Designing Power Amplifiers

Most of this material is included in my latest update to ***Hollow-State Design 3rd Edition****.*

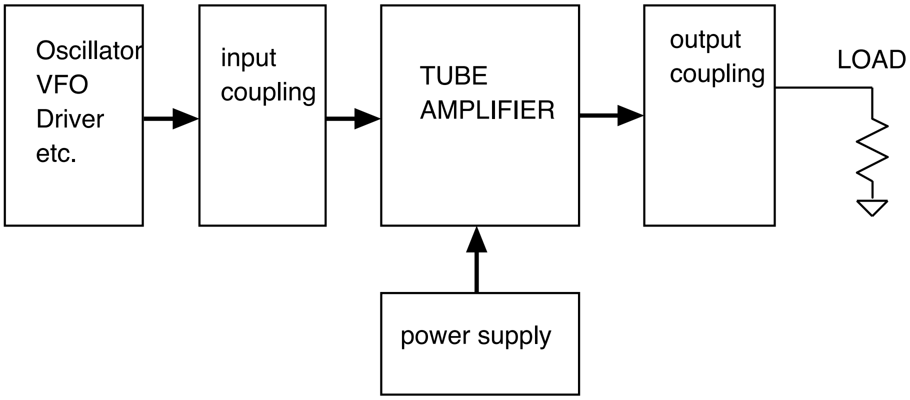
This paper aims to organize and explain what you need to know to design basic RF power amplifier stages for almost any type of transmitter. Power amplifier circuits are designed to increase V x I (power), therefore to keep circuits practical we need to amplify current. To generate 200 watts for example, using a reasonable power supply, say 800 volts, will need output currents in the 250 mA range, so the design of the power supply is just as important as the rest of the amplifier.

A **linear power amplifier** will reproduce the input signal with little or no distortion to the output circuit. All of the amplitude variations of the input are reproduced at the output. This is a requirement for an amplifier to be used for SSB operation. AM can tolerate a bit more distortion, and CW can tolerate less linearity in order to increase efficiency.

Every ham I know who has ever built their own home-brew amplifier, copies a design they found on the internet, from a handbook, or perhaps a ham radio magazine, usually by substituting parts from the “junk box.” Sometimes this works, usually not so much. The problem with this approach is a lot of these designs have major problems: dangerous HV in the wrong place, keying by lifting the cathode, no screen voltage regulation, no bias stabilization, HV on panel meters, no protection for the thermatron if drive is cut off, etc. Just say no.

The Basics

The design of the transmitter/amplifier can be divided into four simple parts: the input coupling, the thermatron amplifier, the output coupling, and the power supply. The thermatron amplifier “modulates” the DC current from the power supply based on the input RF signal and thus provides power amplification. The job of the input coupling is primarily impedance matching as well as previous stage/grid bias voltage isolation. The purpose of the output coupling is similar, to separate the power supply voltage from the



output RF, to filter any non-sinusoidal output from the thermatron, and match the thermatron output impedance to the load impedance.

Basic warning for dealing with circuitry that employs high-voltages (over 75 volts).

Don't touch high voltage, especially when it's on!
Got it? (more on this later)

Designing Power Amplifier Circuits

Power amplifiers are classified according to their "class" of operation (A, AB, B, and C) and the circuit configuration; cathode driven [grounded-grid] or grid driven [grounded-cathode]. Any combination of class and configuration is possible. The amplifier can be used stand-alone as a separate amplifier or part of a full transmitter.

Design Goals

The design goals for a power amplifier are straight forward:

- Amplify the exciter's RF (by 10 dB or more).
- Provide a means to match the amplifier load correctly.
- Amplify complex signals such as SSB with minimum distortion (maximum linearity).
- Transmit a spectrally-pure signal.
- Ensure a safe operating environment.

Step-by-Step Amplifier Design

Most amplifier home-brewers either start with a power level in mind and find a thermatron that will do the job, or they have a thermatron that has been sitting on the shelf and accept whatever power level it can produce. Often this is limited by power supply parts.

1. Decide on a thermatron type and desired output level
2. Decide on a class of operation
3. Decide on a basic amplifier configuration (grounded-grid, grounded-cathode)
4. Design (and build if possible) the power supply
5. Design the thermatron operating conditions
6. Design the grid input coupling circuits
7. Decide on the output tank coupling
8. Determine any neutralization and parasitic suppression
9. Determine the cooling requirements
10. Design any control circuit
11. Build it or a prototype
12. Perform testing and measurements

1. Decide on a thermatron type and desired output level

The power output from the amplifier is limited by two things: the plate dissipation of the thermatron, and the power that the power supply can deliver. The high voltage from the power supply is what ultimately limits the maximum power from the amplifier. P=EI, but it takes a high E to get enough I under load to produce the power. Therefore your power might be limited by using an on-hand, junk box HV transformer.

Triode vs. Beam-Power Tetrode

While you can use almost any thermatron in any circuit if you work at it enough, there are,
from a practical standpoint, two choices. Either use a triode in a grounded-grid configuration (cathode-driven), or use a power tetrode in a traditional grounded cathode configuration (grid-driven). The table below lists some of the more popular and still available power thermatrons. The "family" is just my preferred grouping. I limited the list to the more common power thermatrons. The number in parenthesis is the rated plate power dissipation.

Thermatron Family	Triode	Power Tetrode
RCA 800 Family	810 (175) 811A (65) 572B (160)	807 (30) 1625 813 (125)
EIMAC	3-400Z (400) 3-500Z (500	4-250 (250) 4CX250 (250)
6146		6146 (25) 6883 2E26 (14)
Sweep Thermatrons		6DQ5 (24) 6LF6 (40) 6LW6 (45) 6MJ6 (30) many more…

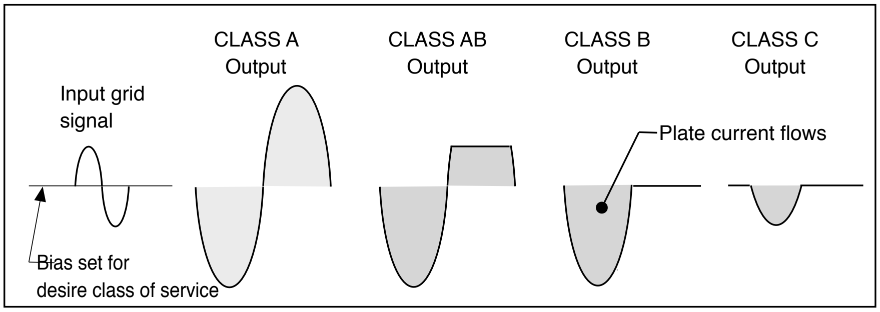
Which thermatron and configuration is better? Mostly depends on what you are going to use it for. To me, the triode works best as a stand alone amplifier driven by an existing transmitter that can generate 50 watts or so. The tetrode is more flexible; it can be easily used as part of a home-brew CW or SSB rig or as a stand alone amplifier for even a QRP rig.

	Triode	Power Tetrode
Advantages	No screen supply Easy to use in GG configuration Neutralization usually not required at HF Drive power added to output	High gain, low drive power More thermatron choices available
Disadvantages	Requires high drive power Low gain Input matching Filament choke	Screen supply Neutralization usually required
Best For:	Stand alone amplifier	Stand alone amplifier or part of multistage transmitter

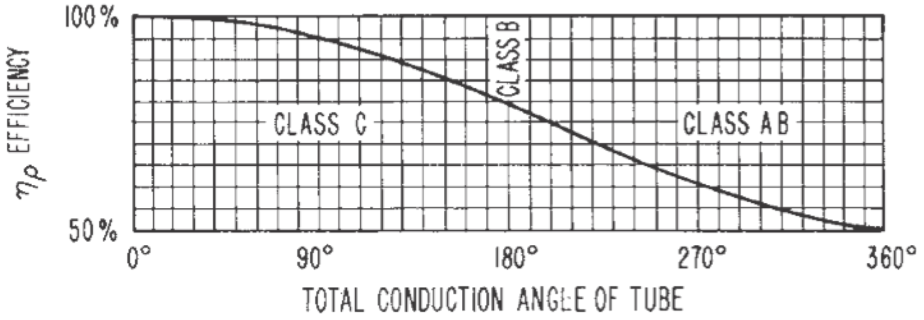
2. Decide on a class of operation

The next decision is to pick a class of service. This is based on modulation and efficiency goals. Class of service is determined primarily by how the amplifier thermatron is biased given a specific HV and screen supply and applies equally to triodes and tetrodes. The details of class of service were covered in Chapter 7 on power thermatrons.

As a general rule of thumb, If you are amplifying AM or SSB, then you need to go for very good linearity and class A, AB1 or AB2. These classes will provide the best signal quality. If you are going to use it for CW, then you can use class C, or any class you want as long as you bias the amplifier off during key up conditions.



Amplifier efficiency is expressed as power delivered to the antenna divided by the amplifier input power, expressed as a percentage. In general, class A is the most inefficient at about 50% with class C providing efficiencies in the 90% range (maybe).

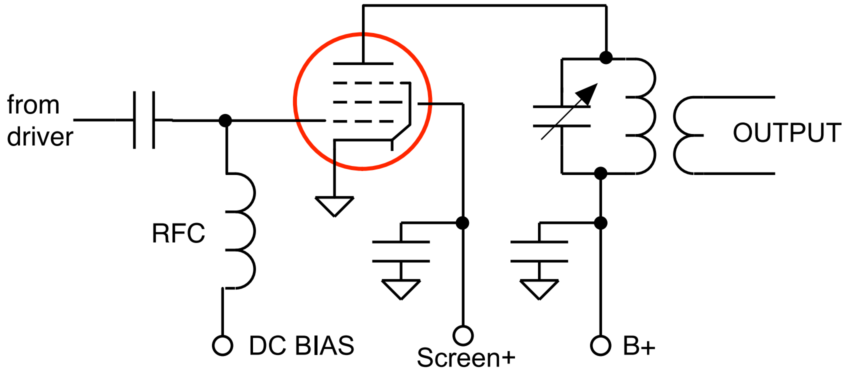


3. Decide on the Basic Amplifier Configuration

There are two basic designs for a power amplifier stage: **grounded-grid**, referred to as cathode-driven; and **grounded-cathode**, referred to as grid-driven.

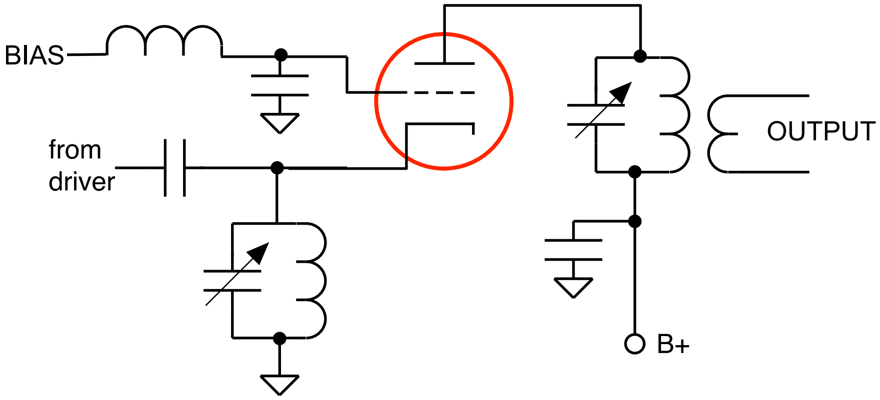
Grounded-Cathode

A typical configuration for the grounded-cathode circuit is shown below. It looks rather like a conventional tetrode amplifier stage and it is. The grounded-cathode amplifier generally uses beam-power tetrodes. It has high gain and is easy to drive from even a small QRP rig. But it requires a stable screen supply and may require neutralization.



Grounded-Grid Amplifier

A typical configuration for the grounded-grid amplifier is shown below. The circuit generally uses power triodes. The control-grid is at RF ground potential and the driving signal is applied to the cathode via a tuned circuit. The control-grid serves as a shield



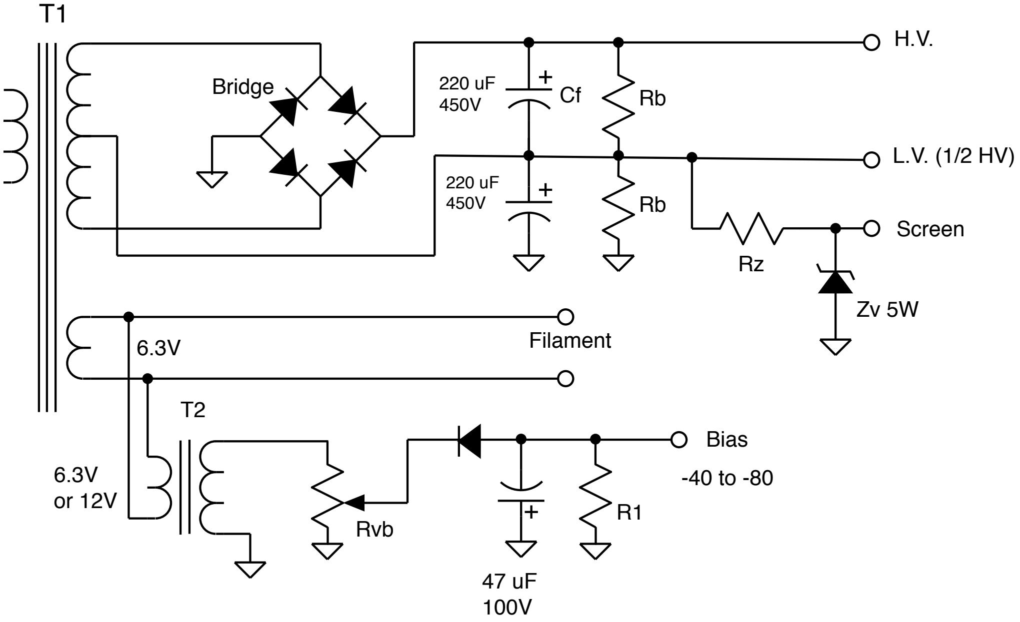
between the cathode and the plate, eliminating most capacitive feedback and usually eliminating the need for neutralization. It requires considerable driving power.

Since the input and output circuits are in series, a certain portion of the input power appears in the output circuit; the driving power is added to the output power. A grounded-grid stage doesn't necessarily mean that it has to use a triode. There are many tetrodes and pentodes that can be configured in a grounded-grid configuration simply by grounding all the grids. Many amplifier designs have appeared in QST using an 813 configured as a grounded-grid thermatron for example.

4. Design the Power Supply

Seems to me that in the design of older novice and entry level thermatron transmitters, that the power supply was an afterthought. Supplies were routinely under rated for the transmitter thermatron, used a minimum of parts to keep costs low, used small gauge wire in the transformer, etc. The result was a big "key-down" voltage drop with a lot of ripple. They also suffered from no bias supply, screen voltage derived from a series resistor to the HV, and distortion due to the amplifier thermatron operating voltages shifting all over the place.

If you are going to the trouble to build a well designed amplifier, don't short-change yourself by building a crummy power supply. An amplifier's signal quality is only as good as the power supply permits. The power available from the supply determines whether the amplifier can meet its intended output power and should be rated for at least 1.5 times the output power of the amplifier.



I'm going to short-circuit some of the design tradeoffs between full-wave, half-wave, capacitor input, choke input, and recommend a supply design that I like. This supply will provide amplifier thermatron HV, a "LV" supply for other input stages if necessary, a screen voltage supply, and a separate bias supply. You need the bias supply, trust me.

Two options on the power supply design. You can either start with a known power transformer and derive the operating voltages and currents for the amplifier, or you can start from the desired operating voltages and currents for a particular amplifier thermatron and work backwards to the transformer.

In a capacitive input bridge supply, the output voltage from the supply will be approximately the transformer HV secondary voltage x 1.3. This assumes that the series resistance of the secondary HV winding of the transformer is 10% or less than the power supply load, RL, (including the bleeder resistors).
So if you want to use a 6146 for example and run it at 600 volts, you would need a transformer with a HV secondary of 460 volts RMS minimum.

Make sure the screen supply is derived from the plate supply. Screen voltage should never be applied to a tetrode unless plate voltage and load also are applied; otherwise the screen tends to act as an anode and will draw excessive current. The screen supply should be regulated separately from the HV supply.

A new 600V, 230ma, Hammond Manuf. power transformer. Retail is about $74.

If you are working backwards from a transformer or an existing power supply, the following table will give you a ballpark idea of what thermatrons are best suited to what voltage.

Vp	**300-500**	**500-750**	**750 - 1200**	**1500 - 2000**
Thermatron	2E26	6146 807 6DQ5 6LF6 6HF5 6LW6 etc.	807 811A 572B 4-65	813 4-125

A capacitor input filter draws current peaks during each half-cycle to charge the capacitors. This current peak adds considerably to the RMS transformer secondary current. A good approximation is 1.5 times the required load current. For example, if the amplifier needs 140 mA of plate current, the transformer HV secondary should be rated at 210 mA.

Transformer T1 is the most important part of the supply and the most expensive. Excellent, brand new, power transformers are available from Hammond Manufacturing.

Rb = Bleeder resistor. Used to help stabilize the supply voltage and to remove the filter capacitor charge when the supply is turned off. A good value is 100 ohms per volt (across resistor). For a voltage of 300 volts:

100 x 300 = 30K ohms 3W

Cf = filter cap. Make sure 6.28 x Cf x Rl is 50 or greater. (F = Cf in farads, RL = load resistance). 100uF is a good value.

The regulated screen supply uses a zener at the required screen voltage. The 1N53xx series is available up to 200 volts in 5W packages.

Rz = (LV - Screen voltage) / (1.2 x screen current)

T2 furnishes bias voltage and can be a 120V to 6.3 or 12V small filament transformer. Rvb adjusts the bias voltage on the amplifier grid and can be a 25K 2W if using a 6.3V transformer or 210K if using a 12V transformer. R1 is an optional load resistor that is used for class C amplifiers where grid current is drawn. 10K is a typical value.

ADDITIONAL HV SAFETY TIPS

When you turn the HV supply on, make sure you are not touching ANY part of the transmitter circuit. If you make voltage measurements, connect the negative lead from test equipment BEFORE you turn on HV and use only one hand to place the HV lead. Keep the other hand in a pocket or behind your back. Treat HV circuitry like you would a poisonous snake!

After you turn HV off, give filter caps awhile to discharge, Never use a power supply that does not have bleeder resistors across the filter caps. Always short any HV point (plate cap, plate chock, etc.) to ground before touching anything.

5. Design the Thermatron Operating Conditions

Once you have a thermatron in mind, a basic configuration, and the class of service, the next step is to determine the thermatron operating conditions. You will need to determine:

The HV (Vp) (nominal power supply output voltage)

The screen voltage (Vs)
The control grid bias for the class of operation (Vg1)
The plate load resistance Rp
The expected power out Po
The required driving power/voltage for max power out

You should already have determined the HV and max plate current from the thermatron data for your class of service for the power supply design. The actual HV output of the supply is the design thermatron HV.

The RCA Transmitting thermatron manual gives typical values for class C RF amplification and usually class AB2 (sometimes for AF amp assuming push-pull operation). These values will work fine for RF applications. If you are using a single thermatron, you will just divide the current values by two for single thermatron operation. The data below was taken from the RCA Transmitting Thermatron manual (TT-5) for a 6146.

6146	**Class AB1**	**Class C**
DC plate voltage Vp	600	600
DC plate current Ip	0.115	0.112
Screen voltage Vg	180	150
Max screen current Is	0.014	0.009
Control grid bias	-45	-58
Plate load resistance Rl	3000	not given (5700 calculated)
Max plate dissipation	25	20
Max power out Po	42	52

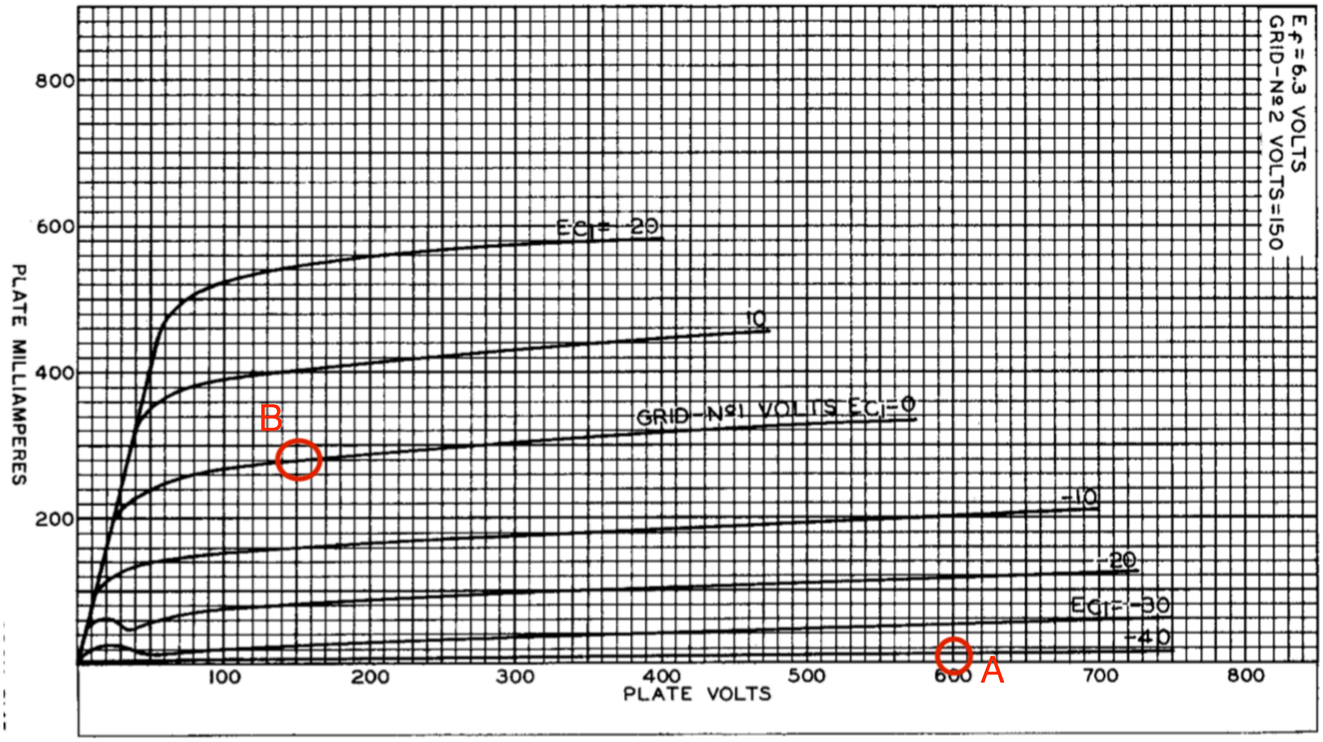
Screen voltage (Vs)
The screen voltage of a tetrode has a significant effect on the static plate current because the plate current of a tetrode varies approximately as the three halves power of the screen voltage. There is usually a screen voltage given in the thermatron data for a class of service and a Vp. This is a good place to start.

Most common transmitter thermatrons have at least a set of plate characteristic curves, usually at one or maybe two screen voltages. These curves can also be used to determine the grid bias for the class of operation and can be used to verify bias and plate voltage swing for a given plate load resistance.

If the values you need are not given or you want to check what is given, you can do your own calculations. To set the initial bias for AB (1 or 2) service, a good rule of thumb is to choose the bias point that will produce about 1/3 to 1/4 plate dissipation. Bias determined in this way will usually produce good linearity.

For the 6146 for example, multiply the plate dissipation by .33 to get resting plate dissipation.

0.33 x 20 watts = 6.6 watts



6146 Plate Characteristics Curves for a Vs of 150V.

Find the resting Ip by dividing resting plate dissipation by Vp.

6.6 watts / 600 volts = 11 ma

Now find the bias that produces this resting Ip for the operating Vp on the characteristic curves. In the case of the 6146 curves, it is hard to make out, but it looks like at least -40V. (point A in the diagram) This is close to “book” value.

If you want to operate class C, the data sheet shows that you will need anywhere from -77V to -87V volts bias which is well beyond cutoff.

You can calculate most of the remainder of what you need to know with a few simple calculations. Next determine the maximum input power.

If efficiency is say 60% (AB), that means 60% of the total power is output to the load , so the 40% power loss is lost as plate dissipation. This must equal the max plate dissipation. Therefore max input power = max plate dissipation / .40

For the 6146 max input power = 25 / .40 = 62 watts

Calculate max signal Ip = max power input / Vp = 62 / 600 = 103 ma

max power input / Vp = max signal Ip

max peak plate current Ipmax = max signal Ip x (2.75 for AB, 3.14 for B, 4.0 for C)
or .103 x 2.75 = 284 ma.

Now find the grid voltage that will produce max peak plate current to the right of the knee of the curves. In this case I chose 150 volts (point B on the curves). This will now give us the max grid voltage swing of 40 volts, and the max plate voltage swing 450V and max Ip swing (about 220 ma).

Power output is now equal to

Po = .78 (Vp - Vpmin) x Ipmax
Po = .78 (450) x .230 = 81 watts.

This shows us that to get that 81 watts output, the grid will need to swing from its resting -40V to 0V or a positive swing of 40 volts on the input driving signal. This means the input signal to the grid will need to be 80Vp-p to get the 40v positive swing.

There are a number of different way to calculate the required plate load resistance.
The one I use is plate load resistance = 1.3 (Vp - Vpmin) / Ipmax = 1.3 (450) /.284 = 2060 ohms.

This is everything you need to know to establish the thermatron operating conditions

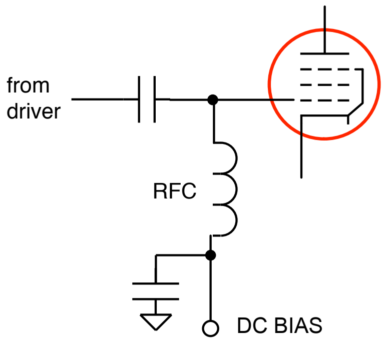
Grid Bias Methods

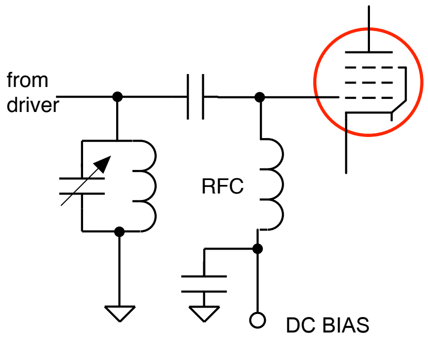
If you are going to design a descent amplifier, don't waste your time with biasing the thermatron using a cathode resistor or, worse, a grid leak resistor. A stable amplifier needs a stable bias if you are going to keep distortion to a minimum.

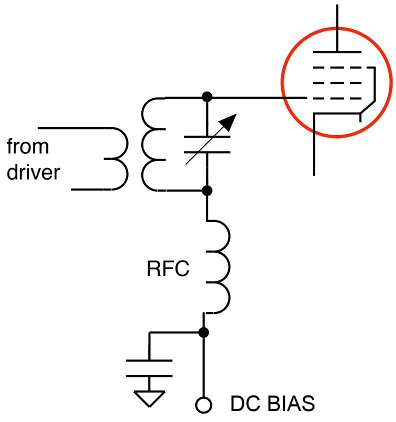
When we discussed the power supply design, we incorporated a variable bias supply that is capable of the much higher negative voltages needed for power thermatrons. It just needs to be adjusted under no signal conditions for idling plate current in the case of AB operation or cutoff and proper conduction angle for class C. This negative bias will protect the thermatron if there is no signal source.

6. Design the Grid Input Coupling Circuits

If the amplifier is operated so it doesn't draw grid current (Class A, AB), then the load on the driving stage is a very high impedance and almost any coupling from the driver stage to the control-grid can be used, even just a single capacitor coupling. The circuit on the right can provide a voltage step-up function for the driving signal.

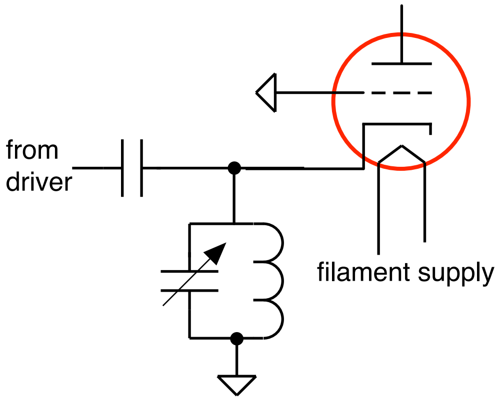


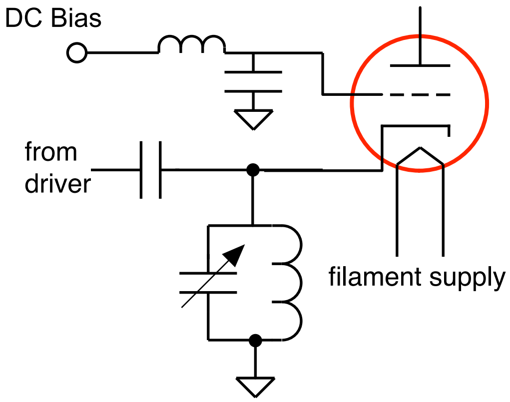




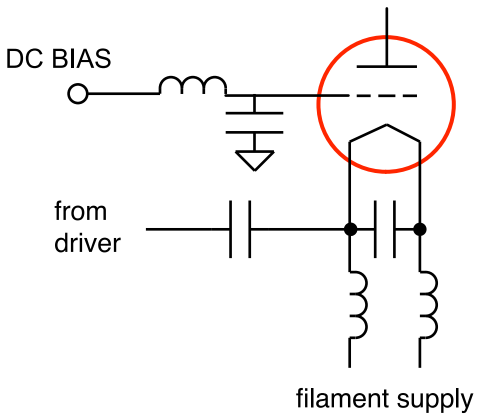
Grounded-Grid Cathode Circuit

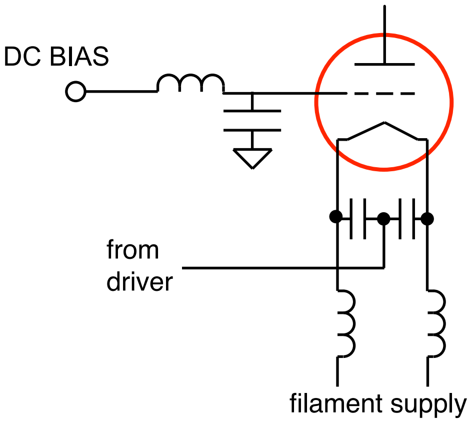
The figures below show typical cathode drive circuitry for ground-grid amplifiers with indirectly heated cathodes. The majority of grounded-grid designs use a medium to high mu or zero-bias triodes. The input to the cathode is a low impedance and considerable drive power is required. As stated earlier, the input power is added to the thermatron amplification power so little is actually lost in the input circuit. The diagrams below shows two situations using a zero-bias triode on the left and a more conventional biased triode on the right. The two circuits differ only in the grid bias technique. The driving signal is coupled directly to the cathode using a tuned input circuit.





The schematics below are similar for filamentary type thermatrons such as the 811A. The input signal is coupled directly to the filament using coupling capacitors.



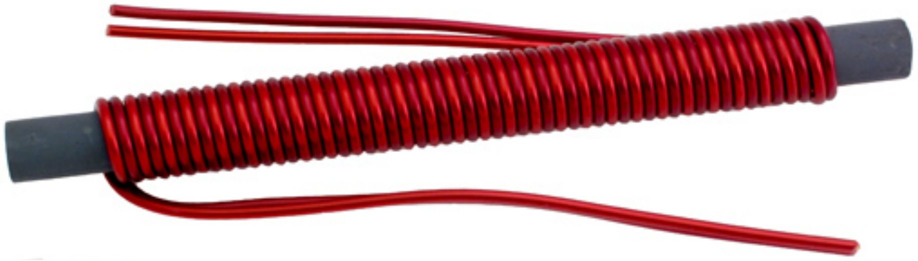


This technique, while widely used, is not the best solution due to the change in impedance throughout the input signal cycle. There should be at least a tuned circuit on the input to the thermatron.

Since the filament is acting as the cathode, there will need to be a high impedance filament choke between the filament connections and the filament transformer to isolate the input RF from the filament transformer.

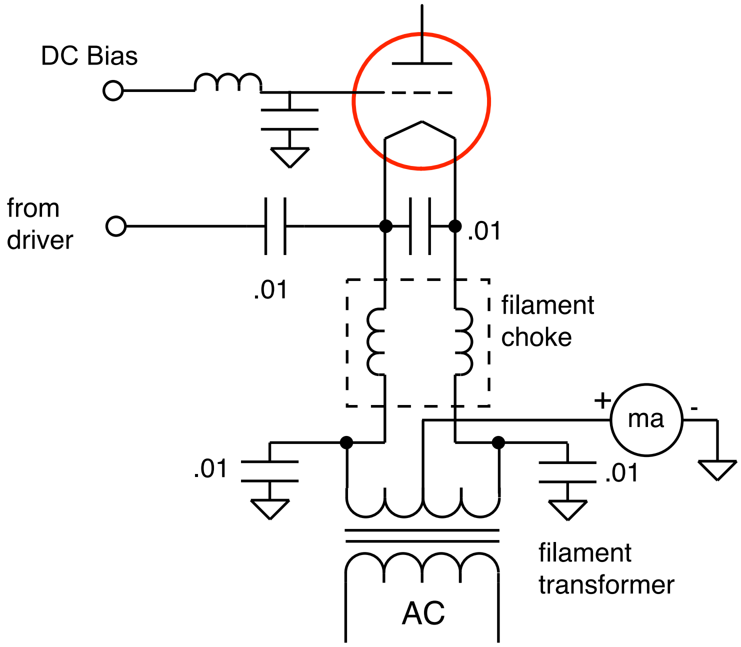
Filament Chokes

The choke most commonly used in this application is a pair of heavy-gauge insulated wires, bifilar-wound over a ferrite rod. The ferrite core raises the inductive reactance throughout the HF region so that a minimum of wire is needed. The bifilar winding technique assures that both filament terminals have the same RF potential



The choke (or chokes, one for each leg) needs to have a high impedance at the RF working frequency of the amplifier and should be at least 10 times greater than the input impedance of the amplifier. Since the input impedance is usually between 50 - 200 ohms, the impedance of the choke should be in the 500 to 2000 ohm range from 3.5 up to 30 MHz.

A center-tapped filament transformer typically powers the filament, as in the schematic below. The center tap is connected to ground and is a good place to put the plate current meter although in the case of a tetrode it also measure the plate and screen current. The transformer legs should be bypassed at each leg with a low impedance cap.



7. Decide on the Output Tank Coupling Circuit

The function of the output coupling circuit is three fold,

1) to act as a tuned circuit filter to remove harmonic content,
2) to provide a plate current “flywheel effect” for plate conduction less than 360 degrees, and
3) to match the output impedance of the thermatron to the attached load.

To correctly couple a tuned RF power amplifier to its load (the antenna or antenna feed line), two requirements must be satisfied:

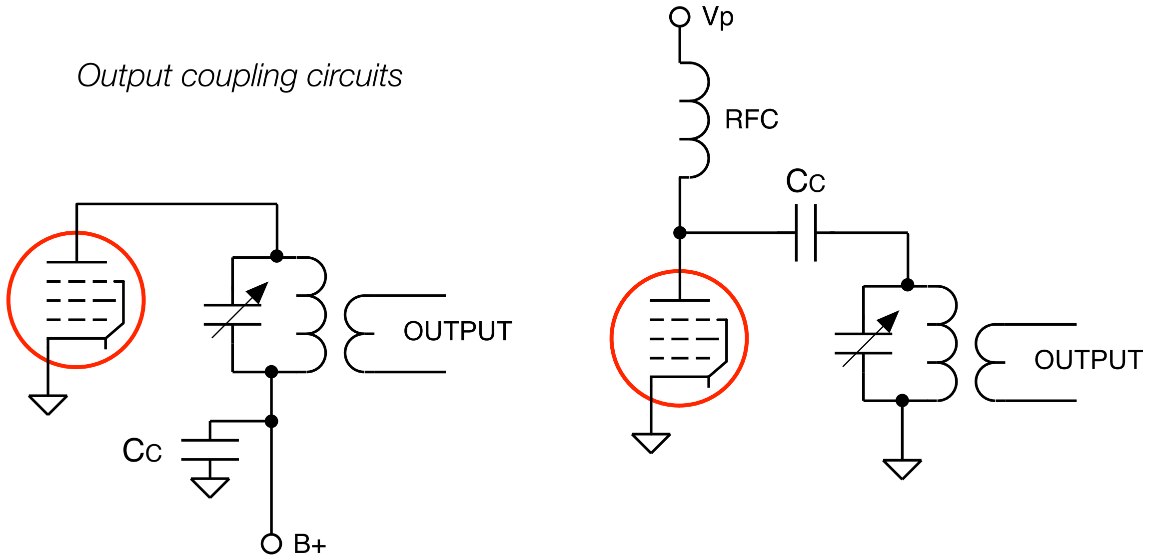
1. The correct load resistance, which will enable the amplifier to deliver its rated power, must be created by the coupling circuit to the amplifier thermatron.

2. The loaded Q of the coupling circuit must be correctly designed. Plate current in a class AB, B, or C amplifier does not flow for the complete cycle of the RF waveform. The waveform is maintained by the current inertia of the tuned output circuit. Too low a Q will cause waveform distortion and increased harmonics. If the Q is too high, it causes excessive power loss in the circuit. A loaded Q of 10 to 12 is considered a good target value.

Link Coupling

In the old days most power amplifiers used **link coupling.** This consists of a L/C tuned circuit as the amplifier thermatron load. A link consisting of a few turns of coil connected to the antenna feed line is coupled to the tuned circuit coil. The turns on the link and the turns on the tank coil constitute an impedance transformer to the amplifier thermatron. The load resistance across the link coil is transformed into the primary circuit to produce the load for the thermatron. While this technique has been largely replaced by the Pi network output circuit, there is nothing wrong with link coupling and for low power and small transmitters, it is still a good solution. Two examples are shown below.

Output coupling circuits



Series tank coupling

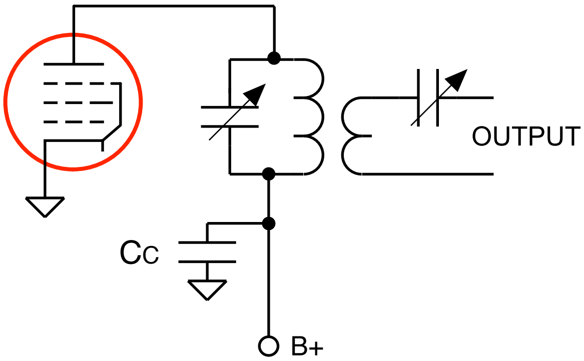
Parallel tank coupling

Series vs Parallel Tank Circuits

The circuit on the left has the resonate “tank circuit” in **series** with the power supply DC current. This is very simple and is used often in receiver and transmitter low power amplifier stages. The disadvantage is a practical one; high voltage is placed on the tuned circuit components. The tuning capacitor must be physically isolated from ground and operators.

The circuit on the right has the resonant circuit in **parallel** with the power supply. The RF is coupled to the tank circuit through Cc and DC current is passed through RFC to the power supply. This has the practical advantage of allowing both the tuning capacitor and inductor to be connected to ground, removing a substantial shock hazard. However, the disadvantage is the addition of two components, the RFC and coupling capacitor. Selection of these components is not trivial since they have a big effect on the amplifier operation. More about these components shortly.

The tuning capacitor and inductor in the tank circuit must be selected for the correct reactance at the frequency of operation. The reactances for the circuit L and C are



$XL = XC = RL/Q$ where Q = loaded Q (typically 10 - 12) and RL is the required thermatron load resistance. Capacitance and inductance are calculated then using the usual formulae:

$C = 10^6/(2\pi fXc)$ pF
$L = X_L/(2\pi f)$ µH   where f = frequency in MHz

The number of turns (Np) on the primary coil of the output transformer is set by the inductance calculated. The secondary link coil turns are

$Ns = Np\sqrt{(Ra/RL)}$ where Ra = antenna or transmission line load resistance.

If using an air wound coil for the primary and secondary (like an airdux) the coupling coefficient is lower and more secondary turns than that given by the previous formula are required. The degree of coupling can be adjusted by either taps on the the coils or by varying the spacing between primary and secondary. Adjustment is usually done by initially resonating the tank circuit with the secondary loosely coupled and then gradually increasing coupling and re-resonating for maximum output. Resonance is indicated by a pronounced dip in plate current while adjusting the capacitor.

Tuned Link Coupling
An alternative is the tuned link. Tuned link coupling adds additional selectivity thus reducing harmonics and allows for a more efficient power transfer to the link. The Q of the link tuned circuit can be as low as 2. The link capacitor is adjusted for maximum power transfer

As in the simple link, the load resistance of the link circuit is transformed into the primary circuit to produce the load for the thermatron.

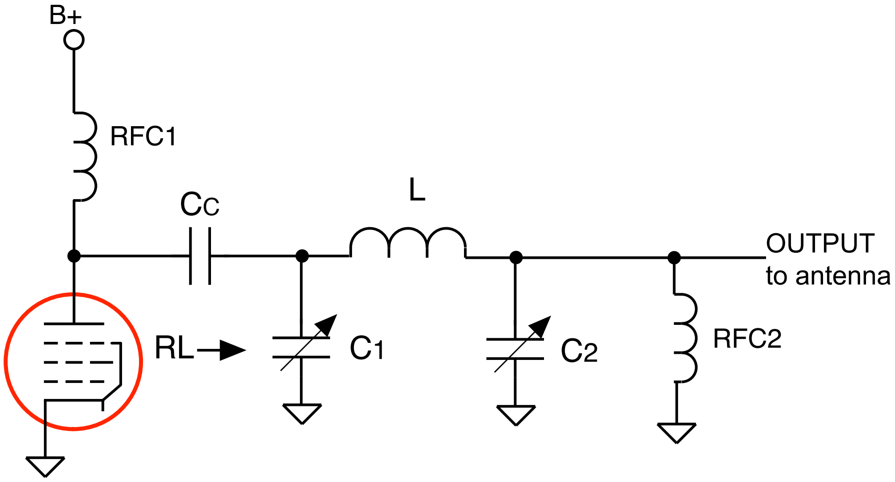
The table below provides values of capacitance and inductance that will produce a link circuit with a Q of 2. The link should be wound so that when it is lightly coupled to the amplifier tank circuit, the anode current of the thermatron rises as the link tuning capacitor is tuned through the value specified in the table. Once the coil has been adjusted to produce this condition, the link capacitor should be left at the value which produced the peak in anode current of the PA. The link coil should be moved close to the ink coil until the desired degree of loading is obtained. Due to the low Q of the tuned link, fairly tight coupling between the link and the tuned circuit will be required

Amateur Band	Tank C value	Tank L value
3.5 MHz	450 pF	4.6 μH
7.0 MHz	230 pF	2.3 μH
14 MHz	115 pF	1.12 μH
21 MHz	80 pF	0.7 μH
28 MHz	60 pF	0.5 μH

Pi Network Coupling

The pi-network circuit gets its name from the fact that the circuit topology sort of resembles a pi symbol. It consists of a “tuning” capacitor C1, an inductor L, and a “loading” capacitor C2. More on that shortly.

The pi-network has a significant advantage over the parallel tank circuit; it functions as a very effective low-pass filter. Capacitors C1 and C2 should be mounted directly to the chassis with C1 close to the amplifier thermatron. The ground connection between C1 and C2 will carry the full circulating current of the network so it should be isolated from input stages to the amplifier.



The pi-network is actually two L-networks, back-to-back. C1 and 1/2 of L constitute an input L-network that transforms the thermatron load resistance to a low value. The other side (1/2 L and C2) forms an output L-network that transforms the low impedance from the input L-network to the antenna load.

C1 is usually referred to as the TUNE capacitor since it tunes the input L network to resonance at the frequency of the amplifier. C2 is usually referred to as the LOADING capacitor since it matches the output L network to the load reactance.

Transmitter output pi-networks are typically designed with a Q in the 10-12 range but it's not critical. This value is a compromise between the need to suppress harmonics, requiring a high Q, and circuit efficiency which is best at a low Q.

You can calculate the values of C1, C2, and L yourself with the following formulas assuming a Q of 12. These formulas give the reactance value of the components which you can convert to an actual capacitor and inductor value using reactance formulas for the desired frequency of operation:
Rp = required amplifier thermatron plate load
R_L = output load impedance

$$XC1 = Rp/12$$
$$XC2 = \mathrm{Sqrt}\left(RpR_L / (145 - (RpR_L))\right)$$
$$X_L = (12Rp + (RpR_L/Xc2))/145$$

Or you can do what most do and go to an online p-network calculator. A nice one:

https://home.sandiego.edu/~ekim/e194rfs01/jwmatcher/matcher2.html

Selecting the RFC Plate Choke

A plate choke and coupling capacitor will be required if the amplifier is designed for parallel connection of the output tank/coupling circuit. The common misconception is that the plate choke merely serves to isolate the DC supply from the RF signal at the plate and the current going through it is purely DC. In fact, some of the energy of each RF cycle is stored in the plate choke and delivered to the output tank during the time when the amplifier thermatron is not conducting, so its operation and value plays an important role in amplifier efficiency. The plate choke can supply up to one-third of the energy required each cycle to the tank circuit. Therefore, the plate choke value should always be above a minimum critical value to ensure maximum energy transfer to the tank circuit.

Dave Gordon-Smith, G3UUR in a June 2008 article in Electric Radio magazine article, calculates that the minimum, or critical, value for a plate choke at a given operating frequency is:

Lcrit (μH) = 0.25 Rp / F (F=operating frequency in MHz.) for class B or AB

Lcrit (μH) = 0.33 Rp / F for class C

For example, in a class C amplifier, if the lowest operating frequency is 3.5 MHz, with an optimum thermatron plate load of 3000 ohms, Lcrit = 0.33 x 3000 / 3.5 = 282 μH.

All inductors, due to the distributed capacitance between coil turns, have self resonance and will behave like a parallel resonate circuit, which means that at that frequency, circulating currents within the coil will be at a maximum, and could potentially overheat and destroy the coil.

It's a good idea to test a potential choke for resonance with a grid-dip meter or vector analyzer prior to using it. Also, keep the choke away from metal parts of the amplifier when mounted to prevent stray capacitance from altering it's resonance frequencies.

Selecting the Coupling Cc

It is a good idea to set the minimum value of Cc so that the voltage variation across is no more than 10% of Vp. Therefor, a minimum value of Cc is

Cc min (pF) = 11 Po / (Vp^2 F)   F in MHz, Vp is kilovolts, Po is output power

Anything from the minimum value up to 10 - 20 times that value can be used.

For example if P0 is 100 watts, Vp = 500 volts, lowest frequency is 3.5 MHz
Cc min = 11x100 / 0.5^2 x 3.5 = 1257 pF
So a practical value would be at least 10 times that or 0.013 μF

The other critical specification is the voltage rating. Since high SWR values of the antenna load can cause very high voltages in the output network, these high voltages can appear across the coupling capacitor. My rule of thumb is to select a voltage rating of four times Vp. If the Vp is 500 volts, you would want to use a Cc rated at 2KV.

8. Determine any Neutralization and Parasitic Suppression

All amplifier circuits are subject to some form of instability, meaning that the amplifier may generate RF oscillations at its tuned operating frequency, or at a much higher (usually VHF) "parasitic" frequency. It is caused by positive feedback from the plate circuit to the grid circuit usually through the grid-to-anode capacitance, but capacitive coupling due to poor component layout can also contribute. The amplifier operates as a tuned grid, tuned plate oscillator.

Neutralizing Tetrodes

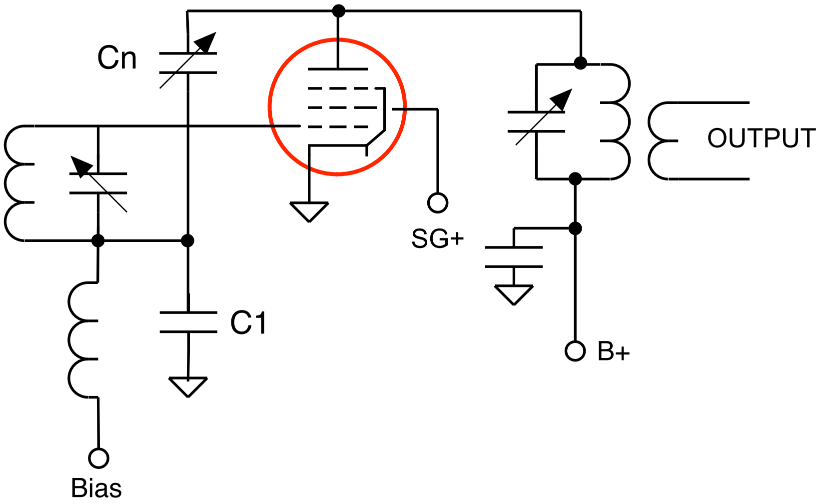
Although screen-grid and beam-power thermatrons are inherently more stable than triodes and may in some cases be used without neutralization, it's a good idea to design it in anyway. The grid circuit's high gain and high impedance in a grounded cathode amplifier means it doesn't take a lot of feedback to create an oscillator.

The first step in preventing HF instability is in the construction of the amplifier, especially the grid circuitry. It has to be physically and electrical isolated from the anode circuitry. Amplifier manufacturers usually put anode circuitry above a metal chassis and the input grid circuitry below the chassis, or they isolate anode circuitry inside a metal enclosure with capacitive feedthrough connections for filament, bias, and HV supplies.

The second step is neutralization. This is the technique of intentionally feeding some of the output signal back to the input out of phase. This cancels the positive feedback that occurs between the plate and control grid of the thermatron. Feedback can be accomplished with link coupling, using a transformer, or capacitive coupling. Capacitive coupling is usually used since it is easy to install and easily adjustable.

Even through the grid to plate capacitance of a power tetrode is very small, the power sensitivity of these thermatrons is so great that only a minimal amount of feedback is necessary to start oscillation.

A common capacitive neutralizing circuit for power tetrodes is shown below. Cn is the neutralizing capacitor. The feedback voltage is usually taken from the anode tank circuit and connected to the grid input circuit through Cn. The capacitance should be chosen so that at some adjustment of Cn, the amount of negative feedback exactly cancels the positive feedback. This is used to cancel out or neutralize the internal positive feedback inside the thermatron and from stray capacitance. Cn is usually in the range of 5-20 pf.



Capacitor Cn and C1 in the diagram form a frequency independent capacitive voltage divider that reduces the amplitude of the anode voltage. The ratio of Cn and C1 should be approximately the same as the ratio of the grid-to-plate capacitance and the grid-to-cathode capacitance.

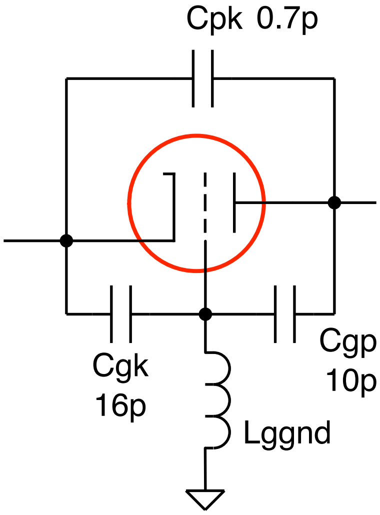
Cn / C1 = Cgp / Cgk

for example, if we were neutralizing a 2E26, it has a Cgp of 0.2 pF, and a Cgk of 13 pF
Cgp / Cgk = .015
If I use a 10 pF variable capacitor for Cn, then C1 should be about 10 / .015 or 666 pF or 680 pF rounded up.

Note that both sides of Cn are above ground for DC and RF so it must be mounted on a standoff insulator, even if it has an insulated shaft. Since one side of C2 is connected to B+ and the other to negative grid bias, adjustments to C2 must be made very carefully to avoid shock or shorting out the plates of the capacitor.

Neutralizing GG Tetrodes

While GG amplifiers are certainly more stable, problems can occur at higher HF and low VHF frequencies when the grid is not RF grounded, but has an impedance to the RF due to poor construction.



The diagram above illustrates the problem. Cgk and Cgp are the internal grid-to-cathode and grid-to-plate capacitance. In a GG amplifier, assuming it is properly constructed, they are connected to ground and their series combination is not enough to allow feedback. However, as the operating frequency is increased, the internal grid wire (from grid to pin), plus the thermatron socket, plus the leads leading to the socket can form enough inductance to “unground” the internal capacitances, allowing enough feedback to cause oscillation. This is more of a problem with the large glass power thermatrons with long internal leads such as the 811, 833, 807, etc.

The solution to preventing oscillation is to use good construction techniques. Make sure the grid circuit is as non-inductive as possible and the leads to any connected capacitors is as short as possible. 1/2” may be too much. Use very short large gauge or metal strip for connections. If a bias supply is connected to the grid, make sure the leads to any connected capacitors are as short as possible. 1/2” may be too much.

Parasitic Oscillation and Suppression

All amplifier circuits, tetrode or triode, are subject to parasitic oscillations; oscillations that occur at a frequency well above the operating frequency, typically at VHF. Two conditions are necessary for parasitics: sufficient feedback from anode circuitry to grid circuitry, and self-resonance at the parasitic frequency in some part of the feedback path.
Neutralization is not effective in preventing parasitics.

Feedback is usually caused by poor circuit layout, long, thin wires, and high impedances in the signal path due to long leads. Thermatrons with thin and long internal leads can be a real pain. In general, a beam-power tetrode amplifier stage is more susceptible since it has a much higher gain than an equivalent triode amplifier, such a stage also has a certain amount of screen-lead inductance that can make matters worse.

Curing Parasitics

The easiest cure for parasitics is to create a resistive loss at VHF frequencies in the feedback path. This can be done by use of a parasitic choke in the plate and/or grid leads of the amplifier. This “parasitic suppressor” is constructed from a parallel coil and resistor combinations.

In operation the resistor loads the parasitic circuit path but is shunted by the coil for lower operating frequencies. The VHF parasitic sees the coil as an impedance that is much higher than the resistor and is attenuated by the resistor. The operating frequency, being much lower, sees the coil as a much lower impedance than the resistor and is not attenuated, neither, in practice, does it dissipate any power in the resistor.

The choke is usually made from a non-inductive resistor shunted by three or four turns of wire, approximately a half-inch in diameter and wound over the body of the resistor (more about this shortly). For medium power levels a 47 ohm 2 watt composition resistor wound with 4 turns of no.18 wire is commonly used. For kilowatt levels up to 30 MHz, 3 220ohm 2 watt resistors with 3-4 turns of no.14 wire should work.

It can be placed in the cathode, grid, or plate lead of the amplifier thermatron, but in practice it’s usually in the plate lead. Either way it should be placed as close as possible to the thermatron.

Collins Radio used a parasitic suppressor in both the grid and plate leads of the 6146’s in the S-line transmitters and transceivers. If the amplifier draws limited grid current, a resistor without the coil can be placed in the grid lead (this was done in the Collins 30L1). Values from 47 to 100 ohms should be effective.

If the resistor runs too hot, it means the coil inductance is too high at the operating HF frequency. Remove a turn on the coil. Just enough turns should be used to suppress the parasitic oscillation, and no more.

Many amplifier home builders recommend keeping the resistor(s) and coil separate because if the coil is wound around the resistor, the magnetic field around it could cause heating of the resistor material.

9. Determine the Cooling Requirements

Most class thermatrons in the under 100 watt catagory are designed for convection cooling and should be fine if there is adequate air circulation around the thermatron. If you want to install them in some metal box hoping to avoid any RF radiation from the thermatron or output coupling circuit, make sure you use highly perforated metal. The photo above is from a Collins 32S transmitter with two 6146s in the final cage. Many transmitters from this era were built very similar. This type of decorative metal is usually available from home supply stores and hobby shops by the sheet. Notice that there is no forced air cooling but if I were building a similar amp I would install some kind of fan.

As long as they are in the open, the larger glass RCA 800 series will work fine with convection cooling. The larger glass Eimac series (3-400, 4-400, 3-500) if used in anything other than very intermittent service, will need some form of forced air cooling. Most commercial amplifiers use a pressurized chassis. This was discussed in more detail in Chapter 7, Power Thermatrons.

10. Design the Control Circuitry

Most amplifiers will need some form of TRANSMIT/RECEIVE changeover circuit. The circuitry should incorporate a T/R relay to bypass the amplifier on receive. The other requirement is to shut the amplifier thermatron off during receiver. This is usually done by increasing the bias on the control grid thermatron to an Ip current cut-off condition. This can be done with the following circuit.

There is an antenna change over relay (two pole, double throw) to handle the signal bypass function and there is a relay (could be the same relay) that needs to handle the bias changeover during receive. During standby the Kc relay opens the ground end of the bias potentiometer which will put the full negative voltage of the bias supply on the grid which will cut the thermatron off. If the thermatron is run in class C, it is probably already cut-off so no relay would be needed.

Steps 11 and 12 are covered in the example below…

Amplifier Design Example

My goal in this design example is to build an amplifier that incorporates the design steps described in this chapter and is relatively straightforward using an easy-to-find thermatron. I tried to keep it easy to duplicate to allow you to experiment with the design. But I wanted something practical that I can use in the shack, so I decided on a single band (20M) stand alone SSB (or CW) amplifier with a rough power output of 50 watts PEP when driven by a 5 watt QRP rig. It also needed to use a common thermatron that I had in my highly organized inventory (junk box).

1. Decide on a thermatron type and desired output level
To keep it simple I chose a 6146 since I had several good spares and it can easily handle the 50 watt output. The 6146 is relatively inexpensive, easy to find at hamfests, and hard to screw up. I want to build another version using the 811A triode in grounded-grid. I will put that up on my blog (kj7um.wordpress.com) later.

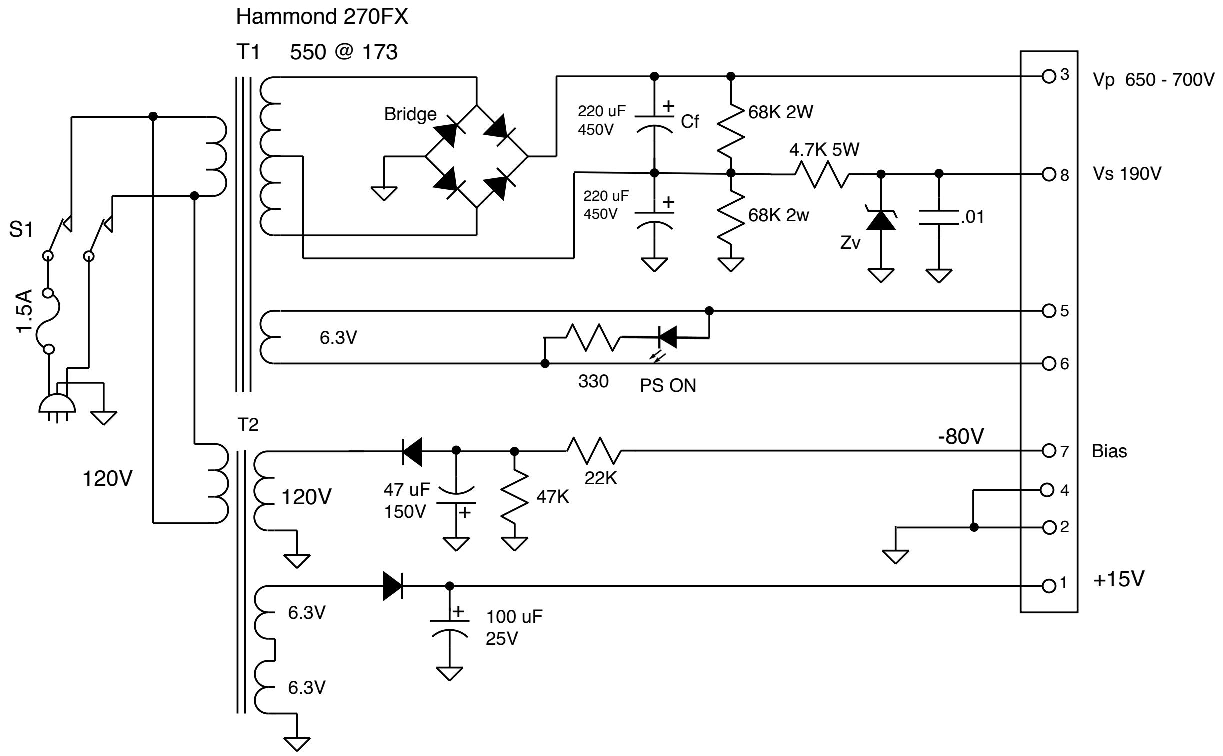
2. Decide on a class of operation
Since I want to use it to amplify the output of a SSB QRP rig, it will work best as class AB1. Later I will redesign it for CW operation as class C.

3. Decide on a basic circuit configuration (grounded-grid, grounded-cathode)
Since the 6146 is a beam-power tetrode, and I need good gain for that 5W input, classic grounded-cathode is the way to go.

4. Design (and build if possible) the power supply
This is usually a bit of a back and forth design process, starting with a ballpark estimate of what the amplifier thermatron will need to produce the desired power output, in this case, around 50 watts. The RCA data book shows a Maximum DC Plate Voltage of 750V for ICAS operation (I assume this is a bit conservative since my Collins 32S-3 runs a pair of 6146s with an 800V plate supply). The typical operating plate voltages run from 400V to 750V, with 600V on average. So I need to find an HV transformer with a secondary in that range that can supply the amplifier peak current at 50W peak output.

Assuming about a 60% efficient amp, and 25W max plate dissipation, I need 125 ma. from the transformer. Also assuming a bridge rectifier into a capacitive input filter, the secondary voltage, to get about 600V out, is 600V/1.3 = 460V. The 6146 will run, with a little less output, down to 400 Vp, so a transformer in the range of 325 - 500Vrms will work fine.

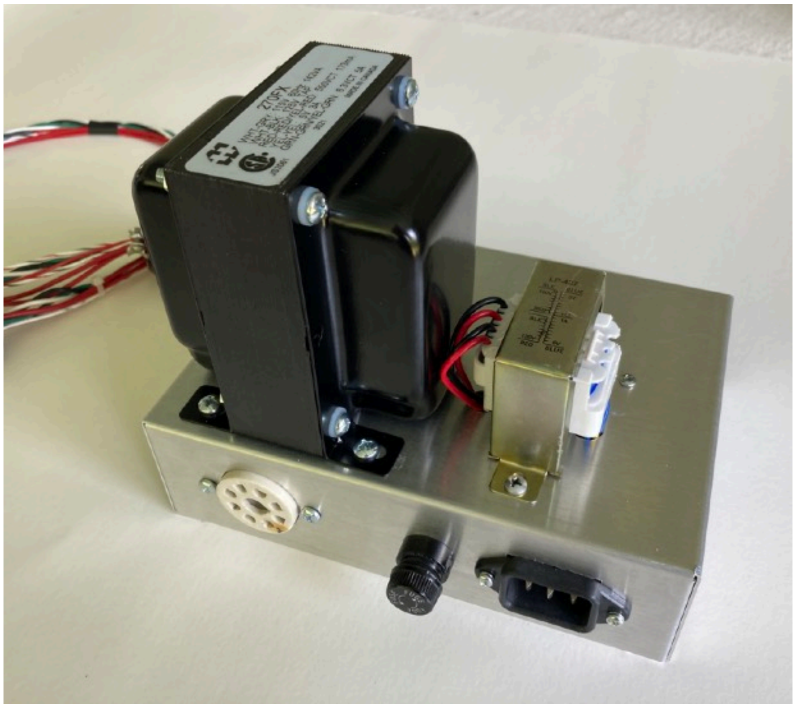
I have a bunch of old power transformers, but unfortunately nothing that high. A search of eBay turns up nothing close. Dayton Hamvention is too far away. So looks like I'll have to buy one (ouch). I found a new Hammond 270FX at 550 volts at 173 mA. That should give me 715ish volts out, so I may have to scale it down a bit. I am going to



assume 650 - 700 volts on the plate. It also supplies 6.3V at 4A for the filament and a leftover 5V supply intended for thermatron rectifiers.
I will also need a regulated Vs supply of around 180 - 200V at 10-15 mA. I can get this from the HV supply. And a bias supply from about -75V to cut the 6146 off to -40ish during transmit. As you saw earlier in this chapter, I may need another small transformer for this. My preliminary design is shown on previous page.

Notes:
Zv: 1n5387 190V 5W zener diode
T1: Hammond 270FX HV transformer (online from many sources)
T2: M.P. Jones LP-487 (mpja.com)

This is my preferred design I introduced earlier, adjusted for the Hammond transformer. I added an inexpensive transformer from Merlin P. Jones (LP-487) that has two 120V primaries and two 6.3V secondaries at 1 amp. I used one of the primaries for the bias supply and the 6.3V windings to make a DC supply for an antenna change-over relay. Now that I have the plate supply selected, I can get the rest of the 6146 operating parameters.



The separate power supply chassis (power switch on the other side). All voltages are brought out to the 8-pin connector. A cable is used to connect it to the amplifier.

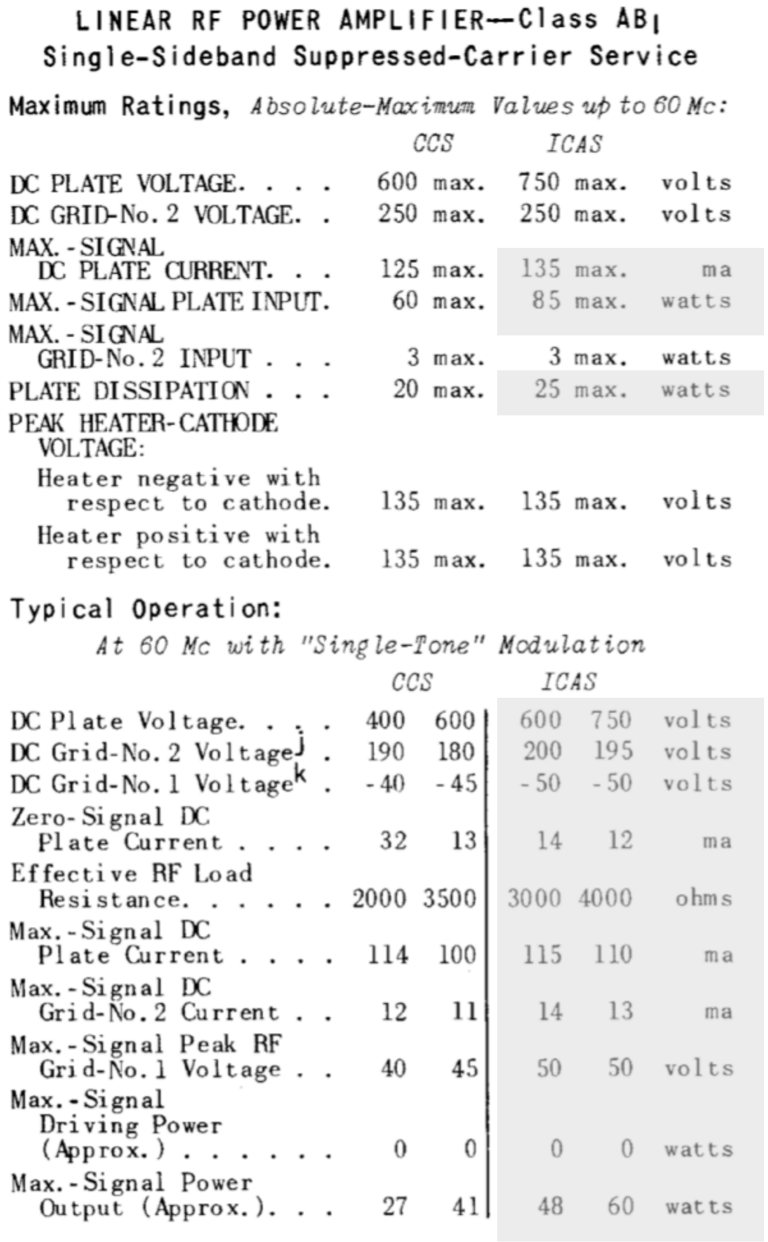
5. Design the thermatron operating conditions

I found a data sheet on the internet for the RCA 6146 that has operating parameters for class AB_1 SSB amplifier service. It is shown below with the parameters of interest highlighted.

I am not too concerned about the max signal plate input because SSB is such a low duty cycle service that plate dissipation will hardly exceed the 25 watts max rating, but it should be observed during tune up conditions. From this data, I extracted the following operating conditions.

Vp = 650V
Vs = 190
Vg1 = -50 bias
Ip zero signal = 13 mA (resting)
Max Ip = 115 mA
Max signal Ig2 current = 14 mA screen current
R_L = 3500 ohms

The preliminary bias voltage will be set to get about 13 mA current under no signal conditions. The final setting will be done with a spectrum analyzer to provide the best shape and the lowest IM distortion at full output.



LINEAR RF POWER AMPLIFIER—Class AB_1
Single-Sideband Suppressed-Carrier Service

Maximum Ratings, *Absolute-Maximum Values up to 60 Mc:*

	CCS	*ICAS*	
DC PLATE VOLTAGE. . . .	600 max.	750 max.	volts
DC GRID-No. 2 VOLTAGE. .	250 max.	250 max.	volts
MAX.-SIGNAL DC PLATE CURRENT. . .	125 max.	135 max.	ma
MAX.-SIGNAL PLATE INPUT.	60 max.	85 max.	watts
MAX.-SIGNAL GRID-No. 2 INPUT . . .	3 max.	3 max.	watts
PLATE DISSIPATION . . .	20 max.	25 max.	watts
PEAK HEATER-CATHODE VOLTAGE:			
Heater negative with respect to cathode.	135 max.	135 max.	volts
Heater positive with respect to cathode.	135 max.	135 max.	volts

Typical Operation:

At 60 Mc with "Single-Tone" Modulation

	CCS		*ICAS*		
DC Plate Voltage. . . .	400	600	600	750	volts
DC Grid-No. 2 Voltage[j] .	190	180	200	195	volts
DC Grid-No. 1 Voltage[k] .	-40	-45	-50	-50	volts
Zero-Signal DC Plate Current	32	13	14	12	ma
Effective RF Load Resistance.	2000	3500	3000	4000	ohms
Max.-Signal DC Plate Current	114	100	115	110	ma
Max.-Signal DC Grid-No. 2 Current . .	12	11	14	13	ma
Max.-Signal Peak RF Grid-No. 1 Voltage . .	40	45	50	50	volts
Max.-Signal Driving Power (Approx.)	0	0	0	0	watts
Max.-Signal Power Output (Approx.). . .	27	41	48	60	watts

6. Design the grid input coupling circuit

The class AB_1 design draws little or no grid current, so a high impedance circuit will work. The output of a 5W transceiver into a 50 ohm load produces about 44Vp-p which may not be enough to drive the amp to full output, therefore I want to get some transformer step-up action on the input. I chose a coupled tuned circuit. It needs to be resonant at the center of the 20M phone band. If the Q is low enough I shouldn't need to adjust it once tuned up. We will see. A toroid works best here to keep stray output RF from feeding back into the input circuit. I simply wound enough turns on a T68-6 core (which seemed about the right physical size) to resonate at 14.2 MHz with a tunable 20-100 uF compression cap. I calculated it would take about 22 turns, but it took me 27. I may need to put a 10K or so resistor across the tuned circuit to lower the Q since I don't want to return this circuit from 14.200 - 14.250. I used 4 turns on the primary. This will look like a fairly high impedance to the output of a transceiver so the 52 ohm resistor on the input may or may not be needed depending on what is driving the input. Experimenting required.

7. Decide on the output tank coupling

I wanted to try a link coupling circuit to compare it with the standard Pi network. They are both easy to build. To keep high voltage off the components I chose to use a **parallel design** on the tank circuit. The tuning capacitor and inductor in the tank circuit must be selected for the correct reactance at the frequency of operation. The reactances for the circuit L and C are XL = XC = RL/Q or XL = 3500/10 = 350. This gives
C = 33 pF   L = 4.0 uH

I also selected the tuned link coupling to provide a bit more filter action. I used the standard values for L and C given in the table earlier for 14 MHz.
C = 115 pF and L = 1.12 uH.

The minimum critical value for the plate choke is 0.25 Rp/F or 0.25 x 3500/14 in μH or 87.5 μH. I have a nice 500 μH unit in the junk box.

The minimum critical value for the coupling capacitor is
11 Po / (Vp^2 F)   F in MHz, Vp is kilovolts, Po is output power.

11 x 50 / (0.65^2 14) = 92 pF

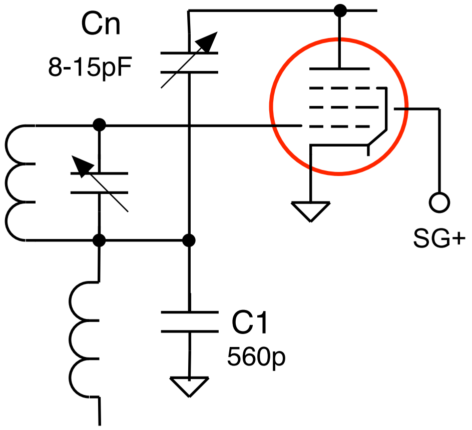
10 times that value is 920pF, so .001μF is more than enough.

8. Determine any neutralization and parasitic suppression

Even though this amplifier will probably be small and spread out, I want to make sure I have enough negative feedback to prevent any possible oscillation. So I added a simple capacitive divider back to the input circuit.

I have several small ceramic 5-15p trimmer caps that should work great for Cn. Cn/C1 = Cgp / Cgk, For the 6146 Cgp = 0.24p Cgk = 13p. Cgp/Cgk = 0.24/13 = 0.018
So 10p/0.018 = 555p, so C1 will be 560p.

To prevent parasitics a 47 ohm 2 watt composition resistor wound with 4 turns of no.18 wire in the HV plate lead, between the thermatron and the filter choke will do the job.



9. Determine the cooling requirements

The 6146 will be out in the open during testing, and hopefully in an open mesh cover later on, so only convection cooling will be used.

10. Design any control circuit and metering

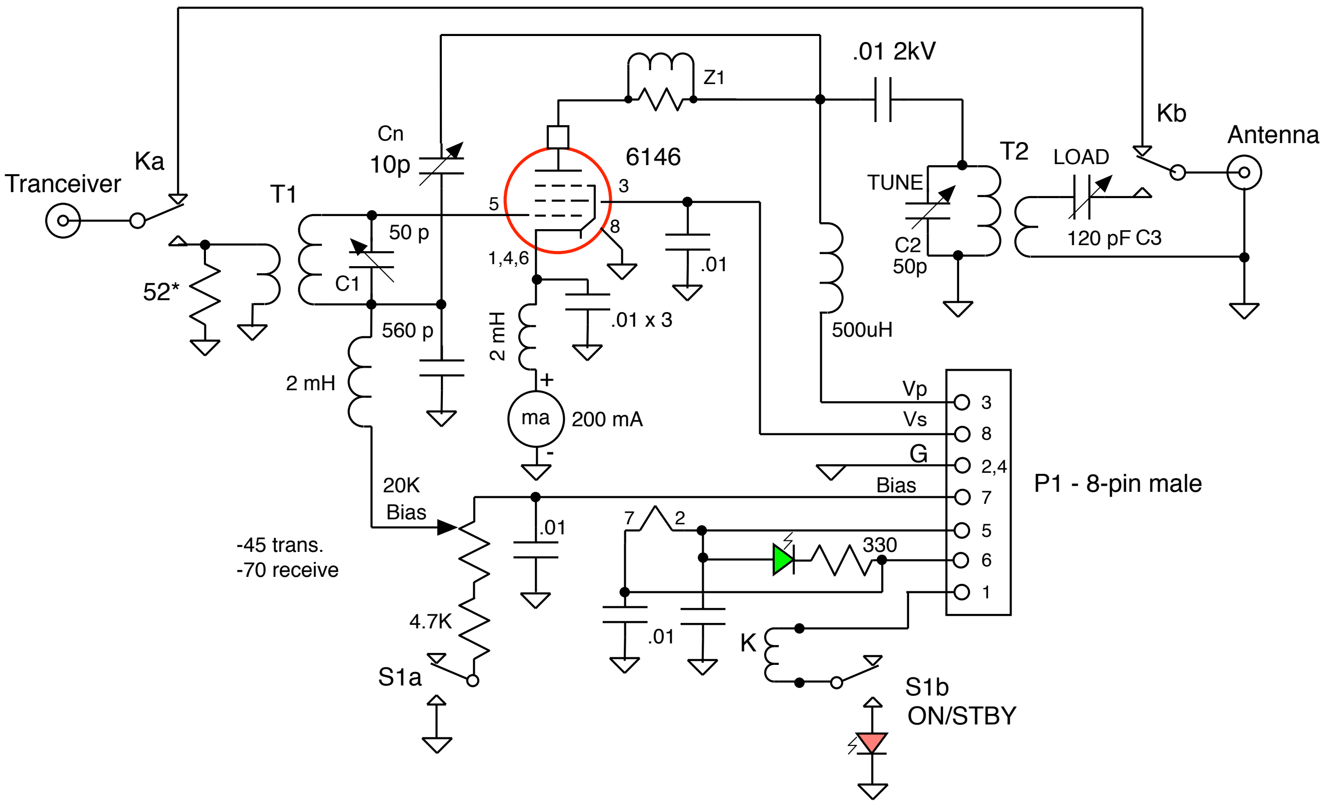
There will need to be control circuitry to bypass the input signal to the output when the amp is off or in the standby mode. Also, when in the standby mode, the bias to the 6146 will need to be made more negative to turn the thermatron off. For the 6146 at 650 Vp, this will take about -70 volts on the control grid. This can be seen from the plate curves. The easiest way to do this is unground the pot that adjusts the bias voltage to the thermatron so the voltage on the grid floats to the value of the bias supply. See my comments about the schematic below.

Metering

Since there is very little or no grid current, there is no need to monitor it. Drive is determined by the output of whatever is driving the amplifier, which determines the amp output power. But in order to tune the output correctly, it is necessary to monitor the plate current. I am not a fan of having the plate current meter in the HV circuit. I was shocked by a meter once that had an internal short to the metal case of the meter. I want the meter as close to ground potential as possible, so I put the current meter in the cathode lead. This measures the combined plate and screen current, but the screen current is just a small percentage of the plate current, so I can ignore it. It is also nice to monitor HV, but I would prefer to do that in the power supply.

11. Build it or a prototype

The final schematic for the amp is shown on the next page..



Notes on the Design:

* The 52 ohm resistor on the input is optional and depends on the requirements of the transceiver or whatever is driving the amp.

T1: Secondary: 27 turns (#24-28) on T68-6 core. Primary: 3-4 turns over primary.

T2: Air wound coil primary and secondary. The reactance of the tuned circuit L and C is 350 ohms. So C = 33p and L = 4.0 uH. The secondary link C = 120p and the L = 1.2uH. The secondary coil should be wound close to or over the ground end of the primary.

Z1 parasitic suppression: 3-4 turns #14, 1/2" diameter, next to or over 47 ohm, 2W resistor (turns out I didn't need it).

Switch S1 is the ON/STBY switch (shown in the OFF position). When off, the full -80 volts is applied to the control grid, effectively shutting the 6146 off. The 4.7K resistor inline with the bias adjustment pot, prevents the bias from being set to zero.

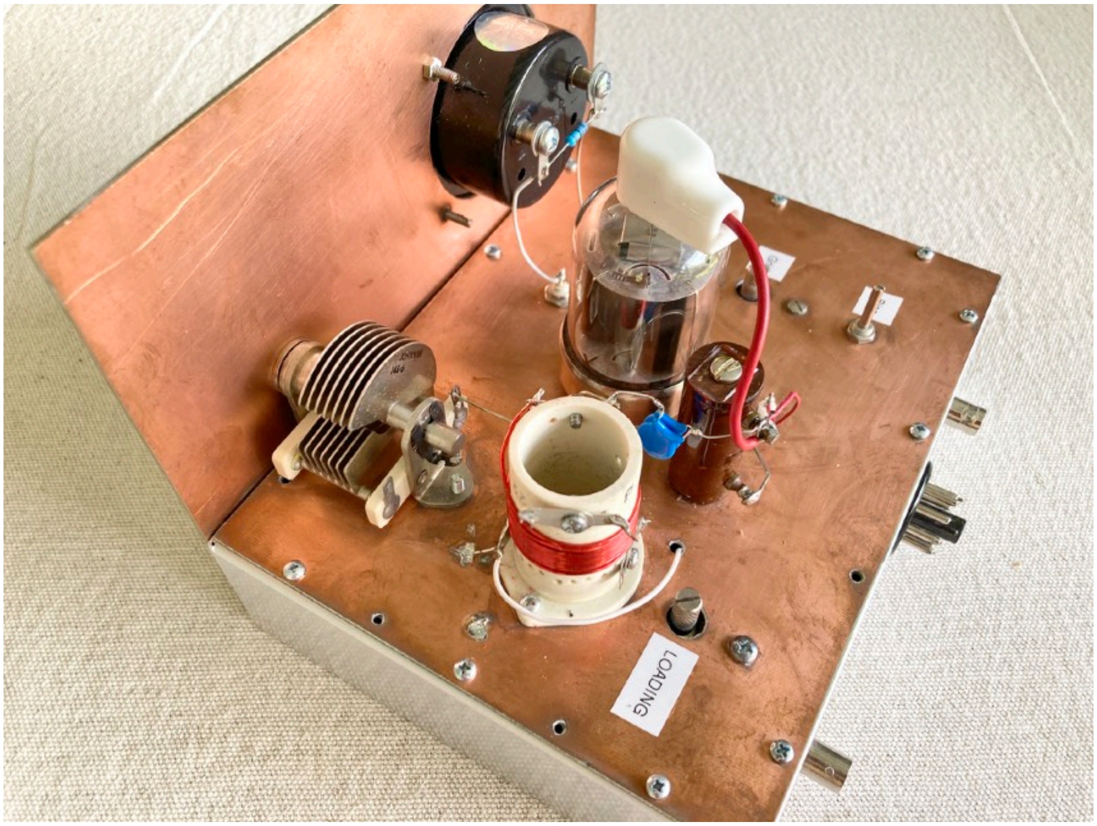
The LED in the filament lines is a power ON indicator.

The relay, K, is the input bypass relay, routing input to output when in the standby mode. My version is a surplus 12V enclosed relay.

Construction

Since this is a prototype, I made no attempt at making it look pretty or try to fit it in a particular chassis space. It is a very simple circuit and construction project.

I built the prototype on a 6” x 9” copper-clad double-sided PC board. I really like having a ground you can solder to everywhere. The board is screwed to a LMB “Omni Chassis Kit” of the same size (lmbheeger.com/omnichassiskit.aspx). The “lid” of the chassis screws on the bottom to enclose the underside. The T2 coils are wound on a surplus ceramic form from the junk box. The variable capacitors that resonate T1 and T2 are compression trimmers (20 - 160pF) mounted under the chassis, with the adjustment screws available on the top.

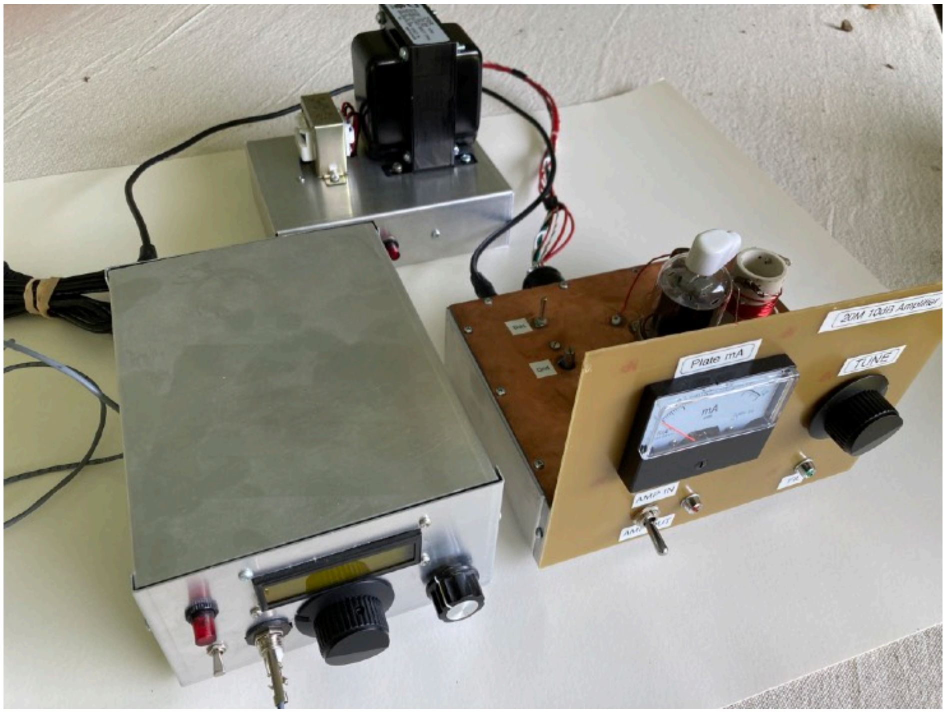


The front panel is a piece of 6” x 8” single-sided PC board. The meter is 0-1 mA with a shunt across its terminals to scale it to 0-100 mA. This is adequate since it is reading average current.

A photo of the component side is shown on the next page. The bypass relay is in the middle back and is super-glued to the board. I used RG174 coax to shield any input leads from the input to the relay, to the input tuned circuit to prevent pickup of the output signal.

The 6146 socket should have each cathode pin tied together and bypassed to ground with a ceramic cap. in the range of 500p to .01μF.

The 8-pin male plug on the back (P1) is for the power connection and the two BNC connectors are signal input and output.



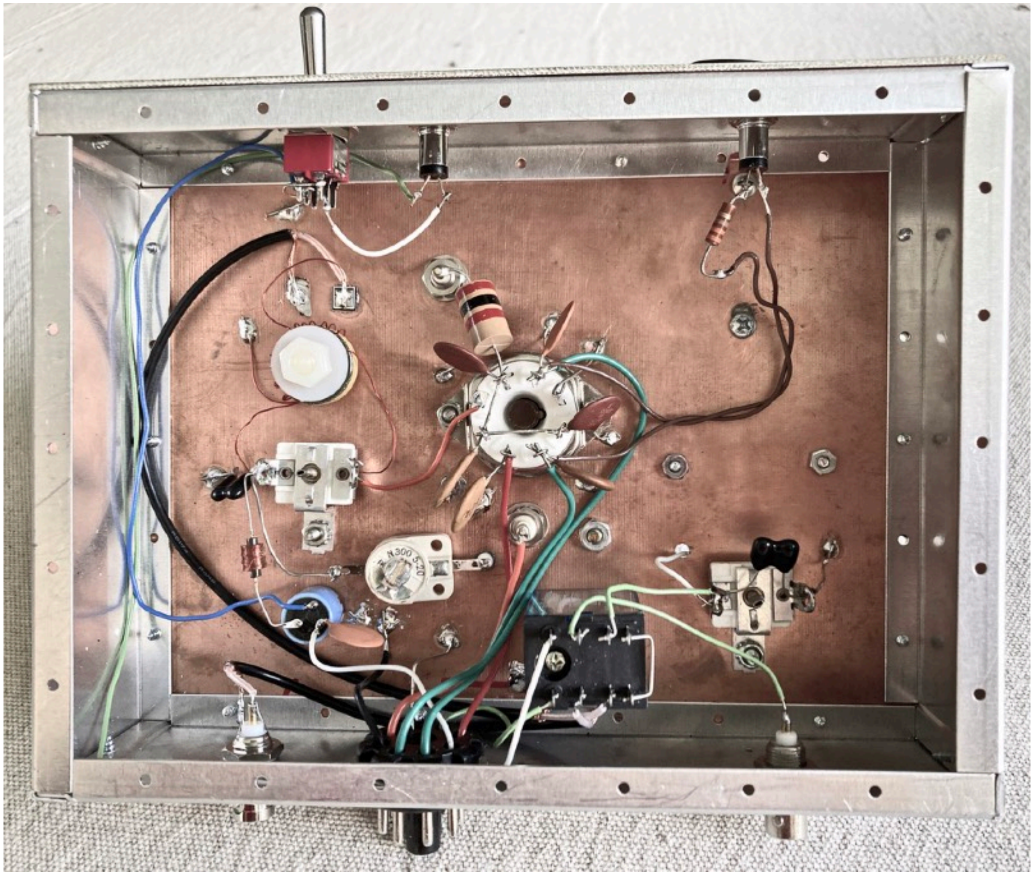


Photo on the page above shows the amp with its companion power supply my homebrew 20M SSB rig.

12. Testing and Measurements

The first step in testing was to start with the 6146 removed and make sure all voltages were correct and on the right pin: filament, HV, screen voltage, and bias. With S1 in the ON position, I set the bias on pin 3 to about -45 volts with the bias control.

I made sure the ON/STBY switch correctly changes input/output path through Ka and b.

Next, I applied a 14.225 MHz signal to the input and with amp ON I resonated C1 (input tuned circuit) for max signal on pin 5.

I then attached a dummy load to the output and grounded the input. I plugged in the 6146, turned on the HV, and rechecked the filament voltage at the socket to confirm it has 6.3V.

Next, I set the neutralization cap Cn. To do this, I need the 6146 installed with power disconnected. I attached a signal generator to the input, set for 14.225, at maximum voltage (20Vp-p) and measured the signal at the top of T2. I then adjusted Cn for a minimum and C2 for maximum signal level and tweaked Cn again for minimum signal.

With HV on and S1 in ON, I then checked for any parasitics or oscillation with a scope and spectrum analyzer. None found. As I mentioned earlier, I did not install the Z1 parasitic suppressor in this prototype. I got lazy.

Time to set the bias. With thermatron voltages on, input grounded, S1 to ON, I set the bias adjust for about 13 mA plate current. It should be about -45 to -50 volts. I will fine tune it later.

For the remaining test I used the output of my Collins 32S-3 SSB transmitter in its TUNE mode with the drive level turned down to provide a large enough signal to drive the 6146, since I do not have a signal generator with enough output.

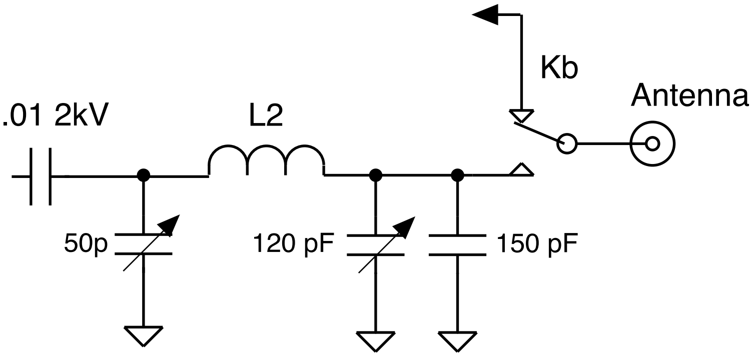
With the LOAD cap (C2) set for about mid range, I applied a steady (CW) input signal in the middle of the 20M voice band (14.225). That will drive the 6146 to about mid range (50 - 80 mA) and make sure I get a plate current dip on the meter while adjusting the tuning cap.

I then adjusted the input cap C2 for max output. Then I increase the loading cap for additional output, retuning the TUNE cap as needed.

Now it was time to check the power output, bias, and harmonic output.
The easiest way to adjust the amp without a spectrum analyzer is to use a scope and watch the output waveform. I used a steady (CW) signal input and monitored the output waveform on a scope, looking for any obvious distortion or flat-topping. I increased the LOADing cap, then re-dipped the TUNE until I got no further increase in output.

A 140Vp-p output waveform into a 50 ohm load represents a 50 watts output. I increased the input until I got a 150Vp-p output, about where it started to slightly flat-top. This occurred with a 38Vp-p input signal from by transmitter. That is 3.6 watts in, 50+ watts out. More than 10dB. Great.

I wanted to compare the results with a Pi network in place of the link coupled output so I recalculated the components for a Pi network (I used the online web site to calculate the values). It turns out the values were very close to what I had in for the link coupling so I just had to rearrange things and add an extra loading cap.



I next checked the harmonic output on my spectrum analyzer with both the tuned link coupled circuit and the Pi network version to compare harmonic suppression.

With the Pi network, harmonic levels (all referenced to carrier level):

2nd harmonic (28 MHz):	-41 dBm
3rd harmonic (42 MHz):	-54 dBm

With the link-coupled tuned circuit:

2nd harmonic (28 MHz):	-31 dBm
3rd harmonic (42 MHz):	-42 dBm

The Pi network provides about a 10 dBm improvement over the link-coupled circuit. There is a reason it's popular!

I also checked the output with a SSB modulated signal from my 32S-3 transmitter. Both the scope display and the spectrum analyzer looked nice, although I did notice a spike in the 3rd harmonic when I yelled into the mic!