PP OPT calcs Page 5.

FOR PP TRIODE CLASS
A1 AND AB1, OPT-2A

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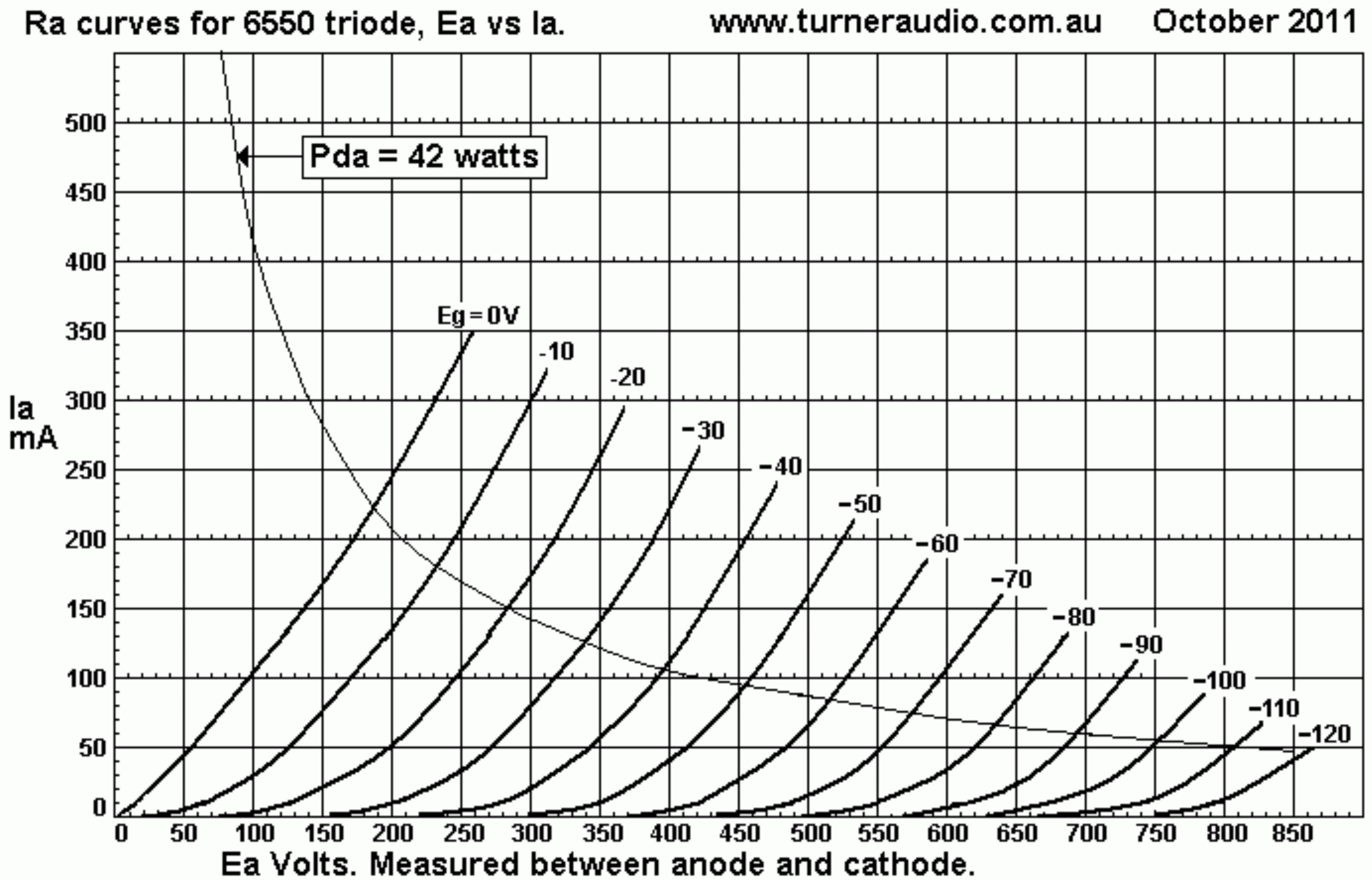
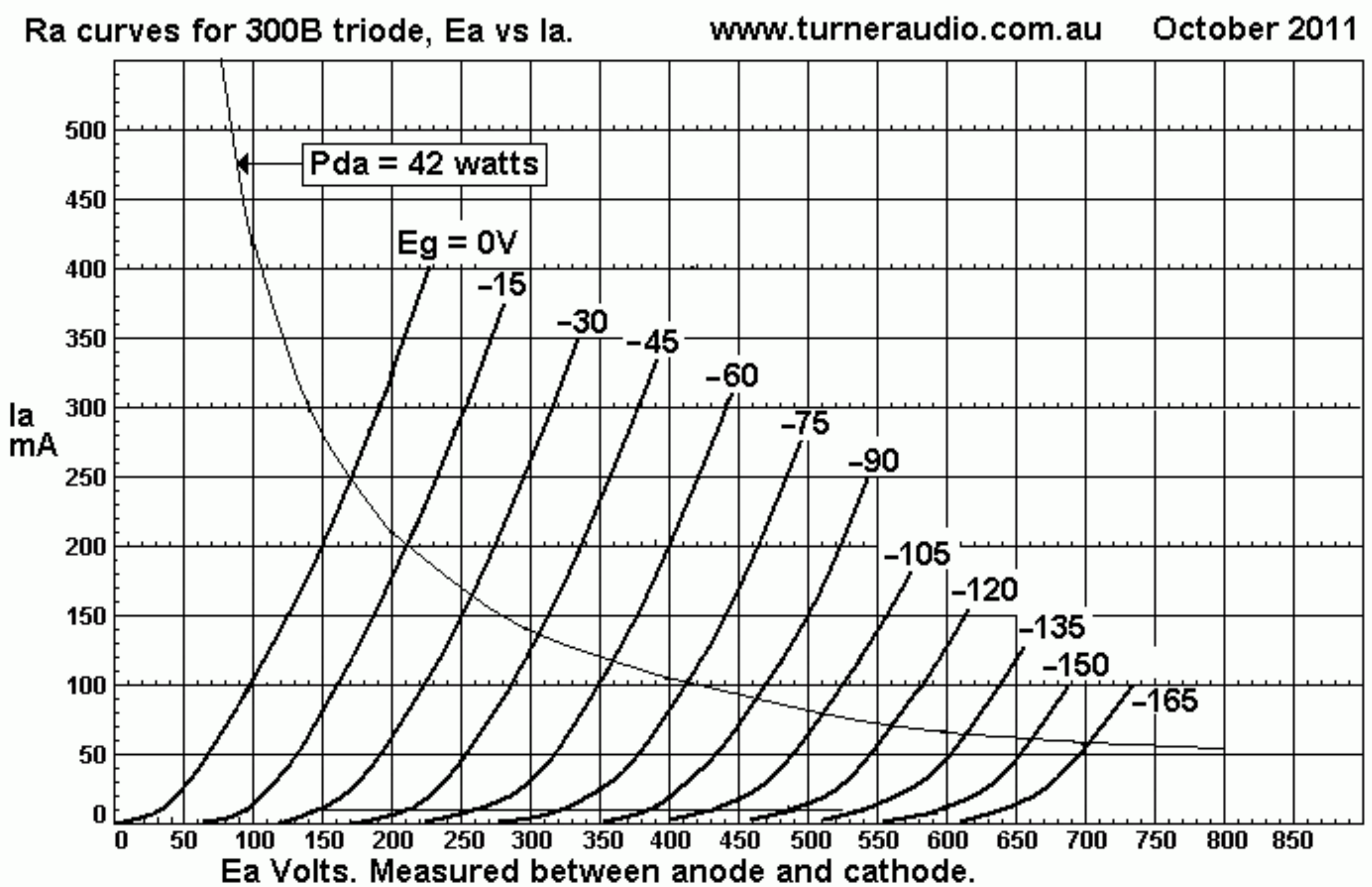
55. Triode PP class A1, AB1.

The example title for Triode OPT will be OPT-2A,
and will be used for 2 x 6550 or KT88 with Ea = +500V,
Ia dc = 50mA in each tube at idle, and tube conditions are the same
as OPT-1A.

Before any calculations for triode PP OPTs begin it will be necessary
to inspect a copy of the Triode Ra curves for any triode chosen in a project,
or for triode connected pentode or tetrode, even if load line analysis is not
done.

Fig 29.





The above **Fig 29** shows the triode Ra curves for Ea vs Ia for 6550 and 300B on the same scale size allowing comparison of the two very differently constructed tubes. Notice that the curves are substantially similar, and any OPT designed specifically for 300B may be used for the following tubes strapped as triodes :- 6550, KT88, KT90, KT120, or vice versa.

56. Understanding Ra curves for triodes.

Fig 30.

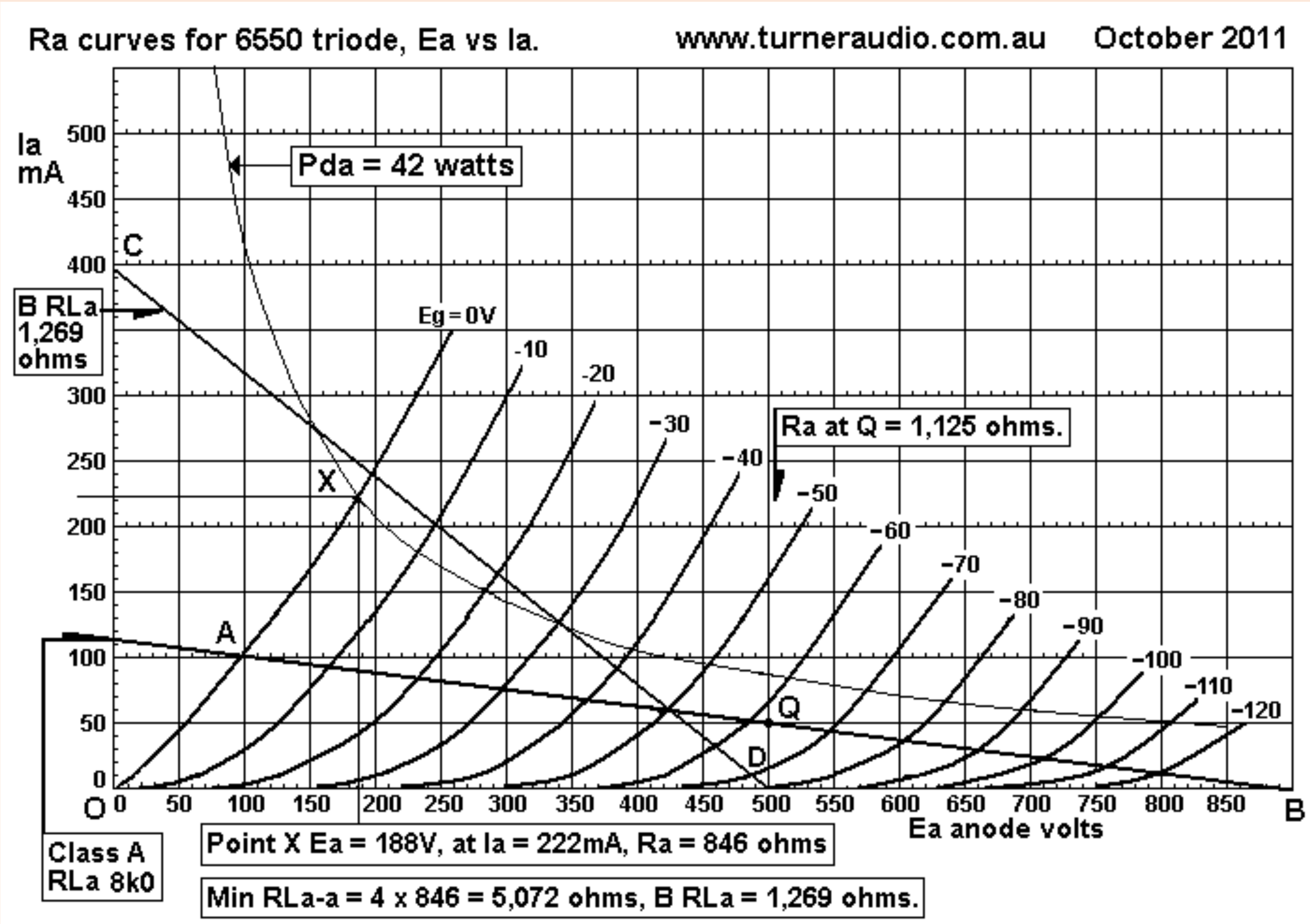


Fig 30 shows 6550 triode curves with curve for Pda limit = 42 Watts. There are also two load lines, and although is not really necessary to draw load lines for the OPT calculations, I have included them anyway and all is explained :-

Inspect the anode Ra curve for where Eg1 = 0V.
Find the Ea and Ia point on this Ra line for Eg1 = 0V where it is intersected by the 42 Watt Pda limit curve for the 6550 triode.
Plot this point on the Ra curve as POINT X.

Calculate the approximate Ra for the triode for where Eg1 = 0.0V.
Ra = Ea / Ia = 188V / 0.222A = 846 ohms.

This is the approximtae resistance value of the line between Point O and Point X.

57. Calculate the minimum PP Triode RLa-a for maximum class AB1 power for OPT-2A.

The minimum RLa-a for triodes should not be less than 4 x Ra, where Ra is calculated between point O and point X, seen in Fig 30 above.
This means the class B RLa for each tube during AB1 operation should not be less than Ra for the Eg1 = 0.0V curve. This applies for all values of Ea used in triode amps.

Pda maximum with continuous sine wave signals should not exceed the Pda rating for the tube, For triodes in class AB1 with restricted Ea swing compared to tetrode operation, the Pda max is usually at clipping with the low RLa-a values.

One might be tempted to use a B RLa-a of less than Ra which means RLa-a will be very low, and tube Pda may exceed the data limit, class A1 portion of total power very low, THD very high, and damping factor very low.

The Pda with sine wave operation up to clipping is dealt with in my page anode-dissipation+waveforms.html

OPT-2A, Ea = +500V, Idle Ia per tube = 50mA,
Minimum RLa-a = 6 x 846 ohms = 5,076 ohms.

Fig 29 above shows the B RLa = RLa-a min / 4,
= 5,076 ohms / 4 = 1,269 ohms.

The amount of output power for PP 6550 triode operation is shown here :-

Fig 31.

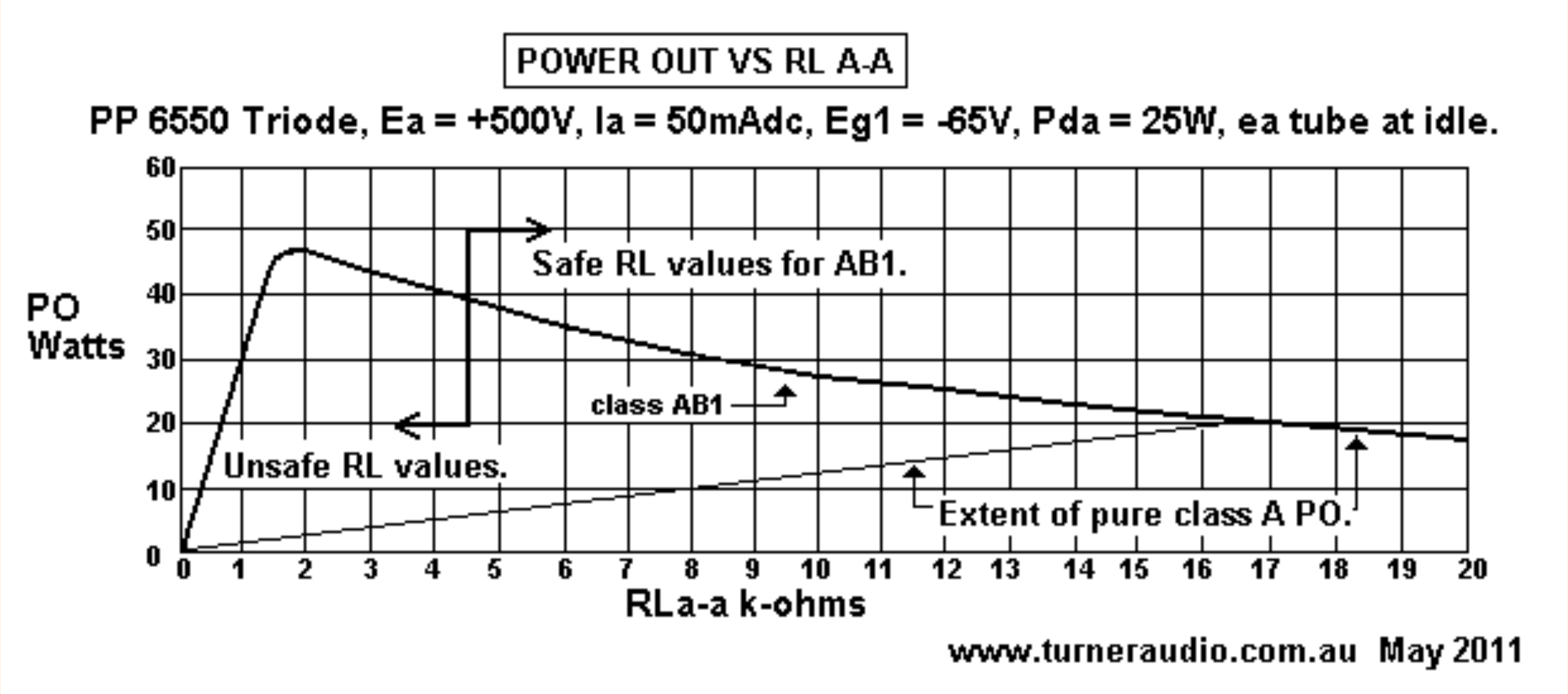


Fig 31 shows the range of loads and output power for PP triodes using 6550.
The graph is only valid for Ea = 500V, and would need completely re-calculating for other values of Ea and different tubes.
Values of Ea for various PP triodes may be chosen within ranges as follows, with Ra values for calculations :-

2A3, Ea = +200 to +300V, Ra at Eg1=0V, 700 ohms approx.
300B, Ea = +300V to +420V, Ra = 680 ohms,
845, Ea = +800V to +1,250V, Ra = 2,200 ohms,
211, Ea = +800V to +1,500V, 3,500 ohms.

6CM5/EL36, Ea = +300V to +375V, Ra = 475 ohms,
13E1, Ea = +300 to +375V, Ra = 300 ohms,

6550, KT88, KT90, Ea = +350V to +520V, Ra = 850 ohms,
KT66, 6L6GC, 807, 5881, Ea = +300V to +430V, Ra = 1,600 ohms,
EL34, 6CA7, Ea = +300V to +430V, Ra = 1,250 ohms,
6V6, Ea = +250V to +350V, Ra = 2,600 ohms,
EL84, Ea = +250V to +350V, Ra = 2,100 ohms.

NOTE. Ra values are all at Eg1 = 0.0V, to enable minimum RLa-a calculations. **Ra will be higher at the idle position,** and will vary depending on Ia at idle, and is high for where Idle Ia is low and Ea is high.
Ra is lowest where Ia is highest and Ea lowest.
Designers MUST NOT assume anything.

58. Calculate maximum AB1 power for minimum RLa-a.

Maximum safe class AB1 Power,

PO = 0.125 x RLa-a x Ea squared

([RLa-a / 4] + Ra) squared

OPT-2A, RLa-a minimum = 5,076 ohms, Ea = +500V,
Ra at Eg1 = 0V = 846 ohms,
Max class AB PO = $0.125 \times \dfrac{5{,}076 \times 500 \text{ squared}}{([5{,}076 / 4] + 846) \text{ squared}}$

= 0.125 x 5,076 x 250,000 / (1,269 + 846) = 35.45 Watts.

NOTE. For any other RLa-a between the minimum RLa-a, and up to the RLa-a for pure class A, the same formula may be used for where the limiting Ra line slope is for Eg1 = 0.0V, and between Point O to Point X on curves.

For those needing to draw loadlines, the line D to C for B RLa = 1,269 ohms intersects Ra limiting curve at Ea = 199V = Ea peak minimum V.
PO = 2 x (Vpeak swing squared) / RLa-a

RLa-a = 5,076 ohms from above, Vpeak swing, one triode = 500V - 199V = 301V.

OPT-2A, PO max = 2 x 301 x 301 / 5,076 = 35.7 Watts

NOTE. This seems about correct for max PO shown in **Fig 31** above.

59. Calculate RLa-a for maximum pure class A1 power.

RLa-a for 1 pair of output tubes in class A1 = 2 x [(Ea / Iadc) - (2 x Ra)].

OPT-2A, RLa-a class A1 = 2 x [(500 / 0.05) - (2 x 846)]

= 16,616 ohms.

NOTE. For more than one pair of output tubes divide above by the number of pairs, for example, if there were 4 x 6550, RL = 16k6 / 2 = 8k3.

60. Calculate maximum class A1 PP triode power output.

PO = 0.5 x Ia squared x RLa-a where Ia is the Idle Ia dc for one tube.

OPT-2A, Pure class A1 PO max = 0.5 x 0.05 x 0.05 x 16,616 = 20.77 Watts.

61. Calculate the Middle RLa-a for triode PP operation.

Middle RLa-a =
Minimum RLa-a x square root (RLa-a for Max class A1 / RLa-a safe minimum.).

OPT-2A, Middle RLa-a

= 5k1 x sq root (16k6 / 5k1) = 5k1 x sq root 3.25 = 9k2.

NOTE. It is coincidental that Middle RLa-a for 6550 Beam Tetrode and Triode have been found to be so close to each other.

62. Calculate PO for Middle RLa-a,

$$\text{Max class AB PO} = 0.125 \times \frac{9{,}200 \times 500 \text{ squared}}{([\,9{,}200 / 4\,] + 846) \text{ squared}}$$

= 29 Watts.

NOTE. This result agrees with Fig 31 above.

63. Conclusions about PP triode OPT design.

OPT-2A, For 2 x 6550, Steps 55 to 63 can be summarized as listed :-

RLa-a Minimum AB1 = 5,076 ohms, PO = 35W, Va-a = 421Vrms.
RLa-a Middle AB1= 9,200 ohms, PO = 29Watts, Va-a = 516Vrms.
RLa-a Max Class A1 = 16,600 ohms, PO = 21Watts, Va-a = 590Vrms.

The core size can be designed according to the Middle RLaa PO and Va-a, and for that the triode OPT is designed by following all the steps after **Step 14, but labelled 14T to 19T :-**

14T. Calculate minimum centre leg cross sectional area, Afe, for triode PP amp.

NOTE. I have left out references and diagrams from steps 14 to 19 above.

Confirm MIDDLE RLa-a and maximum power at clipping, 2 x 6550.

OPT-2A. From Steps above, Middle RLa-a min = 9,200 ohms,
Max PO = 29 Watts.

Afe = 300 x sq.rt (audio power, Watts), in sq.mm.

OPT-2A Theoretical Afe, thAfe = 300 x sq.rt 29
= 300 x 5.385 = **1,615 sq.mm**

15T. Calculate the core tongue dimension, T.

For a square core section, Tongue dimension = Stack height, ie, T = S.

Theoretical T x Theoretical S = th Afe, sq.mm.

Therefore theoretical T dimension = square root th AFe = Th T, mm

OPT-2A, thT = sq.rt 1,615 = 40.2mm.

Choose suitable standard T size from list of available wasteless E&I lamination core materials with assembled E&I plan sizes of :-

T sizes commonly available for wasteless OPTs :-
20mm, 25mm, 32mm, 38mm, 44mm, 50mm, 62.5mm

NOTE. The thT calculated = 40.2mm, which indicates the standard T size of 38mm may possibly be best, because it is closest to 40.2mm.

But with triode there is inefficient operation compared to UL or CFB operation. So T should ALWAYS be larger than the theoretical T calculated.

Therefore T = 44mm should be trialed.

If a smaller T is tried, the weight may be slightly less if the aspect ratio gives a Stack height more than Tongue dimension. If it is found to be difficult to get low winding losses with the slightly lower T size, the stack height may be increased to reduce the number of primary and secondary turns so thicker wire with less resistance may be used.

NOTE. Choosing a standard T size above thT gives lower copper winding losses, higher weight, and choosing T below thT gives higher losses and lower weight. Afe must be the same for either T = 44mm or 50mm so the LF response and Fsat does not change with tongue size. HF peformance depends entirely upon the interleaving geometry and insulations.

OPT-2A, choose core **T = 44mm**

NOTE. Some constructors will be using non wasteless pattern E&I lams, or C cores which do not have the same relative dimensions as E&I Wasteless Pattern cores.

The actual sizes of the T, S, H, & L of the core to be used must be carefully considered.

Other lamination patterns or C-cores have a much larger window area for their effective T dimension so that larger wire sizes for less copper loss may be employed or to give more room for more turns and insulation layers. Regardless of the core pattern, the ratio of Afe size relative to Bac max must be maintained.

16T. Calculate theoretical Stack height.

thS = Afe / T, then adjust to a larger height to suit nearest standard plastic bobbin size if available, mm.

OPT-2A, S = 1,615 / 44 = 36.7mm. This may be increased to suit a standard size bobbin allowing stack height of 38mm. A hand made bobbin need not be used.

OPT-2A Stack height = 38mm.

17T. Confirm sizes for core.

Adjusted Afe = chosen T x chosen S, sq.mm

OPT-1A. Adjusted Afe = 44 x 38 = 1,672sq.mm
T = 44mm, H = 22mm, L = 66mm, S = 38mm.

18T. Calculate the theoretical primary turns, thNp.

thNp = square root (PRL x PO) x 10,000 / Afe = thNp, no of turns.

OPT-2A, RL = 9,200 ohms, PO = 29, Afe = 1,672sq.mm from above,
OPT-2A. ThNp = sq.rt(9,200 x 29) x 10,000 / 1,672 = **3,089 turns.**

19T. Calculate theoretical Primary wire dia, thPdia.

NOTE. The Primary wire used for the transformer will occupy a portion of the window area approximately = 0.28 x L x H. The constant of 0.28 works for most OPT.
Each turn of wire will occupy an area = overall dia squared.
Overall or oa dia is the dia including enamel insulation.
Therefore theoretical over all dia of P, thoaPdia, of wire including enamel insulation = square root (0.28 x L x H / thNp), mm.

OPT-2A, th oa dia P wire = sq.rt (0.28 x 66 x 22 / 3,089)
= sq.rt 0.132 = **0.362 mm**

20T. Find nearest suitable overall dia wire size from the wire size table. oaPdia, mm.

Table 1. Available Wire Sizes.

Cu wire dia mm	Overall dia, including enamel, mm	Cu wire dia mm	Overall dia, including enamel, mm	Cu wire dia mm	Overall dia, including enamel, mm
4.000	4.160	0.950	1.041	0.280	0.334
3.750	3.905	0.900	0.990	0.265	0.312
3.550	3.702	0.850	0.937	0.250	0.301
3.350	3.498	0.800	0.885	0.236	0.285
3.150	3.294	0.750	0.832	0.224	0.272
3.000	3.142	0.710	0.790	0.212	0.258
2.800	2.938	0.670	0.749	0.200	0.245
2.650	2.784	0.630	0.706	0.190	0.234
2.500	2.631	0.600	0.675	0.180	0.222
2.360	2.488	0.560	0.632	0.170	0.211
2.240	2.366	0.530	0.601	0.160	0.199
2.120	2.243	0.500	0.569	0.150	0.188
2.000	2.120	0.475	0.543	0.140	0.176
1.900	2.018	0.450	0.516	0.132	0.167
1.800	1.916	0.425	0.489	0.125	0.159
1.700	1.813	0.400	0.462	0.112	0.143
1.600	1.711	0.375	0.436	0.100	0.129
1.500	1.608	0.355	0.414	0.090	0.117
1.400	1.506	0.335	0.393	0.080	0.105
1.320	1.423	0.315	0.371	0.071	0.095
1.250	1.351	0.300	0.355	0.063	0.085
1.180	1.279	Metric winding wire sizes, 200C temp rated, polyester-imide enamel, GRADE 2.		0.060	0.081
1.120	1.217			0.056	0.076
1.060	1.155			0.050	0.068
1.000	1.093				

OPT-2A, Want oa dia not exceeding 0.362mm calculated in Step 19T.
Choices are :-
0.334mm oa dia for Cu dia = 0.28mm,
0.371mm oa dia for Cu dia = 0.30mm.

NOTE. It will be found that working with wire less than 0.4mm is very difficult. So the wire size immediately above 0.362 might be tried. The core stack may always be increased to reduce the Np needed.

Try oa wire size = 0.371mm, with bare copper dia = 0.30 mm.

21T. Calculate the bobbin winding traverse width.

OPT-2A, For design purposes, the winding will traverse a distance = L - 4mm.

OPT-2A, For core window L = 66mm, **Bww = 66 - 4 = 62 mm.**

22T. Calculate no of theoretical P turns per layer.

ThPtpl = 0.97 x Bww / oa dia from step 12.

NOTE. The constant 0.97 factor allows for imperfect layer filling.
Ignore fractions of a turn.

OPT-2A, thPtpl = 0.97 x 62 / 0.371 = **162 Primary turns per layer.**

23T. Calculate theoretical number of primary layers.

Then round down or up to convenient even number of layers.

Theoretical N pL = (Theoretical Np from step 18T) / PtpL from step 22T, then round up/down.

OPT-2A, thNpL = 3,089 / 162 = 19.067 layers; round UP to **20 layers or down to 18 layers.**

Let us try P layers = 18.

NOTE. Rounding down may reduce Np and raise Fs above wanted 14 Hz. But the actual turns used will give low enough Fs, in this case 14.4Hz, less than a 15% rise above design aim and OK. For those wanting to maintain Fs = 14Hz, or have Fs marginally lower than 14 Hz, the Afe can be increased by increasing S from say 38mm to 44mm or more and still be able to use a standard size of pre-made moulded bobbin 44mm x 44mm, and have Fs slightly lower.
The calculated number of primary layers should be an even number to avoid a primary winding CT in the middle of a layer which is awkward to wind, and because each 1/2 primary winding should have an equal number of turns and a symetrical geometric layout either side of the CT.

24T. Calculate actual Np.

Np = Number of P layers from Step 23 x thPtpl from Step 22.

OPT-1A, Np = 18 x 162 = 2,916 turns.

25T. Calculate average turn length, TL.

TL = (3.14 x H) + (2 x S) + (2 x T), mm.
where 3.14 is pye, or 22/7, and 2 are constants.

OPT-2A, TL = (3.14 x 22) + (2 x 38) + (2 x 44) = **233 mm.**

26T. Calculate primary winding resistance, Rwp.

Rwp = 2.26 x (Np x TL) / (100,000 x Pdia x Pdia), ohms.
where 2.26 is the resistance of 100 metres of 1.0mm dia wire and a constant,

and 100,000 is a constant, and P dia is the copper dia from the wire tables.

OPT-2A, PRwp = 2.26 x 2,916 x 233 / (100,000 x 0.30 x 0.30) = **170 ohms.**

27T. Calculate pri winding loss % with MIDDLE RLa-a,

P loss % = 100% x Rwp / (PRL + Rwp), %.

OPT-2A, P loss = 100% x 170 / (9,200 + 170) = 1.81%.

28T. Is the winding loss more than 3.0%?

If YES the design calculations must be checked and perhaps a larger core stack or window size chosen.
If NO, proceed to Step 29.

OPT-2A, P winding loss is less than 3.0%.

NOTE. The calculations so far are based on using the MIDDLE RLa-a. Under optimal normal operation, RLa-a will be higher or lower than the MIDDLE RLa-a for class AB1. The winding losses for RLa-a of 5k0 are nearly double at about 3.3% and for pure class A of 16k6, losses will be less at about 1%, and in all cases losses are low enough.

It is better to have low winding losses so that the primary windings are unlikely to overheat if a tube malfunctions and draws excessive Idc during a "bias failure event". Such occurences were a main reason why so many OPTs of the past failed so easily after being designed by accountants rather than engineers who know "shit happens" :-).

29T. Choose the interleaving pattern.

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

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.

At this point in the design process for PP triode OPTs, I will now abandon you all and leave you to proceed through all steps to a final design.

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