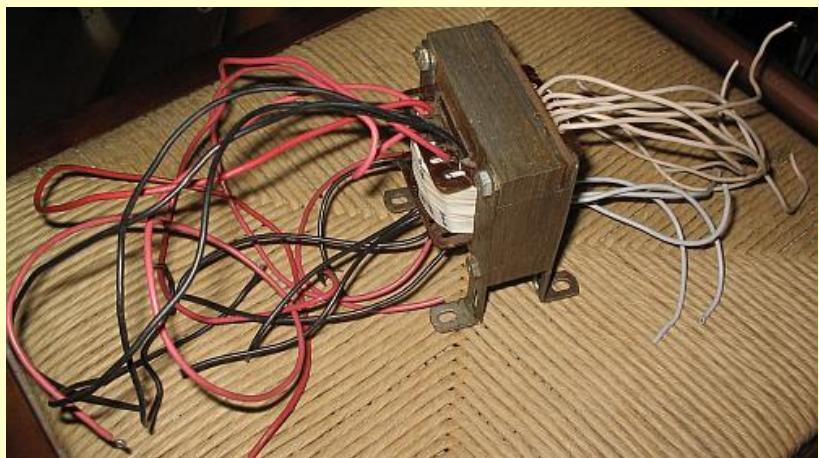
But thin wires should not be treated like that. They are too fragile, and might very easily break later, forcing you to rip up and rewind the whole transformer! Instead, you should take some pigtails of stranded, plastic-insulated wire, strip and tin the ends, solder the thin enamelled wire to the end of a pigtail, and embed it in the winding like is shown in this photo. You need to place enough layers of insulating material both under and over the connection, to make sure that no sharp tip or edge of the wires may puncture through the insulation. This adds quite a lot of bulk, so of course these connections must be done on the sides of the bobbin that will end up outside the core's window!



When you solder these connection, make absolutely sure that the enameled wire stripped properly in the solder bath. It's very frustrating to end up with a nice new transformer, that has one winding that doesn't conduct, because of a badly done connection! In this photo, the first one and a half loops of the thin enamelled wire around the pigtail didn't strip, but the other three loops did, so the connection is secure.

One word about safety: Between the primary and secondary windings, and at any place where there might be high voltage, you need really good insulation. After connecting this pigtail, which is the end of the primary winding, I had to apply such safe insulation. When doing it with adhesive tape on a bobbin like this, it's done by winding several layers of that tape, and winding it not only all the way to the side walls, but even a bit up on these walls, forming a kind of cradle bedding for the secondary winding. You need to get either a perfect seal between the tape and the side walls, or having so much tape, and the wire moved far enough toward the middle of the bobbin, that the creepage distance from primary to secondary, around the insulation, is at least 4 millimeters. This is even a legal safety requirement!

After winding the two secondaries with their lots of taps, and re-assembling the core, the finished transformer looked like this, in all the glory of its dozens of connecting wires! In this Heathkit tube tester, the wires connect directly to the circuit. In other cases, these wires would be neatly dressed and soldered to terminal strips, which are either embedded in the outer layers of insulation in the winding assembly, or bolted to the core.





A winding machine with turns counter is a great tool, but it's not absolutely necessary. Transformers can be wound with much simpler tools too. And despite having my machine, sometimes I have to wind transformers that are larger than what the machine can handle!

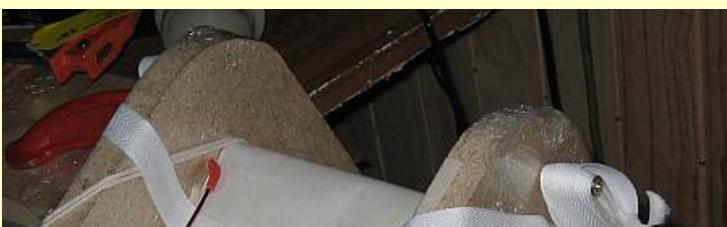
Such was the case in 2008, when I had to build two transformers for 10kVA each, starting from scratch. These are the transformers I chose as an example to put into the spreadsheet before uploading it to this page! In the sheet, the primary voltage is 230V and the secondary is 2000V. In truth, one of the transformers works in this way, while the other is opposite, the 2000V winding serving as primary. In the following discussion, I will use "primary" to refer to the high voltage winding, regardless of how the transformer will be used later.

I built the simple but effective setup shown in the photo. A big wooden bobbin was made, with dimensions such that the complete winding package for the transformer would precisely fit inside. Note that this bobbin is just the support for winding! It will be removed before final assembly of the transformer. For this purpose, it's held together by screws, and the wooden pieces on the inside are designed so that they can be easily removed from the finished coil assembly. This big wooden bobbin got fitted with a hand crank, and mounted on a steel tube serving as axle, which was clamped to the workbench.

Each wooden piece of the bobbin was separately wrapped in kitchen wrap (saran wrap, Sichtfolie) before assembling the bobbin. This assures it can be disassembled after varnishing the winding assembly, without the wood sticking to the coil assembly!

The spools of wire for these big transformers weigh 30 kg for the secondary, and 25kg for the primary. So I made a simple but sturdy support structure for them and placed it at the work site.

Instead of a complete bobbin with side walls, I chose to employ only a basic bobbin, made from a sheet of 1.5mm thick Pressspan (I couldn't obtain a material strong enough with a better temperature rating). The Pressspan was cut to size, half-depth cuts were made with the knife at the bending lines, then it was bent around the wooden bobbin. The overlapping side was smeared with epoxy glue, and the whole thing was compressed with wooden boards and clamps like shown here, to get it nice and straight.



Since the Pressspan might carbonize and become slightly conductive at high temperature, I wound two layers of high temperature NMN laminate over this core, to insure permanent safe insulation between the winding and the core. It's temporarily held in place with plain office type adhesive tape, but this tape is later removed when winding the wire, to keep it from carbonizing and possibly



causing trouble.

This transformer has sufficiently few turns and thick wire to wind it in orderly layers, separated by insulating sheets. To keep the whole thing from falling apart, I bound the layers together with cotton straps, and to make sure the wire turns don't get closer to the edge of the bobbin than 5mm or so, I wound cotton ropes at the edges, used as spacers. These ropes will be removed later.

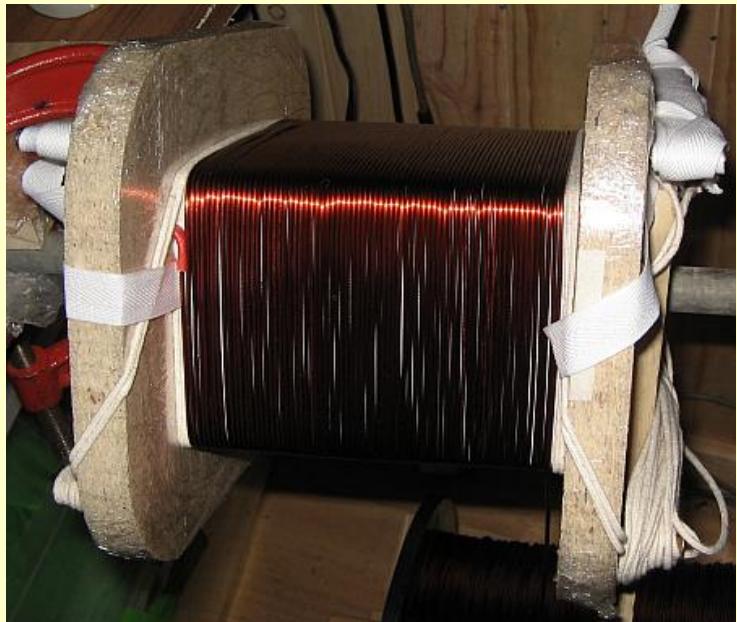
The photo shows the assembly, ready to start winding. A double rope makes one turn on each side of the bobbin, enough spare rope for the successive turns is coiled up on screws driven into the bobbin, and the cotton straps are installed and coiled up too.

The wire end, protected by a piece of high temperature red fiber spaghetti, is anchored in a hole drilled into the wooden bobbin. Time to start winding!

The first layer has to be wound very carefully, pushing each winding into tight contact with the previous one. When that first layer is complete, be sure to count the turns to make sure you actually got as many turns as you calculated! Otherwise, you need to compress the winding a bit more, and then add the remaining turns.

When not using a turns counter, such as in this case, a good thing to do is to wind a full layer, then count the turns, and write it down. Don't forget! Otherwise it's just too easy to loose count of the layers! That sounds stupid, but it's very real. A good way to count the turns is to lightly draw a pointy, non-scratching object (plastic or wood) over the wire turns, and count the clicks as you feel them. Counting by sight tends to be confusing.

Since the wire isn't ever perfectly straight, it's impossible to completely eliminate air between the turns. That's why you have to consider a safety factor when calculating how many turns you can fit in each layer!



The next layers instead are easier to wind, because the wire will embed itself slightly in the depressions between two turns of the previous layer, automatically assuming the correct spacing. Note that this produces either winding layers which alternately have one more or one less turn, or else the windings with the same number of turns in each are alternately offset sideward by one half wire diameter, respective to each other. You need to consider this when designing the transformer, when you intend to do a neat, tight winding like this.



After each layer, the wire is pressed flat, using boards and clamps, on the sides of the bobbin that will end up inside the core's window. This further helps to actually make the winding fit. It doesn't matter at all if the windings bulge out a bit on the other two sides, because these will end up outside the core, where space is plentiful.

If you do this, be careful not to damage the wire's insulation. It's quite tough, but not infinitely so. The boards should have a smooth and not too hard surface. I used a thick paper as cushion between the chipboard and the wire.

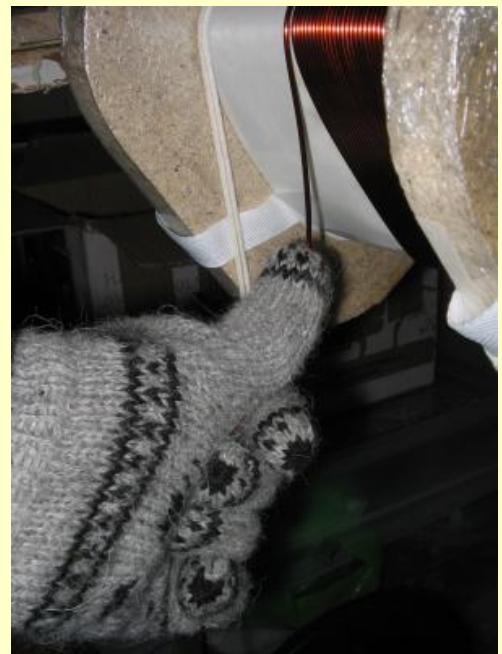
After winding and compressing a layer, a single layer of insulating material (NMN laminate in this transformer) is wound, overlapping it a bit on one side that won't be inside the core window. Then the four ends of the cotton straps are crossed over, pulled tight, and reattached to the bobbin, and the cotton ropes are wound another turn, taking care to avoid tangling the straps with the ropes! The straps will remain in the transformer, while the ropes will be removed. So the straps should hold just the wire and insulation sheets, but not the ropes.



If you simply let the wire unwind from the spool and wind it on your transformer, it will get a bow shape instead of lying flat, and have so much air below it in the center region of each bobbin side, that later when compressing the layer you would get excessive bulging on the other sides. To prevent this, the wire gets a pre-bend in the opposite sense while winding, by guiding it with the thumb like shown here. I used a woolen glove for this, because the wire has to be kept pretty tight, is quite stiff, and it would wear through my skin, despite being quite smooth!

This photo was shot during the winding of an intermediate layer of the primary.

The wire and the cotton ropes are placed between the ends of the insulation sheet, for the transition from one layer to the next. Said in a different way, the insulation sheets are simply wound into the coil of wire and rope.



After winding the last layer of the primary, the spacing rope is anchored in a hole in the bobbin. The end of the wire is treated just like the beginning of it, and brought out through a hole too. I drilled all these holes where needed, while winding.

Then several layers of insulating material are wound, since the voltage between primary and secondary can reach 10kV or more during a nearby lightning strike! These transformers were built to send power over a 600 meter long outdoor transmission line, in a mountainous and lightning-prone area.

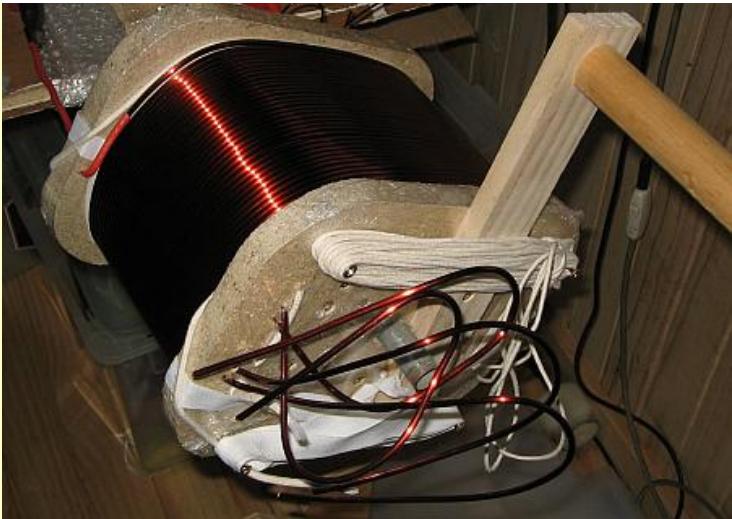
Since the secondary winding uses much thicker wire, the spacing rope needs to be thicker too. I used one strand of thick rope for the secondary, and two strands of thinner rope for the primary. As a result, both windings are spaced about the same 5mm from the sides.

Here you can see how a center tap is made. The winding was arranged in an even number of layers, so that the center point ends up at the transition from one layer to the next. At this point, the wire was brought out and back in through a single hole, and protected with spaghetti. The spacing ropes were also brought out and back in through two holes, to keep them from interfering with the wire tap. Finally, the cotton straps are threaded so that they will hold both wire ends in place.

After this, the insulation layer can be wound, and then the ropes and the wire for the next layer.



The secondary is wound just like the primary. In this

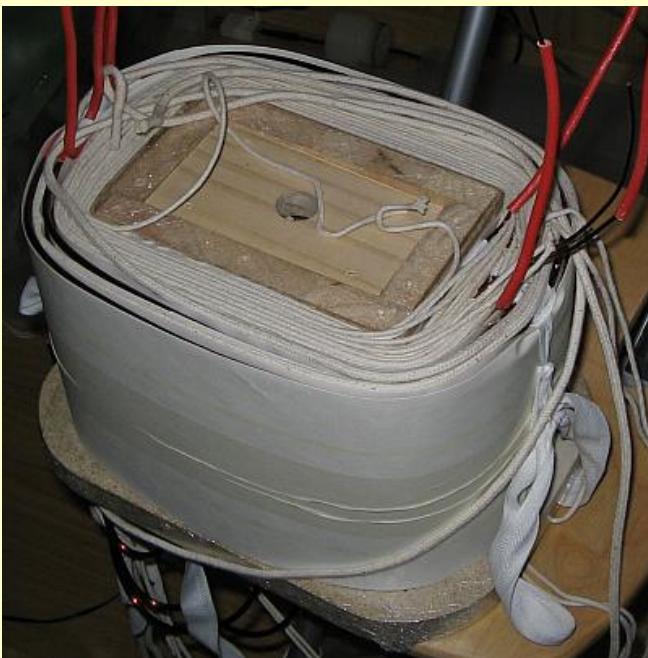


case it was a little more complicate, because I actually wound two secondaries, each of them having a wire half the cross section calculated in the sheet. On top of that, each of the secondaries is center-tapped too. This allows me to do several clever things with my transformers, and as a bonus lets me wind with a thinner, more manageable wire. This is #7, still stiff enough!

The photo shows the completed secondary, before applying the final layers of insulation. You can see the spacing ropes, and how the cotton strap will hold the last turn.

The spacing ropes are pulled through holes and secured, several layers of insulation are wound, the final layer is secured with a loop of masking tape, and then the cotton straps are pulled tight one last time, and knotted together using a special pulling knot, the same sort truckers like to tie down their cargo. If you don't know how to tie such a knot, ask a trucker, a sailor or a boy scout.

At this point, the winding assembly is ready to remove part of the wooden bobbin, and start the varnish impregnation process.



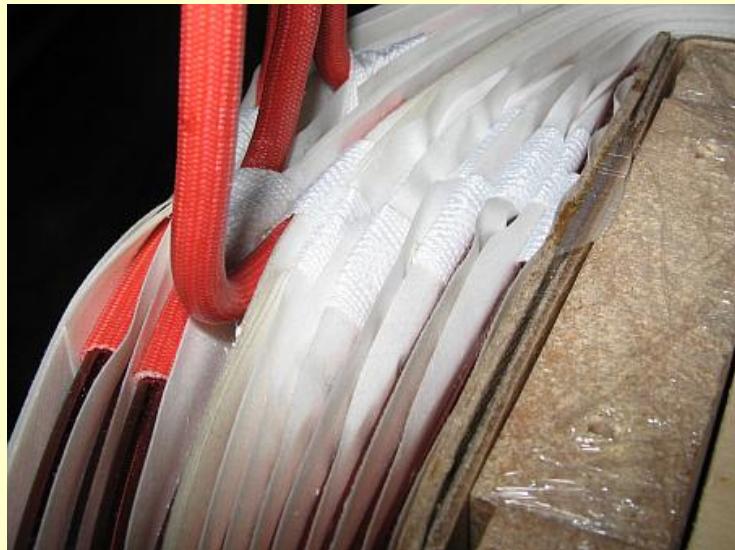
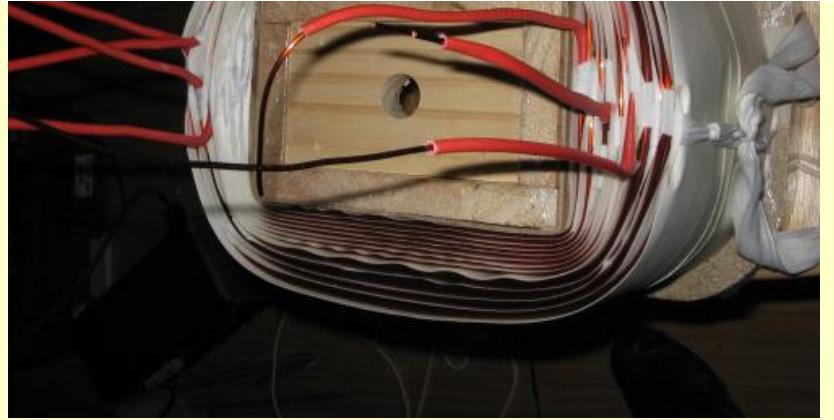
Removing one of the side walls of the wooden bobbin reveals not only the structure of the inner part of the wooden bobbin, designed for strength and easy disassembly, but also you can see the spacing ropes partially falling out, leaving the insulation protruding nicely between the turns of wire. This produces plenty creepage distance for safe operation!

After removing all those ropes, the winding assembly looks like this. Note how the wires are nicely tucked in between the insulation layers.

While the cotton straps do a great job holding the end turns of each layer in place,



preventing them from falling out and the whole thing springing open, this assembly is still far too weak to be used like this. Considerable forces act on wires of big transformers. They need to be secured very well.



And a further closeup showing how the straps hold the wires, and bend the insulation, always maintaining a safe creepage distance.

In this photo you can also see the overlap of the Pressspan bobbin, complete with some epoxy glue that seeped out before setting. Since the bobbin was made 2mm shorter than the core's window length, such seepage and similar imperfections cause no trouble.

Without removing the other remaining parts of the wooden bobbin, I soaked the entire winding assembly in impregnation varnish. I poured the varnish in from the top, until it flowed out profusely from the bottom. Then I let the assembly soak, let the excess drip off, and let it dry somewhat on the surface.

But this is an oven-drying varnish, so it needs to be heated, or it will never dry. I do have a thermostatically controlled oven - but not large enough to fit a winding assembly of this size! So I applied enough DC current to the primary winding to slowly heat up the whole thing to a temperature high enough to dry the varnish.

Every transformer varnish has a recommended drying temperature. To get it right, I occasionally removed the power supply, and measured the resistance of the primary winding. Comparing to its resistance when cold, and considering the thermal coefficient of the resistance of copper, it's easy to calculate the internal temperature! Then I adjusted the DC current to keep the temperature just right.

I removed the other wooden bobbin side, and the spacing ropes on that side, when the exposed side of the assembly seemed to be dry. The newly exposed side was still fresh, so drying continued with the assembly supported only by the wooden parts in the center.

When the varnish stopped smelling, signalling that it was dry, I removed all of the remaining wooden parts. This was quite easy, thanks to the kitchen wrap, which stayed partially adhered to the

Pressspan core. In this photo you can see that. The brownish color is that of the varnish, while the near black sections inside the assembly are partially carbonized kitchen wrap. This stuff doesn't endure the temperature the varnish needs to dry! But no harm was done, except to the wrap, which is of course irrelevant.

At this point, the winding assembly has a monolithic feel, with everything firmly glued together by the varnish. It could actually be used without further work, but the edges of the thin insulation material are quite fragile. Any object striking them could bend or even break them, compromising the creepage distance and thus the safety of the transformer! 2000 volts at 10 kilowatts is not something to take chances with.





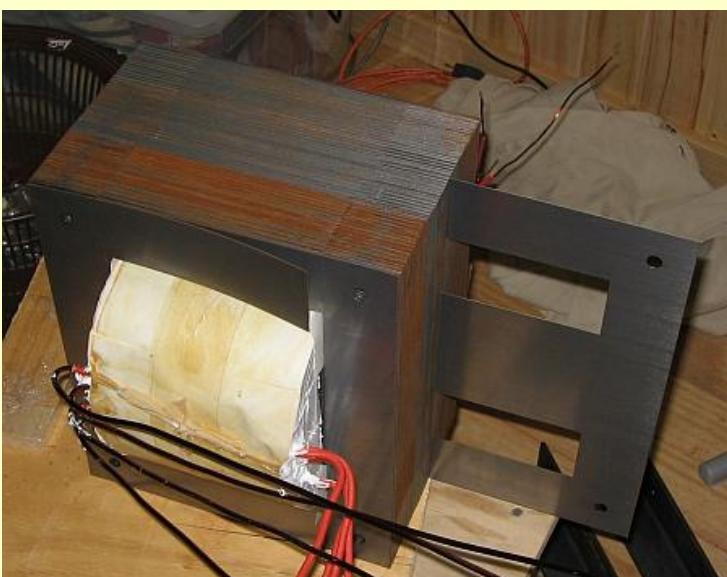
So I filled these areas with silicone caulk. This material is available, inexpensive, easy to work with, tixotropic, permanent, an excellent insulator, and endures very high temperature. In short, it's a nearly ideal material for this task! There is only one point to watch: Be sure to use the neutral curing type, not the more common, acid curing one! The last thing you want to do is releasing highly corrosive acetic acid into your new transformer!

The color of the silicone is your (or in this case, my!) choice.

I didn't do a particularly neat caulking job, but the point was to get the edges sealed and protected, not to do a work of art.

The winding assembly is now ready!

The next step is assembling the core. I usually do this in the same way for every transformer: I place the winding assembly on one side, then I start inserting E laminations from alternating sides. Distributed throughout the core, I occasionally insert two consecutive E's from the same side. When almost all E's have been inserted, things tend to get pretty tight, and forcing additional E's in between the last one and the winding assembly, can lead to damage to the latter!



This is where the E pairs inserted from the same side come into play: They form excellent guides for inserting a third E between each two neighboring E's, even using a wooden block as a hammer to drive them in, if necessary! This is the best trick I have found to obtain a nice, tightly compressed lamination stack.

After all E's have been inserted, the I's are slid into the voids. After that, two wooden blocks and a big hammer are used to knock all the laminations into their correct positions, aligning them with each other, and specially, align the screw holes of all the laminations!

At this point, the transformer is functional, and you can hook it up and try it, if you want. But it will hum like crazy, because all those loose steel laminations will magnetically repel each other at twice the line frequency rate, and vibrate. The core needs to be tightly compressed to stop all that noise.



The performance will also improve when the core is correctly compressed.

In small transformers this is done with clamps. But big ones, like this, use bolts. Often you won't find real bolts long enough and thin enough, though! In those cases, buy some threaded stock, which is sold in great lengths, cut it to size (a Dremel tool with a heavy duty cutoff disk does this very nicely!), and use it with washers and nuts on each end.



In large transformers, these bolts sometimes have enough shorting action to cause significant additional loss and heating! For this reason it's a good idea to insulate the bolts from the core. You can use tubing for that purpose, or like I did here, slide in a sheet of NMN laminate (or plain paper) rolled into a tube.

Installing the bolts just on the core leaves you with an unevenly compressed lamination stack, and what's more important, with nothing to mount the transformer! For that reason usually some angle stock is used. It distributes the force over much of the core, and provides convenient surfaces to drill mounting holes into.

Some transformers use formed caps instead, or complete steel frames.

Note the insulation sheets under the washers of the bolts! Depending on the specific transformer, they might make any difference, from barely noticeable to dramatic!

At this point, the transformer is truly ready for trying. If it still hums, you can try tightening the bolts even further, and inserting wooden or plastic wedge pairs between the winding assembly and the core center leg, to compress the latter. If even this fails, which is often the case, then you have no better option than once again getting your varnish can, and soak the core in varnish! You can loosen the bolts, let varnish flow into every space, then tighten the bolts again and warm up the whole transformer by applying a suitable amount of DC for at least a full day. I have yet to see a transformer that still hummed after that treatment!

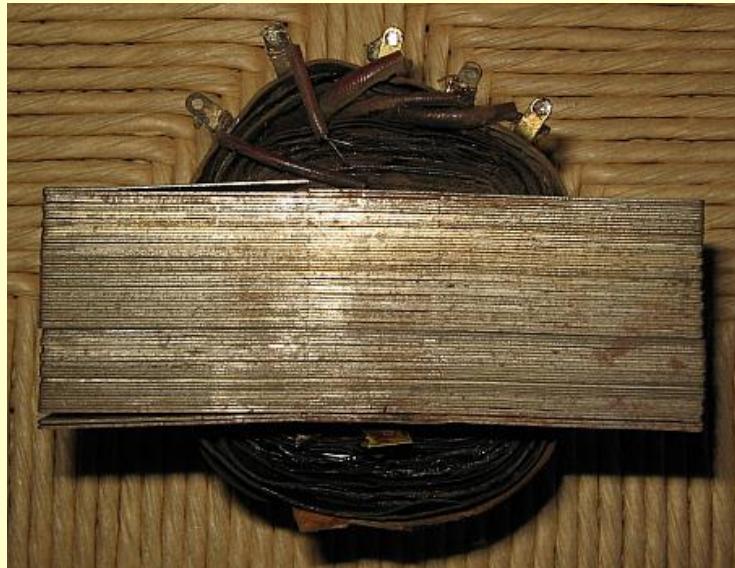


Depending on the application, different things can be done with the connections. If they are made of flexible wire, they might be directly wired into the circuit. In small transformers, often plastic bobbins with pins are used, and the windings are connected to these pins, like shown here, and then the whole transformer is soldered to a printed circuit board. The example shown here is a current sensing



transformer, which also has a one-turn, high current winding, which is brought out separately from the bobbin pins.

Often terminal strips are attached to the winding assembly, and the windings are connected there. But in larger transformers, the most common practice is bolting terminal blocks to the transformer, and connecting the wires there. I did this with my large transformers, leading to the final product shown in the very first photo of this web page. That system is more solid and reliable than most others, and allows repeated solderless disconnection and reconnection, which I need a few times per year to reconfigure my transformers for different conditions of usage.



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Some people wonder whether they should try winding their own transformers, or if they should instead shell out big \$\$\$ to have the job done by a professional winding shop. I can only tell you one thing: If you had the patience to read this long web page from start to end, then you **most certainly** also have the patience required for winding your own transformers!!!

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Back to [homo ludens electronicus](#).

