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30. Choose the interleaving pattern.

Choosing an interlaving pattern may entirely bamboozle many readers or designers who have not much experience with winding audio frequency transformers for wide bandwidth between about 14Hz and at least 70kHz.

Fig 10.

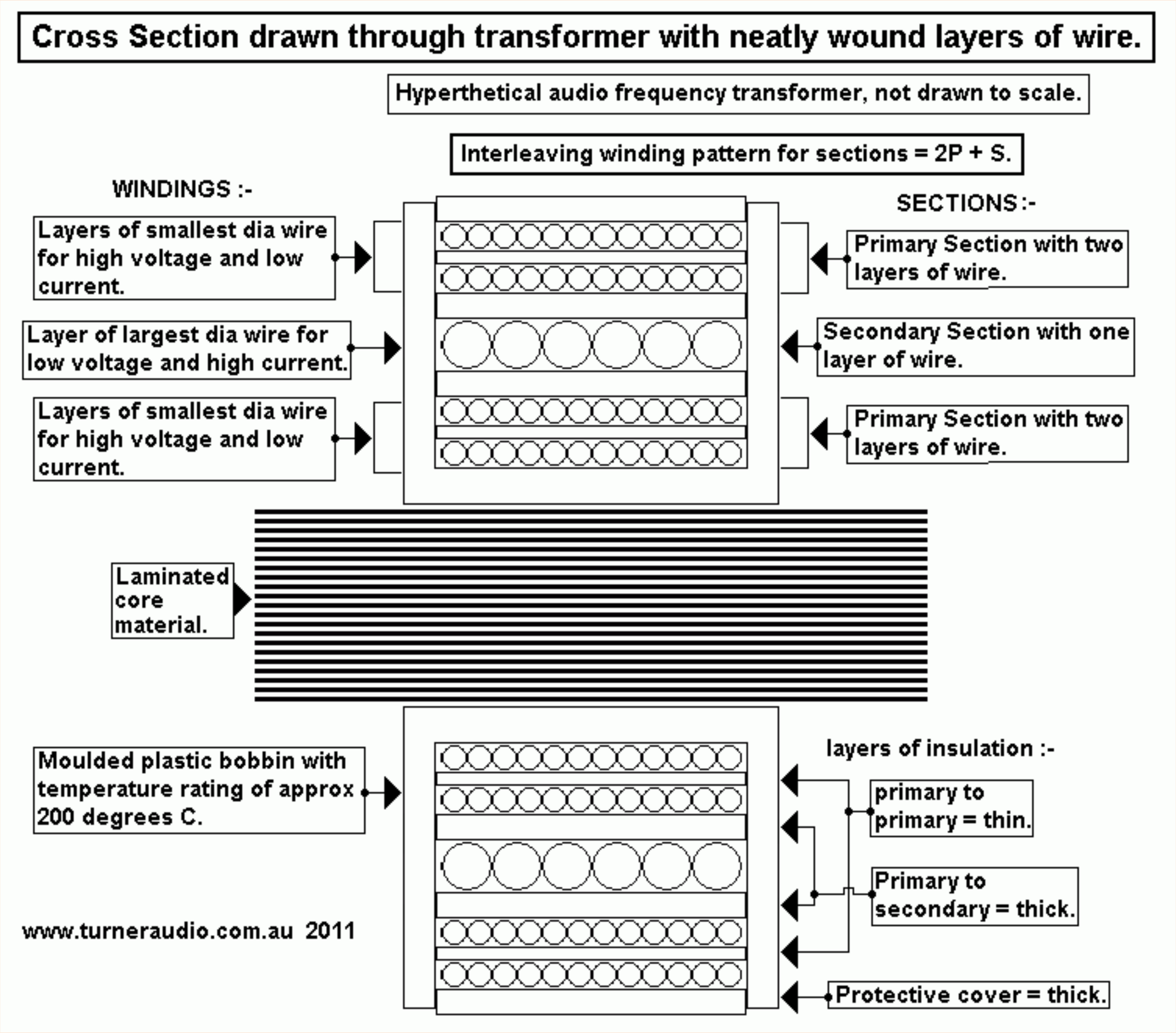


Fig 10 shows a cross section through a hypothetical transformer with concentric layered windings neatly wound with an interleaving pattern of 2P + S, ie, with **two** primary sections and **one** secondary section located between each primary section.

The Fig 10 is drawn to show the contents of a transformer with two windings, a primary and secondary, arranged in 5 layers.
If we say the smaller wire size wire is all for one primary winding then there are 4 layers each with 12 turns, so Np = 48 turns.
The Secondary winding has 6 turns in one layer. There are two layers of P wire wound on before the Sec, and two wound on after the Sec, and each pair of P layers forms ONE section of P winding, so you have 2 P sections with one P section each side of ONE Sec layer which is ONE section. The simple winding pattern can be called a 2P + 1S pattern, or P-S-P pattern.
There is only one section of secondary, but there could have been more located above and below the primary sections shown, if the bobbin space permitted.

This hypothetical transformer in Fig 10 has Turn Ratio = 48t : 6t, , ie, 8 : 1, and Impedance Ratio = 64 : 1.

With OPT-1A, the number of turns and layers and sections is much greater than shown in Fig 10.

The number of LAYERS must NOT be confused with the number of SECTIONS.

A winding "section" is one or more layers of wires devoted solely to either anode primary current, cathode primary current or secondary speaker load current. There is no direct connection between the sections designated for anode, cathode or speaker, and the deignated sections are connected only by way of magnetic coupling only.

I try to design all tube amp OPT with the Secondary arranged so there is never more than one layer of circular section wire in one secondary "section."

The Primary may usually have more than one layer of wire in each Primary section.
So an OPT is built up with groups of layers of Primary wire interleaved with single layer Sections of Secondary wire. Each layer of secondary wire may be subdivided into "secondary sub sections" to allow varied series and parallel connections to give variable load matches to suit a wide range of speaker ohm load values, while keeping the anode load fairly constant and optimal.

There are no designs here which require rectangular section wire or bifilar or trifilar winding winding which is most difficult for low batch number productions.

In general, all OPT should comply with the following P&S layer number relationships :-

Where the first and last winding wound onto the bobbin is in a Primary section, then these sections should have approximately 1/2 the number of layers of the inner P sections.

If there are 3 outer primary layers in a P "outer" section, the inner P sections may have 5, 6 or 7 p layers.
When this guide is adhered to there is the best HF response because the leakage inductance is fairly evenly and symetrically distributed.

When starting and finishing with an S section all internal P sections should have the same number of p layers but it is not always possible and having say 2 sections of 4 p layers and 2 sections of 5 p layers is OK. The size of such "internal sections" should not vary more than 25%. Where such guidelines are adhered to along with equal thickness insulations between P and S sections, there are minimal problems with resonances at HF.

The Push Pull OPT designed here using my methods should display adequate magnetic coupling between each half of the primary winding so that distortion resulting from current cut off in tubes in class AB is minimised, and need not be worried about. In the 1930s, the absense of much interleaving in OPT could create serious problems in class B amplifiers but between then and the 1940s it was realised that adequate interleaving is essential to avoid unwanted magnetic phenomena.

For transformers to suit high current + low voltage drive devices such as mosfets or transistors, the same amount of interleaving is required for a given power level and desired bandwidth. When coupling mosfets or bjts The number of p layers will be reduced as Primary RL becomes low, and wire dia will increase.

An 8 ohm : 8 ohm OPT with very low dc voltage differences between P and S would have equal numbers of turns for P and S and perhaps be simply interleaved so each layer of thick wire is alternatively devoted to either P or S. The bandwidth can then be very easily made to exceed 250kHz.

As the tube amp primary load is reduced, the effect of shunt capacitance diminishes, so insulation thickness can be reduced, but kept to a mimimum of about 0.4mm so that the insulation prevents any arcing and helps to keep layers neat and flat as the bobbin is wound. Transformers for electrostatic speakers which step up the amplifier voltage between 50 and 300 times need to have greater insulation thickness for higher voltages involved and to achieve lower capacitances between adjacent windings and any other windings. ESL step up transformers resemble PP OPTs powered "backwards" and can be designed with the method here. The QUAD ESL57 has a large step up transformer with a primary very much like the secondary of an OPT. The ESL secondary has 11,000 turns of very fine wire all neatly layer wound and the total capacitance seen by the amplifier must be less than the capacitance of the treble speaker panels. For much more information about ESL step up transformers one should read the theoretical modelling work by Peter Baxandal written in the 1950s.

But for matching tubes to normal 3 to 9 ohm speaker loads, the interleaving list below with the number of primary layers per section possible will give at least 70 kHz of bandwidth, and where there is a highest number of interleavings the bandwidth can be 300kHz.

Using more interleaving than listed leads to less available room on the bobbin for wire due to too many layers of insulation, and poor HF due to high shunt capacitances, and higher winding losses. The designs here give good balance between total shunt capacitance and leakage inductance, so that neither is too high, and that the resonant frequency generated between them is at a frequency exceeding 70kHz, and thus able to be damped by R&C Zobel networks without affecting the amplifier performance below 20 kHz.

For lower Primary RL and higher amplifier power the larger the OPT becomes and for a given number of interleavings the HF response becomes less due to increasing leakage inductance. So the larger the OPT becomes, the number of interleaved sections increases. So a small 15 watt OPT may only need 3S + 2P sections for 70kHz, but a 500 watt OPT may need 6S + 6P sections.

Inspect tables 2, 3, 4, 5 below for the power from the transformer.

Tables 2, 3, 4, 5, show interleaving pattern possibilities for PP OPTs :-

TABLE 2.	Total P layers	Primary and Secondary layer distribution.	P&S section pattern
0 to 7W	10p to 24p	S - 10p~24p - S	2S + 1P

7W to 15W	10p to 20p	S - 5p~10p - S - 5p~10p - S	3S + 2P
7W to 15W	10p to 20p	2p~4p - S - 4p~8p - S - 4p~8p - S - 2p~4p	3S + 4P

TABLE 3.	Total P layers	Primary and Secondary layer distribution.	P&S section pattern
15W to 35W	12p	2p - S - 4p - S - 4p - S - 2p	3S + 4P
	12p	S - 4p - S - 4p - S - 4p - S	4S + 3P
	14p	2p - S - 3p - S - 4p - S - 3p - S - 2p	3S + 4P
	14p	S - 5p - S - 4p - S - 5p - S	4S + 3P
	16p	3p - S - 5p - S - 5p - S - 3p	3S + 4P
	16p	S - 4p - S - 4p - S - 4p - S - 4p - S	5S + 4P
	16p	2p - S - 4p - S - 4p - S - 4p - S - 2p	4S + 5P
	18p	3p - S - 6p - S - 6p - S - 3p	3S + 4P
	18p	S - 4p - S - 5p - S - 5p - S - 4p - S	5S + 4P
	20p	3p - S - 7p - S - 7p - S - 3p	4S + 3P
	20p	S - 5p - S - 5p - S - 5p - S - 5p - S	5S + 4P
	20p	2p - S - 5p - S - 6p - S - 5p - S - 2p	4S + 5P

TABLE 4.	Total P layers	Primary and Secondary layer distribution.	P&S section pattern
35W to 120W	14 p	S - 3p - S - 4p - S - 4p - S - 3p - S	5S + 4P
	14p	2p - S - 3p - S - 4p - S - 3p - S - 2p	4S + 5P
	16p	S - 4p - S - 4p - S - 4p - S - 4p - S	5S + 4P
	16 p	2p - S - 4p - S - 4p - S - 4p - S - 2p	4S + 5P
	18p	S - 4p - S - 5p - S - 5p - S - 4p - S	5S + 4P
	18p	2p - S - 5p - S - 4p - S - 5p - S - 2p	4S + 5P

	20 p	S - 5p - S - 5p - S - 5p - S - 5p - S	5S + 4P
	20p	2p - S - 5p - S - 6p - S - 5p - S - 2p	4S + 5P
	22 p	S - 5p - S - 6p - S - 6p - S - 5p - S	5S + 4P
	22p	2p - S - 6p - S - 6p - S - 6p - S - 2p	4S + 5P

TABLE 5.	Total P layers	Primary and Secondary layer distribution.	P&S section pattern
120W to 500W	10p	2p - S - 2p - S - 2p - S - 2p - S - 2p	4S + 5P
	10p	S - 2p - S - 3p - S - 3p - S - 2p - S	5S + 4P
	10p	1p - S - 2p - S - 2p - S - 2p - S - 2p - S - 1p	5S + 6P
	10p	S - 2p - S - 2p - S - 2p - S - 2p - S - 2p - S	6S + 5P
	12p	2p - S - 3p - S - 2p - S - 3p - S - 2p	4S + 5P
	12p	S - 3p - S - 3p - S - 3p - S - 3p - S	5S + 4P
	12p	1p - S - 2p - S - 3p - S - 3p - S - 2p - S - 1p	5S + 6P
	12p	S - 2p - S - 3p - S - 2p - S - 3p - S - 2p - S	6S + 5P
	12p	S - 2p - S - 2p - S - 4p - S - 2p - S - 2p - S	6S + 5P
	14p	2p - S - 3p - S - 4p - S - 3p - S - 2p	5S + 5P
	14p	S - 3p - S - 4p - S - 4p - S - 3p - S	5S + 4P
	14p	1p - S - 3p - S - 3p - S - 3p - S - 3p - S - 1p	5S + 6P
	14p	S - 2p - S - 3p - S - 4p - S - 3p - S - 2p - S	6S + 5P
	16p	2p - S - 4p - S - 4p - S - 4p - S - 2p	4S + 5P
	16p	S - 4p - S - 4p - S - 4p - S - 4p - S	5S + 4P
	16p	2p - S - 3p - S - 3p - S - 3p - S - 3p - S - 2p	5S + 6P

	16p	S - 3p - S - 3p - S - 4p - S - 3p - S - 3p - S	6S + 5P
	18p	2p - S - 5p - S - 4p - S - 5p - S - 2p	4S + 5P
	18p	S - 5p - S - 4p - S - 4p - S - 5p - S	5S + 4P
	18p	2p - S - 4p - S - 3p - S - 3p - S - 4p - S - 2p	5S + 6P
	18p	S - 3p - S - 4p - S - 4p - S - 4p - S - 3p - S	6S + 5P
	20p	3p - S - 5p - S - 4p - S - 5p - S - 3p	4S + 5P
	20p	S - 5p - S - 5p - S - 5p - S - 5p - S	5S + 4P
	20p	2p - S - 4p - S - 4p - S - 4p - S - 4p - S - 2p	5S + 6P
	20p	S - 4p - S - 4p - S - 4p - S - 4p - S - 4p - S	6S + 5P
	22p	3p - S - 5p - S - 6p - S - 5p - S - 3p	4S + 5P
	22p	S - 5p - S - 6p - S - 6p - S - 5p - S	5S + 4P
	22p	2p - S - 5p - S - 4p - S - 4p - S - 5p - S - 2p	5S + 6P
	22p	S - 4p - S - 6p - S - 4p - S - 6p - S - 4p - S	6S + 5P

This example, choose P& S interleaving pattern from 35W-120W table.
Confirm choice of primary layers in step 15, No P Layers = 16.

choose pattern :- 2p - S - 4p - S - 4p - S - 4p - S - 2p = 4S + 5P.

31. Choose insulation thicknesses.

Insulation is used between primary layers to lessen possibility of shorted turns where layers have the same Vdc potential, and to facilitate winding with small diameter.

Usually p to p insulation for all OPT needs to only be 0.05mm thick where layers have same Vdc. pri-pri insulation is nominated as "i".
OPT-1A, i = 0.05mm.

For between Primary and Secondary layers, or between Primary anode layers and cathode layers with full B+ Vdc potential difference between adjacent windings, insulation will be thicker than pri-pri insulation.

NOTE. For any interleaved audio coupling transformer, there will be a sum of

Vdc plus peak Vac between adjacent P and S windings and insulation must have sufficient thickness and dielectric strength to prevent arcing between windings. The insulation thickness selected will always be far more than required to prevent arcing because low capacitance is so important. Insulation thicknesses should be selected from the insulation thickness table 6 :-

Table 6.

Total Vdc + Vac pk, working maximums,	Minimum thickness, Polyester sheet.
0Vdc to 100Vac pk	0.1mm
0Vdc to 400Vac pk	0.2mm
300Vdc to 600ac Vpk	0.4mm
450Vdc to 900Vac pk	0.45mm
600Vdc to 1,200Vac pk	0.5mm
1,200Vdc to 2,400Vac pk	0.7mm
2,400Vdc to 4,800Vac pk	1.4mm

OPT-1A, Calculate probable peak Vac + Vdc between P&S windings :-
500Vdc plus 500peak Vac swing = 1,000V.

Insulation I minimum thickness = 0.5 mm.

NOTE. In fact Vac swing with no secondary load present may exceed +/- 1,500V peak at each anode if clamping diodes are not used. However arcing is unlikely unless the excessive voltages are maintained for some time, or there is moisture or pollution present or if poor insulation material is used.

32. List layers of insulation which are to be used.

Confirm interleaving pattern.
OPT-1A. Interleaving pattern = 2p - S - 4p - S - 4p - S - 4p - S - 2p.
Fig 11.

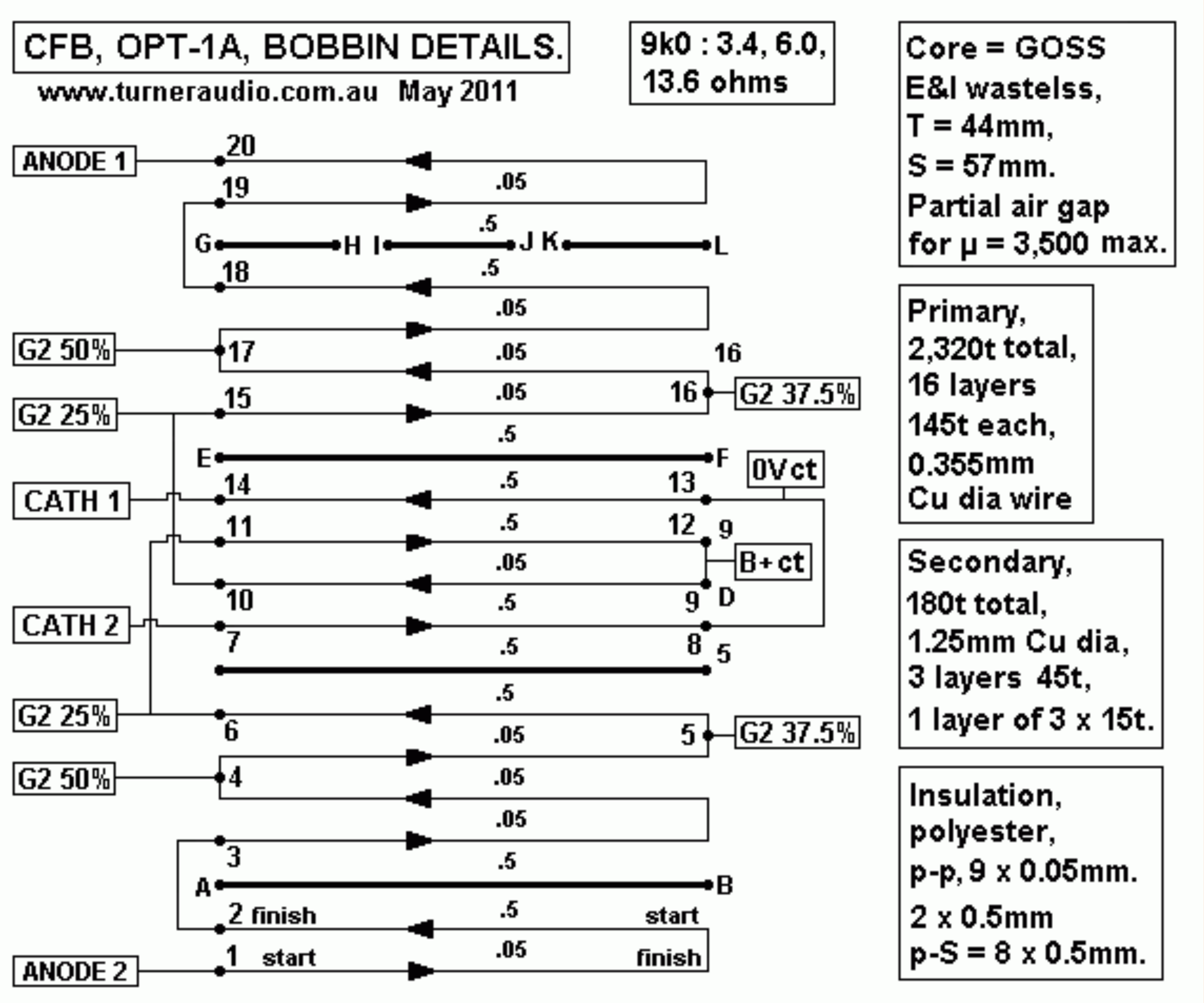


Fig 11 has been inserted here to allow easier determination of the winding insulation layers required.

OPT-1A :-

0.05mm insulation pri-pri layers, i, height = 9 x 0.05 = 0.45mm.
0.5mm insulation between anode primary and cathode primary = 2 x 0.5 = 1.0mm.
0.5mm insulation between anode and cathode primaries and secondary = 8 x 0.5 = 4.0mm.

Total thickness of all insulation = 5.45mm.

33. Calculate height of Primary layers and all insulation.

OPT-1A, Height of 16 Layers of Primary wire of 0.414mm oa dia = **6.62mm.**
Height of all insulation layers = **5.45mm.**
Total height of Primary + all Insulation = 6.62mm + 5.45mm = **12.04mm.**

34. Calculate the max theoretical oa dia of secondary wire.

Calculate available height for layers of secondary wire,
Available Sec height = (Available height in bobbin) - (Height P + all Insulations).
Available height in Bobbin = 0.8 x H window dimension.

OPT-1A, Available bobbin height = 0.8 x 22mm = 17.6mm.
Height of all secondary wire layers =
= Available bobbin height - (height of all insulation + primary wire layers)
= 17.6mm - 12.04mm (from Step 33) = **5.56mm.**

Th Sec oa dia = (Avail Sec height) / no of sec sections with one layer each,
OPT-1A, Theoretical oa dia sec = 5.56 / 4 = **1.39mm.**

35. Find nearest Sec oa dia wire size.

Actual chosen overall wire dia from Wire Size Table must be less than calculated in Step 34.
Inspect wire size table in step 20.

OPT-1A. Try 1.35mm o/a dia wire, Copper dia = 1.25mm.

36. Calculate the theoretical Sec turns per layer.

Theoretical S turns per layer, thStpl = Bww / thSoadia (from Step 35.)

OPT-1A. ThStpl = 62mm / 1.35 = **44 turns per layer, (omit fractions of a turn.)**

NOTE. These calculated turns per layer are for the thickest wire possible, and fewer turns per layer are forbidden because the increased wire size to fill a layer would make the winding height unable to fit onto the bobbin. Wires should never be wound on and spread apart so that the Tpl is reduced while keeping wire size the same, lest secondary winding resistance losses be increased too much.

Calculate load matches available where Ns = Minimum turns per layer above,

OPT-1A, Simplest range of Load Matches possible are with all 4 sec layers in parallel to give Ns = 44 turns,
Np = 2,320t, Sec 44t, TR = 52.7:1, ZR = 2,780:1.

Or with two pairs of paralleled windings in series to give
Ns = 88 turns, TR = 26.36:1, ZR = 695.0:1 :-

Primary RLa-a, k-ohms Primary turns, Np 2,320t	Secondary RL ohms Secondary turns, Ns 44t
4k5	1.61 ohms
9k0	3.23 ohms
18k0	6.47 ohms
Primary RLa-a, k-ohms Primary turns, Np 2,320t	Secondary RL ohms, Secondary turns 88t
4k50	6.47 ohms
9k0	12.95 ohms
18k0	25.90 ohms

What conclusions can be made?

How may useful load matches are there to the Middle RLa-a value between 2.5 and 10 ohms ?

OPT-1A, Middle RLa-a = 9k0, with Ns = 44t, load value = 3.23 ohms.

This will suit many "4ohm" speakers.

There are no other useful matches to the Middle RLa-a.

There is really only one useful load match.

NOTE. This is a typical conclusion which might be made where the initial theoretical number of secondary layers are either all in parallel to give Ns = 1 x Tpl calculated, or to give Ns = 2 x Tpl calculated.

NOTE. The the secondary turns per layer calculated above may be increased up to 1.4 times using smaller dia wire without increasing winding resistance too much, and to possibly allow a greater number of useful load matches to the Middle RLa-a.
OPT-1A. Tpl calculated = 44t, may be up to 44 x 1.4 = 61tpl.

NOTE. In most OPTs, the turns in one or more layers of secondary wire will have to be divided up to allow additional parallel or series combinations of secondary turns to give at least 2 or 3 useful secondary load matches which allow matching of Middle RLa-a to more values of speakers between 2.5 and 10 ohms.

37. Choose Secondary sub-section pattern.

Inspect Fig 12, 13, 14, 15, 16 patterns of Secondary Winding Sub Sections, and Choose the Fig which lists the secondary sub-sections for the number of secondary layers chosen so far.

OPT-1A has 4 layers of secondary winding layers.
Therefore choose Fig 14 where secondary sub-sections are shown for 4 layers of secondary.

Chose a pattern from those shown, 4A or 4B or 4C from Fig 14.

Fig 12.

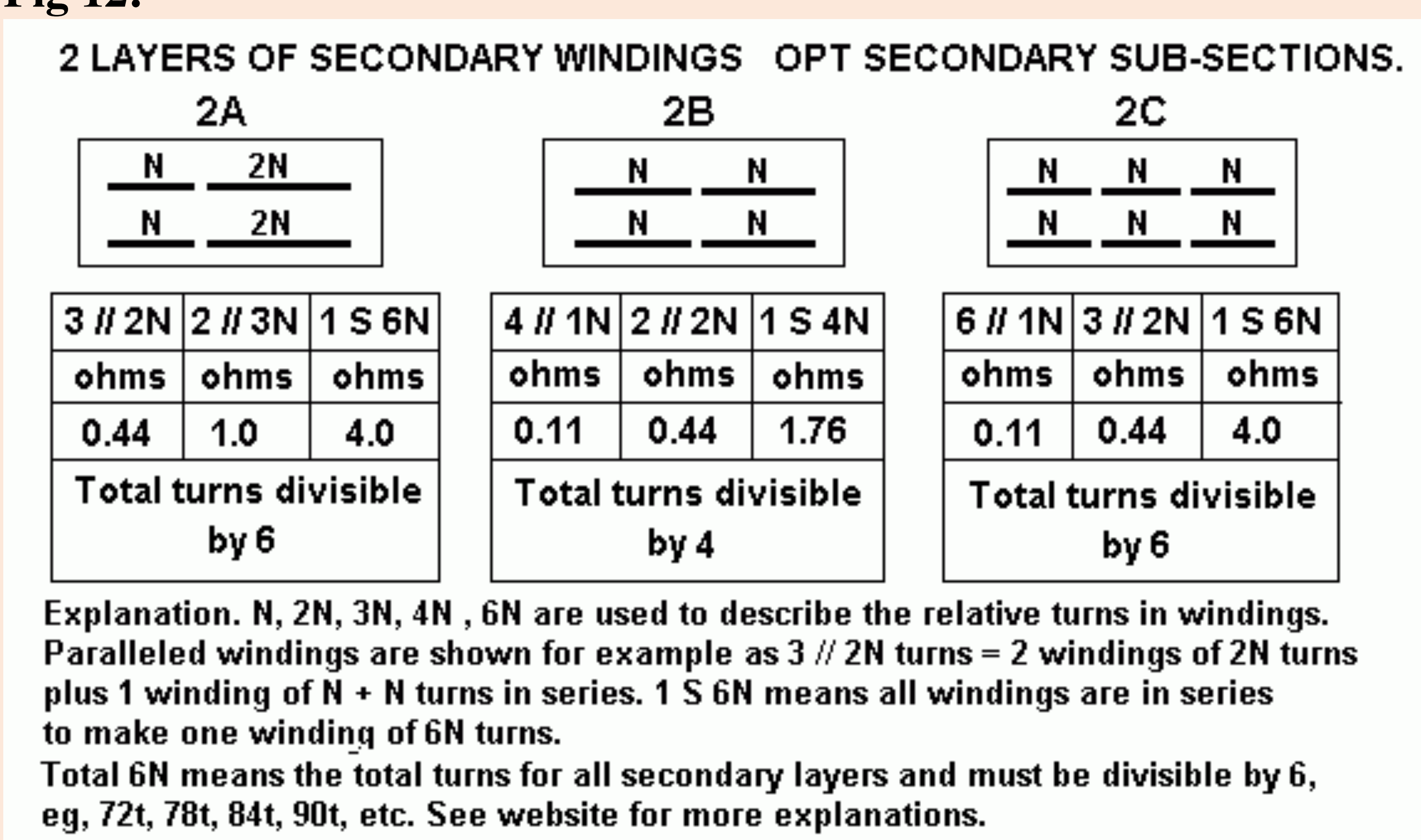
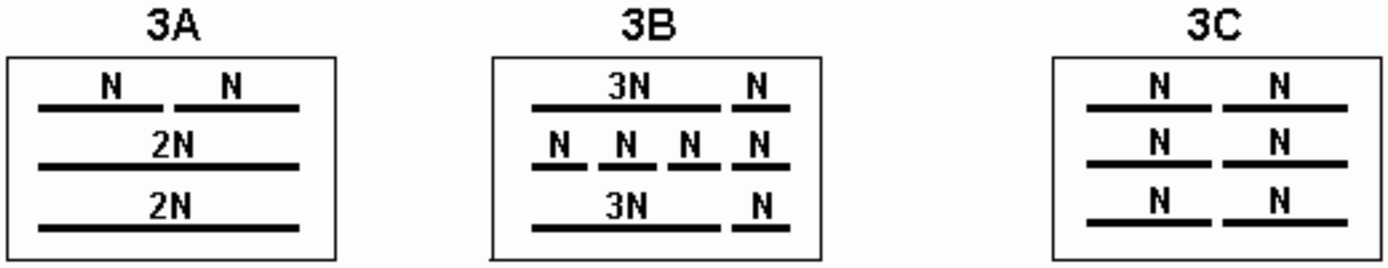


Fig 13.

3 LAYERS OF SECONDARY WINDINGS, OPT SECONDARY SUB-SECTIONS.



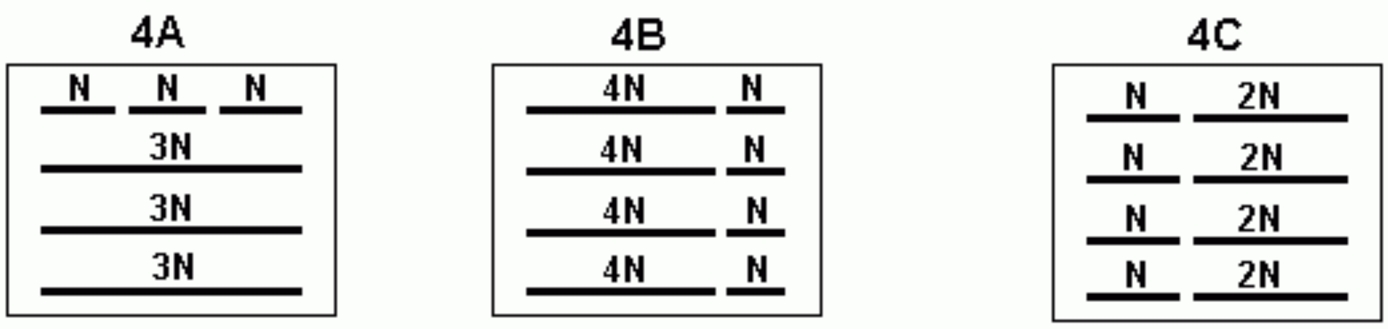
3 // 2N	2 // 3N	1 S 6N
ohms	ohms	ohms
0.44	1.0	4.0
Total turns divisible by 6		

4 // 3N	3 // 4N	2 // 6N
ohms	ohms	ohms
1.0	1.77	4.0
Total turns divisible by 12		

6 // 1N	3 // 2N	2 // 3N	1 S 6N
ohms	ohms	ohms	ohms
0.11	0.44	1.0	4.0
Total turns divisible by 6			

Fig 14.

4 LAYERS OF SECONDARY WINDINGS - OPT SECONDARY SUB-SECTIONS.



4 // 3N	3 // 4N	2 // 6N
ohms	ohms	ohms
1.0	1.78	4.0
Total turns divisible by 12		

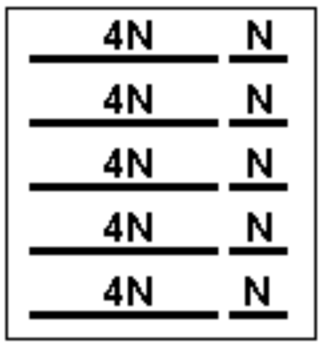
5 // 4N	4 // 5N	2 // 10N
ohms	ohms	ohms
1.78	2.78	11.11
Total turns divisible by 20		

6 // 2N	4 // 3N	3 // 4N	2 // 6N
ohms	ohms	ohms	ohms
0.44	1.0	1.78	4.0
Total turns divisible by 12			

Fig 15.

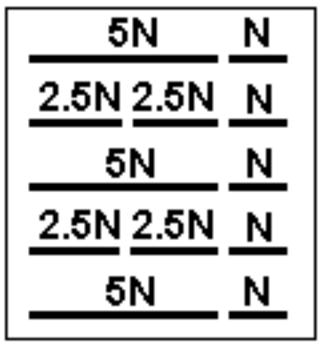
5 LAYERS OF SECONDARY WINDINGS, OPT SECONDARY SUB-SESCTIONS.

5A



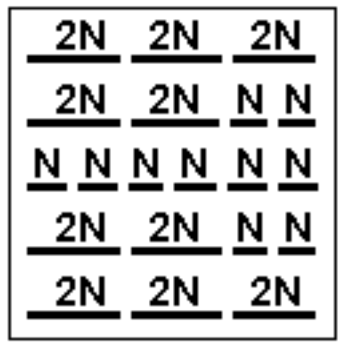
5 // 4N	4 // 5N
ohms	ohms
1.78	2.78
Total turns divisible by 20	

5B



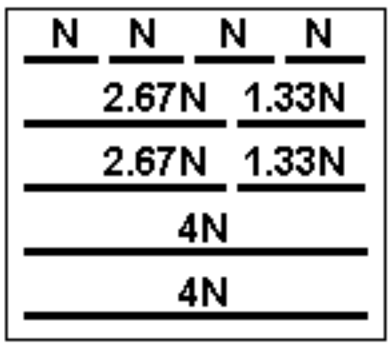
6 // 5N	4 // 7.5N	3 // 10N
ohms	ohms	ohms
2.78	6.25	11.11
Total turns divisible by 30		

5C



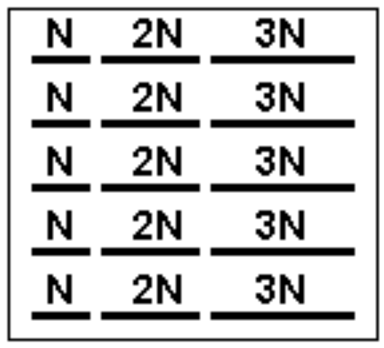
15 // 2N	10 // 3N	6 // 5N	5 // 6N
ohms	ohms	ohms	ohms
0.44	1.0	2.78	4.0
Total turns divisible by 30			

5D



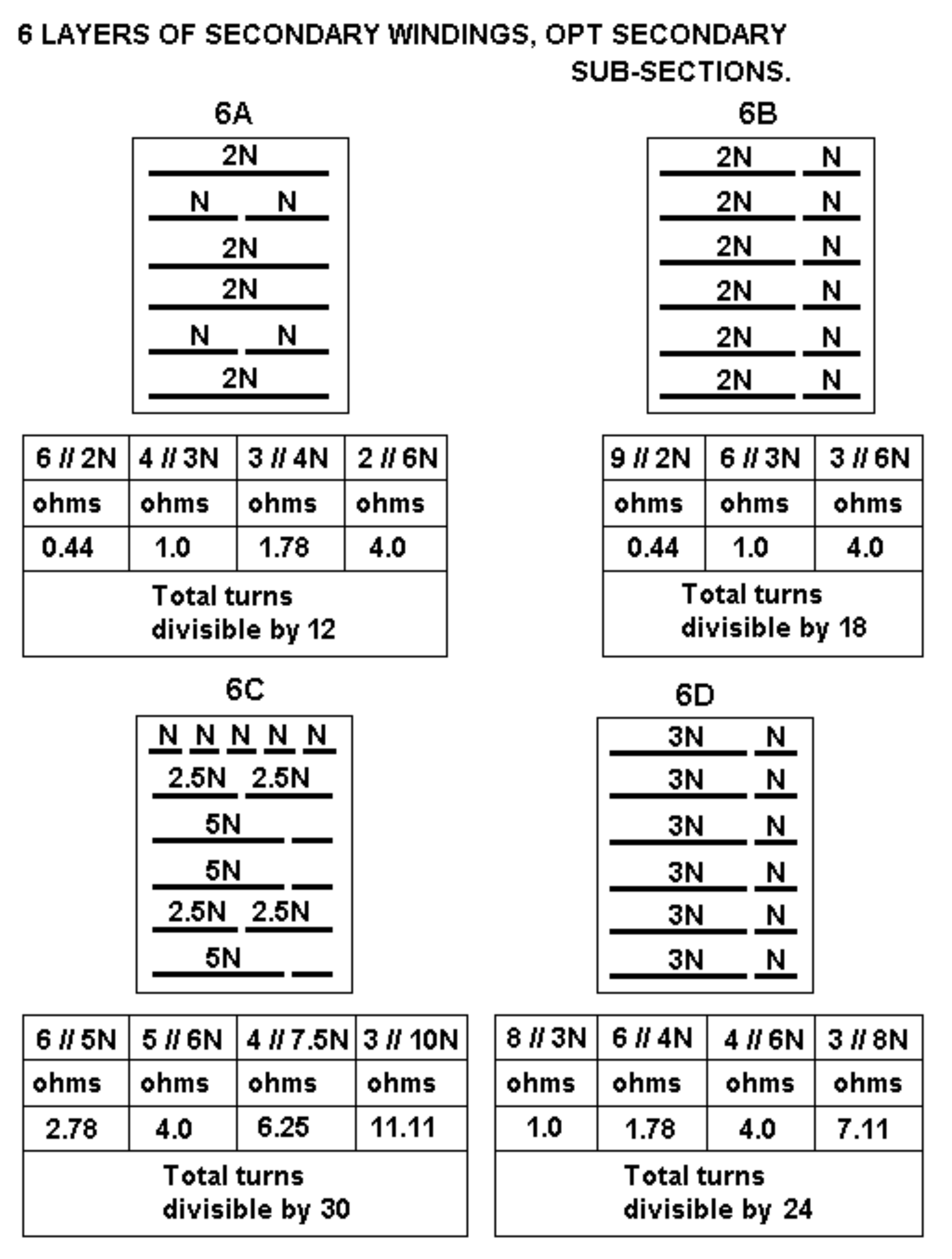
5 // 4N	4 // 5N	3 // 6.67N	2 // 10N
ohms	ohms	ohms	ohms
1.78	2.78	4.94	11.11
Total turns divisible by 60			

5E



10 // 3N	7 // 4N	6 // 5N	5 // 6N
ohms	ohms	ohms	ohms
1.0	1.78	2.78	4.0
Total turns divisible by 60			

Fig 16.



6A

6 // 2N	4 // 3N	3 // 4N	2 // 6N
ohms	ohms	ohms	ohms
0.44	1.0	1.78	4.0
Total turns divisible by 12			

6B

9 // 2N	6 // 3N	3 // 6N
ohms	ohms	ohms
0.44	1.0	4.0
Total turns divisible by 18		

6C

6 // 5N	5 // 6N	4 // 7.5N	3 // 10N
ohms	ohms	ohms	ohms
2.78	4.0	6.25	11.11
Total turns divisible by 30			

6D

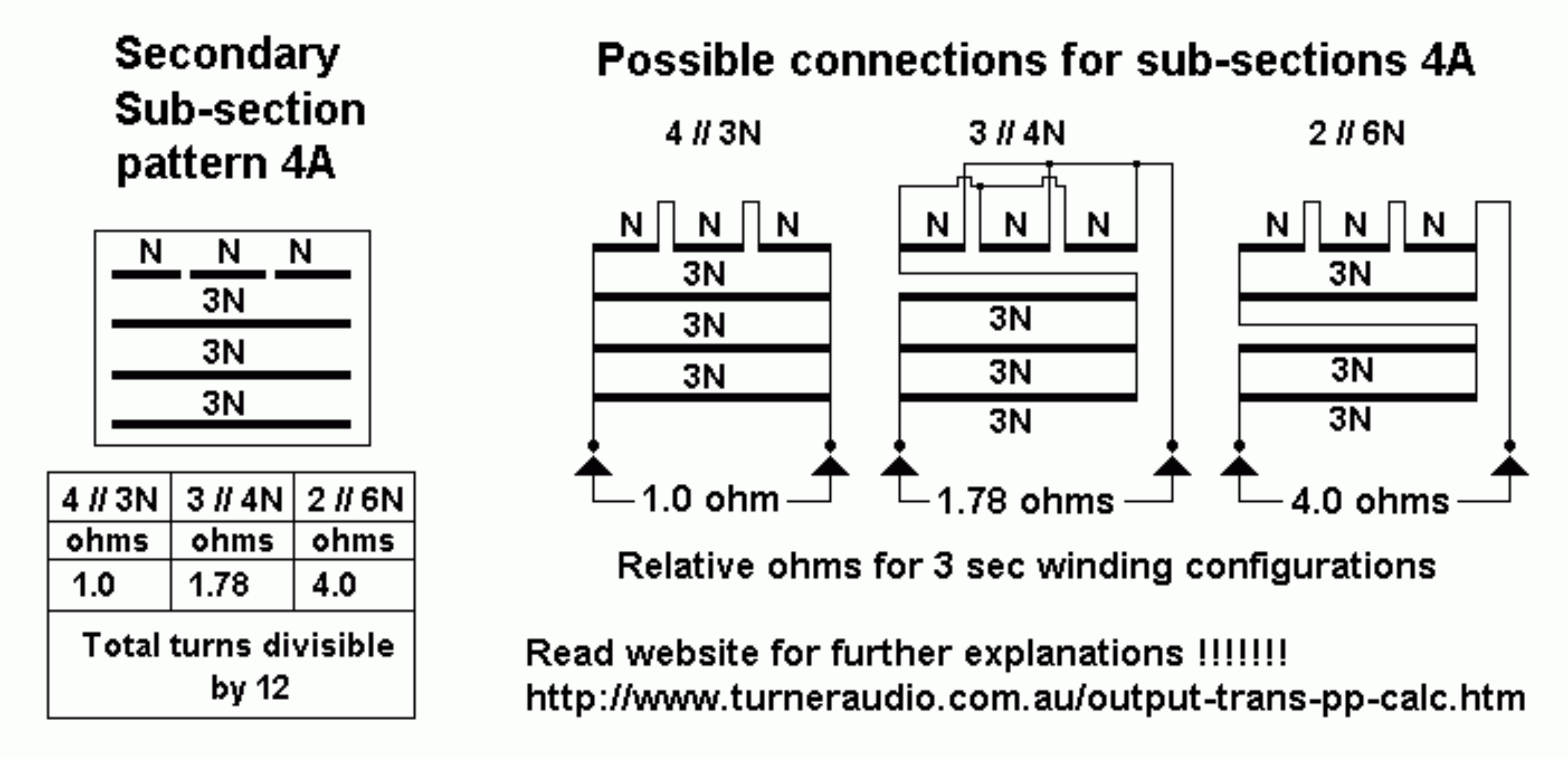
8 // 3N	6 // 4N	4 // 6N	3 // 8N
ohms	ohms	ohms	ohms
1.0	1.78	4.0	7.11
Total turns divisible by 24			

Step 37, Continued... Choose 4A from Fig 14.

NOTE. The chosen sub-section winding pattern requires some futher explanations.

In **Fig 17** below, The letter N is given to represent exactly 1/3 of the turns in a layer of wire. Therefore 1 complete layer of wire has 3N turns.

Fig 17.



In Fig 17, the pattern 4A has a window below the pattern where it says "Total turns divisible by 12" and this means that total turns in all 4 layers of secondary wire MUST be exactly divisible by 12, or else the pattern will just not work properly.

OPT-1A. In above steps, Minimum Tpl calculated = 44 turns.
4 layers of 44Tpl = 176 turns Total.
Now 176t is NOT exactly divisible by 12, but from NOTE above the tpl could be increased by up to 61tpl if desired.

List the numbers above 176 which may be exactly divided by 12, and the Tpl for each layer and impedance matches are :-
180t, get 45tpl,
192t, get 48tpl,
204t, get 51tpl,
216t, get 54tpl,
228t, get 57tpl,
240t, get 60tpl.

OPT-1A. Choose total secondary turns = 180 turns = 45turns per layer.

List impedance matches available to Middle RLa-a = 9k0.
Primary Np = 2,320 turns :-

Np = 2,320t, RLa-a = 9k0	Ns = 4 // 3N = 45t, ZR = 2,658	Ns = 3 // 4N = 60t, ZR = 1,495	Ns = 2 // 6N = 90t, ZR = 665
Sec load, ohms :-	3.38	6.02	13.52

Conclusions. This shows that there are TWO secondary load matches between 2.5 and 10 ohms for Middle RLa-a = 9k0 and that they ideally suit speakers which have a nominal value of 4 ohms and 8 ohms. The third match is good for 16 ohm speakers.

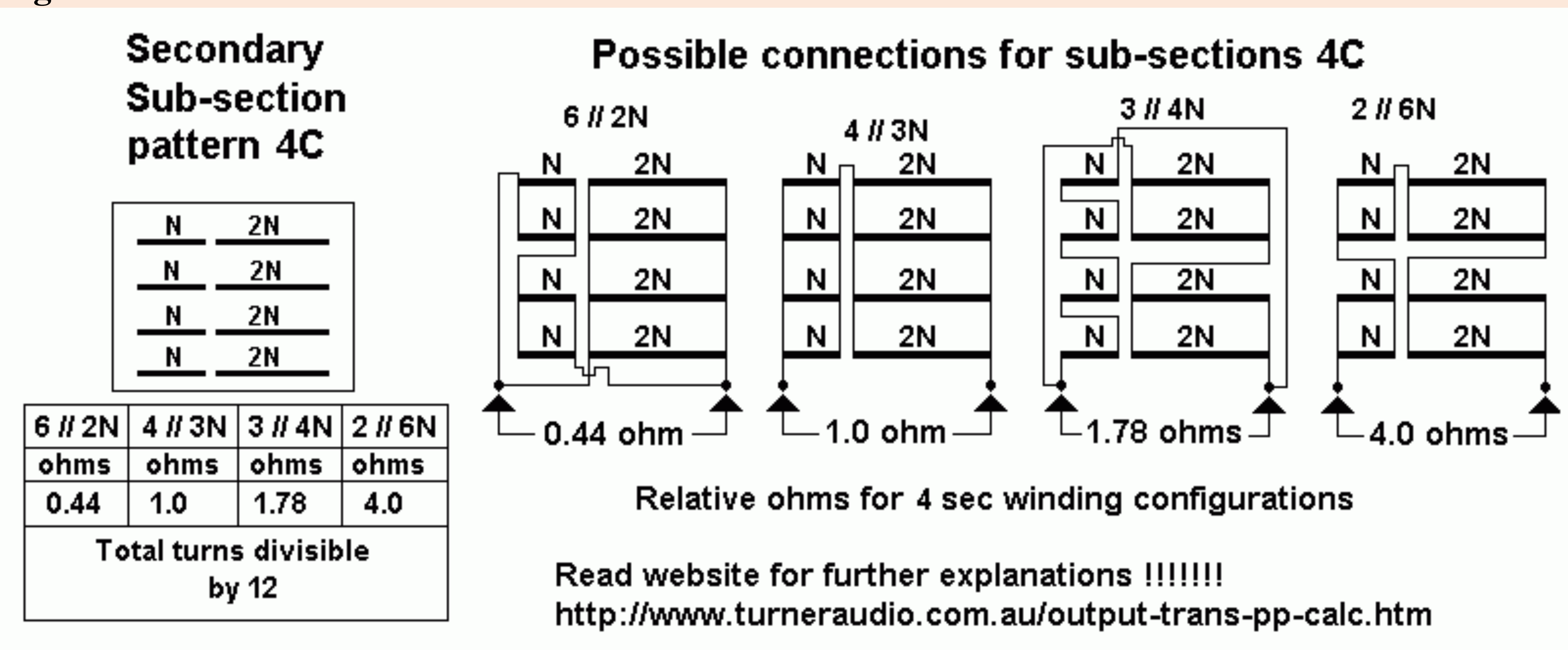
For higher AB power a 3.38 load could be used with Ns = 60t and RLa-a will then become 5k0.
A 6 ohm load could be used with Ns = 90t, giving RLa-a = 4k0.
There is no way high AB power could be generated into a 16 ohm speaker.

For much more pure class A, the 6 ohm load can be used with Ns = 45t, giving RLa-a = 16k0,
A 13.5 ohm load used with Ns = 60t gives RLa-a = 20k2, all pure class A.

But there is no way to all pure class A power for load of 3.38 ohms.

Let us consider using pattern 4C from Fig 14,

Fig 18.



In **Fig 18**, there are 4 impedance matches and a table may be drawn up :-

Np = 2,320t, RLa-a = 9k0	Ns = 6 // 2N = 30t ZR = 5,980	Ns = 4 // 3N = 45t, ZR = 2,658	Ns = 3 // 4N = 60t, ZR = 1,495	Ns = 2 // 6N = 90t, ZR = 665
Sec load, ohms :-	1.50	3.38	6.02	13.52

This arrangement of windings allows all the connections that are available with pattern 4A, plus an extra one which gives pure class A with 3.38 ohms, using Ns = 30t.

Conclusion. Pattern 4C offers the following full range of loads to be used :-

Np =	Ns = 30t,	Ns = 45t,	Ns = 60t,	Ns = 90t,

2,320t	ohms	ohms	ohms	ohms
RLa-a = 4k5, 72 Watts max	0.75	1.69	3.01	6.77
RLa-a = 6k4 57 Watts max	1.06	2.38	4.26	9.52
RLa-a = 9k0 45 Watts max	1.50 ***	3.38 ***	6.02 ***	13.52 ***
RLa-a = 12k7 33 Watts max	2.12	4.78	8.51	19.12
RLa-a = 18k0 24 Watts max All ClassA1	3.01	6.75	12.08	27.04

I have marked the best matches available for most people with *** where the Middle RLa-a = 9k0, and loads can be 1.5, 3.4, 6.0 or 13.5, depending which winding arrangement is chosen.

OPT-1A. The pattern 4C from Fig 14 will require 16 terminals for the secondary windings to be set out on a terminal board to allow soldered wire links of the terminals in 4 different patterns to achieve the desired load matching. To many audiophiles, such complexity is likely to lead to a mistake being made when a new pair of speakers is purchased with different impedance.

Fig 19.

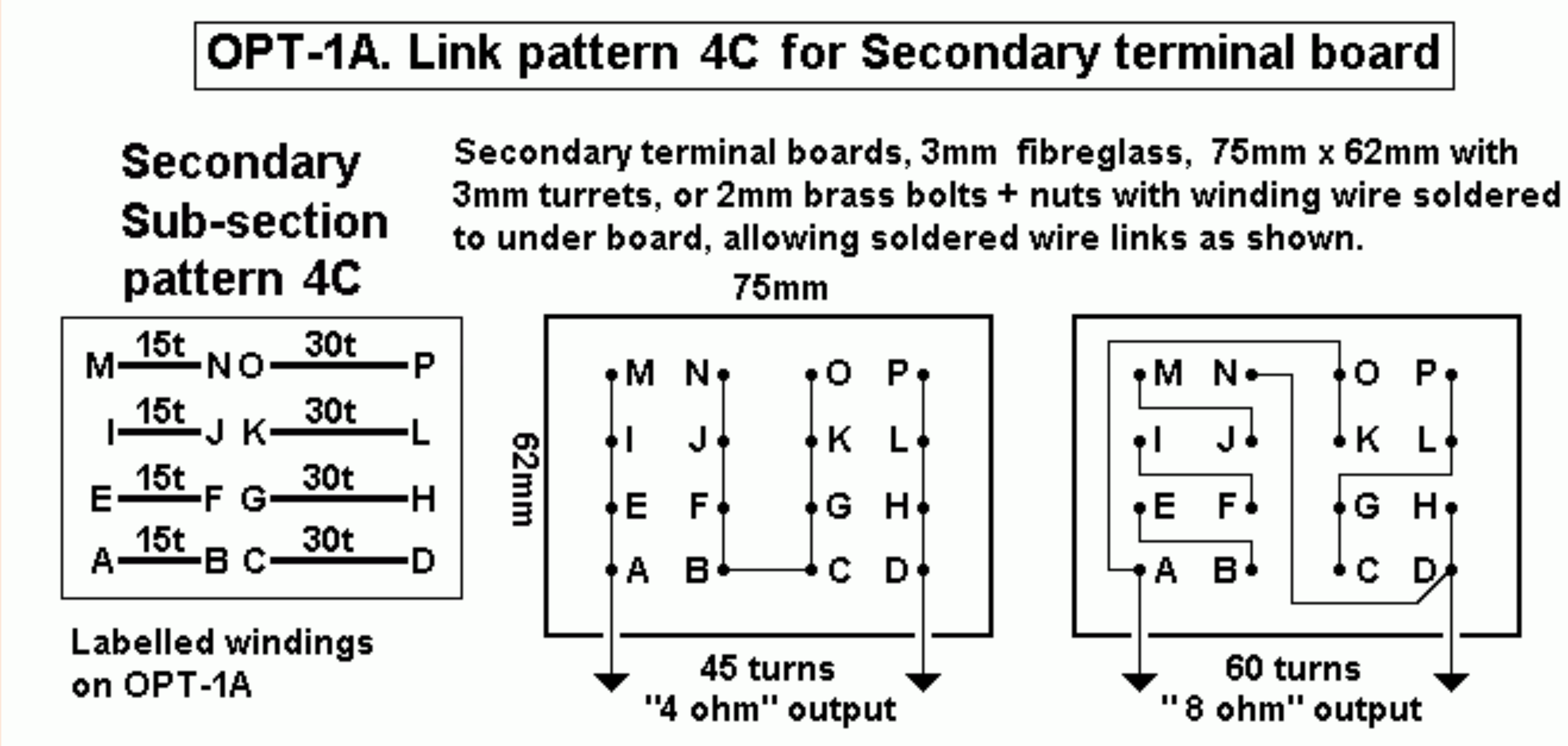


Fig 19 shows how the sec windings should be labelled using alphabet capital letters. This means one may have up to 26 single letter labels for any OPT. It is unlikely that more than 26 terminals would be required.

NOTE. The finished OPT should have a removable cover on the rear panels of OPT potted enclosures and at least both the strapping patterns should be clearly shown on the covers to allow anyone to easily make a visual check to see if the links are correctly wired.
The layout of terminals and links allows the same two terminals to be used for the 0V grounding point and live active output point from the secondary winding.

NOTE. Primary terminals should be on another board with restricted access because there are high voltage connections.
Inevitably, someone will try to change load match links without remembering to turn the amplifier off. Primary Terminals should be numbered and not lettered, to avoid confusion when winding or when servicing the amp.

Fig 20.

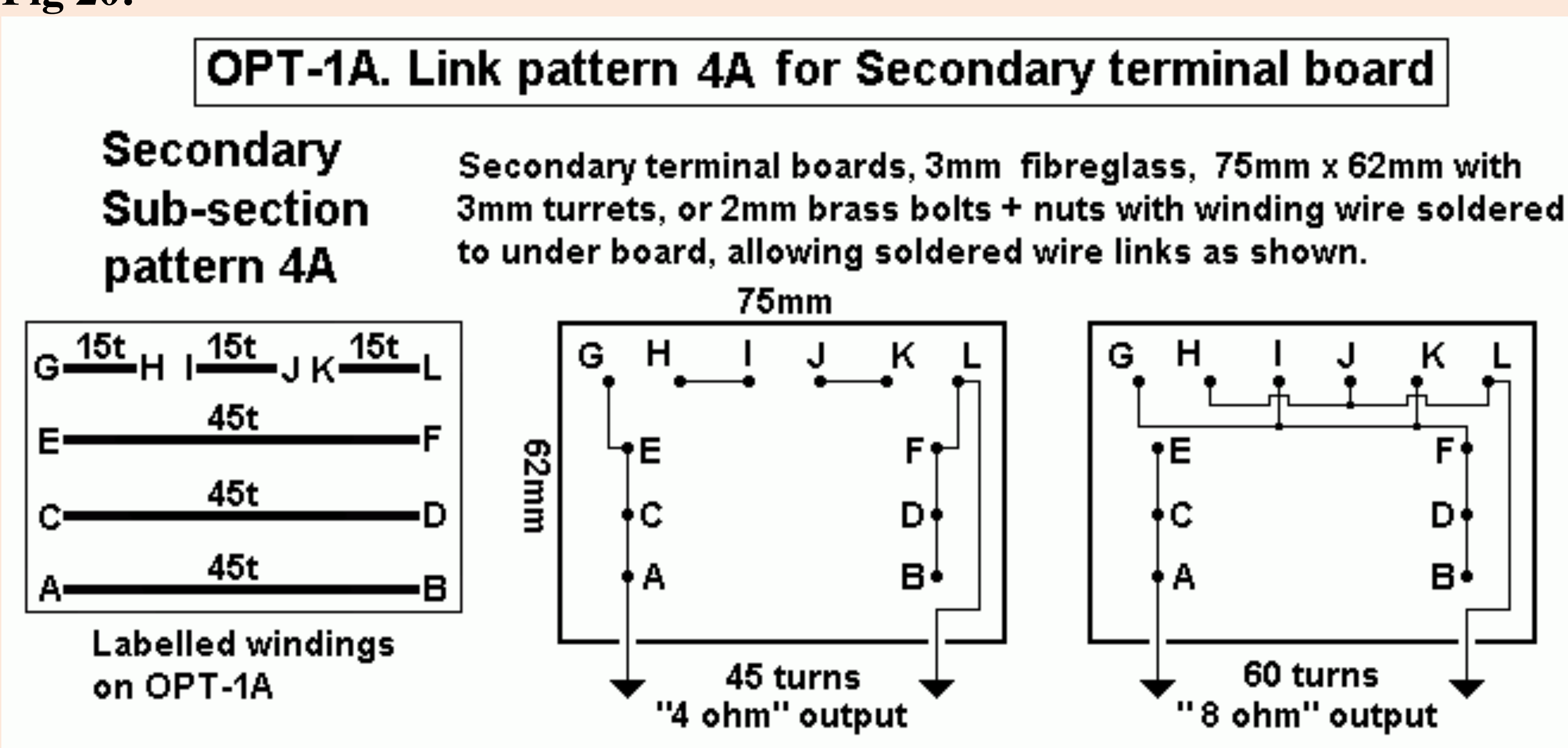


Fig 20 shows the terminal board 4A link patterns for 4 and 8 ohms.

NOTE. The Fig 20 arrangement does not show the links which would allow "16 ohms" to be used with Ns = 90t. If this was never required, then only 8 terminals are required because windings AB, CD, and EF may be taken to just two terminals. Therefore an octal socket could be used to terminate winding wires and octal plugs may used with their pins strapped in different ways to give the 4 ohm or 8 ohm matches. Two plugs are kept with wiring for either 4 or 8 and some means of securing the unused plug to prevent its loss must be devised. Octal plugs are fairly reliable for the job.

Alternative Single Simple termination.

If the amplifier is likely to be used with a wide variety of load values between say 3 ohms and 9 ohms, then the secondary may be configured to give a load match between Middle RLa-a to 5.0 ohms.

OPT-1A. Middle RLa-a = 9k0, and ZR required for Sec = 5.0 ohms = 9,000 / 5.0 = 1,800 : 1.

Required Turn Ratio = square root of ZR = sq.rt.1,800 = 42.4:1.
Therefore Ns required = Np / TR = 2,320 / 42.4 = 54 turns.

Therefore a suitable arrangement of secondaries should chosen to give paralleled windings so that Ns = 54 turns.

Above, we have worked out that the tpl may be between 45turns and 60 turns, and so using 4 layers each with 54 turns will give a suitable load match for 5.0 ohms.

The following load matches are available using Np = 2,320 turns, secondary of 4 parallel windings of 54 turns each, with ZR = 1,845:1:-

Np = 2,320 turns, k-ohms	Ns = 4 // 54turns, ohms
RLa-a = 4k5	2.44 ohms, 72Watts
6k4	3.45 ohms, 57 Watts
9k0	4.87 ohms, 45 Watts
12k7	6.89 ohms, 33 Watts
18k0	9.75 ohms, 24Watts

Conclusion. This table shows that useful load matches exist for all loads between 2.5 ohms and 10 ohms, and that speakers with nominal Z between 4 and 8 ohms will give RLa-a between 7k4 and 14k8 and the sound should be fine if average levels are about 1 watt for speakers rated for 88dB SPL per watt.

Conclusion. The use of variable load match linked windings give the same low winding losses for each pattern chosen for linked windings where the RLa-a remains constant.

Conclusion. Where there is a single fixed secondary winding, the winding losses vary proportionally to the load used at the secondary, so that if total winding losses were 6% with sec load of 2.44 ohms, then at 4.87 ohms the losses are 3%, and at 9.75 ohms they are 1.5%.

38. Calculate secondary winding loss %.

Secondary winding loss % = 100 x Rws / (SecRL + Rws) %, where the Sec RL may be any chosen value likely to be used or nominated.

The number of turns per layer is more than the minimum Tpl calculated in Step 36.

Therefore the wire size must be re-chosen to allow the increased number Tpl.

OPT-1A, Theoretical sec oa dia wire = Bww / (revised Tpl)
= 62mm / 45 = 1.378mm.
Choose from wire tables, try wire oa dia = 1.351mm, = Cu dia = 1.25mm

NOTE. This is the size previously chosen, but for where the Tpl increases further the wire dia will be smaller.

OPT-1A, Np = 2,320 turns, Ns = 45 turns, RLa-a = 9k0,
RL sec = 3.4 ohms.

Secondary Winding = 4parallel windings each with 45 turns of 1.25mm Cu dia wire.

Confirm Average Turn Length = 275mm from **Step 26.**

Sec winding resistance
= 2.26 (Ns x TL) / [100,000 x No parallel secs x Sec Cu dia squared] ohms.
where 2.26 and 100,000 are constants and Cu dia is the wire's copper dia from the wire tables. (The resistance of 100,000 mm of 1.0mm dia copper wire is 2.26 ohms)

OPT-1A, Rws = 2.26 x 45 x 275 / [100,000 x 4 x 1.25 x 1.25] = 0.045 ohms.

Secondary winding loss % = 100 x Rws / (SecRL + Rws) %.
= 100% x 0.045 / (0.045 + 3.4) = 1.30%

NOTE. Winding loss % is only relevant to the load connected to the sec winding. For example, if the sec load = 6.8 ohms, then winding losses are lower at 0.66%, and if Sec load = 1.7 ohms the losses are 2.6%.

39. Calculate total winding losses.

For the chosen winding pattern with stated primary and secondary loads.

Check that winding losses will be less than 7%.

OPT-1A. OPT TR = 2,320t : 45t,
Load ratio RLa-a to sec load = 9k0a-a : 3.4 ohms.

From **Step 28**,
Rwp = 2.26 x (Np x TL) / (100,000 x Pdia x Pdia), ohms.
OPT-1A, PRwp = 2.26 x 2,320 x 275 / (100,000 x 0.355 x 0.355) = **114 ohms.**

Primary losses with RLa-a = 9k0 = 100% x 114 / 9,114 = 1.25%.

Rws from **Step 38 = 0.045 ohms**
Secondary losses with Sec RL = 100% x 0.045 / (0.045 + 3.4) = **1.30%**

Total winding loss % = P loss % + S loss %

= 1.25% + 1.30% = 2.55%

Total losses are less than 3% with RLa-a 9k0 : 3.4 ohms.

Total Losses vary inversely with the secondary load, ie, if the Sec load is halved, the total winding losses are doubled.

If Sec RL = 1.7 ohms and RLa-a is 4k5, then with the same OPT turn ratio, losses will be (3.4 / 1.7) x 2.55% = 5.1%.

NOTE. If total winding losses exceed 7% with minimum RLa-a and sec load, a larger Core T size may be needed to allow thicker wire sizes, or higher stack with fewer turns of thicker wire. The whole design would have to be re-calculated.

40. Calculate total height of bobbin contents.

This includes P and S windings, insulation and bobbin base thickness and total height should be no more tha 90% of the winding window H dimension.

OPT-1A,
Primary wire layers, 16 x 0.414..........................6.624mm.
0.05mm insulation, p to p layers, 9 x 0.05mm......0.450mm.
0.5mm Insulation, p to p layers, 2 x 0.5mm.........1.000mm.
0.5mm Insulation p to S layers, 8 x 0.5mm ....4.000mm.
Secondary wire layers, 4 x 1.351mm...................5.404mm.
0.2mm Insulation wound over last on P layer.......0.200mm.
Bobbin base thickness.......................................2.000mm.

Total winding height including bobbin base.........19.678mm.

Calculate 90% of window H dimension = 0.9 x H.

OPT-1A. 0.9 x 22mm = 19.8mm.

Total height of all bobbin content plus bobbin base is less than 19.8mm, OK.

NOTE. If bobbin content + bobbin base height is more than 90% of H, it may be difficult to insert E shaped laminations into wound bobbin.
If this is the case, it may be

necessary to revise all calculations after selecting a larger Tongue size or larger Stack height with less turns for the core.

NOTE. Wire will not lay perfectly flat as layers are put on and will tend to spring up across the rectangular core. The windings will develop a bulge and apparent winding height will become higher than calculations predict.

Layers of wire and insulations will not be perfectly tight. I suggest it is important to apply slow setting epoxy varnish by brush to all windings and all surfaces of insulations as the bobbin is wound and then gently cramp the wound bobbin with a g-clamp and carefully cut blocks of plywood between bobbin cheeks to flatten the wind up. This will increase the tightness of all bobbin contents and cause varnish to further penetrate any voids.
The well varnished bobbin will need to have all layers of wire and insulation glued well together to minimize audio frequency "howl noise" from the OPT.
Before removing the bobbin from the winding lathe, the completed bobbin is left cramped up for 2 days to give a long enough setting time for the epoxy varnish
This prevents the wound bobbin shape deforming if it is not held between plates on the lathe. Care must be taken to prevent adherence of excessive varnish to parts of the lathe.
The practice of hand winding OPT can be extremely messy and the smelly fumes given off by the epoxy varnish can be quite toxic. The winding work should be done in a well ventilated workshop. I have used Wattyl 7008 two pack epoxy polyurethane floor varnish which has mixed pot life long enough to allow a full day for winding an OPT like OPT-1A.
I found that to clean my hands I needed to use methylated spirits and a clean cloth constantly throughout a winding process.
To gain winding skills, there is no substitute for practice, and I suggest beginners learn by winding a perfectly layered and insulated choke before they even think about an OPT.

41. Draw sketches of bobbin details.

To ensure whoever winds the transformer will be able to adhere to the diagram without any confusion, guesswork, or needing further information.

Fig 21 and **Fig 22** below have the same details for winding and insulation.

Fig 21 shows the connection of the windings if simple Ultralinear taps for screen connection are used. 37.5% screen taps are points 5&16 and 50% at points 4&17. 25% taps are available at 4&13.

Fig 22 shows the way cathode feedback windings are formed using two primary layers, 6-7, 12-13. This CFB winding arrangement means that 12.5% of the Vac between anode and cathode appears at the cathode of an output tube.
For 71 Watts into 4k5, Va-a = 566Vrms, Va-k for each 6550 = 283Vrms, with +247.6 Vrms at anode and -35.4 Vrms at cathode. If the Vgk = -20Vrms, then the grid input voltage to each 6550 = -55.4Vrms. 25% CFB could be used if all 4

central primary layers 6 to 13 were used for 25% CFB. But then grid input signal will rise to 90.8Vrms, and be more difficult to produce without added THD.

Fig 21.

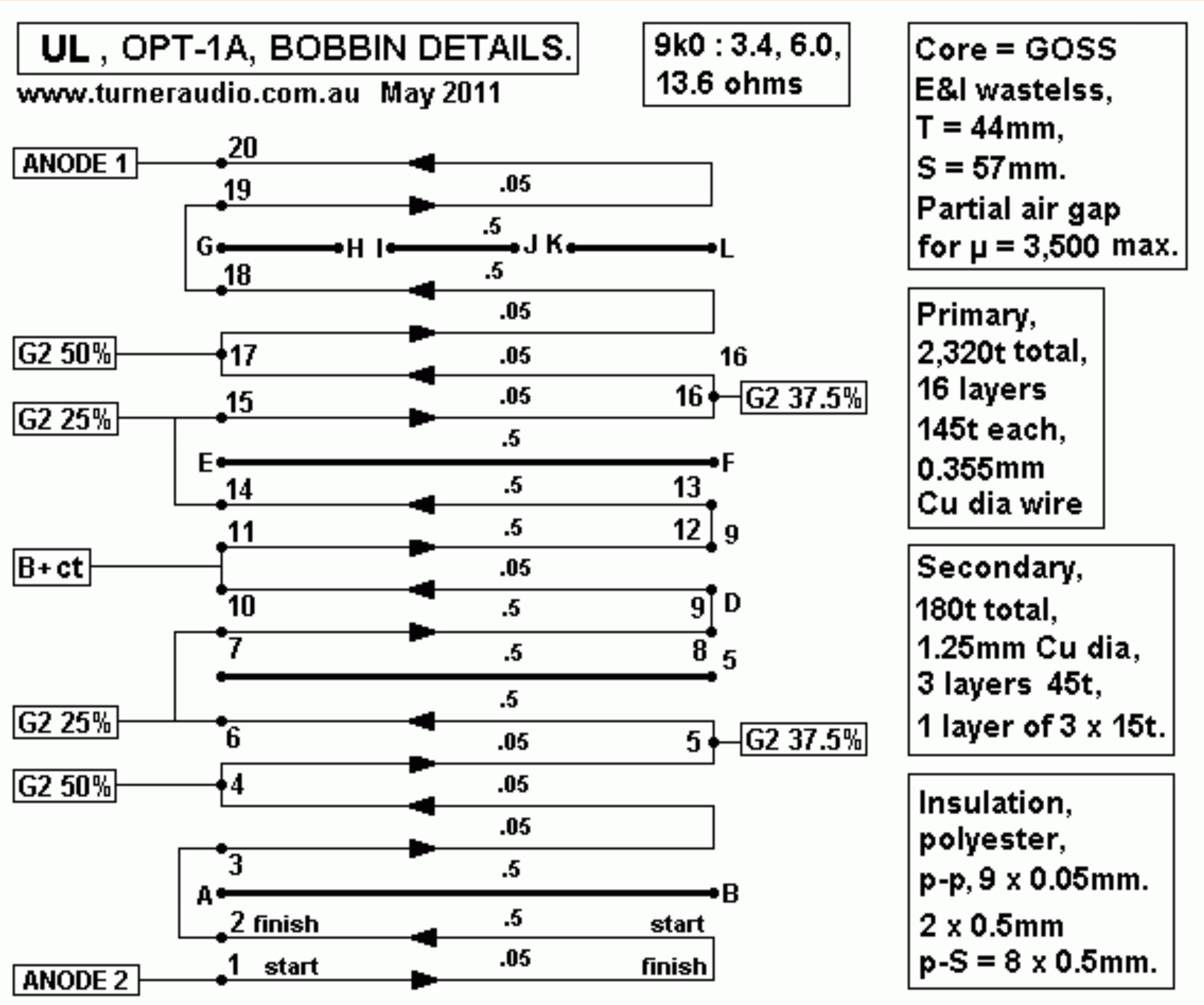


Fig 22.

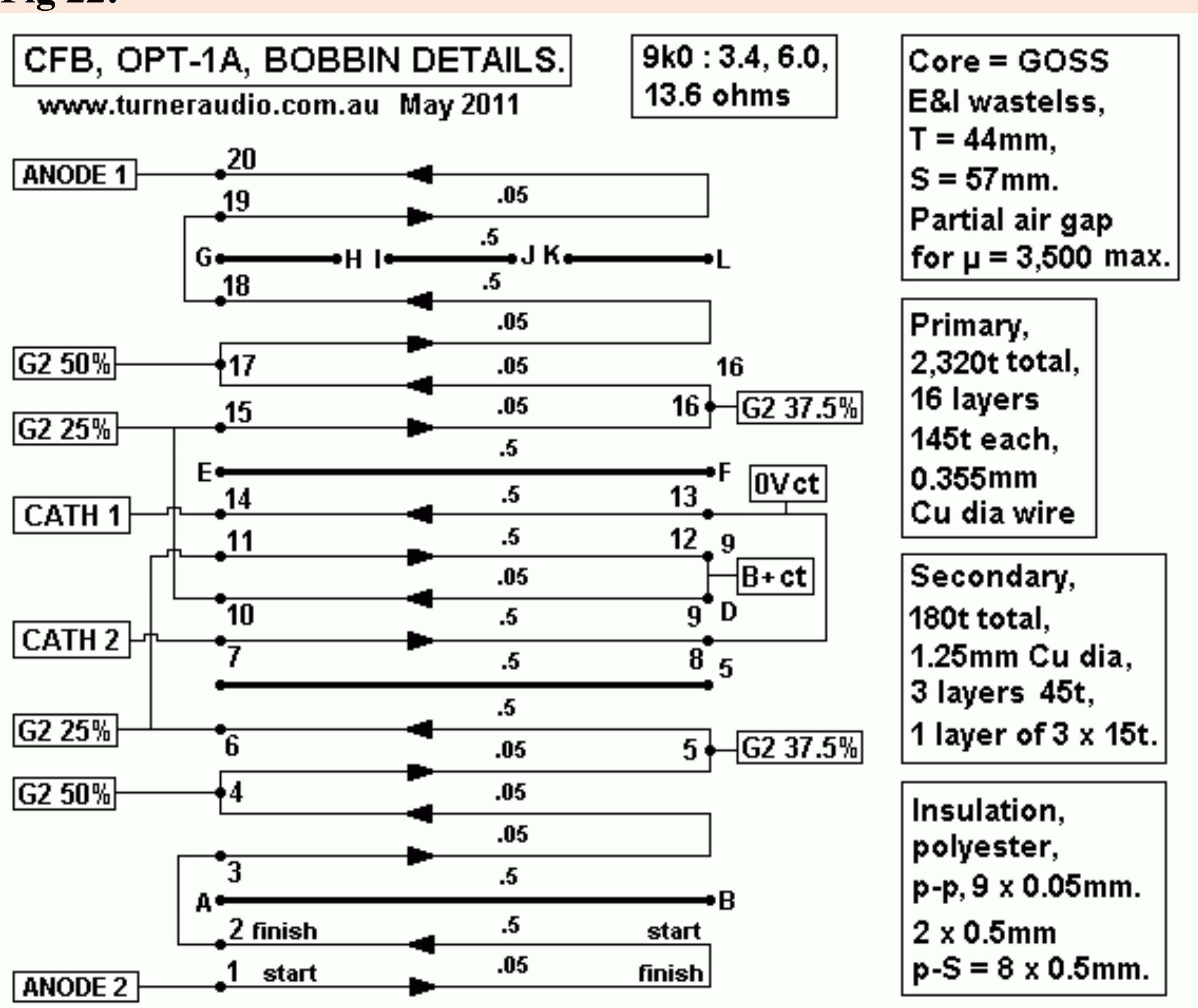
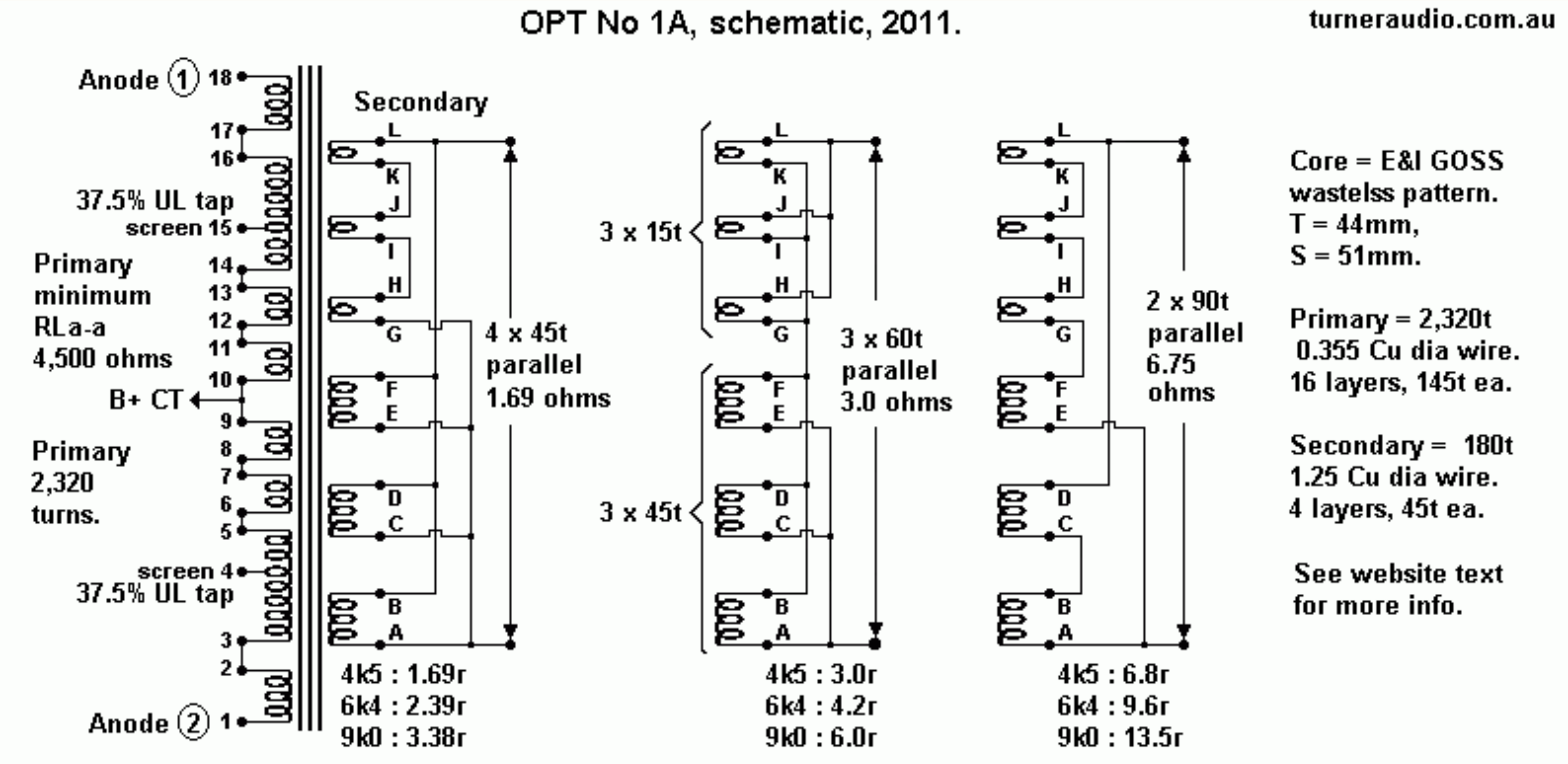


Fig 23.



NOTE. If the design method here is followed so far, there should be no need to make any further calculations of Leakage Inductance, Saturation Frequency at Bac max, Shunt Capacitance, or Maximum safe Idc for the primary wire.
But it is prudent to check all thse things.

NOTE. The design calls for partial air gapping to ensure the OPT does not become saturated too easily at F below 20Hz. The Partial Air-gapping technique is a mostly forgotten and ignored practice in 2011 because to get this done correctly the permeability of the core material must be carefully measured and a gap established experimentally, ie, by trial and error.

42. Calculate Fsat with Middle RLa-a.

$$\textbf{Fsat} = \frac{\textbf{22.6 x V x 10,000}}{\textbf{S x T x Np x B}}$$

where Bac is in Tesla, with 1 Tesla = 10,000 gauss,
22.6 and 10,000 are constants for all transformer equations,
V = Vrms signal voltage across the primary, or sq.rt (PO x PRL)
S = core stack height,
T = core tongue width,
Np = primary turns,
F = frequency at which B is to be measured.

All dimensions in mm!!

OPT-1A, For 45 watts into 9k0, Va-a = 636Vrms, Bac max = 1.6Tesla,
S = 59mm, T = 44mm, Np = 2,320 turns,

$$\text{Fsat at B} = 1.6\text{Tesla} = \frac{22.6 \times 636 \times 10{,}000}{59 \times 44 \times 2{,}320 \times 1.6} = \textbf{14.92Hz.}$$

NOTE. This check on Fsat is necessary in case a gross error may have been made. The initial aim of the design was to achieve Fsat at 14Hz, and if Fsat is not more than 25% of the design aim then the design will work flawlessly.

NOTE. The actual maximum Va-a at bass frequencies occurs when the RLa-a is very high, often because at bass frequencies there are peaks in the bass speaker impedance of perhaps 10 times the nominal speaker load Z. However, most music has very little content below 32 Hz and bass signals cannot be at the maximum possible Va-a level lest there be no headroom for all other musical frequencies. Therefore core saturation is not a problem in most hi-fi amps even where the Fsat occurs at max Va-a at say 32Hz. I prefer all my OPTs to saturate at 14Hz if possible because there is less bass distortion and the bass is subjectively superior. I make no apologies for the size or weight of my designs.

43. Calculate minimum required Lp.

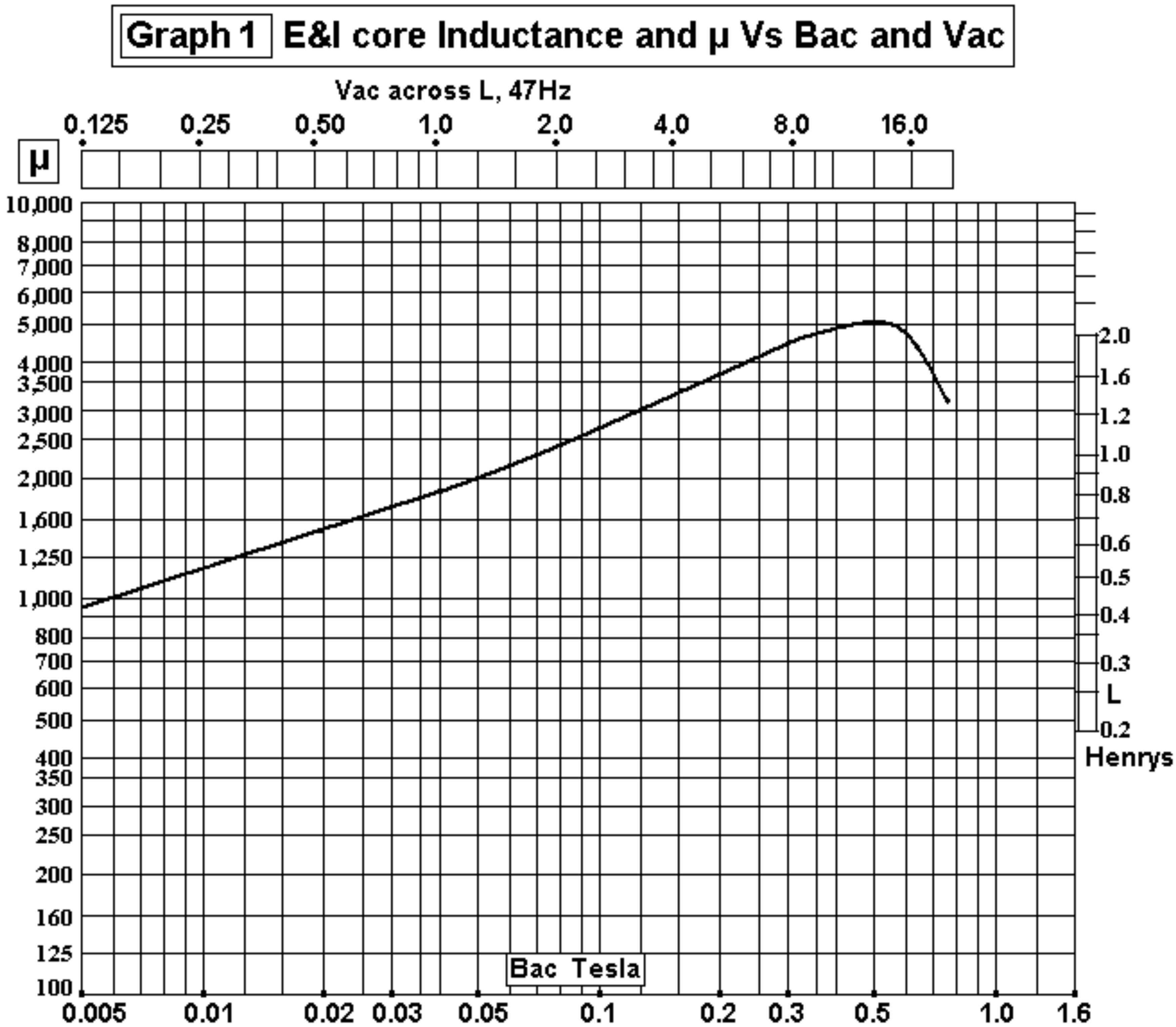
NOTE. For any PP OPT, the primary inductance Lp should have XLp > 2 x RLa-a at Fsat at Va-a > 1/2 the maximum possible sine wave Va-a.

Inductance in iron cored components is not a perfectly linear property and varies with applied voltage, frequency, and the permeability, μ, of the core material. The core material is usually grain oriented silicon steel, GOSS, and its maximum μ may be at aproximately 30Hz. Most manufacturers of GOSS cores do not ever state the μ of their GOSS, because most makers cater for the manufacture of power transformers operating at 50 or 60Hz, and the only relevant core information is the "loss per Kg" in Watts/Kg for a given Bmax, usually at about 1.5Tesla.

But for a PP OPT, the μ needs to be known, and one can determine the μ by using a test coil, Vac source and a sample of the core material.

I have drawn a graph of the results of such a test :-

Fig 24.



Test figures for E&I lams fully interleaved

Vac L	Iac L	XL	L	Bac T	μ
0.125V	0.001	119	0.40	0.005	930
0.25V	0.0016	156	0.53	0.01	1,219
0.50V	0.0026	192	0.65	0.02	1,500
1.0V	0.0043	232	0.79	0.04	1,813
2.0V	0.0063	318	1.08	0.08	2,480
4.0V	0.0093	431	1.46	0.16	3,370
8.0V	0.014	571	1.93	0.32	4,460
12.0V	0.019	631	2.14	0.48	5,000
16.0V	0.029	551	1.86	0.64	4,300
19.0V	0.046	413	1.40	0.76	3220
Saturation, THD > 10%, mainly 3H.					

Test coil = 430t, 0.55mm wire.
Source = 47Hz, sine wave from amplifier. ML = 156mm.
T = 28mm, S = 10mm.

See graph 2 for :-
Curve A, fully interleaved E&I lams,
Curve B, for partial air gapping.

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September 2011.

Fig 24 shows the graph gained after recording the Vac across a test coil with 430 turns around a GOSS core with a 10mm Stack x 28mm Tongue E&I lams.

The graph is on LOG SCALES in both axis.

If the maximum possible *μ* of laminations or C-cores selected is unknown, it may be measured using the method to gain the graph in Fig 23 above.

I used a 10mm high sample Stack of 28mm Tongue size E&I lams which were assembled into a temporary coil of 430 turns of 0.55mm wire on a convenient bobbin into which the sample core fitted. The small stack of laminations was maximally interleaved.

I used a sine wave sig gene set at 47Hz to feed a tube power amp capable of 20Vrms of output. A series resistor of 100 ohms was used to sense current. An oscilloscope used to monitor the voltage across the 100 ohms and to view the increase in the current wave distortions as the voltage to coil was increased from 0.125Vrms up to 19Vrms when THD > 10%. I have recorded the measured Vac and Iac on a table in Fig 23, and then calculated XL = V / I and calculated the inductance L, and the Bac for various applied Vac.
Notice the graph curve for inductance & μ is NOT linear. If the inductance remained constant for all applied Vac levels the graph would be a straight line.

Notice the L curve shows maximum L of about 2.1H at 12Vac at 0.48T.

$$\mu = \frac{\mathbf{Lp \times 1{,}000{,}000{,}000 \times ML}}{\mathbf{1.26 \times Np\ squared \times T \times S}}$$

In this example,

$$\mu = \frac{2.14 \times 1{,}000{,}000{,}000 \times 156}{1.26 \times 430 \times 430 \times 28 \times 10} = 5{,}118.$$

At only 0.125Vac the L has become 0.4H, and μ has become 956.

If we assume the material for OPT-1A is similar to the above sample for a test, it is safe to say the maximum Lp will be when Bac = 0.5 Tesla at 50Hz. In practice, μ may be slightly higher below 50Hz, and above 50Hz the μ reduces and may be 1/10 of its maximum at 1 kHz, and negligible at 10kHz. In fact, at above 10kHz the OPT does not need an iron core and it works perfectly well without any iron core as an air cored OPT.

Most core material measurements are done at 50Hz.

What we can say about the test results is that μ will reduce from its maximum of approximately 5,000 at 0.5T down to approximately 1,000 at 0.005T. The Vac may be reduced by a factor of 0.01 to give a μ reduction of about 0.2.

The maximum Va-a for 45Watts into 9k0 = 636Vrms. At 50Hz, the Bac = 0.48 Tesla, so μ should be at near its maximum of 5,000 and so to LP will be at its maximum = 359Henrys. Therefore if the Vac is reduced from 636Vrms down to 6.36Vrms, the μ will be approximately 1,000, so Lp will be 71.8 Henrys.

At Fsat = 14.9Hz, the 636Vrms produces Bac = 1.6Tesla with core saturation. Not all E&I lams will reach up to 1.6T without saturation and some cores saturate well below 1.6T. But now we are interested in inductance, and at 0.5T at Fsat, Va-a is about 200Vrms and there is no saturation and μ should be at its maximum of 5,000 giving maximum Lp of at least 359H.
At 0.005T, Va-a = 2.0Vrms, and Lp should be 71.8H.

My recomendation for Lp at high level operation is :-
Lp = 2 x RLa-a / (6.28 x Fsat) Henrys.

where RLa-a = Middle RLa-a, 6.28 is a constant of 2 x pye, ie, 2 x 3.1428, Fsat is at full clipping Va-a for max PO at 1kHz.

For OPT-1A, Wanted Lp at high level,
Lp = 2 x 9,000 / (6.28 x 14.9) = 204 Henrys.

Calculate core μ required to achieve the wanted Lp :-

$$\mu = \frac{Lp \times 1{,}000{,}000{,}000 \times ML}{1.26 \times Np\ squared \times T \times S}$$

where μ = permeability, Lp is inductance in Henrys, 1,000,000,000 and 1.26 are constants, ML is the iron magnetic path length, Np is primary turns, T = core tongue size, S = core stack. All dimensions in mm.

OPT-1A, ML for wasteless core T = 44mm is 275mm.

$$\mu = \frac{204 \times 1{,}000{,}000{,}000 \times 275}{1.26 \times 2{,}320 \times 2{,}320 \times 44 \times 59} = \mathbf{3{,}186.}$$

Conclusion. If the core has max μ above 3,186, the Lp will be sufficient to prevent overloading by inductive shunting of tube signal current above Fsat.

The reduction of μ above Fsat from a max = 3,186 but before saturation commences may be approximately 30%, so at full PO load voltage the μ may be 2,230. The inductance would then be down 30% and = 143Henrys.

XLp at full PO and at 14.9Hz = 13,362 ohms.
RLa-a = 9,000 ohms.
Combined impedance of RLa-a and Lp in parallel

$$= \frac{RLa\text{-}a \times XLp}{sq.rt.\ (\ RLa\text{-}a\ squared + XLp\ squared\ )}$$

= 9k x 13.36k / sq.rt (81k + 178k) = 7,470 ohms

Conclusion. The RLa-a at 14.9Hz at the full PO level will be slightly less than the 9,000 ohms so there will be some tube overloading distortion in addition to saturation distortion if the full PO level is maintained.
But at 0.7 x max PO, or 445Va-a, ie, 1/2 full PO, the should be only a very slight reduction of the open loop response level, even with pure beam tetrode operation when Ra-a is very high at about 60k ohms.
Therefore, the core μ may be allowed to be as low as 2,200 at high Bac levels while having a maximum at 3,186 at some lower level

The use of any GOSS with μ above 3,186 is permissable. Even NON grain oriented steel cores may be used, and although the LF distortion may be much higher than GOSS, it is still in audible because it remains lower than tube distortion above 20Hz, but only IF the design theory I have at this website is followed, where my designs use more iron and turns of wire than most other manufacturers.

The reduction of Lp at low levels of Va-a can lead to LF instablity, especially where the tubes operate in pure beam tetrode and if they have no load connected. This problem is entirely solved if a LF shelving network is placed between the input and driver tube stages of the amplifier. See my many power amp schematics for this application.

Some GOSS have a much higher maximum μ well above 5,000, and I have used some E&I lams which have measured a max μ = 17,000. Some C-cores reach 12,000, and toroidal cores using GOSS may have μ = 40,000.

I don't like toroidal OPTs which I have seen used in some very expensive PP amps and which I qualify as "Glorified Garbage" Toroidal OPTs made by Plitron would be the exception, and they are supposed to be excellent, and are so highly priced that none of the low end makers such as made at http://www.garbageaudio.com can afford to install them, even though they want $5,000 for a typical generic 5050 amp with 2 x KT88 per channel.
The horrid samples of toroidal OPTs I have seen do not have enough load matching ability, and the load matches they do have are plain wrong, along with their Ea, and many other details. The OPTs usually have been wound with very thin insulation used between anode primary windings and the earthy speaker secondary and shunt C can be 10 times what it should be.
The other big problem with toroidal cores using a strip of GOSS wound in a tight spiral is the very high μ which can be 40,000. The slightest difference in Idc in each 1/2 primary winding can magnetize the core so much there is little magnetic headroom left for signal magnetization.
In any core, the sum of Bdc and Bac cannot exceed the maximum B for the core. So excellent Idc balancing is needed for any PP amp with a toroidal cored OPT. The other problem with high core μ in OPTs is that the core saturation with Vac applied is extremely sudden, and stray Idc non balance sways and very low F cause saturation all too easily.

Suppose OPT-1A had Np = 2,320 turns, and μe = 40,000,
and net Idc difference across the primary = 5mA, and ML = 245mm.
Then :-

The dc field strength, $$\mathbf{Bdc} = \frac{\mathbf{12.6 \times \mu e \times N \times Idc}}{\mathbf{ML \times 10{,}000}}$$

where Bdc is in Teslas, ue is effective permeability,
N is the turns,
Idc in Amps dc,
ML is the magnetic path length of the iron in mm,
and 12.6 and 10,000 are constants for all equations to work.
Bdc for toroidal OPT1 =
12.6 x 40,000 x 2,320 x 0.005 / (245 x 10,000) = 2.38 Tesla.
This is a "silly formula result" because the GOSS cannot be magnetized more than 1.6 Tesla. But we can conclude that very little Idc non-balance is needed to magnetize the core fully, ruin the music, and cause the tubes to over heat badly.

If the core material has μe = 3,186 which was calculated as the advisable μ above, then Bdc with 5mA of non-balance = 0.189 Tesla, and despite some reduction in distortion bass signals the music would be little affected.
In many amplifiers I have brought to me for servicing, Idc non balance is often more than 20mAdc if the tubes are aged, or the fixed bias has been very poorly adjusted.
To avoid this problem, I like to use self regulating cathode biasing with some

adjustablity of Idc balance with a pot, or have fixed bias with a balance adjust pot and a pair of LEDS to indicate the balance status visually, so that when the balance pot adjusts for LEDS to glow equally bright, the Idc is balanced within about +/- 3mA dc, and nobody has to do any more than use a finger nail in the pot shaft to make the adjustment. Hardly any commercial maker includes such features as I have explained at my 5050 amp and others at my website.

The use of GOSS E&I cores or C-cores may result with μ being too high, say over 4,000. To avoid the problem of the high Bdc and unwanted saturation effects with very low F, the core may be air gapped.....

44. Partial air gap for PP OPTs.

For GOSS E&I laminations or C-cores with excessively high permeability.

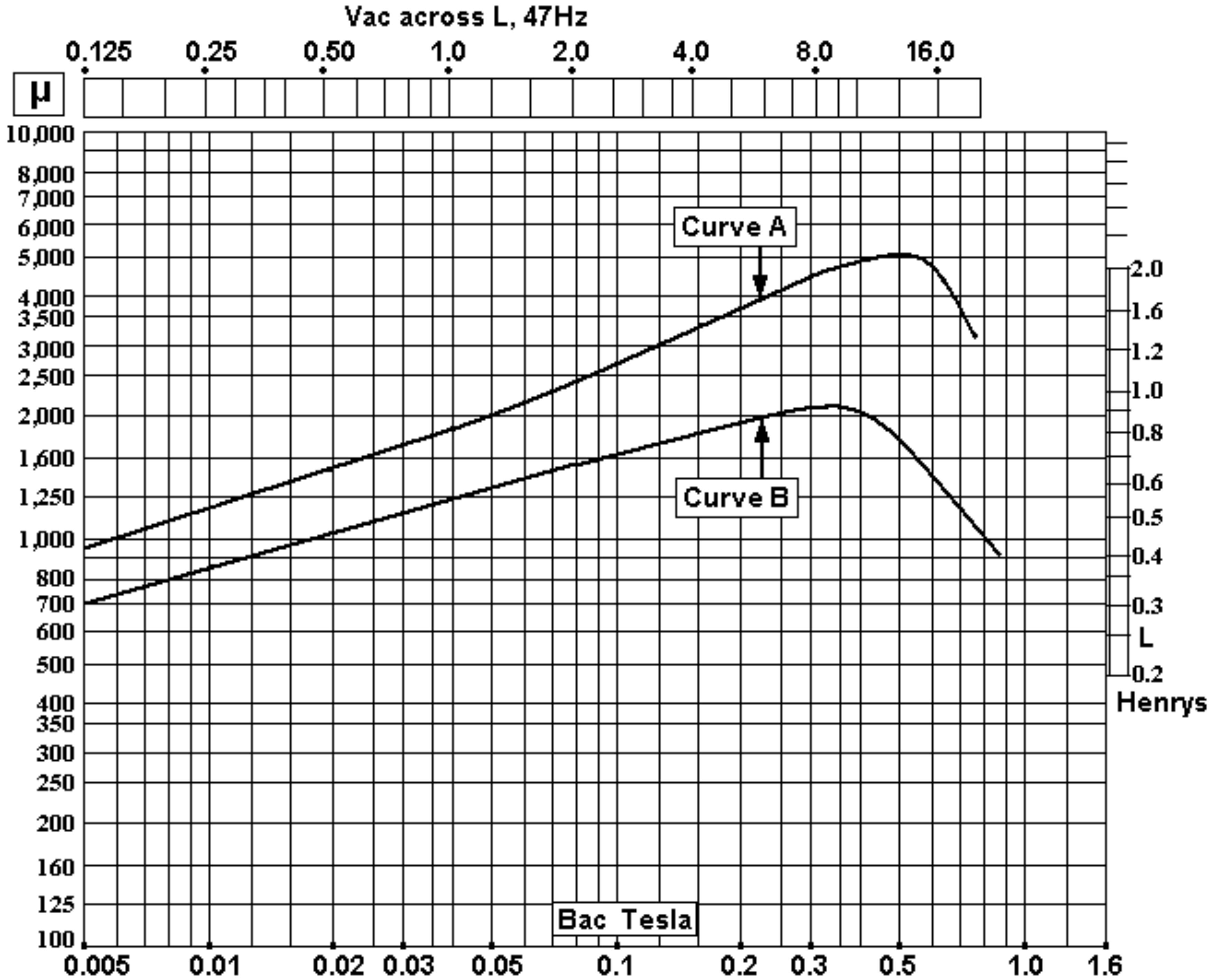
There is rarely any need for maximum μ to be higher than 3,000.

With most GOSS core E&I material, if the Es are ALL facing one way with a pile of Is against them, it is a form of "normal air gapping" even though the Is are hard against the Es. In such a case the μ may only reach a maximum of 800 and it is too low to obtain optimal primary inductance. The use of partial air gapping and partial lamination interleaving gives μ max which is intermediate between full interleavig and normal traditional air gapping.

To achieve a good reduction of maximum μ for high μ material, the Es and Is may be arranged in sub-stacks, with each sub-stack of Es and Is butted together but each set of butted Es and Is facing in opposite directions to give both partial airgapping and a much reduced number of reverse direction interlavings.
I re-arranged the laminations used to draw Fig 24 so that the 20 Es and Is were divided into 3 sub-stacks of 6+7+7 lams thick, and the top stack and bottom stack faced east, while the middle stack faced west.
The same coil was used and test results shown on Fig 25 :-

Fig 25.

Graph 2 E&I core Inductance and μ Vs Bac and Vac



Test figures for partially gapped E&I

Vac L	Iac L	XL	L	Bac T	μ
0.125V	0.0014	90	0.30	0.005	700
0.25V	0.0023	108	0.37	0.01	840
0.50V	0.0038	131	0.44	0.02	1,000
1.0V	0.0064	156	0.53	0.04	1,250
2.0V	0.01	200	0.68	0.08	1,500
4.0V	0.017	235	0.80	0.16	1,800
8.0V	0.031	258	0.87	0.32	2,100
12.0V	0.054	222	0.75	0.48	1,720
16.0V	0.094	170	0.58	0.64	1,300
22.0V	0.185	119	0.40	0.88	900
Saturation, THD > 10%, mainly 3H					

Curve A
E&I lams max interleaving

Curve B
E&I lams partial air gap.

Test coil = 430t, 0.55mm wire.
Source = 47Hz, sine wave from amplifier. ML = 156mm.
T = 28mm, S = 10mm.

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Fig 25 has Curve A being the same curve gained in Fig 24 for maximum E&I interleaving plus the Curve B which was gained with the partial air gapping. The reduction of maximum *μ* by partial air gapping is from 5,100 to 2,100.

The curves shown here are a guide to how the ardent audio enthusiast and amplifier designer may find out the nature of the materials he chooses to use and how to optimise his design for wide bandwidth, low THD/IMD and freedom from adverse saturation effects at low frequencies.

Before anyone finalises their OPT construction the samples of the core should be tested. This may be done using the actual wound bobbin with output tubes as the Va-a voltage generator, and at least with tubes operating in Triode to take advantage of the low Ra-a anode resistance to minimise distortion.

Tests of core material may also be done using a test coil fed with signals from the output of a normal audio amp with low Rout. The Test coil may be the secondary winding of the bobbin to be used, or a conveniently wound coil with perhaps 500 turns of 0.5mm wire to allow a stack of say 20mm high of proposed E&I to be tested.

With C-cores, the partial air gapping is really a normal proper air gap, but it would be much smaller than that used for a similar power rated Single Ended OPT with a high Idc flow. In a 50Watt mosfet powered amp I built before 2000, I used C-cores for a PP OPT and the μ max was about 5,000 max with cut surfaces tightly together, but with a single layer of plastic about 0.02mm thick, the μ max was reduced by 1/2, and the saturation behaviour became much less likely to cause excessive currents in the mosfets. Bass performance is excellent, see the amp details at 50 WATT PP CLASS A AMP.

45. Calculate leakage inductance.

The leakage inductance in written specifications is sometimes described as being "referred to the primary." This means it is considered to be an inductance in series with the primary load looking into one end of the primary with the other end grounded. Typical good values of this inductance would be 10 milliHenrys for where RLa-a = 10ka-a, ie, 1mH per 1k0 of RLa-a.

$$\mathbf{LL = \frac{0.417 \times Np\ squared \times TL \times [\,(2 \times n \times c) + a\,]}{1{,}000{,}000{,}000 \times n\ squared \times b}}$$

Where LL = leakage inductance, in Henrys,
0.417 is a constant for all equations to work,
Np = primary turns,
TL = average turn length around bobbin,
2 is a constant, since there is an area at each end of a layer where leakage occurs,
n = number of dielectrics, ie, the junctions between layers of P and S windings,
c = the dielectric gap, ie, the distance between the copper wire surfaces in P and S windings,
a = height of the finished winding in the bobbin,
b = the traverse width of the winding across the bobbin.

Distances are all in mm!

For OPT-1A, LL =

$$\frac{0.417 \times 2{,}320 \times 2{,}320 \times 275 \times [\,(2 \times 8 \times 0.6) + 19.0\,]}{1{,}000{,}000{,}000 \times 8 \times 8 \times 62}$$

= 0.00444 Henry = 4.44 mH.

Is the leakage inductance low enough?

Method 1:-

The simplest way to answer is to see if there is at least 1mH of LL for each 1k0 of load RLa-a.

The leakage inductance causes the lowest HF pole where RLa-a is the lowest value.

OPT-1A. Lowest RLa-a expected = 4k5.

There are 4.5 1k0 units of RLa-a

No of mH per 1k0 = 4.4mH / 4.5 = 0.977 mH per 1k0 .

This is slightly less than 1.0 and appears OK.

Method 2 :-

Calculate reactance, XLL, of LL at 100 kHz.

XLL at 100kHz = LL in Henrys x 2 x pye x F, ohms.

OPT-1A, XLL = 0.00444 x 6.28 x 100,000Hz = 2,788 ohms.

Is XLL less than minimum RLa-a at 100 kHz?

OPT-1A, RLa-a min = 4,500 ohms, ZLL = 2,788 ohms at 100 kHz.

XLL is lower than RLa-a at 100kHz. OK

46. Shunt capacitance of an OPT.

Capacitance in tube amp OPTs affects the HF response and C exists between primary turns and between primary layers which all sums to an amount of "self capacitance" of a primary winding. With a much interleaved primary winding the self C of each primary section are effectively all in series and the amount of total self C for the whole primary is a negligible amount with very little effect on the response below 100kHz. But there is considerable C between adjacent primary and secondary sections where there is high Vac in the primary sections and negligible Vac in the earthy secondary sections. The total measurable shunt capacitance across the whole primary is of great importance. This is called the "lumped shunt C", or "total primary shunt C".

The easiest way to measure the shunt C between anode and 0V is to set up the OPT as follows :-

1. Connect the secondary windings as they will be used in the amplifier and connect one end of the two secondary terminals to 0V.
2. Do not have any resistance load connected across any windings.
3. Connect the primary winding CT to 0V.
4. Connect one end of the primary winding to a signal generator with Rout = 600 ohms.
5. Connect a series resistance of 5 x RLa-a between sig gene output and one primary end.
6. An oscilloscope with a high impedance input and low capacitance probe is connected between the primary end and 0V.

7. 5Vrms at 1kHz is applied from the sig gene so you can see a good wave form.
8. While keeping the gene level at a constant 5Vrms, you should be able to plot a graph of the frequency response at the OPT primary between 2Hz and 200kHz.
9. For the OPT-1A example, the series R between sig gene and OPT would be 22k0.
10. You should find that the response will show a flat central portion each side of 2kHz with the HF pole at -3dB at say 7.6kHz.
11. C may be calculated,

C = 159,000 / (R x F), where C is in uF, R in ohms and F in Hz.

For the example, C = 159,000 / (22,000ohms x 7,600Hz) = 0.00095 uF
= 950pF.

12. Let us suppose you subtract the probe capacitance of say 40pF from the calculated C value to give Shunt C = 910pF. Now the applied voltage to one end of the OPT primary will appear at the other end of the primary, but of opposite phase.
Regardless of phase, you have effectively applied signal to BOTH sides of the OPT primary, and in fact the capacitance "looking into" one end of the OPT primary is in fact the effects of TWO lots of capacitance, ie, 455pF which exists between each end of the OPT and 0V.
Many people will try to measure capacitance with a DMM, or in ways other than I have specified here and they will make very big mistakes and obtain completely WRONG measurements.

To calculate the primary shunt capacitance in an audio transformer such as OPT-1A, refer to the above bobbin winding layout.

The average distance between the copper surfaces of primary and secondary layers including the insulation thickness of 0.5mm and the wire enamel of about 0.05mm is approx 0.7mm. Then you must allow for the curved surface of the wire turns so total distance = approx 0.75mm. In other words, you may consider layers of wire as pieces of equivalent adajacent sheets of metal.

Capacitance between two metal plates = (A x K) / (113.1 x d)
where Capacitance is in pF,
A is the area in square millimetres of the plates assumed to be of equal size,
K is the dielectric constant of the material between the plates, air being = 1.0,
113.1 is a constant for all equations to work,
d is the distance in millimetres between the plates and is the same for the area of the plates.

For OPT-1A, there is some variation of turn length but calculations will be accurate enough if the TL is the average for all turns, ie, 275mm.
Traverse width across the bobbin = 62mm, so area of each interface = 275 x 62 = 17,050sq.mm. Polyester insulation has K = 2.5 approx but some of the gap between turns is air, so allow K = 2.5.
The d we calculated above = 0.75mm.

C in pF = 17,050 x 2 / (113.1 x 0.75) = 402pF.

The first P-S interface down from 'anode 1', or the top of the wind-up at above the GH-IJ-KL is at a position of 6.5 layers / 8 layers along the P winding from the CT where the signal voltage is zero. This positioning results in the capacitance being subject to the impedance ratio at this position. Therefore the C is transformed to [402pF x (6.5 / 8) squared], = 402 x 0.66 = 265pF.

The next area of 360pF down from anode 1 appears below the sec layer GH-IJ-KL and the impedance ratio is (5.5 / 8) squared = 0.47 so the C due to this interface at anode 1 = 402pF x 0.47 = 189pF.
Next down the Z ratio is above the EF sec and = (2.5 / 8) squared = 0.098, so C = 39pF at anode 1.
Below EF the Z ratio reduces the 402pF by (1.5 / 8) squared = 14pF.

The total C appearing at the anode 1 connection is the sum of all these transformed capacitances = 265pF + 189pF + 39pF + 14pF = 507pF.

507pF is the shunt C from one anode to 0V where the CT is connected to 0V. The actual total C looking into ONE primary end is twice 507pF = 1,014pF. We can consider that each tube powering an OPT in class A sees 507pF between anode and 0V. In class AB, each tube sees 507pF in class A but sees 1,014pF after the other tube cuts off.

Where the number of interfaces is 4 or more, then total C equals aproximately 1/3 of the tptal of all C simply added. In this example, total C = 4 x 402 pF / 3 = 1,608pF/3 = 536pF, fairly close to the 507 calculated before.

Cathode Feedback windings complicates the capacitance calculation.
The effect of the capacitance on amplifier bandwidth is effectively reduced by the CFB because the CFB effectively reduces the Ra of the tubes. The C at the anode is reduced, while C at the cathode has little effect because the CFB winding is a much lower impedance winding than the anode winding.

If OPT-1A is used with a pair of 6550 in pure class A beam tetrode mode the Ra of each tube is 32,000 ohms.
Without any resistance load connected, the gain of the tubes will be close to μ at about 1kHz but reduce by -3dB where the capacitive reactance = Ra.
If C = 507pF, the -3dB pole should occur at the calculated frequency = 159,000 / (32,000 x 0.000507) = 9,800kHz.

In practice this would be only approximately correct, and the better way to test for C is to use a known low Z gene and a real series resistance as explained above. Usually the leakage inductance, LL, will have no effects on any methods described so far because the LL should be such a small value.

The capacitance and leakage inductance will react together to form a tuned circuit and low pass filter with an ultimate slope of more than 6dB/octave. While measuring the shunt C of the OPT the series R used reduces the Q of the tuned circuit to much less than 1.0. But when the OPT primary is tested with a signal source of very low resistance, say 600 ohms, and without any resistance loads, the plot of high frequency response may often show a high peak above 20kHz before rolling off at 12dB/octance. So rapid phase shift increase occurs as F becomes high so it is important to minimise C and LL to force the frequency of resonance to be as far as possible above the audio band and where the phase shift with loop NFB does not cause oscillations.

Trying to establish an exact equivalent LCR model of the OPT designed here is beyond my abilities and there is little point to achieve such modelling. It is simply easier to establish low values of C and LL by empirical methods and then critically damp the HF gain of the amp to achieve low overshoot on square waves with a 0.22 uF across the output without any R load, while maintaining a maximal HF pole with a solely resistive R load.

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