PUSH-PULL OUTPUT TRANSFORMER CALCULATIONS, PAGE 1. Edited 2011.

**FOR ALL OPT WITH TWO BALANCED DC FLOWS
OR WHERE THERE IS NO NET DC FLOW IN ONE DIRECTION.**

**For calculations for Single Ended Output Transformers
go to 'SE OPT calculations'**

**THERE ARE 5 SEPARATE PAGES COVERING
THIS SUBJECT, AND YOU ARE AT PP OPT calcs Page 1.
Pages 2 to 5 are listed below with links.**

Contents, this page 1 :-

PP OPT Calc Page 2 :-

Design of OPT-1A continued....

PP OPT Calc Page 3:-

Design of OPT-1A continued....

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TAPPED SECONDARY WINDINGS.

[PP OPT Calc Page 5 :-]

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

End of list of contents for PP OPT calcs.

General information.

The Radiotron Designer's Handbook, 4th Edition, 1955, contains a lot of good design advice about OPT design.

The trouble with "RDH4" as it is known is that beginners who are good craftsmen are baffled by the mathematics and electronic behaviors described in this great book. Nevertheless, although my basic mathematics and physics education level only extended to high school, I can comprehend the mathematical relationships between items I encountered, eg, R = V / I, which is Ohm's Law. I found RDH4 extremely useful and I gradually began to understand the reason why the book was written.

many say it was because RCA wanted more people to buy vacuum tubes at a time when most electronic things were unreliable and very expensive and mostly non-essential, unless the use was for military, medical or scientific establishments. To me the book comes across as a rare exercise in corporate altruism which enabled so many ordinary people to access cutting edge electronics information for free. If you have no copy on hand, there is a CD you can acquire and you may then print out pages to make a book if you want.

Chapter 5 from page 199 to page 253 should be read repeatedly until the message sinks in. It is not easy to understand if you have no idea about basic tube operation and other basic electronic behaviors, so as soon as you find you don't understand something, you must find out about it from somewhere else in RDH4 or from some other source. I ended up with a few shelves of books with overlapping information, much of which has never been published online, and never will be, because it is now the digital era.

Unfortunately, the associated reference material listed on pages 252 and 253 has mainly been lost or thrown out of many library archives to make way for the huge mountain of more modern knowledge. There is very little new information or better information about output transformers written after 1960 because mainstream development for tube OPTs stopped in about 1959 when tube operated electronics was being dumped in favor of transistors.

Not many folks will have RDH4 in their library nor will there be a nearby technical library with easy browsing access so I shall try to unfold the design method I have evolved based on information in the RDH or other sources I have collected since 1994. To gain real understanding, I began to design OPT then wind them myself after building a simple winding lathe. I then learnt how to test them, and prove to myself the mathematics for design were indeed correct.

After having wound many very fine PP output transformers with bandwidth from 14Hz to 270kHz, I feel well qualified to speak from experience. The list of logic steps involved in producing the best possible OPT is based on designing for low winding resistance losses, core saturation at full power at 14Hz, and adequate interleaving to extend the HF response up to at least 50kHz without reliance on negative feedback. This meant keeping both the leakage inductance and shunt capacitances to low quantities. The end result gives a well filled winding window with several impedance matches possible without having wasted sections of any secondary winding so the winding losses and response is the same for any of the chosen load matches. The only disadvantage of always using all available turns of a secondary is the difficulty of changing the load match which may require technical skill an amp owner does not possess, and there is a high likelihood of a mistake being made.

The trend today is to provide 3 terminals at the rear of an amp, Common, 4 ohms, 8 ohms, and this allows some choice in load matching. Just how to configure secondaries for easily selectable loads is covered below. The disadvantage of this method is the the likelihood that a non technically aware owner will plug the speaker cables into the wrong terminals.

In my page on **'Output Transformer Theory'** , I show the recipe for OPT No1, now shown as Fig15 at the bottom of this page. It was in my 2006 pages. This page of 2011 now shows a similar design example recipe for OPT-1A.

DESIGN OF PUSH PULL OPT-1A EXAMPLE.
For 2 x 6550/KT88/KT90 tetrodes.
Steps 1 to 13:-

1. Define the aim of this design project.

OPT-1A is to be designed for use to allow up to 75 Watts of audio power over a frequency range between 14Hz and 65kHz using 2 x 6550, KT88, KT90, K120 **BEAM TETRODES.** Pda at idle should be 25Watts for each of these output tube types.

4 x 6L6GC, 5881, KT66, EL34, 6CA7 may also be used with Pda at idle for each output tube < 16W for long tube life.

The connection mode may be for pure Beam Tetrode with fixed screen +Vdc supply, Beam Tetrode with CFB windings and fixed screen +Vdc supply, aka Acoustical, Ultralinear with screen taps, Ultralinear with or without CFB windings, AND triode class AB1, or AB2.

The OPT-1A is to have secondary winding layers sub-divided into enough separate windings to allow a number of winding arrangements made up with seriesed and or paralleled windings useful range of speaker loads to suit optimal tube operation, usually about 3 matches between 1.5 ohms and 16 ohms.

The range of anode load values to be considered are nominated as :-
Minimum RLa-a for maximum safe AB1 power,
RLa-a for maximum pure class A1 power,
Middle RLa-a for intermediate power between max AB1 and pure A1 powers.

THERE ARE SEPARATE OPT CALCULATIONS FOR TRIODE AB1 OPERATION OF BEAM TETRODES OR PENTODES BELOW AT TRIODE PP OUTPUT TRANS CALCULATIONS.

2. LOADLINE ANALYSIS for PP BEAM TETRODE modes, but not including triode.

Fig 1.

Ea vs Ia curves for Ra for 6550EH with Eg2 = +250V, approx.

Approximate Ra and Gm for Ia at Ea = +400V, typical bias conditions.

Ia mA	Ra kohm	Gm mA/V
100	24k	10.0
90	26k	9.1
80	27k	8.1
70	29k	7.3
60	31k	6.3
50	32k	5.5
40	36k	4.7
30	40k	4.0

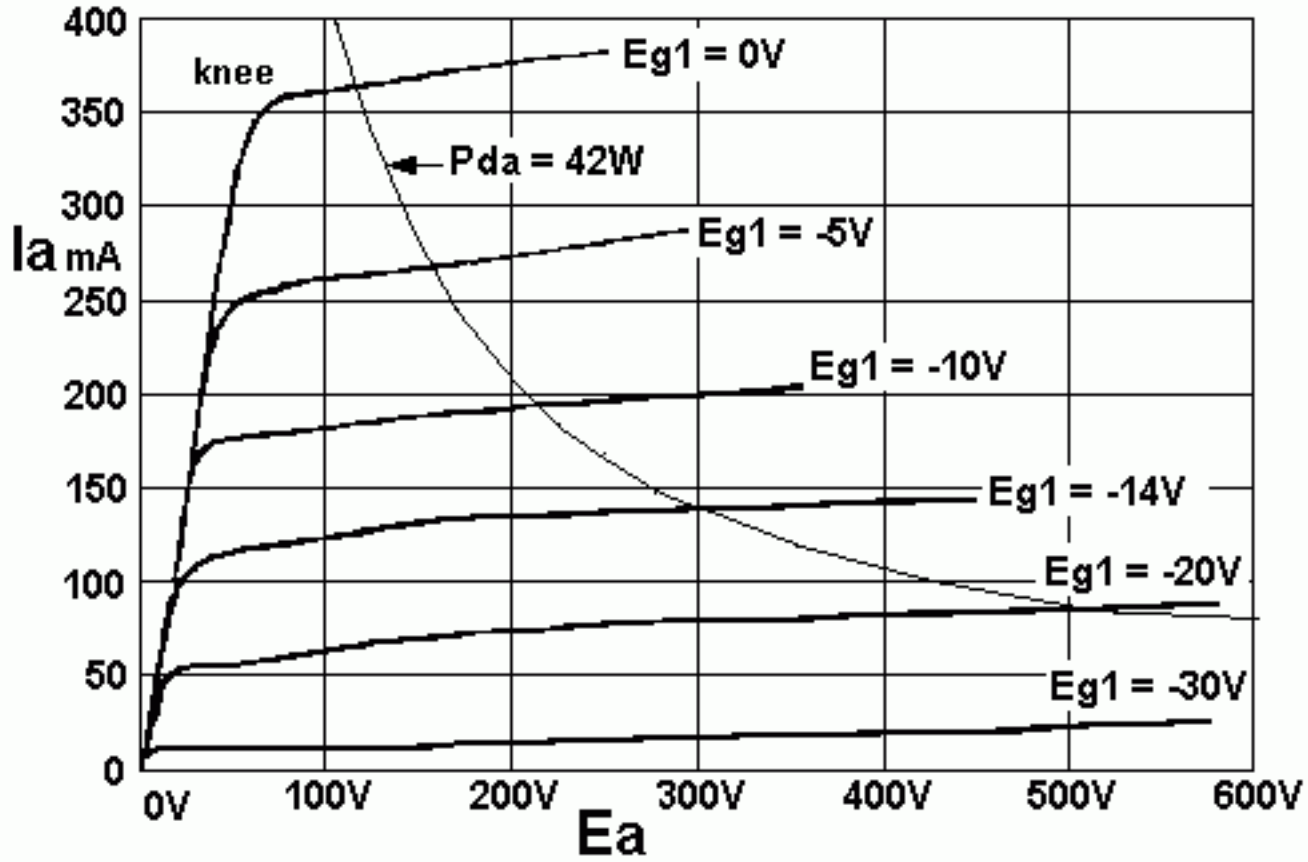


Fig 1 shows my tidied up copy of New Sensor Corp's Ra curves for pure beam tetrode operation of Russian made 6550EH with Eg2 = +250Vdc. Before moving on to Loadline Analysis, everyone might like to become familiar with the basic Ea/Ia Ra curves for the 6550. Higher values of Eg2 will show the Ra line for Eg = 0V giving a "knee" at a slightly higher Ia.

The slope of Ra curves between 0V and Ea = 50V shows a near straight line limiting line for Ea swing. The "slope" of the line has a resistance value which may be calculated as Ea / Ia swing below Ea = 66V.
Ia swing = 300mA for the Ea swing of 50V, so the Ra limiting line = 166 ohms.

I have found the limiting line ohm value for many Russian made output tubes to be a higher ohm value than indicated in the **Fig 1** data curves. In other words, the anode voltage cannot swing as low in recently made Russian tubes compared to the best NOS samples ever made, from which many of the curve sheets were drawn.
Nearly all beam tetrodes and pentodes will never be used in pure tetrode or pentode mode with a stable Vdc as Eg2, and the cathode bypassed to 0V, but in fact most amps will employ UL taps or CFB windings or both.
Where this is the case the Ra limiting line for Eg1 = 0V may be assumed to be 280 ohms or more.
When such multigrid output tubes are strapped in triode mode their Ra limiting line for Eg1 = 0V is simply the Ra value given for the tube, or the triode curve shown in data sheets.
It is usually impossible to swing Ea to the left side of the Ra limiting line even with class A2 or AB2 operation with pentodes or tetrodes. But with a large number of real triodes or triode strapped beam tetrodes the Ea swing can be forced to the left of the triode Ra curve for Eg1 = 0V, but only by means of class A2 or AB2 operation.

I have added a table for Ra and Gm for a range of bias conditions which I found approximately correct within +/-10% for Russian samples of 6550EH, KT88EH, all 'Sovtek' labeled 6550 and KT88, and "winged C" Svetlana 6550 and KT88.

Fig 2.

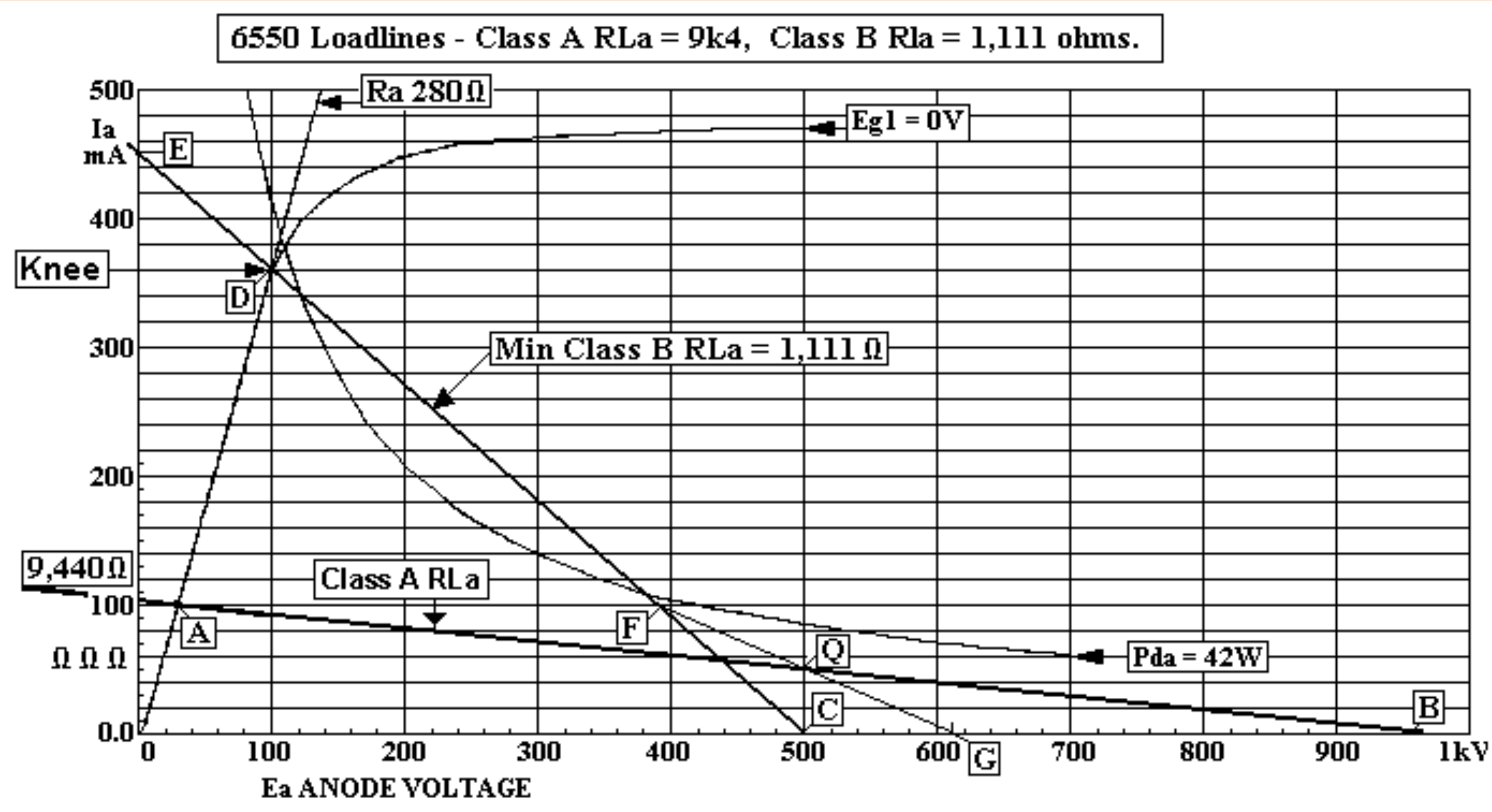


Fig 2 above provides the most basic load line analysis for ONE 6550 in a PP amp to help determine the range of anode load values. It saves everyone the trouble of going to another page on load line analysis.

To draw all required loadlines, all that is needed is the curve of Ra for Eg1 = 0V, for the correct value of Eg2, and the curve for maximum Pda.

The slope of the Ra curve between Ea = 0V and 100V is drawn as a straight line with resistance value = 280 ohms. This part of the Ra curve is also called the "diode line", and it indicates the extent of possible Ea load swing.
The 280 ohms is approximately correct for all output beam tetrodes and pentodes where they are used of hi-fi amps which most probably will have UL screen taps and/or cathode feedback windings.

I have chosen commonly used idle conditions for 6550 with Ea = +500Vdc, Ia dc = 60mA, Eg2 = +350V, which could be between +300V and +400V without changing the design outcome.
The "knee" of the Ra curve where the Ra changes rapidly between a very low Ra below Ea = 100V to a high Ra of thousands of ohms will be at approximately point D where Ea = 100V and Ia = 350mA.

Pda at idle = 25W, therefore Iadc = Pda / Ea chosen = 50mA.
There is no point considering the use of idle Ea above +520Vdc for most power output beam tetrodes or pentodes in Hi-Fi amps because the higher Ea will mean Ia will be low and Pda at idle will be low so there is less initial class A power and most most power made in class AB which means higher distortion. The higher Ea means less reliable operation, and a bigger dependance on fixed bias. The higher the Ea, the higher the RLa-a becomes so the OPT needs more turns per volt to keep the frequency of of saturation low. However, the higher the RLa-a, the higher the tube gain so the use of CFB or UL taps is more effective. All things considered, the following range of Ea should be used for class AB PP hi-fi amps :-

+350V to +520V for 6550, KT88, KT90,
+300V to +430V for KT66, 6L6GC, 807, 5881, EL34,
+250V to +330V for 6V6, EL84.

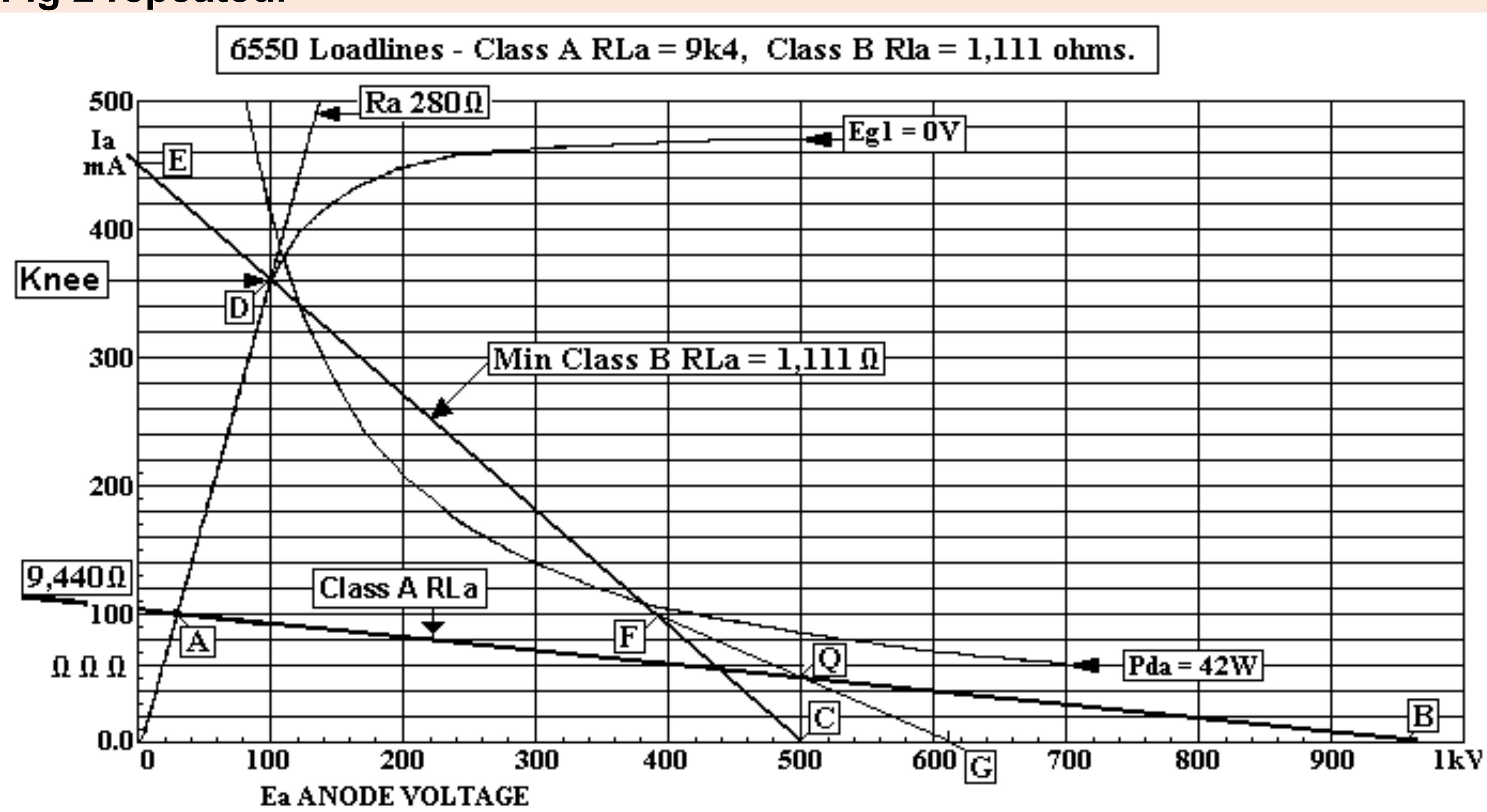
Eg2 for all may equal Ea for UL connection.
For CFB, the fixed Eg2 may be
+300V to +400V for 6550, KT88, KT90,
+250V to +350V for KT66, 6L6GC, 807, 5881, EL34,
+200V to +300V for 6V6, EL84.

NOTE. If no 6550 data curves are available, there is a blank sheet at the bottom of this page for anyone to print and use for amps where 6550, KT88, KT90 are proposed.

NOTE. There is no need to consider harmonic distortion during the load line analysis for load calculations. My methods steer people away from coupling tubes with loads which would generate excessive distortion.
In class AB1 amps, there is considerable distortion in tube *currents* because tube current is switched on and off during each AB wave cycle.
But in the overall *voltage* waveforms at transformer terminals there is usually less than 4% THD at just under clipping and it is reduced to low levels with negative feedback. THD during the first few watts of pure class A is only marginally more than than for the same few watts from a totally pure class A amplifier, and often only 0.03%.

2A. Plotting the Class A loadline, Fig 2.

Fig 2 repeated.



Plot point Q at Ea = 500V and at Ia = 50mA.
Plot point A at twice Ia on Ra curve.
Draw straight line from A through Q and onwards through the Ea axis at point B.

Plot point C at Ea = 500V, Ia = 0.0mA, on Ea axis.

The distance between A and Q should be exactly equal to between Q and B.

AQB is the Class A load line for one 6550 in the pair of PP tubes.

The Ea minimum voltage at B is read off the graph from vertically below
B = 28V.
Ea change = load voltage change = Ea Q - Ea min = 500 - 28 = 472Vpk.
The Ia change = Ia at Q = 50mApk.
RLa for each 6550 = Ea change / Ia change = 472V / 0.05A = 9,440 ohms.
(This is Ohm's law being applied.)

The anode signal voltage = 0.707 x Pk swing voltage = 0.707 x 472V = 333.7Vrms.

The Ia at idle reduces to zero as Ea swings positively. The point B
on the graph should appear at Ea = IaQ x RLa, which is at 972V.
With two tubes working together with oppositely phased voltage and currents,
when one tube anode swings up to 972V, the other swings down to 28V,
and this voltage is applied across the whole primary, and transformed to high
current and low voltage required to drive a speaker.
The anode to anode signal voltage, Vaa, measured from one anode to the other
is twice the anode voltage at each anode = 2 x 333.7Vrms = 667Vrms.
The Class A RLa-a anode to anode primary load is effectively the sum of the
loads of each tube in series, so the RLa-a = twice the class A RLa for one tube.

Calculate PP Class A RLa-a load for maximum pure class A
= 2 x Class A RLa for one tube = 2 x 9,440 ohms = 18,880 ohms.

This formula is true for all class A loads for PP output stages.

The above class A load produces the maximum possible pure class A power.
If the RLa was a lower value, pure class A power is limited to where Ia change
never more than the idle IaQ value. So where the RLa becomes a lower
value than calculated so far, the class A power reduces and maximum output
power rises because the tubes begin to work in class AB.

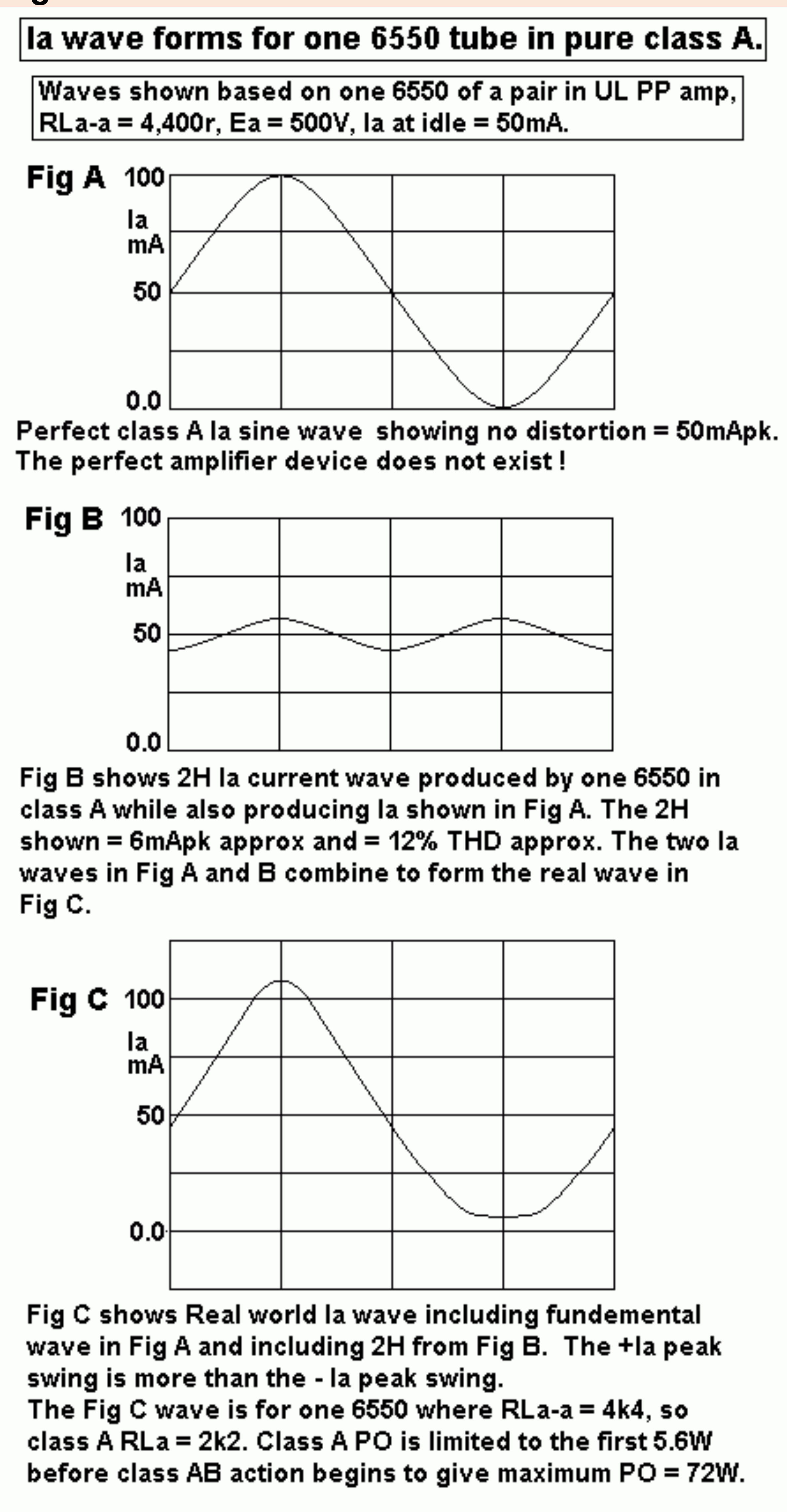
Pure class A1 power = 0.5 x RLa-a x Ia squared, where Ia is Iadc at idle.
This example, Class A PO = 0.5 x 18,880 x 0.05 x 0.05 = 23.6Watts.

Power may also be calculated as Vaa squared / RLa-a, with Va-a in Vrms.
This example, Vaa = 2 x 0.707 x 472Vpk = 667Vrms,
Power = 667 x 667 / 18,880 = 23.7Watts.

The class A load line has less slope than any class AB load lines so the class A
loadline crosses through the least number of Ra curves for the various Eg1
voltage values.
In other words, when the class A loadline is drawn on a full set of Ra curves,
the Ea change requires little Eg1 change, ie, the anode voltage gain is high.
This means that a given negative feedback network will be most effective
to reduce the distortion and effective anode resistance during class A operation.

Tetrodes and Pentodes are not very linear for the whole possible Ea swing in class A. Single ended tetrodes pentodes at clipping might produce 13% THD without any NFB.
In PP, with "cancellation" of even numbered H because of the OPT the THD might be 5% because the odd numbered H are not cancelled by PP action.
The use of the UL screen taps or Cathode Feedback windings may reduce the THD to less than PP triode class A operation.

Fig 3.



Perfect class A Ia sine wave showing no distortion = 50mApk.
The perfect amplifier device does not exist !

Fig B shows 2H Ia current wave produced by one 6550 in class A while also producing Ia shown in Fig A. The 2H shown = 6mApk approx and = 12% THD approx. The two Ia waves in Fig A and B combine to form the real wave in Fig C.

Fig C shows Real world Ia wave including fundemental wave in Fig A and including 2H from Fig B. The +Ia peak swing is more than the - Ia peak swing.
The Fig C wave is for one 6550 where RLa-a = 4k4, so class A RLa = 2k2. Class A PO is limited to the first 5.6W before class AB action begins to give maximum PO = 72W.

Fig 4.

Class A and AB anode current waveforms in tube amplifier.

Class A and Class AB waves are for 6550 in UL beam tetrode mode in a PP amp, Ia idle = 50mA, Ea = 500Vdc.

Fig D

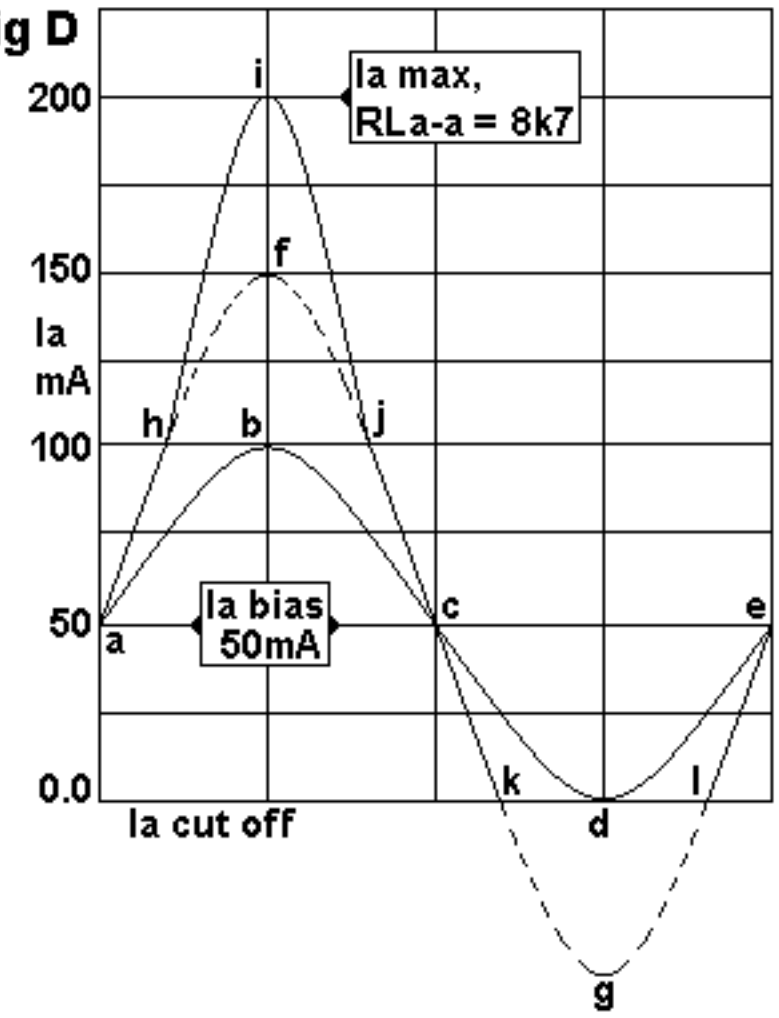


Fig D shows Ia sine wave abcde for class A RLa load for single 6550 = 4.350r when RLa-a = 8,700r, and at the limit for class A power and below AB clipping level.

The wave ahfjckgle is the imaginery wave if only each 6550 could continue to provide equal + and - change of Ia = +/- 100mA. Much more + Ia is possible, but only - 50mA may occur before complete Ia cut off.

With two 6550 in PP, as soon as one 6550 begins to cut off the other 6550 "sees" a load = 2,175r and operates alone to make +Ia for the hij part of the wave shown. The whole curve is described by ahijckle, and there is no - Ia down to point g.

Fig E

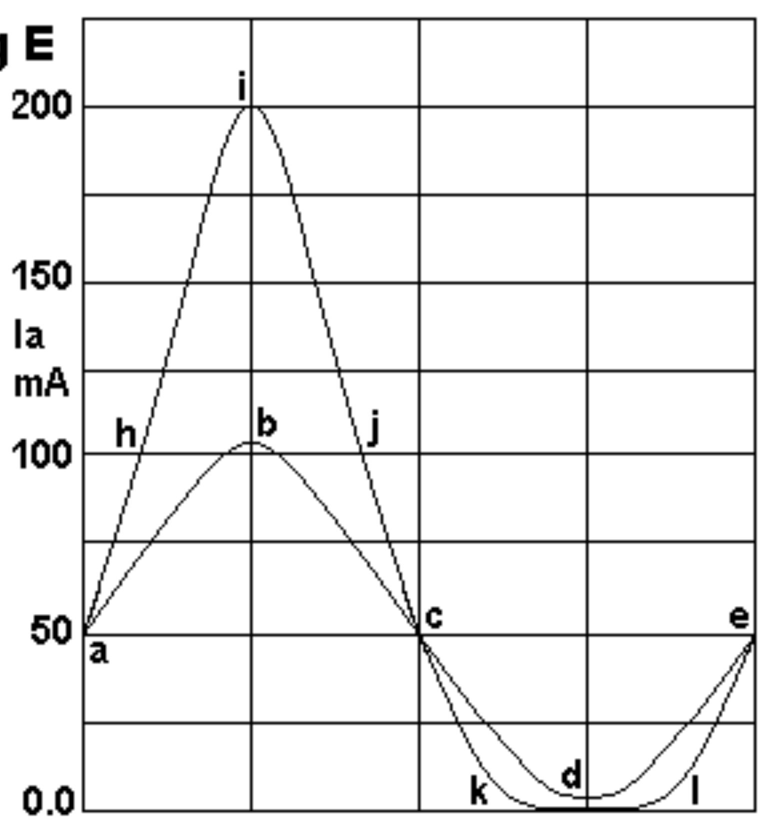


Fig E shows and more realistic wave curve you will be more likely to view on your oscilloscope.

The class A Ia wave abcde for RLa = 4,350 shows some 2H.
Even numbered H rapidly increase after class AB action commences.

While the amp works in PP A or AB, the 2H, 4H and other even number H Ia currents act in common mode on the OPT, ie, the same phase of 2H etc is applied to each end of the OPT primary so 2H voltage does not appear in the OPT secondary.
The full class AB wave ahijckle shows the smoothed kinks in transition from class A to AB. Some 3H is produced but cannot be easily shown graphically, only 2%.

Fig 5.

Class AB anode current waveform in tube amplifier.

Class AB Ia wave for 6550 in UL beam tetrode mode
in a PP amp, Ia idle = 50mA, Ea = 500Vdc.

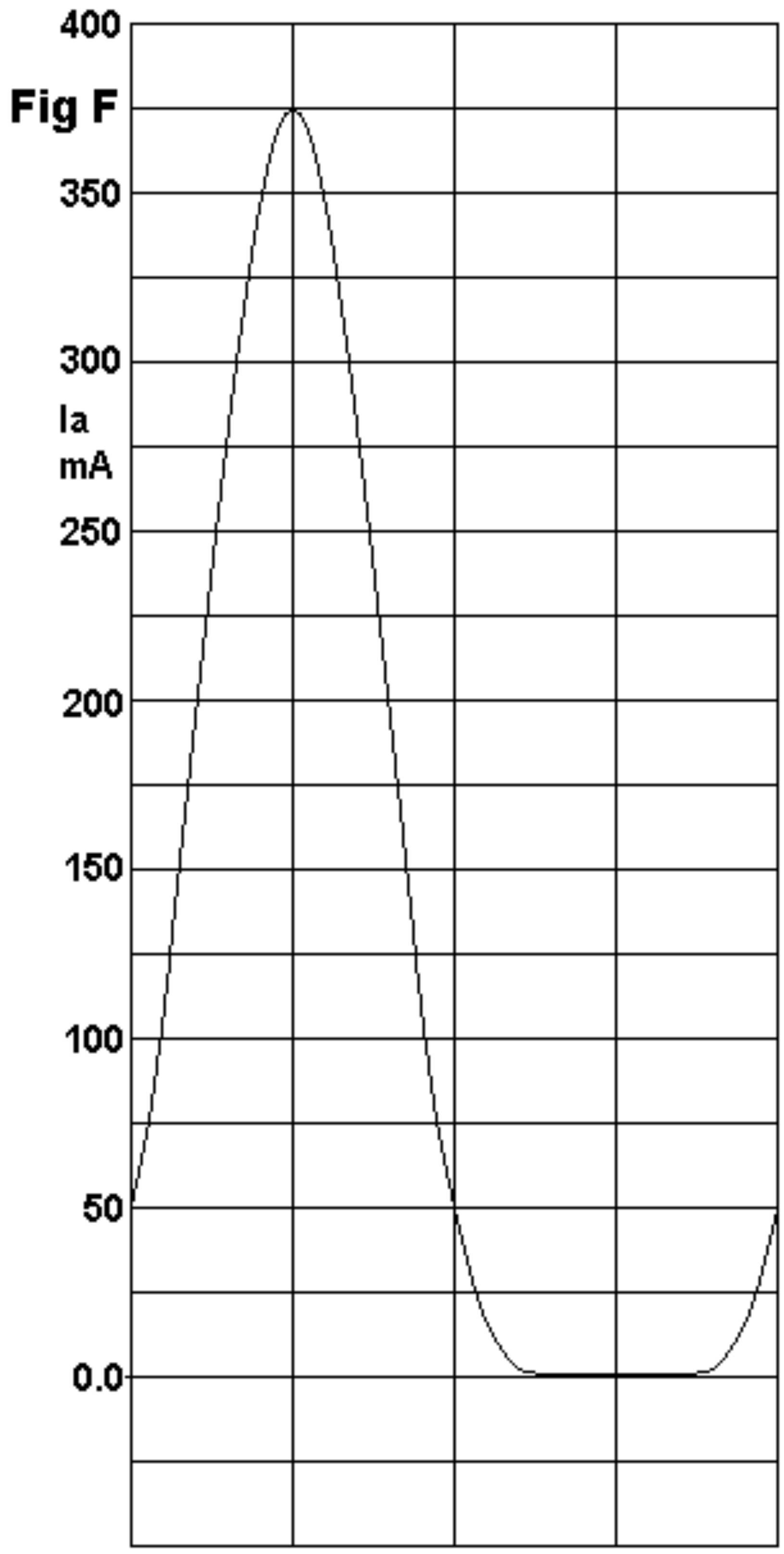


Fig F shows class AB ia wave for one 6550 of a pair in PP with lowest safe RLa-a = 4,400r.

The class A load each 6550 sees for Ia change up to +/- 50mA pk = 2,200r.

Above +100mA, each tube has RLa = 1,100r to the clipping level Ia max of +350mA, for class AB PO = 72W.

The Ia wave has become very similar to a half wave rectifier signal from a sine wave source into a diode and resistance.

The OPT has net 2H currents applied in common mode to the OPT primary and none appear in the OPT secondary. Some 3H is generated and would be about 5% at 72W without any global NFB.

2B. Class AB1 loadlines.

What is a class AB loadline?
The class AB loadline is really two load lines.
Class AB load line ohm values are always less than the RLa-a for pure class A.
The class AB loadline has a Class A loadline and a Class B loadline.

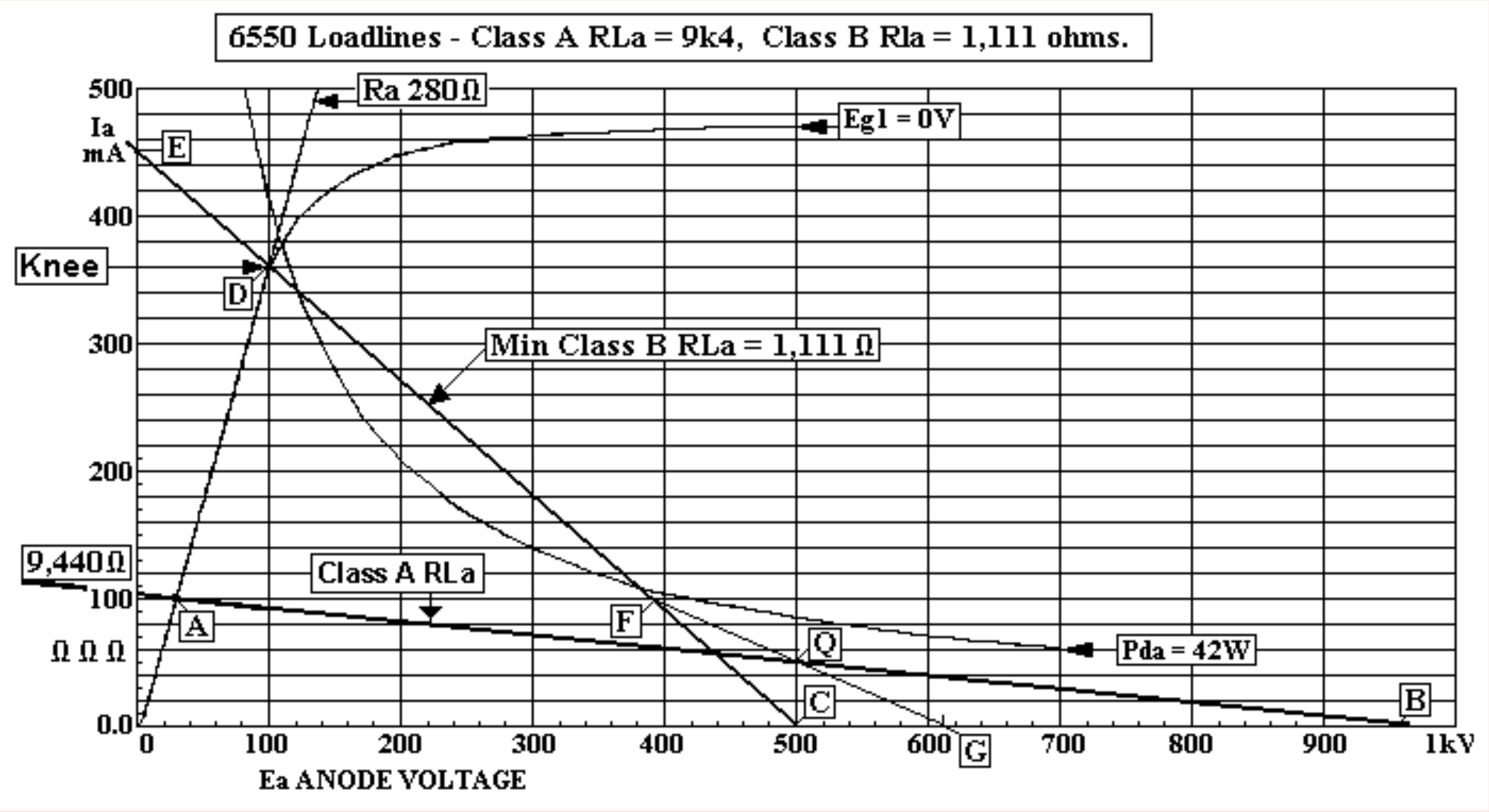
During class AB operation in a full wave cycle up to clipping, the loading for the first few watts for each tubes is pure class A where each tube sees a load = 1/2 RLa-a. During this operation, +/- Ia change in each tube is limited +/- peak current change equal to the idle bias current.
Above the first few watts the operation moves to class AB and the load each tube sees becomes 1/4 RLa-a which is the same loading one would see if the amp was set up to operate in class B without any bias current at idle. The AB amp operation changes to partial class B operation because one tube's Ia becomes completely cut off during 1/2 its wave cycle, while the other

powers the load alone through 1/2 the OPT primary and with a larger peak Ia change than the Idle Ia.
If the tubes were biased to have no idle current and could only increase with a positive going grid signal the tubes would be said to operate in class B, and each tube could only provide power for each half wave cycle.
The load line for class B action in ONE tube is all that is needed to determine possible class B or AB output power and anode voltage swings.

Class AB operation exploits the ability of an output tubes to produce much more peak current change than for pure class A where Ia change is limited to +/- Ia dc at idle. Therefore much more power is possible from a pair of tubes working in class AB than for the same pair working in class A.

Plotting the minimum class AB1 RLa load.

Fig 2. (repeated here the same as above).



For all PP hi-fi amps considered at this website, only class A1 or AB1 will be considered suitable for hi-fi because there are no net benefits of class A2 or AB2 which must include more complicated methods of low impedance drive to output tube grids to cope with grid current. For any hi-fi amp, it is better to use a quad of 6550 in class AB1 than have a pair of 6550 being flogged to death in class AB2 to extract the same PO as the Quad.

To draw the load for minimum Class AB RLa-a the minimum Class B load for a single tube of the pair must be plotted.

Examine Fig 2. This shows the Ra limiting line = 280 ohms.
The Knee of this curve is shown at Ea = 100V and Ia = 350mA.

Plot point D at the Knee.

Point D is usually below the Pda curve and if D appears above Pda limit, then plot point D where Ra curve intersects Pda curve, so that D appears at the lower of the two possible positions.

Draw a straight line from Point C on Ea axis at 500V through D and on to Ia axis and plot Point E.

The line E D C is the minimum class B load for the tube, ie, 6550.

The RLa B load value = Ea at C / Ia at E = 500V / 450mA = 1,111 ohms.

The Class A load line for the AB loading conditions may be plotted :-

Plot Point F on line EDC where Ia = 2 x IaQ.
Point F is at Ia = 2 x 50mA = 100mA.
Draw straight line from F through Q and on to Ea axis and plot Point G.
The distance between F and Q should be equal to between Q and G.

The line FQG is the class A loadline for each tube of the PP pair for AB operation.

FQG is *always* = 2 x Class B RLa. ie, = 2,222 ohms, this example.

The class AB RLa-a is always considered 4 x Class B RLa, or 2 x Class A RLa.

OPT-1A, Minimum Class AB RLa-a = 4 x 1,111 = 4,444 ohms.

The peak anode voltage swing at each anode = EaQ - Ea minimum.
= 500V - 100V = 400Vpk. Ea minimum occurs at point D, and it may be read off the graph looking vertically below D to Ea axis.

The Va-a = 0.707 x 2 x Ea pk swing at each anode
= 0.707 x 2 x 400Vpk = 565.6Vrms.

Class AB output power for plotted AB load = Vaa squared / RLa-a.
OPT-1A, PO = 565.6 x 565.6 / 4,444 = 72 Watts.

Class A power for any class AB RLa-a less than the RLa-a for maximum pure class A = 0.5 x RLa-a x IaQ squared.

OPT-1A, RLa-a = 4,444 ohms, Ia dc per tube at idle = 50mA,
PO = 0.5 x 4,444 x 0.05 x 0.05 = 5.6 Watts.

This means that the power up to 5.6 Watts is pure class A, but all the rest of the power is produced by class B action.

3. Check the anode dissipation for sine wave operation.

The tubes will dissipate varying amounts of heat for varying audio signal levels and varying load values at different frequencies. The anode dissipation, Pda, is the product of sustained voltages x currents flowing in the tube. If a 6550 has Ea = 500Vdc and Ia = 50mA dc, at idle, then its Pda = 500v x 0.05A = 25 Watts. The dc Pda plus signal caused Pda should not be allowed to exceed the limits quoted in data for the tube for more than a very brief time.

If the amplifier is designed by using design methods shown at this website it is unlikely that the load range suitable for the OPT will ever cause tubes to overheat. The 2 main reasons are :-

1. The RLa-a load value is chosen so the class B load line for one tube of the PP pair will intersect the Ra limiting line at Ia lower than where the Pda maximum intersects the Ra limiting line, **see point D in Fig2 above.**

2. Ea voltages chosen are NOT the highest which could be used. Although Ea could be +800Vdc for KT88/6550 etc, and although 140 Watts is available in virtually class B conditions, such high Ea bring reliability problems and high THD. If for any reason the RLa-a is slightly lower than optimal, the tubes may all too easily overheat. Adjusting bias with high Ea can be tricky.

As a general rule, I could suggest the proposed maximum AB power out never be more than 0.7 x Pda limit of all tubes in an output stage.
For example, 2 x 6550, Pda limit for two tubes = 84Watts, so do not design for working loads to give more than 0.7 x 84Watts, ie, 58 Watts of audio power.
2 x EL34, Pda limit = 56Watts, power output < 39Watts.
Even though higher maximum Class AB output power is available if RLa-a is reduced on ohm value, just don't, because it leads to overheating, and increases THD at all levels, reduces class A, increases Rout, and ruins music.

I have enormous reluctance to use Ea higher than :-
+500Vdc for any octal tubes such as KT88, 6550, KT90, KT120, or for non octal industrial tubes like 13E1.
+450Vdc for EL34, 6L6GC, 807, KT66, 5881.
+350Vdc for EL84, 6V6, 6CM5, 6GW8.
+250V for EL86, 6BM8, EL95.
+1,000V for 813.

The same table could be used for most of the above when used in triode or UL connected with some exceptions, ie, +375Vdc for 13E1, and probably lower also for 813. One must be very careful not to use Eg2 too high lest Pg2 exceed limits or cause Eg1 bias to be excessively negative and unable to properly control Ia bias current.

For real triodes, Ea should not exceed :-
+300Vdc for 2A3,
+450Vdc for 300B,
+1,200Vdc for 845, 211, 805, GM70.

Whenever the tubes operate in pure class A1, the anode dissipation will never be higher than the idle Pda, Max Pda = EaQ x IaQ, and in **Fig 2** with 6550, Pda max = 500V x 0.05A = 25 Watts. With a load giving only pure class A the Pda will reduce when any audio power is produced, and Pda in minimum at clipping. In fact, with tetrodes and pentodes in pure class A the anode

efficiency is highest at about 45% so that if there are two 6550 with total Pda = 50Watts, then Maximum pure class A power = 22.5Watts.
At this maximum Class A, Pda = Pin from PSU - PO = 50W - 22.5W = 27.5Watts for both tubes, so Pda per tube = 13.75Watts. But in a class A or class AB amp used for hi-fi the average PO level is rarely above 1/10 of the maximum possible intended PO, so Pda is always nearly constant and temperature is stable unless faults are present or loads are too low.

But with class AB where the amount of possible initial class A power is less than 1/4 of the total AB power possible for the load value, then the Pda will always rise after the first few watts are produced.

Calculating Pda for output tubes for class AB RLa-a.

For where RLa-a is low enough to cause maximum peak Ia to be more than 3 x Pda rating / Ea, the Pda max will not differ much from a pure class B amp, and will be at a maximum at less than the clipping level.
The lower the RLa-a load value, the higher the max Pda will be.

All class AB amps meant for hi-fi performance will have substantial Ia at idle which will have little effect on Pda max for the lowest RLa-a likely to be used.

For much more info on Pda and how to calculate it go to my page
Anode-dissipation+waveforms

Formula for calculating Class AB Pda :-

To calculate AB1 total Pda of both tubes and above class A portion of power, AB1 Pda =

$$\text{Ea} \times \left[(0.364 \times \text{Ia}) + \left(\frac{1.8 \times \text{Vaa}}{\text{RLaa}}\right) + \frac{(0.364 \times \text{Ia squared})}{\left(\frac{2.83 \times \text{Vaa}}{\text{RLa-a}}\right) - \text{Ia}} \right] - \text{PO.}$$

Where Ia = idle Ia dc in one tube.

Audio PO = Va-a squared / RLa-a

To easily calculate Pda in all class A1 operation,
Pda = (2 x Ea x Ia at idle) – class A1 PO, Watts.

OPT-1A. Calculate Pda for Minimum Class AB RLa-a.
RLa-a = 4,444 ohms, Va-a max = 566Vrms, Ia at idle = 50mA.
Maximum class AB PO = 72Watts.

Pda maximum will occur with beam tetrodes or pentodes at approximately 0.67 x maximum class AB PO = 0.67 x 72W = 48 Watts.
Vaa at 48W = 461Vrms.

Pda =

$$500 \left[\left[(0.364 \times 0.05) + \left(\frac{1.8 \times 461}{4,444}\right) + \left(\frac{0.364 \times 0.05 \times 0.05}{\left[\left(\frac{2.83 \times 461}{4,444}\right) - \text{Ia}\right]}\right)\right]\right] - 48$$

= 500 [[0.0182 + 0.1867 + 0.0037]] - 48

= 56.32 Watts for the two x 6550.

Pda per tube = 28.16 Watts.

NOTE. This result is consistent with the Pda graph for RLa-a = 4k0 at my page at **Anode-dissipation+waveforms**

NOTE. In class AB PP amps, Pda max should not be more than 0.67 x Pda limit for the tube.
This allows for some tube heating effects of Eg2 x average Ig2 which may become considerable, and for the speaker loading of the tubes to be less ohms than a nominal load, ie, there is some room for error.

Conclusion. RLa-a should not be less than 4k4 lest Pda rise too high.

4. Calculate idling Ia bias current.

For PP class AB1 6550 for all connection modes, Ultralinear, Beam Tetrode, Acoustical with CFB, or Triode.

Number of output tubes = 2.
Choose Ea = +500Vdc. Confirm Pda limit from data sheets = 42Watts.
For class AB1, choose Pda = 0.6 x Pda limit = 0.6 x 42 = 25Watts.
Calculate **Iadc at idle, each tube = Idle Pda / Ea = 25W / 500V** = 50mAdc.
Calculate **Idle Pda, all output tubes = No tubes x Pda for one tube = 2 x 25W = 50W.**

For output stages where only pure class A is intended, Pda at idle may be up to **0.75 x Pda maximum allowed.** In the case of 6550, Pda for pure class A only = 0.76 x 42 = 31.5Watts. For Ea = 500V, Ia = Pda / Ea = 31.5 / 500 = 63mA.

But longest tube life, Pda at idle should never exceed 0.6 x Pda max.

Instead of using 2 x 6550 for class AB1, it is possibly better to use 4 x 6L6GC or 4 x EL34, with Ea at +400Vdc max, and Pda at idle = 0.6 x Pda max for the tubes. For 6L6GC, Pda = 22 Watts so at idle Pda = 0.6 x 22 = 13.2 Watts. These smaller and cheaper tubes have Ea = 400V so Ia = 13.2 / 400 = 330mA. Two 6L6 will have nearly the same Ia on each side of the PP circuit as for 1 x 6550. The amount of power produced by a quad of 6L6 working with very easy conditions will be similar to 2 x 6550, and sound just as good, and despite the hi-fi cognoscenti prejudice against the 6L6 based on its major use in guitar amps which are designed to have high distortion.

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5. CALCULATIONS FOR PP BEAM TETRODES, without load line analysis :-

(Triodes are separately considered below.)

6. Calculate anode to anode load for maximum pure class A1 power.

RLa-a for 2 tubes = 1.8 x Ea / Iadc where Ea & Idc are for one tube at idle.

OPT 1A, Class A1 RL a-a load = 1.8 x 500 / 0.05 = 18,000 ohms.

For more than one pair of OP tubes, divide the above by the number of pairs of tubes.

7. Calculate maximum Class A1 power.

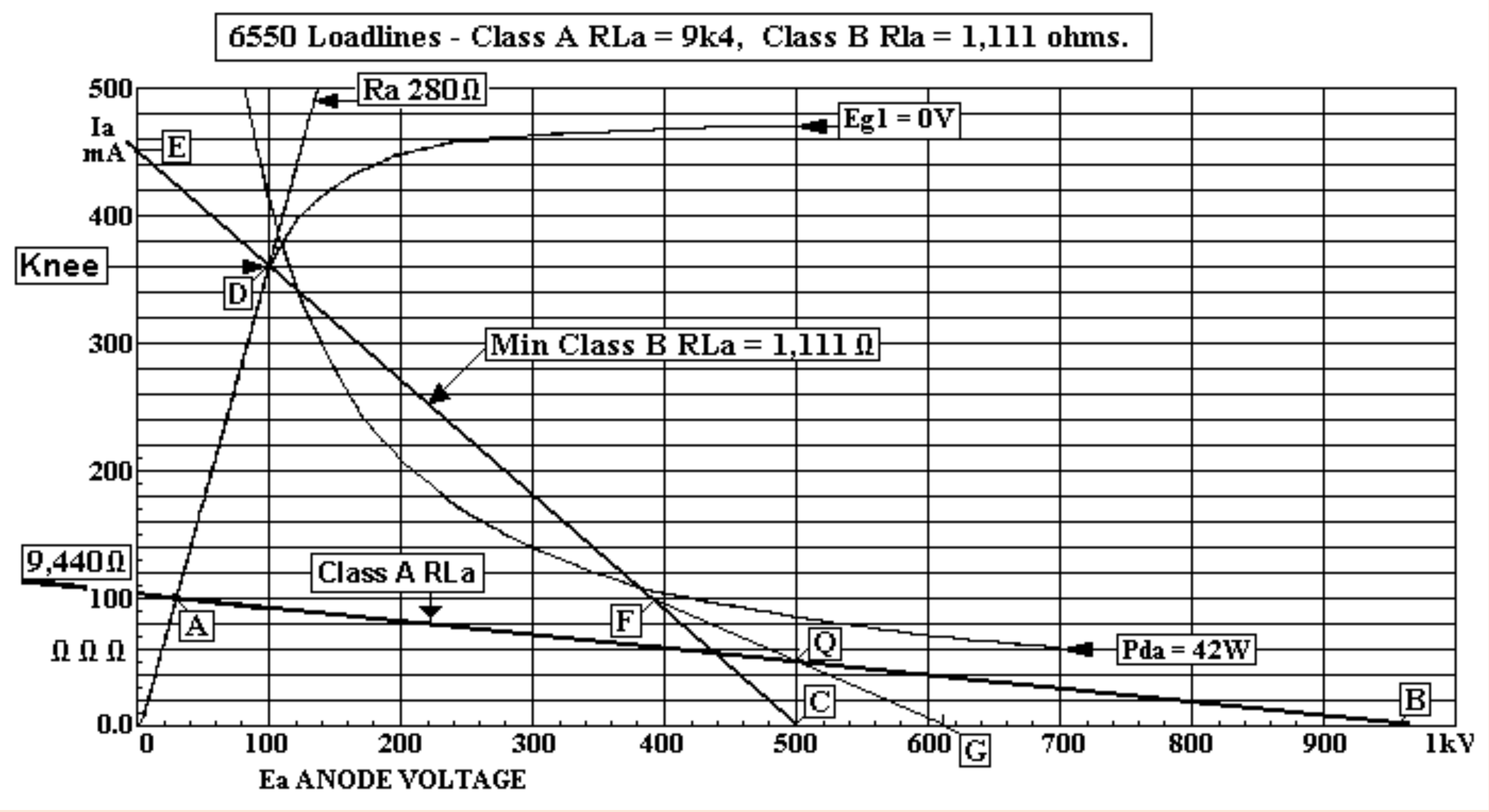
Max class A1 PO = 45% x Pda for all tubes at idle.
OPT 1A, PO A1 max = 0.45 x 50W = 22.5Watts.

Calculate maximum Va-a swing = Square Root (Power x RL),
OPT 1A, Va-a max = sq.rt (22.5 x 18,000) = 636Vrms.

8. Calculate minimum Class AB1 RLa-a load for maximum class AB1power.

To calculate the minimum class AB1 RLa-a, there must be some inspection of the Ea vs Ia anode curves for the tube which show Ra curves for Eg1 and overall value of Eg2. The minimum class B RLa must be calculated.

Fig 2. (repeated again)

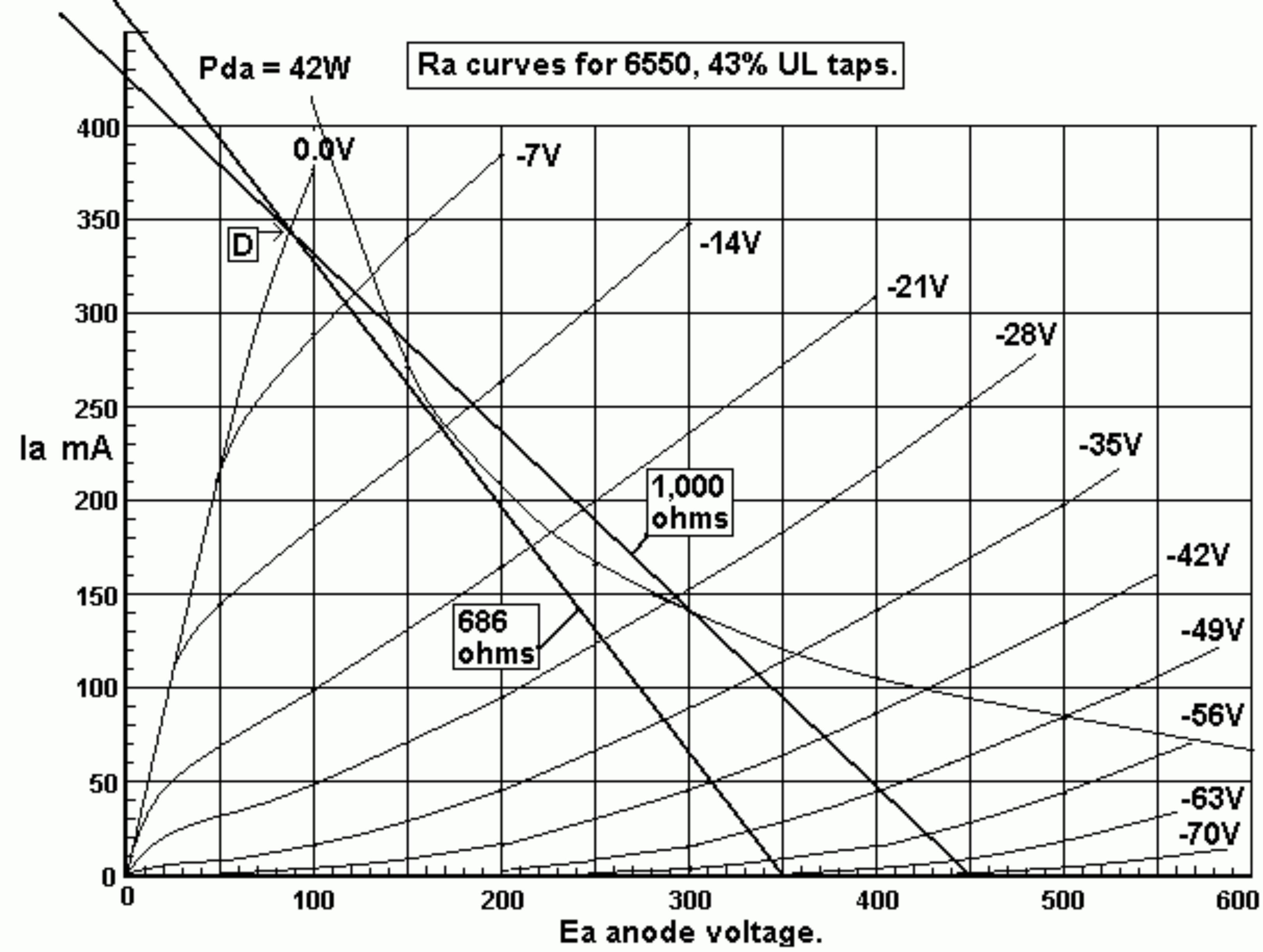


The knee of the Ra curve for Eg1 = 0.0V is at point D, where
Ea minimum = 100V, Ia maximum = 360mA,
The minumum class B RLa = (Ea - Ea min) / Ia max
= (500V - 100V) / 0.36A = 1,111 ohms.

RLa-a = 4 x RLa = 4 x 1,111 = 4,444 ohms.

Examine a set of curves for 43% UL connected 6550 :-

Fig 6.



Ra at	350V	400V	450V
at 60mA	2k5	2k7	2k8
μ = 14.4 , gm = 5.3mA/V averages			

Min Class B RLa :-	Min RLa-a
Ea = +450V, 1,000 ohms	4,000 ohms
Ea = +350V, 686 ohms	2,774 ohms

Fig 6 shows curves for a 6550 with 43% UL taps. The point D is not recognized as an easy to see knee of any curve but it can be established at a convenient point on the Ra curve for Eg1 = 0.0V and below where the Pda curve intersects the Ra curve.
In the above Fig 6 the point D is at Ea = 87V and Ia = 345mA.
For Ea = 450V, RLa minimum = (450V - 87V) / 0.34 A = 1,052 ohms or approximately 1,000 ohms giving RLa-a = 4,000 ohms.

Point D may be constant for all values of Ea between +350V and +500V, thus giving a range of RLa minimum from 686ohms to 1,100 ohms and range of RLa-a = 2k7 to 4k4. Notice that the Ia at idle does not affect the RLa min calculation.

The Output Transformer should give the widest number of load matches depending on the Ea chosen.

Regardless of how useful the Fig 2 and Fig 6 graphs may appear to be, They only suit 6550, KT88, KT90 and KT120. For all other tube types the calculations will involve different Pda, Idle Ea, Ea minimums, and Ia maximum and you MUST examine and understand what you are looking at.

9. Calculate maximum AB1 power into minimum RLa-a.

9A. Calculate max class AB1 PO from the data gained in Step 8.
PO at clipping = 2 x (Ea - Ea minimum) squared / RLa-a

For Ea = 500V, Ea min at point D = 100V, RLa-a = 4k4,
OPT-1A, Max AB1 PO = 2 x (500 - 100) x (500 - 100) / 4,444
= 72.72 Watts.

9B. Assume the value of limiting Ra line = 280ohms for all power tetrodes and pentodes :-

Maximum safe class AB1 Power,

$$\mathbf{PO = 0.125 \times \frac{RLa\text{-}a \times Ea\ squared}{([\ RLa\text{-}a / 4\ ] + 280\ )\ squared}}$$

OPT 1A, RLa-a minimum = 4,444 ohms, Ea = 500V,

$$\text{Max class AB PO} = 0.125 \times \frac{4{,}444 \times 500\ squared}{([\ 4{,}444/4\ ] + 280\ )\ squared}$$

= 0.125 x 4,444 x 250,000 / (1,391 x 1,391) = 71 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 = 280 ohms.

10. Calculate Middle RLa-a for intermediate power and for ideal Class AB1 for Hi-Fi use.

Calculate Middle RLa-a =

Minimum RLa-a x square root of (Class A RLa-a / RLa-a minimum).

OPT-1A, Minimum RLa-a = 4,444 ohms from Step 2B,
Class A RLa-a = 18,800 ohms from Step 2A.

Middle Beam Tetrode RLa-a
= 4,400 x sq root (18,800 / 4,444)
= 4,444 x sq root 4.23 = 9,140 ohms, (say 9k0.)

11. Calculate PO for middle RLa-a.

$$\mathbf{PO = 0.125 \times \frac{RLa\text{-}a \times Ea\ squared}{([RLa\text{-}a / 4] + 280\ )squared}}$$

OPT-1A, PO, RLa-a = 9,140 ohms, Ea = 500V,
PO = 0.125 x 9,140 x 250,000 / (2355 x 2355)
= 51.5 Watts.

10. Calculate pure class A1 portion of power within class AB1 total for middle RLa-a.
Class A1 PO for any RLa-a between RLa-a min and pure class A RLa-a for maximum PO = 0.5 x Ia squared x RLa-a, where Ia is Ia dc at idle.

OPT-1A, Class A PO into 9,140 ohms
= 0.5 x 0.05 x 0.05 x 9,140 = 11.4 Watts.

Maximum AB PO for middle RLa-a will be between maximum class AB1 PO for lowest RLa-a and maximum class A1 PO.

12. CONCLUSIONS ABOUT LOAD CHOICE.

Fig 7.

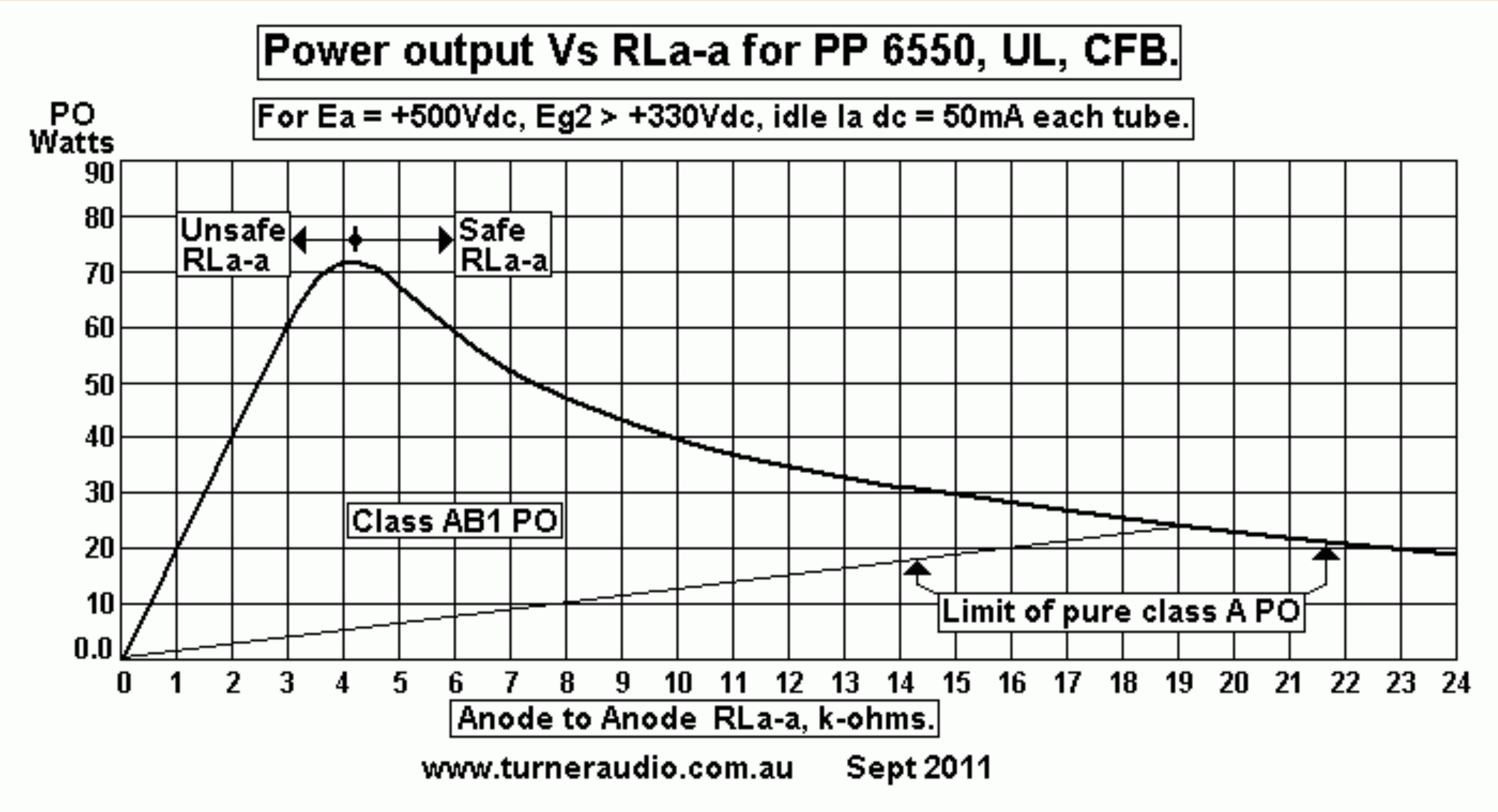


Fig 7 shows the clipping power levels for one pair of 6550 in beam tetrode, UL, or Acoustical with CFB and for Ea = 500V and for various RLa-a values.
The PO curves for limit of class A1 and for total AB1 are only valid for the shown Ea and Ia at idle.

NOTE. The ideal load value chosen by anyone for an OPT should suit everyone, because during any amplifier's life the owner may change and the speaker impedance value may change. I therefore I believe is is stupid to design any OPT for only ONE ideal load value, say 8 ohms.

There should be two or more load values which may be used depending on how multiple secondary windings are configured or on what tapping points are chosen along a single secondary winding. Plenty of dynamic dome&cone speakers which have a nominal Z = "4 ohms" have in fact Z varying between say 2.5 and 25 ohms with the 2.5 ohm dip between the crossover between bass and midrange at say 250hz where there is maximum musical energy. So the amplifier needs to be comfortable driving a low 2.5 ohms, and able to generate high current at low voltage and at low THD. The load of 25 ohms is no trouble to any amp, as current is low, and voltage high. Some full range electrostatic speakers have high Z below 1 kHz, but falling Z above 1kH, maybe only 1.5 ohms by 15kHz. Most amps can cope OK with this because very little musical energy exists above 7kHz.

Therefore the amplifier which may be set for "4 ohms" should be arranged so the RLa-a minimum load seen by the tubes is never less than RLa-a minimum as I have described in previous steps. Many amplifier makers arrange their amps so the absolute maximum PO occurs when the tubes have RLa-a equal to one and only load which gives this absolute maximum

PO. It is done to increase sales figures, and to make their products look better than they really are.

If you look at the **Fig 7** graph you will see that the RLa-a = 3,500 ohms gives PO = 76 Watts. If the OPT has an impedance ratio of 3k5 : 4 ohms, or 875:1, and a "4 ohm" speaker has a dip to 2.5 ohms, then the RLa-a becomes about 2k2, and such a load might overheat the tubes is a high level is used. Old AR9 speakers were classic amp killers, because their bass sensitivity and Z were both so poor.
The low load reduces the output tube gain by half, reduces the amount of class A1 PO, reduces the damping factor while very much increasing THD and IMD all all levels, and all that ruins music.

To avoid overheating tubes, it is better to have the OPT ratio of 4k5 : 2.5 ohms, ie, 1,800:1, or about TWICE what most amp makers provide today. If an amp has 3 terminals on the rear panel and labelled COM, 4 and 8, The use of an "8 ohm" speaker plugged between COM to 4 will give a far better load match and better music than the COM to 8 terminals.

99% of listeners should find a pair of 6550 or KT88 will give excellent sound *if the load-matching* is optimal.

Therefore, for a pair of 6550 in beam tetrode or UL or acoustical mode should have the following ratios :-
RLa-a MIDDLE VALUE : 2.5ohms, 5ohms and 10 ohms.

The steps above have calculated the Middle Value RLa-a at 9k0 approx, and this gives a healthy maximum PO = 45 Watts class AB1, with pure class A max at about 11 Watts.

What is ideally wanted are 3 secondary load matches for between 2.5 and 10 ohms to give RLa-a = Middle RLa-a value.

13. List the possible ranges of primary to secondary load matches, list use possibilities.

OPT-1A. Middle RLa-a = 9k0.
Sec = 2.5 ohms, ZR = 3,600:1, TR = 60.0:1,
Sec = 5.0 ohms, ZR = 1,800:1, TR = 42.4:1,
Sec = 10.0 ohms, ZR = 900:1, TR = 30.0:1.

Table for wanted load match possibilities.

ZR	TR	RLa-a ohms	Sec RL ohms	Nominal RL	PO
3,600:1	60:1	4k5 to 9k0	1.25 to 2.5	2.0	High, class AB
		9k0 to 18k0	2.5 to 5.0	4.0	Medium, class AB

		18k0 to 36k0	5.0 to 10	8.0	Low, pure class A
1,800:1	42.4:1	4k5 to 9k0	2.5 to 5.0	4.0	High, class AB
		9k0 to 18k0	5.0 to 10.0	8.0	Medium, class AB
		18k0 to 36k0	10.0 to 20.0	16.0	Low, class A
900:1	30:1	4k5 to 9k0	5.0 to 10.0	8.0	High, class AB
		9k0 to 18k0	10.0 to 20.0	16.0	Medium, class AB
		18k0 to 36k0	20.0 to 40.0	32.0	Low, class A

NOTE. In Steps below, turn ratios required for load matches for Middle RLa-a to approximate loads of 4, 8 and 16 will be calculated. All easy available matches should evaluated. For example, If a match of 4k5 : 1.0 ohms is found after calculation of secondary turns it indicates that other load matches may be possible, ie, 9k0 : 2.0 ohms and 18k0 : 4.0 ohms.

Some notes about the use of OPT-1A :-

NOTE. OPT-1A, When RLa-a = 9k0, there is an initial 10 Watts of pure class A, with the remainder of 34 Watts produced by class B action. 10 Watts is enough to produce an SPL = 99dB with speakers rated for 89dB/W/M. The total of 44 Watts will generate SPL = 105dB, and for both channels the SPL = 108dB at clipping. The levels heard while standing in the midst of a busy 50 member orchestra may exceed what your speakers could accurately produce, but the recording engineer has probably set a level limiter or signal compressor to reduce excessive dynamic range before 108 dB SPL is reached. 99% of people I know are happy with one pair of 6550 in each channel.

NOTE. It is ALWAYS WRONG to connect a 4 ohm speaker to a winding meant for a higher number of ohms. For example, if 4 ohms is used at a winding meant for 8 ohms, the RLa-a anode load is halved, and may become lower than the safe allowable RLa-a. The result may damage tubes by causing thermal runaway, but at low levels THD and IMD will be at least doubled, and damping factor halved.

NOTE. It is NOT WRONG to use a 4 ohm speaker connected to a winding meant for a lower number of ohms. For example, if an 8 ohm speaker is used at a winding meant for 4 ohms, the RLa-a anode load is doubled and the amp produces a higher amount of class A1 power with a reduced amount of total AB1 power. Providing there is still enough power without clipping, THD/IMD is lower, and damping factor higher, so music will sound better.

NOTE. Because most 16 ohm speakers will be old models made before 1970, and because they are often more sensitive than speakers made after 1970, they require little power to give good results; A pair of 16 ohm 1969 dual concentric 15" Tannoy drivers in 180 Litre ported reflex boxes will make magnificent hi-fi with amps capable of only 10 Watts. Therefore if an amp is capable of 50 Watts with 8 ohms there will be more than enough output voltage for any 16 ohm speaker so there is no need to have a load match for anything above 8 ohms.

NOTE. Quad-II amps have a load match choice for 8 ohms or 16 ohms.
I find that the ESL57 which has quite high Z below 500Hz is better driven with the OPT terminals strapped for 8 ohms. Unfortunately, Quad-II do not have a recommended way of making the OPT match 4 ohm speakers. If one uses 4 ohm speakers with Quad-II amps set for 8 ohms, the RLa-a falls below a safe RLa-a minimum. The use of 6550, KT88, KT90 in Quad-II will give better results than KT66, 6L6GC, 5881, EL34.
Many old amps like Quad-II and many modern amps do not like low impedance speakers at all and they offer very poor performance because not enough load matches are are available. With Quad-II OPT, they may indeed be removed from the amp chassis, gently heated to melt out the the potting compound which is saved for re-use. The OPT may then have the existing wiring from secondaries slightly altered and two added terminals fitted to allow low loss configuration of available secs to give a load match of 4k0 : 4 ohms, with losses being the same as for 4k0 : 16ohms. When 8 ohms is used at the 4 ohm setting, the RLa-a becomes 8k0, and these venerable old ancient amps are then optimized to meet modern expectations for hi-fi.

NOTE. With OPT-1A, and when using the 60t secondary winding configuration, the load match is 10k5 : 8 ohms. Now if someone connects 4 ohms, then RLa-a is halved to become 5k3. But this is still above the safe minimum RLa-a and the tubes will not overheat and fidelity will remain passable. Doing things my way will give you many years of trouble free hi-fi listening.

OPT Calculator program?

As far as I know there is no available "Output Transformer Calculator" program online or available anywhere. My design logic flow could be used to construct a computer program where one would enter the design requirements such as power, secondary load, tube Ra, core dimensions, then with a click on a "calculate" button, out would come a specification sheet listing core size, winding wire details and there would be a detailed diagram showing the layers of wire built up in the winding bobbin, so that a paper copy may be given to a manufacturer who could then proceed to wind the OPT.

Alas, I am not a computer expert, but I can give you the flow of logic plus background notes needed to understand what you may try to achieve when you design your OPT.

Besides a PC with a printer, you will need some tools :-
Exercise book, pencil,
pocket calculator, scale ruler, and open mind, persistent attitude.

I invite anyone interested to prepare a PC program to include all diagrams and details of the windings using a range of common wire sizes and core types. It is October 2011 and so far since 2000, 4 gentlemen have tried to make a program but none have completed the work.

ABOUT THE METRIC WINDING WIRE SIZE CHART

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				

The metric winding wire sizes were kindly given to me by a local Sydney wire and transformer parts supplier. The original chart contained the same copper sizes as shown for grade 1 with less enamel thickness and grade 3 with more enamel thickness.
I only use grade 2 which is the only grade shown in the chart below.
Grade 2 is the only grade stocked by my supplier because it is the industry

norm for 99% of high temperature rated winding wire for electric motors and stressful industrial applications. The range of sizes shown are not all obtainable off the shelf, and to get some sizes a wait for an order is involved, so I sometimes have to design around the wire size available, which adds to the challenge. Anyone not used to measuring in millimetres better start getting used to metric because here the diameter measurement matters more than the wire gauge, and there are AWG, SWG, BS, all very confusing, and I don't have conversion charts so if you work in gauges and inches and feet, provide your own solutions.

Before winding anything, make sure you have an accurate micrometer to confirm that the size is correct. Wire should be measured with enamel coating and with enamel carefully removed.

Fig 32. Blank sheet for printing out for plotting load lines.

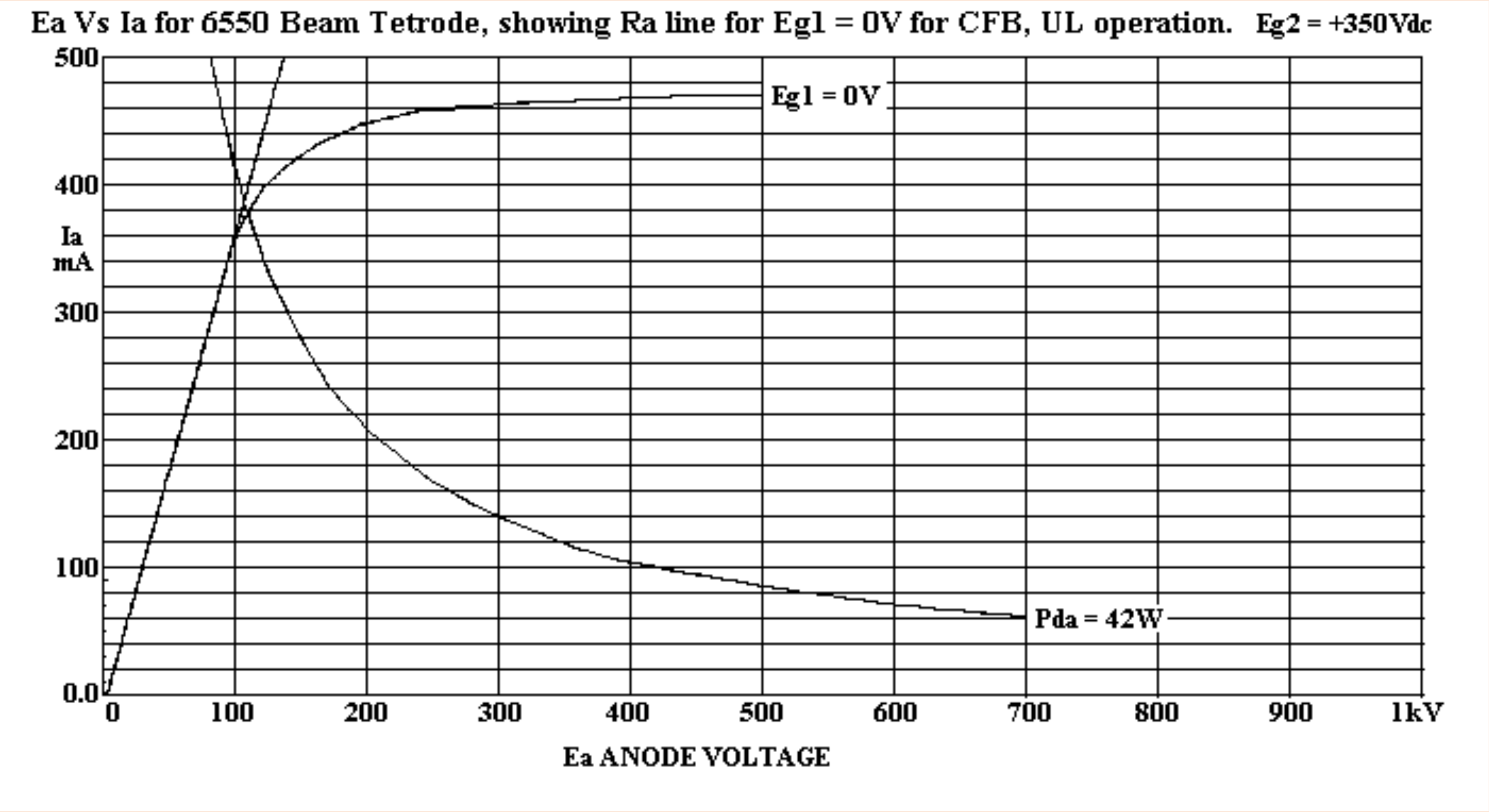


Fig 33. Blank sheet for drawing 6550 beam tetrode load lines.

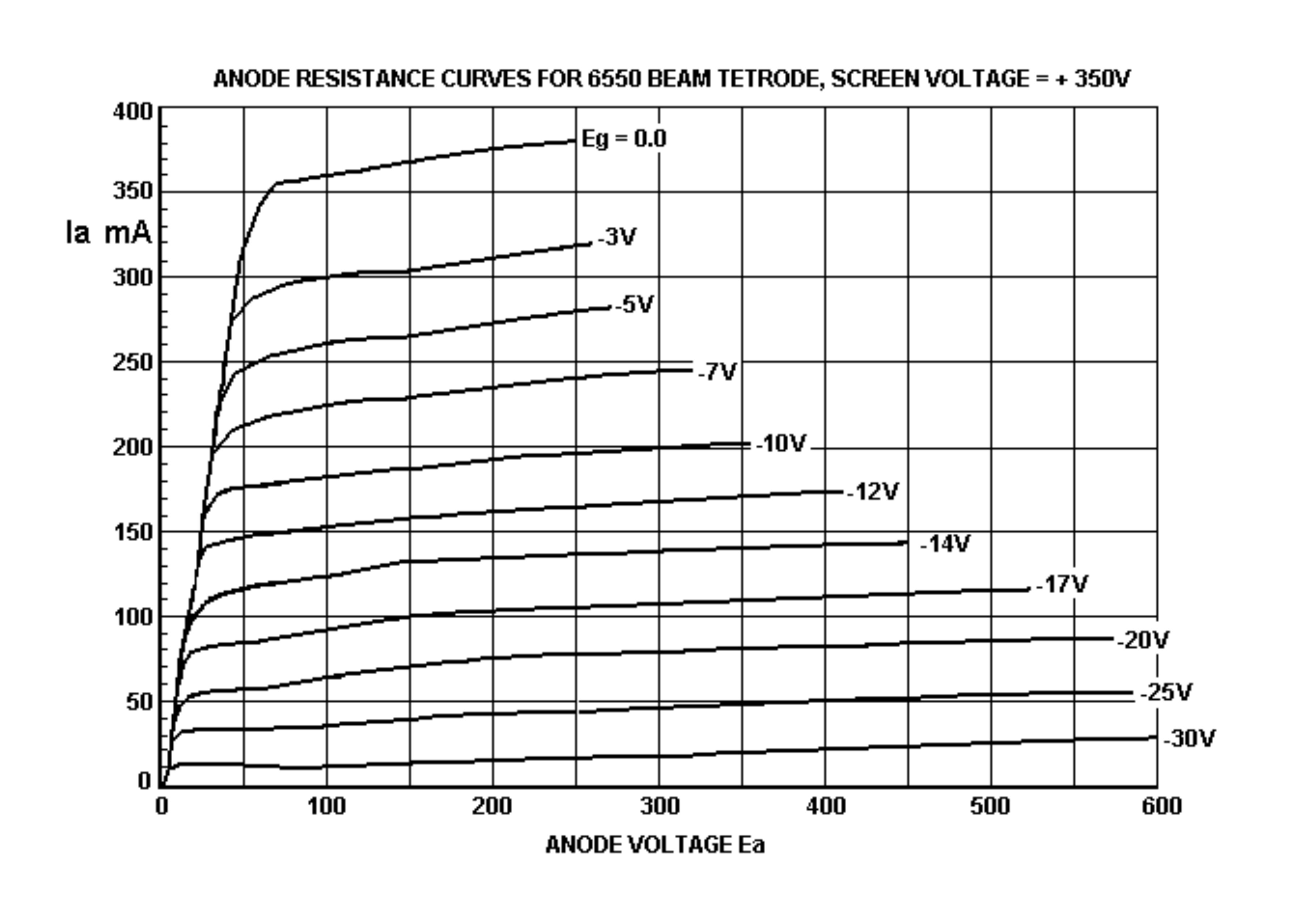


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Fig 34. For Reference.

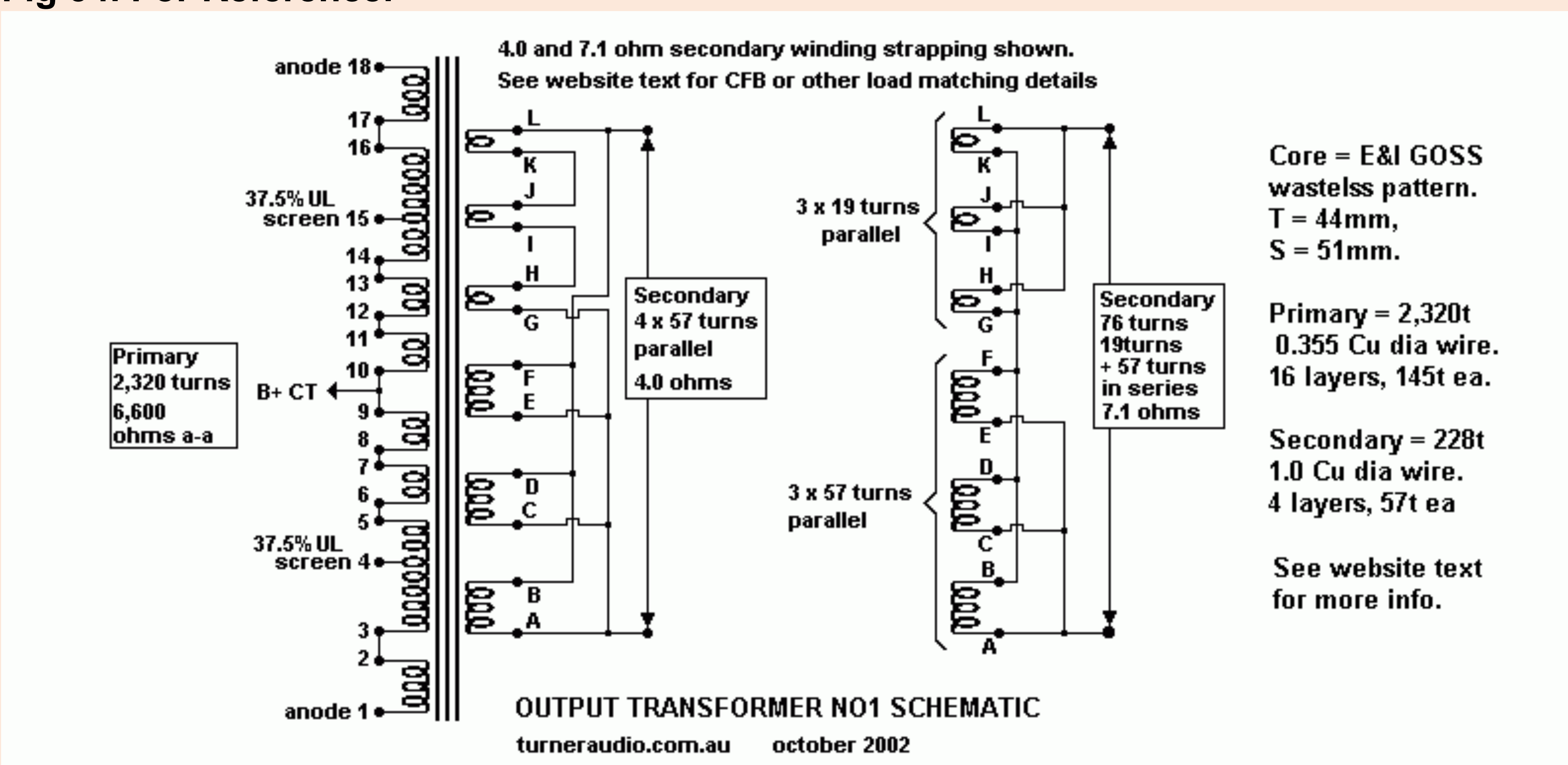


Fig 35. Blank sheet for drawing 6550 triode load lines.

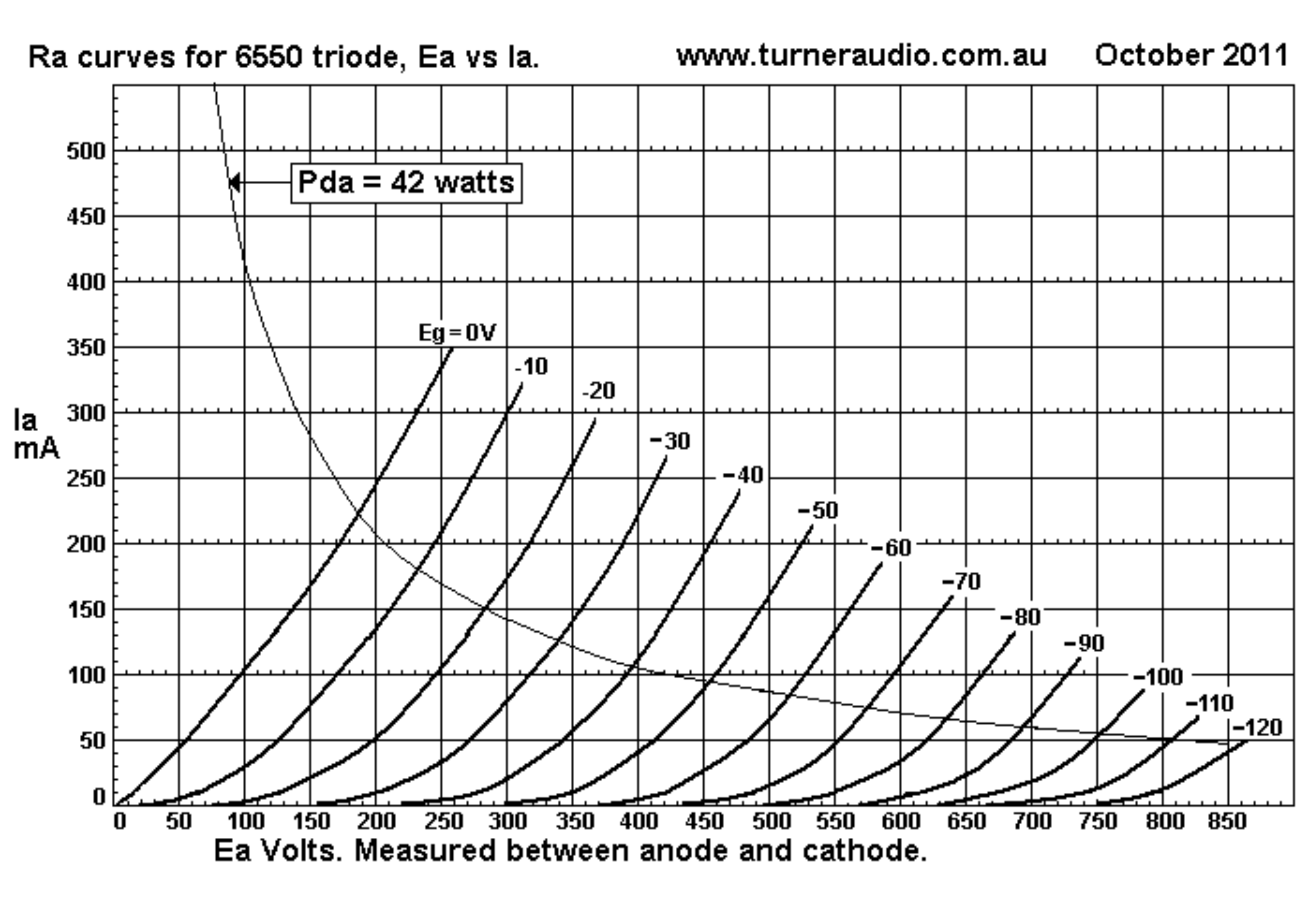
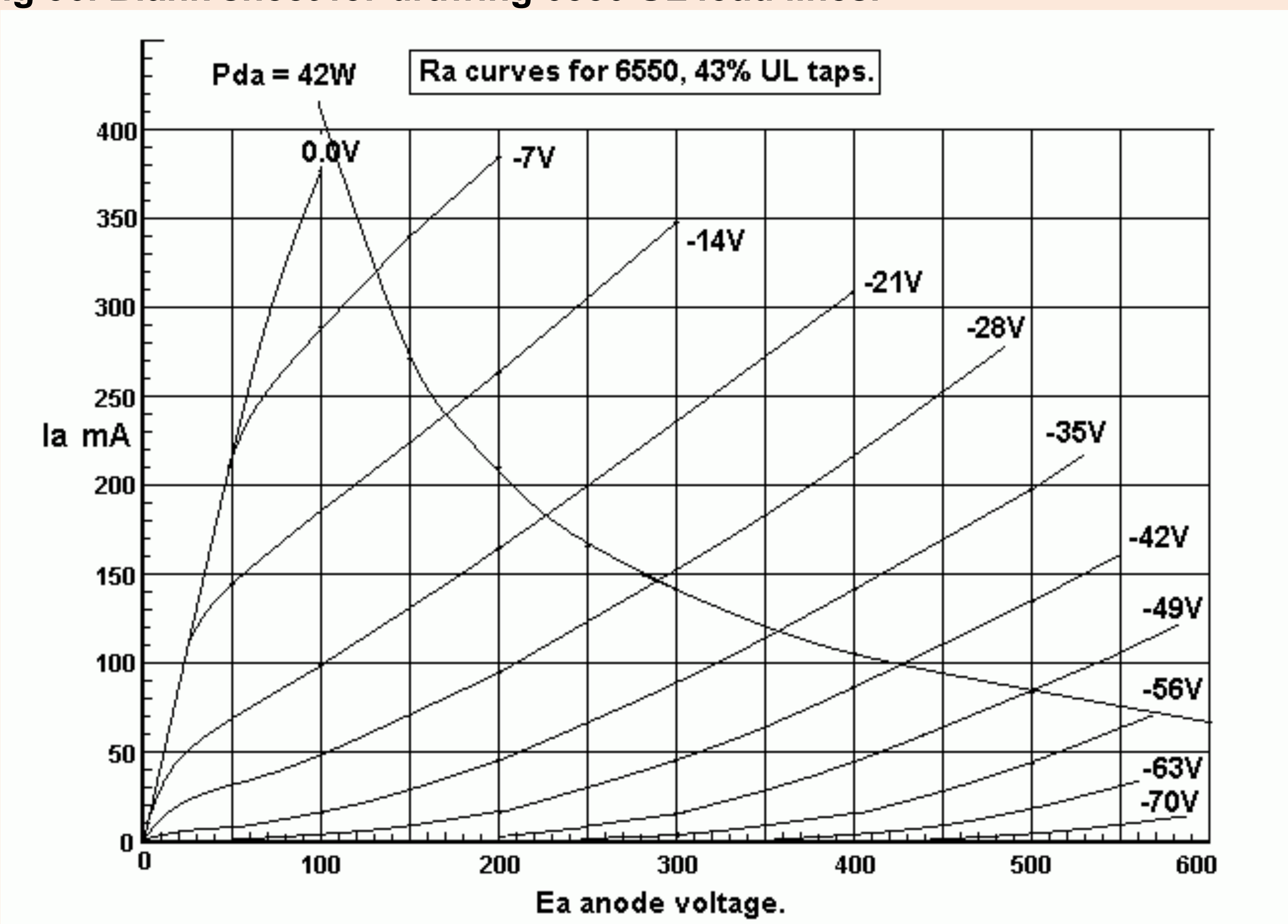


Fig 36. Blank sheet for drawing 6550 UL load lines.



Ra at	350V	400V	450V
at 60mA	2k5	2k7	2k8
μ = 14.4 , gm = 5.3mA/V averages			

Forward to PP OPT Calc page 2.

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