Vacuum Tube Amplifier Basics

Second Edition

EJ Jurich

A basic primer on vacuum tube amplifier design and construction

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Vacuum Tube Amplifier Basics, Second Edition by EJ Jurich
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About This Book

Vacuum tube amplifiers have a sound unique to the characteristics of vacuum tube amplification. When comparing amplifier specifications, vacuum tube or solid state, keep in mind that the amplifier is not the last link. Actual system performance is dependent on other factors such as room acoustics and box & cone speaker systems that introduce distortion, depending on volume levels, up to 10%. What really matters is what sounds good. Beyond the realm of equipment test results, it is an area more appropriately left to the field of psychoacoustics. Regardless of equipment specifications, sound reproduction preference is a matter of the listener's perception.

With basic design knowledge, the hobbyist can design and build vacuum tube audio amplifiers that perform well. Besides taking pride in something that you built, you will have something that is not your typical throw-away electronics. Although there are calculations involved, do not let the math scare you. Most of the formulas used in this book are simple based on Ohms Law. Calculations presented in this book are explained with examples and can be performed on a standard twelve-digit calculator with a square root key. The information in this book is concise with the electronics hobbyist in mind.

As a first time builder, a lower power Class A amplifier that uses a reasonably simple circuit configuration may be the best project to choose. The process of designing and building a working two-channel (stereo) amplifier is presented in steps; with each step the necessary circuit information is explained with examples. To get an idea of the building process of a vacuum tube amplifier, start at page 116, chassis fabrication. With the use of a commercially available metal chassis, drilling and punching holes to produce a traditional fabricated chassis is demonstrated. An example of the design and build of a stereo Class A amplifier starts at page 127.

Use the technical sections, pages 3 through page 112, as a reference guide. It is necessary to be able to solder and follow circuit diagrams. A basic primer on soldering starts on page 8. Reading circuit diagrams is found on page 12.

EJ Jurich

Safety Concerns

While taking measurements or testing a live chassis, stay alert and pay attention to what you are doing. When working on an open chassis that is powered on, never rest your hands on the chassis. Never pick up an open chassis with it plugged in or powered on. In most cases, it is your hands that will get caught by a voltage and cause your muscles to lock up and are unable to let go. If you ever find your hands locked and unable to let go of a chassis, your only option may be to swing your body and fling the chassis out of your hands. The best policy is to assume there is voltage even if the chassis is off and unplugged. Use common sense, don't be careless.

Discharging Capacitors

For filtering capacitors in high voltage circuits of 700VDC or less, capacitors are discharged as shown.

DISCHARGING A CAPACITOR

Use a clip lead (jumper wire with clips) and a resistor to drain current from a capacitor. This can be done while a capacitor is in a circuit.

Capacitors are discharged while the equipment is 'unplugged' from AC power. Use a clip lead long enough to reach all the filtering capacitors.

In a circuit, most filtering capacitors have one terminal or lead connected to ground. One end of a clip lead is connected to ground with the other end of the clip lead connected to a 1K (1,000) ohm 10 watt wirewound resistor.

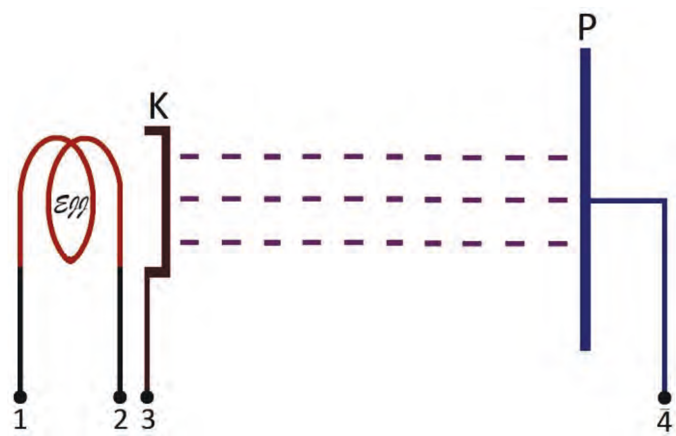
With one hand, using the resistor as a probe, carefully touch the resistor to filter capacitor connections. Keep your other hand away from the chassis. Capacitors should discharge in a second or two. The resistor limits current flow, eliminating any spark. Verify that capacitors are discharged by checking with a DC voltmeter. Be aware that after discharging a capacitor, there may still be residual voltage of less than 20 volts. This is normal and should be safe to handle.

The Electron Tube

Electron tubes have been around since 1906. Although most functions have been replaced by solid state devices, the use of vacuum tubes in audio remains useful. These devices are referred to by various names and may be called vacuum electron tubes, electron tubes, vacuum tubes or valves. Valves because they act as a valve controlling current flow. A vacuum is provided in the form of an evacuated enclosure in which electrons can move without collisions with gas molecules.

The Diode

In the illustration, terminals 1 and 2 connect to a filament. The filament is located inside tubing called a cathode (K). A metal plate (P) surrounds the cathode. All the elements are spaced such that they do not touch each other.



When a vacuum tube cathode is heated by the filament, the energy is sufficient to cause electrons to boil away from the cathode surface, creating a cloud of free electrons. By applying a negative potential to the cathode and a positive potential to the plate, the space charge cloud is directed, and current flow is produced between the cathode and the plate.

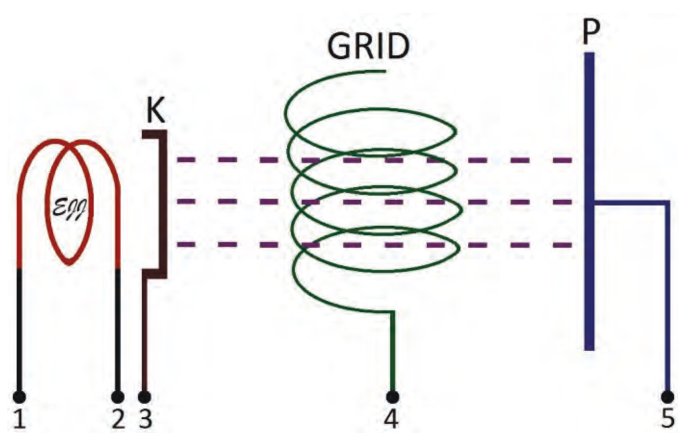
Electron tube diodes are mostly used in power supplies as rectifiers to convert AC to DC. A rectifier with one plate is called a half-wave rectifier because it only rectifies the positive portion of the AC cycle. By adding a second plate, both the positive and negative portions of the AC cycle are rectified. This is called a full-wave rectifier. A transformer with a center-tapped secondary is required for full wave rectification. The center tap connects to ground (negative). One end of the transformer's secondary connects to a plate; the other end of the secondary connects to the other plate. The cathode is the rectified AC output (now positive DC pulses).

Electron rectifier tube characteristics include some internal resistance that exhibit opposition to current flow. This produces a voltage drop across the rectifier. Current loads placed on the rectifier tube will cause a voltage drop across the rectifier resulting in a drop of DC voltage output. Because of this, datasheets specific to a particular type of rectifier tube must be consulted. Each rectifier tube datasheet should have a graph that displays the voltage output based on the current load placed on the rectifier.

By comparison, solid state rectifier diodes have very low internal resistance and exhibit an insignificant voltage drop. The downside of using solid state diodes is that the DC voltage comes on as soon as an amplifier is turned on. This results in a much higher B+ high voltage until the amplifier tubes warm up and start drawing current. A vacuum tube rectifier does not have DC output until its filament warms up. This provides a slight delay in DC voltage, giving the amplifier tubes some time to warm up.

Electron Tubes With Grids

In the illustration, terminals 1 and 2 connect to a filament. The filament is located inside tubing called a cathode (K). A spiral wire surrounding the cathode is called a grid. A metal plate (P) surrounds the grid. All the elements are spaced such that they do not touch each other.



A spiral grid wire in the path of current flow is used to control current flow. This is called the control grid. When made negative, the grid opposes the flow of current; the negative grid does not attract any electrons and so draws no current. If made sufficiently negative, the grid can cut off current flow entirely. If the grid is made positive, it can enhance current flow, but it then draws some grid current itself. Using negligible power, the grid provides a sensitive control of the current flow, enabling the electron tube to be an amplifying device.

The Triode, Tetrode and Pentode

The Triode

A three element electron tube, cathode, grid and plate is called a triode. When a low-level audio signal is applied, the control grid modulates current flow through the tube to the plate. The output signal is the result of current variations on the plate producing a modulated plate voltage at a higher level than the input signal. The amount of voltage amplified is measured as voltage gain.

The Tetrode

The effect of plate voltage on the space charge results in a certain amount of resistance to current flow within a vacuum tube. To eliminate the effect of the plate voltage on the space charge, another grid called the screen grid is placed between the control grid and the plate. If this grid is held at a constant potential, the space charge is "screened" from the effects of changes in plate voltage. The resulting tube is called a screen-grid tetrode.

The Pentode

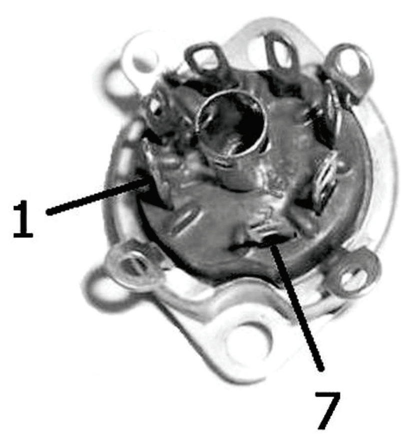
Although tetrodes worked as expected, they had a serious defect. It happens that speedy electrons knock out secondary electrons. In a triode, these are rapidly sucked back to the positive plate. The same happens in a tetrode when the plate voltage potential is higher than the screen grid voltage potential. In normal operation when there is high gain, the plate voltage has a large voltage swing and at times can become less positive than the screen grid. Now all these secondary electrons and some of the primary ones too are attracted to the screen grid, causing a sag in the operating characteristic in this region. To prevent this, it is necessary to establish an electric field near the plate to suppress the escape of secondary electrons. This is provided by a third suppressor grid positioned close to the plate, usually connected to the cathode. Tubes with three grids are called a pentode.

Vacuum tubes have maximum operating parameters. Of prime importance are maximum voltage limits and maximum plate dissipation. Plate dissipation is heat expressed as wattage dissipated by the plate.

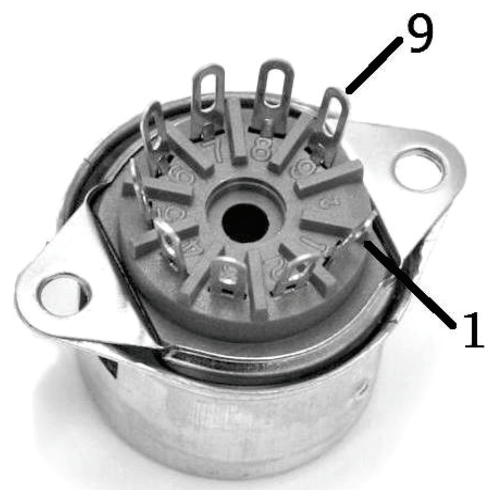
Tube Socket Pins

Vacuum tube socket pins are counted from the bottom, terminal side, of the socket. The most commonly used sockets are the 7-pin miniature, 9-pin miniature and 8-pin octal sockets. From the terminal side, pins are counted clockwise starting from a reference point. On the 7-pin and 9-pin miniature sockets, the reference point is a space between the pins. On the 8-pin octal socket, the reference point is a key (slot) in the center socket hole. When soldering to tube socket terminals, it is best not to hold the iron to the terminal longer than necessary to melt the solder and get good flow. Holding the iron against terminals too long may cause solder to flow into the socket connector blocking tube pins. Never solder with a tube in the socket.

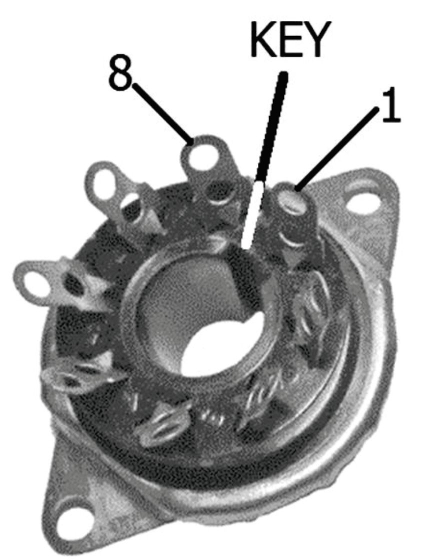
7-PIN MINIATURE SOCKET



9-PIN MINIATURE SOCKET



8-PIN OCTAL SOCKET



Selecting Wire

Wire gauge sizing for use inside electronic equipment is rated for more current than wire used in building electrical circuits. Because wire lengths inside electronic equipment are much shorter, the total resistance per foot is considerably less than building electrical wiring. Wiring inside electronic equipment produces less heat and is less likely to overheat.

Equipment Wiring Gauge Size Current Ratings

24 Gauge Wire – Maximum Current = 3.5 amps

22 Gauge Wire – Maximum Current = 7.0 amps

20 Gauge Wire – Maximum Current = 11.0 amps

18 Gauge Wire – Maximum Current = 16.0 amps

Insulation

Wire used in vacuum tube B+ high voltage circuits should have insulation rated 600 volts for use with voltages up to 500 volts. Beldon type 8530 wire is rated at 1,000 volts. Save on wire costs by using lower voltage rated wire insulation on lower voltage circuits, e.g., 300-volt insulation. There are PTFE insulated versions of hookup wire. PTFE insulation does not melt while soldering and is less likely to dry out with age. However, there could be health issues with PTFE insulation as some people and animals may be allergic to PTFE insulated wire.

Wire Color Code

Wire color standards were established for wiring vacuum tube circuits so that at a glance you would know what some circuits were. Here is a list of basic colors related to US standards.

- Black – Ground
- Gray – AC power
- Red – High voltage B+
- Orange – Screen grid
- Blue – Plate circuits
- Yellow – Heaters (Heaters = Filaments)
- Brown – Heaters, sometimes center taps
- Green – Grid circuits and sometimes heaters

- Bare wire - Ground
- 18 gauge bare wire – Ground buss

Soldering

Lead Based Solder

For manual soldering, solders with lead content such as Kester 44 rosin core provide the best flow. The lead content is in a metallic alloy form, so it has low bioavailability. This is the degree or rate at which a substance is absorbed. When used to assemble vacuum tube amplifiers, solder with lead poses no significant environmental problems when properly handled. Also, a vacuum tube amplifier wired with lead based solder should last many decades and is less likely to wind up in a landfill.

Flux Fumes

Avoid breathing in flux fumes. Have a small fan blow the flux smoke away from you and anyone else nearby while soldering.

Lead Free Solder

Lead-free solder does not flow as well as lead-based solder. Lead-free solder tends to grow tiny spikes of metal whiskers over time that can cause short-circuits. It is not advisable to use lead-free solder for anything you expect to last decades; such equipment will become unreliable as it ages.

Silver Solder

Silver solder without any lead content also suffers from metal whiskers. For silver solder applications, use Sn62/Pb36/Ag2 solder.

Never Use Acid Flux Solder.

A solder with acid flux will eat into your connections and ruin electronics. The most reliable is rosin core solder. Rosin flux left on a connection is the least destructive.

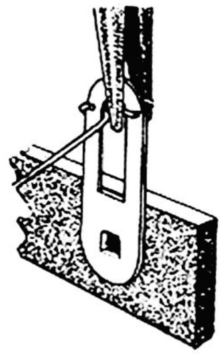
Organic Flux

There is solder with organic flux available. Organic flux must be completely cleaned off your connections, or it will grow a conductive fungus and corrode connections over time. Organic flux cleans with water, but it is impossible to get all the flux off the wiring used in a vacuum tube chassis. It would be advisable to avoid solder with organic flux.

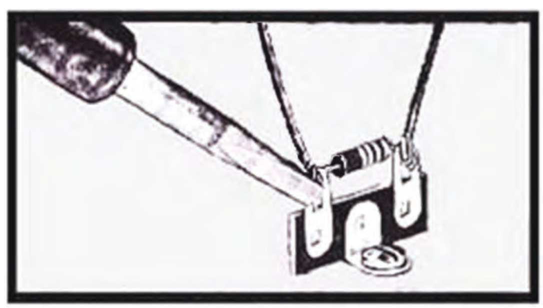
Soldering Review

If you are new to soldering, you might benefit from the following soldering procedure.

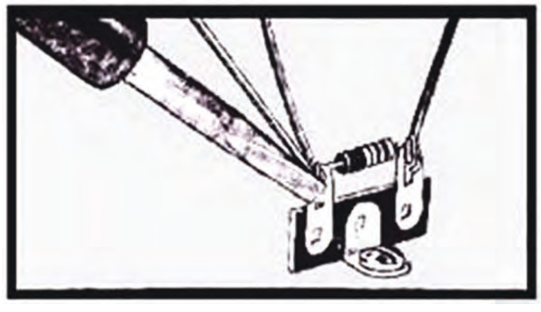
1 - Use long nose or needle nose pliers and neatly secure wire around a terminal.



2 – You will need at least a 35 watt soldering iron. Coat the tip of the iron with solder. Then, firmly press the flat side of the tip against the parts to be soldered together. Keep the iron there while you. . .

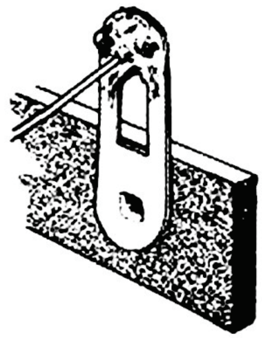


3 – Apply the solder between the connection to be soldered and the iron tip. Use only enough solder to flow over all surfaces of the connection. Remove the solder and iron.



4 – You have a good connection if your solder has flowed over all surfaces to be connected following the shape of the surfaces. It should appear smooth and bright and all wires in the connection should be well soldered.

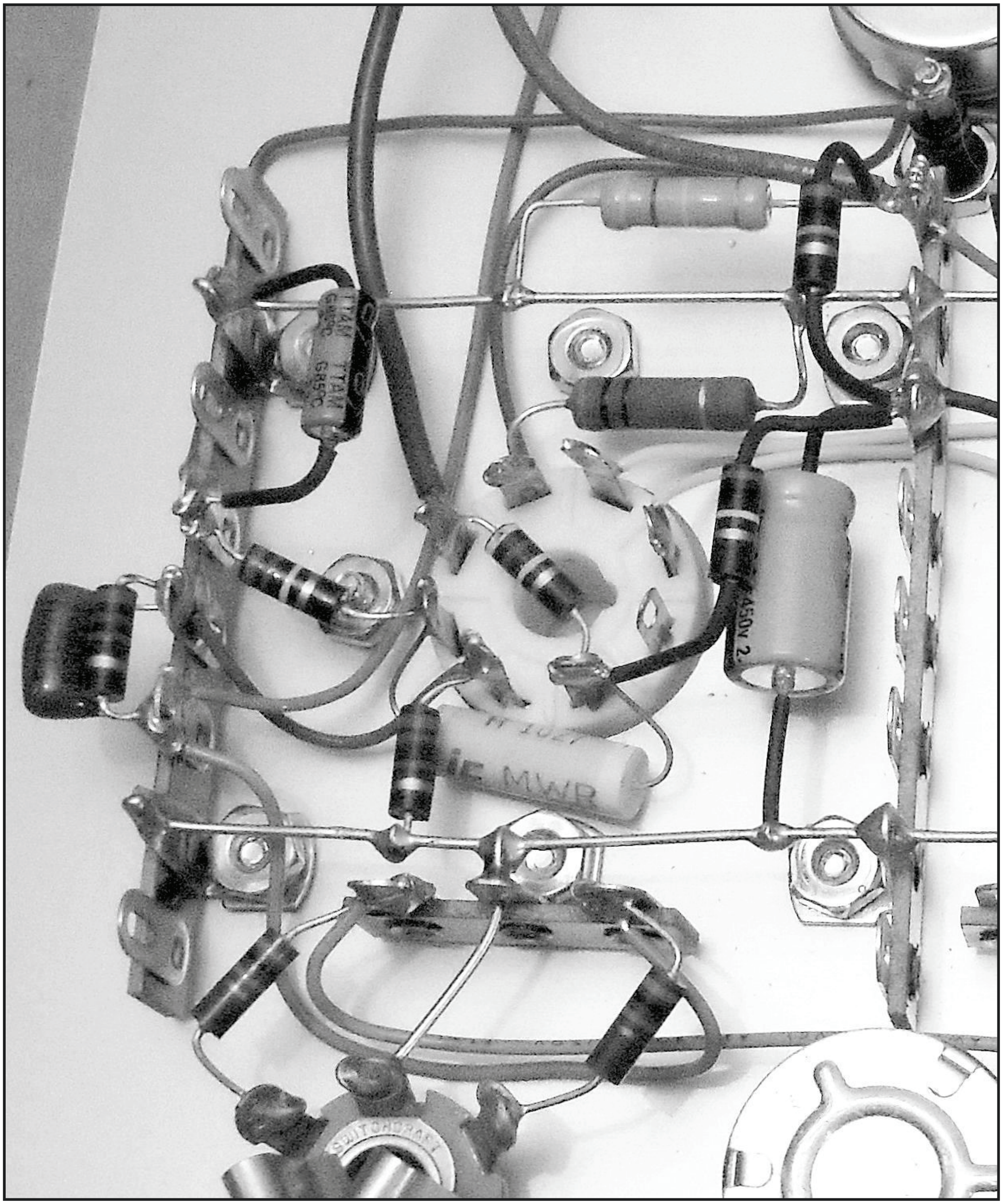
You have not used enough heat if your connection is rough and flaky looking or if the solder has formed a round ball instead of spreading.



For electronic work, a 35-watt iron similar to the one shown below, that will accept different types of soldering tips, works best. For vacuum tube component wiring, a 2.4mm chisel tip provides plenty of heat. A 0.2mm sharp conical tip works well for delicate electronic work.

Component Layout Neat

Solder Joints Should Be Smooth

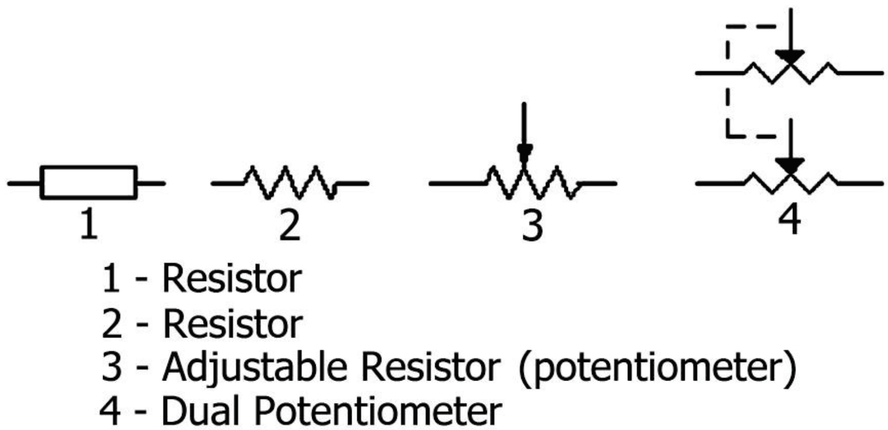


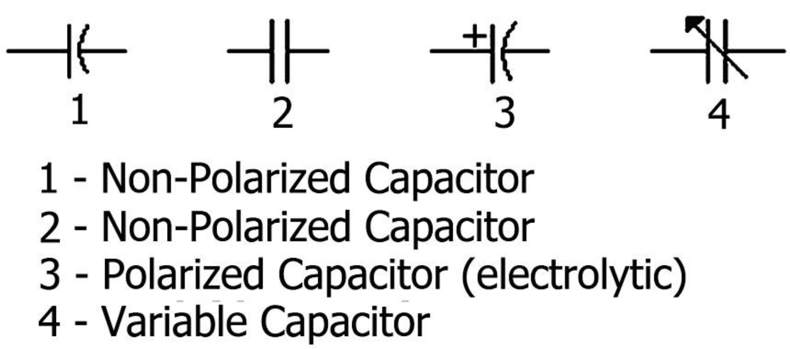
Reading Circuit Drawings

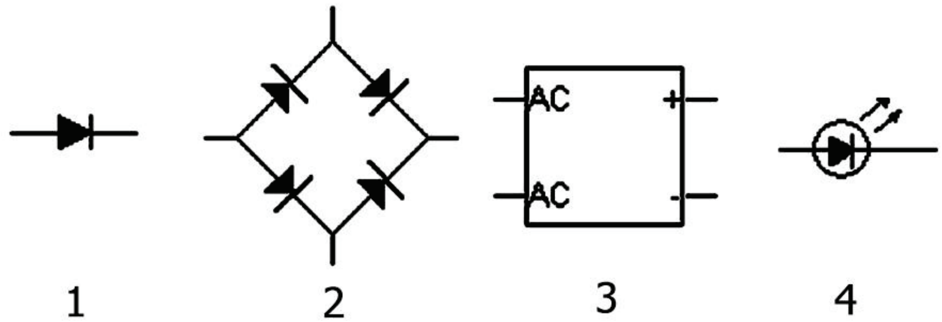
Reading circuit drawings is essential. It will be near impossible to follow circuit drawings if you don't understand the basic drawing technique and symbols used.

Circuit symbols are used in this book as visual illustrations to text. If the reader is new to electronics, as you read, the symbols will become more familiar.

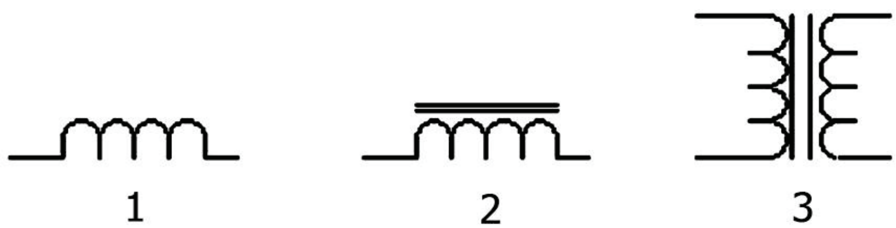
Common Circuit Symbols



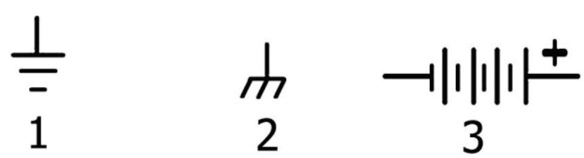




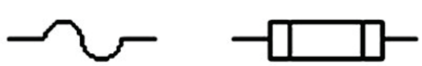
1 - Diode (rectifier)
2 - Bridge Rectifier
3 - Bridge Rectifier
4 - Light Emitting Diode (LED)



1 - Inductor, air core
2 - Inductor, iron core (choke)
3 - Transformer (iron core)

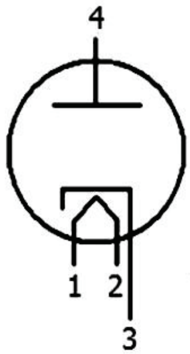


1 - Ground (common)
2 - Ground (chassis)
also earth ground
3 - Battery



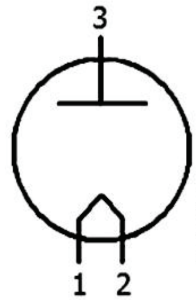
Fuse

Vacuum Tube Symbols



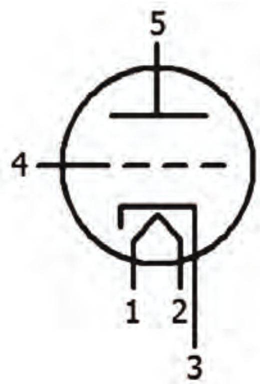
DIODE
RECTIFIER

1 - FILAMENT
2 - FILAMENT
3 - CATHODE
4 - PLATE



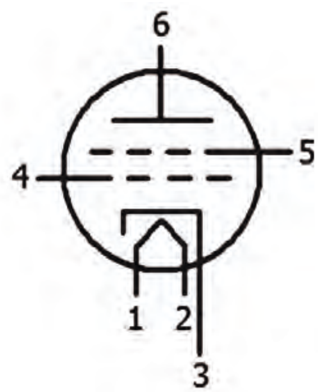
DIODE
RECTIFIER

1 - FILAMENT & CATHODE
2 - FILAMENT & CATHODE
3 - PLATE



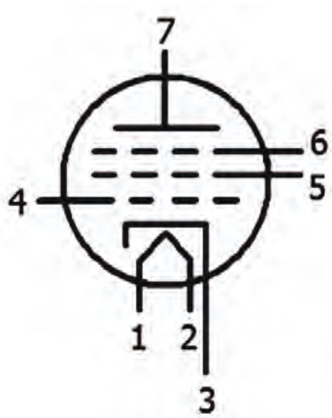
TRIODE

1 - FILAMENT
2 - FILAMENT
3 - CATHODE
4 - CONTROL GRID
5 - PLATE



TETRODE

1 - FILAMENT
2 - FILAMENT
3 - CATHODE
4 - CONTROL GRID
5 - SCREEN GRID
6 - PLATE



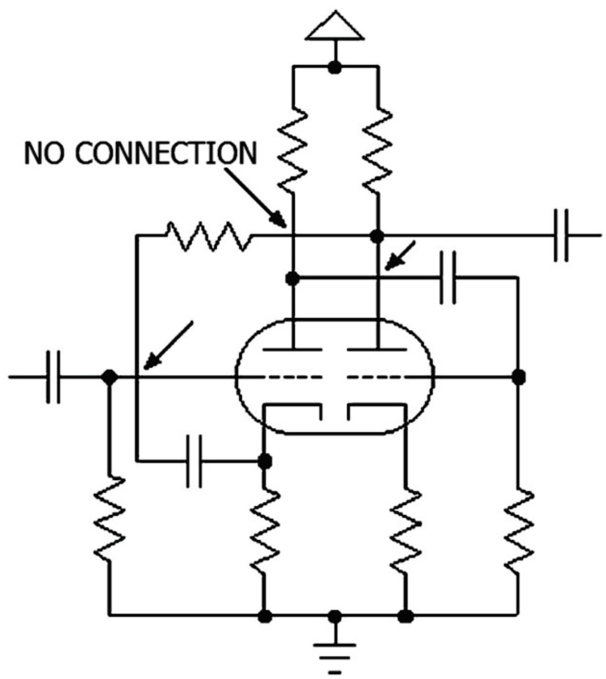
PENTODE

1 - FILAMENT
2 - FILAMENT
3 - CATHODE
4 - CONTROL GRID
5 - SCREEN GRID
6 - SUPPRESSOR GRID
7 - PLATE

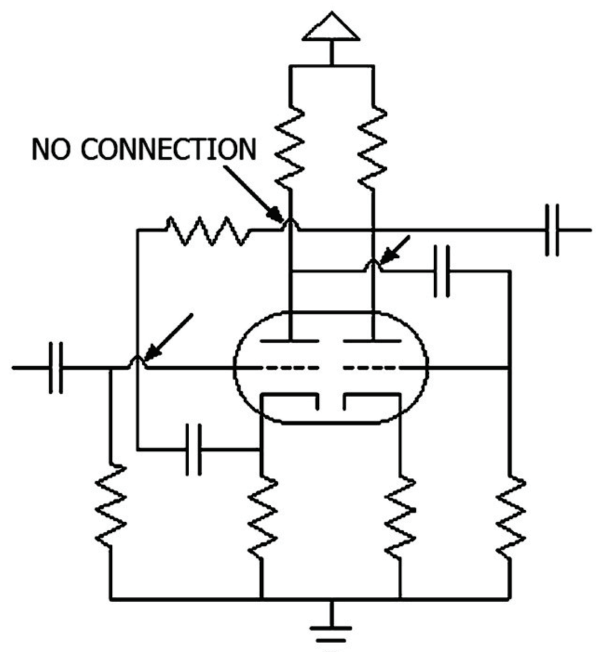
Circuit Drawing Connection Points

In drawing A, lines (circuits) that connect have a dot. Lines that cross without a dot do not connect. Some drawings may show no connection with a line hooking over another line. On drawing B, a hooked line indicates no connection; crossed lines do connect and may not necessarily use a dot.

Drawing A



Drawing B



On the next page, Figure 1 is a schematic of an amplifier circuit. Figure 2 is a pictorial drawing of the schematic that shows the wired circuit. It will help you become familiar with reading schematic circuits by comparing the schematic with the pictorial drawing. Follow the circuit in both the schematic and the pictorial.

You will notice that in the pictorial drawing, the 6V6GT socket has a 150K resistor from pin 5 to pin 6. The 6V6GT does not use pin 6, and most 6V6 tubes do not have pin 6. In this case, pin 6 is being used as a terminal tie point. Using an unused tube socket terminal for a tie point on commercially produced equipment is not uncommon. You need to be careful not to confuse such a terminal tie point with a tube pin connection. Socket terminals used as a tie point are usually not shown on a circuit diagram.

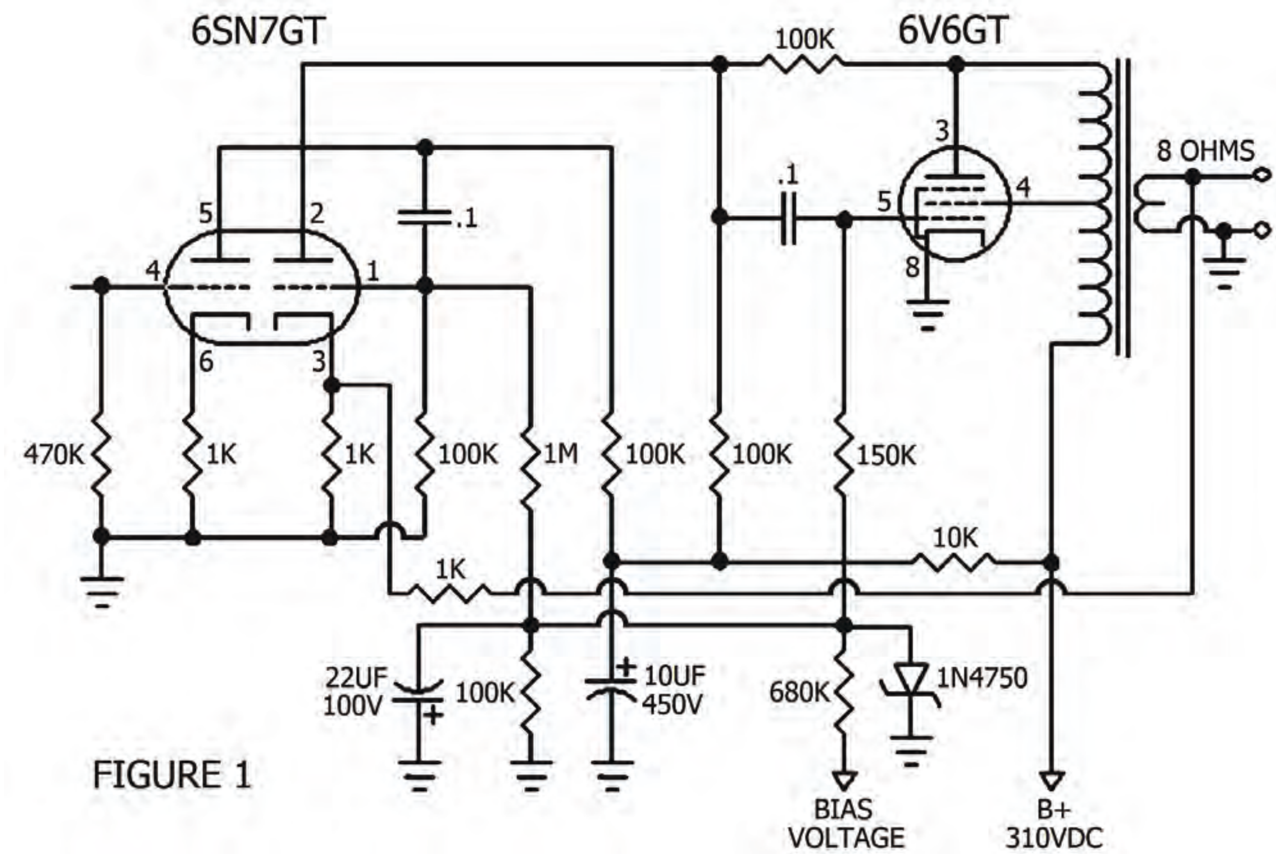


FIGURE 1

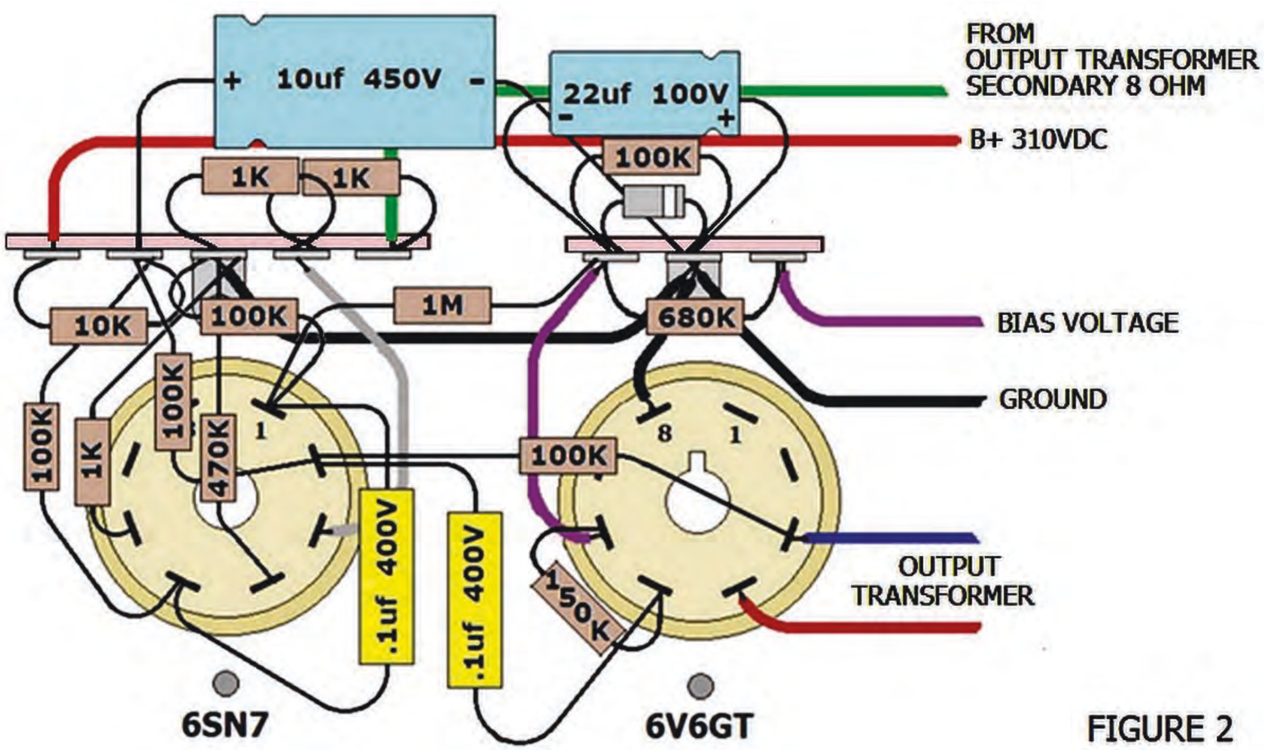


FIGURE 2

Ohms Law

Ohm's Law is a series of basic formulas. The most common are for calculating voltage, current, resistance and power.

Voltage is a potential or force.
Current is the rate of flow of voltage in a complete circuit.
Resistance is anything that works against the current flow.

The most common Ohm's Law formulas are as follows:

E = voltage in volts
I = current in amperes
R = resistance in ohms
P = power in watts

Voltage may be abbreviated volts or V

Amperes may be abbreviated amps or A
mA = milliamperes
1000 mA = 1-ampere

Current must be expressed in amperes when used in formulas. Convert mA to amperes if necessary. Move the decimal point three places to the left.

Examples 12 mA = 0.012 amperes (12.←decimal position)
150 mA = 0.150 amperes
1,200 mA = 1.2 amperes

To find an unknown resistance, divide the voltage by the current.
R = E / I (Resistance = voltage divided by current)

To find an unknown current, divide the voltage by the resistance.
I = E / R (Current = voltage divided by resistance)

To find an unknown voltage, multiply the current by the resistance.
E = I X R (Voltage = current times resistance)

OHM'S LAW PIE

If you can remember "E over I times R" then you will know three basic Ohm's Law functions.

Power and Watts

A watt is the result of work done by voltage and current. A watt is power dissipated in the form of heat. Power is usually stated in watts. There are three formulas for finding power in watts.

P = power in watts
E = voltage in volts
R = resistance in ohms
I = current in amperes

$$P = E \times I$$
(Power = voltage times current)

$$P = I^2 \times R$$
(Power = current squared times resistance)

$$P = E^2 / R$$
(Power = voltage squared divided by resistance)

Power Values

mW = milliwatt
1000 mW = 1-watt or 1W

Power must be expressed in watts when used in formulas, convert mW to watts if necessary. Move the decimal point three places to the left.

Examples 12 mW = 0.012 watts (12.←decimal position)
150 mW = 0.150 watts
1,200 mW = 1.2 watts

Convert watts to mW by moving the decimal point three places to the right.

Examples 0.010 watts = 10. mW
0.150 watts = 150. mW
0.500 watts = 500. mW

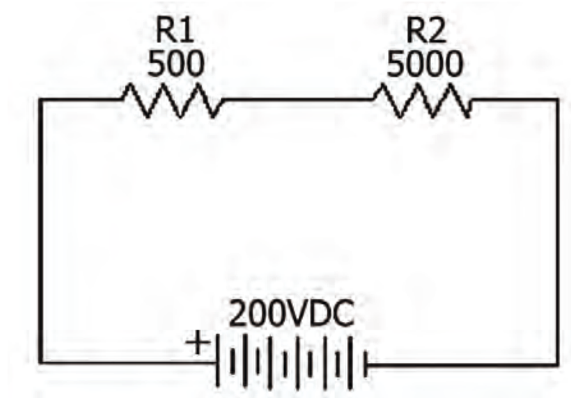
It is necessary to calculate the wattage dissipated to correctly select resistors. You would not want to place a resistor rated at one watt in a circuit that will dissipate two watts of heat, the resistor will operate too hot and fail.

In Figure 1, we have a 500-ohm and 5000-ohm resistor in series connected across a 200V battery supply. Using Ohm's Law, we calculate the current in the circuit with I = E / R.

R = R1 + R2 = 5,500

I = E / R = 200 / 5,500 = 0.036 amps
(0.0363636 rounded off)

Figure 1



Using a formula for watts, we can find how many watts are dissipated from each resistor. Since we know the current and resistance, we use $P = I^2 X R$.

$P = I^2 X R$
(square the current first)

0.036 X 0.036 = 0.0013
(0.001296 rounded off)

R1 Dissipation
0.0013 X 500 = 0.65 Watts

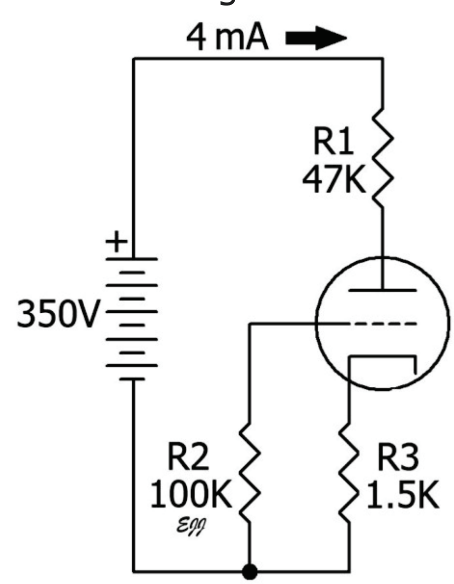
R2 Dissipation
0.0013 X 5000 = 6.5 Watts

Even though current flow is the same, the higher resistance dissipates more power in the form of heat. R1 would need to be rated at least one watt and R2 at least seven watts. Good engineering practice would dictate adding some safety factors by increasing the wattage rating some. For instance, R1 rated two watts and R2 rated ten watts.

Figure 2 is similar to Figure 1 except we have a vacuum tube load. We already know the supply voltage is 350 volts and current in the circuit is 4 mA. We only need to calculate the power that is dissipated by R1, R2 and R3.

The functions of a vacuum tube will be explained later. All you need to know is that R2 has no current flow, so it can be rated at 1/2 watts. In order to be used in an Ohms Law power formula, current must be in amperes (amps). 4 mA = 0.004 amps.

Figure 2



$P = I^2 \times R$
(square the current first)

$0.004 \times 0.004 = 0.000016$

R1 Dissipation
$0.000016 \times 47{,}000 = 0.75$ Watts

R3 Dissipation
$0.000016 \times 1{,}500 = 0.024$ Watts

Since R1 dissipation is close to 1-watt, it would be best to use a 2-watt resistor. R3 can safely be a ½-watt resistor.

Additional Formulas Related To Power

E = voltage in volts
R = resistance in ohms
I = current in amps (amperes)
P = power in watts

Finding an Unknown Resistance

$R = P / I^2$ Divide the power by the current squared.
(Square the current first)

$R = E^2 / P$ Divide the voltage squared by the power.
(Square the voltage first)

•

Finding an Unknown Voltage

$E = P / I$ Divide the power by the current.

$E = \sqrt{P \times I}$ Square root of the power times the current.
(Multiply P by I first before performing square root)

•

Finding an Unknown Current

$I = P / E$ Divide the power by the voltage.

$I = \sqrt{\frac{P}{R}}$ Square root of power divided by resistance.
(Divide power by resistance first before performing square root)

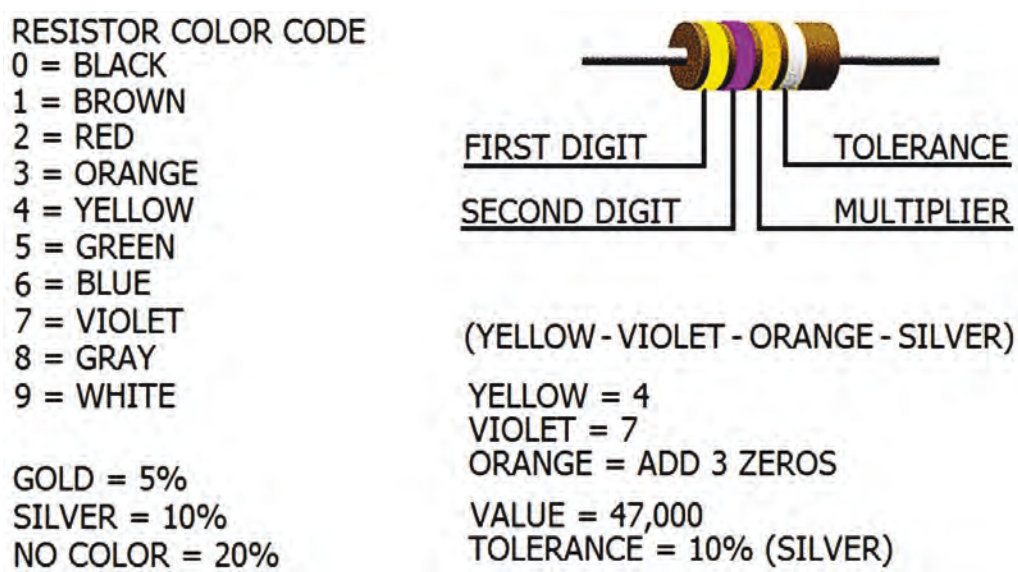
Resistors

Resistors are used to limit current and create voltage drops. They are crucial for use in amplifier stages and power supplies. Resistors have a resistance value stated in ohms with a range of less than one ohm to over one million ohms. Resistors have a power rating, the maximum amount of watts they can dissipate as heat. For vacuum tube circuits, resistors are most commonly rated from 1/2 watts up to 20 watts and sometimes higher. Lower-wattage metal and carbon-based resistors are used in amplifier stages. Carbon composition resistors are able to withstand surges in high-voltage circuits better than film-type resistors. Metal oxide resistors with higher voltage ratings are available and less likely to break down. Wire-wound resistors are best for power supply applications.

Reading Resistor Values

A resistor may have its value printed on it in text. Resistors that use color bands must be read using a color code.

Standard Four Band Color



Value abbreviations

K = Thousands

M or meg = Millions

Examples

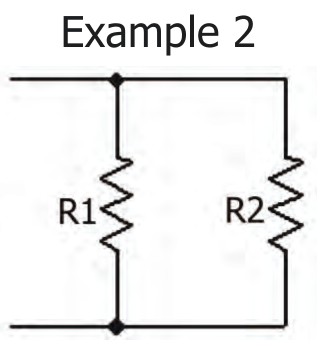
2.2K = 2,200 ohms

2.2M = 2,200,000 ohms

Series and Parallel Resistor values

Resistors can be connected in circuits in various ways. When they are connected end to end, one after the other, they are connected in series.

In Example 1, to find the total resistance, you simply add the values of all the resistors in a series circuit. If R1 is 2000 ohms, R2 10,000 ohms and R3 22,000 ohms, then the total resistance is 34,000 ohms.



When resistors are connected across each other, they are said to be connected in parallel.
In Example 2, R1 and R2 are connected in parallel. Two resistors in parallel result in a total resistance less than the value of either resistor. If the values of R1 and R2 are identical, then the total resistance is exactly half their value.
For example, if R1 is 1000 ohms and R2 is 1000 ohms, then the total resistance would be 500 ohms.

When parallel resistors are not the same value, then calculations need to be made using the product over sum method.

Product over Sum Method

$$\frac{R1 \text{ X } R2}{R1 + R2}$$

Product means to multiply. Sum means to add. One number over another number means dividing the upper number by the lower number.

If R1 has a value of 1,000 ohms and the R2 value is 2,200 ohms, then the total resistance (Rt) is found as follows.

R1 X R2 = 1,000 X 2,200 = 2,200,000
R1 + R2 = 1000 + 2,200 = 3,200
Rt = 2,200,000 / 3,200 = 687.5 ohms

As you can see, you would be working with some very large numbers if R1 was 100,000 ohms and R2 was 220,000 ohms.

The easy way to handle large numbers with zero digits to the right is to drop the zeros for your calculations, then add the zeros back to the answer. Make sure you drop the same number of zeros from both numbers; you cannot drop five zeros from one number and four zeros from the other.
When you add the zeros back, add them as zeros after the decimal point. Then, move the decimal point to the right, the same number of zeros that were previously dropped. For example, if you are adding four zeros back to a number, move the decimal point four places to the right.

R1 = 100,000 ohms
R2 = 220,000 ohms

(Drop four zeros from both numbers)

R1 X R2 = 10 X 22 = 220
R1 + R2 = 10 + 22 = 32
Rt = 220 / 32 = 6.875

Add four zeros (the number of zeros dropped) to the answer
then
Move the decimal point four places to the right.

6.875
+.0000 ⇐ ADD 4 ZEROS AFTER DECIMAL POINT
6.8750

68,750. ⇐ MOVE DECIMAL POINT 4 PLACES TO THE RIGHT

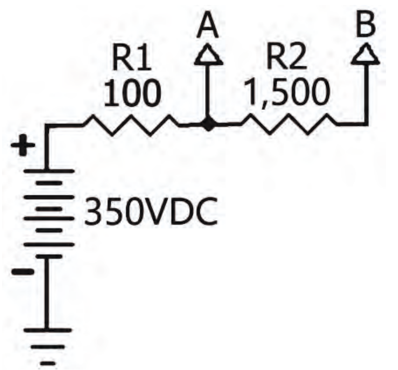
68,750 ohms

Resistance Voltage Drop

Any time there is resistance in a circuit, there will be a voltage drop across the resistance. The amount of voltage drop depends on the current flowing through the resistance. Higher current flow will induce more voltage drop across a resistance. When designing a circuit, Ohms law is used to calculate how much voltage drop there is using the formula E = I X R.

E = voltage in volts I = current in amps R = resistance in ohms

Voltage = I X R (current times resistance)



In the circuit to the left, 350VDC is supplied to circuits A and B, via R1 and R2. Load A draws 100 mA and load B draws 20 mA. To calculate the voltage at points A and B, use Ohms Law.

First, you must convert the currents to amperes. This is simply a matter of moving decimal points three places to the left.

100 mA = 0.100 amps and 20 mA = 0.020 amps

E = I X R (Voltage = current times resistance)

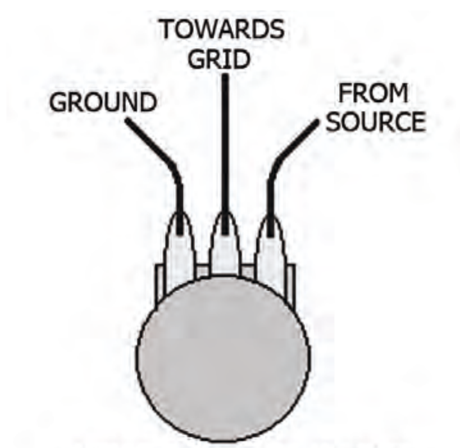
Voltage drop across R1 = 0.100 X 100 = 10 volts.
Voltage at point A is 350 – 10 = 340 volts.

Voltage drop across R2 = 0.020 X 1500 = 30 volts.
Voltage at point B is 340 – 30 = 310 volts.

Potentiometers

A potentiometer (pot) is an adjustable resistor. For vacuum tube amplifier volume and tone controls, they are usually in the range of 100K (100,000) ohms to 1M (1,000,000) ohms with a 1/2 watt power rating.

Potentiometers come in different tapers. The taper is how resistance changes as the pot shaft is rotated. For a linear taper, the resistance changes equally throughout the rotation of the pot shaft.

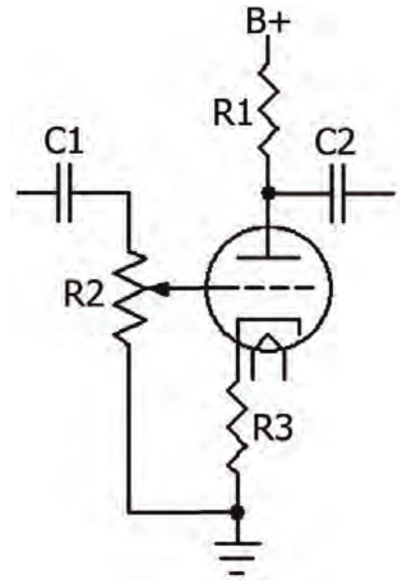


VOLUME CONTROL WIRING
(POT VIEWED FROM REAR)

A pot with an audio taper changes resistance more rapidly as the pot shaft is turned clockwise in a logarithmic manner to follow how the ear perceives loudness. The outer terminals of a pot connect to both ends of the resistance, the fixed resistance value of the pot. The center terminal of a potentiometer connects to a rotating wiper that the pot shaft turns, varying the resistance between the center terminal and the outer terminals.

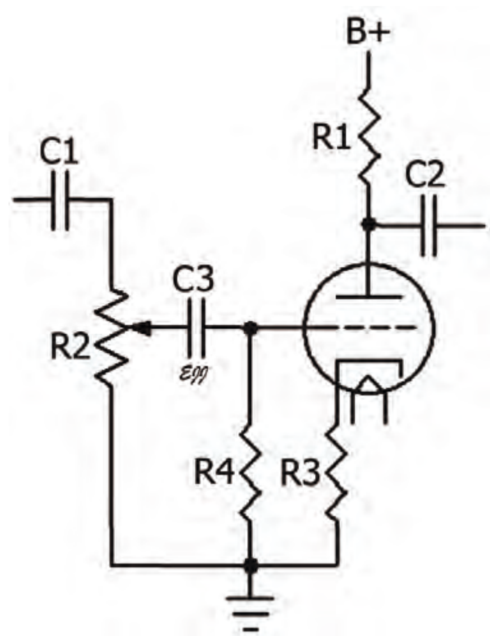
Volume Control

Figure 1



The circuit in Figure 1 shows a common volume control arrangement. The volume control, R2, serves two purposes. First as the volume control and second as the vacuum tube control grid leak resistor[1]. This is not the best arrangement. Performance of a high impedance vacuum tube stage can be affected depending on the position of the volume control. As R2 rotates, the input resistance varies between 0 ohms and the full value of R2. C1 and R2 form an adjustable series tuned circuit to the tube control grid. The tuning effect of C1 and R2 can resonate at audio frequencies and alter the amplifier stage frequency response. Tests done by this author have shown that under certain conditions, as R2 is rotated clockwise towards full volume, frequency response varies as R2 passes through center rotation. Also, R2 can become noisy over time depending on whether grid current passes through the wiper as R2 is rotated.

Figure 2



A better arrangement is shown in Figure 2. In this circuit, C3 is between the R2 wiper and the tube input grid. An additional R4 grid leak resistor is required. The input is more stabilized with a fixed value grid resistor isolated from the volume control by C3. Also, C3 blocks any grid current from flowing through the R2 wiper. To minimize the chance of R2-C1-C3 tuning effects, use an R2 value of 100K. The tuning effect becomes more pronounced with 500K or 1 Meg potentiometers. If R2 connects to an input jack, C1 can be eliminated.

[1] The grid leak resistor drains any built up static voltage that may be at the grid.

Voltage and Current

Very often it is convenient to use one standard reference for all the various potentials throughout a piece of equipment. For this reason, the potentials at various points in a circuit are generally measured with respect to the metal chassis on which all parts of the circuit are mounted. The chassis is normally ground and considered to be at zero potential, all other potentials are either positive or negative with respect to the chassis.

Large values of voltage may be encountered, in which case the volt becomes too small a unit for convenience. The kilovolt (KV), meaning 1,000 volts, is frequently used. As an example, 20,000 volts would be written as 20 KV. In other cases the volt may be too large a unit, as when dealing with very small voltages. For this purpose, the millivolt (mV) meaning one-thousandth of a volt and the microvolt (uV) meaning one-millionth of a volt are used. For example, 0.001-volt could be written as 1 mV and 0.000025-volt could be written as 25 uV.

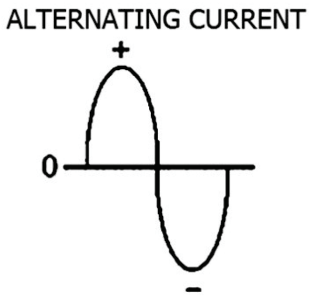
Electric current has been defined as the directed movement of electrons. However, current flow is the terminology most commonly used when describing the directed movement of electrons.

Frequently, the ampere is much too large a unit for measuring current. Therefore, the milliampere (mA) meaning one-thousandth of an ampere or the microampere (uA) meaning one-millionth of an ampere is used. The device used to measure current is called an ammeter.

Direct Current

Direct current (DC) is current with constant polarity, either positive or negative, a steady flow of electrons in a single direction. DC is measured as both current and voltage. For example, 400 volts of DC voltage would be 400VDC and 200 mA of DC current would be 200 mADC. Positive DC is referenced to a common point[1]. For negative DC voltage circuits, positive is the common reference point. Batteries are a source of DC voltage and current.

[1] A common reference point is what measurements are referenced to, usually common ground.



Alternating Current

Alternating current (AC) is constantly changing polarity, swinging from positive to negative back to positive and so on. The center of the wave is usually considered 0 volts as referenced to a common ground.

AC meters usually read the average value. Most low-cost instrumentation such as hand held multimeters carry out this conversion by filtering the AC peak value into an average value and applying a correction factor. The correction factor applied is only correct if the input signal is a sine wave and not a complex wave. In most common multimeters, the AC correction factor is only accurate with a low frequency sine wave, 60Hz (60 cycles per second) for example. Hertz (Hz) is the term used for cycles per second[1]. Multimeters that use AC averaging are accurate enough to measure AC power voltages in an amplifier. They are usually not accurate enough for audio level measurements. For audio measurements, a true RMS meter is required.

A True RMS AC Voltmeter

[1] The term Hertz, used to describe the frequency of alternating current, is named after German physicist Heinrich Rudolf Hertz who proved the existence of the electromagnetic waves predicted by James Clerk Maxwell's equations of electromagnetism. Heinrich Hertz passed away in 1894. The term Hertz was adapted around 1930. However, the term cycles per second was widely used into the 1950s. In 1960, the General Conference on Weights and Measures (CGPM) officially adopte Hertz as the unit for frequency. Since cycles per second made more sense, this resulted in a period of confusion. The change also brought about many corny jokes such as, turn that tone down, it hertz!

Measuring Voltage and Current

High voltage used on vacuum tubes is a shock hazard. Take measurements carefully. Make sure your meter is on the correct range and scale before measuring. This includes an analog or digital meter.

Measuring Voltage

In Figure 1, to measure voltages referenced to ground, you will connect one meter probe to ground, the other meter probe connects to the point being measured. When measuring AC voltages, it does not matter which meter probe you connect to ground, analog or digital meters.

Figure 2 shows measuring an entire transformer's secondary winding. To measure from each side of a transformer's secondary to a grounded center tap, then you should use ground for the meter reference.

FIG 1

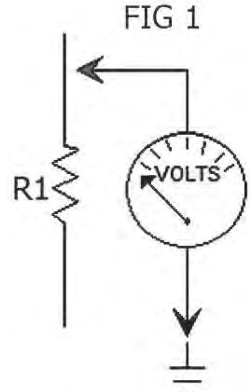
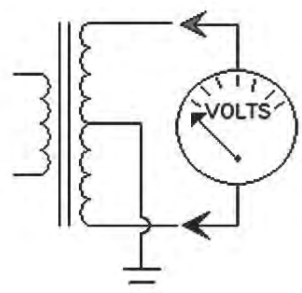


FIG 2



Measuring DC on an Analog Meter

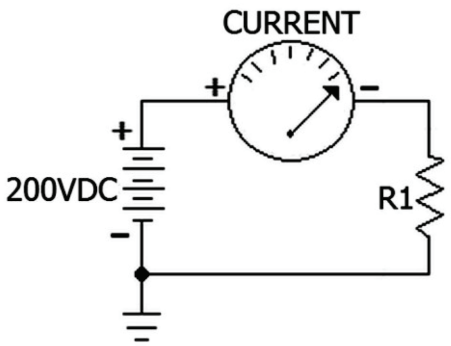
To measure a positive DC voltage such as B+ voltage, you should have the positive meter probe on the point being measured and the negative meter probe connected to ground. When measuring a negative DC voltage such as a grid bias voltage, the negative meter probe should be connected to the point being measured and the positive meter probe connected to ground. When measuring DC with an analog meter connected backwards (reversed), the needle will try to move to the left and could possibly be damaged.

Measuring DC on a Digital Meter

Test probe placement is not critical. Digital meters will read correctly and indicate if the voltage is plus or minus, allowing you to keep the black test probe on ground for all measurements.

Measuring Current

To measure current, you must connect the meter in series with the circuit you are measuring. This requires opening the circuit and inserting the current meter into the circuit.



Measuring DC Current

Analog current meters must be in the circuit with the positive lead towards positive voltage and the negative lead towards negative. Digital meters can be inserted into a circuit without concern for polarity; the meter will read correctly and indicate plus or minus.

AC current

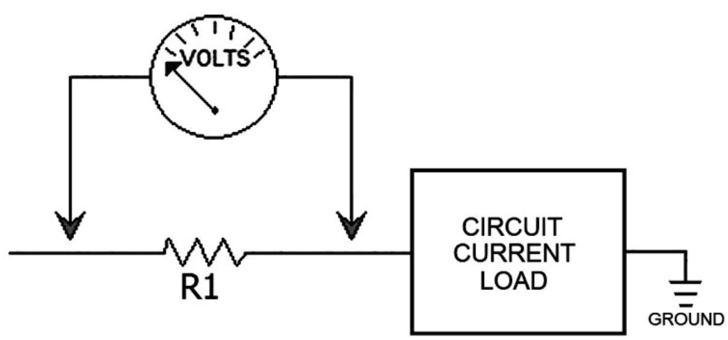
For AC current, meters can be inserted either way into a circuit.

When measuring current with either an analog or digital meter, it is important to make sure you have the meter set to the correct scale. If you feed more current than the meter scale indicates, you will most likely be replacing a fuse in the meter or possibly damage the meter. When in doubt what scale to use, always start with the highest current scale and switch down the scales until you get a reading.

Measuring Current Across A Resistor

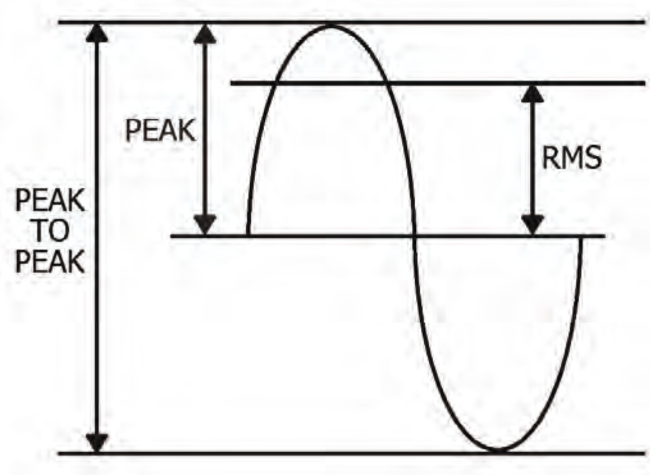
You can use a volt meter to measure the current flowing in a circuit by measuring the voltage across a resistor in series with the circuit. Then, using the values of the resistor and the measured voltage, you can use Ohm's Law to calculate the current. In the illustration, if R1 is 2K (2000) ohms, and you measure 150 volts across R1, then using Ohm's Law,

$$I = E / R \quad I = 150 / 2000 = .075 \text{ amps } (75 \text{ mA})$$



RMS and PEAK

When measuring AC with a volt meter, you normally will be reading the RMS[1] value. The RMS value is an average of the peak value of the AC voltage. It is the peak and RMS values of AC voltage that are usually referred to.



Consider that you are measuring from a reference point of 0; the center of an AC waveform is 0. What you are measuring on a volt meter is the positive or negative values and not the entire waveform. Most digital meters read RMS values, although some may have an option to read the peak value.

A voltmeter is seeing the positive (or negative) as separate cycles and not as a whole cycle. In order to measure peak to peak, you need to measure across the entire waveform, such as with an oscilloscope. The oscilloscope sees both positive and negative as a complete cycle of the waveform. There are conversion constants to convert from RMS to peak or peak to RMS.

To find the peak voltage when you know the RMS voltage,

(RMS VOLTAGE) X 1.414

To find the RMS voltage when the peak voltage is known,

(PEAK VOLTAGE) X .707

[1] The root-mean-square (abbreviated RMS) is a statistical (average) measure of the magnitude of a varying quantity. It is especially useful when variants are positive and negative, e.g., sinusoids (sine waves).

Voltage Dividers

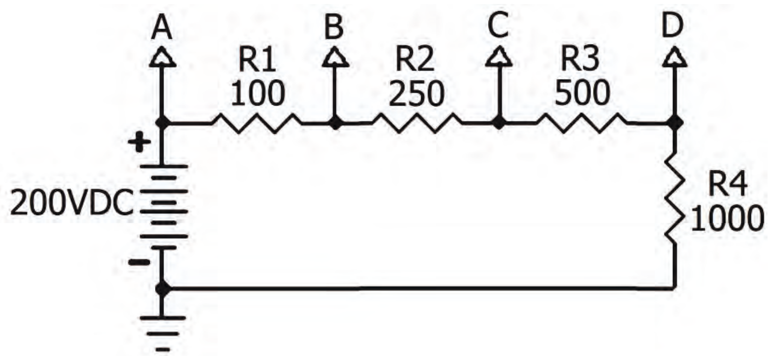
Closed Loop Circuit Divider

In Figure 1, because the divider is a complete series circuit from the 200 volt supply positive to negative, it is considered a closed loop. The negative side of the battery is connected to the ground circuit. Using ground as 0 volts for our reference, we want to know the voltages at points A, B, C and D. Since point A connects directly to the battery power source, we know A is 200 volts. In order to find the voltages at B, C and D we need to calculate the current in the circuit. The value of each resistor is known. To find current in the circuit, add up the total resistance of the circuit. Then, use Ohms Law to calculate the current.

Total Resistance
R1 + R2 + R3 + R4
100 + 250 + 500 + 1000
=1850 ohms

Current in the Circuit
I = E / R
200 / 1850 = 0.108 amps

Figure 1



Voltage along a series circuit will decrease as it passes through resistance. This means the voltage at point B will be lower than at point A, voltage at point C lower than at Point B and point D lower than point C.

To find the voltage at point B, calculate the voltage drop across R1, then subtract the R1 voltage drop from the 200V supply voltage.

The voltage drop across R1 = 0.108 X 100 = 10.8 volts (E= I X R).
Subtract 10.8 volts from 200 volts, 200 − 10.8 = 189.2 volts.
The voltage at point B = 189.2 volts.

To find the voltage at point C, calculate the voltage drop across R2, then subtract the R2 voltage drop from the voltage at point B.

The voltage drop across R2 = 0.108 X 250 = 27 volts (E= I X R).
Subtract 27 volts from 189.2 volts, 189.2 − 27 = 162.2 volts.
The voltage at point C = 162.2 volts.

To find the voltage at point D, calculate the voltage drop across R3, then subtract the R3 voltage drop from the voltage at point C.

The voltage drop across R3 = 0.108 X 500 = 54 volts (E= I X R).
Subtract 54 volts from 162.2 volts, 162.2 − 54 = 108.2 volts.
The voltage at point D = 108.2 volts.

Closed loop voltage dividers are not very accurate. Loads between taps interact with each other. Setting the divider current high to reduce interaction wastes power in the form of heat dissipated from the divider. Closed loop voltage dividers can be useful in low current applications.

Series Fed Voltage Divider

Series fed voltage dividers are basically a string of resistance in series that is not connected in a loop configuration. One end of the divider connects to the B+ supply and the other end of the divider ends at the last load.

Vacuum tube amplifier power supplies usually use a series fed method of B+ distribution starting from the rectifier and then going through a series of voltage dropping resistors.

Figure 2

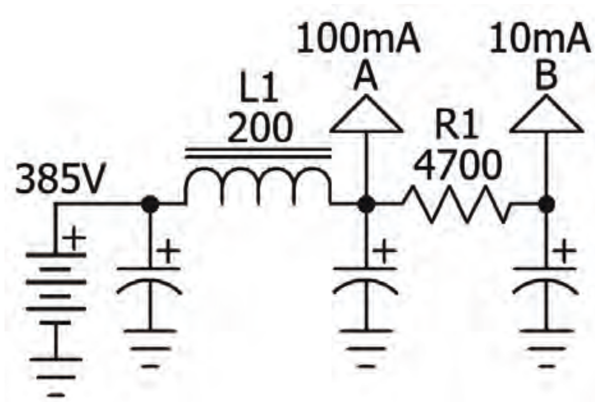


Figure 2 is B+ distribution in a vacuum tube power amplifier. Point A would feed the output tube and point B would feed the driver stage. Since the divider has no loop to common ground, there is no current flow through the divider itself. Current flow is dependent on the loads at A and B.

Calculating load voltages is similar to that of a closed loop voltage divider.

Current L1 = 100 mA + 10 mA = 110 mA = 0.110 amps
E = I X R   0.110 X 200 = 22 volts
Voltage drop across 200 ohm L1 = 22 volts
Voltage at point A = 385 − 22 = 363 volts

Current R1 = 10 mA (0.010 amps)
E = I X R   0.010 X 4700 = 47 volts
Voltage drop across R2 = 47 volts
Voltage at point B = 363 − 47 = 316 volts

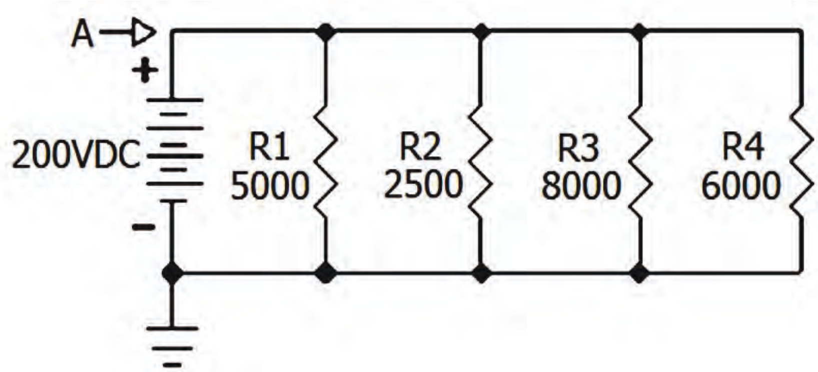
Calculating the power dissipation in resistor R1 so we know what power rating R1 needs to be.
$P = I^2 \times R$ I R1 = 0.010 amps
R1 = (0.010 X 0.010) X 4700 = 0.0001 X 4700 = 0.47 watts
Use a 2 watt resistor

Parallel Circuit Current Divider

Parallel circuits are circuits that are connected across each other. When circuits are in parallel, the current splits between all the circuits. The total current is equal to the sum of all the circuit currents added together. The voltage across each resistance equals the supply voltage.

In Figure 3, R1 through R4 are connected across the supply battery. There is a voltage across each resistor equivalent to the supply voltage of 200 volts.

Figure 3



To find the total current load at point A, we need to calculate the current going through each resistance, and then add up all the currents.

I = E / R
R1 Current = 200 / 5000 = 0.040 amps.
R2 Current = 200 / 2500 = 0.080 amps.
R3 Current = 200 / 8000 = 0.025 amps.
R4 Current = 200 / 6000 = 0.033 amps.
Total Current At Point A
0.04 + 0.08 + 0.025 + 0.033 = 0.178 amps

Inductors and Transformers

Inductors are coils of wire wound in even flat layers with several layers of windings on top of each other; the number of turns or layers depends on the inductors application. Current through an electrical conductor induces an electromotive force in the conductor setting up a field around the conductor. Inductance is a property of a conductor which opposes any change in current through the conductor. There are two basic types of inductors, air core and iron core. Air core inductors are wound on a coil form with nothing but air within the coil form. Iron core inductors are wound on an iron core. Adding iron to the core increases inductance. Air core inductors are primarily used for RF work. Iron core inductors are used for audio and power supply applications.

Inductive Reactance

When AC current flows through an inductor, a back or counter-force is developed opposing any change in the initial current. This property of an inductor causes it to have opposition or impedance to a change in current. The measure of impedance of an inductor to AC current is known as inductive reactance. Iron core inductors called chokes are used in power supply circuits. The inductive reactance of a choke opposes the AC component of the DC, filtering out a large portion of the AC component from the DC.

Inductive Coupling

When one inductor is placed next to another inductor and the first inductor has AC current passing through it, the first inductor produces a varying magnetic field that cuts through the second inductor, inducing an AC current in the second inductor. This is the basis of how a transformer works.

Transformers

A transformer is made up of two or more inductors wound on the same iron core. AC current is fed to the input inductor called the primary winding. The alternating current creates a magnetic field and the primary AC current is induced into the other transformer inductors called secondary windings.

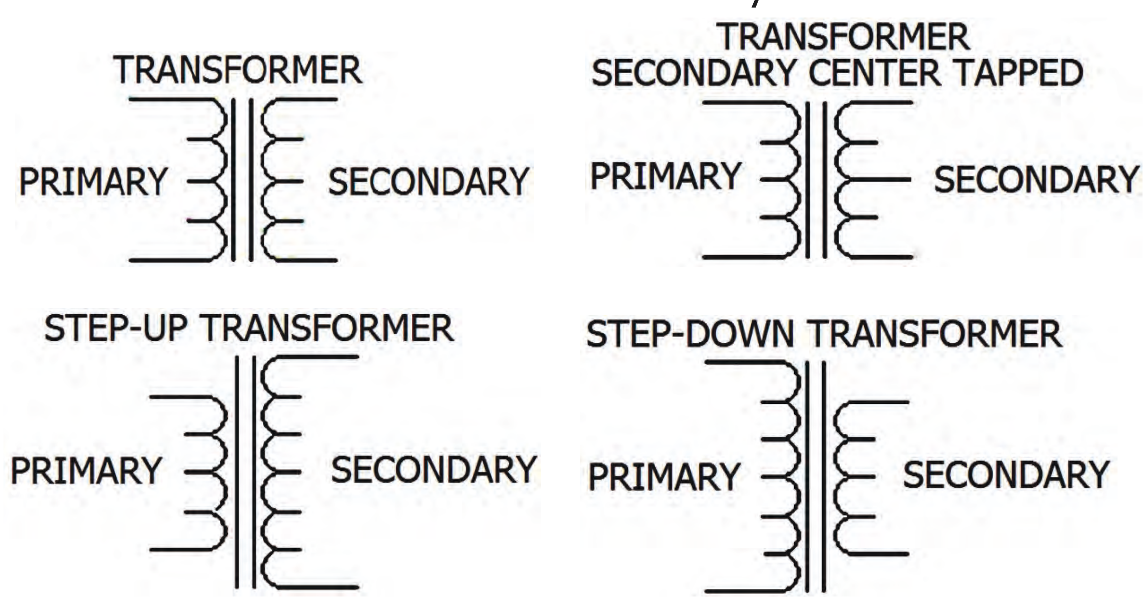
The number of windings on an inductor can be different. If the secondary winding is larger than the primary winding, the secondary will have more voltage than the primary. This is called a step-up winding. If the secondary has fewer windings than the primary winding, the secondary will have less voltage than the primary. This is called a step-down winding.

Eddy Currents and Hysteresis Loss

Transformers have some loss due to magnetic flux currents known as eddy currents induced on the surface of the iron core which in turn produce heating and reduce the amount of power to the secondary coil. Also, each time the direction of AC magnetization is reversed, some energy is wasted in overcoming internal electrical friction. This is known as hysteresis loss and also produces heating. Transformers are about 95% efficient; the lost energy is dissipated as heat depending on the amount of secondary loading. A transformer that is loaded at its maximum current rating will run warmer than if loaded at half its current rating.

Because there are separate windings in a transformer, isolation is provided between the primary and secondary. In power transformers, this isolation reduces shock hazard between the device and the 120V (or 240V) mains supply. A transformer may have several secondary windings wound on a single core.

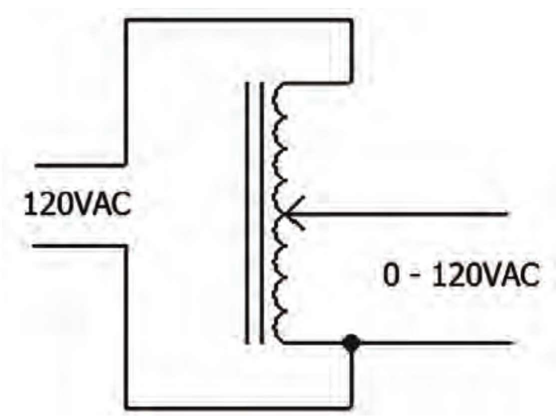
Transformer circuit symbols



Adjustable Transformer

An adjustable transformer, also known as an auto-transformer, is a tapped single winding transformer with the tap being adjustable. Adjustable transformers are used when there is a need to have continuous adjustment of the AC voltage by rotating a knob similar to a potentiometer. The entire winding is the primary and the adjustable tap and one portion of the winding is the secondary.

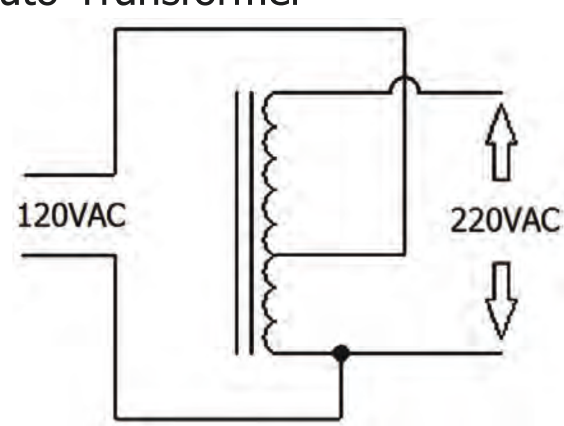
Adjustable Auto-transformer



Unlike a dual winding transformer, the adjustable transformer offers no isolation between primary and secondary windings. Auto-transformers tend to be quite expensive and generally are only used when it is necessary to adjust the primary voltage of equipment. Some auto-transformers have taps, allowing the primary voltage to be boosted, usually around 20% higher.

Non-Adjustable Auto-Transformer

A non-adjustable auto-transformer is sometimes used to boost or reduce voltage. The transformer shown to the right would be a step-up auto-transformer. As with the adjustable transformer, there is no isolation between the primary and secondary.



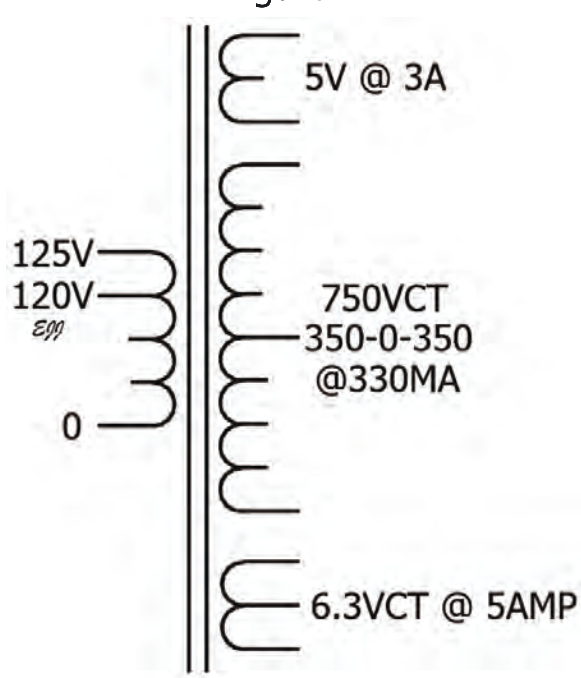
Power Transformers

Figure 1

Figure 1 is a typical power transformer for use in a vacuum tube amplifier. The circuit drawing for a power transformer is shown in Figure 2.

Power transformers are available in different transformer enclosures. The one shown is a chassis top mount style where the wires feed through holes in the chassis. A variation of chassis top mount requires a large square or rectangle hole that the bottom of the transformer fits through. With this style, there may be wires or terminal connections. Regardless of the style of enclosure, all transformers work the same.

Figure 2



Specifications for a power transformer are usually stated as shown in Figure 2. The primary is shown as having two voltage selections, 120 volts or 125 volts. The high voltage winding is center-tapped for a full wave rectifier. There is a five volt winding for a 5U4 rectifier tube filament. The 6.3-volt filament winding has a center tap. By grounding the 6.3-volt center tap, the filament line is balanced for reduced filament induced hum.

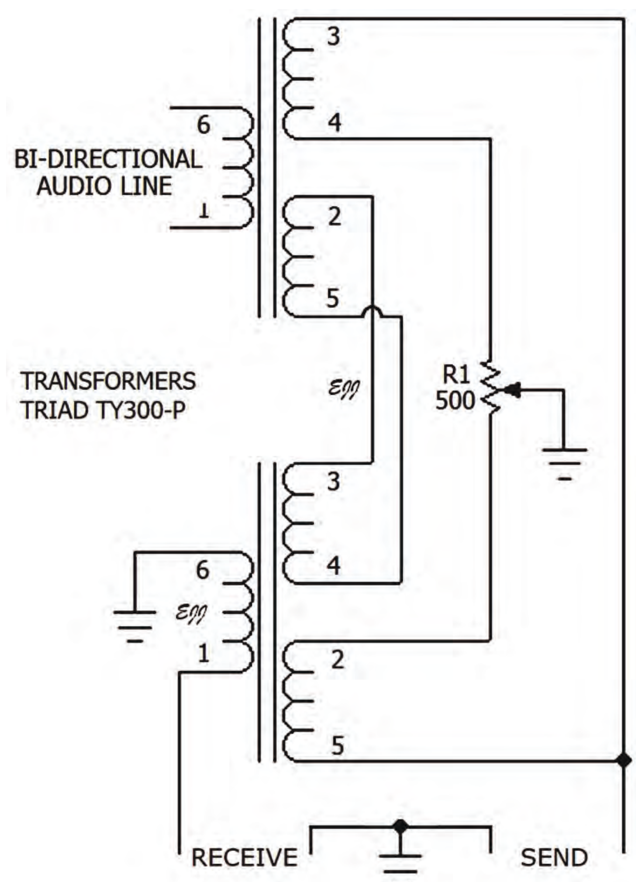
Input Transformers

A transformer can be useful for low level inputs. A 150 ohm to 20,000 ohm transformer provides a balanced input ideal for long low impedance microphone cable runs. Using an input transformer provides significant voltage gain, requiring less amplifier gain, reducing amplifier noise.

Transformer Hybrid

Audio hybrid circuits allow separating send and receive audio from a single pair of wires; hybrids were originally used with telephone landlines. These days, hybrid functions are pretty much done with digital circuits that automatically balance the hybrid. On occasion, it may be handy to have a simple transformer hybrid.

Special hybrid transformers are used that have three identical windings that are usually 600-ohm impedance. Two transformers are required. Operation is such that a line connected to a bidirectional winding has audio going in both directions. Audio coming from the bidirectional line is received through the hybrid and audio is fed down the bidirectional line through the hybrid. Using two sets of windings out of phase and a null balancing circuit (R1), the send audio is canceled out of the receive winding. Audio coming into the hybrid through the bidirectional winding is coupled to receive.



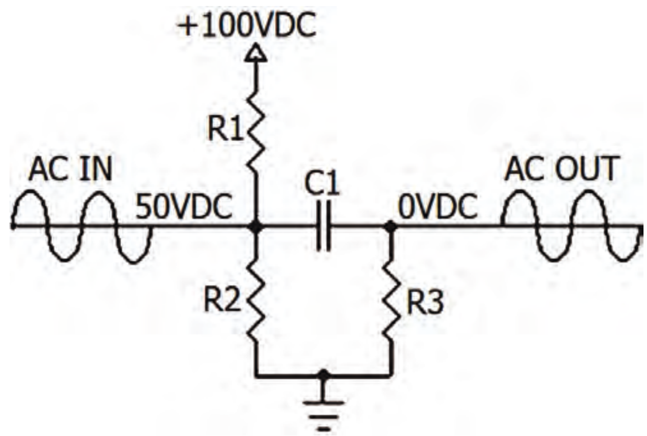
In practice, the best you can expect to null is about 40 dB separation between send and receive.

Circuit is from EJ Jurich broadcast archive.

Capacitors

A capacitor is a device that contains two plates separated by an insulator; the plates are not electrically connected. Since the plates have no electrical path, current will not flow across them. This completely blocks DC from passing through. However, when DC is applied to a capacitor, there is a static charge created that produces a momentary pulse across the plates.

AC will pass, or at least appear to pass through a capacitor. The AC signal does not actually pass through the capacitor plates. The AC signal charges and discharges the plates as the AC signal cycles positive and negative. As the capacitor charges and discharges during the AC cycle, a cycling charge will be present on the second capacitor plate.



In the illustration, if R1 and R2 were equal values of resistance, then the voltage in the middle would be 50 volts. R2 and R3 are grounded, providing a complete current path for current to flow. When 100VDC is first applied, capacitor C1 will charge through R3. While the capacitor is charging, there will be a DC charge pulse on the R3 side of the capacitor. The DC pulse at R3 will rapidly decrease as the capacitor plates charge. Once the capacitor has charged, there will no longer be any charge voltage on the R3 side of the capacitor. The DC charge at R3 can be a fast pulse or gradual depending on the capacitance value.

When an AC signal is applied, the charging and discharging across the capacitor plates is equal to each positive and negative cycle of the AC signal. This will allow the AC signal to appear on the R3 side of the capacitor.

Although most capacitors provide satisfactory performance, certain types of capacitors may be preferred for use in an amplifiers' audio path. A Texas Instruments Analog Design Journal article, Selecting Capacitors to Minimize Distortion in Audio Applications, written by Zak Kaye, Applications Engineer, ran tests on capacitors to find those that induce the least distortion.

In the article, there are two types of capacitors recommended for lowest distortion. The C0G/NP0 multilayer ceramic capacitors and polyethylene or polypropylene type film capacitors. Multilayer ceramic capacitors are physically smaller, but tend to have short wire leads. Polyethylene or polypropylene film capacitors are what would be considered a standard size with long wire leads.

The difference between Class I and Class II multilayer ceramic capacitors (MLCC) are explained. MLCC capacitors are organized into different classes depending primarily on their thermal range and stability over that range. Class II ceramics are often referred to as "high k" because their relative permittivities[1] (of insulator dielectric) range from 3,000 (X7R) up to 18,000 (Z5U). By contrast, Class I C0G/NP0 capacitors tend to have relative permittivities in the range of 6 to 200. They are "high-performance" ceramic capacitors because their capacitance is more stable than most other dielectrics. Plastic film capacitors that use materials like polyethylene or polypropylene tend to have even lower relative permittivities, typically less than 3, and also offer very good stability.

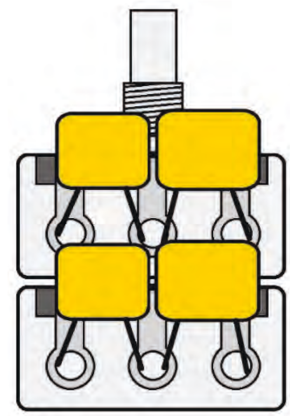
The article explains the sort of distortion that is encountered depending on the dielectric materials used to insulate between the capacitor plates.

When a capacitor's dielectric relative permittivity is very high, its capacitance changes significantly over applied voltage and temperature, which can degrade signal-chain performance. Applying a time-varying voltage to the capacitor results in a time-varying capacitance, distorting the current flowing through the capacitor. The change in capacitance with applied voltage is known as the capacitor's voltage coefficient, and it can be the dominant source of distortion in the low-frequency spectrum where capacitor impedance is relatively high. Minimizing the voltage drop across the capacitor will mitigate distortion. One approach to doing this is to increase the impedance in series with the capacitor to limit the current flowing through it. Another option is to increase the value of the capacitor until its impedance is low enough in the band of interest to reduce its distortion.

[1] Permittivity: the ability of a material to store electrical energy under the influence of an electric field with respect to capacitance and dielectric, the lowest value being preferred.

In Zak Kaye's article, he mentions that to reduce its distortion, increase the value of a capacitor until its impedance is low enough in the band of interest (for instance, 20 Hz to 20,000 Hz). It's a matter of calculating the –3 dB cutoff frequency of the capacitor-load impedance to the lowest possible value. For instance, a .47 uF capacitor will have a lower –3 dB cutoff frequency than a .1 uF capacitor. Calculating the –3 dB cutoff frequency is covered on page 47.

Although Class 1 (C0G/NP0) multilayer ceramic capacitors have short wire leads, their smaller size may be ideal for use where a capacitor connects across terminals that are close together. For example, across terminals on a potentiometer.



The Texas Instruments Analog Design Journal article, Selecting Capacitors to Minimize Distortion in Audio Applications, written by Zak Kaye, should be readily available online.

Leakage

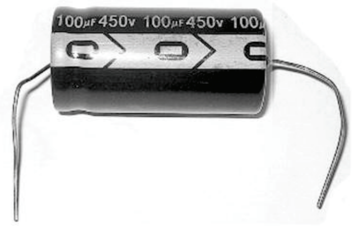
Leakage is when the dielectric insulating material used to isolate the capacitor plates allows some current to pass between the plates. For some applications such as power supply filtering, some leakage is not a problem. Electrolytic-type capacitors tend to leak current more than dry-type capacitors especially as they age.

Voltage Rating

The voltage rating of a capacitor should be higher than the voltage of the circuit the capacitor is used in. For instance, in a 400-volt circuit, you would use a capacitor rated at 450 or 500 volts. A good rule of thumb is to select the high voltage capacitor ratings for the no-load voltage value. This would be the initial high voltage before the tubes warm up and start drawing current.

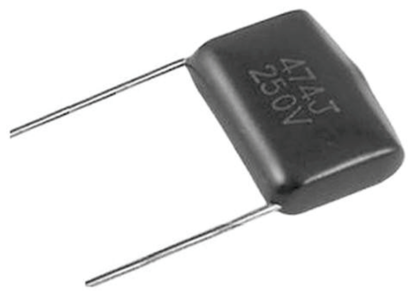
Electrolytic Type Capacitors

Band or arrow indicates negative lead



Dry Type Capacitors

Used in the amplifiers audio path



Reading Capacitor Values

Capacitor values are usually in uF, nF or pF

(uF, microfarad, one-millionth of a farad)

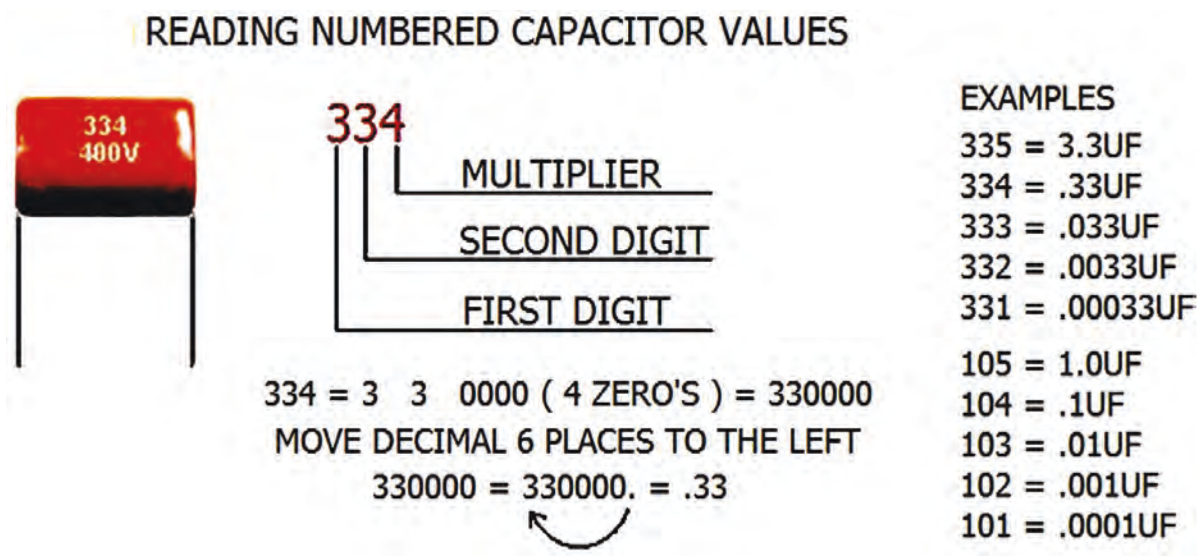
(nF, nanofarad, one billionth of a farad)

(pF, picofarad, one trillionth of a farad)

.01 uF = 10 nF = 10,000 pF

Abbreviations may be all lower case
E.g., uf, nf, pf

Capacitors may be marked using a number system or their actual value. No matter how they are marked, their value is always some division of a Farad. In vacuum tube circuits, microfarads are the majority of capacitor values.



Decimal Placement Examples

101 = 100 pF or .1 nF or .0001 uF

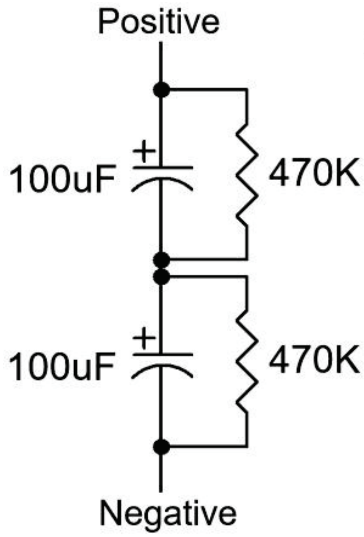
(10 + one zero = 100. pF)

474 = 470,000 pF or 470 nF or .47 uF

Connecting Capacitors Together

When connecting capacitors in parallel, the total capacitance will be the total of adding all the capacitor values together. For instance, with .01uF, .022uF and .047uF connected in parallel, .01 + .022 + .047 = .079 uF. In parallel, all capacitors should have the same voltage rating.

When connecting capacitors in series, the total capacitance will be less than the lowest-value capacitor. Two capacitors with the same value in series will have a total capacitance of 1/2 the value of either capacitor. Voltage will split about equal across both capacitors. For instance, two .01 uF capacitors in series will have a total capacitance of .005 uF. Capacitors of unequal value in series will not split the voltage equally between the capacitors with the higher voltage across the smaller capacitance value.



A higher voltage capacitor can be created using lower voltage capacitors. For instance, power supply filtering using two electrolytic 100 uF 450V capacitors connected in series. This would have a combined value of 50 uF with a total voltage rating of 900 volts, the voltage divided between the two capacitors. However, unless the capacitor values are closely matched, the voltage will not split equally across each capacitor. Connecting a 470K two-watt resistor across each capacitor will help equalize the voltage across the capacitors. Using values lower than 470K will better equalize the voltage, but has the same effect as increasing leakage.

Even with equalizing resistors, the voltage will be slightly different across each capacitor. It would be best to reduce the voltage rating a bit. This method of stacking capacitors in a power supply circuit can save some money. Higher voltage filtering capacitors with axial wire leads are getting hard to find and can get very expensive. Lower voltage radial lead filtering capacitors are less expensive.

As with any polarized capacitor, the positive end must connect towards a positive potential and the negative end must connect towards a negative potential. Polarized capacitors must be connected with proper polarity.

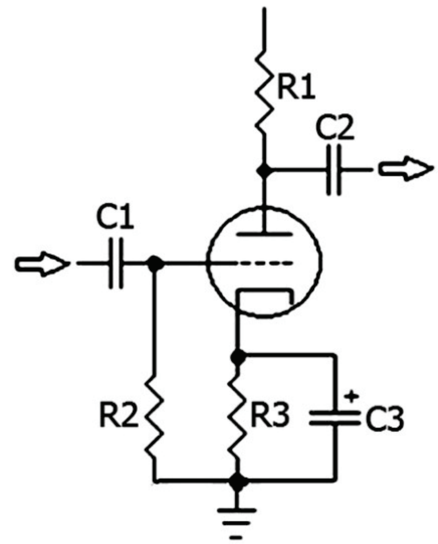
Classic Amplifier Kits

Cathode Bypass Capacitor

A cathode bypass capacitor is a capacitor connected across the cathode resistor of a vacuum tube. Cathode bypass capacitors are used only in self-bias circuits where resistance in the cathode circuit is sufficiently high to make the cathode a few volts positive.

In Figure 1A, C3 is the cathode bypass capacitor. Capacitors used to bypass the cathode are usually electrolytic types with values in the range of 10 uF to 100 uF or higher. Voltage rating can range from 25VDC to 100VDC depending on the voltage at the cathode. The bypass capacitor serves as an AC bypass. The cathode biasing resistor R3 is used to develop bias voltage on the cathode. The C3 capacitor is used to regulate the current flow through the bias resistor by giving the AC signal a direct path to ground.

Figure 1A



This is considered bypassing or eliminating the effect of the AC input signal on the cathode; the input signal flows through the capacitor to ground. Without the bypass capacitor, the input signal would be present at the cathode, causing bias voltage to vary with the input signal.

Sometimes, in the case of push-pull or balanced circuits, a pair of tubes driven by identical signals may share a common unbypassed cathode resistor. The cathodes are connected together using a single cathode resistor without a bypass capacitor. Then, differences in tube conduction are balanced by bias variations that tend to reduce distortion.

Capacitors and Heat

When wiring components, it is often convenient to place the output tube bypass capacitor over the cathode resistor. However, it is important that the bypass capacitor is not touching the cathode resistor. Heat from the cathode resistor can shorten the life of the bypass capacitor.

Without A Bypass Capacitor

Although a cathode bypass capacitor is recommended for output tubes, there may be an advantage to eliminating bypass capacitors on voltage amplifiers that precede the output tube.

In Figure 1A, without C3, consider the voltage drop at the cathode end of R3 to be +10 volts. When applying a positive-going signal to the grid of the tube, as the positive signal is applied, conduction through the tube will increase. The current through R3 will also increase.

This will increase the voltage drop across R3 and the cathode voltage will now be greater than +10 volts. At the same time, positive voltage at the plate is going down due to increased conduction through the tube and the resulting increased voltage drop across R1. The combination of the ‘negative-going’ plate and ‘positive-going’ cathode work against each other, effectively canceling some of the gain.

When a negative-going signal is applied, conduction through the tube decreases. Current through R3 decreases and the voltage drop across R3 decreases. This causes the cathode voltage to be less than +10 volts. The negative-going signal decreases plate current, reducing the voltage drop across the R1 plate resistor, allowing positive voltage on the plate to increase. The combination of the ‘positive-going’ plate and ‘negative-going’ cathode also work against each other, effectively canceling some of the gain.

Without a bypass capacitor across the cathode resistor, allowing cathode biasing to follow the input signal, gain of the amplifier stage is reduced. Conventional thinking is that without a cathode bypass capacitor, distortion increases as gain is reduced. In fact, just the opposite is true. The degeneration effect of not bypassing the cathode is similar to negative feedback, reducing distortion. This is especially true in a voltage amplifier stage when high input levels drive the tube closer to saturation. Without a cathode bypass capacitor, the stage will achieve a higher output level before reaching 1% total harmonic distortion than with a bypass capacitor. The 12AX7 chart of measured values on page 71 demonstrates circuit performance without and with a bypass capacitor.

Capacitor Reactance

As explained on page 60, Capacitors have high values of reactance at low audio frequencies, but at higher frequencies the reactance falls to a lower level. Capacitive reactance can restrict lower range frequency response and cause low frequency phase shift. To keep low frequency cutoff and phase shift distortion at a minimum, capacitor and resistor values should be selected for a low frequency 3 dB cutoff point as low as possible.

When using capacitors to couple between amplifier stages, the combination of the capacitance and the value of load resistance on a capacitor results in a cutoff frequency. In Figure 1B, the R2 load on C1 will result in a cutoff frequency. The same is true with the R4 load on C2. Using the formula for frequency cutoff (f_c) we can calculate the minus 3 dB point of roll-off.

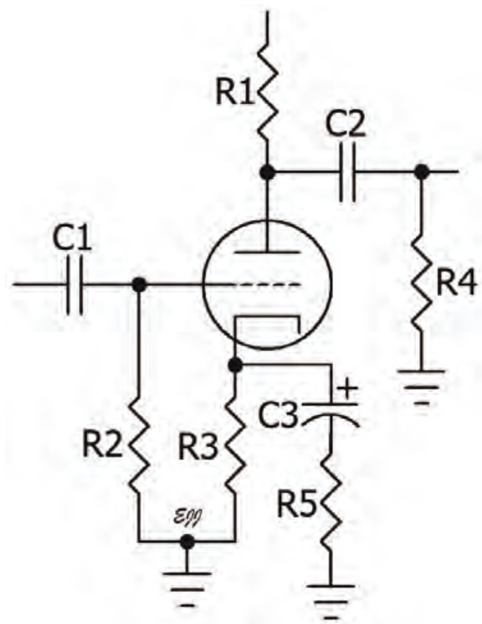


Figure 1B

$$fc = \frac{1}{2\pi RC}$$

fc = frequency cutoff
$2\pi = 3.14 \times 2 = 6.28$
R = Resistance
C = Capacitance

For example, consider a C1 value of .01 uF and an R2 value of 470K.

$f_c = 1 / 2\pi$ X (R X C)
$f_c = 1 / 6.28$ X (470,000 X 0.00000001)[1]
$f_c = 1 / 6.28$ X .0047
$f_c = 1 / .0295$
$f_c = 34$ Hz

$\pi = 3.14 \quad 2\pi = 6.28$
π = symbol for pi

You can save time calculating the capacitor resistor 3dB frequency cutoff point by searching online for 'RC high pass filter frequency cutoff calculator'.

A 3 dB roll-off at 34 Hz may not seem bad. However, the capacitive reactance phase shift at 100 Hz is 19° and 34° at 50 Hz. (° is the symbol for degrees).

[1] Values must be resistance in ohms and capacitance in Farads. Convert uF to Farad by moving the decimal point six places to the left, .01 uF = .00000001 Farad.

To reduce low frequency phase shift, capacitor values should be selected for a 3 dB cutoff frequency of less than five hertz (5Hz). Cutoff frequencies for other values in the Figure 1B circuit, C1/R2 and C2/R4 (phase shift at 50 Hz).
.1 uF and 470K ohms, 3 dB cutoff frequency = 3.4 Hz (3.9°)
.1 uF and 100K ohms, 3 dB cutoff frequency = 15.9 Hz (17.7°)
.47 uF & 100K ohms, then 3 db cutoff frequency = 3.4 Hz (3.9°)

Adding Resistance to Cancel Reactance

In Figure 1B, the cathode bypass capacitor C3 has a resistor in series with it. The resistance acts to offset capacitive reactance of the capacitor. Any value capacitor will have voltage lagging current by ninety degrees. When resistance is added in series with a capacitor, the voltage lag (phase shift) decreases.

For example[1],

100 uF with series resistance of 0 ohms at 50 Hz = 90°
100 uF with series resistance of 50 ohms at 50 Hz = 33°
100 uF with series resistance of 100 ohms at 50 Hz = 18°
100 uF with series resistance of 200 ohms at 50 Hz = 9°
200 uF with series resistance of 0 ohms at 50 Hz = 90°
200 uF with series resistance of 50 ohms at 50 Hz = 18°
200 uF with series resistance of 100 ohms at 50 Hz = 9°
200 uF with series resistance of 200 ohms at 50 Hz = 4.5°

It can be seen that larger values of capacitance require less series resistance to lower voltage/current phase shift. It is best to use a large value capacitor when bypassing a cathode. Adding resistance in series with the bypass capacitor not only reduces phase shift, but will also slightly reduce stage gain.

Although adding resistance in series with a cathode bypass capacitor reduces voltage phase shift, it is not practical to add resistance in series with capacitors used for plate/grid coupling. The required series resistance would be high enough to cause unwanted signal attenuation.

[1] Calculations using Series RC Circuit Impedance Calculator at mathforengineers.com. www.mathforengineers.com/AC-circuits-calculators/series-RC-circuit-Impedance.html

Grounds

All ground circuits should be connected together with wiring. Terminal strips with ground lugs are usually connected to the chassis through the terminal strip mounting screw. Wiring all the ground terminal connections together will maintain a good ground circuit, even if terminal mounting screws become loose. This author has wired many projects using the chassis grounded terminal of terminal strips. Essentially, this creates multiple ground points, but generally does not cause ground loop problems. The key is wiring all the ground circuits together. The chassis may be a conductor, but not as good a conductor as copper wire.

Shielded Wiring

Shielded wiring (cables) inside a chassis should have the shield connected at only one end, preferably away from sensitive amplifier stages.

Connector Grounds

Unbalanced Connector

Unbalanced line level input and output connectors such as RCA jacks can usually be mounted directly onto a chassis. To insure a good ground, run a ground wire from the RCA jack ground lug to the ground circuits. On high gain circuits such as a turntable pre-amplifier, it would be best to use RCA jacks that are insulated from the chassis. Then, using the shield wire of a shielded cable, run an isolated ground wire, connected at both ends, from the RCA jack to a ground circuit at the turntable pre-amplifier tube input.

Balanced Connector

Balanced XLR connectors have an isolated ground connection and can be mounted directly onto a chassis. There are usually three connections on a balanced XLR connector. Pin 1 is grounded and is normally connected to the chassis. On cables used for a balanced input or output, pin 1 ground is the cable shield. Since the cable shield is subject to picking up noise, it is best not to connect pin 1 of a balanced input near a critical pre-amp ground.

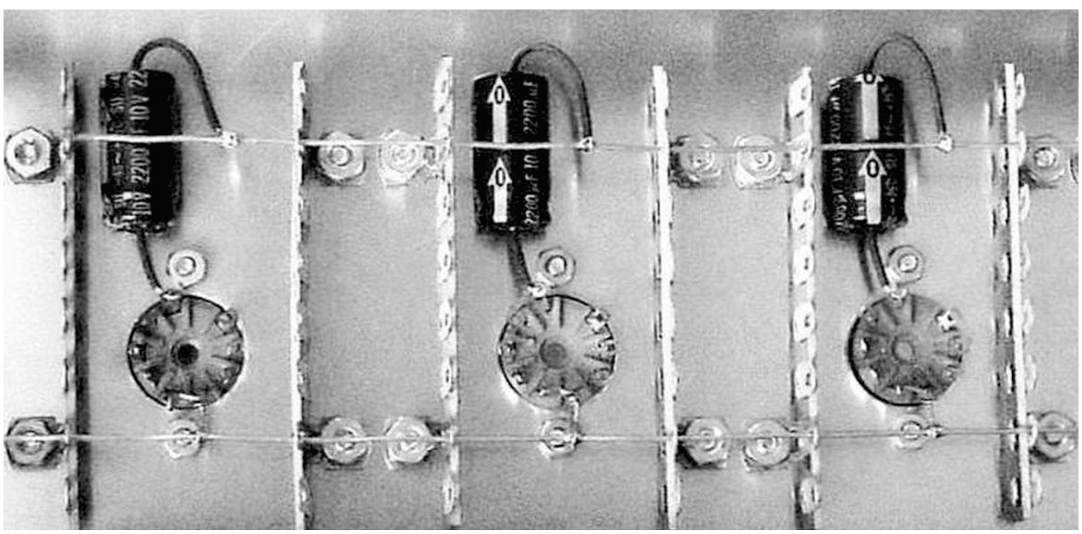
Ground Loops

When a terminal strip mounting tab is also a ground lug connection point, there is a chance of creating ground loops. The chassis is not as good a conductor as copper wire. An aluminum chassis is a better conductor than steel, but copper is better.

Depending on a chassis for a common ground can create unpredictable ground circuits that mix power supply currents with audio circuits. The result can be power supply hum and other noise in sensitive audio circuits.

Terminal strip grounded lugs may be used for ground connections as long as they are wired together in a ground circuit. This author has used this method on several projects without any hum problems.

Create a ground buss through terminal strips. If possible, line up terminal strips such that you can run a buss wire through the terminals. If you need to ground a component lead, you can solder anywhere along the buss wire. Tinned #18 gauge solid wire is a good choice for ground buss use.



Another option that involves more work is a ground circuit that is isolated from the chassis, preferably with 20 AWG-sized wire.

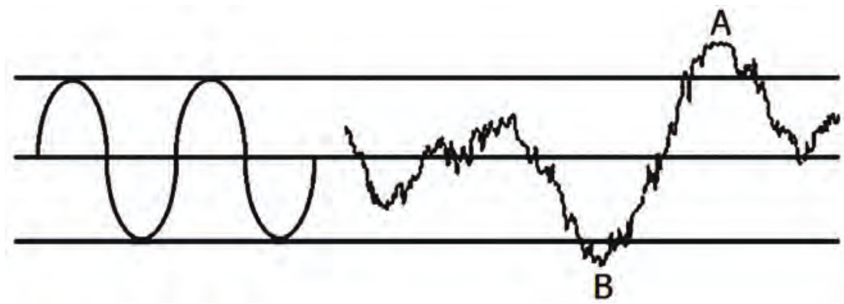
Although turret style terminal boards provide easy access to components, they tend to make circuits more spread out. With circuits more spread out, the chance of picking up hum and other noise increases.

Headroom

Headroom in an amplifier refers to how close the signal is to the amplifier's clip point (saturation). When a signal reaches the point of maximum amplification, it is cut off or clipped. The signal going into the amplifier may increase, but the signal output flattens past the clip point. The result is an increase in distortion as you exceed the clip point.

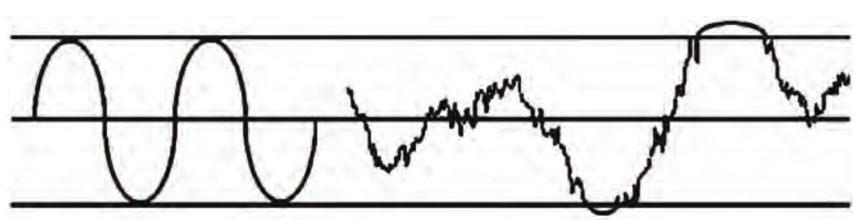
The clip point can be found by feeding a continuous tone into an amplifier. While monitoring the amplifier's output on an oscilloscope[1], increase the input level until you observe the signal flattening. Then, reduce the input level until you are just below clipping. This is the point of maximum amplification. At maximum amplification, there is no headroom. To insure complex audio signals do not get clipped, you would want to operate an amplifier with plenty of headroom below this point. If you will be operating an amplifier at full volume, make sure you have a load on the amplifier output. For power amplifiers, an 8-ohm wire wound power resistor should work[2].

Figure 1



In Figure 1, the amplifier level has been set with a continuous sine wave just below the clip point of the amplifier. But, when program material (normal audio such as speech or music) is applied, some of the peaks exceed the clip point at points A and B, Figure 2.

Figure 2



[1] If you lack an audio (tone) generator or oscilloscope, search the internet for PC oscilloscope or audio generator software.

[2] The few turns of resistance wire in a power resistor should not resonate at audio frequencies.

Obtaining plenty of headroom requires having a power supply sufficient to produce the voltage necessary to achieve high dB levels. Voltage amplifying stages need voltage to swing[1]. The higher the supply voltage to the stage, the more voltage the stage has to swing. Depending on circuit values, the output voltage swing of an amplifier stage is about 45 percent of the supply voltage. The higher voltages used in vacuum tube circuits make it easy to achieve 30 dB of voltage amplifier headroom; the higher the voltage the more voltage swing is available to the tube.

Supplying plenty of voltage will keep the stage operating well below distortion thresholds. A good practice is to provide voltage amplifying stages with plenty of B+ high voltage, but not over 80% of the tubes maximum plate voltage rating[2]. Operating a tube at or over the maximum plate voltage rating can cause tube arcing and possible failure. When considering B+ supply voltages, keep in mind that tube maximum voltage ratings are the actual voltage across the tube and not necessarily the B+ supply voltage. For instance, consider that you have a 350-volt B+ supply on a typical voltage amplifier tube with a 300-volt maximum plate voltage rating. There will be about a 170 volt drop across the tubes plate resistor. The voltage drop across the plate resistor reduces the voltage to the tube by 170 volts. This means the actual voltage on the plate, and across the tube, would be about 180V, well below the tubes 300-volt plate maximum voltage.

Headroom in a power amplifier is critical for low distortion audio. However, having 20 dB of headroom could mean having excessive amounts of extra watts depending on how loud the system is played. Since the power output (volume) of a power amp is adjustable, you would want to have enough amplifier wattage to stay below the clip point at the desired listening level. Higher efficiency speakers are key to reducing amplifier power requirements.

[1] Voltage swing refers to the level of AC signal positive and negative amplitude.

[2] Voltage amplifiers are usually biased for Class A operation. As such, voltage swing should not exceed the plate voltage maximum value.

DB and Voltage Audio Levels

Having a feel for dB levels is important. Everything in audio is referenced to dB or voltage levels and connecting devices together is dependent on matching the correct level. For instance, a microphone with an output level of −50 dB will not work if connected to an amplifier with a 0 dB input. And you should not connect something with a 0 dB output level to a −50 dB amplifier input; you would overload the input and severely distort the audio.

A dB is a unit of measurement to indicate the strength or level of a signal. There is a reference point where 0 dB = the reference voltage. Then, any voltage above 0 dB is +dB and anything below the 0 dB reference point is −dB. In audio, there are three different types of reference. In all three cases, it is a logarithmic ratio scale. The decibel (dB) is a logarithmic unit used to measure sound level, a way of describing ratios of sound pressure, power and voltage. Logarithmic ratio scales are used in many applications.

Definitions

dBv Logarithmic voltage ratio where a reference voltage of 1.0000 volt equals 0 dBv.

dBm Logarithmic ratio with a reference power of 1 milliwatt (.001 watt) equaling 0 dBm using a 600 ohm load.

dBu Logarithmic voltage ratio where a reference voltage of 0.7746 (.775) volts = 0 dbu; dbu can be used regardless of impedance, but is derived from a 600 ohm load dissipating 0 dBm (1 mW).

Home audio equipment usually uses dbv where −10 dBv, 0.3162 volts, is the standard output level.

Professional audio equipment usually uses dbm where 0 dbm, 0.775 volts, is the standard output level with +4 dB or +10 dB sometimes used.

Professional equipment is usually referenced using 600 ohms, home audio equipment around 10,000 ohms. When measuring dbm, the load may not always be 600 ohms. In practice, the actual load resistance is ignored when taking measurements or setting levels. From a practical standpoint, dBm measurements without reference to load impedance are sufficient.

Frequency response specifications are stated as plus or minus so many dB using any dB level as the baseline reference. For example, using an output level of –10 dB as the baseline reference. Measurements then taken between 20 cycles per second and 20,000 cycles per second would be used to state the response of the amplifier as so many dB plus or minus from –10 dB.

How much is a dB, and can you actually hear any difference? A 1 dB difference is barely perceptible to the human ear; it usually takes a 2 dB difference to notice a slight change in level. Audio signal dB levels should not be confused with sound pressure dB levels (SPL). Sound pressure levels refer to the level of sound in the air and to our ears, such as the loudness of a speaker system.

Noise Floor

Noise levels are relative to a reference point. The reference point can be any level; –10 dB, 0 dB or +10 dB, for instance. The noise floor of an amplifier is anything audible with the volume turned all the way up with no input signal to the amplifier. In a tube amplifier, there is some normal tube noise usually in the form of a gentle hiss. Low frequency hum is another form of noise.

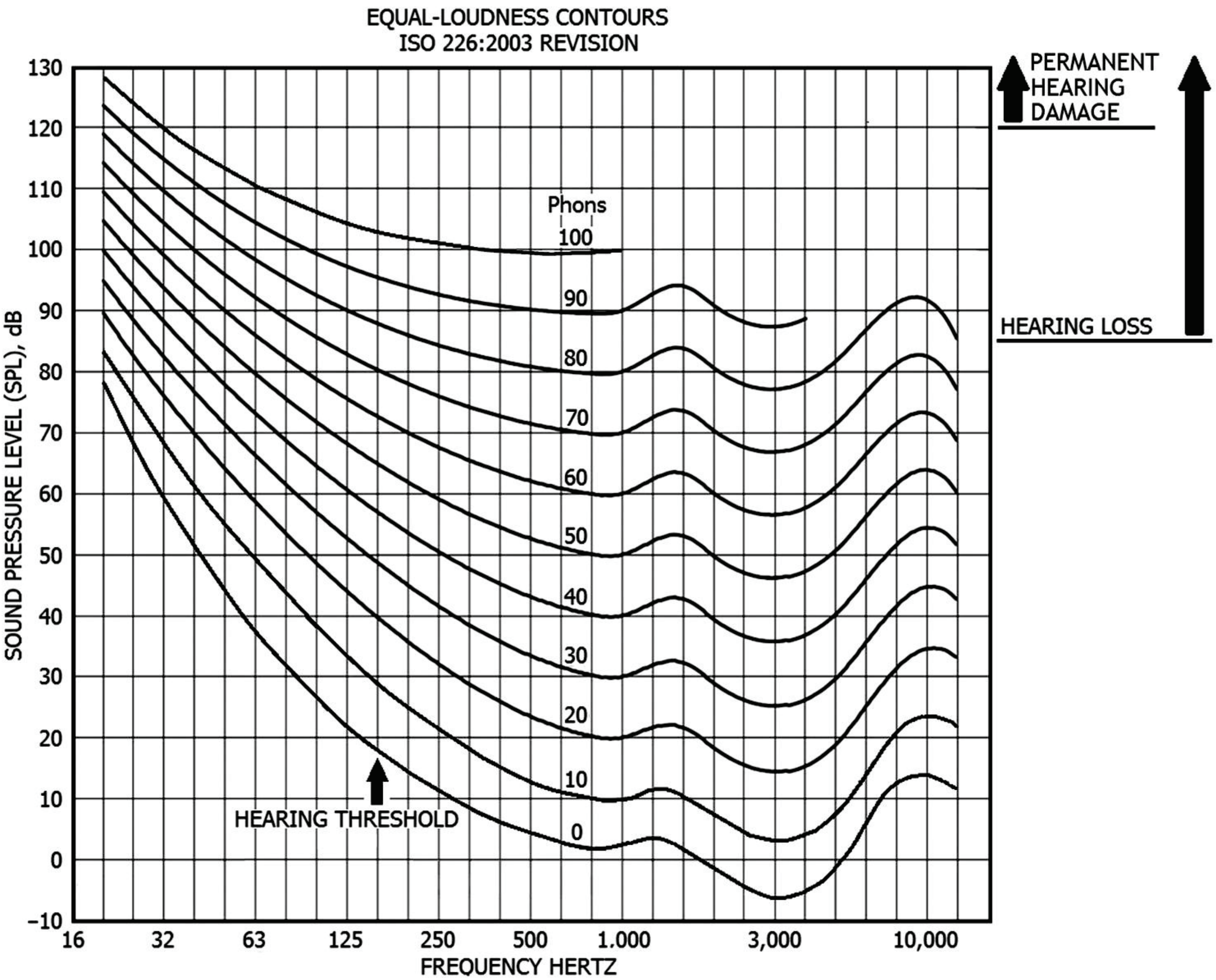
Measuring noise requires a very sensitive voltmeter, usually a meter calibrated in volts and dB. The meter is connected to the amplifier's output. An appropriate load should also be connected to the amplifier's output. With the amplifier's volume turned all the way up, noise is measured with no input to the amplifier. Using a multi-meter that has an AC 200 mV or lower scale, you can convert the measured noise level to dB using the dB to voltage chart on page 56.

For power amplifiers that drive speakers, the noise floor is the output noise level with any power amplifier volume controls set to full volume level. For any amplifier that has a line level output, use the normal dB output operating level for reference and not the amplifier's maximum output level. If the amplifier has a normal output level of –10 dB, then –10 dB should be the reference. Once you determine where your reference point is, for example –10 dB, then you subtract that value from your noise reading.

For example,

If you measure noise as −65 dB and the amplifier reference level is −10 dB.	(−65) − (−10) = −55 Noise is 55dB down
If you measure noise as −65 dB and the amplifier reference level is +10 dB. (Change sign of the smaller number and add.)	(−65) − (+10) = (−65) + (−10) = −75 Noise is 75 dB down

The following Equal Loudness Contours graph is another example of a logarithmic ratio scale. This one is for sound pressure levels (SPL).



DB (dBm or dBu) To Voltage Chart

The dB to voltage chart can be used to convert dBm or dBu levels to audio voltage levels. The chart can also be used to convert audio voltage levels to dBm or dBu levels.

DB (dBm or dBu) To Voltage Chart

dbm	V
+50	245.0
+49	218.0
+48	194.6
+47	173.4
+46	154.6
+45	137.8
+44	122.8
+43	109.4
+42	97.5
+41	86.9
+40	77.5
+39	69.0
+38	61.5
+37	54.8
+36	48.9
+35	43.6
+34	38.8
+33	34.6
+32	30.8
+31	27.5
+30	24.5
+29	21.8
+28	19.46
+27	17.34
+26	15.46
+25	13.77
+24	12.28
+23	10.94
+22	9.75
+21	8.69
+20	7.75

dbm	V
+19	6.90
+18	6.15
+17	5.48
+16	4.89
+15	4.36
+14	3.88
+13	3.46
+12	3.08
+11	2.75
+10	2.45
+ 9	2.18
+ 8	1.946
+ 7	1.734
+ 6	1.546
+ 5	1.377
+ 4	1.228
+ 3	1.094
+ 2	.975
+ 1	.869
0	.775
- 1	.690
- 2	.615
- 3	.548
- 4	.489
- 5	.436
- 6	.388
- 7	.346
- 8	.308
- 9	.275
- 10	.245
- 11	.218

dbm	mV
-12	194.6
-13	173.4
-14	154.6
-15	137.7
-16	122.8
-17	109.4
-18	97.5
-19	86.9
-20	77.5
-21	69.0
-22	61.5
-23	54.8
-24	48.9
-25	43.6
-26	38.8
-27	34.6
-28	30.8
-29	27.5
-30	24.5
-31	21.8
-32	19.5
-33	17.3
-34	15.5
-35	13.8
-36	12.3
-37	10.9
-38	9.8
-39	8.7
-40	7.7
-42	6.2
-44	4.9

dbm	mV
-46	3.9
-48	3.1
-50	2.4
-52	1.9
-54	1.5
-56	1.2
-58	1.0
-60	.8
-62	.6
-64	.5
-66	.4
-68	.3
-72	.2
-78	.1

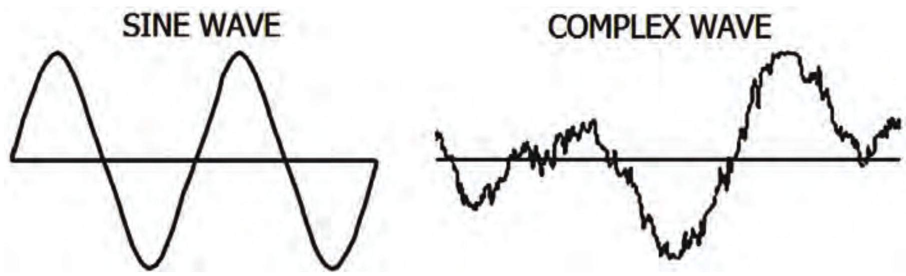
To use this chart for dBv, multiply the measured audio signal voltage by 0.775, then find the calculated dB voltage on the chart. For example, if you measure 0.056 volts, to find the dBv value, multiply 0.056 X 0.775, dBv = 0.0434. For millivolts, move the decimal point three places to the right, 43.4 mV. Find 43.4 mV, or the closest point, and you have −25 dBv.

dB conversions are rounded off

Frequency, Phasing and Wavelength

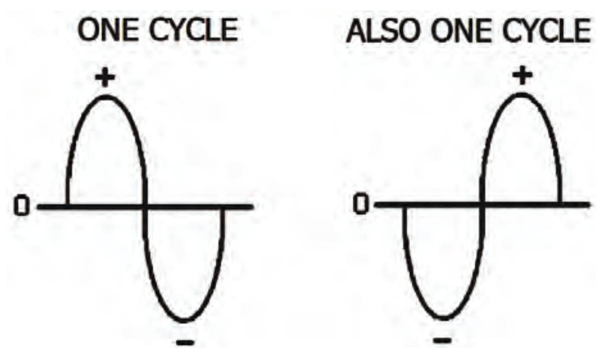
Frequency

The number of waves that pass a fixed point in a specific time. Frequency is a term associated with alternating current (AC). A frequency with equal positive and negative cycles is referred to as a sine wave. The most common denotation of frequency is by cycles/second. The unit of frequency is Hertz (Hz), named after the German physicist Heinrich Hertz.



Audio is alternating current in the form of a complex wave. Audio includes a mix of fundamental frequencies and harmonics. Ideally, an amplifier amplifies signals in a linear manner, producing an output that is an exact replica of the input. If an amplifier has any non-linear characteristics, it will produce harmonics that are not part of the original input signal. These extra harmonics mixed in with the original signal is called harmonic distortion.

Frequency is said in terms of cycles per second. One cycle per second is one complete cycle, positive to negative or negative to positive. One complete cycle is considered 360 degrees, one half of a cycle is 180 degrees and one quarter of a cycle 90 degrees. 1000 Hz is 1000 cycles per second.



Phase Relationship

The phase relationship between signals refers to the differences in phase between the signals. The phase difference is stated in degrees, one complete cycle equaling 360 degrees.

Figure 1

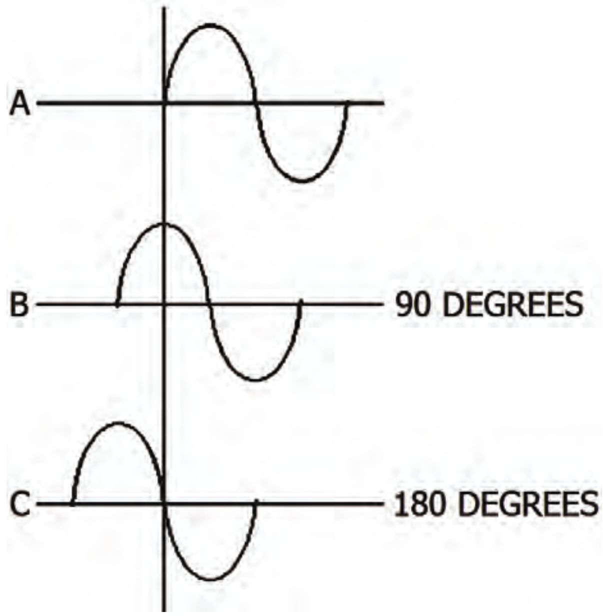


Figure 2

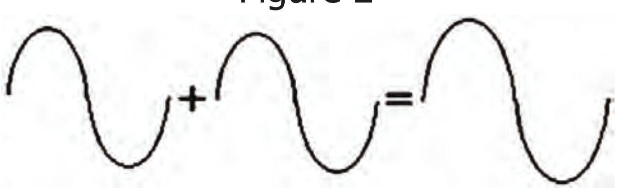
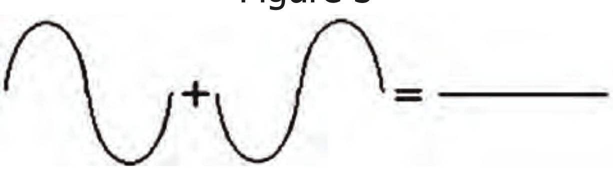


Figure 3



In Figure 1, signal B is 90 degrees behind signal A, commonly referred to as 90 degrees out of phase. Signal C is 180 degrees out of phase from signal A.

In Figure 2, two identical in phase signals are mixed together. This results in an increase in the combined signal level as the two signals add.

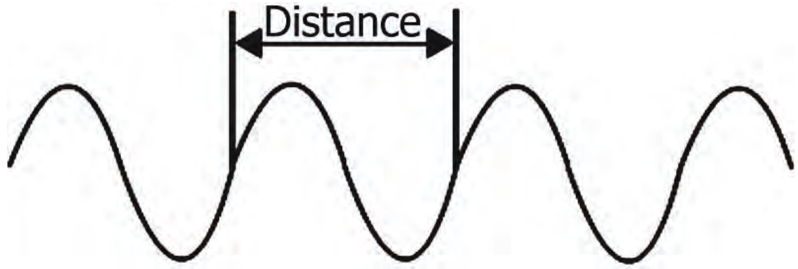
In Figure 3, two identical signals are mixed together 180 degrees out of phase, there is a decrease or cancelation in the combined signal level as they cancel or null each other.

Controlled phasing of a signal can be used for special effects. This requires continuous control of the phase angle between the input and output signal.

The phase relationship between multiple audio channels must be observed. It is critical that the channels are in phase with each other. When multiple channel signals are not properly in phase with each other, the sound will become altered. There may be a noticeable loss of low-end response and the direction of sound may not be definitive; sound seems to be coming from all around. To test multiple channels for phasing, connect the channels together to a mono mix. In mono, phasing errors may cause a hollow sound, some instruments may be hard to discern or not audible at all. Mono mixing should be done at amplifier inputs. Never connect power amplifier outputs together for a mono mix. Depending on the amplifier's output design, connecting power amplifier outputs to each other may cause damage.

Wavelength

Wavelength is the distance between two points of the same phase or, simply put, the distance one complete cycle of a signal travels.



The formula for wavelength is $\lambda = \frac{v}{f}$

λ = Wavelength in kilometers
v = Velocity of propagation
f = Frequency of the wave

The velocity of propagation is the speed of light ≈ 300,000 kilometers[1] per second.

In electronic devices, signals travel as electromagnetic waves. For audio signals, using the speed of light as the velocity of propagation constant will give reasonably close wavelength calculations.

For example,
20,000 Hz
λ = 300,000 / 20,000 = 15 kilometers (49,213 feet) per second.

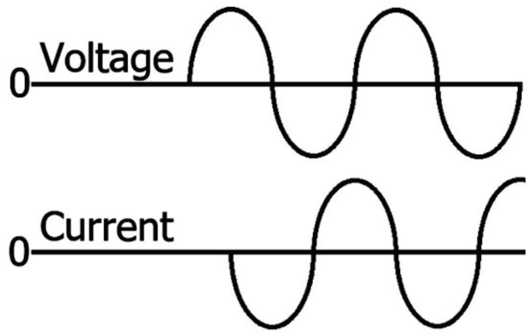
Frequencies lower than 20,000 Hz have a longer wavelength. At 1,000 Hz the wavelength is 300 kilometers or 984,252 feet per second.

The wiring inside an analog audio amplifier has no effect on the phase relationship to signals. The wavelength of audio frequencies is too great to be affected by the physical length of the wiring itself. The same is true with interconnecting cables between equipment. Except for extremely long cable runs, the physical length of speaker wire has little or no effect on phasing. In the case of extremely long speaker cable runs, the slower sound pressure propagation from the speakers will have more effect on phasing than the cable lengths.

[1] Calculating in kilometers instead of meters allows working with smaller numbers. 300,000,000 meters = 300,000 kilometers.

Frequency Response and Phase Errors

Ideally, an amplifier's signal path passes all frequencies equally and in the same phase relationship from input to output.



The current through a capacitor reacts against a change in voltage across it. The voltage is at a peak whenever the current is zero and current is at a peak whenever the voltage is where it crosses the zero line. This results in a voltage wave that is 90 degrees out of phase with the current wave. The current leads the voltage and voltage lags behind the current.

In addition, frequency response errors resulting from capacitance changes during applied voltages or with temperature variations can add distortion. Depending on the amount of frequency response error or low frequency phase error, bass frequencies can take on a dull or lifeless sound.

Capacitors have high values of reactance at 5Hz, but at higher frequencies the reactance falls to a lower level. For low AC frequencies near DC (for instance 5 Hz), the capacitor acts as a near open circuit restricting signal flow, while at higher frequencies it passes signal. Opposition to signal flow in any capacitor is inversely proportional to the frequency. As frequency increases, reactance decreases. Reactance is also inversely proportional to the value of capacitance. The value of reactance at any frequency will be less in larger value capacitors than in smaller values. This reaction is known as capacitive reactance (*Xc*).

Capacitive reactance can restrict lower range frequency response and cause low frequency phase shift. To keep low frequency cutoff and phase shift at a minimum, capacitor and resistor values should be selected for a low frequency 3dB cutoff point as low as possible.

Selecting capacitors for low errors resulting from capacitance changes during applied voltages or with temperature variations was covered on page 40. Low frequency cutoff and phase shift were covered on page 47.

Distortion

Harmonic Distortion

Harmonics are frequencies that are multiples of some fundamental frequency. For instance, the frequency of 800 Hz has harmonics at 1600 Hz, 2400 Hz, 3200 Hz, 4000 Hz, etc.

Each harmonic has a name. If the primary frequency is 800 Hz;

1,600 Hz is the second harmonic	2,400 Hz is the third harmonic
3,200 Hz is the fourth harmonic	4,000 Hz is the fifth harmonic
4,800 Hz is the sixth harmonic	and so on…

Even order harmonics are the second, fourth, sixth and so on. Even order harmonics are considered musical in nature. Musical instruments that are not electronic, such as piano, acoustic guitar, wind instruments, etc., generate even order harmonics. Even order harmonics add warmth to the sound.

Odd order harmonics are the third, fifth, seventh and so on. Odd order harmonics are considered nonmusical in the form of an unnatural sharp edge to the sound. In a Hi-Fi (audiophile) system, odd order harmonic distortion is undesirable. On the other hand, in a guitar amplifier, added odd order harmonics might be used to enhance the sound in some way for effect.

Perceptual Distortion

Anything that is added and not part of the original signal is distortion. Conversely, anything missing from the original signal is also distortion. This includes harmonics.

Harmonic distortion is easy to understand as any nonlinearity resulting from an amplifying process that creates extra harmonics.

If an amplifying or recording device removes or filters any portion of a signal, then the signal is no longer an exact duplicate of the original. This could be described as perceptual distortion. Perceptual distortion is difficult to quantify depending on how it is perceived. An analogy might be a vinyl LP record played through a linear analog amplifier sounding better than audio that has been digitally compressed by eliminating some of the original information.

Negative Feedback

Negative feedback is a method of feeding some amount of signal from an amplifier stage back to a preceding stage, but inverted 180 degrees out of phase. Since the signal fed back is 180 degrees out of phase, there is a nulling effect resulting in reduced distortion.

Figure 1

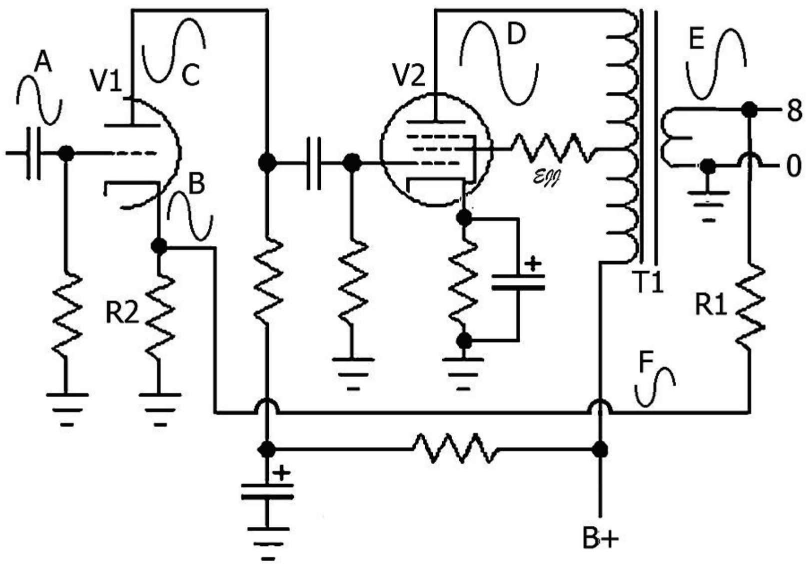


Figure 1 shows the signal path of a Class A single ended amplifier. The input signal A is amplified and flipped 180 degrees at C. The input signal also appears on the cathode B, but is not flipped or amplified. The signal at D on the output tube plate is amplified and flipped 180 degrees. The output transformer T1 flips the signal again at E. At this point, the output signal E is 180 degrees out of phase in relation to the signal at the cathode of V1. The amount of negative feedback F is set by R1 and R2.

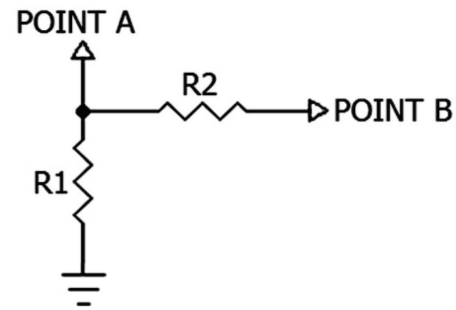
There is no DC blocking capacitor required for this type of feedback loop. Using this method requires being careful that the transformer secondary is wired correctly for proper 180 degree phase reversal and not in phase with the driver cathode. Correct phasing should result in some reduced gain with feedback connected.

The value of R1 is about two times the value of R2. Since R1 is connected to ground through the output transformer's 8 ohm secondary, it is, in effect, in parallel with R2. To keep the correct cathode bias on the V1 driver tube, you need to increase the value of R2 by 50%. The value of R1 would then be two times the increased R2 value. For example, if R2 would normally be 1.2K ohms, increase the value of R2 by 50% to 1.8K ohms. R1 is then two times 1.8K or 3.6K ohms. 1.8K ohms in parallel with 3.6K ohms is 1.2K ohms, thus maintaining the 1.2K cathode R1 resistance value.

Negative Feedback Gain Loss

A way to approximate the gain loss from the feedback loop is to do a voltage divider ratio. Then, use the ratio to calculate voltage gain loss. In the divider pictured to the right, point A would connect to the driver cathode and point B to the amplifier output transformer's 8 ohm winding. R1 is the driver stage cathode resistor and R2 the feedback resistor.

Feedback Loop
Output to driver stage



Calculate current in the divider using a value of 10 for the voltage at point B
I = E / R,
R1 = 1800 ohms
R2 = 3600 ohms
Total divider resistance = 5400 ohms
Current in divider using I = E / R = 10 / 5400 = 0.0019 amps

Next, calculate the voltage at point A.
Voltage drop across R2 using E = I X R = 0.0019 X 3600 = 6.84
Value at point A = 10 – 6.84 = 3.16

Then, divide the value at point A by the assigned value of 10.
3.16 / 10 = 0.316. The ratio of the divider is 0.316.

Multiply the calculated voltage gain of the driver stage by the ratio.
If the voltage gain is calculated at 18,
18 X 0.316 = 5.69

Subtract the result from the calculated voltage gain.
18 − 5.69 = 12.31

The adjusted voltage gain of the driver stage is 12.31.

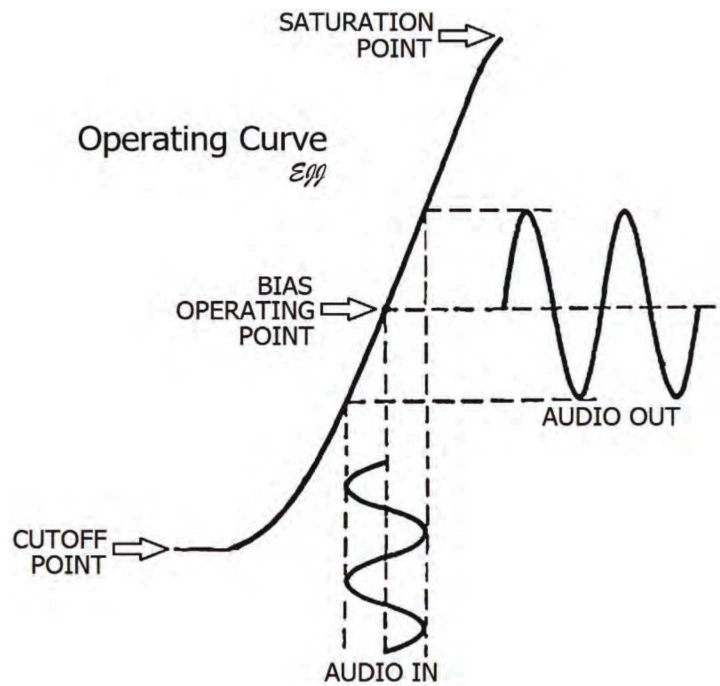
Divide the required driver output by the adjusted voltage gain.
If the required output tube grid drive is 12.7 volts, 12.7 / 12.31 = 1.032. It will take approximately a driver grid input of around 1 volt RMS for 12.7V RMS output from the driver stage.

Grid Bias

A vacuum tube has three points of operation that are of main interest; cut-off with no electron flow, full-on saturated with full electron flow and mid-point between cut-off and full-on. What is needed for Class A linear undistorted amplification is to be at the midpoint between cut-off and full-on saturated.

If the control grid is made sufficiently negative, there is no electron flow. When the control grid is positive, there is full electron flow. For Class A operation, the tube's operating point must be at the center of its operating curve. Applying a bias voltage to the control grid may be required. See Figure 1. The amount of bias voltage depends on the type of tube being biased. Voltage amplifying tubes only require a small amount of bias voltage.

Figure 1

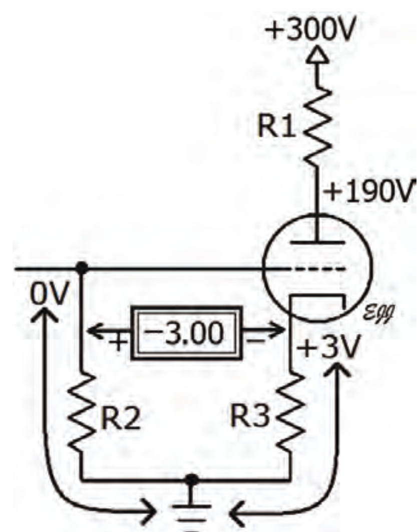


Power output tubes require a significantly higher value of bias voltage. In many cases, the required bias voltage is specified in tube datasheets.

Cathode Self Bias

The simplest method to bias a tube is to place a resistance in series with the cathode. Figure 2 illustrates using cathode resistor R3 to raise the cathode above ground resulting in a positive voltage at the cathode. When measured with respect to ground as the reference, the cathode is +3 volts while the grid is 0 volts.

Figure 2

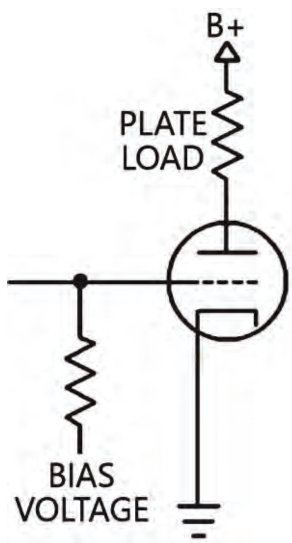


However, think of it as the control grid negative with respect to the cathode. In Figure 2, if you connect a digital DC volt meter between the grid and cathode, with the negative lead on the cathode, you will read –3 volts.

R2 is called a grid-leak resistor used to stabilize the control grid bias point. If you omit the R2 grid resistor, the high impedance of the grid may allow static voltage on the grid to slowly increase, shifting the grid bias point.

In a voltage amplifier stage, cathode self bias provides the best performance. The required amount of grid bias voltage usually varies with the level of plate voltage. Generally, higher levels of plate voltage require a higher negative grid bias voltage. Plate current usually increases when the plate voltage increases. Cathode self bias will self-adjust by increasing the voltage at the cathode along with increased plate current.

Figure 3



Fixed Bias

Figure 3 shows the method of fixed grid bias by applying a negative bias voltage to the grid, usually via the grid leak resistor. The cathode is then connected directly to ground. Fixed bias is primarily used in power output stages.

Applying a grid bias voltage provides absolute control over the tube's operating curve. If a vacuum tube is not correctly biased, then the operating point of the tube becomes off center, either too close to cutoff or saturation.

Vacuum tube data sheets usually give a grid bias voltage value. However, the ideal bias point varies with plate voltage and component values. With fixed bias, it may be necessary to use test equipment to verify the tube is operating in the correct portion of its operating curve.

A power output vacuum tube that has a glowing red spot on the plate is a sign of improper biasing. Besides possibly ruining the tube, components in the output circuit may be damaged.

Miller Effect

Miller effect, the increase in the effective grid-cathode capacitance of a vacuum tube due to the charge induced electrostatically on the grid by the plate through the grid-plate capacitance. Or simply put, the effective input grid capacitance of the tube. The effective input grid capacitance is increased due to the Miller effect, similar to connecting a capacitor from the grid to ground. This can reduce the bandwidth of the amplifier, restricting its range of higher frequencies. Pentode and tetrode tubes don't suffer as much from the effects of Miller capacitance because of the shielding effect of the screen grid which drastically lowers the grid to plate capacitance.

The majority of the input capacitance of a triode stage is made up of the combination of the grid to cathode capacitance plus the Miller capacitance formed by the grid to plate capacitance multiplied by the stage gain plus one. The formula for determining the total input capacitance of a triode stage is as follows.

Cin = Cgk + {Cgp X (Vg+1)}[1]

Cin = input capacitance

Cgk = grid-to-cathode capacitance, composed of the internal tube capacitance plus any stray capacitance

Cgp = grid-to-plate capacitance, composed of the internal tube capacitance plus any stray capacitance

Vg = stage voltage gain

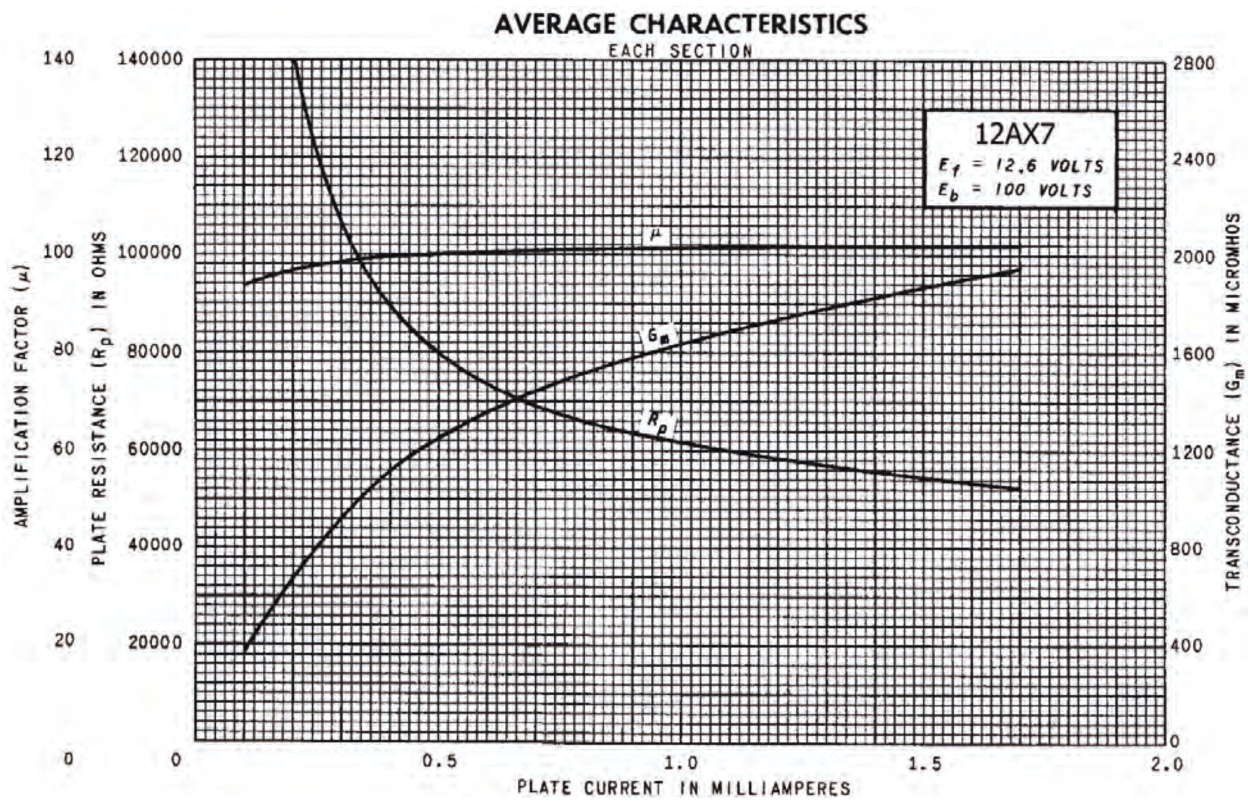
For example, a typical 12AX7 stage has the following capacitances and gain.
Cgk = 2.2 pF
Cgp = 2.0 pF
Vg = 60

Therefore, the total input capacitance would be:
Cin = 2.2 pF + {2.0 X **(**60+1**)**} = 2.2 pF + **{**2.0 X 61**}** =
2.2 pF + 122pF =124.2 pF

[1] Solve formulas from the innermost brackets first, then work your way out.

Voltage Gain

The characteristics of a tube are measured by two factors. The first factor is transconductance or g_m, the second factor is Mu (μ) or amplification factor. Transconductance is the change in plate to cathode current divided by a corresponding change in the grid to cathode voltage. Amplification factor (represented as ***Mu***, ***&mu*** or μ) of a tube is equal to the ratio of a change in voltage at the plate to a change in grid voltage required to cause the same change in plate current. We are mainly interested in the ***Mu*** factor. Many tube data sheets will have graphs with Mu (μ) plotted. For example, in the 12AX7 graph, average characteristics indicate μ as about 100.



Mu is a measure of the ability of a tube to amplify. The higher the Mu, the higher the voltage gain of the tube. Vacuum tubes with higher Mu have a higher plate current to input voltage ratio (plate current increases as input voltage increases).

The voltage gain of a stage affects the input Miller Effect capacitance of the stage. Some design considerations can reduce the effect of high frequency loss due to Miller Effect capacitance.

Using lower value plate and grid resistors will lower the input and output impedance of the amplifier stage. Lowering the stage input and output impedance effectively lowers the plate to grid capacitance by increasing the RC (resistance and capacitance) time constant. The time constant (in seconds) of an RC circuit is equal to the product of the circuit resistance (in ohms) and the circuit capacitance (in farads). Lowering the value of the circuit resistance or capacitance will raise the time constant to a higher frequency. A value of 100K ohms for both the plate and grid will still provide good gain, less affected by Miller capacitance. Also, consider reducing the output impedance of the previous stage by reducing its plate resistor value.

Using a lower value plate resistor also lowers the voltage gain of a stage as the voltage drop across the plate resistor will be less per milliampere of plate current. This means less output voltage gain per input volt. Generally speaking, it will achieve better performance if two stages of lower gain are used instead of a single high gain stage.

Calculating Required Voltage Gain

When designing an amplifier, it will be necessary to calculate how much voltage gain is needed. For example, if you are building a single ended 6L6GC power amplifier, and you want to drive the amplifier to full volume with a 0.5-volt RMS input, you need to calculate how much voltage gain is required. The data sheet for a 6L6GC indicates there is a peak AF grid No. 1 (the input grid) voltage of 18V required for 10.8 watts output. To find the minimum required voltage gain for a voltage amplifier stage to drive the 6L6 to full power, you divide the 6L6 RMS grid drive voltage by the amplifier input voltage. First, convert 18 volts peak to RMS, 18 X 0.707 = 12.7 volts RMS. Input = 0.5 volts RMS, required minimum voltage gain = 12.7 / 0.5 = 25.4.

Once you know the minimum required voltage gain, you can calculate the voltage gain of tubes with different Mu ratings. Then, select the tube with the closest match to the minimum required voltage gain.

You can use the following formula to calculate the approximate gain of a voltage amplifier stage. The plate resistance and Mu (amplification factor μ) can be found in tube datasheets.

Voltage Gain (V_g)

$V_g = (Mu \times R_p) / (R_p + R_a)$

M_u = Tube Amplification Factor

R_p = Plate Resistor

R_a = Tube Plate Resistance[1]

This is a simplified formula that does not take into account loading on the plate from circuits after the stage. However, it is accurate enough to give you an idea of how many stages you will need to achieve the required gain.

12AX7 → Mu = 100, Plate Resistance = 65K (65,000)
12AT7 → Mu = 60, Plate Resistance = 10.9K (10,900)
12AY7 → Mu = 44, Plate Resistance = 24K (24,000)
6SN7 → Mu = 20, Plate resistance = 7K (7,000)

Plate Resistor for all calculations = 100,000 ohms

Using a 12AX7
$V_g = (Mu \times R_p) / (R_p + R_a)$
$V_g = (100 \times 100{,}000) / (100{,}000 + 65{,}000)$
$V_g = (10{,}000{,}000) / (165{,}000) = 60.6$

Using a 12AT7
$V_g = (Mu \times R_p) / (R_p + R_a)$
$V_g = (60 \times 100{,}000) / (100{,}000 + 10{,}900)$
$V_g = (6{,}000{,}000) / (110{,}900) = 54.1$

Using a 12AY7
$V_g = (Mu \times R_p) / (R_p + R_a)$
$V_g = (44 \times 100{,}000) / (100{,}000 + 24{,}000)$
$V_g = (4{,}400{,}000) / (124{,}000) = 35.5$

Using a 6SN7
$V_g = (Mu \times R_p) / (R_p + R_a)$
$V_g = (20 \times 100{,}000) / (100{,}000 + 7{,}000)$
$V_g = (2{,}000{,}000) / (107{,}000) = 18.7$

The calculated voltage gain is for one triode section of each tube. If you needed a voltage gain of 25.4, then one section of a 12AY7 would work, but for a 6SN7 you would need to use both sections.

[1] The a in R_a refers to anode. The plate of a vacuum tube is also known as an anode.

It's better to have too much voltage gain then to find out you came up a little short due to circuit loading effects. Expect some loss of voltage gain.

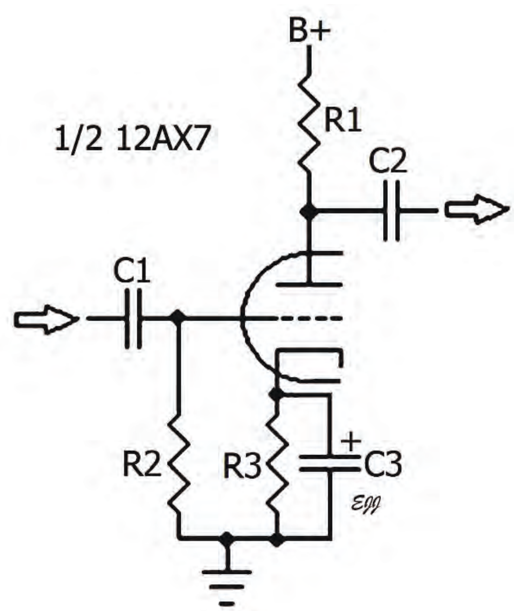
Ideally, circuits would perform exactly as calculated. In reality, calculations are just approximations of how a circuit will function. There are variables that can skew calculations. Plate resistance values used in calculations are usually listed on datasheets as approximate under only two or three plate voltage selections. Actual tube performance may vary between manufacturers.

An example of measured tube performance under different operating conditions is shown in the 12AX7 Chart of Measured Values. Test equipment is a Heath IG1272 low distortion audio generator and Heath IM5258 distortion analyzer[1].

The same vacuum tube and same frequency of 1K Hz is used for all test measurements. For each test, the output level at 1% distortion and the maximum output just below clipping is measured.

Each set of measurements includes different values of R1 plate, R2 grid and R3 cathode resistance, without and with a C3 cathode bypass capacitor. The C1 and C2 capacitor values were the same during all measurements.

Circuit used for 12AX7 measured values chart



[1] Tests were conducted in 2014 for the first version of the book. Test equipment was verified by connecting the audio generator directly to the distortion analyzer. Distortion at 1KZ test frequency indicated at .05%

12AX7 Chart of Measured Values

12AX7 AMPLIFIER STAGE CIRCUIT VALUES
CHART OF MEASURED VALUES
VALUES ARE FOR 1/2 12AX7

out DB = output level at 1% harmonic distortion @ 1KHZ
max DB = maximum output just below clipping

	B+ vdc	R1 Plate	R2 Grid	R3 Cathode	C3 Bypass	gain DB	out DB	max DB
1	200	100K	100K	1K	-	29DB	+20DB	+32DB
2	200	100K	100K	1K	22UF	34DB	+14DB	+32DB
3	300	100K	100K	1K	-	29DB	+27DB	+35DB
4	300	100K	100K	1K	22UF	34DB	+22DB	+35DB
5	300	100K	1M	1K	-	29DB	+27DB	+35DB
6	300	100K	1M	1K	22UF	34DB	+22DB	+35DB
7	300	100K	1M	2.2K	-	25DB	+24DB	+35DB
8	300	100K	1M	2.2K	22UF	33DB	+16DB	+35DB
9	300	100K	1M	3.3K	-	22DB	+23DB	+33DB
10	300	100K	1M	3.3K	22UF	32DB	+12DB	+33DB
11	300	100K	1M	4.7K	-	20DB	+22DB	+30DB
12	300	100K	1M	4.7K	22UF	32DB	+8DB	+30DB
13	300	220K	1M	1K	-	31DB	+25DB	+35DB
14	300	220K	1M	1K	22UF	35DB	+20DB	+35DB
15	300	220K	1M	2.2K	-	28DB	+25DB	+35DB
16	300	220K	1M	2.2K	22UF	34DB	+18DB	+35DB
17	300	220K	1M	3.3K	-	25DB	+24DB	+35DB
18	300	220K	1M	3.3K	22UF	34DB	+14DB	+35DB
19	300	220K	1M	4.7K	-	23DB	+24DB	+33DB
20	300	220K	1M	4.7K	22UF	33DB	+13DB	+33DB

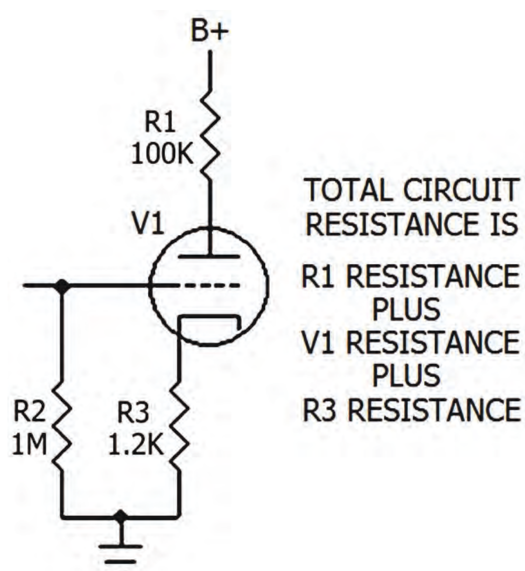
For those who may not be aware, the triodes in a 12AX7 are electrically identical to the triode in a 6AV6 radio tube. The only difference is that the 12AX7 has a higher plate dissipation rating.

Plate Dissipation

Plate dissipation is heating of the plate that is dissipated as current flows through a vacuum tube. The amount of current flowing through the tube depends on the values of the plate load resistance, internal resistance of the vacuum tube, the cathode resistor and the value of B+ voltage.

You should never exceed the maximum plate dissipation rating of a vacuum tube. The maximum or never exceed values can be found in tube manuals and tube data sheets. For example, a 12AX7 listed in a 1961 RCA tube manual specifies maximum ratings as 330VDC plate voltage and 1.2 watts plate dissipation for each plate[1].

When designing an amplifier stage, plate dissipation should be calculated. This requires a preliminary calculation of the current flow in the vacuum tube, V1 in the illustration. To calculate the current, you need the total circuit resistance. The total circuit resistance is the resistance of R1 + V1 + R3. There is little or no grid current flowing through R2, so it can be ignored.



For example, one section of the 12AX7. Plate resistance is listed in the RCA tube manual as 80,000 ohms at 100V plate voltage and 62,500 ohms at 250V plate voltage. Actual tube plate resistance will depend on circuit values and voltage across the tube. Voltage across the tube means from the plate to the cathode, not the B+ voltage. Voltage on the plate will be some value less than the B+ voltage because there will be a voltage drop across the load resistance R1. For a voltage tube operating in the center of its operating curve, voltage at the plate will be approximately half the B+ supply voltage. If the B+ voltage is 350 volts, then the voltage on the plate will be about 175 volts.

[1] The maximum dissipation rating may vary between manufacturers. Some rate 12AX7 maximum plate dissipation as 1.0-watt per plate.

175 volts is halfway between the 12AX7 datasheet plate resistance values of 100 volts or 250 volts plate voltage. For plate dissipation, it would be best to calculate the worst case scenario. The higher plate resistance value will result in more heat being dissipated from the tube plate[1].

Calculate the current through the tube.

B+ = 350 volts   R1 = 100,000 ohms   V1 = 80,000 ohms

R3 = 1,200 ohms   R1 + V1 + R3 = 181,200 ohms

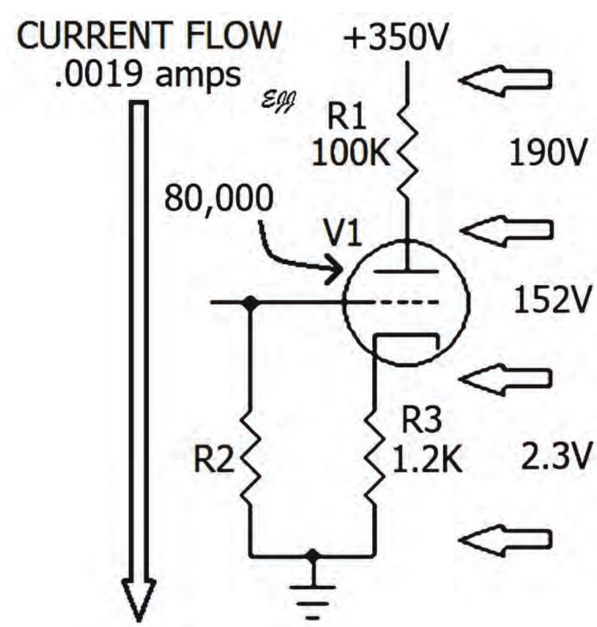
I = E / R   350 / 181,200 = 0.0019 amps (1.9 mA)

Calculate the voltage across the tube.

E = I X R   I = 0.0019 amps   R = 80,000 ohms

E = .0019 X 80,000= 152 volts

Plate dissipation in watts (power) can be calculated using plate voltage times plate current (P = E X I).



There will be a voltage drop across the plate resistor so the full B+ voltage will not be the voltage on the plate. To calculate plate dissipation, use the voltage across the tube times the current flow through the tube.

P = E X I

E = 152V

I = 0.0019 amps

P = 152 X 0.0019 = 0.29 watts

A plate dissipation of 0.29 watts is well below the 12AX7 dissipation limit.

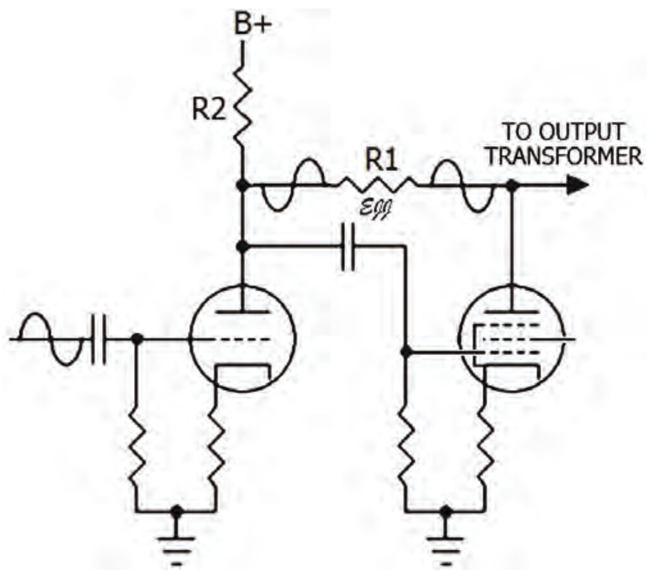
There are some errors that can be attributed to rounding off numbers. For example, the voltages across R1, V1 and R3 add up to 344.3 volts. One would expect the three voltages to equal the B+ voltage of 350 volts. These are, as with most electronic calculations, approximations.

[1] You might think the lower plate resistance would result in the highest plate dissipation. It would result in a slightly higher plate current, but the lower plate resistance would be calculated out to a slightly lower plate dissipation because of its lower resistance.

Integrating Stages

Integrating consecutive stages is a form of negative feedback. Since each stage reverses phase from input to output, an integrating resistor from plate to plate will feed back signal from one plate to the other out of phase. Because both plates are positive, a DC blocking capacitor is not necessary.

Figure 1



In Figure 1, R1 is the integrating resistor. This works best if the plate resistor, R2, is a value between 100K and 220K; the R1 resistor would be a value of 200K or higher. Using this method between the plates of a Class A single ended output stage to the preceding driver stage helps stability when the output is driven into overload.

Integrated Dual Triode

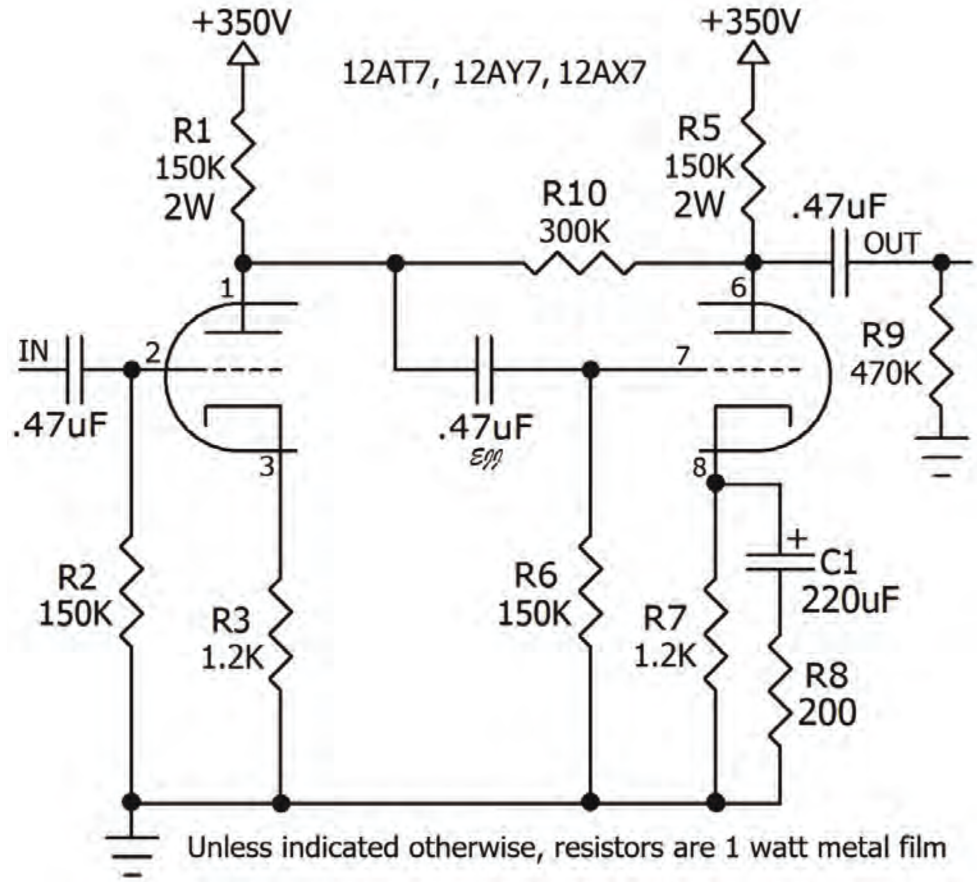
This is for dual triode tubes where both triodes have identical characteristics.

- Plate and cathode resistor values are selected for linear operation as they would be operating as individual triode sections.
- Values of the plate and cathode resistors are the same for both sections.
- Only the second triode has a cathode bypass capacitor.
- The plate to plate integrating resistor is twice the value of the plate resistor.

When integrating a dual triode, the formulas used to calculate voltage gain in a single stage tube circuit do not apply. However, there is a constant that can be used to approximate voltage gain. In Figure 2, Figure 3 and Figure 4, if the values of R1, R5 and R10 are doubled, the voltage gain also doubles. Therefore, if you increase the values of R1, R5 and R10 by 50%, voltage gain will also increase by 50%. Depending on the amount of voltage gain change made, performance measurements like those made in Figures 2, 3 and 4 may be required. See page 78.

Figure 2 is an integrated dual triode circuit that works well with a 12AT7, 12AY7 or 12AX7 tube. The component values selected work with all three tubes. Measurements were made using a modified Heath IG-18 audio generator and an HP 331A distortion analyzer. If the output connects to the grid of a following stage that has a grid leak resistor, then the 470K R9 load resistor should be omitted.

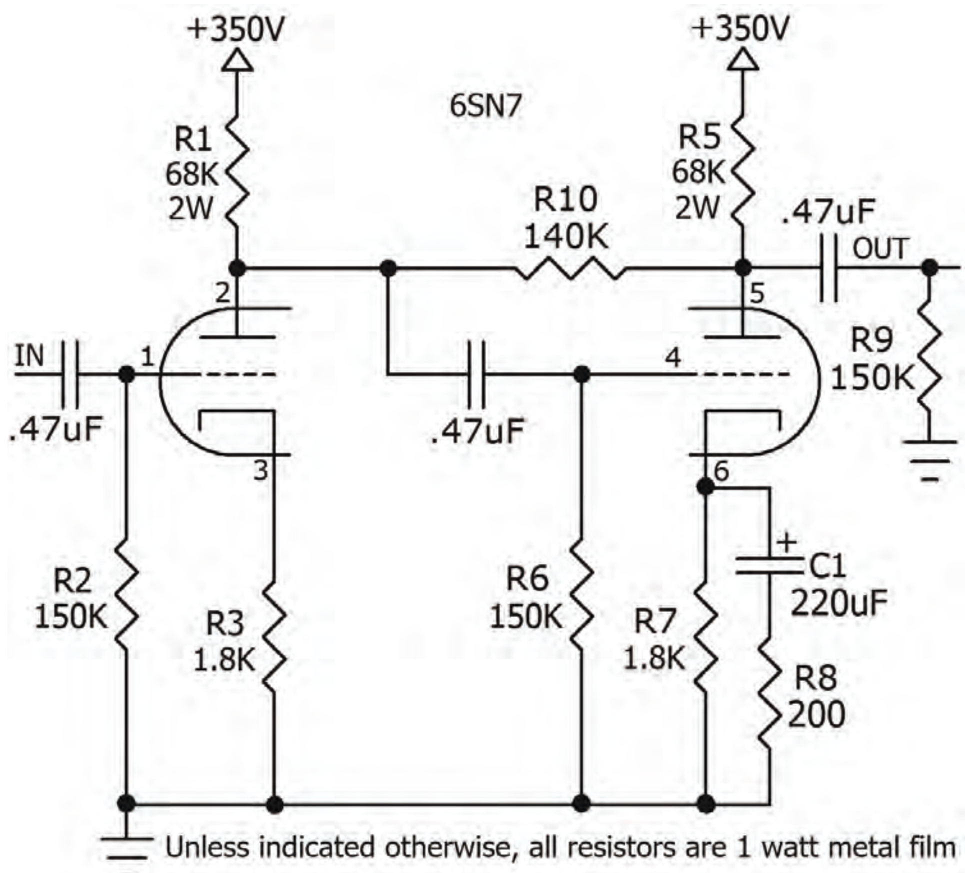
Figure 2



	12AT7	12AY7	12AX7
Output Level	10V RMS	10V RMS	10V RMS
Voltage Gain	116	122	152
Dist @ 20Hz	0.10%	0.10%	0.26%
Dist @ 100Hz	0.10%	0.09%	0.25%
Dist @ 1KHz	0.19%	0.15%	0.26%
Dist @ 10KHz	0.62%	0.34%	0.34%
–1 dB points	7 Hz & 25K Hz	5 Hz & 30K Hz	7 Hz & 25K Hz

Figure 3 is for use with a 6SN7. Measurements were made using a modified Heath IG-18 audio generator and an HP 331A distortion analyzer. If the output connects to the grid of a following stage that has a grid leak resistor, then the 150K R9 load resistor should be omitted.

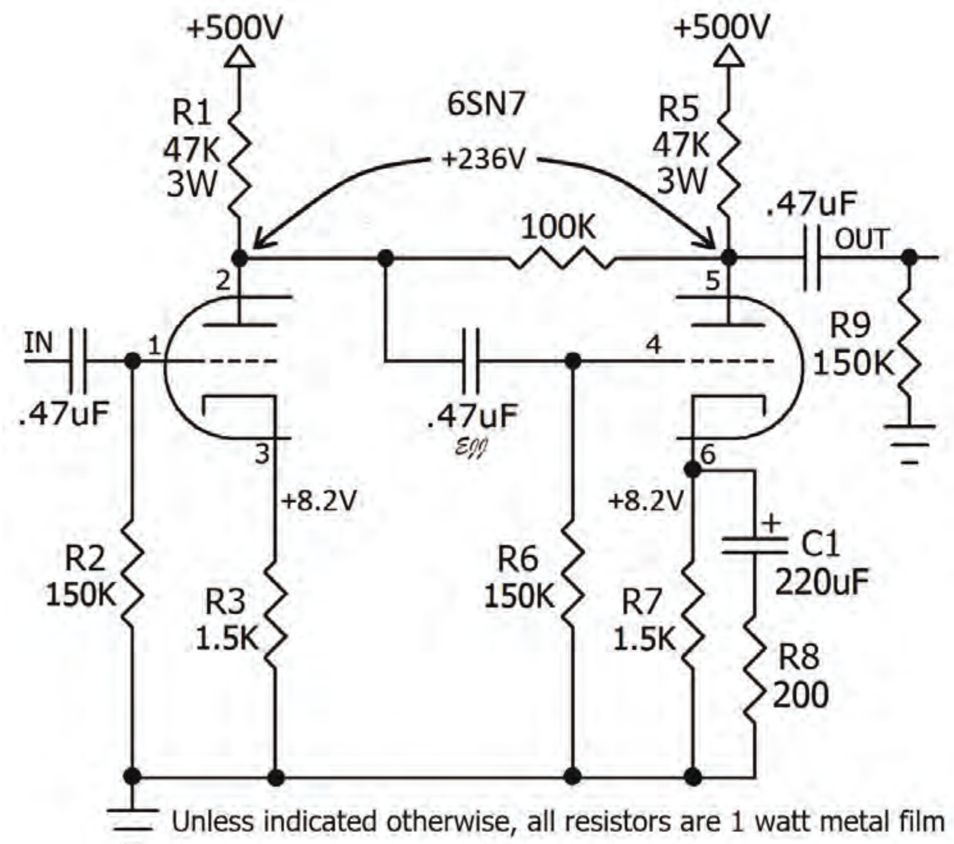
Figure 3



Output Level	10V RMS	20V RMS
Voltage Gain	40	40
Dist @ 20Hz	0.07%	0.15%
Dist @ 100Hz	0.07%	0.15%
Dist @ 1KHz	0.15%	0.23%
Dist @ 10KHz	0.22%	0.38%
–1 dB points	7 Hz & 48K Hz	7 Hz & 48K Hz

Figure 4 is for use where a high audio drive is needed. This circuit requires a 500 volt B+ supply and should only be attempted by those experienced with working higher voltage circuits. Measurements were made using a modified Heath IG-18 audio generator and an HP 331A distortion analyzer. If the output connects to the grid of a following stage that has a grid leak resistor, then the 150K R9 load resistor should be omitted.

Figure 4

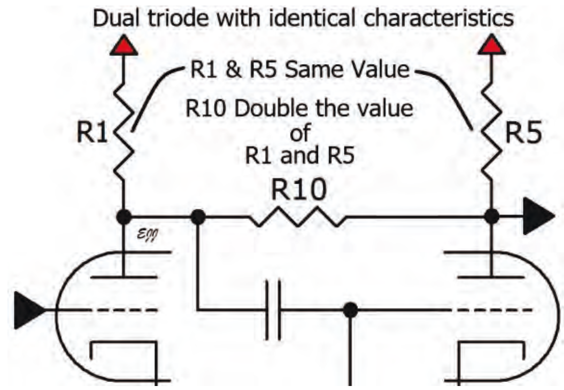


Output Level	30V RMS	65V RMS
Voltage Gain	36	36
Dist @ 20Hz	0.12%	0.46%
Dist @ 100Hz	0.10%	0.46%
Dist @ 1KHz	0.20%	0.52%
Dist @ 10KHz	0.32%	0.80%
–1 dB points	7 Hz & 55K Hz	7 Hz & 55K Hz

The percentage of change in the values of R1, R5 and R10 equals the percentage of change in voltage gain.

This only applies if both triode units have identical characteristics, and R1 and R5 are the same value, with R10 double the value of R1 and R5.
For example, R1 and R5 are 100K ohms, then R10 would be 200K ohms.
Normally, the cathode resistor values can remain unchanged[1].

Figure 6



In order to calculate a specific voltage gain, reference points must be established. This would involve first creating a reference circuit. Using a 1KHz tone, measure the input and output voltage. Divide the output voltage by the input voltage to find the voltage gain. You will then use the values of R1, R5, R10 and the voltage gain of the reference circuit as reference points.

For the 12AT7, 12AY7, 12AX7 and 6SN7, the values of Figures 2 and 3 can be used as reference points. In Figure 4, it would be best not to lower any of the values. To do so might exceed plate dissipation limits.

First, decide how much you want to increase or decrease the voltage gain.
For example, the 6SN7 in Figure 3. You want a voltage gain increase from 40 to 60. Calculate the percentage of change from 40 to 60.

$$\%\ Change = \frac{Larger\ Value - Smaller\ Value}{Larger\ Value}\ X\ 100$$

$$\%\ Change = \frac{60 - 40}{60}\ X\ 100 = \frac{20}{60}\ X\ 100 = .33\ X\ 100 = 33\%$$

Increase the values of R1 and R5 by 33%.
R1 and R5 = 68,000 X .33 = 22,400 + 68,000 = 90,400 ohms (90K ohms).
R10 = 90,000 X 2 = 180,000 ohms (twice the value of R1 and R5).
Results will usually come up with odd values. Choose standard values that are the required wattage plus maintain the 2 to 1 ratio of R10 to R1 & R5.

[1] In the case of an extreme change of R1, R5 and R10 resistor values, it may be necessary to adjust the cathode resistor values to place the tube at the center of linear operation.

Power Supplies

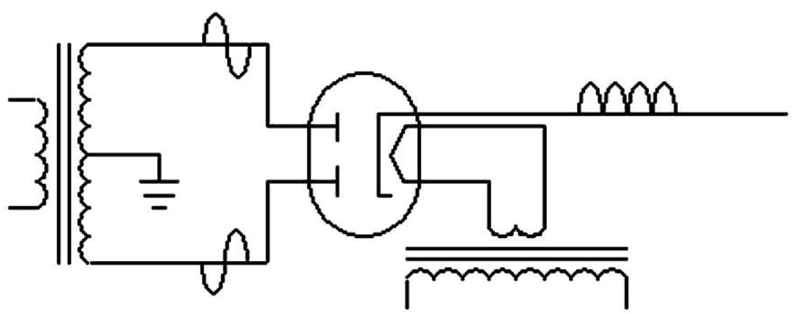
The Rectifier

Amplifying vacuum tubes requires a positive DC voltage to operate. A rectifier circuit is needed to convert AC to DC. The most common rectifier circuits used in vacuum tube amplifiers are of the full wave type. A full wave rectifier rectifies both the positive and negative halves of the AC voltage. A power transformer with a center tap provides the AC voltage. Full wave rectification using a center-tapped transformer requires two diodes.

Vacuum Tube Rectifier

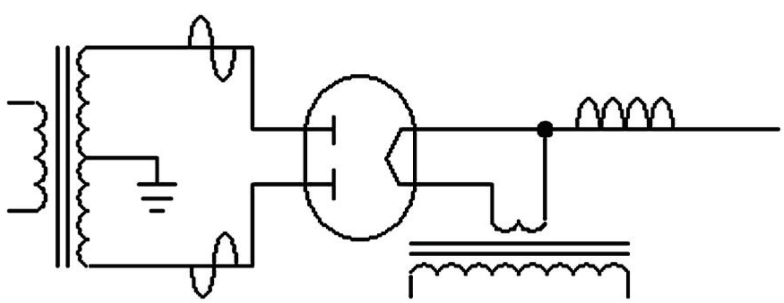
A full wave vacuum tube rectifier has two AC connections (called plates or anodes) and one DC out connection, the cathode. Each plate has current flow with the cathode and is, in effect, a diode. The transformer winding supplies each plate AC voltage that is 180 degrees out of phase referenced to the center tap; the center tap is negative common ground. The rectifier rectifies both halves of the waveform with the current load split between each half of the winding. The cathode output is made up of positive pulses from both plates.

Figure 1



Some rectifier tubes do not have a physical cathode, but instead use the filament as the cathode.

Figure 2



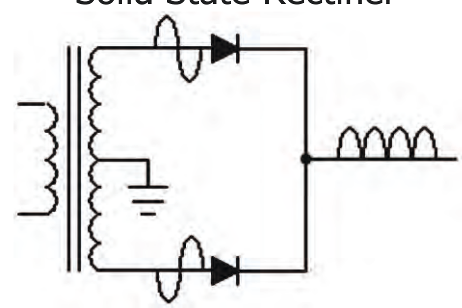
The AC voltage to be rectified is half the value of a transformer's rated voltage. For example, a 600-volt center-tapped transformer actually provides 300 volts of AC voltage to be rectified. This is why most transformers have a dual rating. For example, 600VCT, 300-0-300. VCT = voltage center-tapped.

Although rectifier tubes may look vintage, they do not provide a solid B+ voltage as they tend to sag under a heavy load. The internal resistance of a vacuum tube rectifier is fairly high. As the current load on the tube increases, the output DC voltage decreases. Rectifier tubes have a slight delay before voltage is produced.

Solid State Rectifier

Solid state rectifiers do not have high internal resistance and will provide a more steady DC voltage output over a wide range of current loads. When using solid state rectifiers, the high voltage will be significantly higher until the amplifier tubes warm up and start drawing current from the transformer.

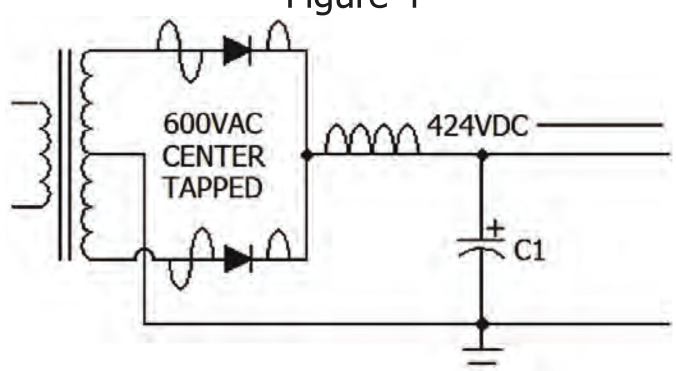
Figure 3
Solid State Rectifier



Filtering

Figure 3 shows a full wave rectifier circuit using a center-tapped transformer. The windings on each side of the center tap feed the rectifier diodes the AC voltage 180 degrees out of phase; each rectifier rectifying half the AC cycle. The outputs of the rectifiers are connected together, resulting in a series of positive pulses. In order for these pulses to be useful, we need to smooth them out. This is done by filtering with a capacitor C1 placed on the rectifier output, Figure 4.

Figure 4

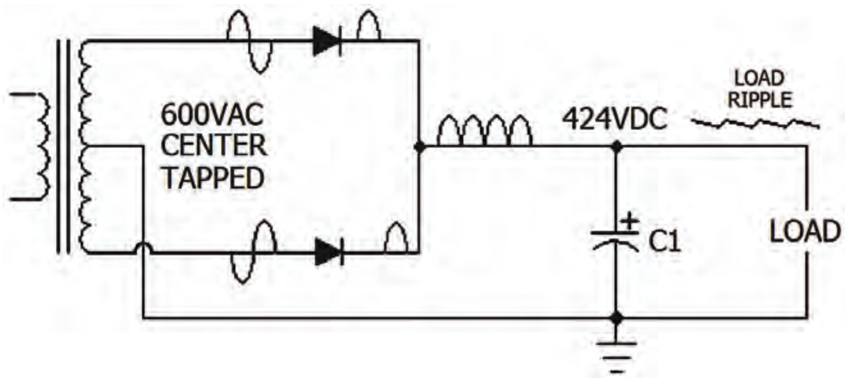


In a no-load condition, the positive pulses charge the capacitor to the peak value of the AC voltage and the capacitor holds the charge, essentially smoothing out the pulses.

Load Effect on Filtering

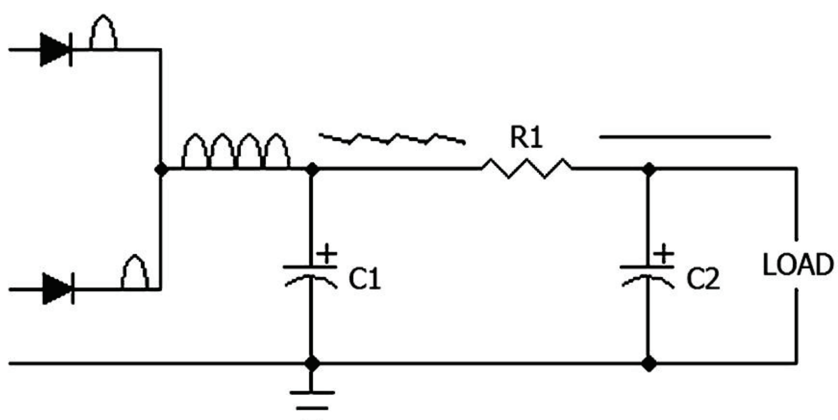
Any load placed on the power supply is also a load placed on the filtering capacitor. When a load is placed on the capacitor, it will discharge the capacitor between pulses. The effect of the load discharging the capacitor produces an AC ripple effect on the DC voltage. A 60 Hz AC primary voltage will cause a 120 Hz ripple in the DC voltage, Figure 5.

Figure 5



Increasing the value of C1 capacitance will reduce ripple, but will also increase current surge when the amplifier is turned on as the capacitor initially charges. In order to reduce ripple without having a large power-up current surge, more filtering circuits are required.

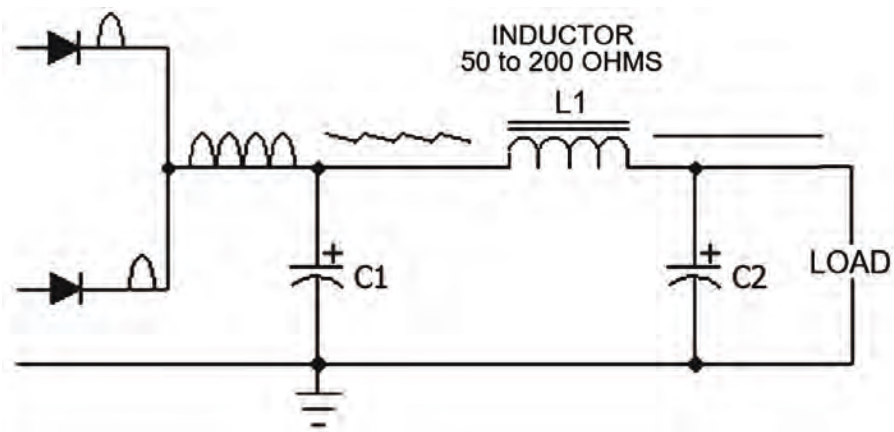
Figure 6



In Figure 6, adding R1 plus a second capacitor will reduce ripple. R1 limits current, allowing the value of C2 to be very large without causing excessive power-on current surge. Because R1 is limiting current, the load at C2 will cause a voltage drop across R1 with a reduction of DC voltage at C2.

High current loads, such as an amplifier power output tube circuit, will cause a significant voltage drop across R1. In Figure 7, replacing R1 with inductor L1 will keep the voltage drop to a minimum plus improve filtering.

Figure 7

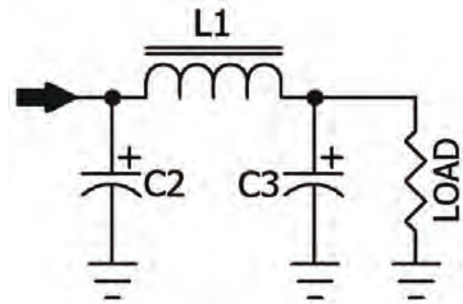


Inductive reactance gives the inductor high resistance to AC, but the only resistance to DC is the resistance of the wire used in the inductor. Inductors for power supplies are rated in Henry's (H). For vacuum tube power supply applications, inductors of 1H or higher are generally used.

Choke Inductor LC Pi Filter

The circuit in Figure 8 is a capacitor input filter after the rectifier. It is an LC filter with both inductance (L) and capacitance (C). It is a Pi filter because it is arranged to resemble the Greek letter pi. Figure 8 is configured as a low pass filter with a low 3 dB cutoff point of around 4Hz, effectively filtering out AC ripple from the DC supply voltage.

Figure 8
LC Pi Filter



A choke by itself acts as a filter restricting alternating current. When paired with capacitors in a pi filter configuration, the filter provides more AC reduction with a sharper roll-off. Chokes also limit sharp rises in current protecting circuits from damage.

Figure 9

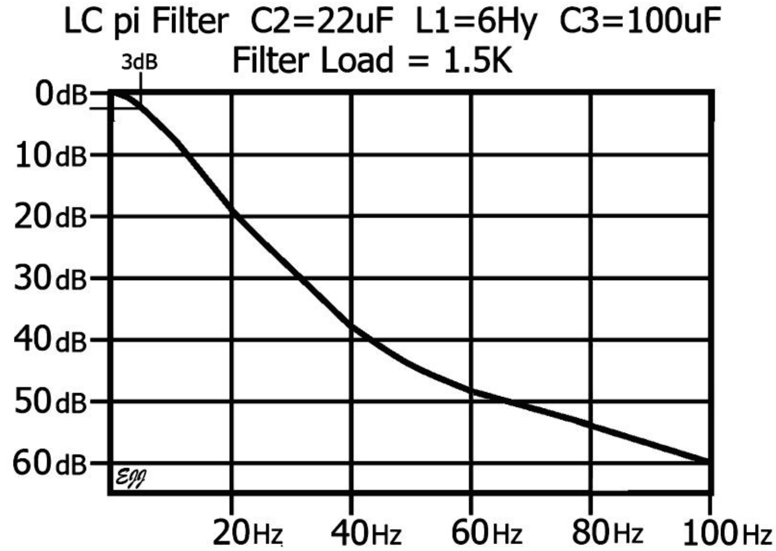


Figure 9 is a graph of the measured response of the filter in Figure 8. In a full wave rectifier circuit, ripple is twice the frequency of the AC mains. AC mains of 50 Hz produce 100 Hz ripple. AC mains of 60 Hz produce 120 Hz ripple. The graph in Figure 9 shows ripple at 100 Hz being reduced by 60 dB, 120 Hz was measured as reduced by 64 db.

Filtering after the power supply pi filter will reduce ripple even further. Response measurements were made using a reference of so many dB down from zero. Using dB down from 0 is easier to visualize, 0 being referenced to the B+ DC voltage.

Capacitor Loading

At the bottom of page 30, it was stated that the peak value of an AC RMS voltage could be calculated by multiplying the RMS value by 1.414. And, on page 80, it was stated that the power supply capacitors will charge to the peak value of the rectified AC voltage. This is true under no load conditions.

Compensate For Capacitor Loading

Solid State Rectifiers

Using solid state rectifiers, the load on a capacitor will prevent the capacitor from charging to a full peak value. Capacitor loading will cause B+ voltage to be about 19% lower than the 1.414 peak value of the rectified AC voltage.

For a solid state power supply, multiplying the desired rectified DC voltage by .707 provides the transformer unloaded secondary AC voltage. For example, a 450VDC B+ supply would require a 318-0-318 (636VCT) volt AC secondary (450 X .707). Rectified 318 volts would provide 450VDC of voltage with no load on the capacitors. Factoring in how much more secondary AC voltage is required to compensate for capacitor loading requires a little calculating.

For a 450VDC B+ supply,
Multiply 0.19 (19%) times the transformer's secondary no load AC voltage.
318 X .19 = 60
Add the result to the unloaded AC value.
318 + 60 = 378VAC

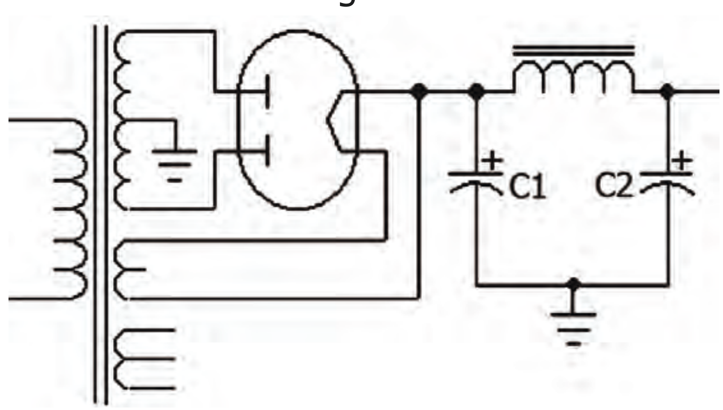
A close match would be a transformer rated 760VCT (380-0-380). The loaded 380 volt AC rectified supply voltage would be approximately 450VDC. The current rating of the transformer would depend on the calculated load currents. The calculated load currents are found by adding up all the transformer circuit loads. This is covered in creating an amplifier, page 133.

Vacuum Tube Rectifier

In the case of a vacuum tube rectifier power supply, you will first need to calculate the high voltage current load. Then use the rectifier current load graph for the rectifier tube type used. For example, see pages 85 and 86. Capacitor loading is already factored into the tube rectifier graphs.

There are two types of vacuum tube rectifier configurations. The most common is a capacitor-input filter and the other is a choke-input filter.

Figure 10



In figure 10, C1 is at the input to the filter. This makes it a capacitor-input filter. For a choke-input filter, C1 is omitted.

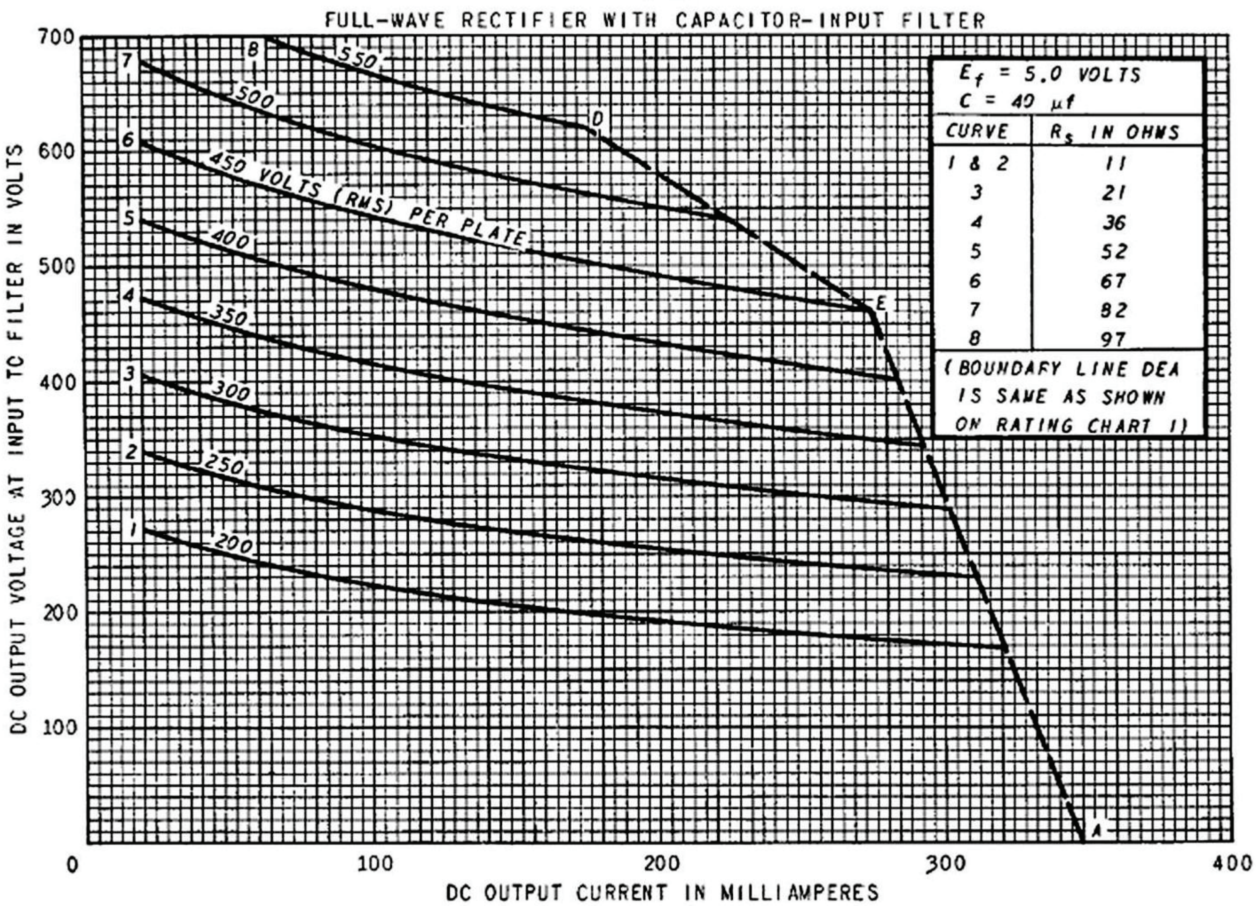
Using a choke-input provides a more stable B+ supply. However, the DC output voltage is lower and requires higher voltage applied to the rectifiers. Higher voltage transformers are required for a choke input and can be significantly more expensive. Besides being less expensive, lower voltage transformers are more readily available.

Vacuum Tube Rectifier Current Load Graphs

Load graphs like Figure 1 and Figure 2 are used to find the rectifier output voltage under various loads. The graphs shown are for a 5U4 Rectifier.

FIGURE 1

5U4

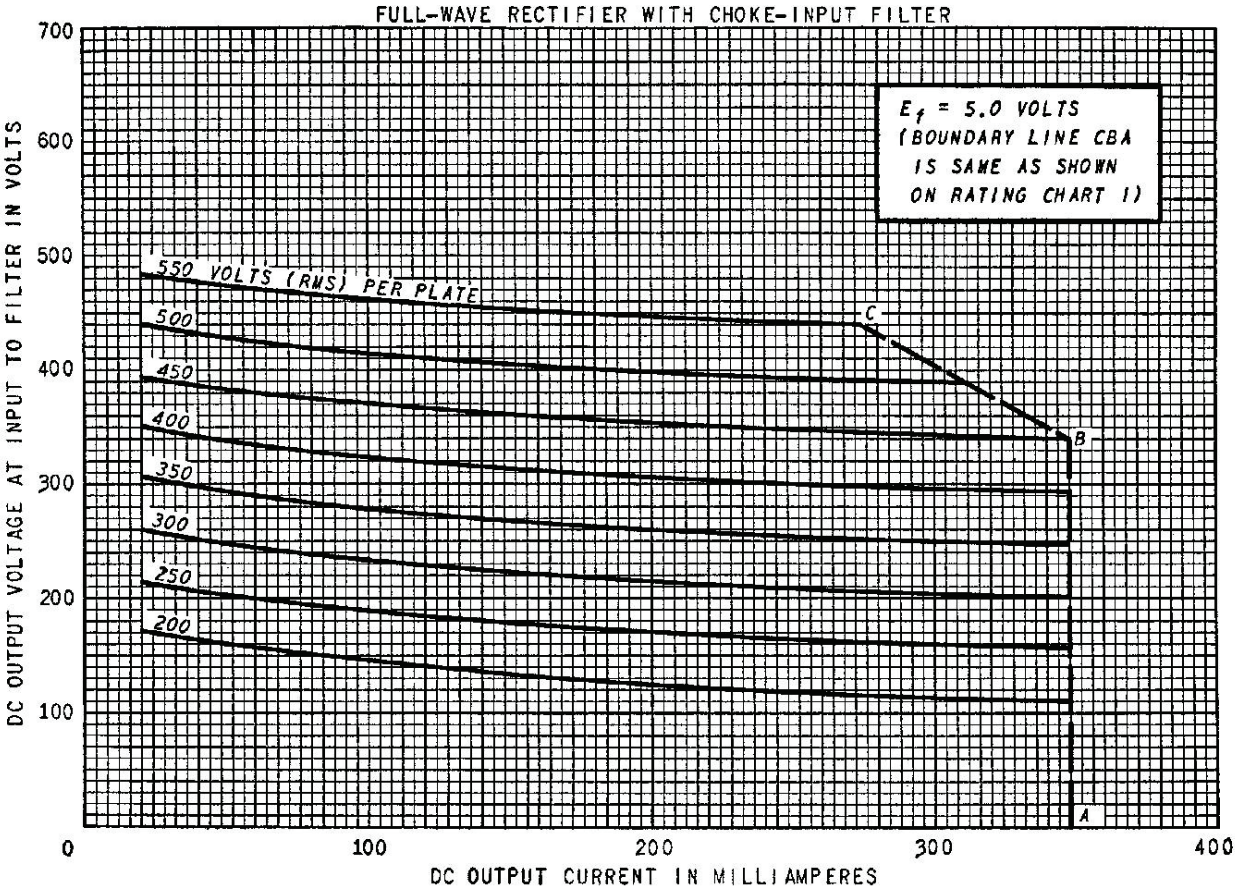


The left side of the graph shows DC voltage at input to the filter. This is the voltage coming off the rectifier cathode. The bottom of the graph is the current load (in mA) placed on the rectifier tube. The graph plot lines are different power transformer secondary voltages stated as (RMS) per plate.

The graph is easy to use. For example, a 700VCT (350-0-350) transformer secondary would provide 350 volts RMS per plate. If 100 mA is the current load, find 100mA at the bottom of the graph. Follow the 100 mA line upwards until it meets the 350-volt graph plot line. Follow the intersecting line to the left side of the graph (DC output voltage at input to filter) and you will find that the voltage coming out of the rectifier cathode is about 415VDC. If the current load is 200 mA, then the voltage coming out of the rectifier cathode will be about 370VDC.

In the case of a choke input filter, you would need to consult an appropriate graph such as the one in Figure 2.

FIGURE 2 5U4



As can be seen in Figure 2, with a choke input, the DC voltage at the 5U4 cathode is less than with a capacitor input filter. With 350VAC at each plate and a 100mA DC current load, the voltage from the 5U4 cathode is about 280VDC.

Although the DC voltage output is lower with a choke input filter, the voltage is less affected by load change than in a capacitor input filter. With the capacitor input filter, 350VAC on each plate, there is about a 100VDC difference at the tube cathode from 25mA to 200mA loads. With the choke input filter, the difference is around 50VDC over the same range.

Using a choke input provides a more stable B+ supply, but requires higher voltage on the rectifier plates. To obtain the same 415VDC @ 100 mA using a choke input filter will require a transformer high voltage winding of about 500V per plate, 500-0-500 (1000VCT).

Solid State High Voltage Loading

The graph in Figure 1 below is primarily for use with solid state rectifiers. For a vacuum tube rectifier, graphs like those on pages 85 and 86 should be used. The graphs for vacuum tube rectifiers take into account loading as well as the internal resistance of the rectifier.

When selecting a power transformer, it may not be possible to find an exact voltage and current match for the high voltage load of an amplifier design. In most cases, you will wind up with a transformer rated at a higher current than the load.

The power transformer's high-voltage secondary's actual voltage will vary depending on the load. Tubes that draw less current will result in an increase in the secondary voltage. A higher secondary AC voltage at the rectifier input means a higher DC B+ voltage at the rectifier output.

For example, the high-voltage transformer winding for an amplifier is rated 640VCT (320-0-320) at 200 mA. However, the actual current load is 148 mA.

Figure 1

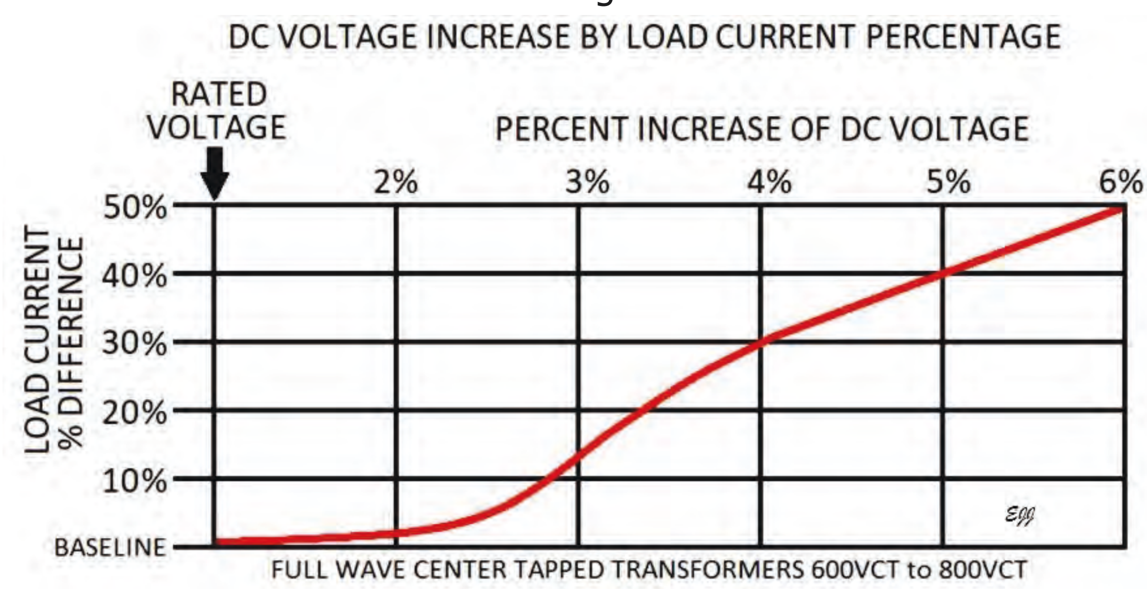


Figure 1 is a graph that can be used to estimate how much higher the DC high voltage will be if a transformer with a higher current rating than required is used. To use the graph, you must first find the percentage difference between the full current load rating and the actual current load. In this case, 200 mA and 148 mA.

The following formula is used to calculate the percent difference between two numbers:

% = [{(Lv – Sv) / Lv} X 100]

Lv = Larger value = 200 mA
Sv = Smaller value = 148 mA

Note: You can use mA or amperes.
(200 mA = 0.2 amps, 148 mA = 0.148 amps).
Both numbers must be the same, mA or amperes.

– = Subtract
/ = Divide by
X = Multiply by

(Solve the innermost brackets first, then work your way out.)

Using mA:
% = [{(Lv – Sv) / Lv} X 100]
% = [{(200 – 148) / 200} X 100]
% = [{52/ 200} X 100]
% = [0.26 X 100]
% = 26

The results are a 26% current load difference. To use the graph in Figure 1, find 26% on the left side of the graph. Follow the 26% point to the right until it meets the plotted line, then go straight up. A 26% load difference indicates about a 3.7% increase in B+ voltage.

3.7% = .037 (percent converted to decimal by moving the decimal point two places to the left.)

380 X .037 = 14. There is about a 14 volt increase.

Add 14 volts to 380, 380 + 14 = 394.

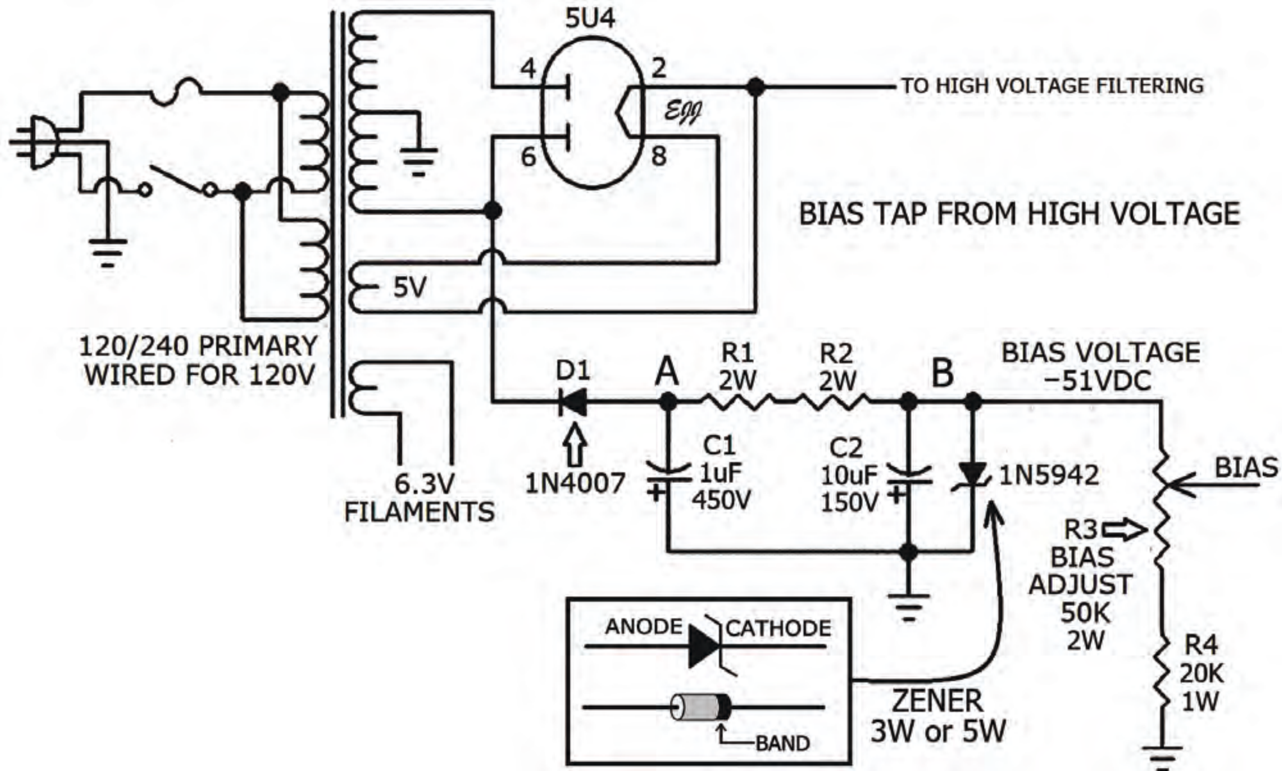
This will increase 380 VDC to approximately 394 VDC.

Tap Bias from High Voltage Secondary

When a negative grid bias voltage is required for an output tube circuit, and a suitable transformer with a bias winding cannot be found, it is possible to tap voltage from a transformer's high voltage winding.

Figure 1 shows a method of tapping off one side of a high voltage secondary for a negative bias supply voltage.

Figure 1



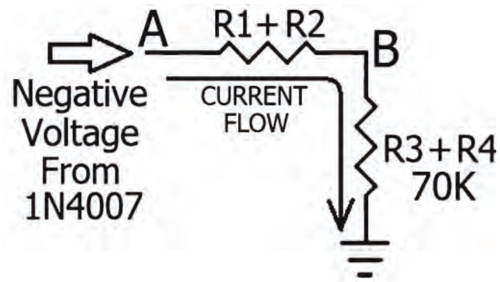
The reason for using two resistors at R1 and R2 is to avoid exceeding resistor maximum voltage ratings. Using two resistors in series splits the voltage between the two resistors. The resistor values should be close to identical.

The values shown in the Figure 1 circuit and the following example of calculations are based on a 600VCT transformer secondary and a 51 volt zener diode.

A zener diode is selected for the maximum bias voltage value, a value about 40% higher than the required bias voltage. The R3 bias adjust potentiometer sets the required value of bias. R4 sets the minimum bias voltage value. Depending on the required voltage bias range, the value of R4 may need to be adjusted. Resistors R1, R2, R3, and R4 are power rated as shown.

For a bias voltage of –35 volts, a 51 volt zener diode would be used. Figure 2 illustrates the current path through R1, R2, R3 and R4. Since the grid of an output tube draws very little current, only current through the bias supply circuit is considered.

Figure 2



R3 and R4 have a total resistance of 70K ohms. To calculate the voltage rating of C1, calculate the voltage at point A. Multiply half of the high voltage AC secondary by 1.414. For a 600 volt center-tapped secondary, (300-0-300), use 300 volts. 300 X 1.414 = 424 volts DC.

The C1 capacitor should be rated at least 450VDC. Capacitor C2 is across the 51 volt zener diode. A voltage rating of 150 volts for C2 is sufficient as the zener will keep the voltage clamped at 51 volts.

In Figure 1, for a 51 volt zener diode you would want about 77 volts DC at point B (voltage about 50% higher than the zener rated voltage). Calculations are made as if the 51 volt zener is out of the circuit. However, do not actually power up the circuit without the zener diode in the circuit.

The current that will provide a 77 volt voltage drop across R3 and R4 is calculated using I = E / R, 77 / 70,000 = 0.0011 amps (1.1 mA).

Since R1, R2. R3 and R4 are connected in series, the current flow through R1 and R2 will also be 1.1 mA. Remember that Ohm's law formulas work with current in amperes. 1.1 mA = 0.0011 amps.

For a 51 volt zener, the voltage drop across R1 + R2 is 347 volts, (424 – 77).

Calculate the resistance value of R1 + R2 that will produce a voltage drop of 347 volts across R1 + R2 using R = E / I, 347 / 0.0011 = 315,455 ohms.

Splitting 315,455 ohms between R1 and R2, 315,455 / 2 = 157,728.
R1 = 157,728 ohms and R2 = 157,728.

The closest standard value is 160,000 ohms for R1 and R2.
With the 51 volt zener in the circuit, there should be sufficient voltage at the zener to keep the zener voltage clamped.

Filament Voltage Loading

The secondary winding of a transformer will produce its rated voltage when loaded at the winding's ampere rating. For instance, a 6.3-volt @ 2 amp winding will produce 6.3 volts with a 2 amp current load. If the winding is loaded at 1 amp, the voltage will be higher than 6.3 volts. If the winding is loaded at 3 amps, the voltage will be less than 6.3 volts. It is not good practice to exceed a transformer's secondary current rating. Excessive loading of a secondary winding can cause a transformer to run hot and possibly fail.

The following is stated in the RCA Tube Manual.

> When the (filament) voltage is low, the temperature of the cathode is below normal, with the result that electron emission is limited. The limited emissions may cause unsatisfactory operation and reduced tube life. On the other hand, high heater voltage may cause rapid evaporation of cathode material and shorten tube life.

Calculate Filament Voltage under Actual load

When a power transformer provides significantly more current than the actual filament current load, the voltage applied to the filaments may be too high.

Use this formula to calculate how much filament voltage will be applied to filaments when supplied with more current than the filament load.

EuL = {[(1 − (IaL/IfL)) X 0.1] X EtR} + EtR

EuL = VOLTAGE UNDER LOAD in volts
(Voltage under actual load)

IfL = FULL LOAD CURRENT in amps
(Transformer’s rated current)

IaL = ACTUAL LOAD CURRENT in amps
(The actual current load)

EtR = TRANSFORMER RATED VOLTAGE
Transformer’s specified filament voltage

− = Subtract, / = Divide by, X = Multiply by, + = Add

Do not let formulas scare you. Formulas that contain more than one set of brackets are worked by solving the innermost brackets first, then work your way out solving the next innermost brackets.

For example, a transformer's 6.3-volt filament winding is rated at 4 amps, but with an actual load of 2.7 amps.

IfL = 4 amps
IaL = 2.7 amps
EtR = 6.3 volts

Write out the formula, then plug in the numbers[1].

EuL = {[(1 − (IaL/IfL)) X 0.1] X EtR} + EtR

EuL = {[(1 − (2.7/4)) X 0.1] X 6.3} + 6.3

(Solve the innermost brackets first, and work your way out.)

EuL = {[(1 − **(**2.7/4**)**) X 0.1] X 6.3} + 6.3

EuL = {[**(**1 − 0.68**)** X 0.1] X 6.3} + 6.3

EuL = {**[**0.32 X 0.1**]** X 6.3} + 6.3

EuL = **{**0.032 X 6.3**}** + 6.3

EuL = 0.20 + 6.3

EuL = 6.5

To drop the voltage closer to 6.3 volts, you need to add some resistance in series with the filament supply. Use Ohms' law to find resistance. You need to drop 0.2 volts (6.5 – 6.3).

R = E / I E = 0.2 volts I = 2.7 amps R = 0.2 / 2.7 = 0.074 ohms

To find the wattage rating of the resistor, you must measure resistance across each tube's filament pins. When vacuum tubes are cold, the filament resistance is very low. Using I = E / R, calculate each tube's cold filament power-on current surge[2]. Then, add up all the filament current surges. If the total cold filament current is 16.4 amps, the wattage rating required for the 0.074-ohm resistor is I^2 X R, (16.4 X 16.4) X .074 = 269 X 0.074 = 20 watts. An example of calculating cold filament resistance can be found on page 145.

[1] Where appropriate, round out the numbers. E.g., 0.2016 becomes 0.20

[2] Tubes must be completely cold to measure cold filament surge resistance.

Filament Induced Hum

Filament induced hum can be a problem in low-level high gain input stages. Since the filament is inside the vacuum tube near the control grid, AC hum from the filament voltage can be picked up by the control grid. When using filament transformers with a center tap, an effective method to cancel hum in the filament line is to ground the center tap of the transformer filament winding. With the center tap grounded, each side of the filament line is 180 degrees out of phase, substantially reducing AC hum by cancelation.

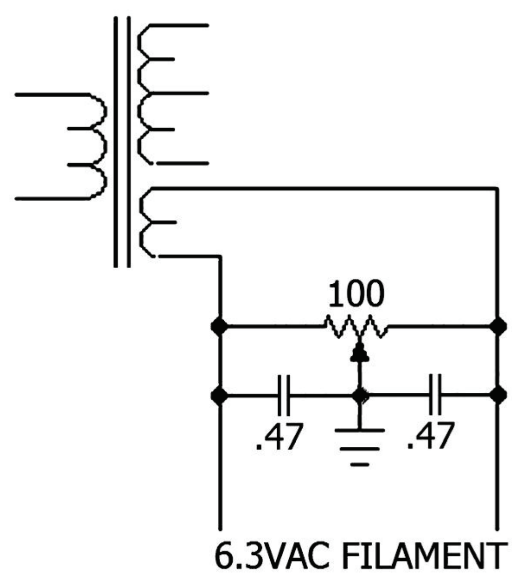
Hum Balance Pot

When you have a filament transformer winding without a center tap, you can use a potentiometer to balance out hum. The potentiometer acts similar to the center tap of a filament winding by placing a ground potential near the center of the winding. Although a hum balance potentiometer works to some degree, the grounded filament center tap method does a better job of canceling hum.

Figure 1 shows a hum balance pot in a 6.3-volt filament circuit.

The .47 uF caps are multilayer ceramic capacitors rated at 100 volts. They are TDK part # FG24X7S2A474KRT06, or equivalent. They are very small and fit nicely soldered directly onto the potentiometer terminals. The 100-ohm pot connected across the 6.3-volt filament supply will dissipate .4 watts of heat. A wire-wound potentiometer rated at about four or five watts should be used. Overrating the potentiometer wattage will reduce the chance of failure over time. The potentiometer should not be a conductive plastic, cermet or carbon type.

Figure 1



Do not include a filament balance potentiometer on a filament line that has a grounded center tap.

Hum cancelation is not 100% using a balance potentiometer because there is some resistance in the balance pot connected to each side of the transformer winding.

Sometimes, when including a filament hum balance potentiometer in a new amplifier build, you may find that there is no noticeable hum regardless of where the pot is set. This means there was no hum problem to begin with. Just leave the potentiometer at the center of rotation.

Never use a hum balancing potentiometer or ground the filament winding for a vacuum tube rectifier. The filament of a rectifier tube will not induce any hum into the audio. Grounding the filament of a rectifier tube that uses the filament as the cathode would effectively short out the high voltage and destroy the tube.

Never connect either side of a filament winding directly to ground. This will unbalance the filament line and cause hum. Only ground the center tap of a center-tapped filament winding.

Figure 2

If you're having no luck dealing with a hum problem, you might try using .47 uF multilayer ceramic capacitors at the amplifier stage in question. As shown in Figure 2, add a ground lug to the tube socket mounting screw. Then, add a .47 uF cap from each filament terminal to the ground lug.

It is true that a .47 uF capacitor is not a large enough value to bypass 50 or 60 Hz. However, this author has used this method to eliminate low level hum in a project where the filament transformer did not have a center tap. The science behind this is unsure; the capacitors may provide a ground reference or shielding effect. Another possibility is that the hum may not be a hum, but the result of an oscillation. Consider it as a possible 'if all else fails' solution.

Calculate Fuse Size

To determine what size fuse is needed, use volt-amperes to calculate the current load of the transformer primary. In order to do this, the volt-amperes in each secondary winding must be calculated, then all added up for a total volt-amperes load of all the transformers' secondaries. Use the transformer rated secondary voltages and the maximum current loads.

Volt-Amperes = E X I

On a high voltage transformer, without a center tap, use the entire voltage rating. With a center taped transformer, use half the rated voltage.

High Voltage: 700VCT (350-0-350) @ 0.200 amps
(1/2 of 700V = 350V) 350V X 0.200 amps = 70 volt-amperes

5V Filament, 5 volts @ 3 amps, 5V X 3 amps = 15 volt-amperes

6.3V Filament, 6.3 volts @ 4 amps, 6.3V X 4.0 amps = 25.2 volt-amperes

Add all the secondary volt-amperes; 70 + 15 + 25.2 = 110.2 volt-amperes

The volt-amperes are essentially the same on both sides of the transformer. To find the current load in the primary, divide the total volt-amperes by the primary voltage.

Primary amps = total secondary volt-amperes / primary voltage.
120V Primary
110.2 / 120 = 0.92 amps

A 3 amp fuse will work; using a slow-blow (delayed) type fuse will allow for possible power-on current surges.

Power Switch

For the power switch wiring, it makes no difference if the power switch is placed on the hot or neutral AC primary power, the circuit will still open. Since AC neutral is essentially at ground potential, running neutral AC wiring from the back of the chassis to a front chassis power switch reduces the chance of hum from the AC wiring being picked up by sensitive amplifier circuits. The fuse should be in the AC primary power hot circuit.

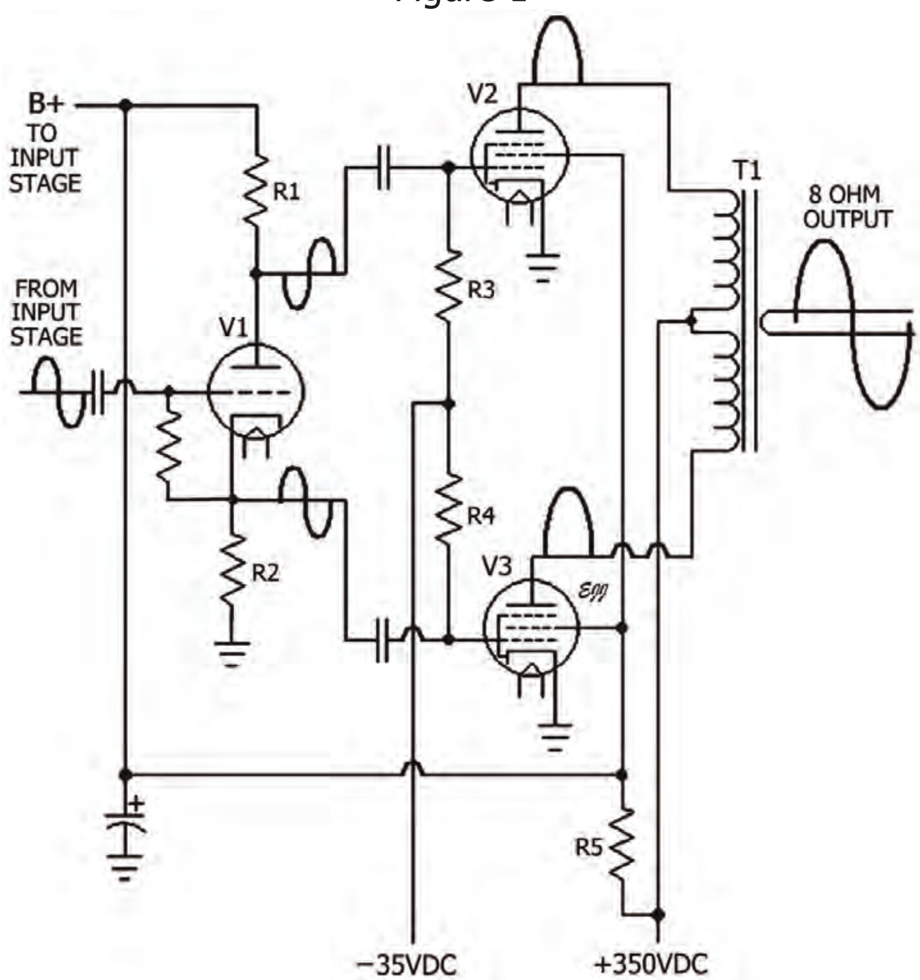
Power Amplifiers

Power amplifiers are designed to deliver power to a low impedance load, typically a four to sixteen ohm speaker system. Any amplifier with an output that can directly drive a speaker qualifies as a power amplifier. The traditional method of coupling a vacuum tube to a low impedance load is by using output tube plate coupling, an output transformer.

Class AB Push-Pull

In push-pull, each output tube only amplifies a positive signal. A signal phase inverter is required to flip the negative portion of the input signal to positive. The phase inverter V1 splits the input signal into two signals 180 degrees out of phase from each other. In effect, the negative portion of the input signal is now positive.

Figure 1



The primary advantage of push-pull is the ability to achieve much higher output levels while drawing less current.

In Figure 1, each output tube is only amplifying half of the waveform; this allows the power tubes to be biased near cutoff, conducting only during half the waveform. Drawing considerably less current, operating the tubes near cutoff allows the tubes to operate more efficiently and much cooler. The tubes can be biased for Class AB or Class B operation. Class B is biased closer to cutoff than Class AB, increasing efficiency of the output stage. The disadvantage of Class B operation is noticeably higher distortion at low volume levels.

The output transformer T1 primary winding is center-tapped. This sets each output tube output 180 degrees out of phase from each other. The result is that the negative portion of the signal is returned to normal at the output.

Although push-pull increases efficiency, unless everything is balanced, the signal splitting process introduces some undesirable effects. One anomaly is the cancelation of the more desirable even order harmonic distortion, while odd order harmonic distortion is allowed to pass. Balanced push-pull is covered in depth in the article Push-Pull Balance by W T Cocking from Wireless World in November 1947.

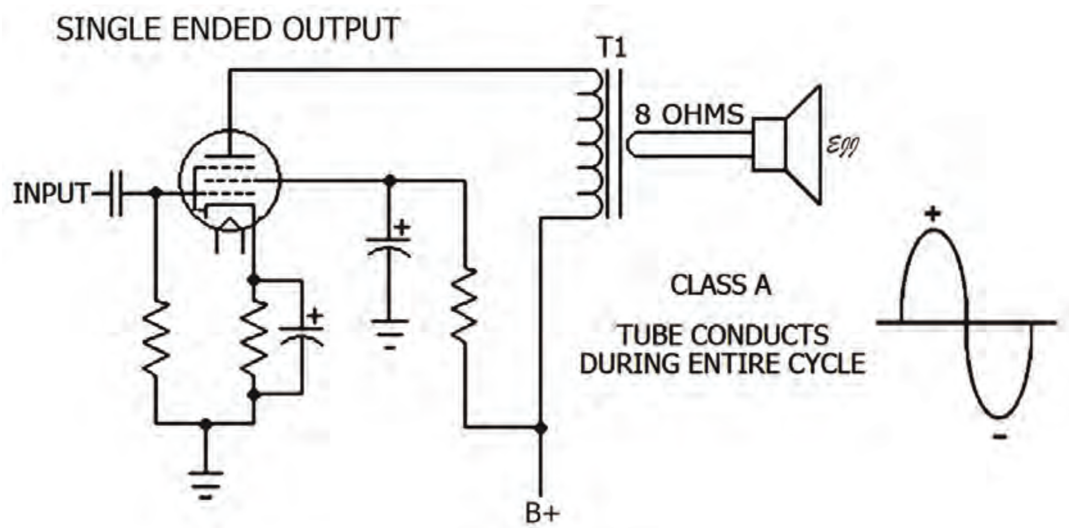
Adjusting or modifying bias component values in a push-pull Class AB output circuit for Class A operation does not eliminate phase inversion balancing problems. Biasing a push-pull amplifier for Class A output operation would still leave the signal splitting process and its balancing issues. Operating a Class AB circuit like Class A may result in increased current in the output tubes. This could possibly increase output tube plate dissipation past its maximum value. With increased current, the load resistance of the output tubes may change enough that the output transformer impedance intended for Class AB operation is no longer a good plate load match.

On the subject of power output, two output tubes connected in parallel in Class A linear operation will produce the same power output as the same two tubes operated in push-pull Class AB operation. This, of course, requires careful attention to plate dissipation values.

Class A Single Ended

A single tube output stage is biased Class A to operate in its linear operating range. Power tubes operating Class A require current at all times and are not as efficient as class AB push-pull.

Figure 2



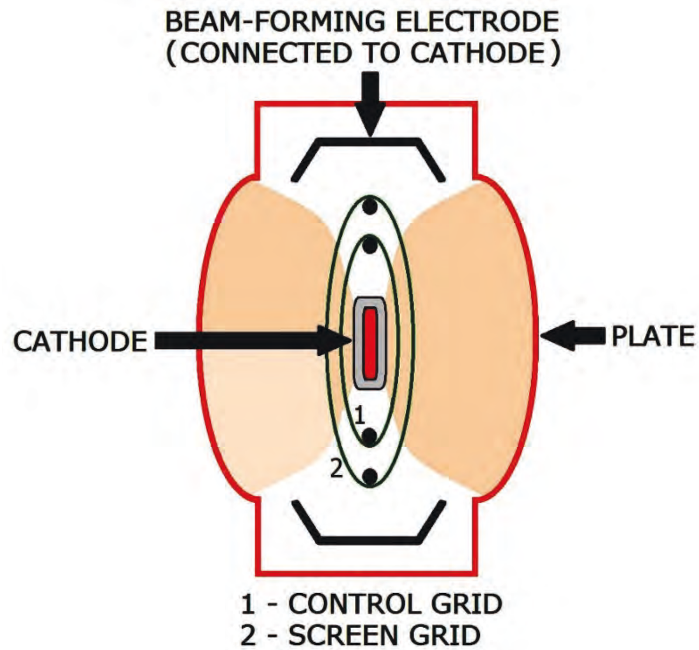
Class A is linear amplification, where the signal is simply amplified and not manipulated. For an audio system in the home where higher efficiency speakers are used, a Class A output might be desired.

Pentode & Beam Power Output Tubes

The circuits in Figure 1 and Figure 2 are both shown using pentode power output tubes containing a control grid, a screen grid and a suppressor grid.

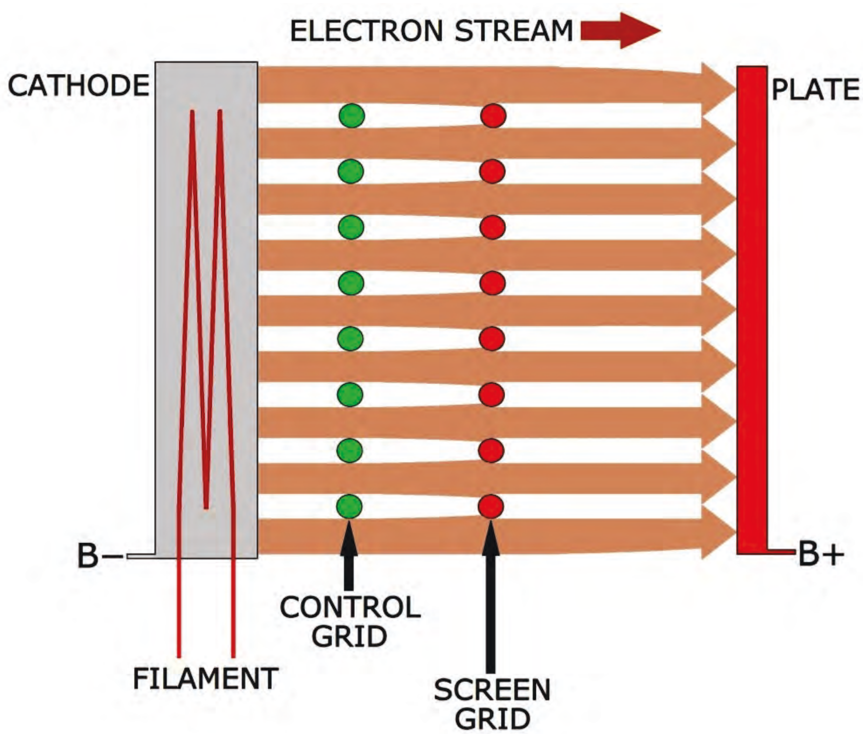
Figure 1 depicts fixed grid bias and Figure 2 depicts cathode grid bias. Although the circuit diagram in Figure 1 and Figure 2 indicates three grids, some power output tubes do not have a third grid. Beam power tubes use beam-forming electrodes instead. Beam power tubes use electron field confining electrodes at cathode potential to produce a beam effect. The beam restricts stray electrons repelled off the plate from being attracted to the screen outside the beam, see Figure 3. Beam power tubes have higher power output, higher power sensitivity and higher efficiency. Even though a beam power tube has no third suppressor grid, on circuit diagrams, a third grid may be shown.

Figure 3



The control grid and screen grid are spiral wires wound such that the screen is behind in the shadow of the control grid wire shielding the screen from the cathode. This creates a stream of electrons traveling between the control grid and the screen grid, reducing the number of electrons that hit the screen grid. This shielding of the screen grid results in low screen current, Figure 4.

Figure 4



Output Tube To Speaker

Coupling a power tube to a speaker usually involves the use of an output transformer. The tubes themselves are resistive and not inductive. However, the output transformer is inductive. There is a lot going on between the output tube, the output transformer and the speaker that affects the overall sound that is heard. In the next few pages, coupling a vacuum tube to a speaker is briefly discussed.

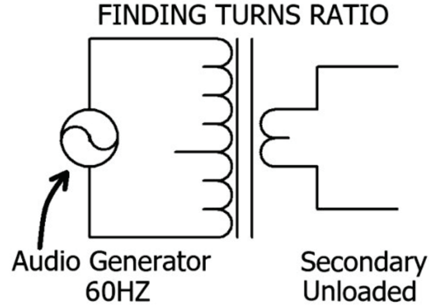
Impedance

Output transformers are used for coupling the plate resistance of the output tube to a speaker. An output transformer has no impedance by itself; it reflects the impedance load on the secondary back to the primary. The primary impedance can be determined by the ratio of the number of primary coil turns to the number of secondary coil turns. The following is a method to approximate this ratio without knowing the actual number of coil turns.

The transformer that was used for this example has a 3,300 ohm primary. You can approximate the turns ratio by applying an AC signal to the transformer primary. Any frequency from 50 Hz to 500 Hz can be used. The AC signal is applied across the entire primary. The secondary should be unloaded. A digital voltmeter is preferred for measurements.

Figure 1

FINDING TURNS RATIO



Using an audio generator to generate a test signal removes the risk of shock that might be encountered trying to tap voltage off a transformer powered by the AC mains. Use of a digital AC voltmeter will provide sufficient accuracy. Set the AC primary signal to a convenient reference level, if possible, 5 volts up to 10 volts. Measure the AC signal voltage across the primary. Also measure the AC signal voltage across the secondary. The ratio is determined by dividing the primary voltage by the secondary voltage.
If you measure 5 volts across the primary and 0.257 volts across an 8 ohm secondary, 5 / 0.257 = 19.5, the turns ratio is 19.5 to 1 (19.5 : 1).

The primary impedance would then be, $Z = (\&ratio^{2})$ X (R).

$Z = (\&ratio^{2})$ X (R) = the turns ratio squared times the secondary load.
Z = Impedance ***&ratio***^{2} = Ratio squared ***R*** = Load resistance
Turns ratio= 19.5, load = 8 ohms, (19. 5 X 19.5) X (8) = 380 X 8 = 3,040.

Using this simple method will usually result in a value slightly lower than the actual impedance value. Multiplying the calculated impedance by 1.1 will provide a value closer to the correct value. 3,040 X 1.1 = 3,344 ohms.

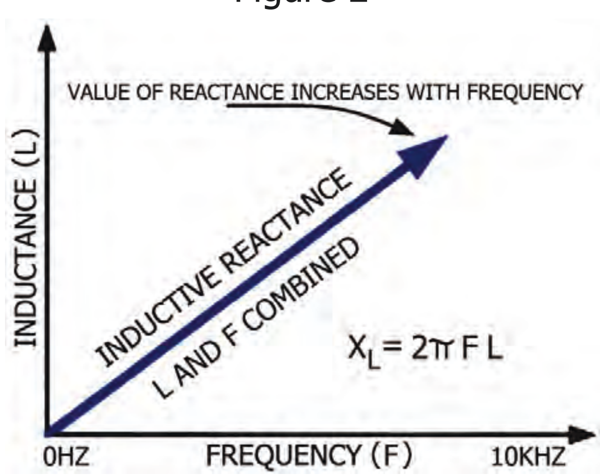
This method is sufficient to approximate the primary impedance of an output transformer based on the secondary load, regardless of what a transformer's impedance is stated. For example, in the case of a 3,300 ohm transformer primary. If the 8 ohm secondary is loaded 16 ohms, then the primary impedance would be (19. 5 X 19.5) 380 X 16 = 6,080 ohms (X 1.1 = 6,688). Using inductive reactance to calculate impedance provides more accurate results. With inductive reactance, impedance can be measured at 1,000Hz.

Inductive Reactance

An applied AC signal across an inductor produces a phase difference between the voltage and the current waveforms. This phase difference between current and voltage creates opposition (resistance) to AC current flow. The opposition to AC current flow through the coil winding not only depends upon the inductance of the coil, but also the frequency of the AC signal. If the frequency is increased, the overall inductive reactance value of the inductor will also increase. As the frequency decreases, the inductor's reactance will also decrease. Inductive reactance is directly proportional to frequency and has a small value at low frequencies and a high value at higher frequencies.

In Figure 2, the center arrow represents the inductive reactance (X_L) of inductance and frequency combined. The impedance of an output transformer primary winding follows inductive reactance. The value of inductive reactance is a key factor in output tube plate loading.

Figure 2



The inductive reactance (X_L) can be found using the following formula.

$x_L = 2\pi f L$ = 2π X f X L (2π = 6.283) (X = Multiply)

f is the frequency in Hz and L is the inductance of the coil in henries (H)

In order to calculate the inductive reactance of an output transformer primary at a certain frequency, you need to know the inductance (L) of the inductor. Inexpensive hand-held inductance meters have sufficient accuracy for this.

In Figure 3, a transformer with a 2,300-ohm primary is used for inductance measurement tests. The 8-ohm secondary is loaded with an 8-ohm resistor. The inductance meter measures 0.37 henries across the primary.

Figure 3

The inductive reactance at 1,000 Hz.

X_L = 6.283 X 1,000 X 0.37 =
2,325 ohms

The inductive reactance at 100 Hz.

X_L = 6.283 X 100 X 0.37 =
232 ohms

The inductive reactance at 10,000 Hz.

X_L = 6.283 X 10,000 X 0.37 =
23,247 ohms

Inductance is also measured with 6 and 10-ohm resistors connected to the 8-ohm secondary.

With 6-ohms connected to the 8-ohm secondary, the primary inductance becomes 0.23 henries. X_L @ 1000 Hz = 1,445-ohms.

With 10 ohms connected to the 8-ohm secondary, the primary inductance becomes 0.54 henries. X_L @ 1,000Hz = 3,393 ohms.

The following formula is used to calculate the primary impedance of an output transformer based on the DC resistance of the primary and the inductive reactance of the primary. $Z = \sqrt{R^2 + X_L^2}$

Where Z = Impedance, R is the DC Resistance of the wire and X_L is the inductive reactance.

$Z = \sqrt{R^2 + X_L^2}$ R^2 = R squared, X_L^2 = X_L squared.

First calculate $R^2 + X_L^2$, then find the square root of the answer.

The transformer used in Figure 3 has a DC resistance of 98.4 ohms.

The 8 ohm load inductive reactance calculated at 1,000Hz is 2,325 ohms.

Impedance at 1000Hz,

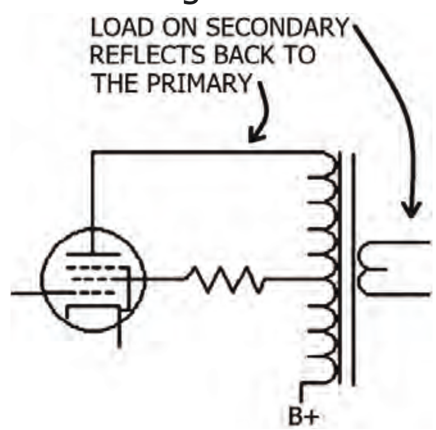
$$Z = \sqrt{98.4^2 + 2{,}325^2} = \sqrt{9{,}683 + 5{,}405{,}625}$$

$$= \sqrt{5{,}415{,}308} = 2{,}327 \text{ ohms}$$

Impedance at 1,000 Hz is about 2,327 ohms, very close to the inductive reactance.

As mentioned on page 100, an output transformer reflects the impedance load placed on the secondary back to the primary. In Figure 3 on page 102, the load placed on the 8 ohm secondary was 8 ohms. Then, 6 ohms and later 10 ohms. At 1,000 Hz, the primary inductive reactance with an 8-ohm load was 2,325 ohms. With a 6-ohm load, the primary inductance was 1,445 ohms and with a 10-ohm load, 3,393 ohms.

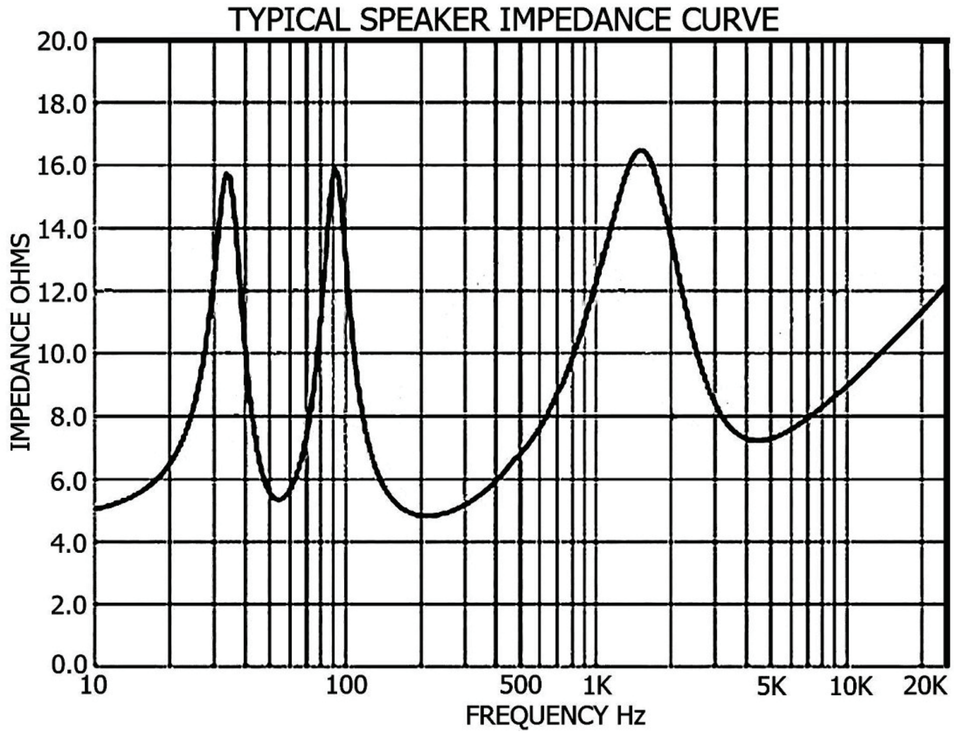
Figure 4



If the load on the secondary is decreased, the inductive reactance and impedance of the primary also decreases. If the load on the secondary is increased, the inductive reactance and impedance of the primary also increases.

Speakers are also inductive. The actual impedance response of a speaker is unique to the design of a speaker or speaker system. Depending on the impedance curve of a particular speaker, the frequencies of an audio signal can affect loading on the output transformer's secondary. In effect, the speaker is a load whose impedance varies with frequency reflected back to the primary, varying the primary impedance load to the output tube plate. Figure 5 is the impedance curve of a cone speaker in a typical enclosure.

Figure 5



A speaker's impedance response can alter the inductive reactance of the output transformer primary and loading on the output tube plate. Very low values of loading on an output tube plate may cause increased distortion, particularly at the lower frequencies where inductive reactance values can get very low. Be wary of the total inductive reactance and the resulting impedance of an output transformer primary at lower frequencies.

Plate Load

As mentioned at the top of page 100, power output vacuum tubes are not inductive; there is no inductive impedance to match. Vacuum tubes have a resistance sometimes referred to as impedance, but in fact, it is a resistive value. For an output tube, it is the plate load that must be considered.

While the vacuum tube load resistance is a static value set by circuit values, an output transformer is not a static impedance. The impedance of an output transformer depends on its inductive reactance, which in turn is dependent on frequency and secondary loading. A speaker's impedance response on the secondary is reflected back to the primary and determines the inductive reactance and primary impedance. The impedance of the output transformer primary is the load placed on the output tube.

Because the output transformer impedance is lowest at lower frequencies, it is important that the primary impedance does not get so low that it loads down the output tube excessively, increasing low-end distortion.

It would be best to design close to voltages listed on a datasheet. Doing so should provide the best plate load value. Otherwise, load line graphs must be used, a process that is advanced for a novice builder.

In the event a datasheet does not provide a plate load resistance for Class A single-ended operation, for pentode and beam power output tubes, a close plate load value approximation is plate voltage divided by plate current. Finding the load resistance for a Class A single-ended triode output, the plate resistance times three is a close match.

Many box & cone speaker systems have an impedance response similar to Figure 5. Although the impedance swing is dramatic, the output tube can handle the resulting plate load swing. From 1K HZ up, the datasheet plate load specified should perform well. Below 1K HZ, lower frequencies can excessively load down the plate.

There is a limited number of stock output transformers. In an effort to avoid loading down the output tube plate at lower frequencies, if you cannot find a transformer with a primary impedance specified by a datasheet, select a primary impedance higher rather than lower.

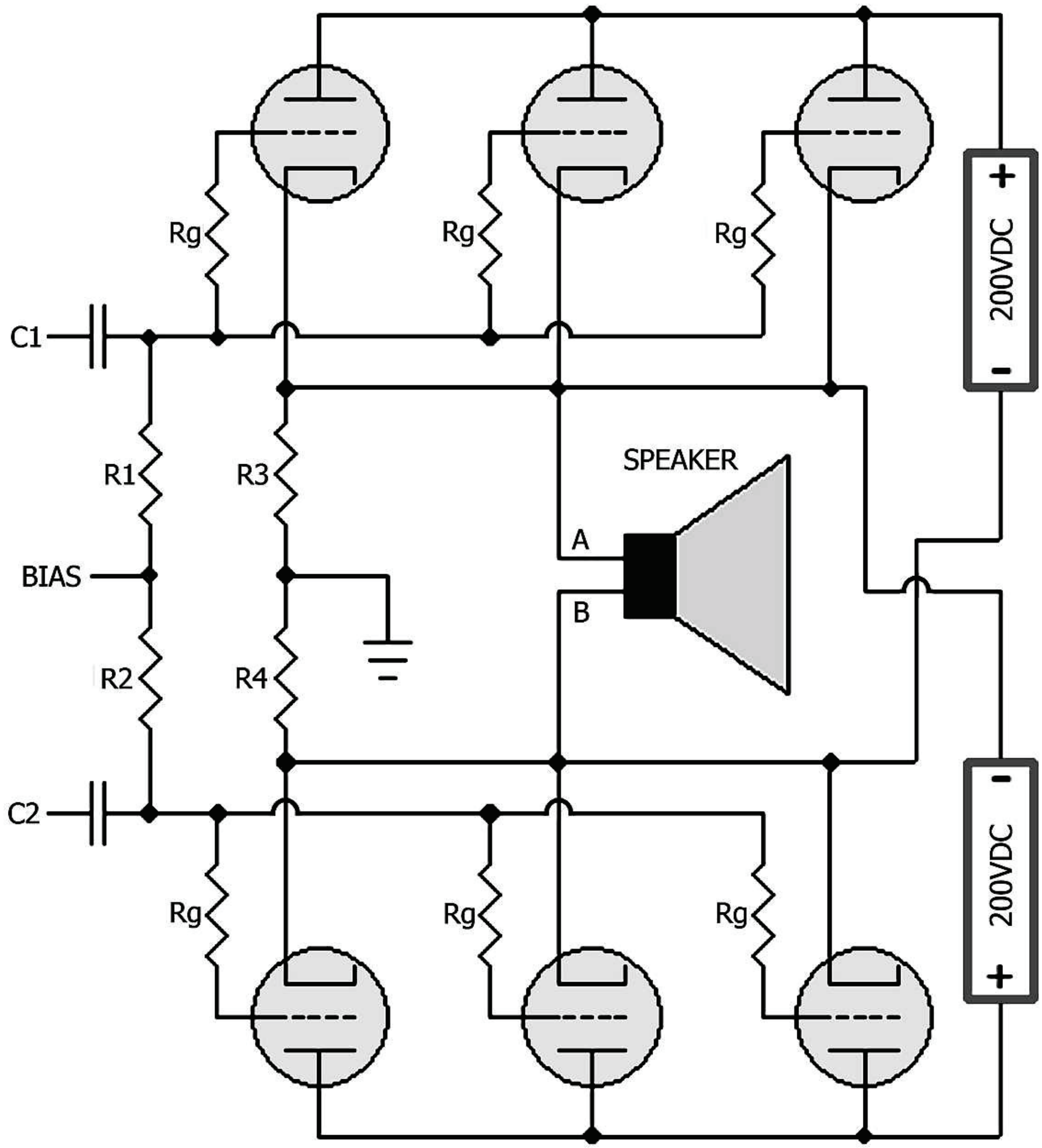
Negative Feedback

It is possible to reduce some of the effects of output transformer inductive reactance by using negative feedback from the output transformer secondary back to a previous voltage amplifier stage. Page 62 explains negative feedback used on a single-ended Class A output. For a push-pull output, the arrangement is similar except that the feedback signal connects to an amplifier stage cathode prior to the phase inverter. For either Class A single-ended or push-pull, the important thing is that the negative feedback voltage is 180 degrees out of phase. When a feedback loop is connected, the amplifier volume level should drop a bit. When checking for proper feedback, it will be easier to detect a drop in volume while listening at a low level.

OTL Amplifier

OTL (output transformer-less) amplifiers, as the name suggests, do not use output transformers. Figure 1 is one of several different concepts for direct coupling vacuum tubes to a speaker. This circuit is a cathode follower arrangement using a push-pull circuit with dual power supplies.

Figure 1



Each power supply has a negative return through the speaker; as long as both supply voltages are identical, no DC voltage appears across the speaker.

The output tubes need to be biased with identical current flow at the cathodes. If you measure across A and B, there should be no voltage difference. The OTL output stage power supplies must be matched and not connected directly to common ground. R3 and R4, around 1K ohms, are required to give the output power supplies a reference to ground.

The Rg resistors help reduce parasitic oscillations by adding some resistance to the grid circuit, usually a value between 470 ohms and 1K ohms for cathode follower circuits. C1 and C2 go to a phase inverter. The phase inverter and other pre-amp stages require a separate power supply isolated from the output power supplies.

There is a certain amount of risk involved with directly coupling vacuum tubes to a speaker. The problem is what happens when there is a circuit failure. A tube failing may cause a circuit imbalance and result in DC reaching the speaker. Besides the possibility of damage to the speaker, any DC voltage applied to a speaker's voice coil will displace or pull the voice coil out of position like an electro-magnet. Displacing the voice coil will add distortion. A tube shorting could cause high voltage to reach a speaker, damaging the voice coil. Over-driving the amplifier can also cause circuit imbalance as the amplifier starts to clip. Overload protection circuits are usually avoided as they tend to degrade audio performance. Fuses don't always react fast enough. One option to protect against an imbalance caused by output tube filament burnout is to wire all the output tube filaments in series. If one filament fails, all the tubes shut down.

Reasoning Behind OTL Designs

Most OTL amplifier designs were intended to save money by eliminating the cost of a high-quality output transformer. Another OTL concept is that by eliminating the output transformer, distortion induced by non-linearity in the transformer is eliminated; a reasonable assumption. The added output tubes required for OTL operation mean extra power consumption costs and extra expense when it's time to retube the amplifier. Then, the cost of high-quality output transformers seems insignificant. Output transformer non-linearity can be reduced to low levels with proper output circuit design.

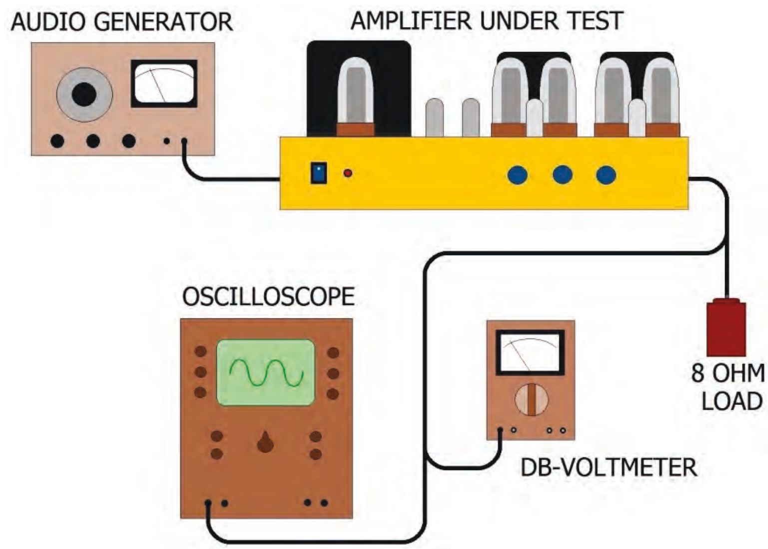
Measure Power & Frequency Response

Power Output

Measuring the power output of an amplifier requires an AC voltmeter, sine wave audio generator to provide a 500 Hz source, an oscilloscope (or PC software) and a resistor load.

The voltmeter can be a standard multi-meter with an AC scale or a dB meter with an AC scale. The load is normally a non-inductive resistor, but at 500 Hz a standard wire-wound power resistor can be used. Make sure the load is rated to handle the amplifier power.

Figure 1



Over-rating the load would be wise. For example, a 50-watt load to test 25 watts. The load will get hot, isolate or place the load away from anything that might be heat damaged and away from anyone; a hot load resistor can cause a serious burn. The oscilloscope, load and voltmeter are connected across the amplifier output. Make sure the test equipment ground or shield wire is connected to the amplifier output speaker ground terminal. If you connect a ground to the amplifier's positive output, you may short circuit the output and might damage the amplifier.

Set amplifier tone controls (if any) for a flat response. Connect the audio generator's sine wave output to the amplifier input. Set the audio generator to 500Hz with the generator level all the way off. If there is a gain control on the amplifier, turn it up. After the amplifier has warmed up, slowly increase the generator level while watching the oscilloscope until the waveform on the oscilloscope starts to clip or distorts. Reduce the generator level to just below clipping. Read the voltmeter at full output. Volts should be read as RMS. Calculate the power output in watts by using the formula $P = E^2 / R$.

Example, 5 volts RMS across an 8 ohm load at full output.

R = LOAD RESISTANCE

P = (5 X 5) / 8

P = 25 / 8

P = 3.125 watts

An amplifier's output wattage is logarithmic; doubling the voltage will increase the wattage four times. If, instead of 5VAC, you measure 10 volts across the 8 ohm load at full power.

P = (10 X 10) / 8

P = 100 / 8

P = 12.5 watts

Although the voltage was doubled from 5VAC to 10VAC, the power output increased four times from 3.125 watts to 12.5 watts.

Calculating Desired Wattage

If you are trying to achieve a specific power wattage out of an amplifier, you need to know how much voltage is required across the speaker. This can be calculated using the following formula.

$$\left(\sqrt{\text{WATTS}/\text{LOAD IMP}}\right) \text{ X } \text{LOAD IMP} = \text{VOLTAGE ACROSS LOAD}$$

Example

Load Imp= 8 Ohms

Desired Watts = 30

$$\left(\sqrt{30/8}\right) \text{ X } 8 = \text{VOLTAGE ACROSS LOAD}$$

$$\left(\sqrt{3.75}\right) \text{ X } 8 = \text{VOLTAGE ACROSS LOAD}$$

$$\left(1.936\right) \text{ X } 8 = \text{VOLTAGE ACROSS LOAD}$$

$$\left(1.936\right) \text{ X } 8 = 15.488$$

It will require about 15.5 volts across an 8-ohm load to achieve 30 watts.

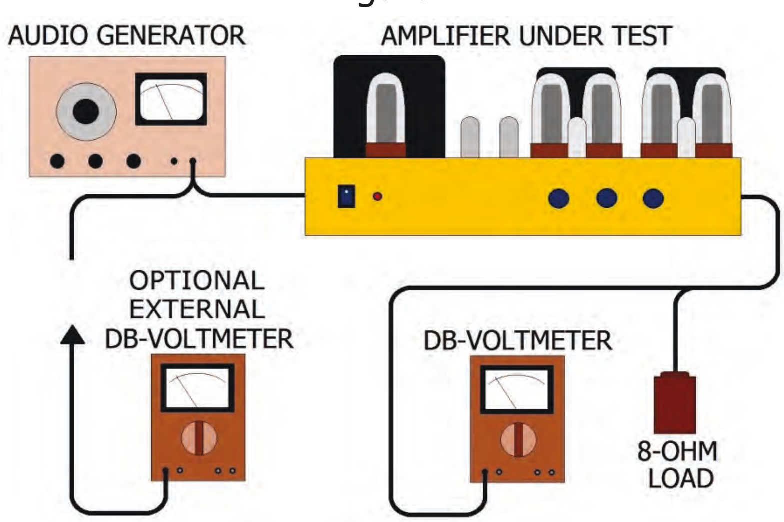
Measuring Frequency Response

Frequency response is measured over a range of frequencies in dB (decibels) deviation from a reference point. Generally, 1000 Hz is used as a reference point and any deviation is plus or minus so many dB from this reference. Amplifiers are specified with frequency response within a certain dB range, for instance, ±2dB 20 Hz to 20,000 Hz.

Test equipment required to measure frequency response is an audio generator with an accurate dB/AC voltage meter (either built-in meter or external), a resistive load for the amplifier (4, 8 or 16 ohms for power amplifiers) and an accurate dB/AC voltage meter to measure the amplifier output. A wire-wound resistor will not resonate at audio frequencies and should work fine as a load on power amplifiers. Use a resistor load with a power rating large enough for the amplifier under test. If your meters do not have a dB scale, you can use a true RMS[1] AC volt meter and refer to the dB to Voltage Chart on page 56 to find the matching dB value. Another option to test equipment is software that uses a computer's sound card.

In Figure 2, the generator output connects to the amplifier input. If the generator does not have a built-in level meter, connect an external meter across the generator output. The amplifier output connects to the load and a meter. The load and meter are connected across each other in parallel.

Figure 2



On multichannel amplifiers, test one channel at a time.

If a speaker is used for a load, speakers are inductive and may alter readings. On the other hand, a speaker will provide actual amplifier performance.

[1] A true RMS AC meter is accurate over a wide range of frequencies. A standard AC meter or standard AC multimeter is only accurate at lower frequencies.

Let the amplifier warm up for a few minutes before testing. If the amplifier has tone controls or tone boost settings, set them to flat. Select 1000 Hz on the generator and adjust the generator output level for a convenient reference reading on the generator meter. Use the generator meter and generator output level adjust control to maintain a constant generator output level at all test frequencies.

Set the generator to your 1,000Hz reference level. If you plan on using the dB to voltage chart on page 56, adjust the amplifier volume control for a reference reading on the output meter at 0.775V (0 dB). If the amplifier under test does not have a volume control, you will have to use an external control wired in series with the amplifier input.

The procedure is to set the generator to different frequencies, maintaining the same generator output meter level for all frequencies, adjusting the generator output level as necessary. Once you have set the amplifier output reference level at 1000 Hz, do not change the amplifier volume control or other amplifier controls. If you do, it will void all readings, and you will need to start over.

Write down the amplifier output meter reading at 1000 Hz reference. Then, starting at a low frequency, select test frequencies while maintaining a constant generator output meter level; write down the amplifier output level meter reading for each frequency. Suggested test frequencies: 20 Hz, 40 Hz, 100 Hz, 400 Hz, 5,000 Hz, 10,000 Hz, 15,000 Hz and 20,000 Hz. Frequencies above 20,000 Hz depend on the capabilities of the test equipment. The more test frequencies you use, the more accurate the results will be.

Once you have tested and written down the results of all frequencies, you can state the frequency response bandwidth using readings that were higher or lower than your 1000 Hz reference. The frequency with the lowest reading is the minus dB point and the frequency with the highest reading is the plus dB point. For example, –2 dB at 20 Hz, +2 dB at 2K Hz and –2 dB at 20K Hz would be written as from ±2 dB 20 Hz to 20K Hz.

Computer software that graphs frequency response will save a lot of writing, time, and patience.

Amplifier Power and Loudness

Our ears respond to sound pressure levels. Therefore, any increase in loudness is a result of increased sound pressure levels. Rather than considering volume levels in terms of amplifier watts, it is more accurate to use sound pressure levels. When selecting an amplifier for home use, how much power should an amplifier be rated? To get an idea of how loud different levels of sound pressures are, consider the loudness of different sources in our environment.

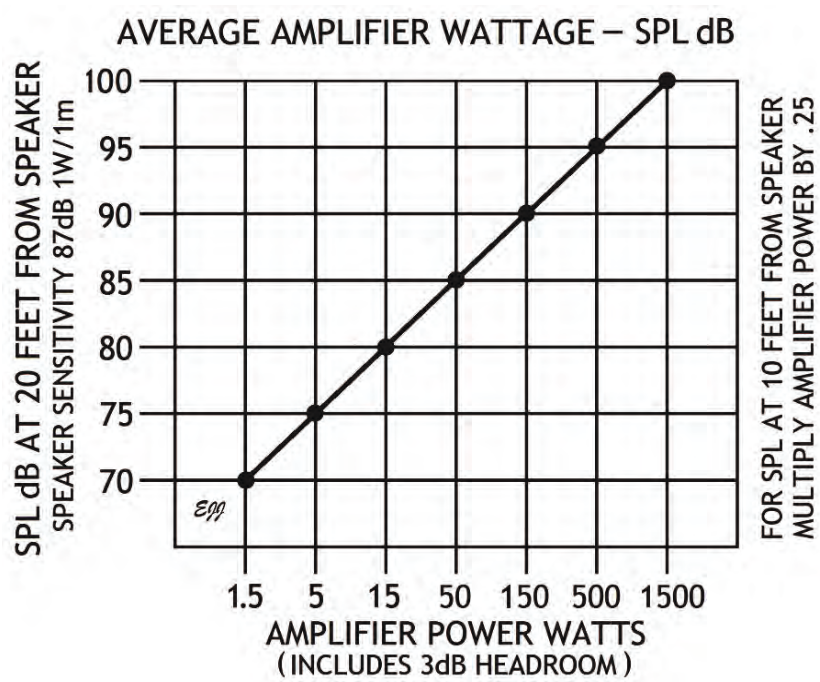
SPL dB Comparison

SPL dB		SOURCE
40	—	Quiet library
50	—	Average Home
60	—	Speech @ 3 feet
70	—	Vacuum Cleaner @ 3 feet
80	—	Side of Busy Street
90	—	Diesel Truck @ 30 feet
100	—	Jack Hammer @ 3 feet
110	—	Chainsaw @ 3 feet
120	—	Pneumatic Drill @ operator
140	—	Train Horn @ 20 feet

To protect your hearing, you would never want to be near a train blasting its horn or be around a chainsaw without hearing protection. If you avoid these sound pressure levels outside your home, you will want to avoid them inside as well. For a home sound system, it might be prudent to use a top-end sound pressure level of 85 dB, possibly 90 dB for short periods. The effects of hearing loss between 85 dB and 120 dB SPL may not become apparent until you notice reduced hearing perception. Above 120 dB SPL, permanent hearing damage will most likely occur. Hearing damage brings the possibility of tinnitus, ringing or buzzing in the ears.

At low sound pressure levels starting around SPL 45 dB, it takes about 6 dB (four times the amplifier power) to double the apparent loudness. At higher SPL levels, the ear starts to compress, reducing apparent loudness. You will notice this effect after listening to music at higher volume levels for a period, then stop. Your hearing will be somewhat diminished, slowly returning to normal. Although our ears seem to recover after long periods of high volume listening, repeated high SPL exposure over time will cause some degree of hearing damage. At higher SPL levels, it takes approximately a 10 dB increase in sound pressure level to double the apparent loudness. A 10 dB increase in SPL relates to an increase of ten times the amplifier power.

The graph plots the relation between higher sound pressure levels and amplifier wattage at a distance of 20 feet from a speaker. The graph is based on a speaker sensitivity of 87 dB 1W/1m. The table below can be used to adjust the graph amplifier power watts to higher speaker sensitivity ratings.



Spk Sen dB 1W/1m	Multiply Amp Power By	Spk Sen dB 1W/1m	Multiply Amp Power By
88	0.793	96	0.127
89	0.627	97	0.100
90	0.500	98	0.080
91	0.400	99	0.060
92	0.313	100	0.047
93	0.253	101	0.040
94	0.200	102	0.033
95	0.140	103	0.020

Engraved Panels
Front Panel
Although somewhat expensive, you can have custom engraved panels made. The front panel pictured below was custom fabricated and engraved. Here are a couple of sources for single panel fabrication as of 01/2025.

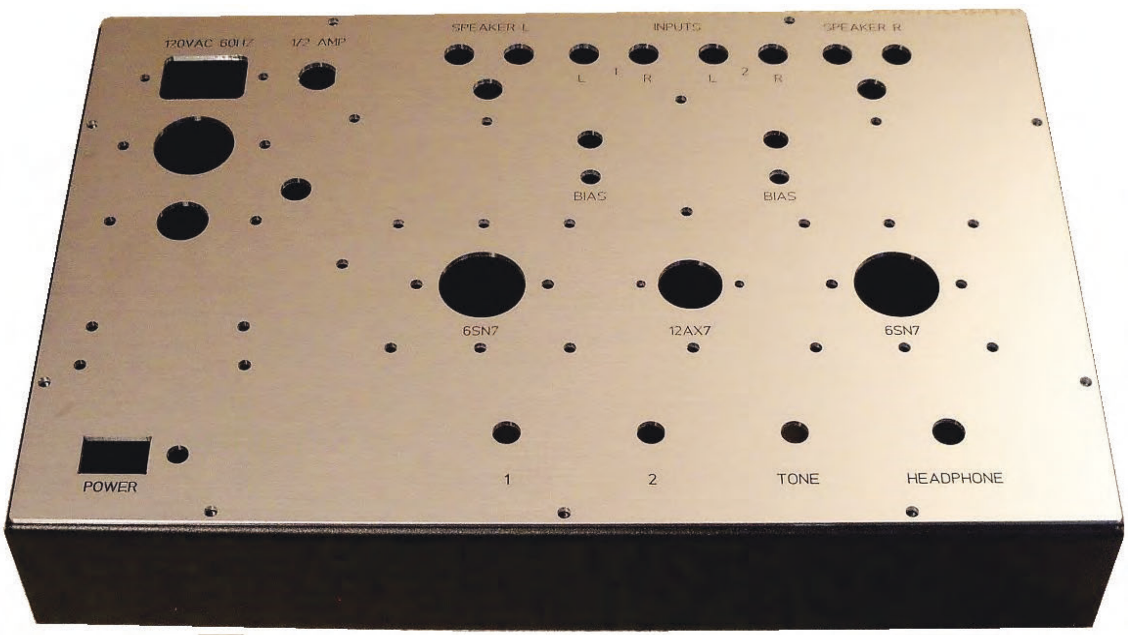
CAM EXPERT	FRONT PANEL EXPRESS
www.cam-expert.com	www.frontpanelexpress.com

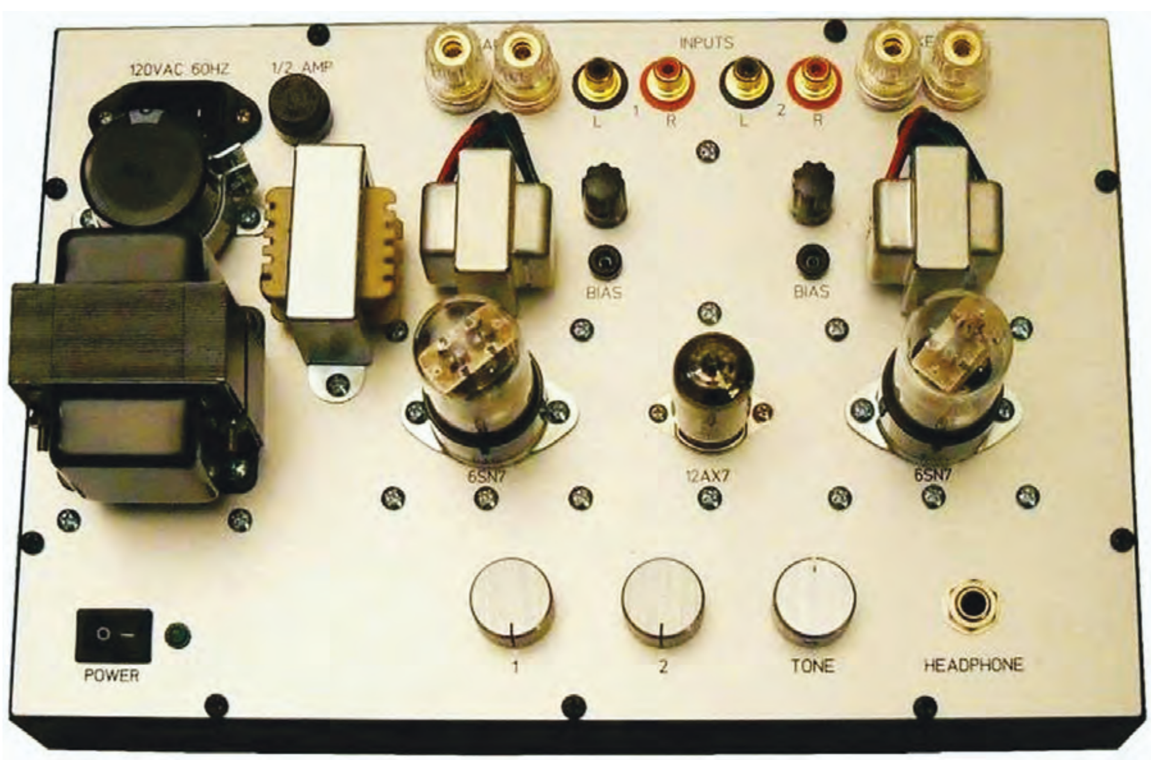
Panels are made out of a durable aluminum alloy. Engraving options include filling in lettering with paint. Having a panel fabricated will require you to provide the fabricator with a CAD file of the panel. Front Panel Express can provide software for producing a CAD file. Engraved panels are available in different thicknesses, from 1.5mm to 4mm. A front panel 2mm thick is good and reasonably rigid. For the rear panel, 1.5mm thick is adequate. Remember that front and rear panels have to be thin enough to allow components, such as connectors, potentiometers and switches, enough shaft thread for mounting through the panel and the chassis.

Custom Engraved Front Panel Example

Engraved Chassis Plate

Using a custom engraved aluminum panel as a chassis plate gives your amplifier a professional look. Pictured below is a project built by this author using a custom engraved panel as a chassis. The chassis plate is 2mm thick with all components installed on the plate. The chassis plate mounts on the bottom side of a standard chassis; the chassis serves as a base. The base could also be a custom wood cabinet.





• Chassis Fabrication

The following several pages are an example of the traditional fabrication of an amplifier chassis using a commercially manufactured blank chassis.

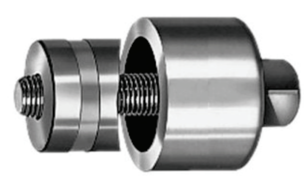
The chassis and wiring layout used in the following amplifier project is by the author. This layout is used to allow placement of the filter choke inductor and all filter capacitors inside the chassis. Doing so provides a sleeker look to the amplifier by keeping ugly parts inside the chassis. Careful placement of parts inside a chassis uses less surface area on the chassis' top side, allowing a smaller chassis size to be used.

For vacuum tube components, you will usually need at least a two-inch-high chassis; a three-inch-high chassis might be preferred depending on the largest component going inside the chassis. It's best to mount heavy components in a corner or along the edge of a chassis where the chassis has better support.

Suggested Tools

For a more professional-looking chassis, in addition to your regular tools, the following tools are recommended.

Chassis Punch (hole punch)
Best for
Making tube socket and large holes.
Maxium thickness 18 guage steel.



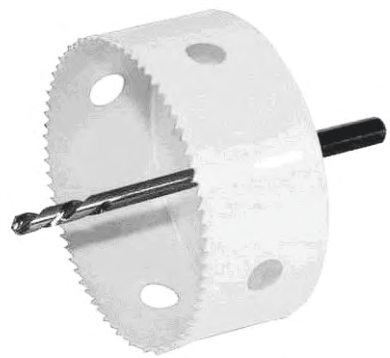
Tapered Reamer
Allows reaming holes bigger
to an exact size up to 1/2-inch.
Hole may need deburring.

Alternative for a chassis punch

Step Drill
Requires careful drilling.
Hole not as clean as a chassis punch
and may need deburring.

Alternative for a chassis punch

Metal Cutting Hole Saw
Requires careful drilling.
Hole not as clean as a chassis punch
and may need deburring.



CAUTION

If you plan on using a step drill or metal cutting hole saw, keep in mind that using a hole saw or a step drill requires drilling slowly with light pressure. Let the tool do the cutting slowly.

A hole saw in particular is prone to seizing and spinning whatever you are drilling. For safety, it may be wise to secure the chassis. Since clamping the chassis could cause damage, you might consider making a jig out of wood that the chassis sits in. Then, secure the jig to a drill press or work surface.

When using a step drill or hole saw, it is best to use tube sockets that are mounted on the top side of the chassis. This will cover imperfections in the chassis hole.

Wear safety glasses.

Machining the Chassis

Masking tape will aid in marking hole drilling locations. For tube socket holes, only mark the big hole used for the tube socket body. The smaller tube socket mounting holes should be marked and drilled <u>after</u> you make the large tube socket hole. This will minimize hole position errors.

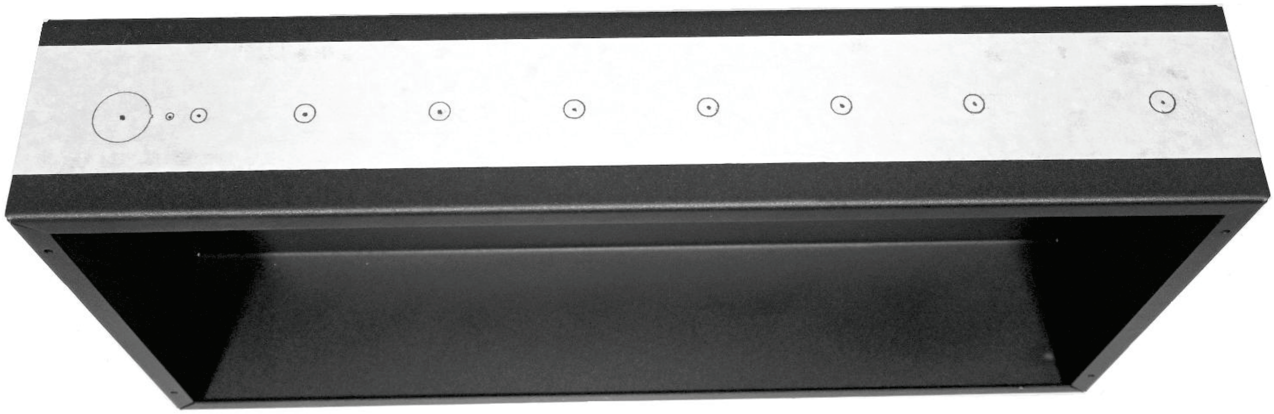
Several custom engraved plates were made for this chassis project. Holes for a custom front panel will be drilled first.

A strip of wide masking tape is placed across the front edge of the chassis.

The front panel is positioned in place.
Front panel was fabricated and engraved by Cam Expert

This is a Hammond steel chassis. Normally, this type of chassis has a bottom plate that screws onto the bottom flange of the chassis. To hide the front edge of the bottom plate, the front panel is positioned 0.031 (1/32) inches low to cover the edge of the bottom plate from view.

Using a pencil, the front panel holes are carefully scribed onto the masking tape. Center points are marked in the center of each hole.



Holes can be made using a hand drill, a drill press or a combination of both. The following process applies to all drilling methods.

A bench-top drill press was used in this project. The drill press head is turned 180 degrees. This allows the chassis to be set on the rubber table pad. In this configuration, one has to be careful not to tip the drill press forward.

Blocks of wood are used to adjust the height of the chassis. As a pre-caution, the motor belt has been set very loose to reduce torque. The lowest speed of 750 RPM is used. All drilling is done slowly using only sharp drills.

The center points are first drilled with a 0.0625 (1/16) inch drill. This is a pilot hole and will prevent the larger drills from "walking" as you drill. Then, the holes are drilled with the correct size drill.

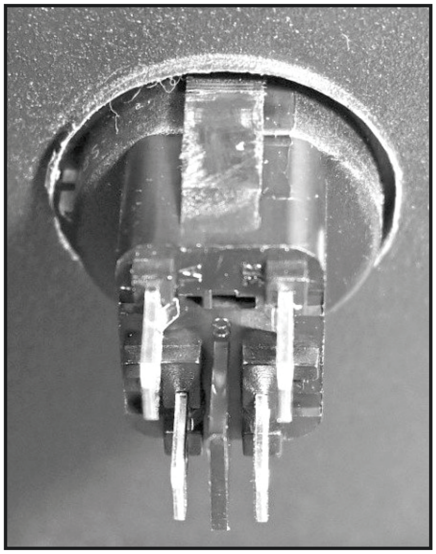
Clamping the chassis down is impractical. The chassis will be repositioned as holes are drilled. In this case, the chassis is painted, and the finish might be damaged by clamping. A thick leather work glove was used to hold the chassis firmly in place. Using gentle pressure as you drill should prevent the drill from grabbing the chassis.

Wear safety glasses.

Holes for the front panel

The large chassis hole on the left is a clearance hole for the power switch to fit through. The power switch will snap securely into the front panel. The hole was first punched out with a 3/4-inch punch, and then drilled larger using a stepped drill.

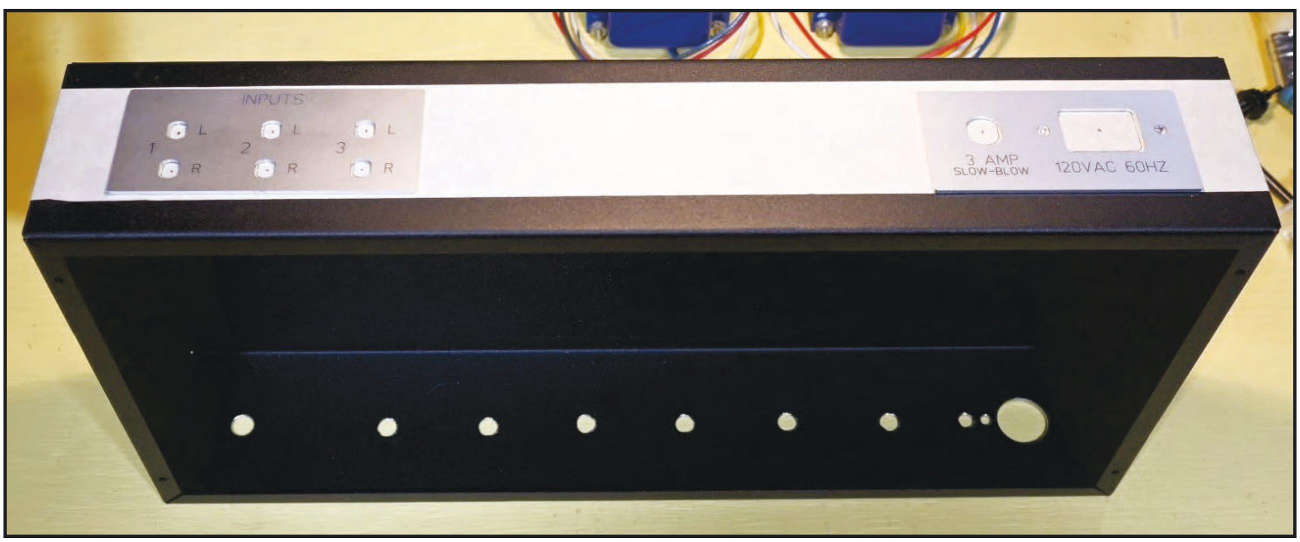
Power Switch Hole



The stepped drill pushed a large burr (ridge) facing into the chassis. The burr is fairly uniform and was not removed. Removing the burr might create an uglier hole than leaving the burr.

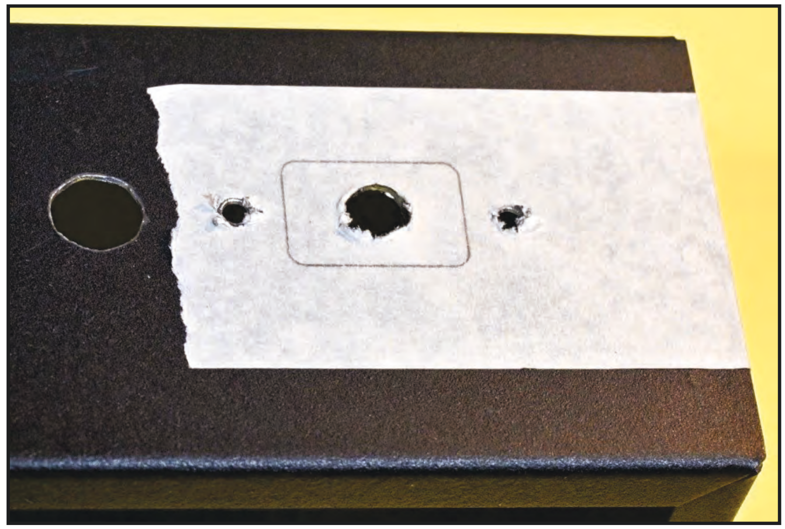
The drilling process continues with holes on the back side of the chassis.

The rear panel plate holes are marked in the same manner. In this case, there are two small engraved plates. One engraved plate on the left is for three stereo inputs, the other engraved plate on the right is for the fuse and removable AC power cord connector.

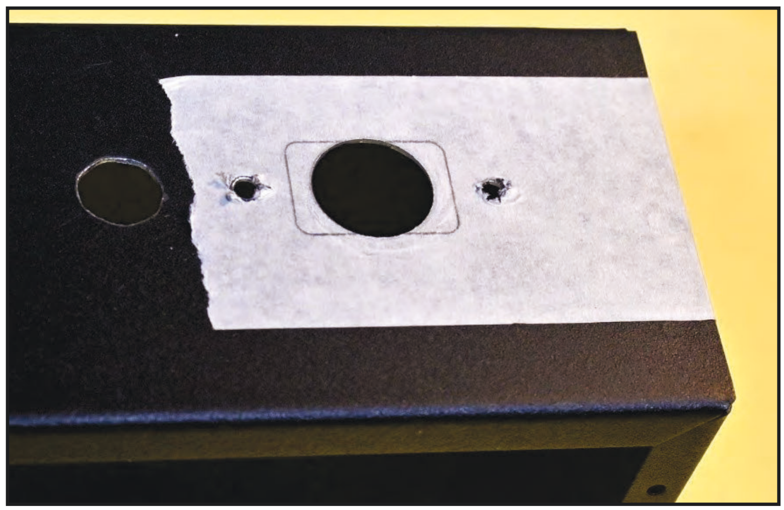


The AC cord connector is in the shape of a rectangle. There is a knockout punch that would make the correct size chassis hole, but it has a hefty price tag. Instead, a 3/4-inch round punch and a 3/4-inch square punch will be used to make the hole.

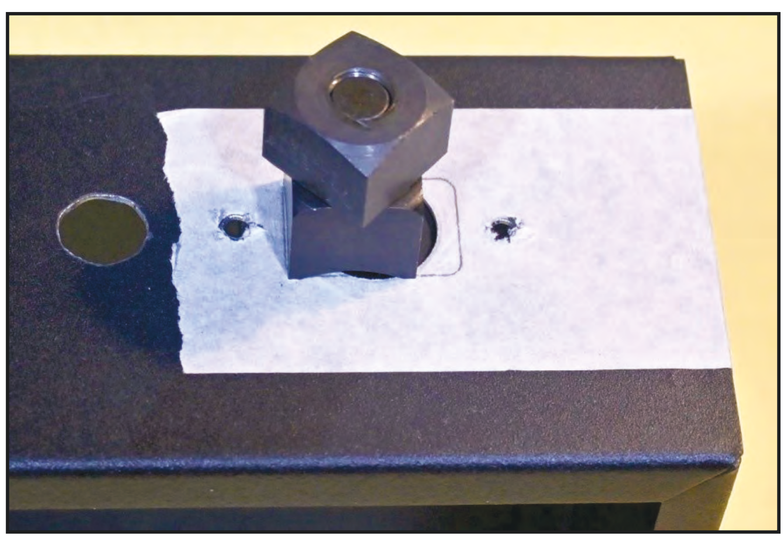
In the center of the scribed rectangle for the AC cord connector, a hole is drilled. This is for the 3/4-inch round punch pull bolt.

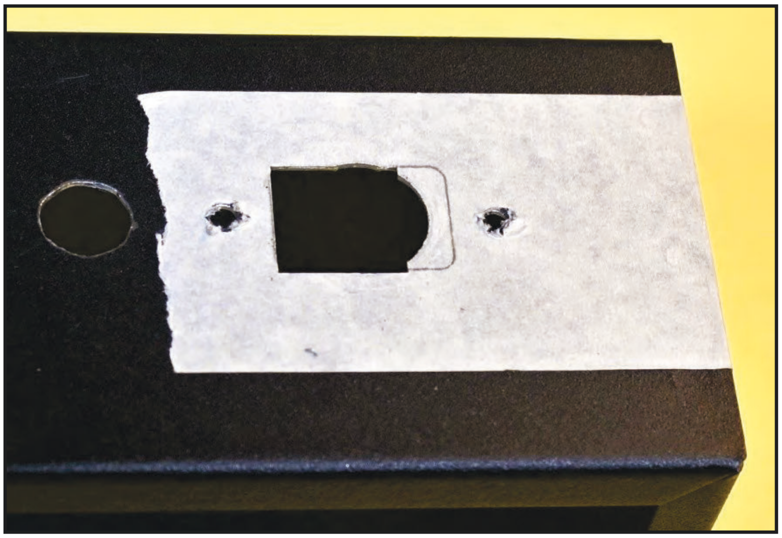


The large 3/4-inch round hole will allow aligning the 3/4-inch square punch.

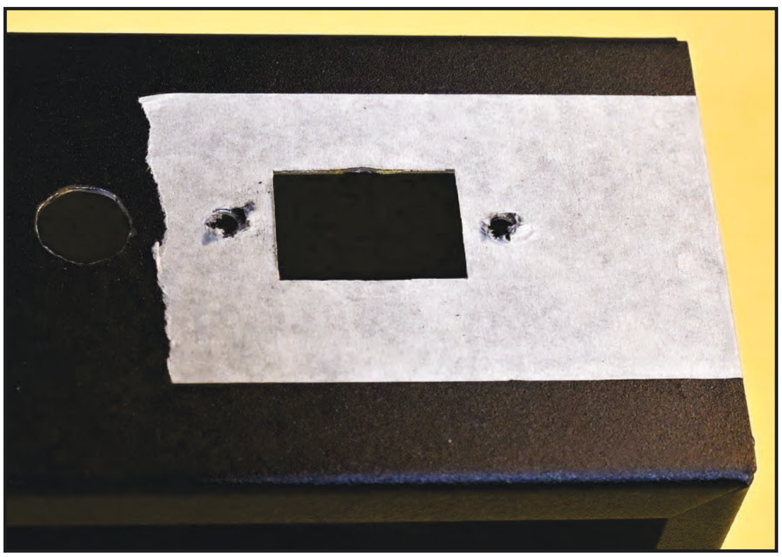


The 3/4-inch square punch aligned to punch out the left side of the rectangle.



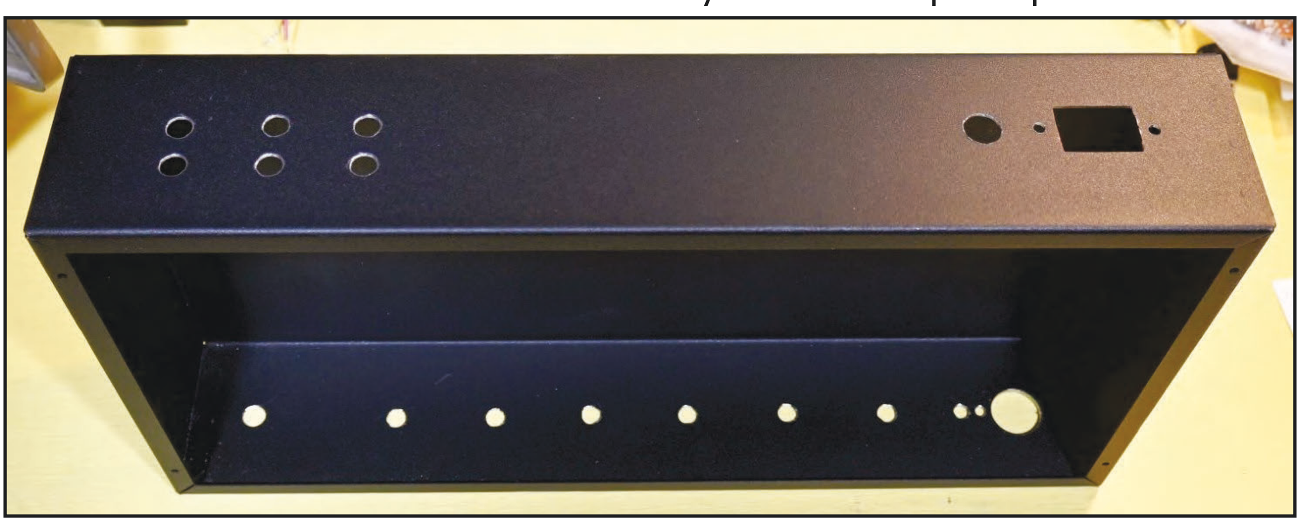


The left side of the rectangle punched out. The 3/4-inch square punch is then aligned to punch out the right side of the rectangle.



A file is used to touch up the hole to fit the AC power cord connector.

The back side of the chassis ready for the rear panel plates.

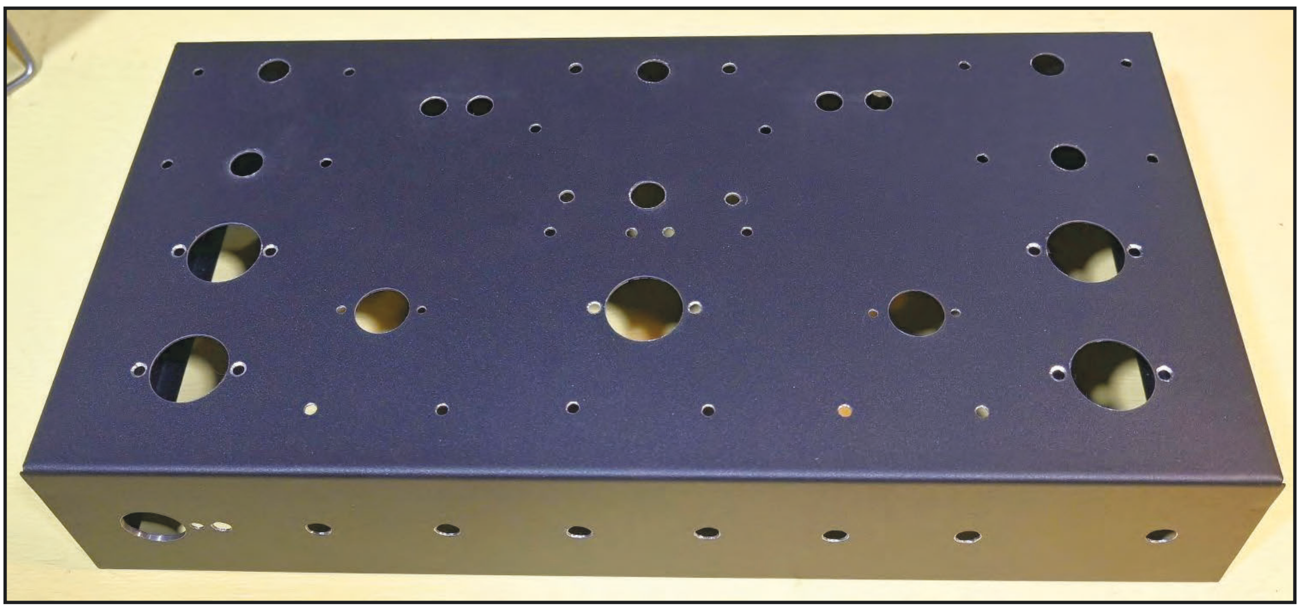


In order to use the drill press for drilling the top of the chassis, a large flat surface that can be adjusted up and down is required. The adjustable table that comes with the bench-top drill press is too small. Larger tables that bolt onto a smaller drill press table can be bought. Many of the bolt-on tables have options that could be useful. However, primarily what is needed is a large secure flat surface that is smooth.

An option is to make one out of wood. The bolt-on wood table in the picture below is 12 by 24-inch, high-quality pine, straight with no knots. It bolts onto the smaller drill press table with two 3/8 by 2-inch carriage bolts. The bolts are secured under the table with 3/8-inch washers, lock washers and nuts.

The carriage bolt heads must be countersunk so a chassis can slide over without touching the bolt heads.

The chassis completely drilled and tube socket holes punched.



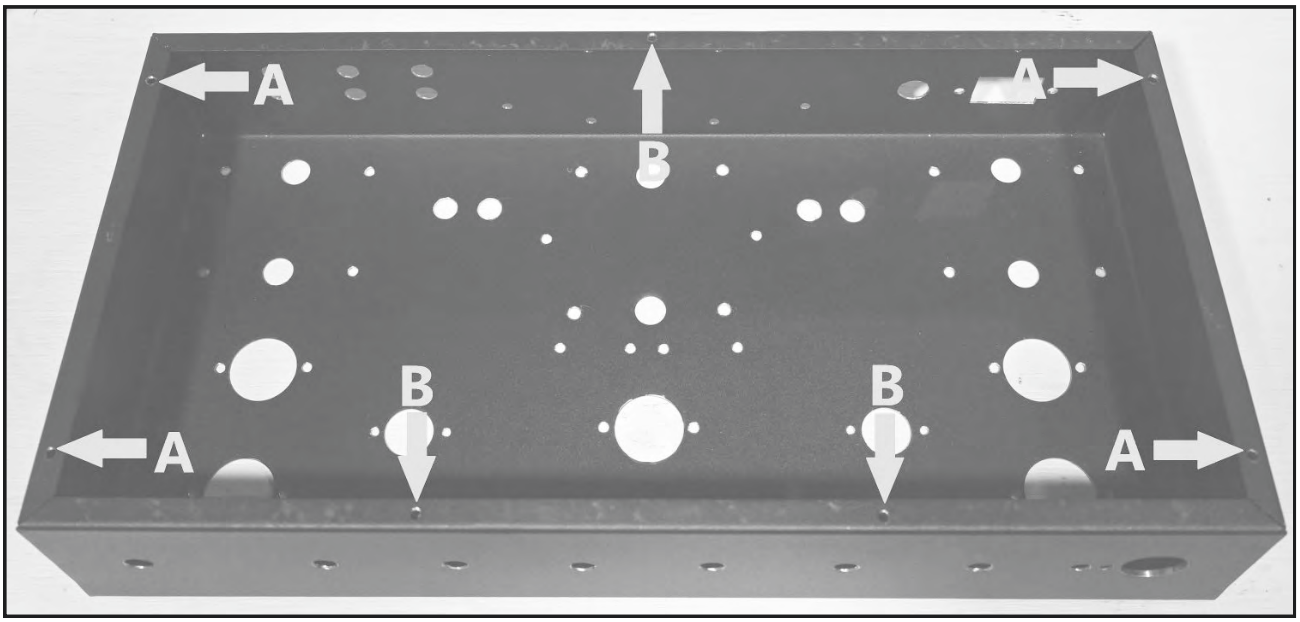
The screw mounting holes for the octal tube sockets are slightly countersunk. This is not normally done. The reason for doing it here is to ensure that the engraved plates that mount over the socket holes are flush with the chassis.

The holes that the transformer wires feed through the chassis are 1/2-inch. Rubber grommets will go into these holes. Holes larger than 3/8-inch can be difficult to drill with nice round smooth results. It was decided to use a 1/2-inch punch for the grommet holes.

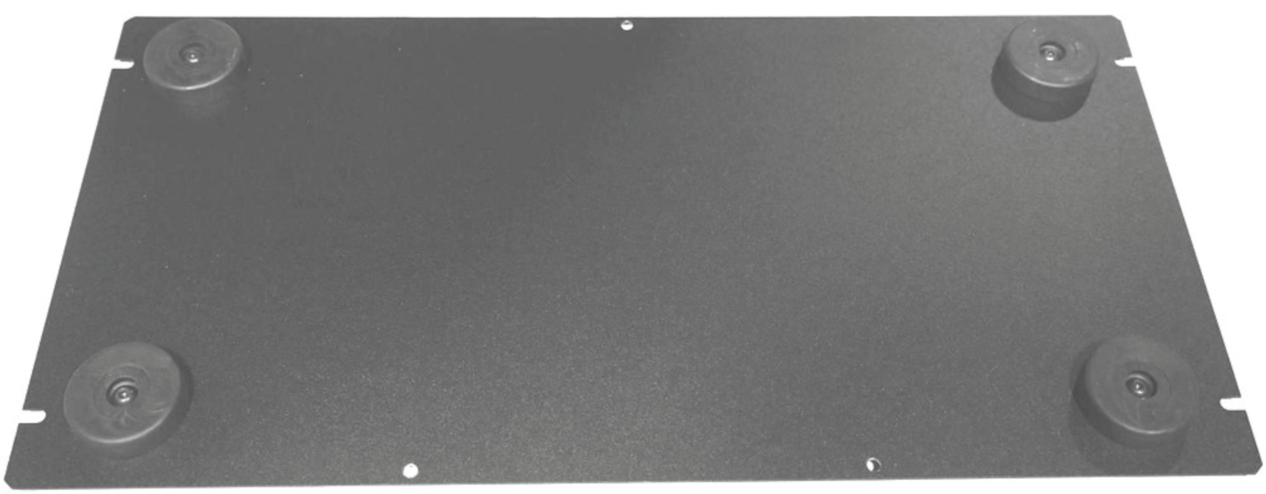
The chassis bottom plate that Hammond provides has four screw mounting holes that match four holes in the chassis bottom flange. The usual method of securing the bottom plate is by using self-threading screws.

Rather than use self-threading screws that are hard to screw in straight, the holes are drilled out with a #29 drill bit, then threaded with an 8-32 tap for use with 8-32 screws. The four original bottom plate mounting holes are shown in the picture below at point A.

With the bottom plate secured to the chassis using screws at point A holes, additional holes are drilled with a 1/16-inch ‘pilot hole’ drill bit through the bottom plate and chassis flange. Then, with the bottom plate removed, the extra flange holes are drilled with the #29 drill bit and tapped for 8-32 screws. The additional holes are shown at point B.



The extra holes in the bottom plate are drilled out using a #16 (0.1695) or #7 (0.196) drill bit. Rubber feet are mounted on the bottom plate.



• Creating an Amplifier

This project is an example of designing and building a vacuum tube amplifier using point-to-point wiring. Circuit design is provided with examples of formula use. Although the project includes pictures during assembly, the primary focus of the project is circuit design. The assembly pictures provide insight into component layout. Although this project could be duplicated, it is not recommended. The density of wiring in some areas will make it difficult to visually duplicate circuit connections via pictures. An amplifier project should be an individual venture, your own one-of-a-kind creation.

Your skill level will determine your progress. For the novice with little or no electronic experience, it will be a slow process. If you have little or no soldering experience, read soldering starting at page 8. Practice stripping off insulation and soldering together a few pieces of scrap wire.

All the information required is provided in a logical sequence. The process of maching a chassis is covered starting on page 118. The procedure of design and assembly of an amplifier is outlined as follows.

Procedure from Start to Finish

- Select tube types. This is required before acquiring components to determine maximum voltage ratings and circuit current loads. Finding tube specifications will provide information needed to purchase components including output and power transformers. You need components on hand before fabricating a chassis.
- Come up with a power supply design. It is important that the power supply can deliver the proper voltages and currents.
- It is possible to design circuits as you go along. Using known working circuits is also acceptable. You at least need to know what tube types and how many will be used. Besides the tubes, you need to have the tube sockets and terminal strips on hand.
- After you have the components that will be mounted, a chassis layout of components is developed. The chassis is prepared with holes drilled or punched out. Chassis fabrication was covered beginning on page 118.
- The process of assembling and wiring begins.

Preliminary Information

Output Stage

Power Output Tubes

Power output tubes provide the power necessary to drive a loudspeaker. They can be triodes with one grid or tetrodes and pentodes with an added screen grid. Power output tubes deliver power and draw significantly higher levels of current than pre-amplifier voltage amplifiers.

The output stage can either be a single-tube Class A or a dual-tube push-pull class AB circuit. The considerations are power output and audio quality.

Class A single tubes essentially amplify the audio signal intact from input to output, but produce the lowest power output. Power output is limited because the tube is a linear amplifier. Being linear, the tube has a high level of current flowing through it. Since power is related to current flow, power output is lower to keep current and the related heat dissipation within a tube's maximum limits; otherwise the tube might destroy itself.

Class AB dual tube push-pull operates with the output tubes biased such that each tube only conducts current for about 60% of the audio waveform cycle. This reduces the amount of heat dissipated, allowing higher power output levels approximately three times higher than Class A. Push-pull outputs use phase inversion to split the waveform, then combine the waveform back to normal. There is some loss of audio quality in the process, but probably only noticeable to the most discernible listener.

Class B dual tube push-pull operates with each output tube biased to conduct current for about 50% or slightly less of the audio waveform cycle. This further reduces the amount of heat dissipation, allowing much higher output levels. However, quality is substantially reduced; distortion is especially high at lower volume levels. Class B might work for a PA system, but certainly not for high fidelity.

The amplifier as a system layout must be decided. Should the amplifier be all self contained as a single unit, or as separate units?

Monoblock amplifiers are single-channel amplifiers. As such, for a dual-channel stereo setup, you will need two monoblocks. If there are to be volume and tone controls, having separate controls on each channel will be somewhat awkward. Monoblocks usually do not have tone or volume controls. However, input level controls can be used to balance channel levels. Main volume and tone controls would be on a unit preceding the monoblocks.

Stereo amplifiers are dual-channel amplifiers. Since both channels are powered by a single power supply, only one power transformer is required. This saves a little money on parts costs. Volume and tone controls will adjust tone on both channels simultaneously and can be included.

Voltage Amplifiers

The amplifier stages that precede the output stage are voltage amplifiers that are biased for Class A operation. Voltage amplifiers are used to amplify weak signals to a level suitable to drive the output stage to full output. Typically, voltage amplifiers draw significantly less current than an output stage, usually around 1 to 4 mA.

The power supply rectifier can be either a vacuum tube or solid state. Solid state rectifiers provide a more solid DC voltage. However, since solid state DC voltage comes on instantly when the power is turned on, the designer must allow for a higher voltage level until the amplifier tubes warm up and start drawing current.

A vacuum tube rectifier provides a delayed DC B+ supply voltage while the tubes warm up. However, a vacuum tube rectifier provides a less solid DC voltage. This is due to the tubes' high internal resistance. At higher volume levels, the DC voltage will tend to sag a bit as the output tube draws more current, creating a higher voltage drop across the rectifier.

Using Datasheets

Datasheets provide important information. Datasheets are available online and should be consulted. Before searching for a datasheet, you should have specific tube types in mind. The information on a datasheet is important and will be discussed as the amplifier example project progresses.

Selecting Tube Types

When designing a vacuum tube circuit, datasheets should be consulted for the following tube specifications. The ‘never exceed’ maximum voltage and dissipation ratings are usually listed first.

Heater (filament) voltage
Heater current

Maximum Plate Voltage
Maximum Plate Dissipation

Tubes with a screen grid
Maximum Screen Voltage
Maximum Screen Dissipation

Sample of Popular Tubes

Voltage amplifying tubes include:

12AX7, 12AT7, 12AY7, 12AU7, 12BH7, 6SN7 and 6SL7.

Pentode and Beam Power output tubes include:

6V6GT, 6L6GC, 6CA7, 5881, 7581, EL34, KT66, KT77 and KT88.

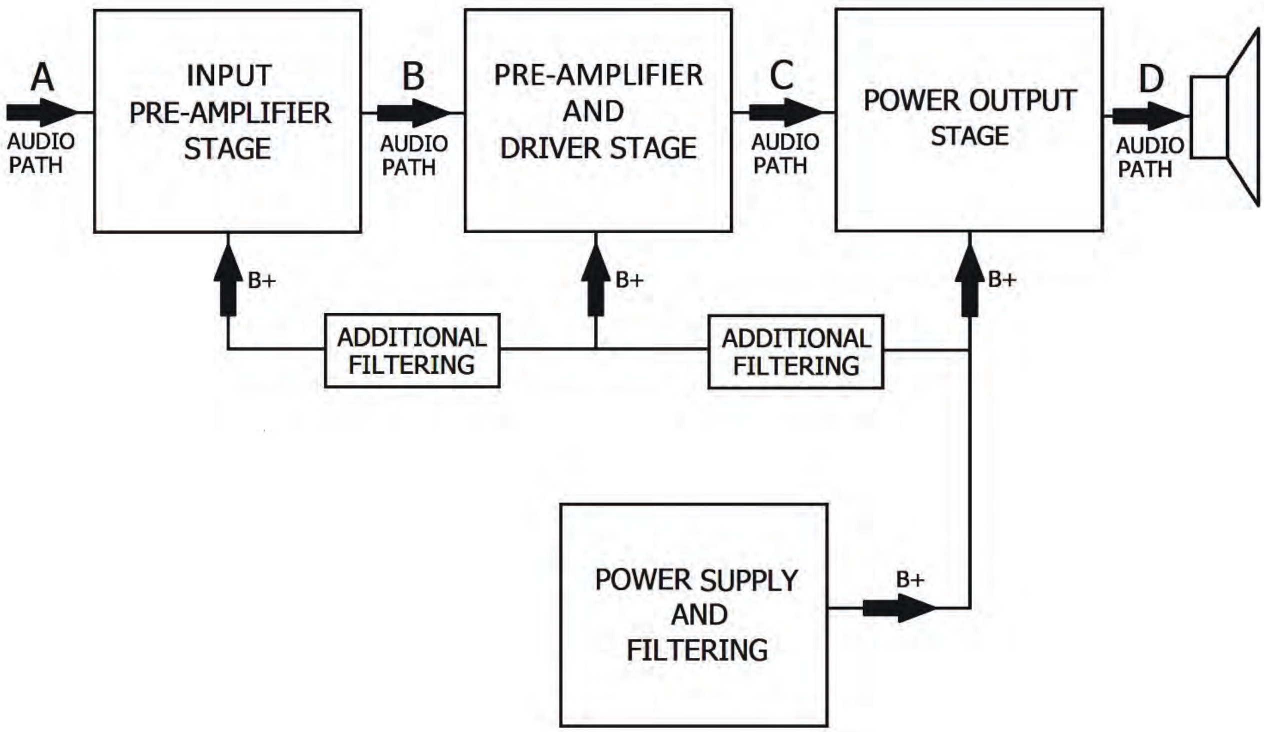
There are tube types specific to different countries. The ones listed above are popular in the United States and Great Britain.

For this design project, a single tube Class A pentode output stage will be used in a two-channel stereo amplifier. The circuit will be designed such that the following output tubes can be directly plugged in. This includes the 6L6GC, 5881 or 7581. All three of these tubes have identical pin connections and similar operating specifications.

A combination pre-amplifier and driver stage will use a 6SN7. There may be other similar tubes. However, because the 6SN7 is a great-sounding tube, no other tubes are specifically recommended as a direct plug-in replacement. The 12AX7/ECC83 voltage amplifier is used for the input stage. The input stage makes up for gain lost in the tone and volume control circuits. As such, the input stage has no gain. Other tubes that can be used in place of the 12AX7/ECC83 include 12AT7/ECC81 and 12AY7/6072. The 12AY7 was originally designed for low noise use.

Sometimes it helps to draw out a design plan similar to the one in Figure 1.

Figure 1



In Figure 1, the B+ voltage path has filtering in addition to the filter in the power supply. When an amplifier has several stages of amplification, the B+ voltage needs additional filtering to isolate the B+ supply of preceding amplifier stages from the output stage. Otherwise, there is a chance of the output stage interacting with the preceding stages. Without the additional B+ filtering, a type of pulsating feedback called motorboating can occur.

The power output stage will draw the highest current. There should be little resistance in the B+ path to the output stage. The B+ supply directly supplies voltage to the output stage.

From the output stage, B+ goes through additional filtering to the pre-amplifier/driver stage. Additional filtering is simply resistance followed by a filtering capacitor.

After the driver stage, B+ goes through a second additional filter for the input pre-amplifier stage.

Although several tubes with similar operating characteristics may be used in the same output circuit, A primary tube should be used for circuit design. The 6L6GC will be used.

The following is from a 1961 RCA Receiving Tube Manual.

6L6GC Datasheet Excerpts

Heater (filament) voltage	6.3 volts
Heater current	0.9 amp
(These maximum ratings should never be exceeded.)	
Maximum Plate Voltage	500 volts
Maximum Screen Voltage	450 volts
Maximum Plate Dissipation	30 watts
Maximum Screen Dissipation	5.0 watts

There will be specifications for several different modes of operation. For this book project, we are interested in a single-ended Class A_1 operation. The zero-signal and maximum-signal currents are the expected currents when operated as specified under each voltage column. It is the maximum-signal current load that is used to calculate power transformer current ratings.

Class A_1 Amplifier – Pentode Connection*

Plate Voltage	250	300	350	volts
Screen Voltage	250	200	250	volts
Grid #1 Voltage	–14	–12.5	–18	volts
Peak AF Grid #1 Voltage	14	12.5	18	volts
Zero-Signal Plate Current	72	48	54	mA
Maximum-Signal Plate Current	79	55	66	mA
Zero-Signal Screen Current	5.0	2.5	2.5	mA
Maximum-Signal Screen Current	7.3	4.7	7.0	mA
Load Resistance	2500	4500	4200	ohms
Maximum-Signal Power Output	6.5	6.5	10.8	watts

* Datasheets may list Class A operations in both triode and pentode configurations. For triode operation, the screen grid is connected to the plate.

• Power Supply

Calculate Supply Requirements

The following vacuum tubes will be used for this stereo amplifier design.

(1) – 5U4 Rectifier tube
(2) – 6L6GC Power output tube (the primary design tube)
(2) – 6SN7 Pre-amp and driver (dual triode tube)
(2) – 12AX7 Input pre-amplifier (dual triode tube).

All the current loads must be added up. Information about current loads is found in datasheets. This includes filament and high voltage current loads.

5U4 Rectifier

Heater voltage and current = 5 volts @ 3 amps.

6L6GC Power output

Heater voltage and current = 6.3 volts @ 0.9 amps.
Using datasheet specifications under the 350V column.
Maximum-Signal Plate Current = 66 mA (0.066 amps).
Maximum-Signal Screen Current = 7.0 mA (0.007 amps).

6SN7 Pre-amplifier and output driver

Heater voltage and current = 6.3 volts @ 0.6 amps.
Specifications under the highest operating voltage column.
Maximum plate current = 9 mA (0.009 amps) for each section.
Average in circuit plate current = 4 mA (0.004 amps) for each section.
Total plate current both sections = 8 mA (0.008 amps).

12AX7 Voltage amplifier

Heater voltage and current (parallel operation) = 6.3 volts @ 0.3 amps.
Specifications under the highest operating voltage column.
Maximum plate dissipation = 1.2 watts for each section.
Average in circuit plate current = 1 mA (0. 001 amps) for each section.
Total plate current both sections = 2 mA (0. 002 amps) total.

Average plate current for voltage amplifiers based on experience.

The transformer loads are as follows. This is a dual-channel stereo amplifier, so the total maximum current load for both channels must be included.

Filament (heater):

5U4 rectifier = 5 volts @ 3A (amps)

All other tubes = 6.3 volts @ {.9 + .6 + .3} X 2 = 3.6A

High voltage total current load:

Transformer high voltage current ratings are in mA (milliamperes).

(66 + 7) + 8 + 2 X 2 = (73 + 8 + 2) X 2 = 166 mA

Calculations in Ohms law formulas require current to be in amperes.

166 mA = 0.166 amperes (166/1000)

The voltage rating of the transformer's high voltage winding depends on two factors. The maximum current load and the desired rectified B+ DC voltage. The current load is now known, a target B+ voltage must be decided. For this project, a B+ voltage from the 5U4 cathode[1] of around 385 to 390 DC volts would be ideal. After voltage drops in the DC filtering circuits, there would be around 350V B+ for both output tubes. Using the capacitor input graph on page 135, it can be seen that the required voltage from the transformer for 385 volts DC with a 166 mA load is close to 350 volts per plate (700 volts center-tapped).

Power Transformer

A close match is a Hammond 274BX transformer.

700VCT (350-0-350) @ 201 mA

5VCT @ 3 amps

6.3VCT @ 5 amps

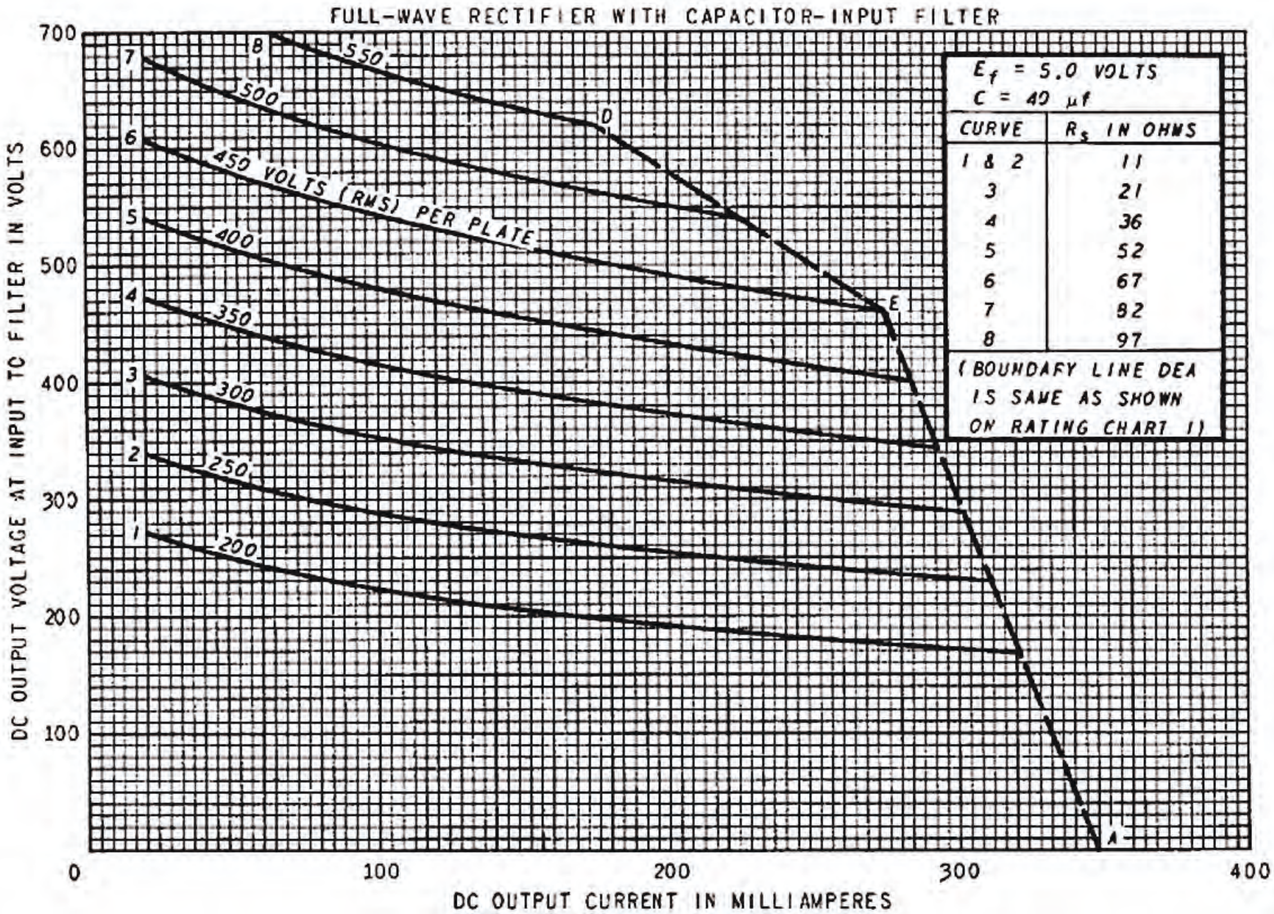
When selecting a power transformer, never use one with lower current ratings than the maximum load current.

Another output tube that could be plugged in is a KT66. The KT66 operation is similar to a 6L6GC, but has a higher heater current load of 1.27 amps. The 5-amp rating of the transformer's 6.3 volt winding would allow the use of KT66 output tubes.

[1] Be aware that the heater filament in a 5U4 is also the cathode.

Figure 2

5U4



The left side of the graph shows DC voltage at input to the capacitor-input[1] filter. The bottom of the graph is the current load (in mA) placed on the rectifier tube. The graph plot lines are different power transformer secondary voltages stated as (RMS) per plate.

The graph is easy to use. For example, a 700VCT (350-0-350) transformer secondary would provide 350 volts RMS per plate. If 100 mA is the current load, find 100 mA at the bottom of the graph. Follow the 100 mA line upwards until it meets the 350-volt graph plot line. Follow the intersecting line to the left side of the graph (DC output voltage at input to filter) and you will find that the voltage coming out of the rectifier cathode is about 415VDC. If the current load is 200 mA, then the voltage coming out of the rectifier cathode will be about 370VDC.

[1] Capacitor-input refers to when a filter capacitor is connected to the rectifier cathode. This is the most common tube rectifier circuit configuration.

Power Supply Components .

Refer to Figure 4 on page 138. It is a basic power supply circuit using a 5U4 rectifier tube that, with component recalculations, is adaptable.

P1 is an AC cord connector for a removable AC cord. The center pin is the AC cord safety ground. The safety ground connects directly to the chassis near P1. AC hot is the AC voltage and AC neutral is at ground potential. AC hot is fused using F1 and AC neutral connects to the power switch. In effect, both the fuse and power switch are in the same circuit. The reason for switching with the neutral wire is to reduce the chance of hum that might be caused if the AC hot wire were to be wired to the front panel power switch.

The T1 transformer has primary taps for 115-volt or 125-volt operation. In the US, AC voltage typically is in the 120-volt to 125-volt range.

Capacitor C1 provides some filtering of noise that might be in the AC power source. These are interference suppression type capacitors.

Inductor L1 is an iron core filtering choke. Inductors are rated using values of henries (H). For this type of application, the minimum value would be 1H with available values up to 10H. The higher the H value, the better it will filter AC out of the DC voltage. The current and voltage ratings of the inductor are important. For this application, it should be rated at least 200 mA with a voltage rating of 600 volts or higher. Inductors with the required voltage and current rating will vary in physical size depending on their H value, the higher H values being the largest.

The bleeder resistors, R1 and R4 in this design, are safety resistors used to discharge the B+ filtering capacitors when the amplifier is not powered on. Bleeders act as a shunt connected from B+ to B– (ground). They are usually selected to bleed one to three mA of current. For safety, there should be a bleeder resistor just before the L1 filter choke plus at least one after the L1 filter choke in the B+ supply. Bleeder resistors should have a voltage rating significantly higher than the no-load voltage of the B+. Power dissipation of the resistor must also be considered.

D1 is the power on LED light next to the power switch. R7 limits current to extend the LED life.

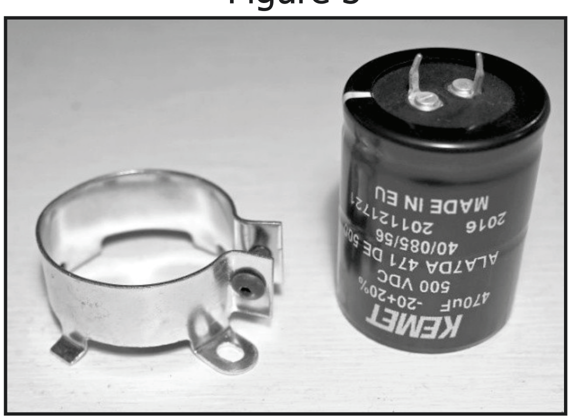
The values of R5 and R6 must be calculated to provide 6.3 volts to the filaments. The current limiting provided by resistance in series with the filament supply reduces the sudden shock to the filaments when 6.3 volts are applied. Current limiting plus setting voltage close to its specified value, e.g., 6.3 volts, will extend the life of the tubes. In order to allow placing resistance in series with the filament supply, a transformer with a higher current rating than the actual filament load must be used. Over-sizing the transformer current rating also allows the transformer to operate cooler by reducing the transformer's load losses dissipated as heat.

Capacitors C2, C3, C4 and C5 are filtering capacitors. Depending on the type of rectifier, the value of C2 may be limited. After L1, capacitors can be 100 uF or higher. R2 and R3 provide some B+ isolation between each channel B+ supply. Since R2 and R3 are in the filtering supply that provides B+ to the output tubes, their value should not be very high, or they will restrict too much current. R2 and R3 values range from 47 to 200 ohms each. The largest value of capacitance is in the final filter. Filter capacitor C4 is the final filter for channel one and C5 is the final filter for channel two. Besides filtering, higher values of C4 and C5 will better hold a charge, keeping the B+ voltage more stable at higher volume levels.

Filament noise-filtering capacitors C6, C7, C8 and C9 are multilayer ceramic capacitors with a C0G(NP0) dielectric.

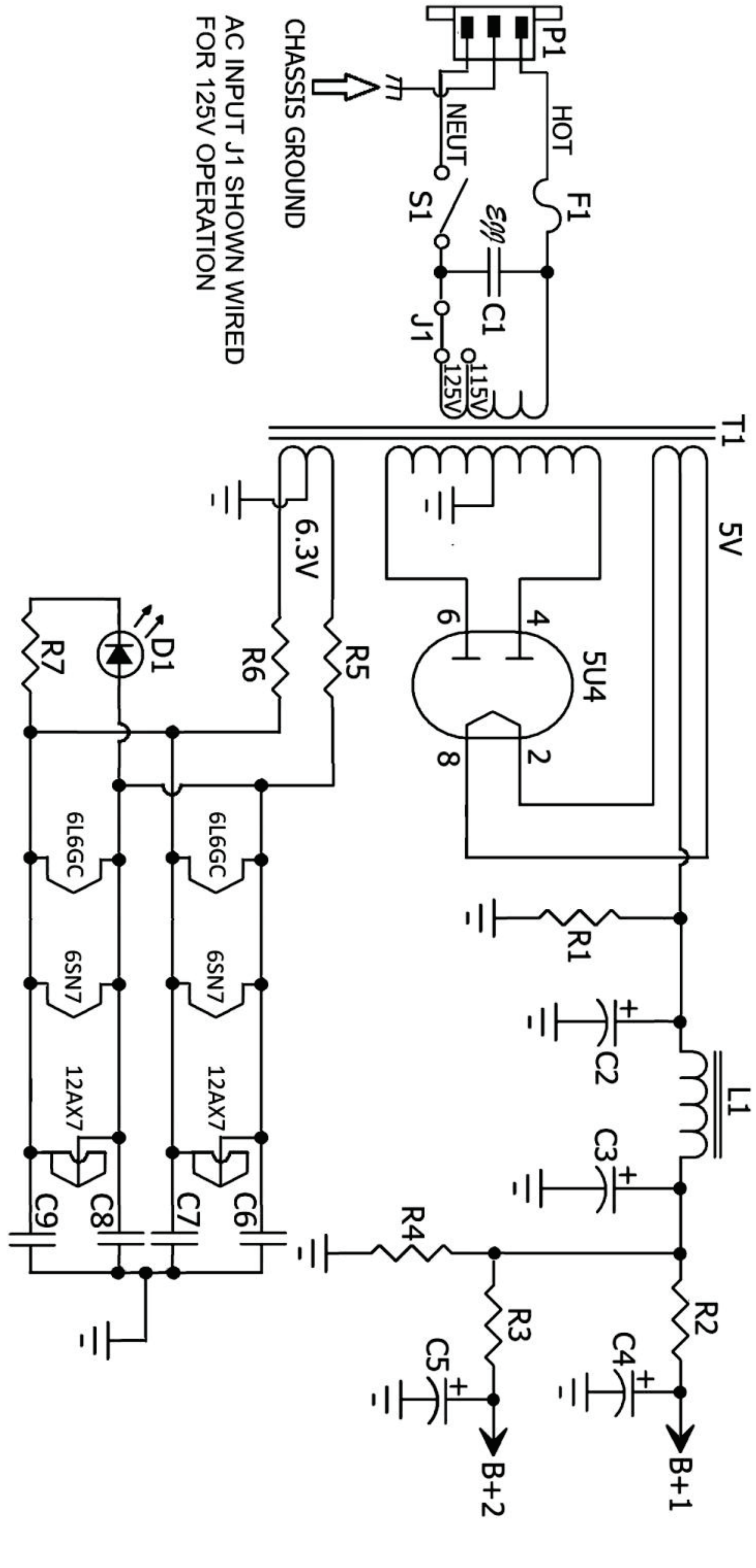
B+ 1 provides B+ high voltage to channel 1 and B+ 2 provides B+ high voltage to channel 2.

Figure 3



C4 and C5 are snap-in type capacitors as shown in Figure 3. Although intended to snap into printed circuit boards, the terminals are easy to wrap wire around and solder. C4 and C5 should have a 35mm diameter to fit a Cornell Dubilier VR3A mounting clamp.

Figure 4


P1
HOT
NEUT
F1
S1
C1
J1
115V
125V
CHASSIS GROUND
AC INPUT J1 SHOWN WIRED
FOR 125V OPERATION
T1
5V
6.3V
5U4
6
4
8
2
R1
R2
R3
R4
R5
R6
R7
D1
L1
C2
C3
C4
C5
C6
C7
C8
C9
6L6GC
6SN7
12AX7
B+1
B+2

Using Formulas

Most of the formulas will be simple, requiring one, two or three steps and are usually based on Ohms Law. Electronic formulas contain symbols that relate to resistance, voltage and current.

R = Resistance
E = Voltage
I = Current

Operations to be performed are also indicated by symbols.

+ = Add
– = Subtract
X = Multiply
/ or ÷ = Divide

Sometimes a value must be squared by multiplying the value by itself.

For example, I^2 X R = (I X I) X R
If I = 5, then I^2= 5 X 5 = 25

In order for Ohms law formulas to work, all values should be as follows.

Resistance must be in ohms.
Voltage must be in volts.
Current must be in amperes (amps).

If necessary, you must convert as follows.

Volts = millivolt ÷ 1,000 (1 millivolt = 0.001 volts).
Amps = milliamps ÷ 1,000 (1 milliamp = 0.001 amps).

As you follow the text, calculations using formulas will have conversions made. For example, milliamps are converted to amps. Most of the formulas are simple, using two known values to find an unknown value. There is an exception where the following formula is used.

EuL = { [(1 – (IaL / IfL)) X .1] X Etr } + Etr

The way to solve multistep formulas is to first perform operations in the innermost brackets, then work your way out. The formula is worked out step by step in the text.

Calculate Fuse Size

To determine what size fuse is needed for F1, use volt-amps to calculate the current load of the transformer primary. In order to do this, the volt-amps in each secondary winding must be calculated, then all added up to find the total volt-amp load of all the transformer's secondaries. Use the transformer secondary rated voltages and the calculated maximum current loads.

Volt-Amps (VA) = E X I (voltage times current)

→The current must be converted to amps.

The transformer high voltage winding is for a full-wave rectifier circuit using a center tap. In effect, the actual voltage being rectified is half of 700 volts.

High Voltage Volt-Amps, 700VCT (350-0-350)

1/2 700V = 350V, 350V X 0.166 amps = 58.1VA

5V Filament Volt-Amps, 5V X 3A = 15VA

6.3V Filament Volt-Amps, 6.3V X 3.6A = 22.7VA

Add all the secondary Volt-Amps, 58.1 + 15 + 22.7 = 95.8VA

The volt-amps are essentially the same on both sides of the transformer. To find the current load in the primary, divide the total secondary volt-amps by the primary voltage.

Primary amps = Total secondary volt-amps / Primary voltage
120V Primary
95.8/ 120 = 0.8 amps

The fuse should be somewhat larger than 0.8 amps to prevent the fuse from opening under surge load stress. A 2 or 3 amp fuse will work; using a slow-blow (delayed) type fuse will allow for possible power-on current surges.

No Load Voltage

Looking at the graph on page 135, if you follow the 350 volts (RMS) per plate curve all the way up to the left (0 DC output current), it shows the DC output voltage at about 500 volts. This is the no-load voltage. Filtering capacitors and other components connected with the high voltage B+ should be rated at the no-load voltage, in this case, 500 volts.

Capacitor Values

C1 is an interference suppression rated capacitor. A value of .1 uF @ 253VAC will be used.

C2, C3, C4 and C5

On the datasheet for a 5U4 rectifier, 40 uF is specified for the capacitor at the 5U4 cathode (filament). See Figure 5, C = 40 uF. This is the maximum value. If a surge were to occur, higher values of capacitance might cause damage to the 5U4. For this project, a 33 uF 500 volt capacitor will be used for C2.

Figure 5

E_f = 5.0 VOLTS
C = 40 µf

CURVE	R_s IN OHMS
1 & 2	11
3	21
4	36
5	52
6	67
7	82
8	97

(BOUNDARY LINE DATA IS SAME AS SHOWN ON RATING CHART 1)

Also, there is a list of R_s values. These are current limiting resistor values that would be placed in series between the transformer high voltage winding and the 5U4 plates. Since we used the datasheet curve number 4 (350 volts per plate), there would be a 36 ohm resistor in series with each 5U4 plate. For lower power amplifiers, the rectifier series plate resistors are optional and not used in this project.
L1 needs to be a fairly large inductance to insure there is no background ripple hum in the output stage audio. A value of 6 H (Triad C-14X) for L1 will be used.

The value of C3 after L1 is 100 uF and rated at 500VDC.

The final stage of power supply filtering is R2/C4 and R3/C5. The capacitance values of C4 and C5 should be considerably higher, providing a reserve charge to help keep the B+ supply voltage steady under load. Both C3 and C4 will be 470 uF, rated at 500VDC.

Filament noise filtering capacitors C6, C7, C8 and C9 will be .47 uF rated at 50VDC. These should be multilayer ceramic capacitors with a C0G(NP0) dielectric. The filament noise-filtering capacitors will be connected to the filament supply at the 12AX7 sockets.

D1, R1, R2, R3, R4 and R8

The D1 LED power on light will tap filament voltage from whichever tube is closest to the LED. R8 in series with D1 is added to limit current and extend LED life. a value of 500 ohms at 2 watts will be used.

Using E= I X R, the voltage drop across the L1 choke is calculated. The DC resistance of L1 = 150 ohms (the resistance of the wire used to wind L1). The total current through L1 calculated on page 134 is 0.166 amps.

E = I X R = 0.166 X 150 = 24.9V

The graph on page 135 indicates the DC voltage at the 5U4 cathode with a 0.166 amp load to be at 385V. The voltage after L1 is,

385 – 24.9 = 360.1V.

In order to have 350VDC after R2 and R3, R2 and R3 must each drop about 10.1 volts. The total current load is divided between both channels. The current load in each channel is the total current load of L1 divided by two.

0.166 / 2 = 0.083 amps.

The values of R2 and R3 is found using R = E / I (resistance = voltage divided by current).

R = 10.1 / 0.083 = 121.7 ohms.

Using 120 ohm wirewound resistors, power dissipated in watts by R2 and R3 is calculated using $P = I^2 X R$ (power = current squared times resistance).

(0.083 X 0.083) X 120 = 0.007 X 120 = 0.84 watts.

For a reasonable safety factor, five-watt resistors will be used.

R1 and R4 Bleeder Resistors

Using 1 mA to determine the resistance value of a bleeder will allow the use of 3 watt metal film power resistor's voltage rated at 750 volts. To determine the bleeder resistor value, the no-load voltage is divided by 1 mA.

The no-load voltage is 500 volts. 1 mA converts to 0.001 amps (1 / 1,000).

R = E / I = 500 / 0.001 = 500,000 (500K) ohms.

Using standard values, R4 and R5 will be 510K ohms.

Calculate the power dissipation of each bleeder resistor using $P = I^2 X R$.

(.001 X .001) X 510,000 = .000001 X 510,000 = 0.51 watts

Calculate Filament Series Resistance

When a power transformer's 6.3-volt filament winding is rated at a higher current than the actual filament load, the voltage will be some value higher than 6.3 volts. Transformer voltages are rated at a specified current load. If there is less load, the voltage will be higher and if the load is higher, the voltage will be lower[1].

The power transformer used in this project design has a 6.3-volt filament winding rated at 5 amperes. The actual load is 3.6 amps. The transformer's 6.3-volt @ 5-amp winding is 1.4 amps higher than the 3.6-amp load. With less load on the filament winding, the voltage will be higher than 6.3 volts. The following formula can be used to calculate how much higher than 6.3 volts the filament voltage will be with a 3.6 amp load.

EuL = { [(1 – (IaL / IfL)) X 0.1] X Etr } + Etr

EuL = Voltage under load
(Voltage under the actual load)

IfL = Full load current in amperes
(The transformers rated current)

IaL = Actual load current in amps
(The actual current load)

Etr = Transformers rated voltage
(Transformer specified rated voltage)

IfL = 5 amps
IaL = 3.6 amps
Etr = 6.3 volts

Write out the formula and plug in the numbers.

EuL = { [(1 – (IaL / IfL)) X 0.1] X Etr } + Etr
EuL = { [(1 – (3.6 / 5)) X 0.1] X 6.3 } + 6.3

[1] You should never load a transformer winding more than its rated current. Besides reducing voltage below the transformers' rated voltage, the transformer will run hotter and possibly fail at some point.

(Solve the innermost brackets first, then work your way out)

EuL = { [(1 – **(** 3.6 / 5 **)**) X 0.1] X 6.3 } + 6.3
EuL = { [(1 – **(** 0.72 **)**) X 0.1] X 6.3 } + 6.3
EuL = { [**(** 1 – .72 **)** X 0.1] X 6.3 } + 6.3
EuL = { [**(** 0.28 **)** X 0.1] X 6.3 } + 6.3
EuL = { **[** 0.28 X 0.1 **]** X 6.3 } + 6.3
EuL = { **[** 0.028 **]** X 6.3 } + 6.3
EuL = **{** 0.028 X 6.3 **}** + 6.3
EuL = **{** .176 **}** + 6.3
EuL = 0.176 + 6.3 = 6.48V

To find the value of resistance needed to drop the voltage down to 6.3 volts, divide the voltage to be dropped by the load current, R = E / I.

E = 6.48 – 6.3 = 0.18 (Voltage that needs to be dropped).

I = 3.6 amps (The load current).

R = 0.18 / 3.6 = 0.05 ohms = 50 mOhms (milliohms)

Calculate the power dissipation of the resistor using P = I^2 X R.

P = I^2 X R = (3.6 X 3.6) X 0.05 = 12.96 X 0.05 = 0.65 watts.

Such a low resistance may not seem effective for reducing voltage until you calculate the voltage drop across 0.05 ohms.

E = I X R = 3.6 X 0.05 = 0.18 volts
Voltage drop across 0.05 ohms @ 3.6 amps = 0.18 volts
6.48V – 0.18V = 6.3V

The 0.05 ohm resistance is split between R5 and R6, 0.05 / 2 = .025 ohms.
R5 = .025 ohms and R6 = .025 ohms.

When buying components for an amplifier project, you may find resistor values below one ohm listed as values in milliohms (mOhms). To convert ohms to milliohms, use milliohms = ohms × 1,000.
0.025 ohms = 25 mOhms.
(0.025 X 1,000 = 25)

Cold Filament Current Surge

The resistance of a 6L6GC filament is 7 ohms when hot (6.3 volts applied). However, the resistance before voltage is applied is only .8 ohms. When voltage is applied to the filament, for a brief moment, the filament draws 7.9 amps. Besides the two output tubes, there are two 6SN7 tubes each with a cold filament resistance of 5.0 ohms (1.3 amps each) and two 12AX7 tubes each with a cold filament resistance of 8 ohms (.79 amps each)[1].

The cold filament total current load.

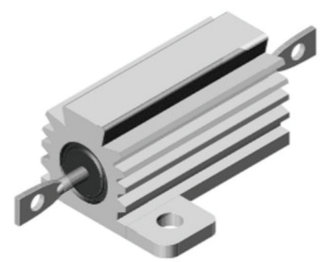
7.9 + 7.9 + 1.3 + 1.3 + .79 + .79 = 19.98 amps.

$P = I^2 X R$ = (19.98 X 19.98) X 0.025 = 399 X 0.025 = 9.98 watts

This means that R5 and R6 will each dissipate 9.98 watts until the filaments warm up. R5 and R6 should be rated at least ten watts to handle the filament voltage turn-on current surge.

A possible choice would be a 0.025 ohms 12.5 watt Dale part number RH010R0250FE02 resistor with solder terminals. This type of resistor is intended to be mounted on a heat sink. The high current surge is very short with continuous current only dissipating .324 watts. A small aluminum heat sink will be fine.

Figure 6



Heat Sink For R5 and R6

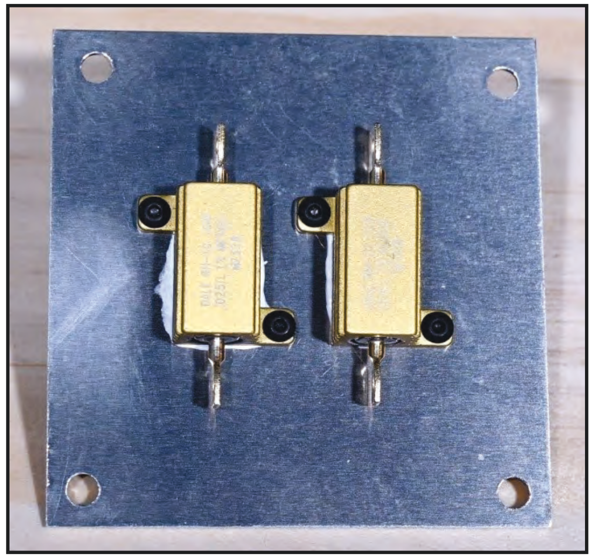
A small heat sink is fabricated from a piece of bare aluminum. The amount of heat dissipated from R5 and R6 is very small after the initial turn-on surge. A 2 1/2 inch by 2 1/2 inch piece cut off from a small aluminum chassis bottom plate is sufficient. The aluminum is 0.047 inches thick.

Both resistors are mounted on the heat sink, creating an assembly. The mounting holes for the resistors are small, requiring #2 screw hardware. As an assembly, R5 and R6 will be easier to install inside the chassis. Four holes in the corners are clearance holes for 6-32 screws. Heat sink compound is applied to the heat sink before mounting the resistors. See Figure 7.

[1] The cold resistance is measured across the filament pins of a vacuum tube with an ohm meter (no voltage applied). To measure, tubes are removed from their socket. The hot resistance of a filament is found by using ohms law, R = E / I, filament voltage divided by the filament current. For example, a 6L6GC filament, R = 6.3V / .9A = 7 ohms.

Figure 7

Figure 8



Both resistors are mounted on the heat sink assembly as shown in Figure 8. The assembly will be centered on the back side of the chassis. It will occupy what would normally be wasted space next to the filter choke. The filter choke will also be inside the chassis under the power transformer.

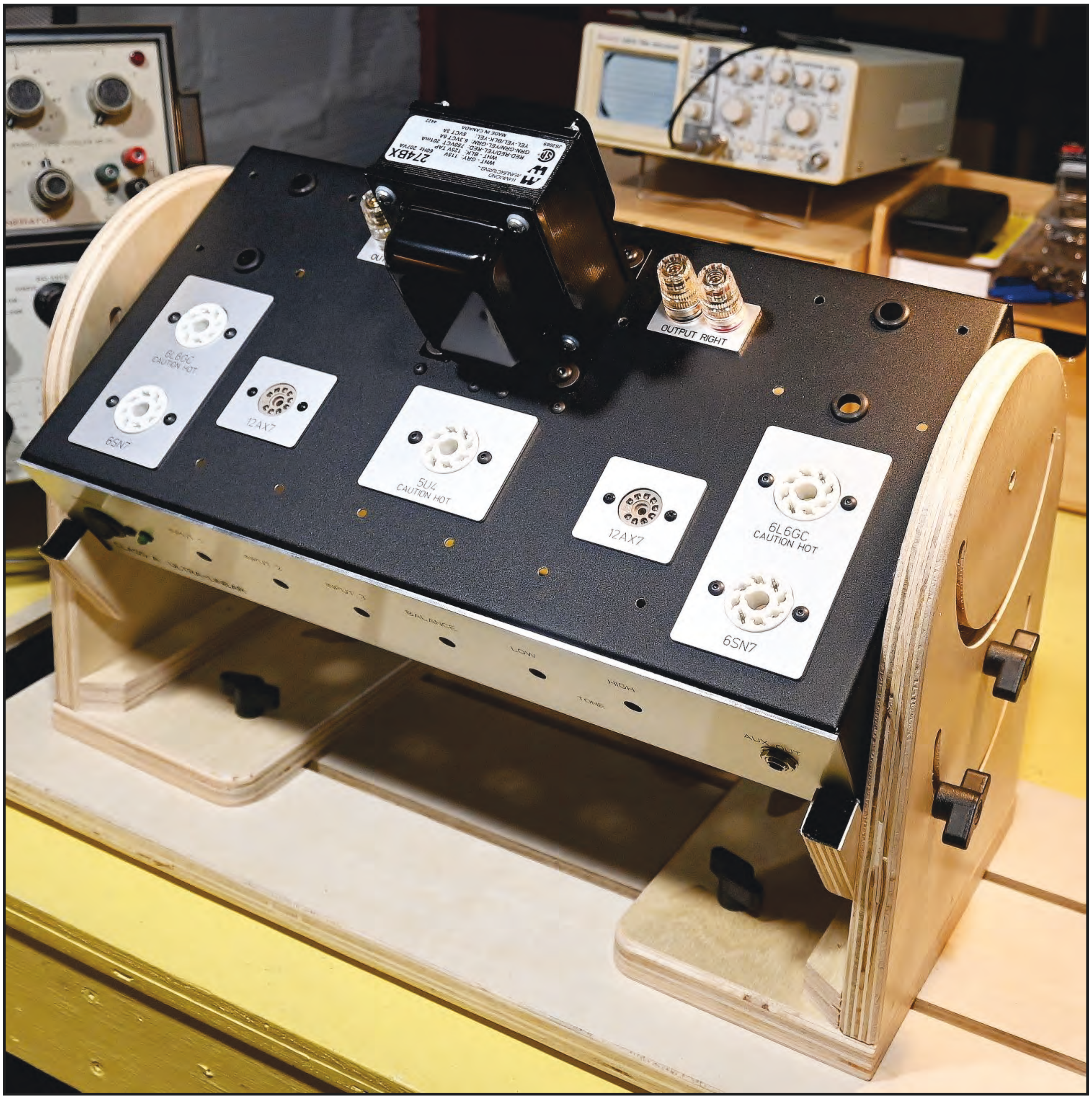
A traditional chassis layout will be used for this project. The traditional layout with components mounted on the top and inside the chassis with all controls on the front panel helps to keep the amplifier dimensions down to a more convenient size.

To get an idea of the required chassis size, all the major amplifier components were placed on a flat surface as they would be on a chassis. Capacitor and resistor wiring between tube sockets was taken into account. Terminal strips are provided for tie points. The 8-pin tube sockets used are a ceramic type with a separate mounting ring that allows mounting the socket from inside the chassis or on top of the chassis. The tube socket mounting rings are a perfect fit for terminal strip mounting tabs. Terminal strips are also mounted using the 12AX7 9-pin socket mounting screws. Using socket mounting screws for terminal strips reduces the number of visible screws on top of the chassis. It also keeps wiring as short as possible to reduce the chance of noise or AC hum pickup.

Wiring the Power Supply

The components necessary for wiring the power supply are on the chassis. This includes all the tube sockets because the filament wiring is part of the power supply circuits. The speaker connector jacks were also mounted because it was more convenient to mount them with the chassis empty. The 16-inch-wide by 8-inch-deep by 3-inch-high chassis fabricated earlier was for this project.

Figure 1



Although the pictured chassis jig looks like it makes working on an amplifier easier, it was found to be cumbersome. Later work was done by simply propping the chassis.

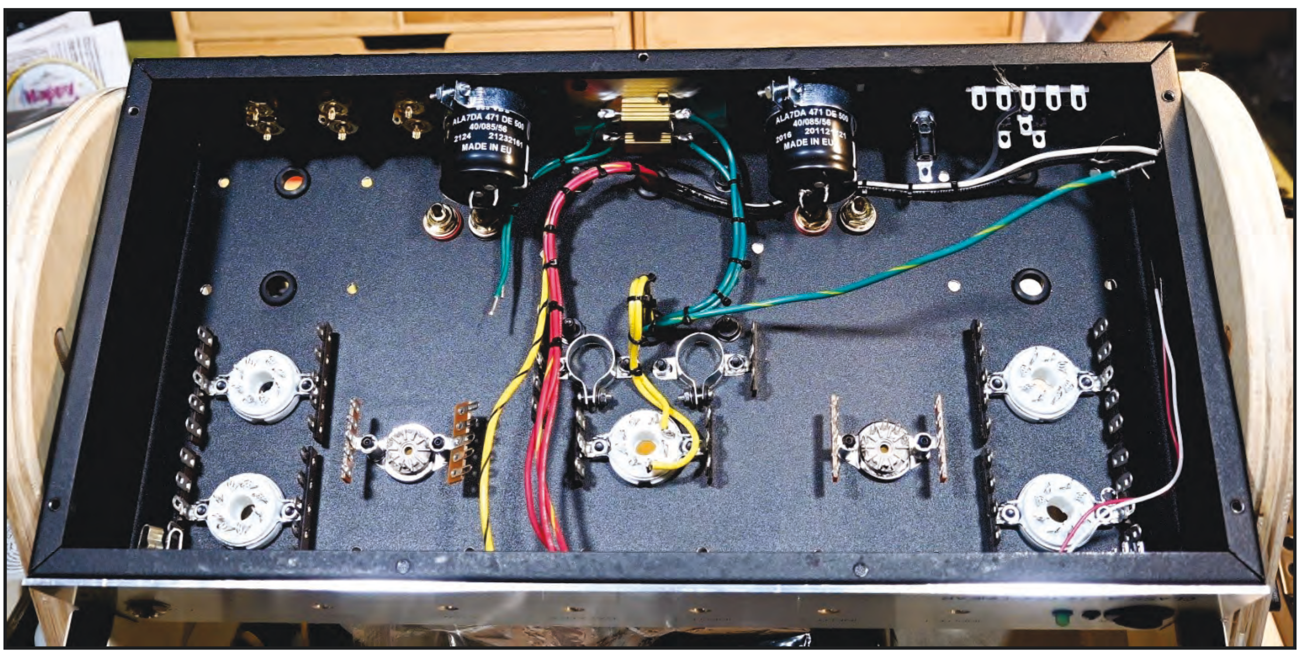
The L1 choke inductor will be mounted inside the chassis. The heat sink with R6 and R7 must be wired into the filament circuit before L1 is mounted. The mounting holes for L1 are at both sides of the power transformer.

C2 and C3 will be mounted on the chassis using small capacitor clamps next to the 5U4 rectifier socket. In Figure 2, C4 and C5 can be seen mounted on the back of the chassis.

When wiring, do not solder terminal connections until you are sure all wires that go to a terminal are secured in the terminal.

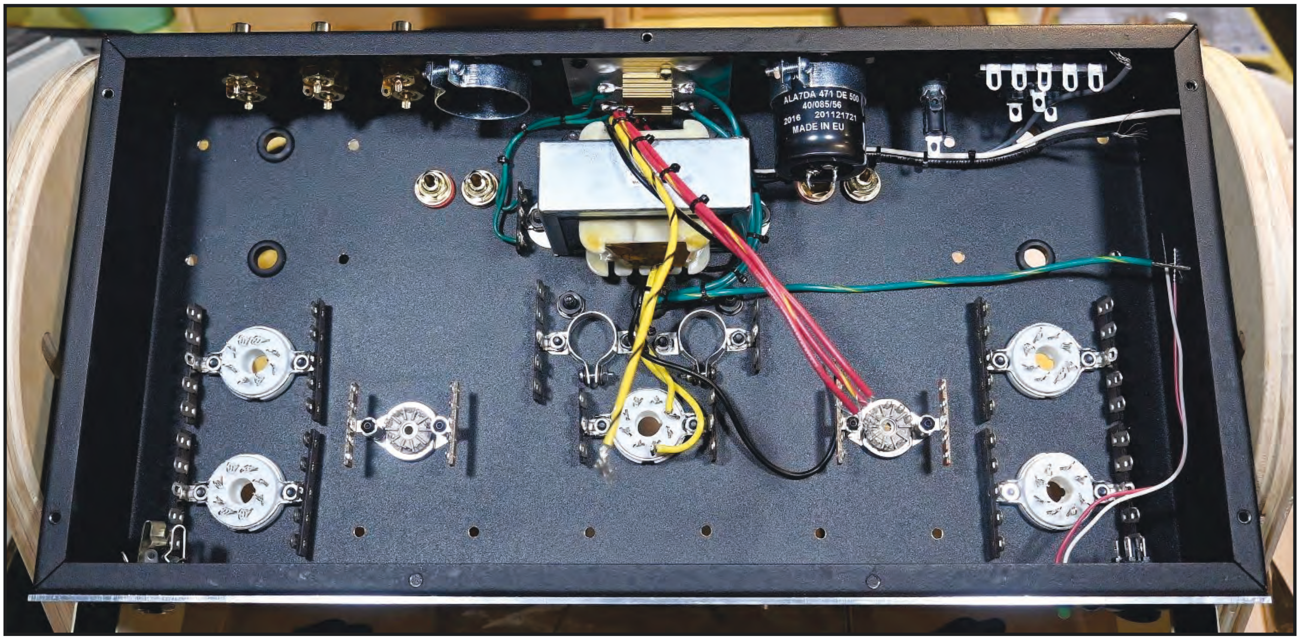
Mounting terminal strips using tube socket mounting screws reduces the number of screws seen on the top side of the chassis. It also keeps circuit components close to the sockets. Keeping component leads as short as possible reduces the chance of noise pickup. The terminal strips for the two 9-pin miniature sockets are of the half-sized type. They are mounted on 1/2-inch spacers to raise them up from the socket terminals. The 6.3-volt filament wires are soldered onto R5 and R6, see Figure 2.

Figure 2



In Figure 3, the filter choke inductor is mounted. One of the 8-32 inductor mounting screws (left) also mounts a terminal strip. For the 8-32 screw, the terminal strip mounting hole had to be reamed larger using a tapered reamer. The 6.3-volt wires coming from R5 and R6 are soldered into the lower small holes of the terminal strip (see Figures 4 and 5).

Figure 3



The small terminal crimp holes, points A & B, can be used to solder wires or component leads.

Figure 4

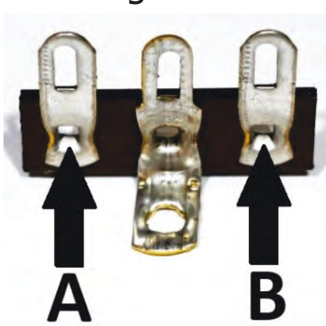
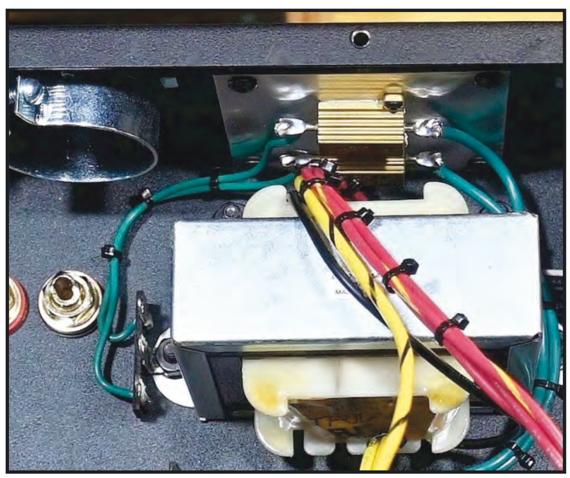
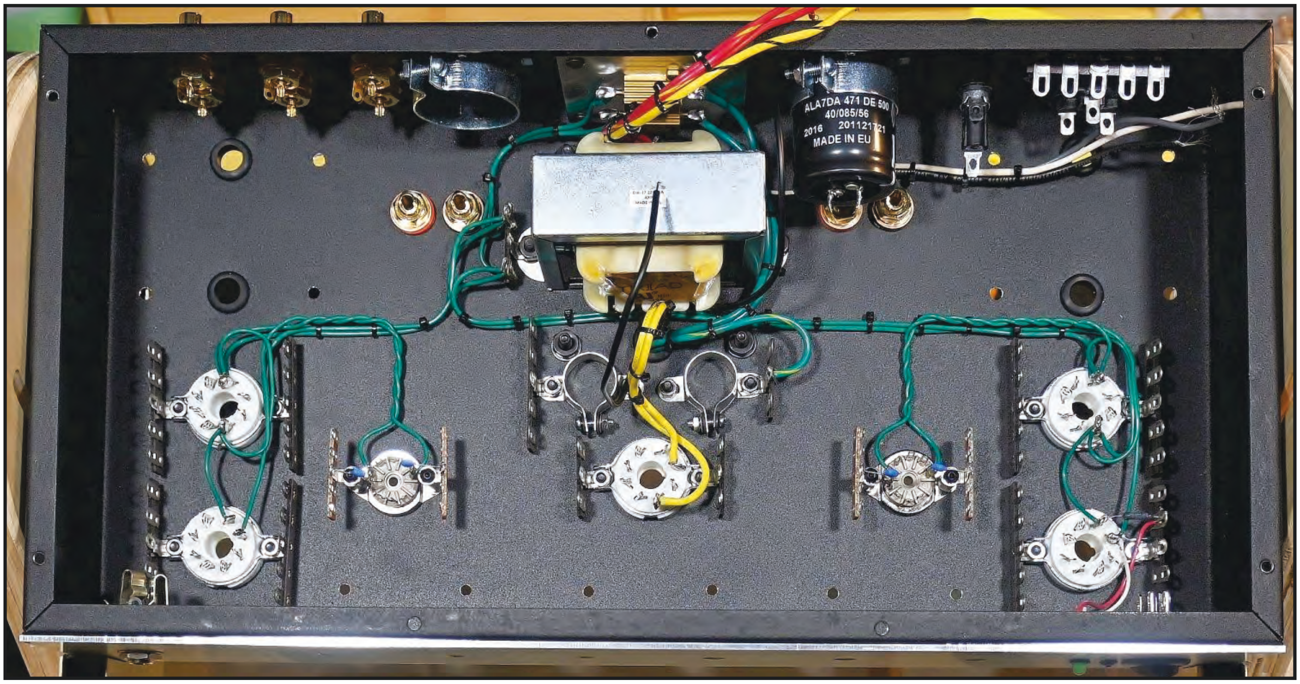


Figure 5



Using 18-gauge wire, wires from the 6.3-volt terminal strip after R4 and R5 (see Figure 6) connect to the output tube socket filament terminals 2 and 7. From the output tubes, using 20-gauge wire, 6.3 volts is supplied to the 6SN7 pre-amplifier/driver tube filaments. From the output tube terminals 2 and 7, 20-gauge wire supplies 6.3 volts to the 12AX7 voltage amplifier tube filaments. See Figure 6.

Figure 6



Although twisting filament wires does little to reduce hum, the filament wires to the 12AX7 pre-amplifier tubes are twisted. Keeping the 6.3-volt filament supply balanced with a grounded center tap provides the best hum reduction.

The .47 uF 50VDC multilayer ceramic capacitors (C6, C7, C8 and C9) are connected at the 12AX7 sockets, from each 12AX7 filament terminal to ground. They serve to filter noise that may be on the filament AC supply.

In Figure 7, the power supply is completely wired and functioning. All the terminal strip ground lugs will be wired in a common ground circuit. This provides a better ground circuit than only depending on the chassis for a common ground. At this point, several ground points are wired, including all the power supply ground points.

A front row of terminal strips associated with the front panel control wiring has not been mounted yet. The front panel controls will be among the last items to be wired.

It would be wise to double-check the power supply wiring against the power supply circuit drawing. The power supply will be tested later.

This is a good time to take a break. In fact, you should have taken several breaks by this point. Never rush a project like this.

Figure 7

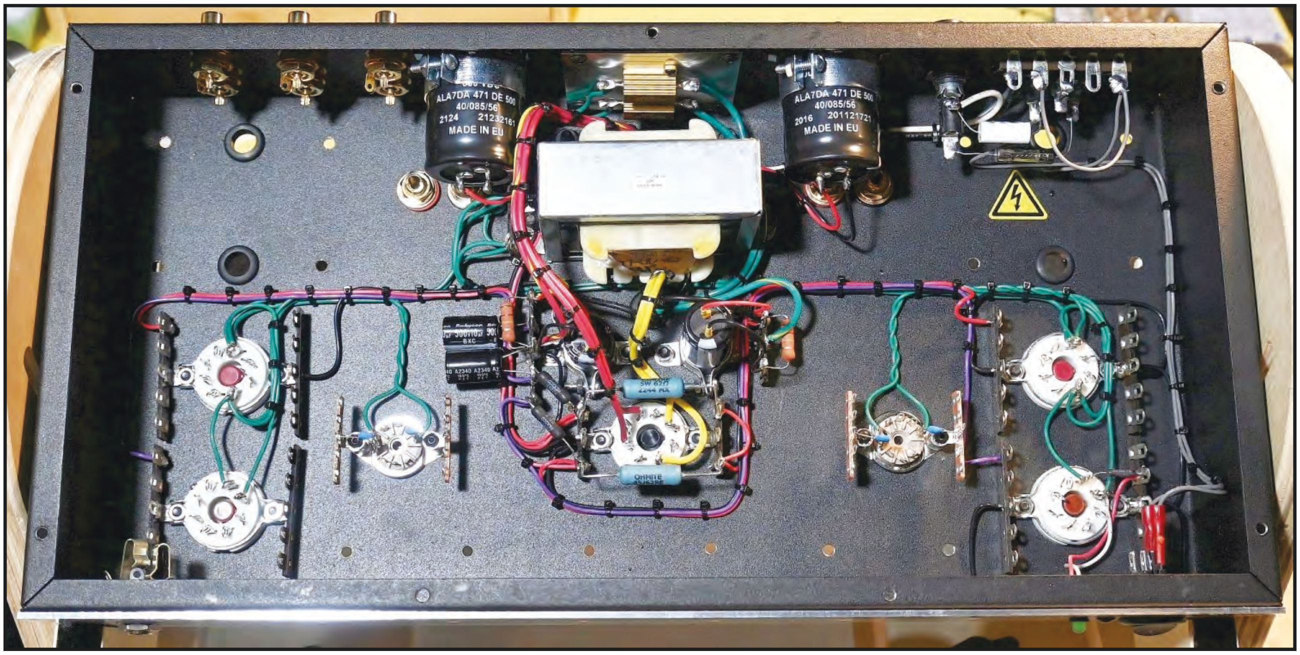
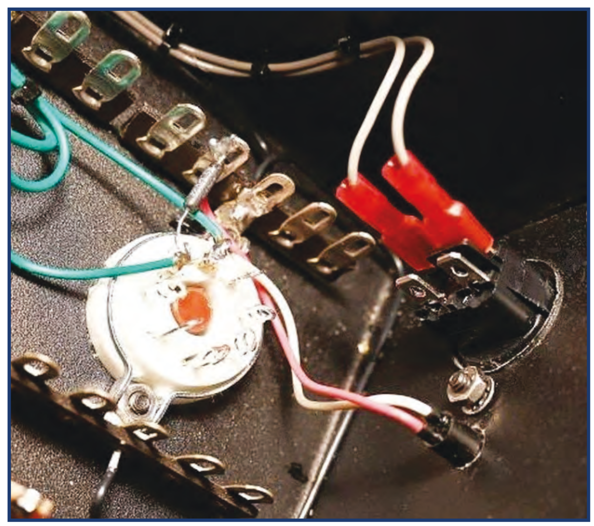


Figure 8



In some cases, power switch terminals should not be soldered; soldering may damage the switch. Switch datasheets should be consulted before attempting to solder switch terminals. The power switch used for this project could not be soldered. Instead, insulated push-on female terminal connectors are used. In this case, Panduit #DNF18-187FIB-3K. A terminal crimp tool must be used.

Figure 9

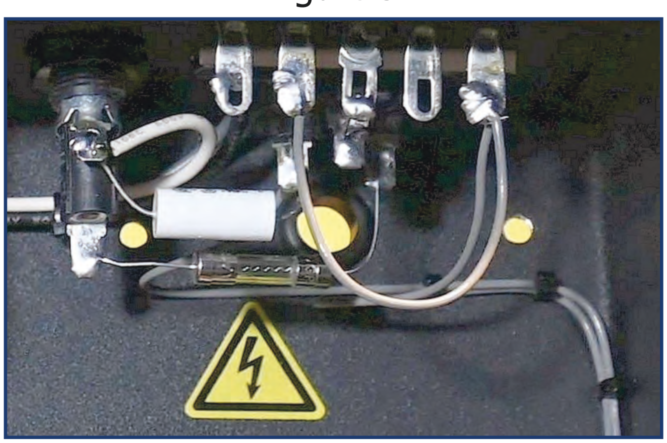
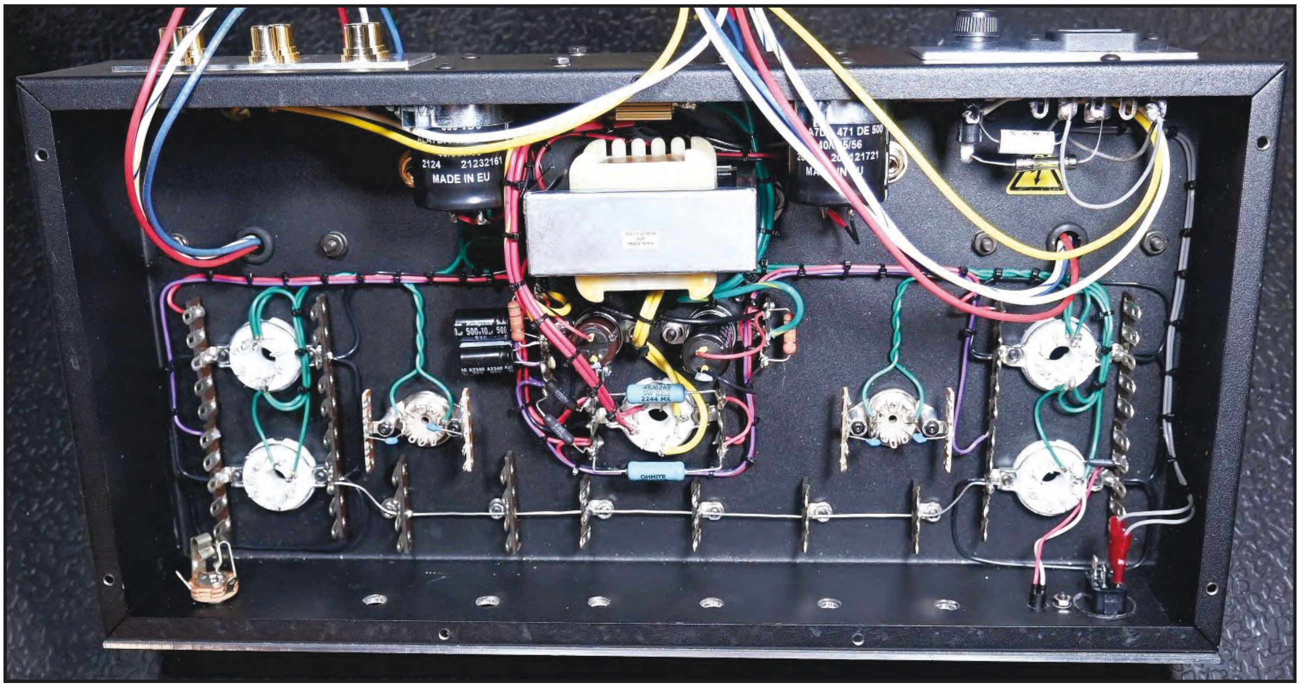


Figure 9 shows the J1 jumper wire used to select either 115 to 120VAC operation (terminal 1 from the left) or 120 to 125VAC operation (terminal 2 from the left). You may also notice a fuse in series with the main fuse. This is a 5-amp fast blow fuse not shown on the circuit diagram. This is added by the author for safety.

• Output

At this point, the output transformers and front row of terminal strips are mounted. An 18-gauge ground buss wire is fed through the center terminal crimp holes of the front panel terminal strips. The ground buss is soldered at every crimp hole.

Figure 10



The 6L6GC is a popular output tube capable of producing around 10 watts of Class A power.

The 6SN7 is a dual triode, two tubes in a single glass enclosure. For this project, one triode is used as a pre-amplifier and the other triode provides the voltage necessary to drive the output tube to full power output.

Designing the Output Circuit

Figure 11 is 6L6GC data from a 1961 RCA tube manual. This is our reference for maximum and typical operating conditions.

Something you seldom see in power output tube data is an amplification factor number. This is because power output tubes have very little gain. The small amount of gain can be ignored when doing gain calculations.

The 350 plate voltage column of the tube data will be used for data required for this project.

Figure 11

Class A_1 Amplifier

MAXIMUM RATINGS	6L6 Design-Center Values	6L6GC Design Maximum Values	
Plate Voltage	360	500	volts
Grid-No.2 (Screen-Grid) Voltage	270	450	volts
Plate Dissipation	19	30	watts
Grid-No.2 Input	2.5	5	watts

TYPICAL OPERATION				
Plate Voltage	250	300	350	volts
Grid-No.2 Voltage	250	200	250	volts
Grid-No.1 (Control-Grid) Voltage	—14	—12.5	—18	volts
Peak AF Grid-No.1 Voltage	14	12.5	18	volts
Zero-Signal Plate Current	72	48	54	mA
Maximum-Signal Plate Current	79	55	66	mA
Zero-Signal Grid-No.2 Current	5	2.5	2.5	mA
Maximum-Signal Grid-No.2 Current	7.3	4.7	7	mA
Plate Resistance (Approx.)	22500	35000	33000	ohms
Transconductance	6000	5300	5200	µmhos
Load Resistance	2500	4500	4200	ohms
Total Harmonic Distortion	10	11	15	per cent
Maximum-Signal Power Output	6.5	6.5	10.8	watts

Output Transformer

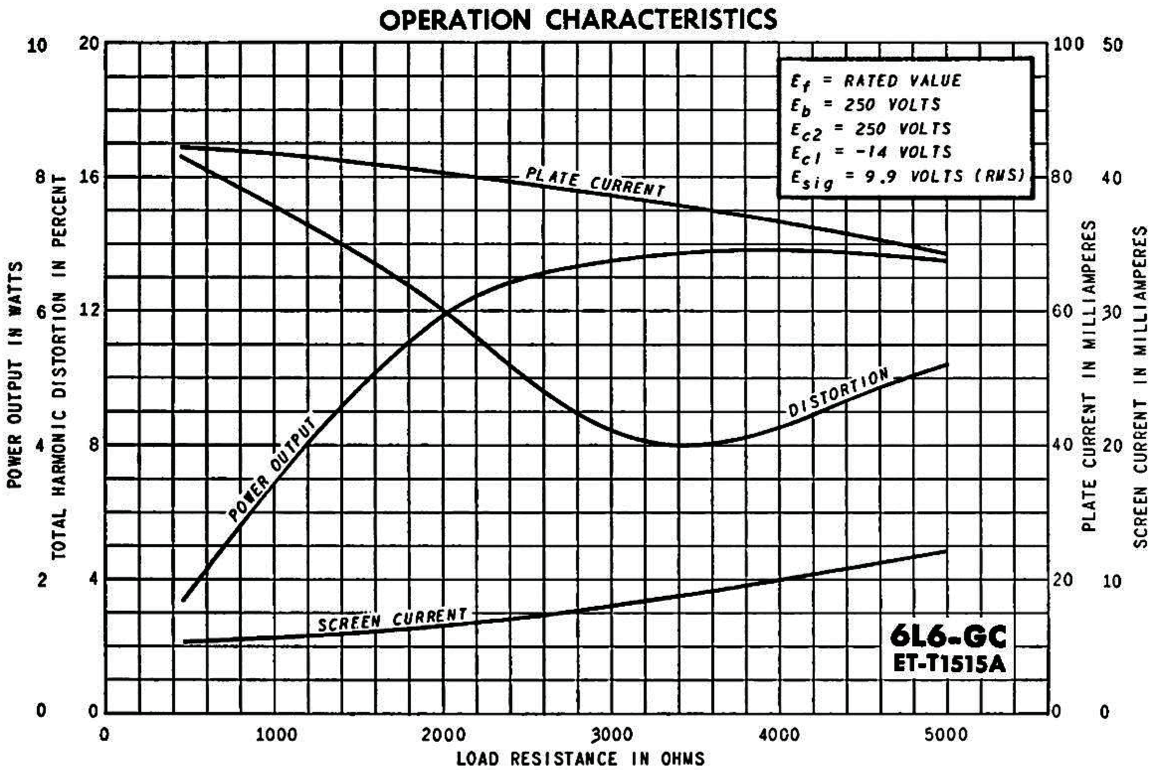
The output transformer couples the output tube plate to a loudspeaker. The load resistance for the 6L6GC is specified as 4,200 ohms. This would be the impedance of the output transformer primary specified as resistance in ohms. The specified load resistance is a design value that is a trade-off between the most power output and the least distortion. This is shown in the graph of Figure 12[1]. The graph is from an old RCA tube manual.

A primary impedance of 4,200 ohms in a single ended Class A transformer may not be a stock item. You may have to choose between a 3,500 ohm or 5,000 ohm primary. To avoid placing too much load on the plate, it would be better to go with a 5,000 ohm primary. Selecting a transformer rated at a higher wattage will provide more iron in the transformer's core. More iron provides better performance. Additional information on output transformers is found on page 100.

Grid number 2, the screen grid, will be connected to a tap of an ultra-linear output transformer. In an ultra-linear configuration, the screen grid may be operated with voltages up to the plate maximum voltage.

[1] The graph in Figure 12 is not specific to this project. Although the graph is for a 6L6GC in Class A1 operation, it is for use with a plate and screen grid voltage of 250 volts. It is shown as an example only.

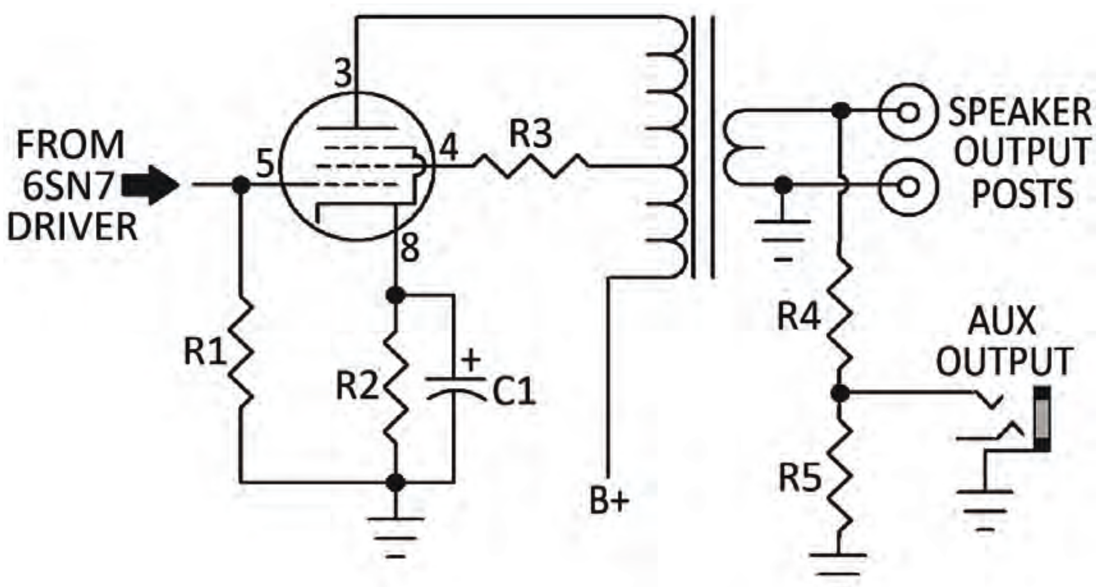
Figure 12



Graph is for Class A_1 operation using a single output tube

Figure 13 is a typical Class A output stage circuit. This will be the circuit used for the amplifier project.

Figure 13



R1

Grid leak resistor R1 can be any value from 100K to 470K ohms. A value of 330K for R1 is a good choice. The 6L6GC, as well as most pentode output tubes, do not suffer from high frequency loss with higher input grid resistor values. Also, the higher value reduces loading on the 6SN7 driver.
R1 = 330K.

R2

Cathode resistor R2 should be a value that provides the required grid bias voltage. The 6L6GC data in Figure 11 indicates that grid number one voltage (bias) should be around –18 volts. This means that the cathode resistor R2 should provide around +18 volts at the cathode. This is achieved by calculating a resistor value that will produce a voltage drop of 18 volts across the cathode resistor.

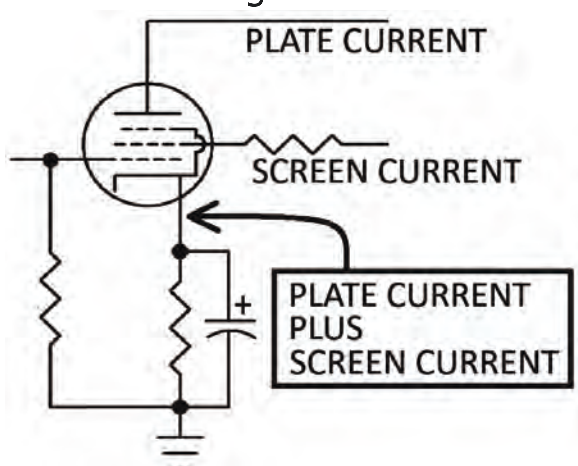
To calculate a resistor value, we use the Ohms Law formula for resistance, R = E / I, voltage divided by current.

R = resistance E = voltage in volts
I = current in amperes

The voltage is 18 volts (the desired voltage drop across the resistor).

The current is current flowing through the cathode and resistor.

Figure 14



As shown in Figure 14, the current flowing through the cathode is the plate current plus the screen current. The current we need is the zero-signal (idle) current. According to the data in Figure 11, the zero-signal plate current is 54 mA and the grid number 2 (screen) zero-signal current is 2.5 mA. This adds up to 56.5 mA of current flowing through the cathode and cathode resistor. The formula requires current in amperes; 56.5 mA must be converted to amperes. Convert mA to Amperes by dividing mA by 1,000, (0.0565 amps).

R = E / I, R = 18 / 0.0565 = 319 ohms (318.584 rounded off).

The closest standard value to 319 ohms is 330 ohms.
R2 = 330 ohms.

As current flows through a resistor, heat is generated. Resistors are rated at the maximum watts they can safely dissipate. It is important to calculate the amount of watts that a particular value of resistance will dissipate. This is done using the formula $P = I^2 X R$, (P = current squared times resistance.)
P = power in watts
I^2 = current in amperes squared (I X I)
R = resistance in ohms

The amount of watts a 330-ohm resistor will dissipate with 0.0565 amps.
$I^2 = 0.0565 X 0.0565 = 0.0032$
$P = I^2 X R$, 0.0032 X 330 = 1.056 watts

Because different types of output tubes may be plugged into the output circuit, the cathode resistor should have a wattage rating with a significant safety factor. For this project a five-watt cathode resistor will be used.
R2 = 330 ohms at 5 watts.

R3

The R3 resistor in the screen circuit is called a grid suppressor and limits screen current to control instabilities such as oscillating (a sustained high frequency signal). A value of 150 ohms will be used. The screen current is usually only a few milliamperes. A power rating of two watts is sufficient.
R3 = 150 ohms at 2 watts.

R4 & R5

An auxiliary jack on the front of the amplifier provides low-impedance output audio to an external device, including headphones. You would not want a headphone connected directly to an amplifier output. This is because any amplifier noise or hum would be noticeably distracting. The same is true with an external device. The value of R4 along with R5 attenuates the output level of the auxiliary jack. A guideline for values would be that R5 is 150 ohms; R4 should not be lower than 300 ohms or higher than 1K ohms. The selected values are R4 = 330 ohms and R5 = 150 ohms. Both are rated at 2 watts.

C1

The cathode bypass capacitor C1 will have a value of 220 uF. High values of C1 help to keep capacitive reactance and lower frequency distortion low. The voltage rating of C1 should be rated at about twice the cathode voltage. In this case, the cathode voltage is 18 volts.

C1 = 220 uF at 40 volts.

Figure 15

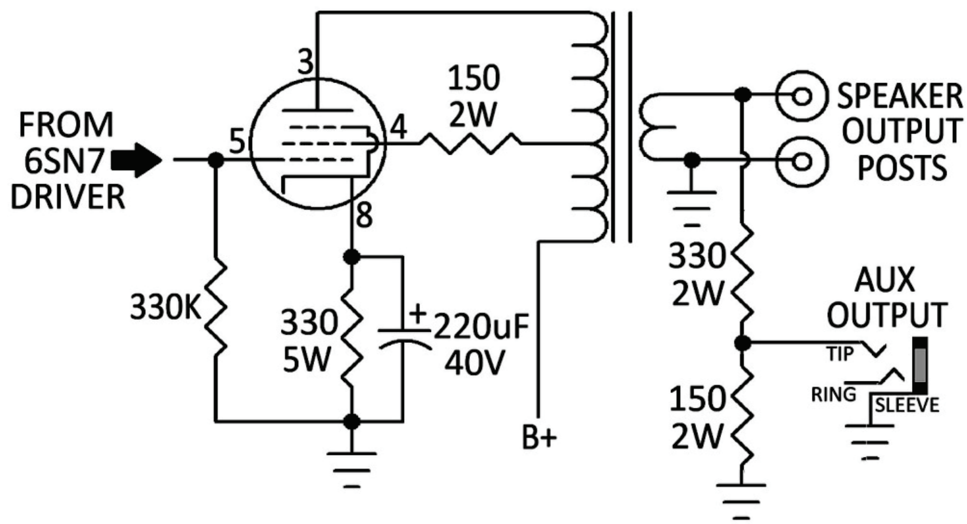


Figure 15 is the output stage circuit with all the values. Both channels use the same output circuit. The aux output jack is a stereo three-circuit jack; tip, ring and sleeve. The tip terminal is wired to the left channel output. The ring terminal that is shown as not connected goes to the right channel output.

Headphone Use

The reason there is not a switch to disconnect the speakers is that switches tend to develop dirty contacts over time. At higher volume levels, there is a fair amount of current applied to the speakers. Dirty contacts have a diode effect that can induce distortion, especially at higher current levels, as if a diode is placed in series with the speaker. The amplifier speaker outputs are accessible on the top of the chassis. The speaker posts are spaced to allow the use of a double banana plug. For headphone use, the double banana plugs can be unplugged. With the speakers removed, loading on the output tube is reduced, providing lower output distortion.

Component placement while wiring is determined as we progress.

Wiring the Output Circuit

When wiring, do not solder terminal connections until you are sure all wires that go to a terminal are secured in the terminal. Soldering directly to a speaker post requires a hotter iron. The amount of heat necessary to get good solder flow may damage plastic parts on the posts.

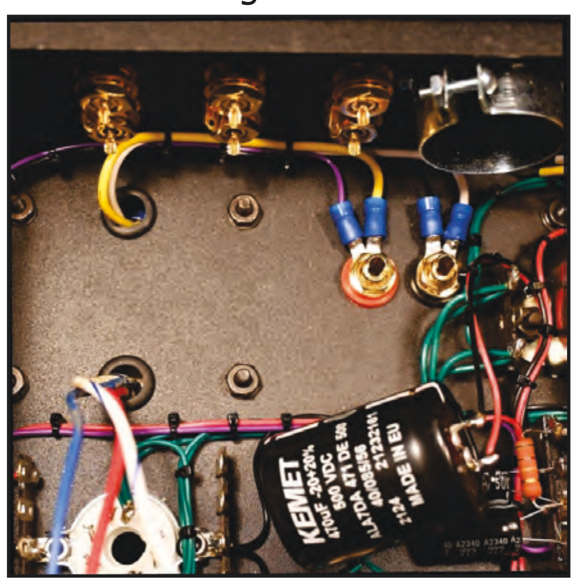
Rather than trying to solder onto the speaker posts (if there is a provision to solder), crimp lugs should be used. The wires connecting to the lugs will be crimped and soldered. Figure 16 is a lug that has been crimped and soldered. The lug has a blue plastic insulator on it. The insulator shrinks back as the lug gets hot when soldering. While the lug is still hot, hold the open terminal ring with long nose pliers and push the insulator forward.

Figure 16

Looking at the chassis from the bottom, the right channel amplifier is to the left and the left channel is to the right. In Figure 17, the right channel output transformer 8-ohm speaker wires are connected to the speaker posts. There are two terminal lugs on each post. The extra wires are a ground wire and a wire to the front panel auxiliary jack. The ground wire provides ground to the output transformer’s common output wire.

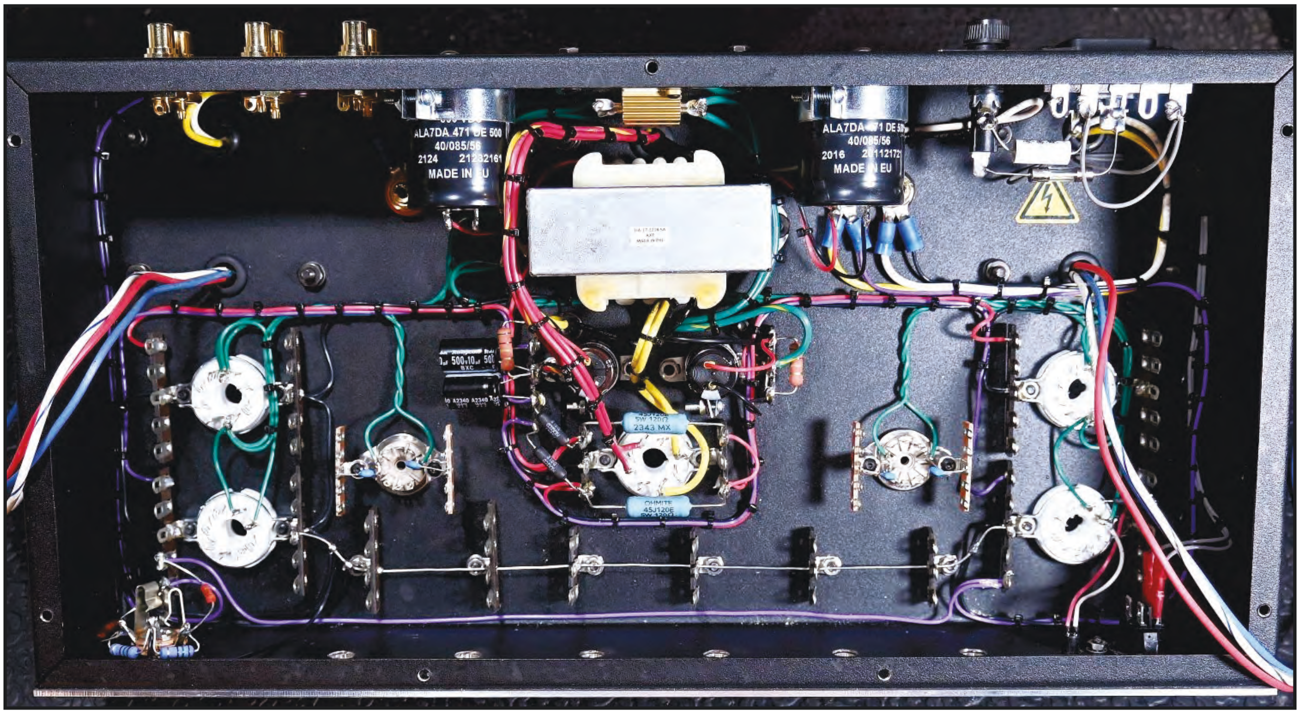
When the large filter capacitor mounting clamps were installed, they were positioned such that the screw securing the capacitor was easy to access. There is some extra slack in the wires to the capacitors. This allows the capacitors to be removed for easy access to the speaker posts. After the speaker posts are wired, the filter capacitors are secured back into the clamps.

Figure 17



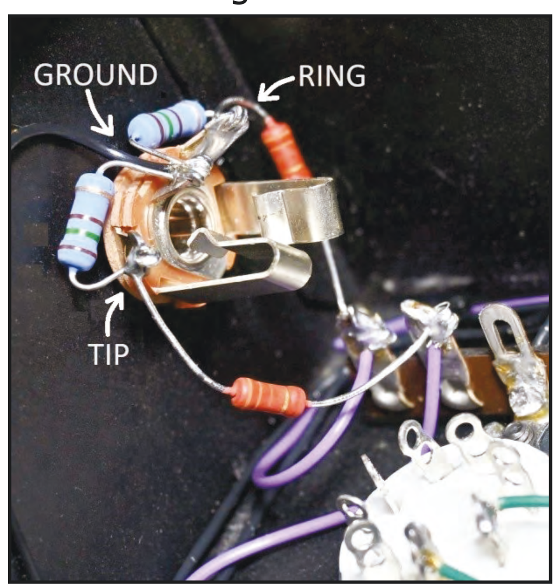
The left channel output speaker post terminal connections are the same as the right channel speaker post. As viewed from the bottom, the left channel amplifier is to the right. For the left channel, the output transformer's 8-ohm speaker wires are positioned away from the AC primary wiring.

Figure 18



The output wiring includes the auxiliary output jack. Figure 19 shows the wired jack. If you look at the bottom left side of Figure 18, you can see that the auxiliary output jack extends over the terminal strip.

Figure 19



For ease of wiring, the jack is removed from the chassis. A ground wire connects to the center ground terminal. Two 150-ohm 2-watt resistors are connected to the center ground terminal. The other end of one resistor connects to the tip terminal; the other resistor connects to the ring terminal.

The ground terminal is soldered. The tip and ring terminals are not soldered.

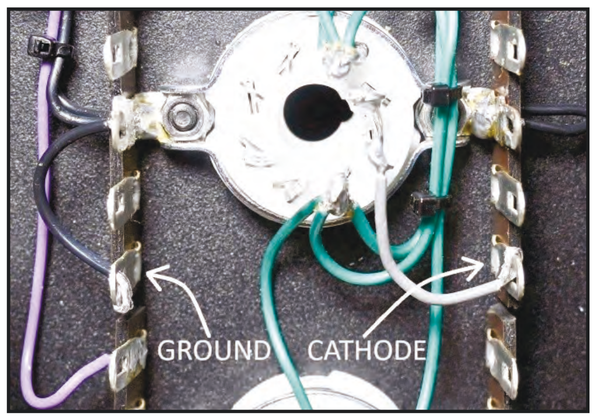
The auxiliary output jack wires from the speaker posts connect to the terminal strip under the auxiliary output jack. A 330-ohm 2-watt resistor is soldered onto each terminal strip connection. The other end of each resistor is left loose.

The auxiliary output jack is mounted back onto the chassis. The 330-ohm resistor soldered to the left channel output wire is connected to the auxiliary output jack tip terminal and soldered. The 330-ohm resistor connected to the right channel output wire is soldered to the auxiliary output jack ring terminal and soldered, see Figure 19.

The output tube components, left and right channels, are connected as the output circuit is wired. As you make a connection on the left channel, make the same connection on the right channel.

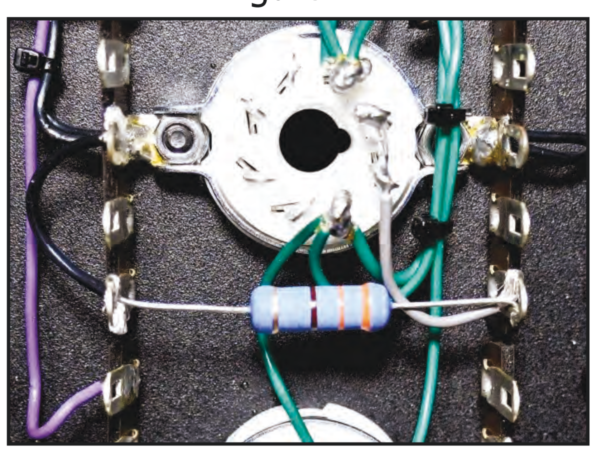
The 330-ohm 5-watt cathode resistor will connect across two terminal strips. A short wire is cut to run from the output tube terminals to a nearby terminal strip. One end of the wire needs to be stripped with enough exposed wire to fit through terminal one of the tube socket and terminate at pin eight of the tube socket. In effect, you connect pin 1 to pin 8. Solder tube socket pins one and eight.

Figure 20



The other end of the wire connects to a terminal strip. On a terminal strip across, connect a terminal to ground, see Figure 20. The 330-ohm 5-watt cathode resistor connects across these two terminals, Figure 21.

Figure 21



The ground and cathode terminals are not soldered yet; a cathode bypass capacitor needs to be included later.

Parts placement continues to be determined as you go along. Remember that both channels need to be wired as you place components.

The 150-ohm 2-watt screen grid suppressor is connected between terminal 4 of the output tube socket to a nearby terminal strip empty terminal. Only pin 4 of the tube socket is soldered.

The output transformer's screen wire is connected to the terminal strip terminal where the 150-ohm screen grid suppressor resistor is connected, and is soldered. See Figure 22.

The output transformer's B+ wire (usually red) is connected to the B+ terminal strip terminal. This should be a connection after the 120-ohm filter and isolation resistor and 470 uF filtering capacitor. The terminal is soldered.

The output transformer's plate wire (usually blue) is connected to the output tube socket pin 3. Pin 3 is soldered.

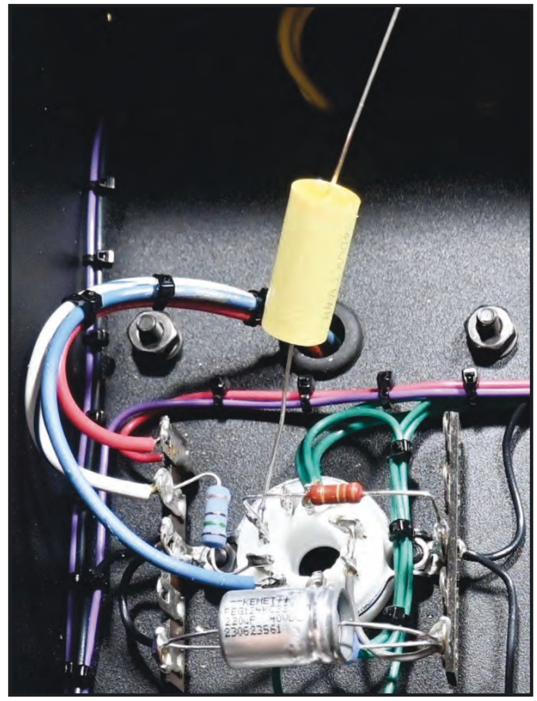
The 330K grid leak resistor is connected from pin 5 of the output tube socket to a nearby ground terminal. Only the ground terminal is soldered.

The 220 uf 40-volt cathode bypass capacitor is connected across the 330-ohm cathode resistor at the terminal strip terminals used for the 330-ohm resistor. There should be a 1/4-inch of airspace between the bypass capacitor and the cathode resistor. The airspace between the cathode bypass capacitor and cathode resistor is to prevent heat transfer from the resistor to the capacitor. Continuous heat will shorten the life of capacitors. Be sure to connect the bypass capacitors positive (+) lead towards the cathode. Solder both terminal connections.

To allow testing the output stage, a .47 uF 400-volt capacitor needs to be temporarily soldered to the input grid of the output tube. Do not cut the capacitor leads for this test. Solder a small bead of solder onto the end of one capacitor lead. Place the capacitor lead with the solder bead onto pin 5 of the output tube socket. Using a soldering iron, temporally attach (tack solder) the lead to the tube socket pin 5.

This is a good time to check your wiring of both output tubes against the circuit drawing.

Figure 22



The right channel output socket wiring is shown in Figure 22. It's best to try and wire neatly, although sometimes circuits around a tube socket can get dense. The output tube circuits do not have many components and component layout is usually easy. The .47 uF capacitor tack soldered to pin 5 of the output tube is used for signal testing. After the testing, it will be removed. The capacitor will later be permanently installed to couple the 6SN7 output to the output tube input grid.

Testing Power Supply and Output Circuits

Testing does require a volt-ohm meter that can read up to 600 volts DC, usually a meter with a 1,000-volt DC scale. An analog meter can be used, but a digital meter might be more convenient.

All tubes must be inserted into the correct sockets. Only the output tubes will function (hopefully), but the filament supply should have a full load on it to keep the filament voltage within tolerance.

Connect a speaker to each channel's output post. These can be small test speakers with a 4, 8 or 16 ohm impedance.

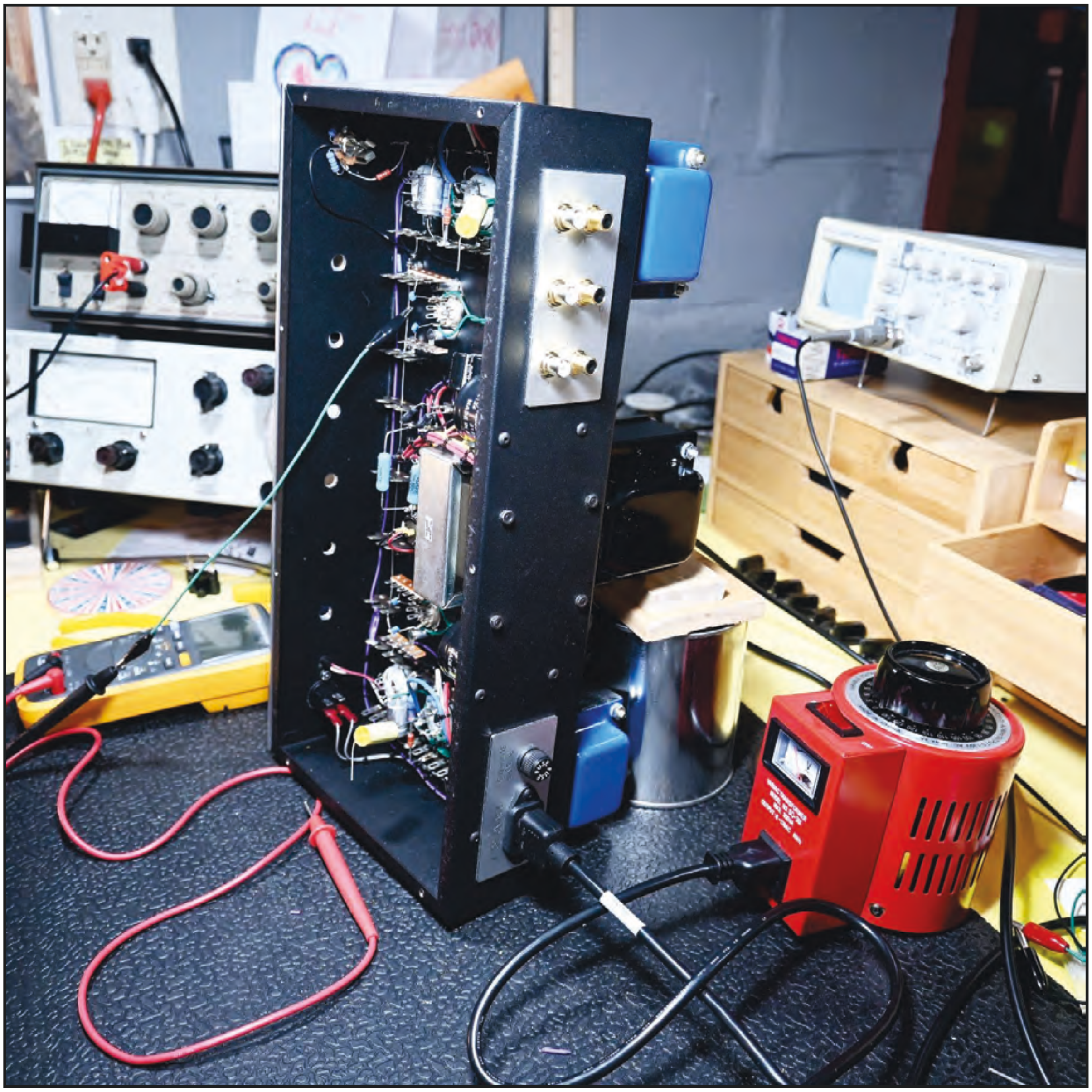
Prop the chassis[1] to allow easy access to the wiring inside. Figure 23 shows the chassis propped with an empty quart paint can and a couple of wood pieces. The amplifier's power switch should be set off.

If not already installed, insert a three-amp fuse into the fuse holder.

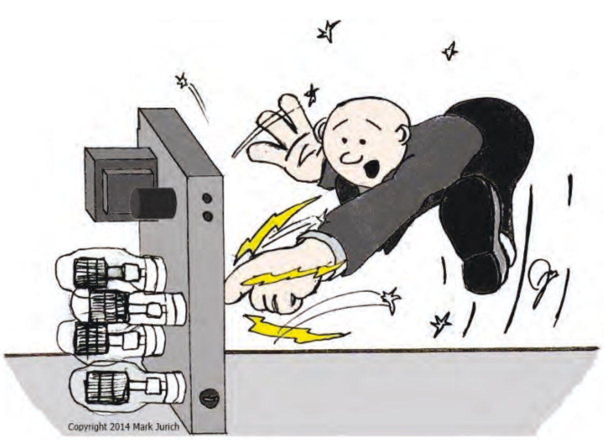
At this point, the amplifier can be plugged into AC power. In Figure 23, a variable transformer is used to slowly raise the voltage. In the event of wiring errors, a variable transformer can prevent damage to components. If you have checked and double-checked your wiring, there should be no problems.

[1] When the 5U4 is operated horizontal, pins 2 and 4 should be in vertical plane.

Figure 23



Voltage Readings

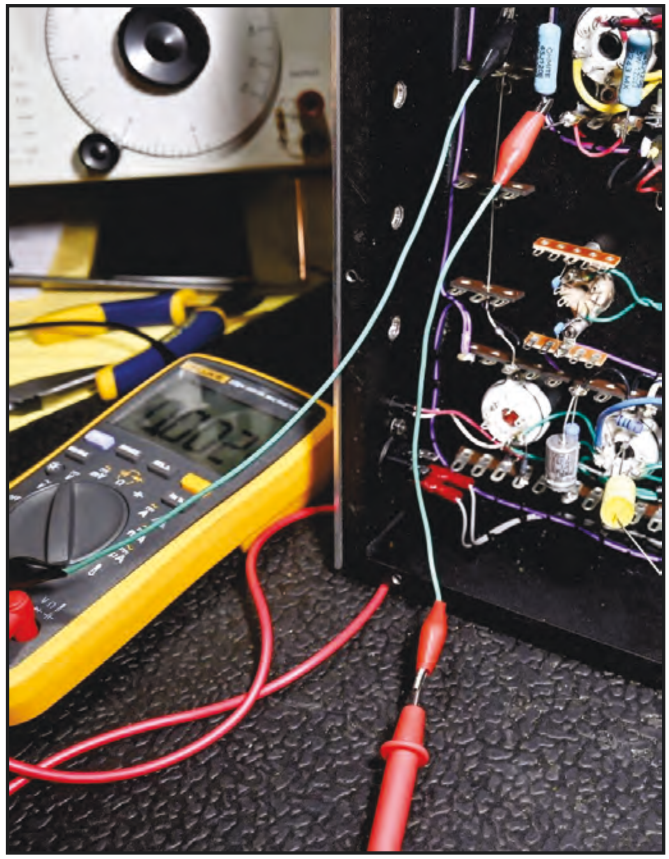


When taking voltage readings, be extra careful where you put your fingers. This is especially true when taking readings with no load on a power supply. Connect your voltmeter negative test probe to ground using a clip lead. This allows taking measurements with just one hand. <u>Never rest either hand on the chassis</u>.

Always check that your test meter is on the correct scale before measuring.

The positive test probe of the volt meter is clip lead connected to a point in the B+ supply right after the filter choke inductor, Figure 25.

Figure 25



The positive clip lead should not touch any part of the chassis or ground circuits.

The volt meter is set to the 1,000-volt DC scale.

With the amplifier plugged into an AC outlet, the amplifier power switch is turned on.

After six seconds, there should be an indication of the B+ voltage rising up to around 500VDC, then settling down to about 385VDC.

The power supply checks good.

Note: The no-load voltage is dependent on the primary AC voltage. If the primary AC voltage is high, B+ voltages higher than 500 volts are possible.

Switch the power switch off and unplug the amplifier from the AC outlet. With the amplifier switched off, the B+ voltage should rapidly start to drop as the tubes cool down, then taper off to a slow discharge. Let the amplifier sit untouched to allow bleeder resistors to bleed the voltage off. Then, before working with any circuits, check the B+ voltage with a meter to insure it has dropped below twenty volts DC.

For a 5U4, or any rectifier tube, if there is no indication of B+ voltage starting to rise at 8 seconds, the amplifier should immediately be switched off. If you are certain the volt meter was set correctly and the clip leads are good, then the circuits will need to be checked. See page 167.

Leave the negative probe of the test meter clip lead connected to ground for the following measurements.

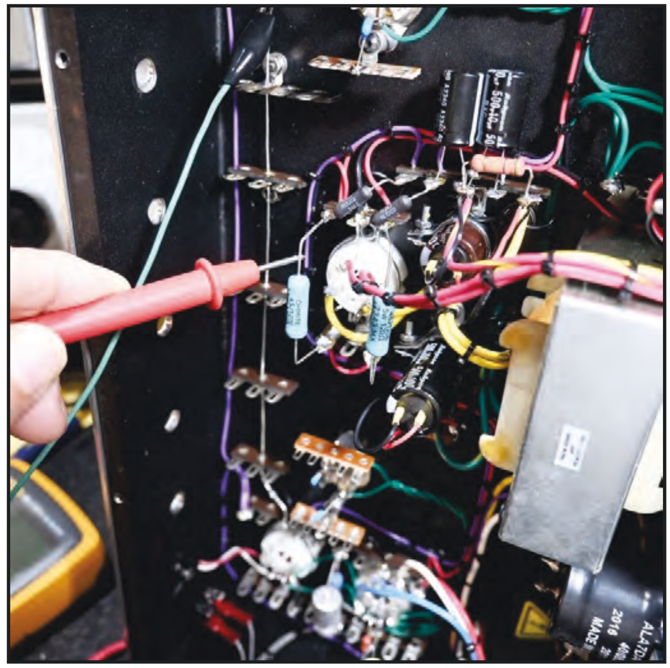
The meter is set to read 1,000VDC.

One hand is used to hold the meter positive probe used for measurements. Measuring the B+ voltage for the left channel is demonstrated in Figure 26.

Switch the amplifier on.

After the tubes warm up, measure the B+ voltage for the left channel 120 ohm resistor. In this case, the meter should read around 380VDC.

Figure 26



Measuring the B+ voltage to the right channel on the other 120-ohm resistor, the meter should also read around 380VDC.

Care must be observed not to short circuit pins on tube sockets.

Measuring the voltage on the left channel 6L6GC plate pin 3, the meter should read around 370VDC.

Measuring the left channel 6L6GC screen voltage pin 4, the meter should read around 375 volts.

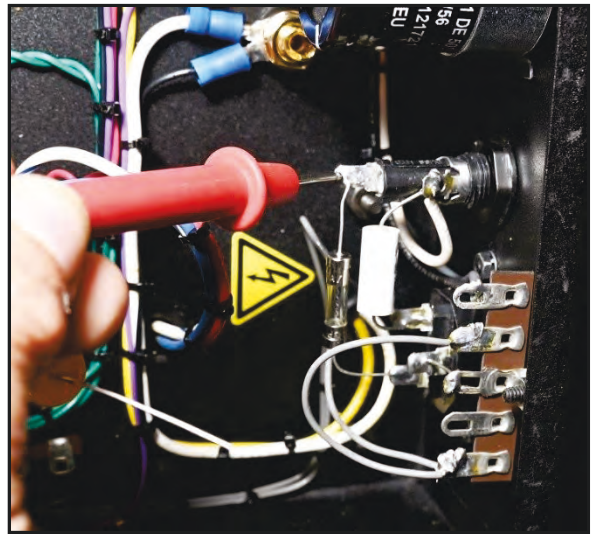
Measuring the left channel 6L6GC cathode voltage pin 8, the meter should read between 18VDC and 25VDC[1].

The right channel 6L6GC measurements should be very close to the left channel readings.

The AC power voltage can be measured by switching the meter to read AC volts on the 250 volt scale (depending on your meter range). Carefully place the positive probe onto the fuse holder terminal, Figure 27.

[1] If current through the tube is higher than anticipated, voltage at the cathode will also be higher. This is not a problem.

Figure 27



When the adjustable transformer was set for 125VAC power, the high voltage readings were 4.5% higher. Once the 6SN7s are wired up, there will be a few more milliamps of load on the B+ power supply, loading the voltage down some.

The filament voltages are carefully read across tube socket filament pins using a 10-volt AC or higher scale.

	120VAC	125VAC (power transformer primary voltage)	
5U4	4.9V	5.1V	Voltages are read with all the tubes installed.
6.3V	6.1V	6.3V	

Set the amplifier power switch off. After a few moments, measure the B+ voltage to insure the B+ filtering capacitors have discharged below 20 volts.

Audio Test

Be aware that the amplifier is still plugged into an AC source and there is a shock hazard in the area of the fuse holder and the 5U4 rectifier.

If you have an audio source such as an analog tone generator, you can audio test the output stage. Another option for testing audio is an online tone generator. Search for ‘audio generator test tones’. In order to use a computer’s audio output, you will need a plug that fits the computer headphone jack with a cable long enough to reach the amplifier under test.

The amplifier should have speakers connected to both output posts.

The test meter negative probe is removed from the ground clip lead. The tone generator audio negative lead connects to the amplifier ground clip lead. The tone generator signal output lead is then clipped lead connected to the .47uF input capacitor, one channel at a time. The amplifier power switch is set on. A tone generator signal is applied to the input capacitor. Tone should be heard in the speakers, one channel at a time.

Troubleshoot the Power Supply

If the amplifier specifies a slow-blow (time-delayed) fuse, replace the fuse with a fast-blow fuse of the same current rating. This may save rectifier tubes from being damaged. Fuses are less expensive to replace than rectifier tubes. After the amplifier is repaired, insert the original specified fuse back in.

The following tips may help when troubleshooting the power supply. The amplifier power cord should be unplugged from AC power.

In both a vacuum tube and solid state rectifier supply, if the fuse blows every time the amplifier power switch is set on, there may be a short in the B+ circuit. Another possibility is a bad rectifier. If the rectifier tube fails when the power switch is set on, there is most likely a short in the B+ circuit.

Be sure all the filtering capacitors are discharged. Using a clip lead, one end of the clip lead is clipped to ground. Clip a 1,000-ohm 10-watt resistor onto the clip leads free end. For several seconds, touch the free end of the resistor wire to the large B+ filtering capacitors and B+ wiring termination points.

Check the B+ circuit using the 10K-ohm scale of a multimeter. This is a case where an analog meter might be easier to read, although it will work with a digital meter. Connect the negative meter probe to the ground clip lead. Using the 10K-ohm scale, touch the meter positive probe to a B+ point near or at the rectifier high voltage output. The meter should read very low resistance at first, then the resistance will increase[1] as the filtering capacitors charge. This is normal and indicates no short in the B+ circuit. A constant low resistance could mean a short to ground in the B+ circuit, possibly a bad capacitor. In the case of a new amplifier build, a wiring error or wire short.

Another possibility is an open filter choke inductor. Measure the resistance across the choke inductor using the 1K scale of the ohms scale. The meter should read the resistance of the choke wire, usually very low resistance in the 50 to 500 ohm range.

For a new amplifier build, check the power supply and B+ circuits for wiring errors. Check that resistor values are correct.

[1] After the filtering capacitors have charged from the ohm meter, B+ circuits will measure around 200K ohms or higher, depending on bleeder resistor values.

• Pre-Amplifier & Output Driver

Calculate Required Gain

Looking at the datasheet for a 6L6GC output tube, it takes 18 volts peak of grid voltage to get 10.8 watts output. In terms of audio signals, an 18-volt peak is a fairly hefty signal and much higher than the normal audio signal level of about one-half volt RMS of most home audio equipment. This means that amplification of the signal before the output tube is required.

The gain of stages preceding the output tube must be calculated. This is done using the amplification factor of the preceding stages. The amplification factor (represented as ***Mu***, ***&mu*** or ***μ***) of a tube is given as a number in tube datasheets. The following excerpt of a 6SN7 datasheet in Figure 28 specifies the amplification factor for each 6SN7 triode unit as 20[1].

Figure 28

Class A_1 Amplifier (Each Unit)

MAXIMUM RATINGS (Design-Center Values)			
Plate Voltage		450	volts
Cathode Current		20	mA
Plate Dissipation:			
For either plate		5	watts
For both plates with both units operating		7.5	watts
CHARACTERISTICS			
Plate Voltage	90	250	volts
Grid Voltage	0	—8	volts
Amplification Factor	20	20	
Plate Resistance (Approx.)	6700	7700	ohms
Transconductance	3000	2600	μmhos
Plate Current	10	9	mA
Plate Current for grid voltage of —12.5 volts	—	1.3	mA
Grid Voltage (Approx.) for plate current of 10 μA	—7	—18	volts
MAXIMUM CIRCUIT VALUE			
Grid-Circuit Resistance, for fixed-bias operation		1	megohm

Audio signal levels are usually measured as RMS (Root Mean Square). To convert a peak value to an RMS value, multiply the peak value by .707. Also, see page 30 concerning RMS, peak and peak-to-peak.

For the 6L6GC output tube, 18 X .707 = 12.7 volts RMS. It will take about 12.7 volts RMS of grid drive signal for 10.8 watts output power.

[1] Do not be concerned about how the amplification factor is arrived at, just know you find the amplification factor in a tube datasheet.

To find the minimum required voltage gain for a voltage amplifier, divide the RMS grid drive voltage by the amplifier input voltage. The average stereo amplifier input sensitivity is 0.5 volts RMS for full output power. Some single-channel (a.k.a. monoblock) power amplifiers may require more input signal level. This is because a stereo audio control unit capable of producing higher output levels will normally precede a pair of monoblock power amplifiers.

Input = 0.5 volts RMS, the 6L6GC grid drive voltage = 12.7 volts RMS.
Minimum required voltage gain = 12.7 / 0.5 = 25.4

When using triodes, for good high frequency response, the grid leak resistor and plate resistor values should not be any higher in value than 150K. Using 150K, or lower, plate and grid resistor values reduces Miller effect grid capacitance. For more information on grid effect capacitance and loss of higher frequencies, see page 66.

You can use the following formula to calculate the approximate voltage gain of any voltage amplifier stage. Both the Mu (amplification factor μ) and the plate resistance R_a can be found in tube datasheets.

Voltage gain (V_g) = (Mu X R_p) / (R_p + R_a)
Vg = (Mu X plate resistor) divided by (plate resistor + plate resistance)

M_u = Tube Amplification Factor
R_a = Tube Plate Resistance
R_p = Plate Resistor
The plate resistor is a resistor that connects from B+ high voltage to the plate (anode) of a tube. Plate resistor values have a lesser effect on voltage gain. It is the Mu of a tube that has the most effect on voltage gain.

As stated in the 6SN7 datasheet, Mu = 20 and plate resistance = 7,700.
A plate resistor value of 100,000 ohms will be used.

V_g = (Mu X R_p) / (R_p + R_a)
V_g = (20 X 100,000) / (100,000 + 7,700)
V_g = (2,000,000) / (107,700) = 18.6

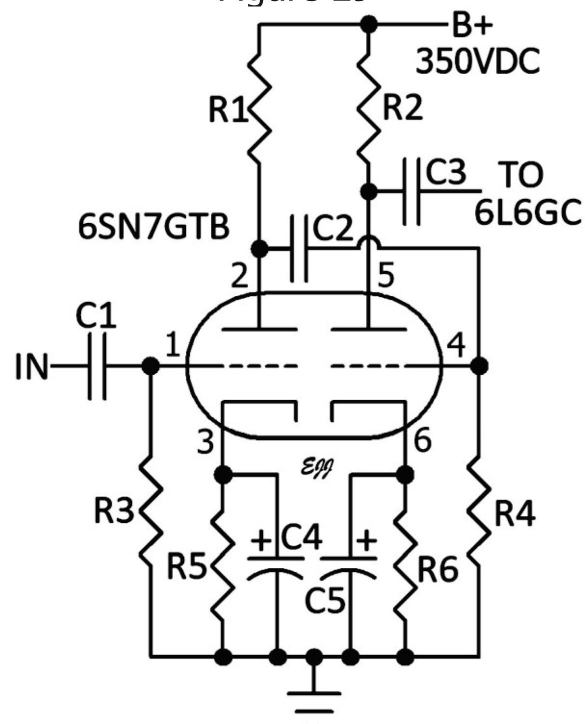
The minimum required voltage gain is 25.4; one unit of the 6SN7 does not provide enough gain. Both halves of the 6SN7 would need to be used.

Figure 29 shows a typical dual triode circuit. Plate resistors R1 and R2 plus the Mu (amplification factor) of the tube determine the gain of each triode unit. In the case of a 6SN7, a value of 100K ohms is a good R1 and R2 value. It has already been calculated that with a 100K ohm plate resistor, the voltage gain is around 18.6. Once a plate resistor value is determined, a cathode resistor value can be found.

Grid resistors R3 and R4 are grid leak resistors that drain any static voltage that might develop in the grid, possibly affecting grid bias voltage. A value of 150K ohms is a good value for R3 and R4.

Cathode resistors R5 and R6 provide grid bias. The voltage drop across R5 and R6 sets up a positive voltage at the cathode of each unit. On the grid, the positive voltage at the cathode appears negative. A digital voltmeter, with the negative probe at the cathode and the positive probe on the grid, will measure voltage on the grid as negative.

Figure 29



Capacitors C1, C2 and C3 couple audio signals while blocking any DC voltage that might be present. For reduced distortion at low frequencies, capacitors C1, C2 and C3 would be .47 uF to 1 uF. For more information on distortion and capacitor reactance, see pages 40 and 47. The voltage rating of C1, C2 and C3 is dependent on the DC voltage of the circuit the capacitors are used in.

Capacitors C4 and C5 are a polarized electrolytic type and could have a high value up to 200uF. They are used to bypass the effects of signal voltage at the cathode. The voltage rating of C4 and C5 should be in the range of 25VDC to 50VDC. As with all polarized capacitors, the positive connection of the capacitor should be connected to positive voltage. The negative connection is connected to negative (normally ground).

The following is a method of using Ohms Law to calculate a cathode resistor (R5) value for one triode unit in Figure 29. The other triode unit would use the same procedure. Calculate current flow through the tube using the value of R1 (plate resistor) and the plate resistance of the 6SN7.

Although the circuit in Figure 29 has a B+ voltage of 350 volts, the datasheet for a 6SN7 specifies plate resistance of only up to 250 volts B+. A 250-volt plate resistance of 7,700 ohms will be used. The plate resistor R1 will be 100,000 ohms previously used to calculate a voltage gain of 18.6.

100,000 + 7,700 = 107,700 ohms

Calculate current flow through the tube using the Ohm's Law I = E / R, current = voltage divided by resistance. (E = 350, R = 107,700).

350 / 107,700 = .0032 amps (3.2 mA).

The datasheet specifies the grid voltage (bias) as –8 volts[1]. This means that the voltage drop across R5 must provide +8 volts at the cathode. Use Ohm's Law to calculate the resistance that provides an 8-volt drop.

Resistance = voltage divided by current, R = E / I. Current must be in amps.

Resistance that provides an 8-volt drop across R5 = 8 / .0032 = 2,500 ohms. The closest standard value is 2,400 ohms.

R1 = 100,000 ohms, 6SN7 plate resistance = 7,700 ohms, R5 = 2,400 ohms.

Plate Dissipation

Plate dissipation must be considered. Plate dissipation is heat dissipated by the plate as current flows through the tube. Plate dissipation is stated as so many watts. In order to calculate the wattage being dissipated, current flow through the tube must be calculated. Power in watts is calculated using current squared times resistance, $P = I^2 X R$. The current through the tube and the plate resistance of the tube is used.

Continued on the next page

[1] The actual bias voltage at the cathode may not always match datasheet specifications. For instance, operations at voltages other than those specified in a datasheet may result in a plate resistance higher or lower than expected, skewing circuit calculations. In most cases, tube performance will not be degraded.

Total resistance of the circuit must be found first. Resistance for one section of the 6SN7 in Figure 29 would be the total resistance of the plate resistor R1 plus the plate resistance of the tube plus the cathode resistor R5.

100,000 + 7,700 + 2,400 = 110,100 ohms

Use the total circuit resistance and the B+ voltage of 350 volts to calculate current flow through the tube.

Current flow through the tube is calculated using I = E / R
350 / 110,100 = .00318 amps (3.18 mA).

Power in watts is calculated using current squared times the plate resistance.
$P = I^2 X R$
(Current must be in amps)
(.00318 X .00318) X 7,700 = .00001 X 7,700 = 0.077 watts.

With both triode units in operation, the total plate dissipation is 0.154 watts.

The 6SN7 datasheet states that maximum plate dissipation is 7.5 watts total with both triode units operating. 0.154 watts is well below the 7.5-watt maximum limit.

Multiple Stages, Gain Multiplying

With both 6SN7 units coupled one to the other, there would be a significant increase in overall voltage gain, calculated as follows.

Unit one amplifies 0.5 volts as 0.5 X 18.6 = 9.3 volts into unit two.
Unit two then amplifies 9.3 volts as 9.3 X 18.6 = 173 volts.
The total voltage gain is 346 (voltage gain unit 1) X (voltage gain unit 2).

However, you will not get 173 volts. The second 6SN7 unit is limited by the amount of B+ voltage and would start clipping the signal before getting close to 173 volts. With a 350-volt B+ voltage, the 6SN7 will start clipping at around 66 volts RMS output. Also, any output voltage over 12.7 volts RMS applied to the 6L6GC grid would drive the 6L6 into overload clipping. Although it is better to have extra gain, with such a high gain, it may be difficult to adjust the volume control. Another problem with such high gain is the possibility of hum and static noise pickup.

Using an attenuation pad to lower the signal level going into the first 6SN7 unit would in effect lower the gain of the 6SN7. However, with such a high gain after the pad, there would still be the problem of hum and noise pickup.

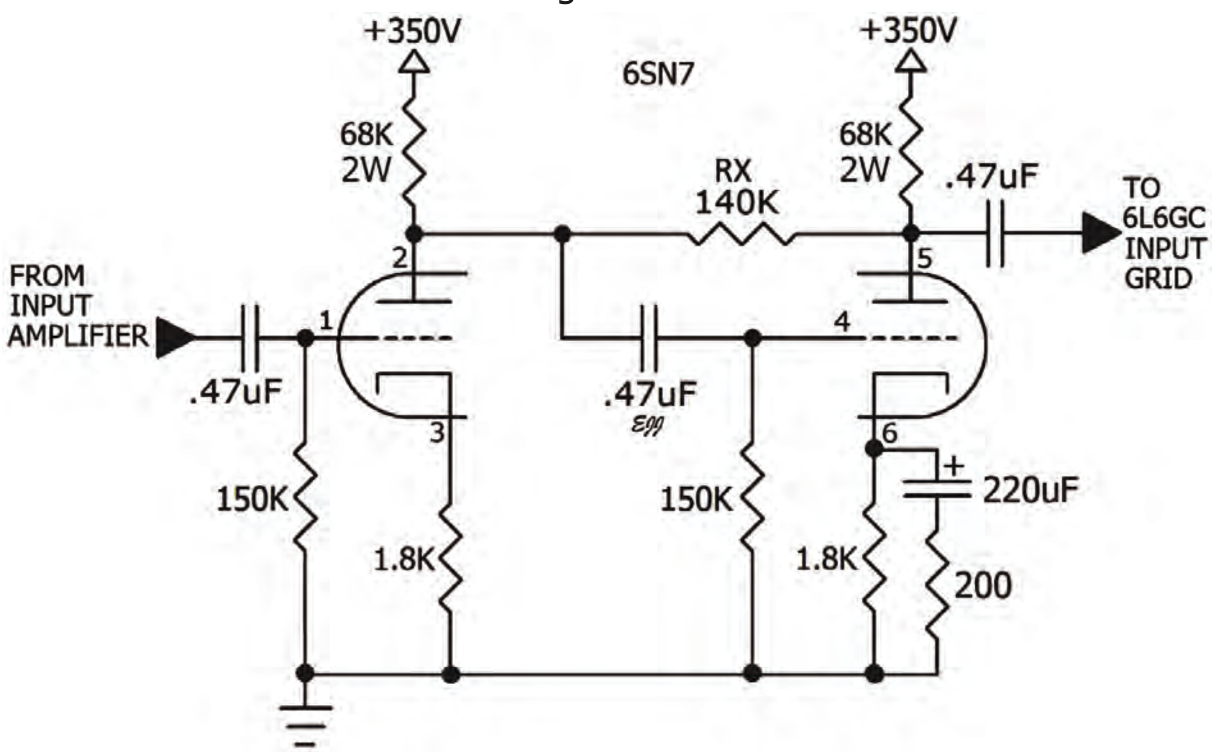
In a situation like this, the usual method of design would be to use a higher gain tube such as a 12AY7 with a single unit voltage gain of 44 or a 12AT7 with a single unit voltage gain of 60. Then, use one triode unit for the left channel and the other triode unit for the right channel.

However, the 6SN7 was selected as the pre-amplifier and output tube driver. We can provide a voltage gain closer to our minimum required voltage gain of 25.4 using a 6SN7 by integrating both triode units.

Integrated Dual Triode

The circuit in Figure 30 is similar to Figure 29 in that unit one output of the dual triode connects to the input of unit two. Other than that, the circuit has some key differences. The units are integrated by RX. Also, the first unit does not use a cathode bypass capacitor. The second unit has a 200-ohm resistor in series with a cathode bypass capacitor to reduce the capacitance reactance of the bypass capacitor.

Figure 30



Using the component values in Figure 30, the circuit has a total voltage gain of 40. If a bypass capacitor were added to the cathode of the first unit, the voltage gain would be 108. However, doing so degrades performance.

Increasing the values of the plate resistors and linking resistor RX will also increase gain. For instance, using the arrangement in Figure 30, if the plate resistor values were 100K ohms and RX was 200K ohms, the voltage gain would be 86. For this design, extra gain is not needed.

The circuit values as shown in Figure 30 provide the following performance for only the 6SN7. The output tube is not included in these measurements.

Voltage gain = 40.0.
Frequency response –1 dB points = 7 Hz and 48K Hz.
Distortion at 10 volts RMS output,
20 Hz = 0.07%, 100 Hz = 0.07%, 1K Hz = 0.15%, 10K Hz = 0.22%
Distortion at 20 volts RMS output,
20 Hz = 0.15%, 100 Hz = 0.15%, 1K Hz = 0.23%, 10K Hz = 0.38%

For reasons of keeping both units of the dual triode balanced, both plate resistors are the same value. The cathode resistors are also the same value. The plate-linking resistor RX is twice the value of the plate resistors.

Because linking the plates alters the electrical operation of the dual triode, standard formulas for calculating gain do not apply. The circuit values in Figure 30 were arrived at by breadboarding the circuit and running tests for frequency response, distortion and gain. For more on adjusting the voltage gain of an integrated dual triode, see page 78.

The circuit in Figure 30 was pre-planned before this amplifier project was started to allow the use of the 6SN7 as a single select gain dual triode. The previous text for calculating voltage gain related to Figure 29 was included so that the builder has the ability to calculate and work with voltage gain.

At this point, the 6SN7 circuits can be wired. The process is similar to wiring the output tube circuits. Space will be tight, wiring will take some time. Components are placed with care that component leads do not touch, causing a short circuit.

Wiring the Pre-Amp and Driver Circuits

It is best not to solder terminal connections until you are certain that all wires and component leads are connected to a terminal. This is especially true with dense wiring. Wire both the left and right channel 6SN7 sockets.

Figure 31

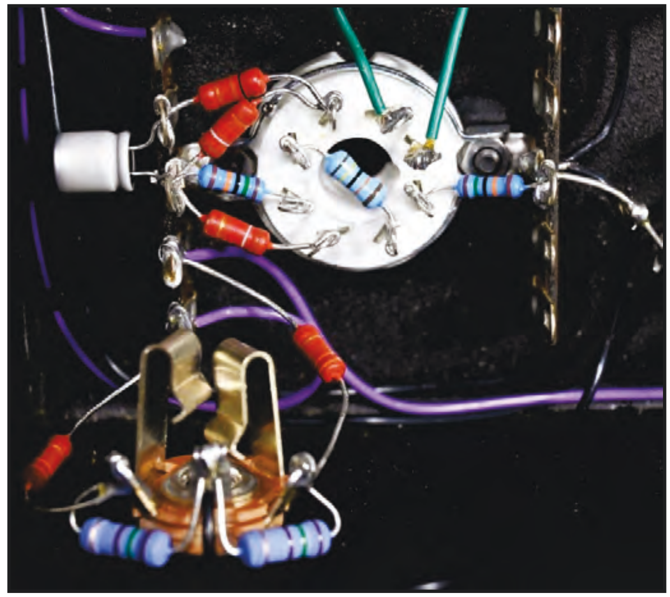
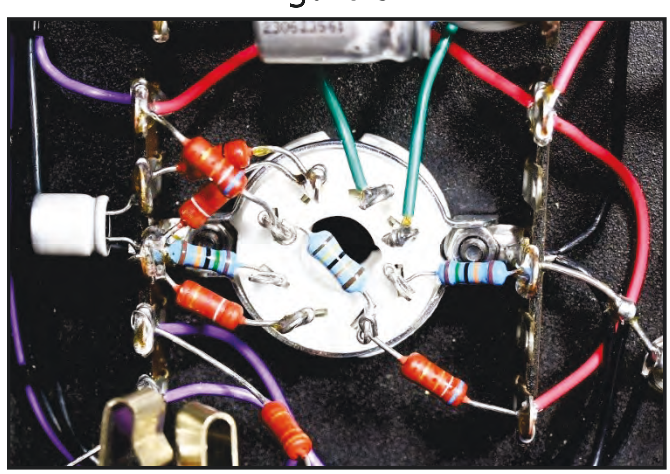


Figure 31 shows the start of wiring components on the right channel 6SN7 socket using the circuit in Figure 30.

The resistor that is connected from pin 2 to pin 5 of the socket is the plate to plate RX 140K-ohm. The silver-colored capacitor on the left is the cathode bypass capacitor. It is an aluminum organic polymer capacitor with a value of 220 uF at 25VDC. You can compare the circuit drawing in Figure 30 to the socket wiring in Figure 31. The center terminal on both terminal strips is ground.

The remaining components will be positioned over the resistors that you see in Figure 31. This includes the plate resistors and the .47 uF coupling capacitors. The coupling capacitors are a high-quality film type with a 400-volt rating. Compared to other components, film capacitors with high voltage ratings are fairly large. Positioning them in a tight space can be challenging.

Figure 32

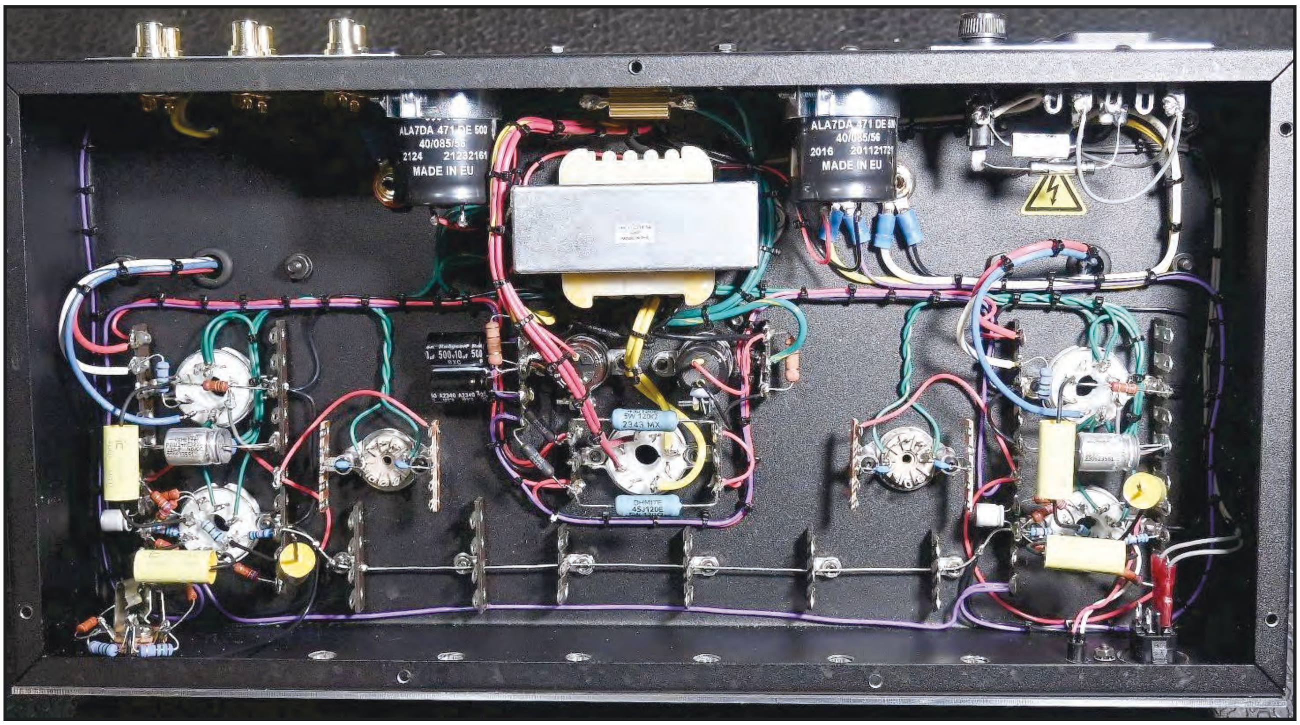


In Figure 32, the 6SN7 B+ supply voltage is extended to the right terminal strip at the top and bottom terminals. The 68K 2-watt plate resistors are connected to the B+ terminals and to each 6SN7 plate, tube socket pins 2 and 5. A few completed connections are soldered.

The .47 uF 400 volt coupling capacitors are wired into the circuit next. Because of their size relative to the other components, they are positioned over other circuits. In the event a capacitor is blocking access to a section of circuit, the capacitor wire leads should be long enough that the capacitor may be pushed to the side. Tubing added to the capacitor wire leads for insulation helps to prevent shorts. The remaining completed connections are soldered. A .47 uF capacitor is tack-soldered to terminal 1 of the 6SN7 socket. The other end of the capacitor is left loose. See Figure 33.

Double-check your wiring against the circuit drawing.

Figure 33



A quick test of the amplifier build at this stage can be done by connecting speakers to the amplifier output. With the amplifier powered on and warmed up, using a finger, touch the loose end of each 6SN7 .47uF input capacitor connected to pin 1 of the 6SN7 socket. Pin 1 is the grid and no voltage will be present. If properly wired, you will hear a solid hum. Switch the amplifier off and unplug it from the AC mains. The amplifier should sit for a few minutes allowing the filtering capacitors to discharge.

Wiring the 12AX7 input amplifiers will be next.

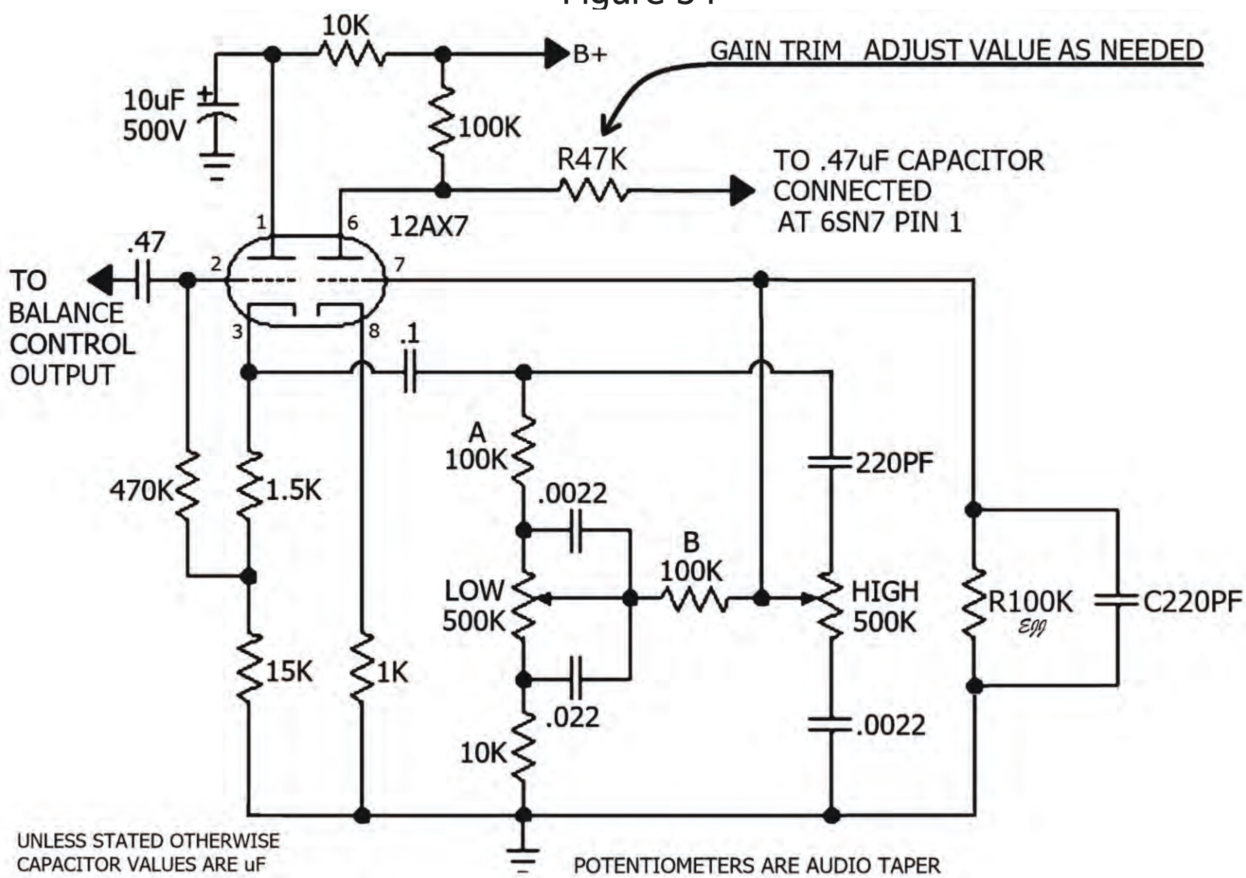
• Input Amplifier

12AX7 Input Amplifier

The 12AX7 input amplifier circuit in Figure 34 is based on a 1961 RCA tube manual circuit. It is a classic circuit that works well as a general-purpose low and high-end tone control.

The circuit as shown has very little gain. The input triode unit is a no-gain cathode follower. The second triode unit does have voltage gain, but the gain is used to make up for the gain lost through the tone control circuits.

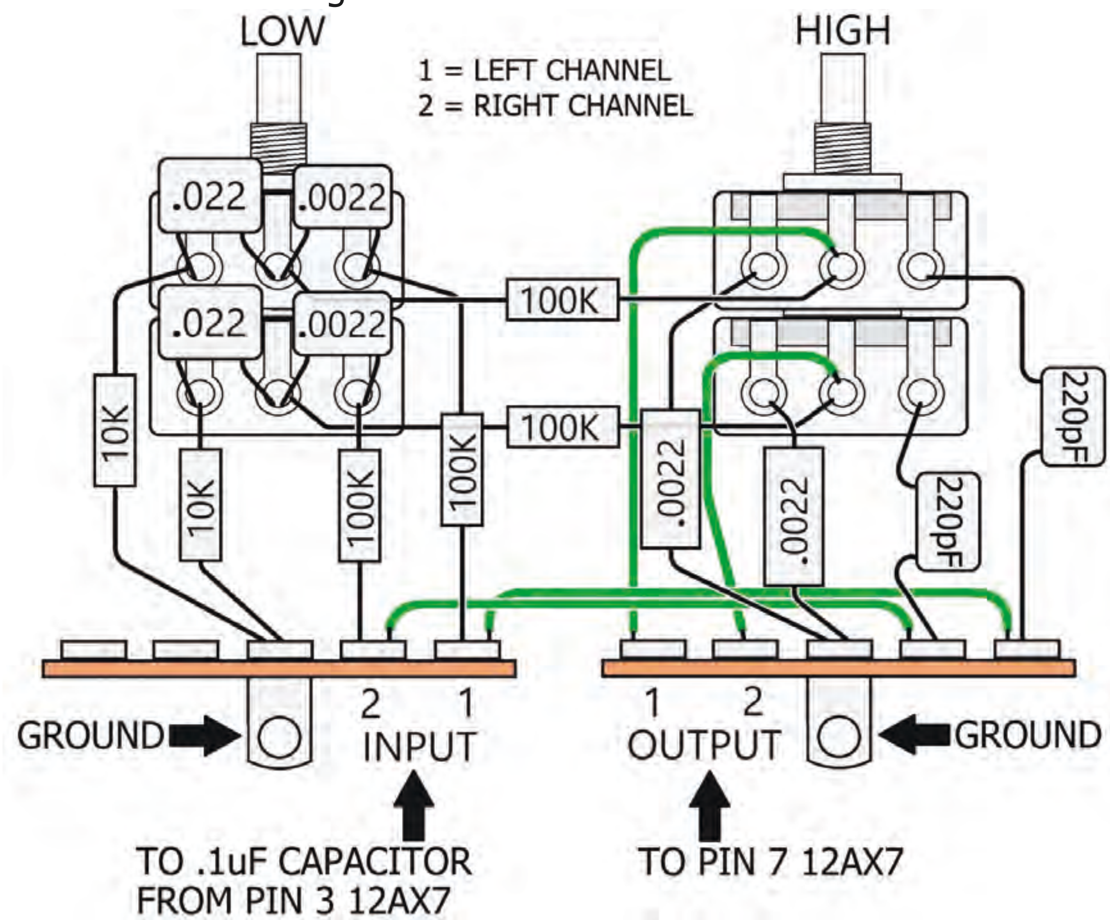
Figure 34



The cathode follower input is a high impedance to low impedance circuit. This isolates the input level controls from the tone control circuits, reducing interaction between the level controls and tone controls. The resistance of the 500K tone control potentiometers plus the two 100K resistors (A & B) act to reduce capacitance reactance of capacitors in the circuit, reducing phase and frequency response errors. R47K is used to adjust the gain of the input amplifier and its value can be adjusted as needed.

The tone control potentiometers can be pre-wired on the bench. The wiring layout in Figure 35 illustrates how the tone control potentiometers are wired. This layout should eliminate any confusion as to how the controls are wired. There is some flexibility in how the terminal strip connections are made. The terminal strip connections do not have to be laid out exactly as shown in Figure 35. Just be sure that the 100K resistors are connected to the 220 pF capacitors at a terminal strip near the tone controls.

Figure 35 - Tone Control Circuit



R100K and C220 pF in Figure 34 are best located at pin 7 of the 12AX7s. The capacitors on the low-frequency tone control are multilayer ceramic-type capacitors with a C0G/NP0 dielectric. The 220 pF capacitors are silver mica types. The high frequency tone control .0022 uF capacitors are film type capacitors. The 100K and 10K resistors plus the 220 pF and .0022 uF capacitors require long leads. You might consider these components with leads that are at least 1 1/2 inches (3.8 centimeters) long. The resistors can be 1-watt or 2-watt metal film type.

Tubing on resistors and capacitor leads helps to prevent short circuits. Leads that connect to ground do not require tubing.

Normally, tone controls are positioned on a front panel so that the low-end adjustment is to the left and the high-end adjustment is to the right of the low adjustment. If you use the layout in Figure 35, and you mount the potentiometers from the inside of the chassis to the front panel as shown in this amplifier project, they should be properly positioned.

Hookup wire for shorter lengths of audio wiring is OK. But, for longer lengths, shielded wire should be used to reduce noise pickup. Since the input jack wiring runs under all the front panel controls, the inputs must be wired first before completing the tone control, balance and volume control wiring. To reduce noise pickup, shielded cable must be used on the longer input wires.

For this project, Gavitt shielded wire is used. The shield on Gavitt wire is braided with a cloth-insulated tinned inner copper conductor. It holds its shape and will stay in place. However, because the shield is bare (uninsulated), it is important that the shield does not cause a short circuit.

A ground buss wire added over the 12AX7 input amplifier socket provides convenient grounding points. See Figure 43. The .47 uF filament bypass capacitors are connected to the ground buss wire.

As with any point-to-point wiring, the wiring process of the input amplifier is to primarily follow the circuit drawing. Since the space around the 12AX7 socket is tight, components are placed with care, and leads should be separated enough to prevent them touching each other. See Figure 43 for an example of component placement. Wiring the 12AX7 socket follows the same wiring method as the 6L6GC and 6SN7 sockets.

Be careful while soldering the terminals of the 12AX7 sockets. If you hold the soldering iron on a terminal too long, solder may flow into the pin contact hole preventing tube pins from being inserted into the socket. If solder should flow into a socket pin contact hole, you will need to position the chassis such that the terminal is facing down (pin contact hole facing up). Then, hold a hot soldering iron to the terminal and let the terminal get hot enough that gravity pulls the solder out of the pin contact hole.

• Final Assembly

Inputs, Tone, Balance, & Volume Controls

Because the wires either connect or run under the front panel controls, wiring associated with the rear panel input jacks must be wired first. These wires are shielded to avoid noise pickup. A ground buss wire is added and soldered across the input jack ground lugs. The input wiring shields are connected at only one end, to the ground buss wire. See Figure 36.

Figure 36

All the front panel potentiometers are dual units, separate potentiometers operated by a single shaft. To keep the left and right channel wiring in proper order, all potentiometer units closest to the front panel are wired for the left channel audio. All the potentiometer units farthest from the front panel are wired for the right channel audio.

Each input level control potentiometer has a terminal strip positioned below where each potentiometer mounts to the front panel. There are two terminals available for each potentiometer. The terminal closest to the front panel will be for the left channel input jack. The terminal farthest from the front panel will be for the right channel input jack. The shielded wires for the rear panel left channel input jacks are wired first.

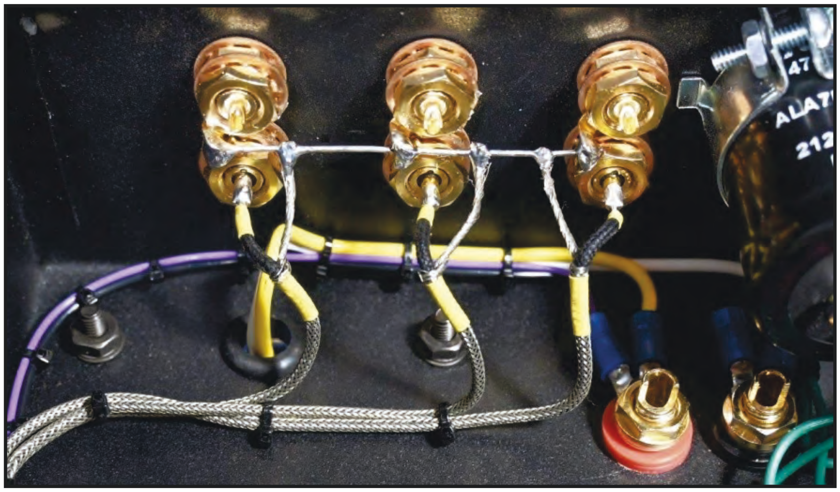
Input jack one, left-channel, is wired to the input-one level-control terminal strip terminal closest to the front panel.

Input jack two, left-channel, is wired to the input-two level-control terminal strip terminal closest to the front panel.

Input jack three, left-channel, is wired to the input-three level-control terminal strip terminal closest to the front panel. See figures 37 and 38.

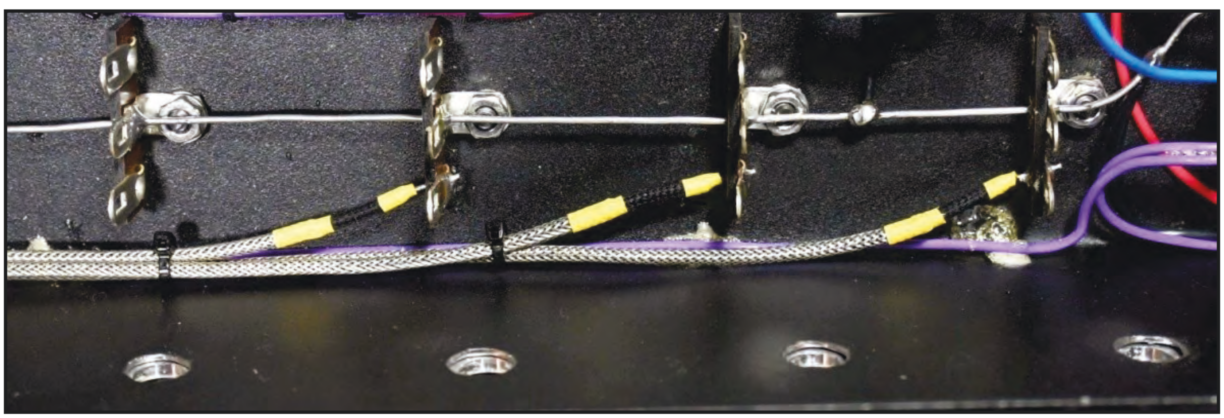
Looking at the chassis from the bottom, the left channel input jacks are the jacks closest to the chassis' top side. See Figure 37.

Figure 37



If you look closely at Figure 38, you can see that the left channel input jack shielded wires that go to the input level control terminal strips use the terminal rivet hole to solder the inner conductor.

Figure 38



Although not absolutely required, yellow shrink tubing is used to dress up the ends of the wire. The tubing also keeps the cloth insulation of the inner conductor from fraying. Using heat-shrink tubing requires the use of a heat gun. A heat gun that produces a small focused heat similar to the Weller #6966C heat gun works best.

The right channel input wires are wired in the same manner as the left channel input wires except that they run from the right channel input jacks to the right channel terminal strip terminals. See figure 39.

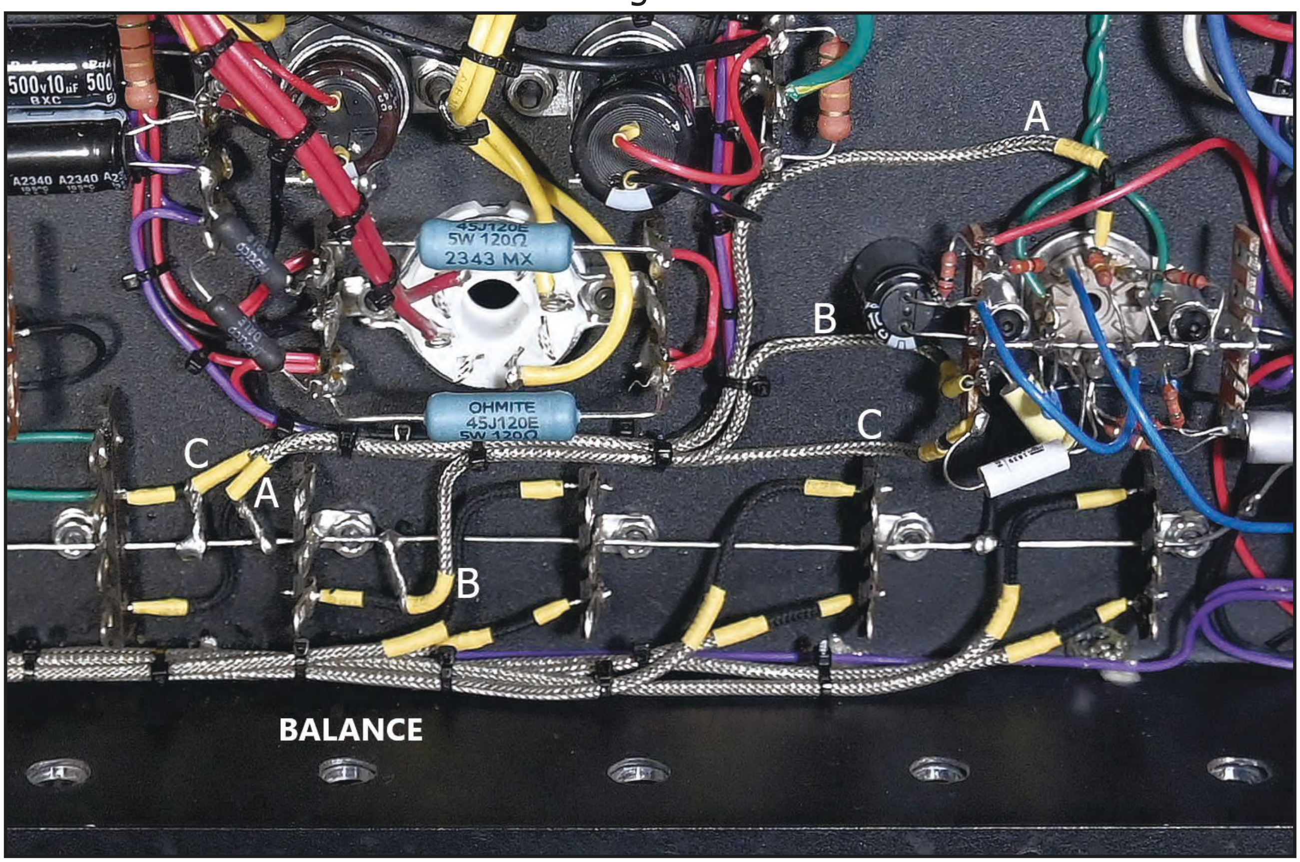
The input amplifier wiring is sensitive to hum and noise pickup. Shielded wires are used on the longer signal wires associated with the input amplifier. Besides the input jack wiring to the input level controls, it includes longer wires that interconnect between the input level controls, balance and tone controls to the input amplifier. Figure 39 is an example of three shielded wires.

Shielded wire "A" connects from the terminal for the left channel tone control output to the left channel 12AX7 input amplifier pin 7.

Shielded wire "B" connects from the balance control left channel terminal strip to the left channel input .47 uF capacitor connected to the 12AX7 pin 2.

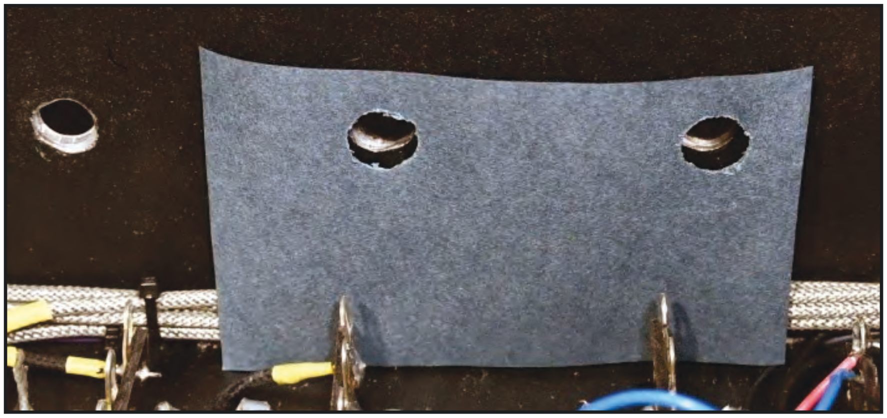
Shielded wire C connects from the left channel tone control input terminal to the left channel .1 uF capacitor connected to the 12AX7 pin 3.

Fig 39



A strip of insulating fish paper is cut with two holes that fit the front panel holes used for the tone controls. The tone controls will hold the fish paper in place. The fish paper will hold the shielded wires in place. This is a precaution against gravity causing the wires to sag over time. See Figure 40.

Figure 40



If you did not pre-wire the tone controls, wire the capacitors, but not soldering, onto the low frequency tone control will make wiring the tone control potentiometer terminals easier. Follow Figure 35 on page 178.

Mounting Front Panel Controls

The insulating fish paper and tone controls are mounted on the front panel with low and high frequency controls in the proper front panel holes. The input amplifiers and tone controls are wired following circuit drawings (e.g., on pages 177 and 178). To view the finished input amplifier and tone control wiring, see Figure 43 on page 185.

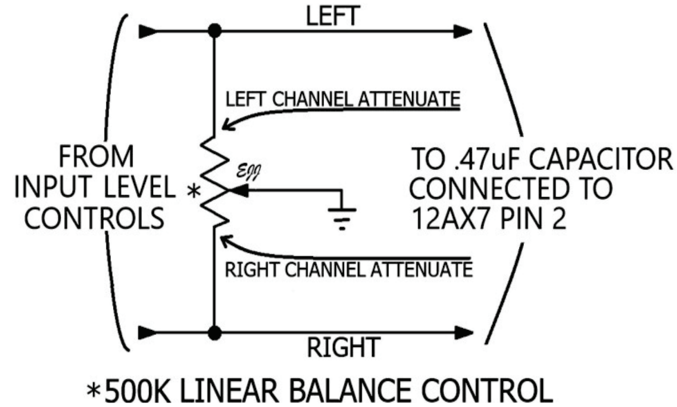
At this point, both channels of the amplifier should be wired from the 12AX7 input amplifier, at the .47 uF capacitor connected to the 12AX7 pin 2, to the speaker output.

This is a good time to check wiring connections against the circuit drawings. Be certain that the left and right channels did not get reversed at some point.

Balance Control

The circuit in Figure 41 is a basic balance control. The 500K ohm balance control has a linear taper providing equal resistance change through full rotation. One side of the potentiometer connects to the left channel audio and the other side connects to the right channel audio. The center terminal is the rotating wiper that connects to ground. The balance control works by placing an adjustable 0 to 500K ohm resistance load on each channel. In the center position, there is a 250K load on each channel.

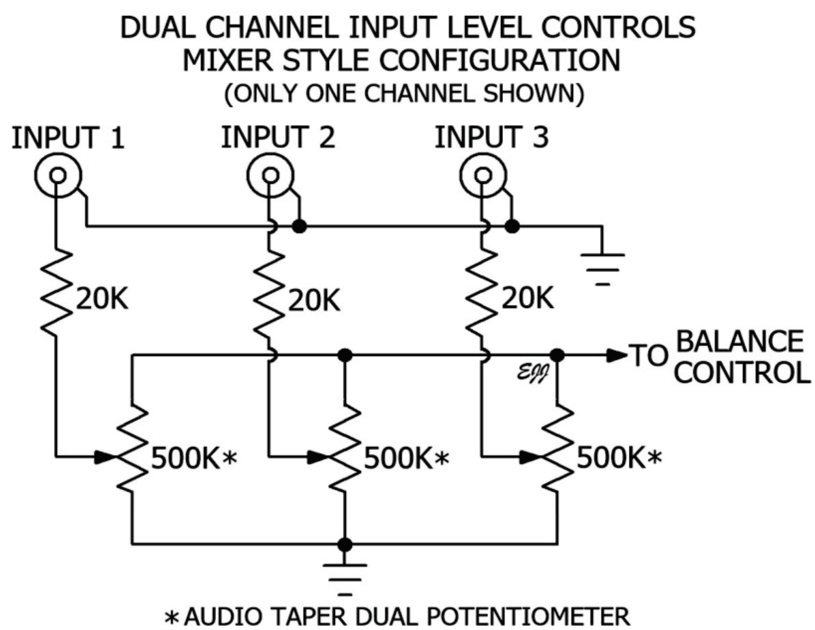
Figure 41



The balance control is mounted into the front panel. When the balance control is rotated to the right, the left channel is attenuated. When rotated to the left, the right channel is attenuated. A wire connects the left channel attenuate terminal of the balance control to the left channel amplifier input. A wire connects from the balance control right channel attenuate terminal to the right channel amplifier input. The center terminal of the balance pot connects to ground. For longer wire lengths, shielded wire should be used. First, connect the balance control center terminal to ground. Using a multimeter's ohm scale, figure out which balance control terminal goes to ground (least resistance) when rotated to the left. Connect that terminal to the right channel .47 uF input capacitor, 12AX7 pin 2. Connect the other balance control terminal to the left channel .47uF input capacitor. See Figure 43.

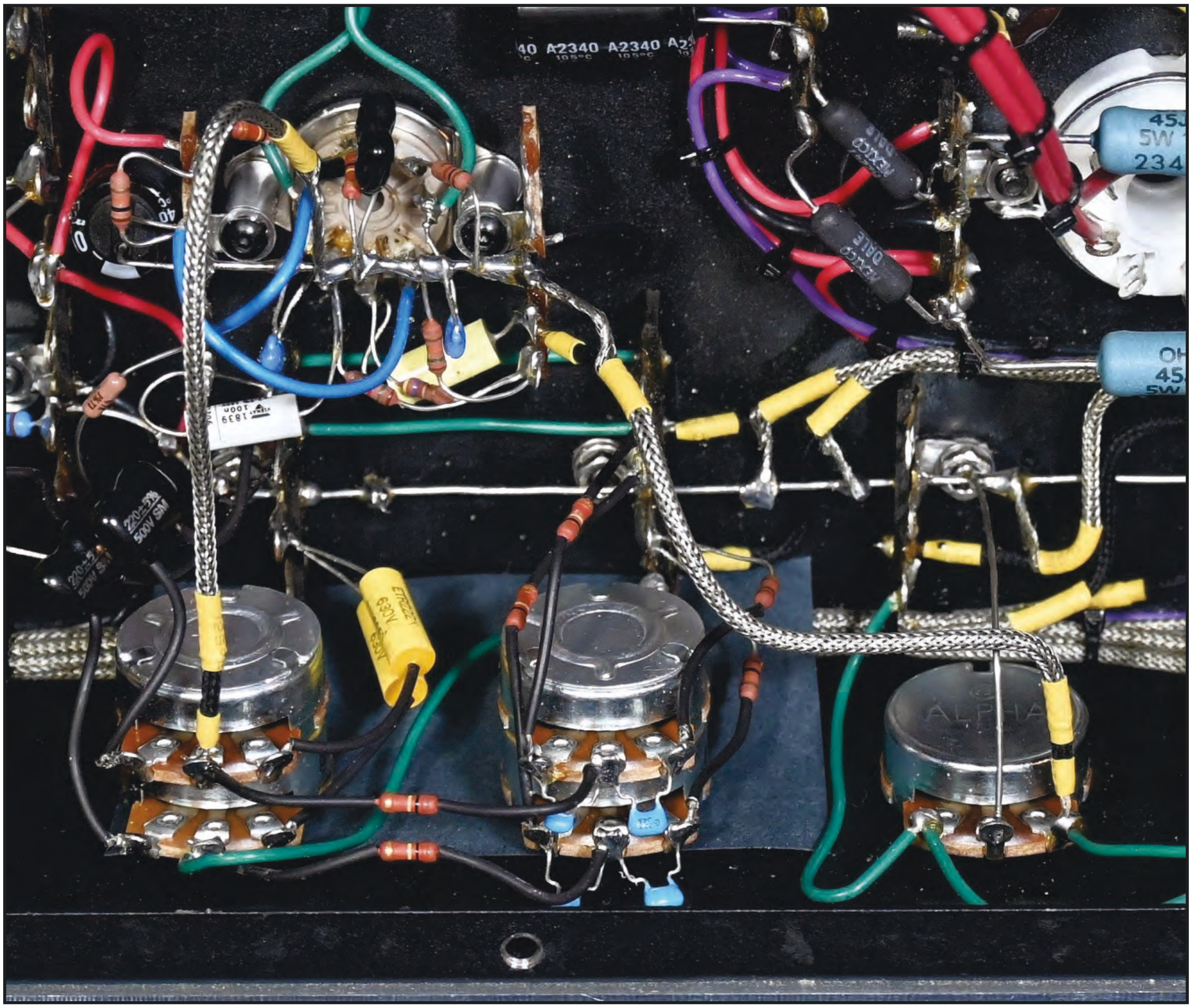
The input level controls use a mixer configuration where each input has its own level control. The input level controls connect to the balance control.

Figure 42



In Figure 42, the 500K ohm level controls are wired for a mix buss resistance of about 167K ohms (500K / 3). When connected to the balance control, the mix buss resistance will be 167K in parallel with 250K, about 100K ohms with the balance control in the center of rotation.

Figure 43

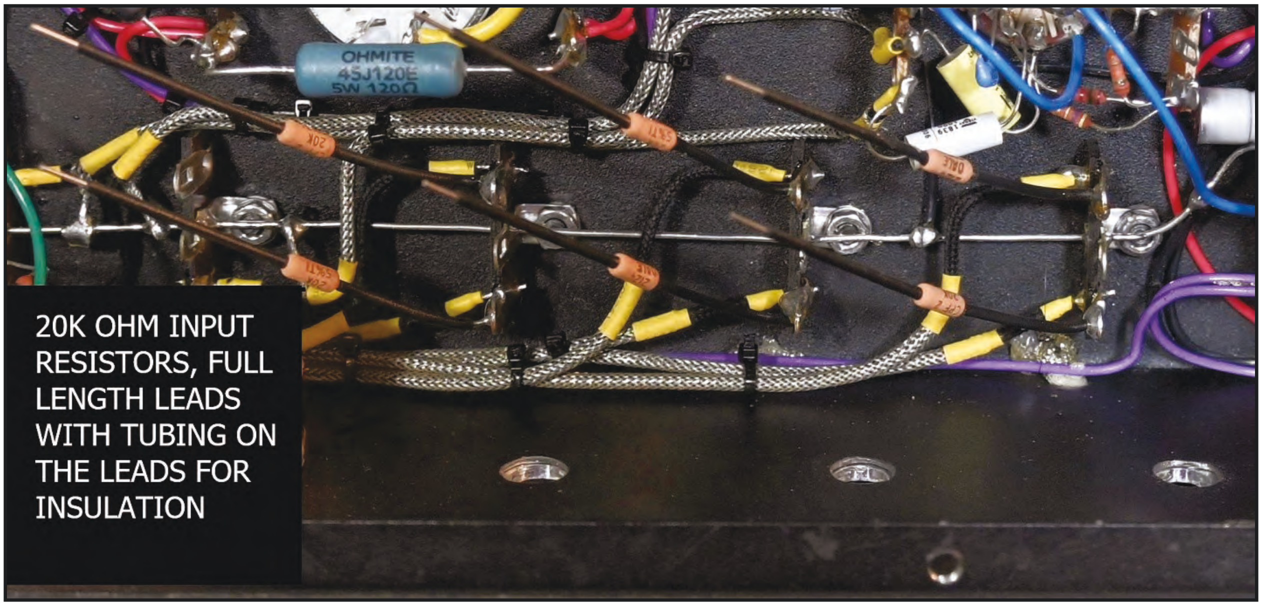


The 20K-ohm resistors provide some isolation between inputs. Also, when a level control is set to the full off position, there is a 20K load placed on the input source rather than a dead short.

Metal film 2-watt 20K-ohm resistors are used. These resistors need to have long leads. The two-watt rating has heavier gauge leads that better hold the resistors in position. Dale brand resistors were used for the input resistors. Tubing is placed on the resistor leads to prevent circuit shorts.

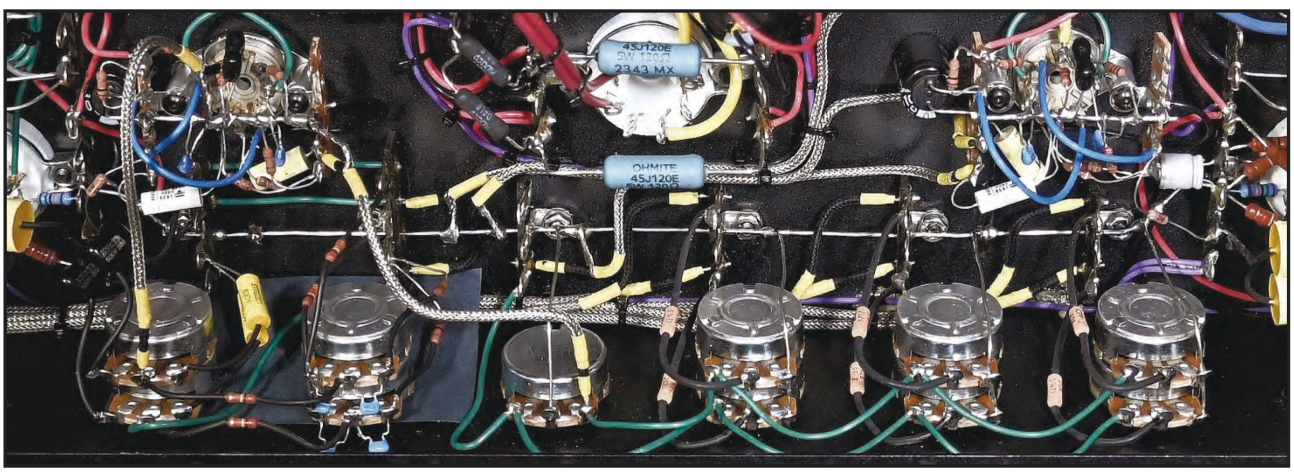
The 20K-ohm resistors need to be connected to the terminal strips below the input level controls before mounting the level controls to the front panel. See Figure 44. Figure 45 shows the front panel controls installed and wired.

Figure 44



The front panel input level control potentiometers are mounted and wired.

Figure 45

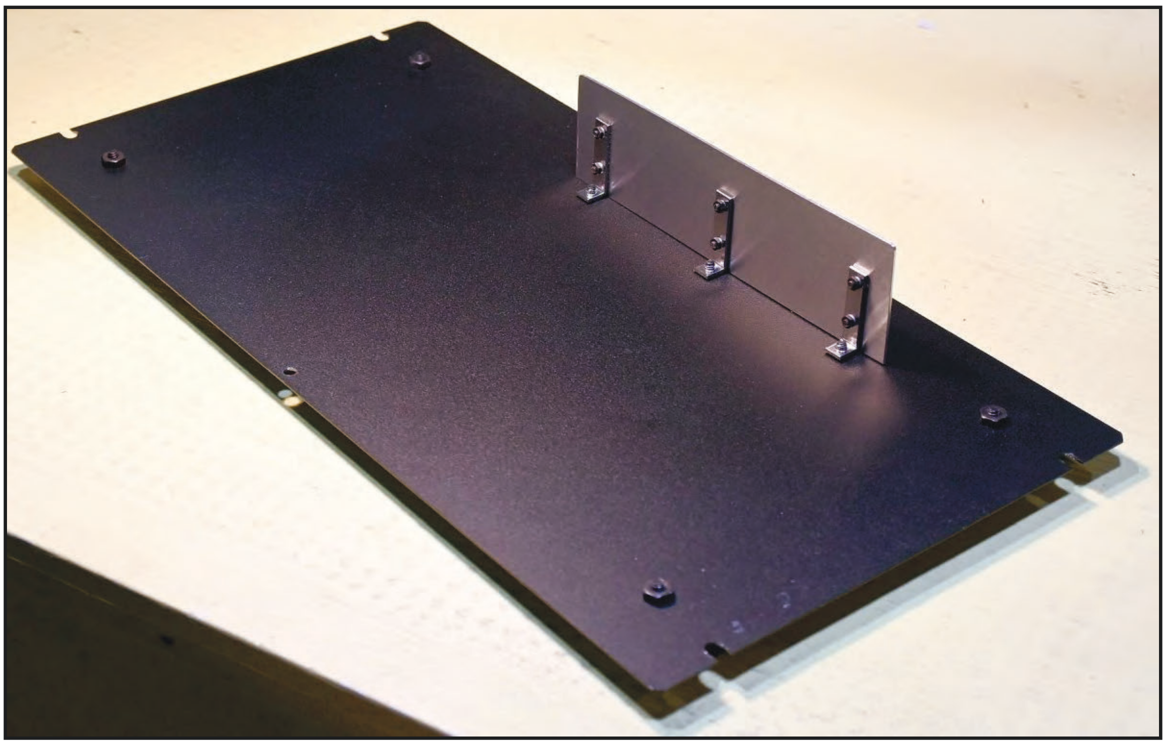


The wiring for the input mix buss uses regular hookup wiring connected from input level 1 control to input level control 2 to input level control 3, then to the balance control. Using regular hookup wire opens the possibility of hum and noise pickup. However, connecting short lengths of shielded wire would be tedious and there would still be some open points for noise pickup. Instead, a shield attached to the bottom plate will be positioned close to the input level controls and the balance control providing shielding.

The shield is a piece of cut aluminum attached to the bottom plate by three steel L brackets. See Figure 46. Purchasing an extra aluminum chassis bottom plate is a good resource for making custom chassis components.

When the bottom plate is secured to the chassis, the shield is positioned right behind the three input controls and the balance control. The shield L brackets have internal tooth lock washers between the brackets and the bottom panel. The lock washers cut through the paint, providing a good ground connection to the shield. The screws for securing the bottom plate to the chassis are tightened sufficiently to score the paint. This provides plenty of ground points to the bottom plate from the seven mounting screws.

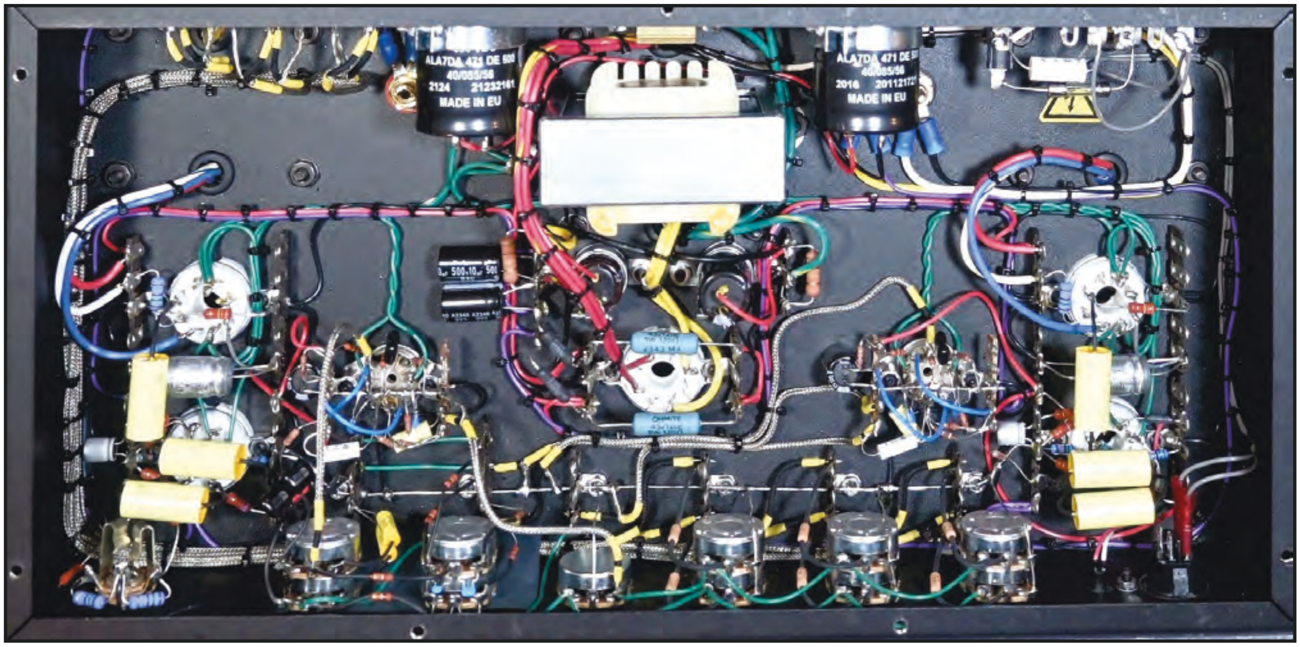
Figure 46



Taking on such a project, as presented here, may seem challenging, requiring full use of your abilities and resources. To some extent, this is true. This is not a weekend project. A project like this for the novice may take a few months to complete.

If you are working on a tight budget, you can purchase components and tools over time until you have what you need to fabricate a chassis. You can postpone some expense by not ordering tubes until you are ready to conduct power supply tests.

Figure 47, the amplifier completely wired.



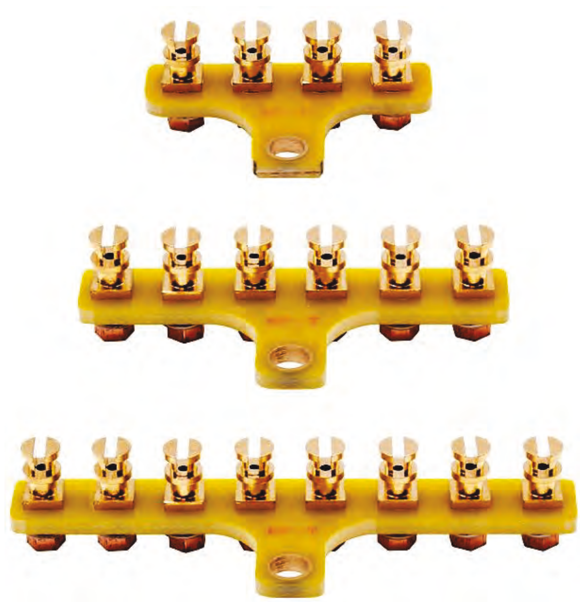
Notes:

The amplifier was built using some components that were on hand, including the power transformer, filter choke, output transformers and chassis. The engraved plates were custom-made for this project.

The amplifier fits on a shelf next to a turntable. A chassis of the same width, but deeper, would have provided more room in the chassis for wiring and still fit on the shelf; something to keep in mind when laying out a chassis.

Standard size turret strips, also known as terminal boards, were not used for this project. Besides taking up a lot of room, turret strips spread out wiring, providing more chance of hum and noise pickup. You might consider using small turret strips like those shown in Figure 48. They mount next to a tube socket using the screws that secure the tube socket. Close to the style of traditional terminal strips, they keep components near the tube socket.

Figure 48



Although carbon composition resistors can withstand a current surge better, their resistance value is prone to change over time. Metal film resistors are more stable, but may fail under a current surge. For better current surge protection, metal film resistor wattage should be generously overrated. For example, a two-watt metal film resistor is about the same physical size as a half-watt carbon composition resistor, but handles more current.

Film capacitors with a polypropylene dielectric provide stability and good performance. Also, ceramic capacitors should specify a C0G/NP0 dielectric.

For this project, a 5U4 rectifier tube was selected as an example of a vacuum tube rectifier. Solid state 1N4007 rectifiers could also be used. Solid state rectifiers have virtually no voltage drop and a transformer with a lower high-voltage winding can be used. Read pages 79 through page 84.

Operational Testing

As of this date, 01/30/2025, the amplifier has been in daily use for about a month. All things considered, the amplifier sounds pretty good.

The 330-ohm R4 resistor used in the aux jack output circuit was changed to 750 ohms to reduce background noise.

One problem I ran into was interference from a T-Mobile internet box. The box was about two feet away from the amplifier and the 12AX7s were picking up data interference. I was able to cut the interference down to a whisper by placing tube shields over the 12AX7s. I really did not like spoiling the look of the amplifier, so I moved the T-Mobile box to the other side of the basement. Now I can see the friendly glow of the 12AX7s.

EJ Jurich

Projects

Building From Scratch

The following sections provide circuit drawings including component values for a few projects. These projects will require component placement, drilling a chassis and soldering. All the projects use point-to-point wiring. If you are new at this, the best advice is to take your time and work carefully.

First-time project builders will find working with an aluminum chassis to be far easier than a steel chassis. Besides aluminum being easier to drill and punch holes, aluminum is a better conductor than steel. However, for projects that include heavy transformers, the 30-watt monoblock amplifier, for example, a steel chassis may be the better choice for strength.

Soldering is much easier on a chassis with plenty of room. You can get an idea of the size of chassis you need by laying out the parts on a table, positioning transformers and tube sockets. When laying out the chassis for drilling, you should not place sensitive pre-amplifier stages or inputs near the power supply or primary AC wiring. This will help reduce hum pickup. Using top-mount tube sockets will help cover imperfect chassis socket holes, improving the appearance of the finished project.

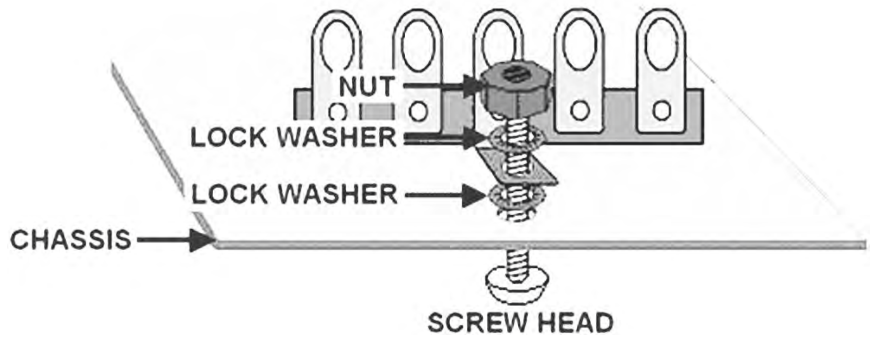
It is a good idea to run all the wiring first, positioning wires against the chassis. Other components such as resistors and capacitors are positioned over the wiring. Do not solder terminals until all wires and components that go into a terminal are in place.

Do not keep a soldering iron on a tube socket terminal for too long. The molten solder may travel up into the pin contact area where the tube pins plug in, making it impossible to insert a tube. In the event you have solder travel into a tube socket pin contact, read how to clear solder out of tube socket pin contacts on the bottom of page 179.

Only use electronic solder with rosin core flux. Do not use acid flux solder or water-soluble flux solder. Acid flux residue will eat into wiring and water-soluble flux residue grows a conductive fungus over time. Due to reliability issues, it is wise to avoid lead-free solder. Kester 44 solder is recommended.

When mounting terminal strips, use two lock washers as shown in Figure 1.

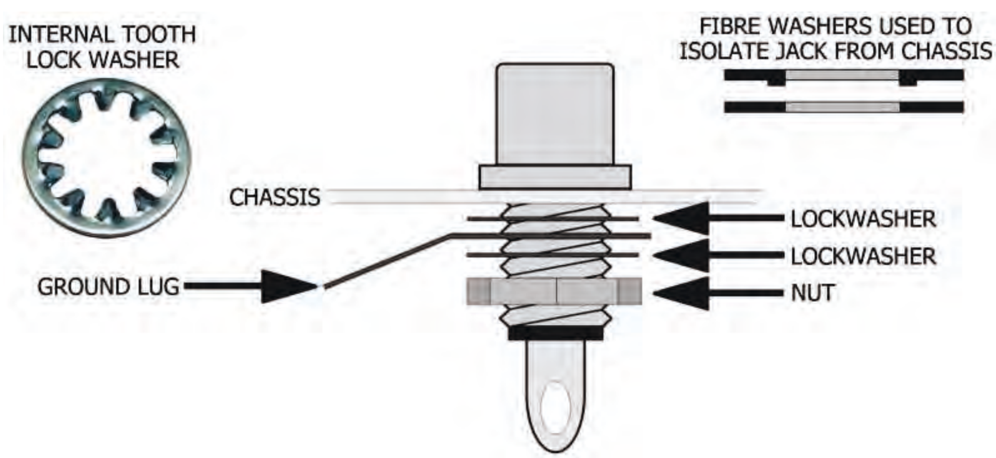
Figure 1



The lock washer between the mounting tab and chassis will help keep the tab from twisting when tightening the nut. It also insures good contact between the tab ground terminal and chassis.

For RCA jacks that mount in a 1/4-inch hole, use standard 1/4-inch internal tooth lock washers as shown in Figure 2. The lock washers will help prevent the jack from coming loose as connectors are plugged in and out of the jack.

Figure 2



If you need to isolate the jack from the chassis ground, there are Keystone part #3135 & #4711 fiber washers with 1/4-inch holes where a standard RCA jack will fit. One of the fiber washers has a lip to keep the washers centered in the chassis hole. Fiber washers require a larger chassis hole.

Project Power Supply

The following power supply is good for low current projects where only voltage amplifier stages are used. The supply can be used to provide filament and high voltage for the buffer line amplifier on page 195 or the turntable Pre-Amplifier on page 199.

Power supply component layout is not critical; just follow a few general suggestions. Mount the fuse holder and AC power cord connector at the rear of the chassis (always fuse your projects). The power switch is mounted on the front of the chassis. Transformers and large filtering capacitors are normally mounted on the top of the chassis. The wires are fed through holes into the chassis. Use rubber grommets on the transformer holes to prevent the chassis from pressing and cutting into the wires over time. To help reduce hum, keep power supply components fairly close to each other and as far from sensitive higher gain amplifying circuits as possible.

Figure 4

Large filtering capacitors can be mounted on the top side of the chassis using a mounting clamp. Selecting capacitors that have a diameter of 35mm will allow a Cornell Dubilier VR3A mounting clamp to fit around the capacitor. The capacitor is then mounted on top of the chassis over a 1 1/8 inch hole. This is the same size hole for many 8-pin octal tube sockets. If you do not have a 1 1/8 inch chassis punch, you can drill two holes large enough so the capacitor terminals feed through the chassis without touching the chassis. To prevent arcing, the chassis metal must be at least 1/8 inch away from the capacitor terminals, and remove any sharp edges from the holes.

Figure 5 on the next page is the power supply circuit. Figure 6 is a component layout drawing.

The power transformer specified in the parts list has a 115VAC or 120VAC primary. Other transformers may be substituted as long as the secondary high voltage is around 480VCT (240-0-240), 500VCT (250-0-250) would work, and is rated at about 40mA current. The filament voltage should be 6.3VCT @ 1 to 2 AMPS. The center tap on the 6.3 volt filament supply is important for reduced hum.

VCT = Volts Center Tapped

Figure 5

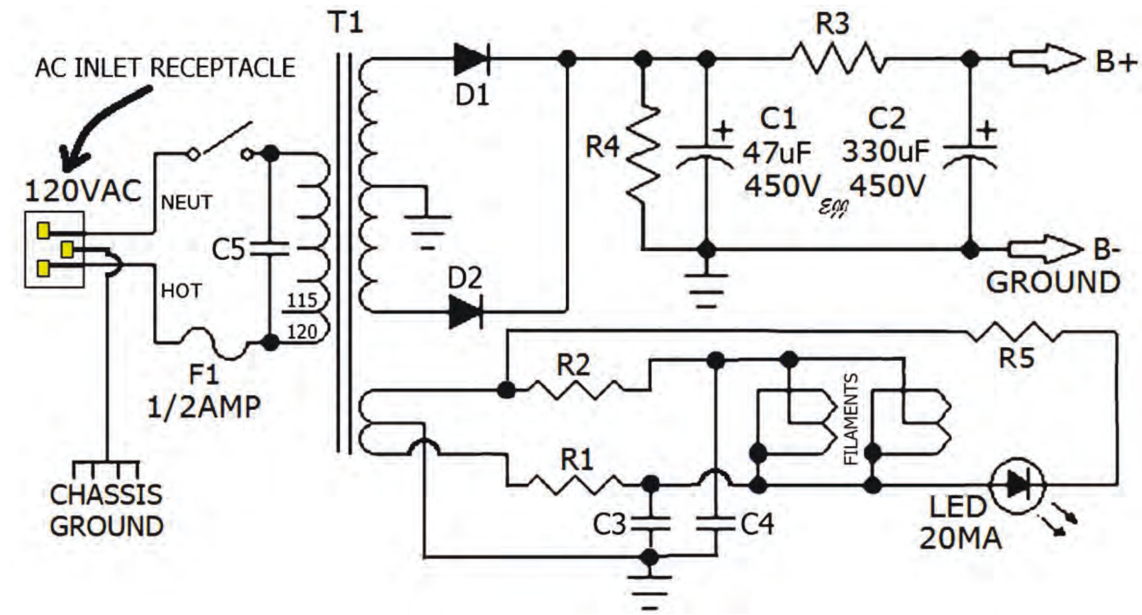
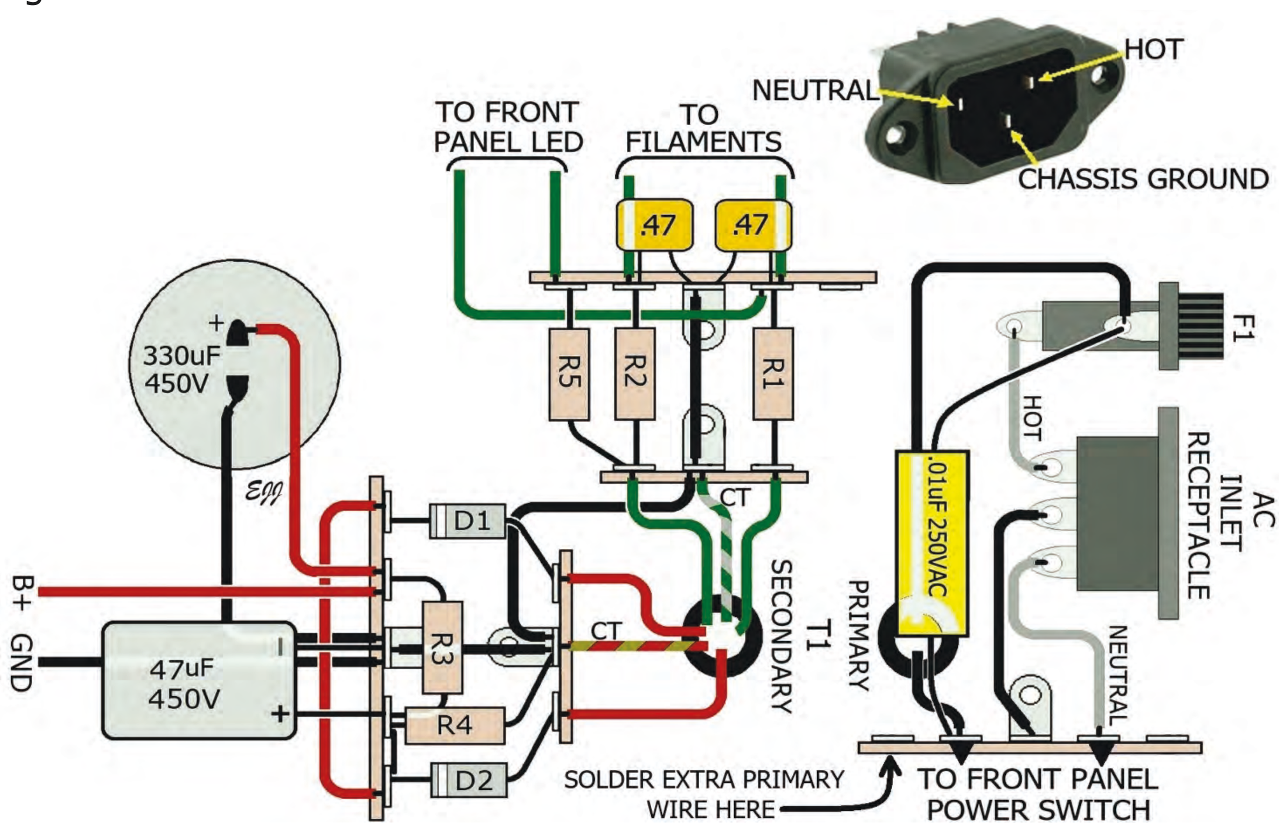
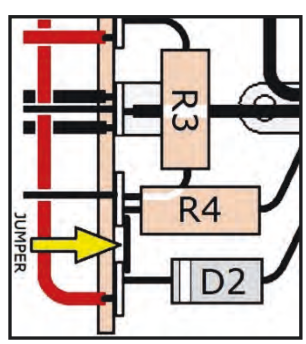


Figure 6





Note the jumper wire between R4 and D2. Be certain not to forget this jumper.

The dual voltage transformer primary extra wire can be soldered to a spare terminal as shown in Figure 6.

Project Power Supply

Parts List

(1) – T1, Power transformer, PT240 from Musical Power Supplies, Inc.
    480VCT (240-0-240) @ 40-mA, 6.3VCT @ 1-amp.
(1) – AC inlet receptacle
(1) – Removable power cord
(1) – Power switch
(1) – Fuse Holder
(1) – Fuse 1/2-amp slow blow (delayed)
(2) – D1 and D2 – 1N4007
(1) – C1 – 47 uF 450VDC capacitor radial leads
(1) – C2 – 330 uF 450VDC capacitor snap-in type terminals
    Must be 35mm diameter to fit VR3A mounting clamp
(1) – Cornell Dubilier VR3A mounting clamp for C2
(2) – C3 and C4 - .47 uF capacitor ceramic, TDK part # FG24X7S2A474KRT06
(1) – C5 .01 uF 250VAC capacitor, VISHAY part # F17733102000
(1) – Mounting clamp for 330uF capacitor
    Cornell Dubilier type VR3A
(2) – R1 and R2 = .05-ohm (50-mOhms) 3-watt wirewound
    (.1-ohm (100 mOhms) 3-watt wirewound with 2-amp filament supply)
(1) – R3 = 4.7K-ohm 3-watt resistor wirewound
(1) – R4 = 330K-ohm 3-watt resistor metal film rated at 750 volts
(1) – R5 = 470-ohm 2-watt resistor
(1) – LED power indicator light 20 mA, VCC part # 5100H5
(2) – Terminal strip, 3-terminal center terminal ground
(3) – Terminal strip, 5-terminal center terminal ground

With no load, the DC output voltage of the power supply will be about 340 volts DC. When loaded up to the maximum value of the power transformer, for example 40mA, the DC output will be about 300 volts.

It is good practice not to depend on the chassis as a common ground. All ground circuits should be wired together, including those soldered to a ground terminal on terminal strips. The exception is the AC power third prong safety ground which should connect directly to the chassis near the AC inlet receptacle.

Buffer Line Amplifier

The following is a project circuit to build a high-quality dual-channel vacuum tube buffer line amplifier adjustable from unity gain to 25 dB of gain. The input and output load impedance make the amplifier suitable for connecting between vacuum tube or solid state equipment.

Two tubes are used, a 12AX7 input voltage amplifier and a 12AU7 cathode follower output. The 12AX7 voltage amplifier stage does not use cathode bypass capacitors; this allows reduced distortion at higher audio levels. The 12AU7 with its higher current rating is well suited for cathode follower use; a 12BH7 in place of the 12AU7 could also be used.

This amplifier is useful for boosting the gain of low-output pre-amps to drive line level inputs or to provide a ‘tube sound’ in a solid state system.

There is a component layout drawing provided for the amplifier circuit that can be used as a guideline, or you can come up with your own layout. The component layout drawings are not drawn to scale. Use actual components as a template when drilling holes. Remember to space tube sockets and terminal strips such that there is plenty of room to fit and wire capacitors and resistors without crowding everything. Tubing on component leads will help prevent the leads from shorting to other components.

Power supply requirements
High Voltage B+ Supply – +250VDC to +350VDC @ 15 mA
Filament voltage – 6.3VCT @ 1 amp

The power transformer secondary current ratings must be rated for at least the value stated. A transformer with higher current ratings may be used, although voltages will be slightly higher. Care should be taken to make sure the filament voltage is not too high or else tube life will be shortened. The 6.3VAC filament winding must be center-tapped to avoid filament-induced hum problems.

NOTE: The 12AX7 and 12AU7 filaments each draw 0.3 amps for a total of 0.6 amps. Some tubes such as the 12BH7 draw 0.6 amps. A transformer with a one-amp filament winding should accommodate either combination of tubes.

Buffer Line Amplifier

Component list

(1) – 12AU7 OR 12BH7
(1) – 12AX7
(2) – 9-pin miniature tube socket
(2) – .1 uF @ 400VDC axial leads (film type capacitor)
(2) – .47 uF @ 400VDC axial leads (film type capacitor)
(2) – 2.2 uF @ 100VDC axial leads (film type capacitor)
(2) – 1K-ohm 1/2-watt resistor 5%
(2) – 10K-ohm 1/2-watt resistor 5%
(2) – 22K-ohm 1-watt resistor 5%
(2) – 100K-ohm 1/2-watt resistor 5%
(6) – 220K-ohm 1/2-watt resistor 5%
(2) – 470K-ohm 1/2-watt resistor 5%
(2) – 100K-ohm Potentiometer audio taper
(4) – RCA jacks (2 input, 2 output)
(4) – Terminal strip, 3-terminal center terminal ground

Wiring with 22 AWG wire is best. The maximum current rating of 22 AWG wire is 7 amps and can be used for all wiring in this project, including filament wiring.

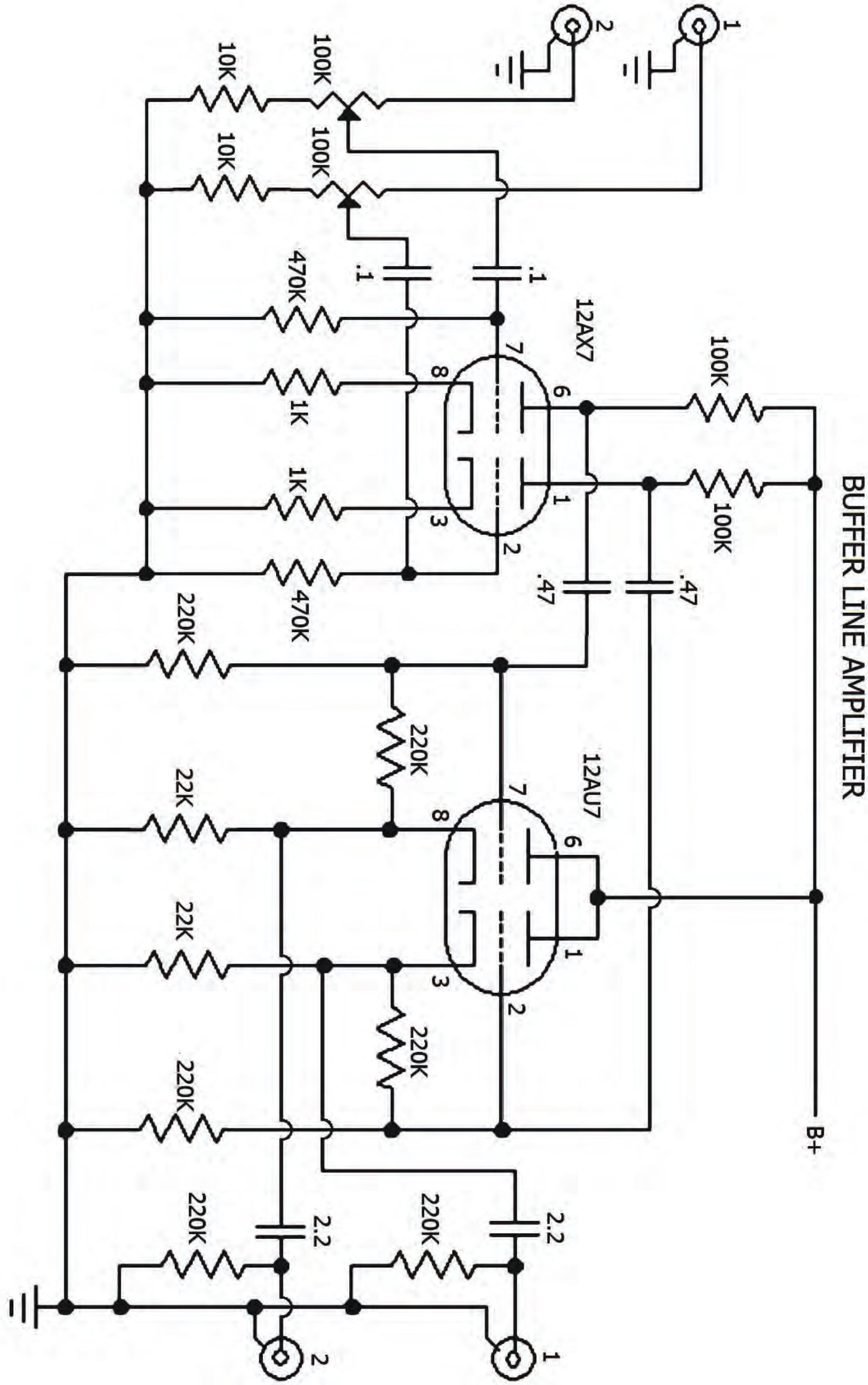
Be aware that wires with PTFE insulation may pose a health problem as some people and animals have an allergic reaction to PTFE.

When ordering 1/2-watt resistors, if you choose metal film type resistors, consider increasing the watt rating to 1 or 2 watts. The reason being that 1/2-watt metal film resistors are much smaller and may be awkward to wire onto terminals.

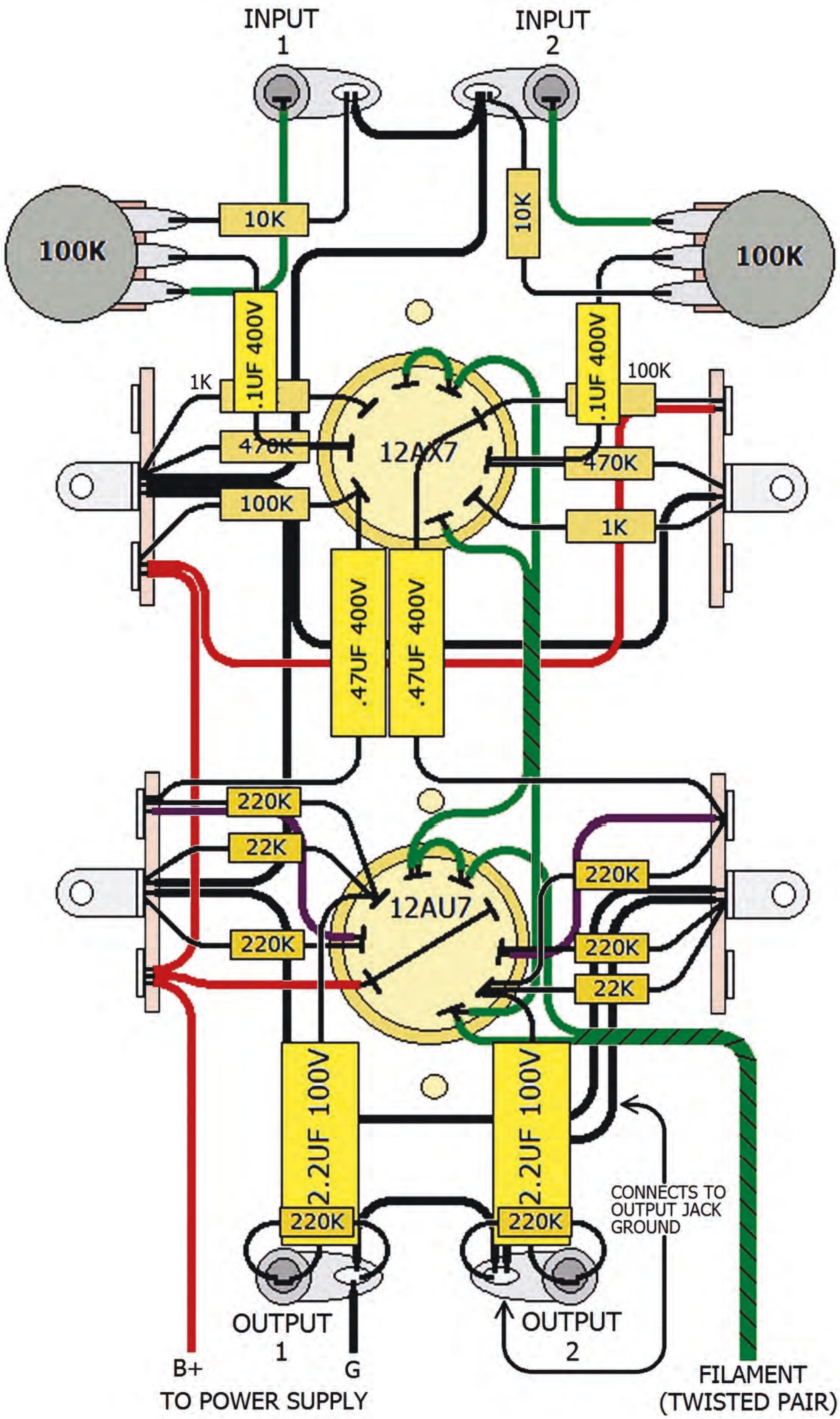
To allow individual level control of the channels, use separate potentiometers.
To allow simultaneous level control of the channels, use a dual-gang pot.
To allow full level (volume) off, replace the 10K resistors from each potentiometer terminal to ground with a wire.

Buffer Line Amplifier

Circuit drawing



Buffer Line Amplifier
Component layout guideline

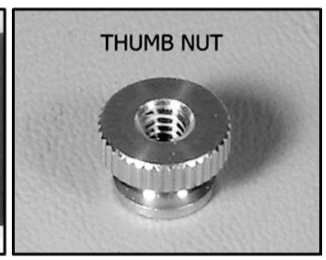


Turntable Pre-Amplifier

This is a vintage RCA two-stage turntable magnetic pickup pre-amplifier from the 1950s with RIAA equalization. The circuit uses a 12AX7 with enough voltage gain to provide about 0.4 volt output signal with the average magnetic pickup.

The standard input jack for a turntable is an RCA female. It helps prevent ground loops if the RCA input jack is isolated from (not touching) the chassis. There are chassis mount RCA female jacks available that come with isolation washers. When an isolated input jack is used, the ground wire from the jack should connect to the same ground point as the input grid R1 resistor.

Most turntables have a ground wire, you will need to provide a 6-32 screw and thumb nut next to or between the input jacks. A 5/8" long screw should work.



If more than two inches long, the wire to the tube grid needs to be shielded. Use a shielded wire and connect the shield wire to the input jack ground. Shrink tubing can be used to cover the exposed shielding on the cable ends.

There is a component layout drawing provided for the amplifier circuits that can be used as a guideline or you can come up with your own layout. The component layout drawings are not drawn to scale. Use actual components as a template when drilling holes.

To help reduce pre-amp hum pickup, avoid excessive lead lengths on pre-amplifier wiring. Keep the filament wiring as far as possible from the input pin-2 grid circuits. The power transformer filament winding must have a center tap to ground, or filament-induced hum will be a problem.

Turntable Pre-Amplifier

Power supply requirements

(Single channel, for dual-channel stereo double current loads)

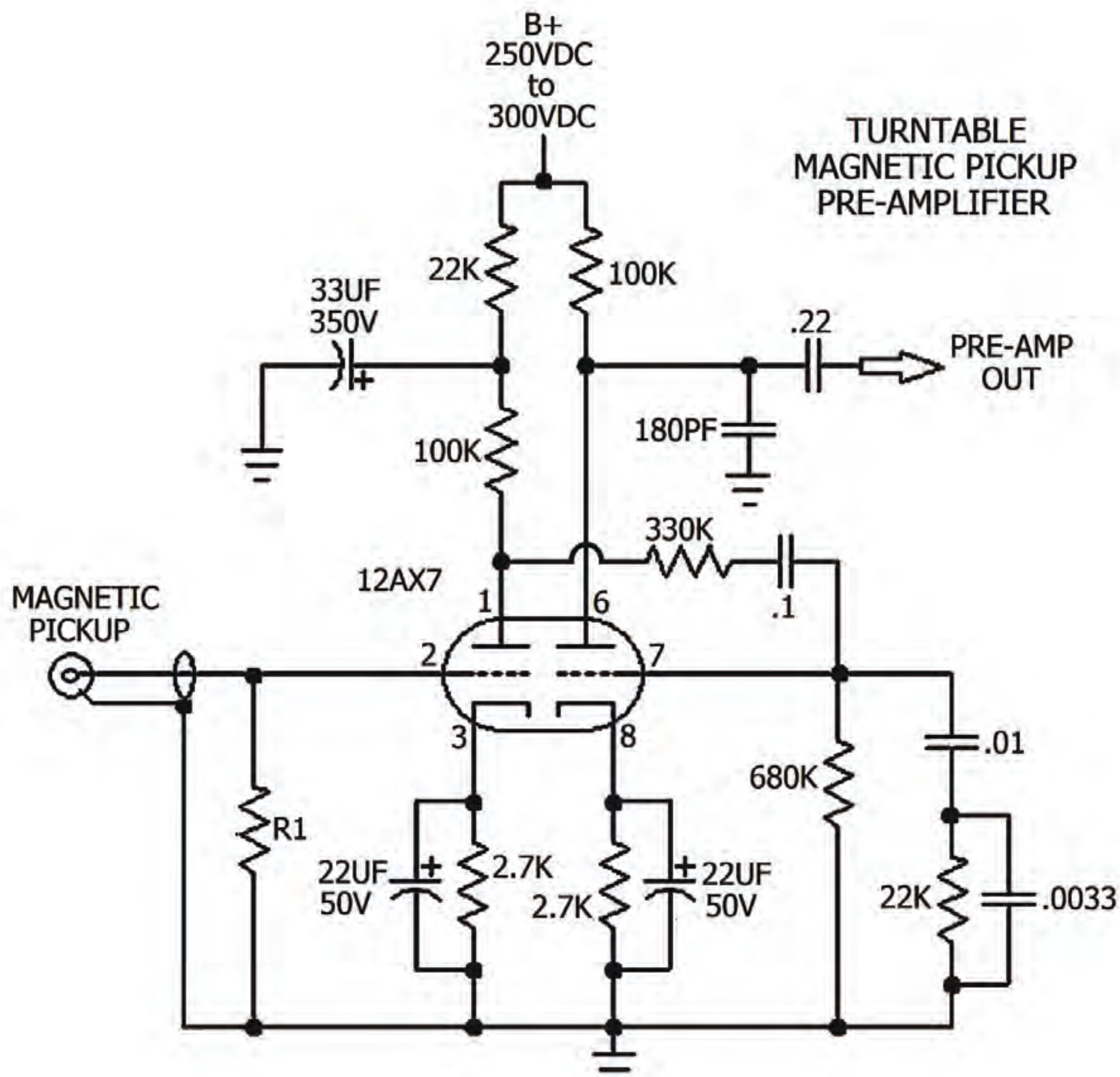
High Voltage B+ Supply – +250VDC to +300VDC @ 4 mA

Filament voltage – 6.3VCT @ 0.3 amps

Circuit drawing

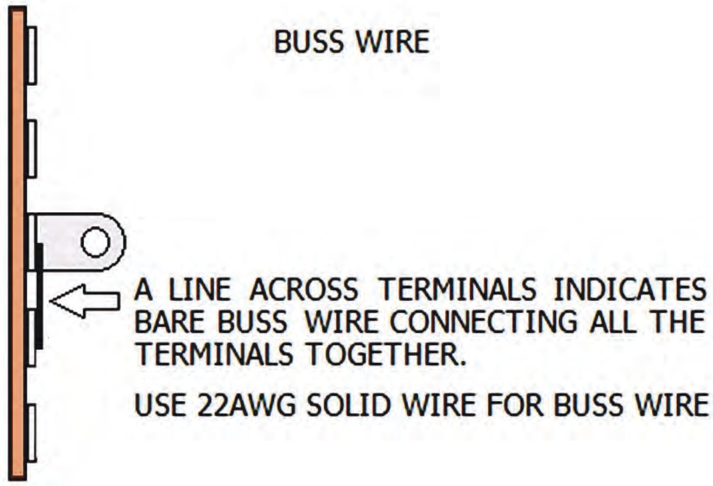
The circuit shown is a single channel.

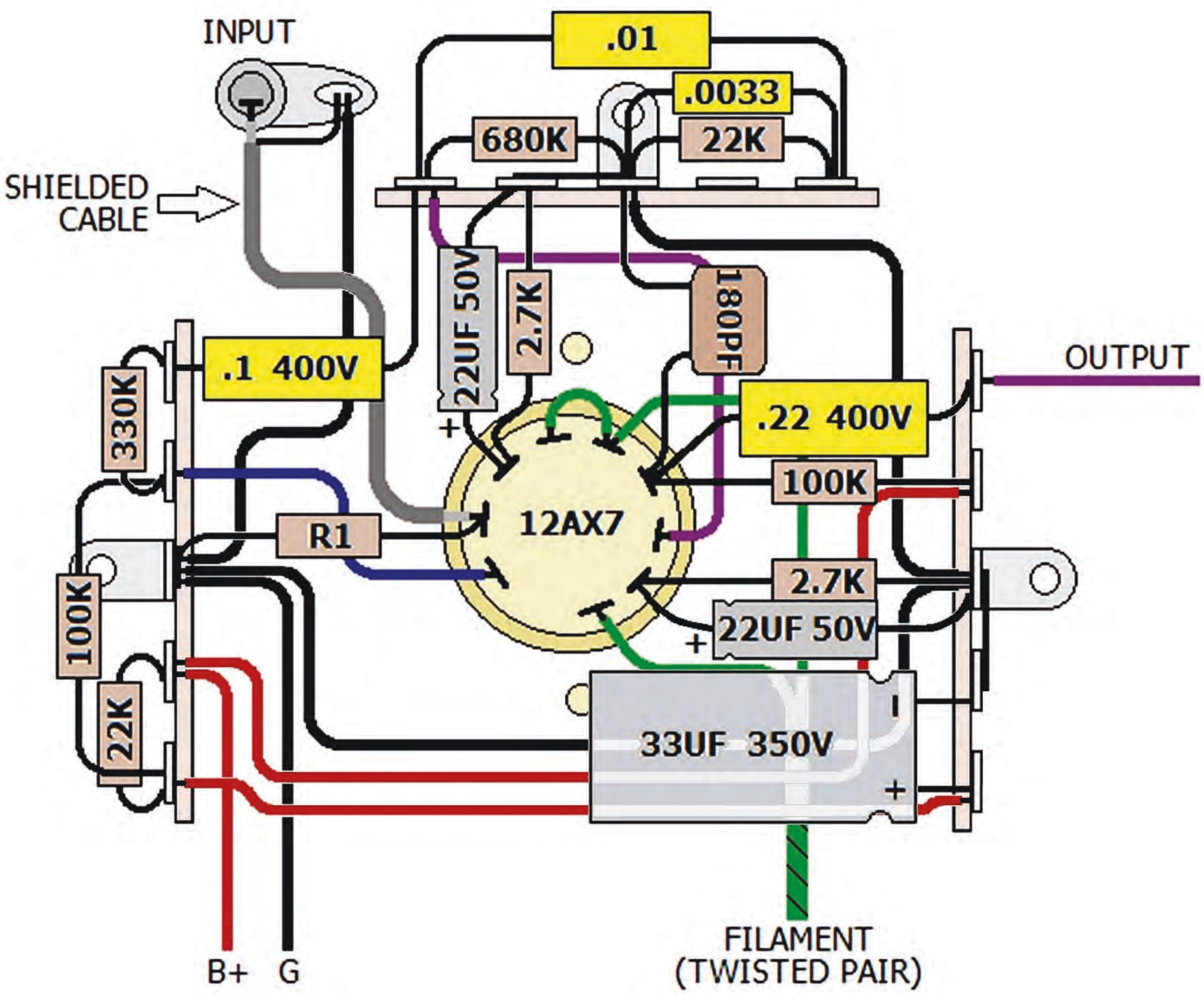
For dual-channel stereo you will need to build two circuits.



Consult magnetic pickup specifications for R1 value. If unknown, use 100K ohms.

Turntable Pre-Amplifier
Component layout guideline





Turntable Pre-Amplifier

Component list

Double quantities for dual channel stereo

(1) – 12AX7
(1) – 9 pin miniature tube socket
(2) – 2.7K-ohm 1/2-watt resistor 1%
(2) – 22K-ohm 1/2-watt resistor 1%
(2) – 100K-ohm 1/2-watt resistor 1%
(1) – 330K-ohm 1/2-watt resistor 1%
(1) – 680K-ohm 1/2-watt resistor 1%
(1) – R1 value depends on magnetic pickup
 if value is unknown, use 100K-ohm 1/2-watt 1%
(1) – 180PF mica capacitor
(1) – .0033 uF 400VDC or 630VDC capacitor axial leads
(1) – .01 uF 400VDC or 630VDC capacitor axial leads
(1) – .1 uF 400VDC capacitor axial leads
(1) – .22 uF 400VDC capacitor axial leads
(2) – 22 uF 50VDC capacitor axial leads
(1) – 33 uF 350VDC capacitor radial leads
(3) – Terminal strip, 5-terminal center terminal ground
(1) – RCA jack (or 2 if 1 input, 1 output)
 (RCA jack should have chassis isolation washers)

Wiring with 22 AWG wire is best. The maximum current rating of 22 AWG wire is 7 amps and can be used for all wiring in this project, including filament wiring.

Be aware that wires with PTFE insulation may pose a health problem as some people and animals have an allergic reaction to PTFE.

When ordering 1/2-watt resistors, if you choose metal film type resistors, consider increasing the watt rating to 1 or 2 watts. The reason being that 1/2-watt metal film resistors are much smaller and may be awkward to wire onto terminals.

6V6GTA/6L6GC 5-Watt Monoblock Amplifier

Output tubes that can be directly plugged in include the 6V6GTA, 6V6EH, 6V6S, 6L6GC, 5881 or 7581. The 6V6EH and the 6V6S are a custom version of the standard 6V6GTA except with higher maximum plate and screen voltages. Power output is about 5 watts, depending on output tube type.

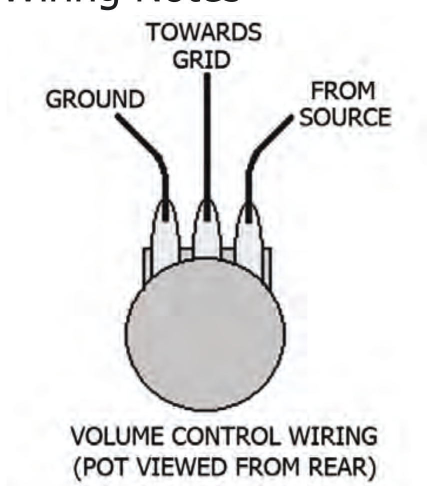
This is a basic single-ended class A amplifier operating ultra-linear using a screen tap primary output transformer. Older RCA tube manuals specify the maximum 6V6GTA plate voltage as 350VDC and screen voltage maximum as 315VDC. In an Ultra-Linear configuration, the screen can be at the same potential as the plate.

The circuit is self-biased, so there are no bias concerns. Input sensitivity is about 0.5 volts. The amplifier is single channel mono. For dual channel stereo, you will need to build two amplifiers.

The extra current draw of a 6L6GC/5881 will drop the B+ high voltage by about 20 volts as the load on the power supply increases.

There is a component layout drawing provided for the amplifier circuit that can be used as a guideline, or you can come up with your own layout. The component layout drawings are not to scale, use actual components as a template when drilling holes. Remember to space tube sockets and terminal strips to insure there is plenty of room to fit and wire capacitors and resistors without crowding everything. Tubing on component leads will help prevent the leads from shorting to other components.

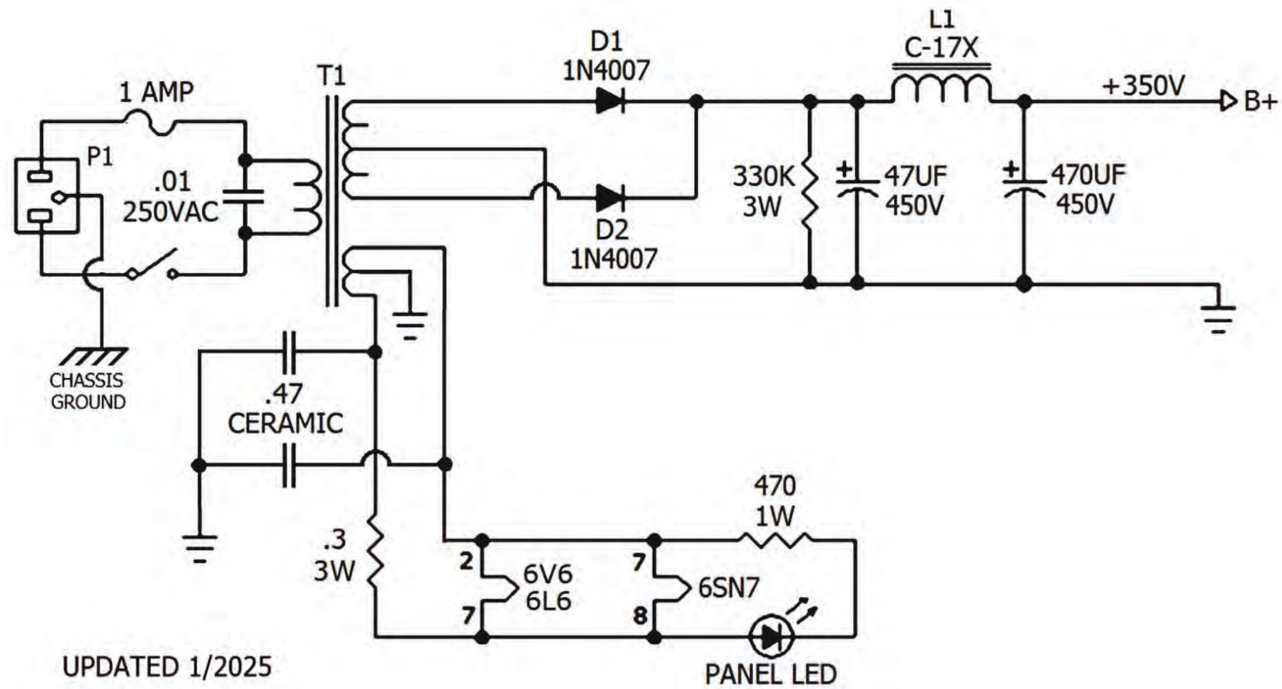
Wiring Notes



The correct way to wire a volume control is shown in the illustration. Potentiometers used for volume should have a logarithmic audio taper.

To check the negative feedback circuit, amplifier gain should drop slightly with the 1.5K feedback resistor connected to the output transformer secondary. If not, then the secondary wires need to be reversed.

6V6GTA/6L6GC Monoblock Amplifier
Power supply circuit drawing



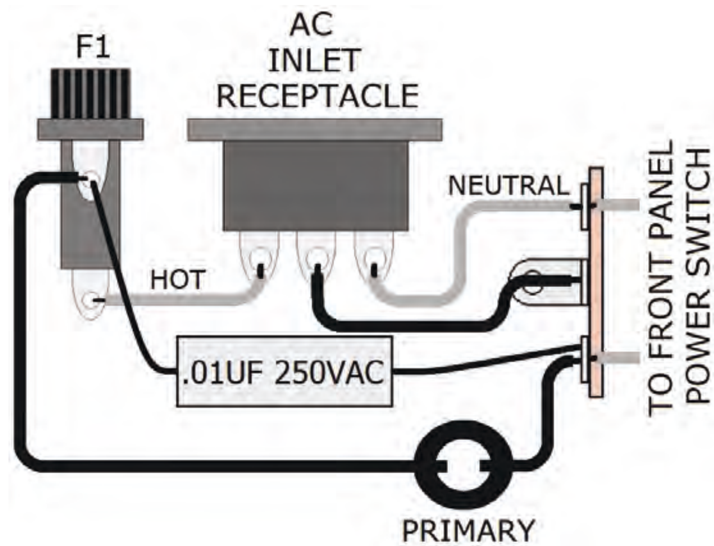
Be aware that wires with PTFE insulation may pose a health problem as some people and animals have an allergic reaction to PTFE.

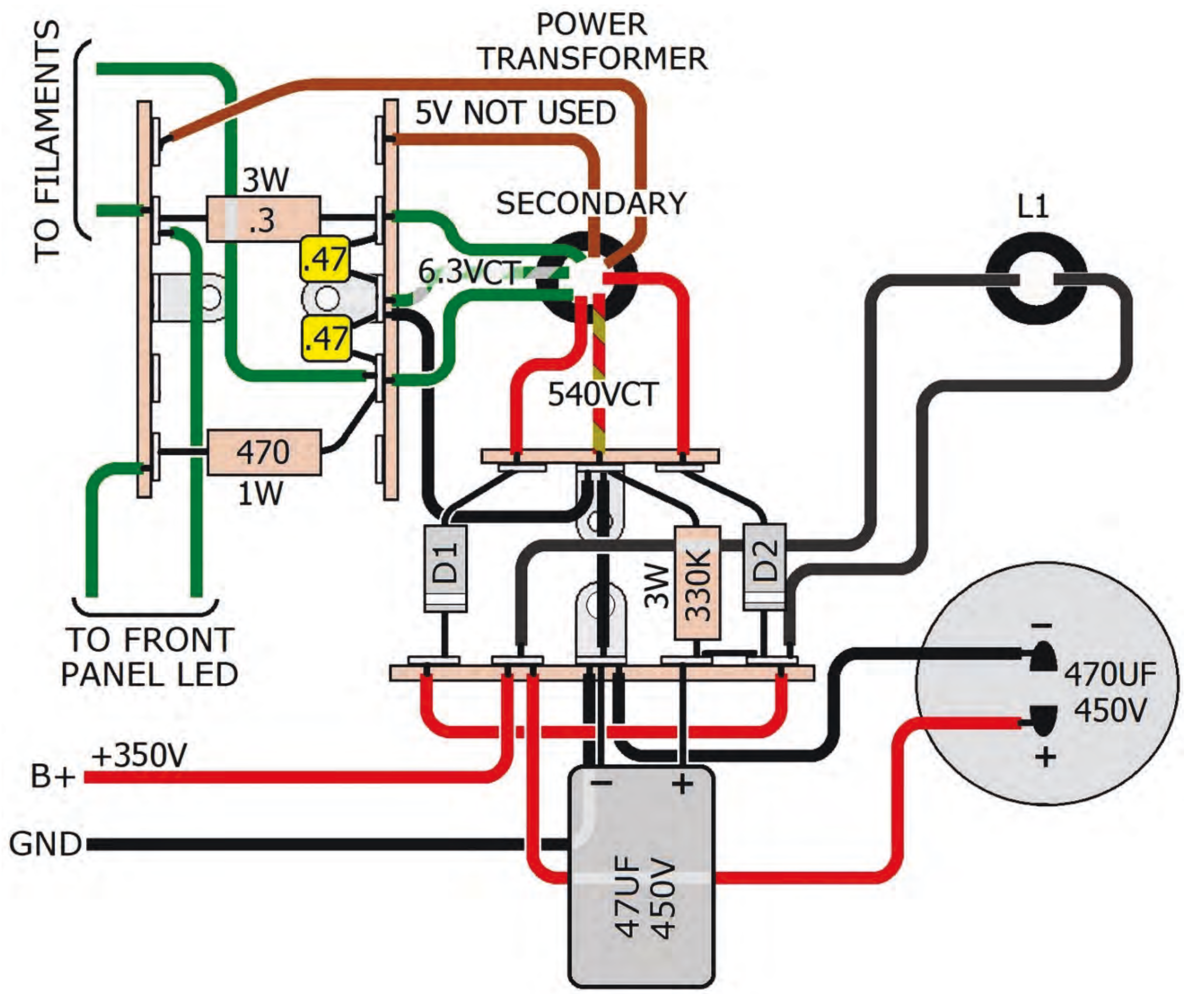
The power transformer selected for this power supply is rated 540VCT with a current rating of 125 mA. The actual B+ current load with a 6V6GT + 6SN7 will be about 45 mA. With the high voltage winding being so lightly loaded, the resulting B+ voltage will be somewhat higher. The factors involved here are capacitor loading (see page 83) and high voltage loading (see page 87). There is a 178% difference between the current load and the transformer's rated current load. When factoring in capacitor loading B+ voltage loss, then B+ voltage gain due to the low current load, the B+ voltage will be around 350VDC. The reason for such a high transformer current rating is to accommodate the higher current 6L6GC type tubes.

This is an unusual voltage – current combination and is why the result (178% difference) is off the graph on page 87. Normally, the difference is less than 50% between the current load on a power supply and the transformer's rated current load.

Component layout guideline
6V6GTA/6L6GC Monoblock Amplifier

Wire the AC inlet receptacle as shown in the illustration.





6V6GTA/6L6GC Monoblock Amplifier

AC Noise Filtering

The filaments have two .47uF 100VDC ceramic capacitors to filter noise that may be present in the filament supply. There is also a .01uF 250VAC capacitor across the power transformer primary to filter noise (make sure you use a capacitor rated 250VAC and not VDC).

Power Supply Parts List

(1) – 470-ohm resistor 1-watt 5%
(1) – 330K-ohm resistor 3-watt 5%
(500-volt or higher rating)
(1) – 0.3-ohm resistor 3-watt
(1) – .01uF 250VAC capacitor
VISHAY F17733102000
(2) – .47 uF 100VDC ceramic
TDK FG24X7S2A474KRT06
(1) – 47uF 450VDC cap radial leads
TDK B43890A5476M000
(1) – 470uF 450VDC capacitor
KEMET ALA7DA471DD450
(must be 35mm diameter)
(1) – Capacitor mounting clamp
Cornell Dubilier VR3
(1) – AC Inlet Receptacle
(1) – Power cord
(1) – Fuse holder
(1) – 1-Amp fuse slow-blow (delayed)
(1) – Power switch
(1) – T1, EDCOR XPWR224
540VCT (270-0-270) @ 125 mA
6.3VCT @ 3 amps
(5V winding not used)
(1) – TRIAD C-17X filter choke L1
1.5HY @ 300mA 40 ohms
(2) – 1N4007 rectifier diodes
(1) – LED panel mount rated 20mA
VCC 5100H5

Terminal Strips

(2) – 3-terminal center terminal ground
(3) – 5-terminal center terminal ground

The T1 XPWR224 power transformer can be ordered with a 120VAC or 240VAC primary.

If desired, the .01 uF capacitor across the power transformer primary can be upgraded to a higher 400VAC rating, Vishay MKP18423104000.

6V6GTA/6L6GC Monoblock Amplifier

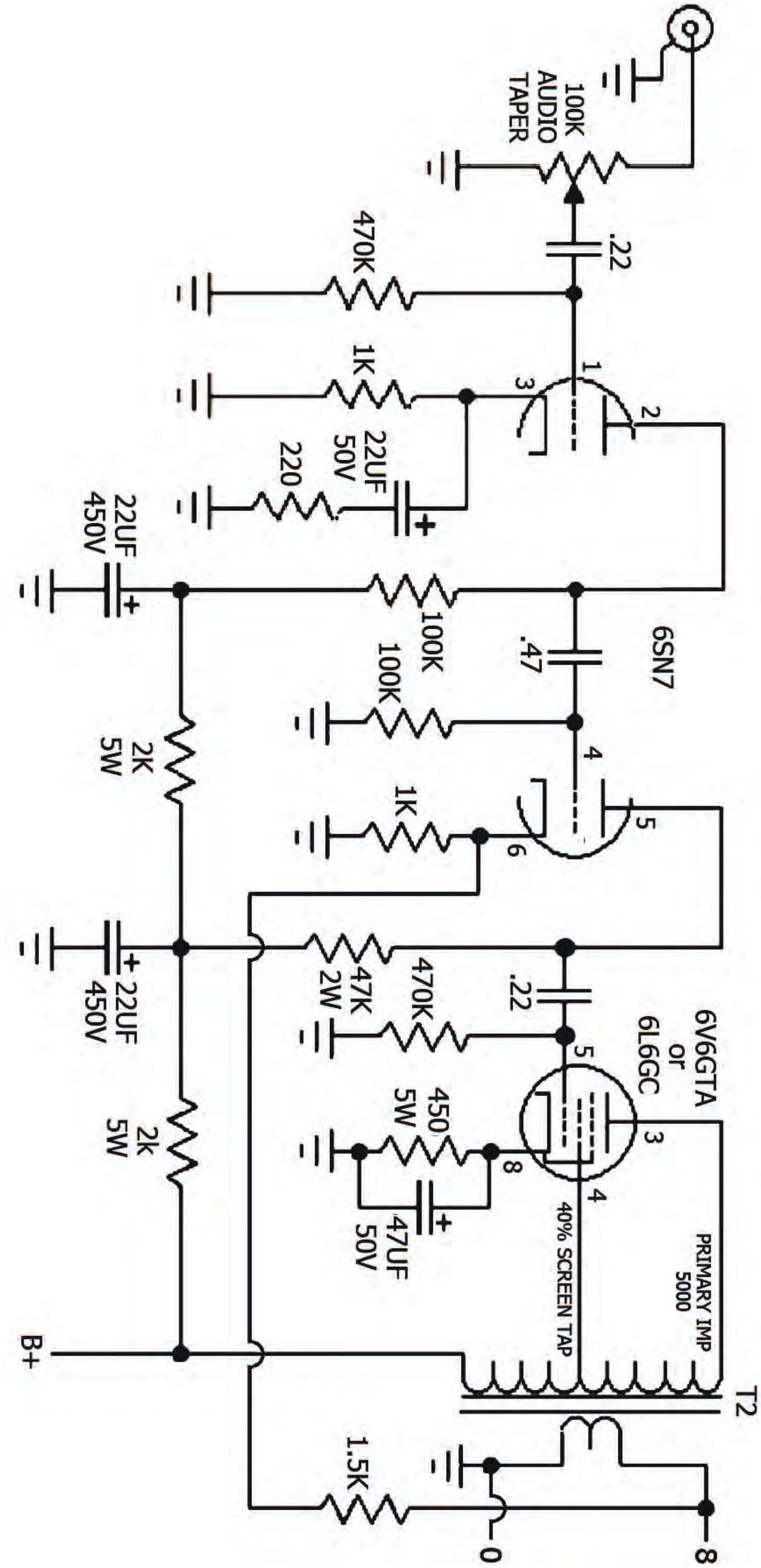
Amplifier Parts List

(1) – 6V6GTA (or 6V6EH or 6V6S) or 6L6GC, 5881 or 7581
(1) – 6SN7
(2) – Octal tube sockets
(1) – T2 output transformer, EDCOR GXSE15-5K
  Power rating 15 watts, 5000 ohm primary, 8 ohm secondary
(1) – Dual connection speaker binding post
(1) – 220-ohm 1/2-watt resistor 5%
(1) – 450-ohm 5-watt resistor wirewound
(2) – 1K-ohm 1/2-watt resistor 5%
(1) – 1.5K-ohm 1/2-watt resistor 5%
(2) – 2K-ohm 5-watt resistors wire wound
(1) – 47K-ohm 2-watt resistor metal film
(2) – 100K-ohm 1/2-watt resistor 5%
(2) – 470K-ohm 1/2-watt resistor 5%
(1) – 100K-ohm potentiometer audio taper
(1) – .47 uF 400VDC capacitor axial leads
(2) – .22 uF 400VDC capacitor axial leads
(1) – 22 uF 50VDC capacitor axial leads
(1) – 47 uF 50VDC capacitor axial leads
(2) – 22 uF 450VDC capacitor radial leads
(1) – input connector
(3) – Terminal strip, 3-terminal center terminal ground
(2) – Terminal strip, 5-terminal center terminal ground

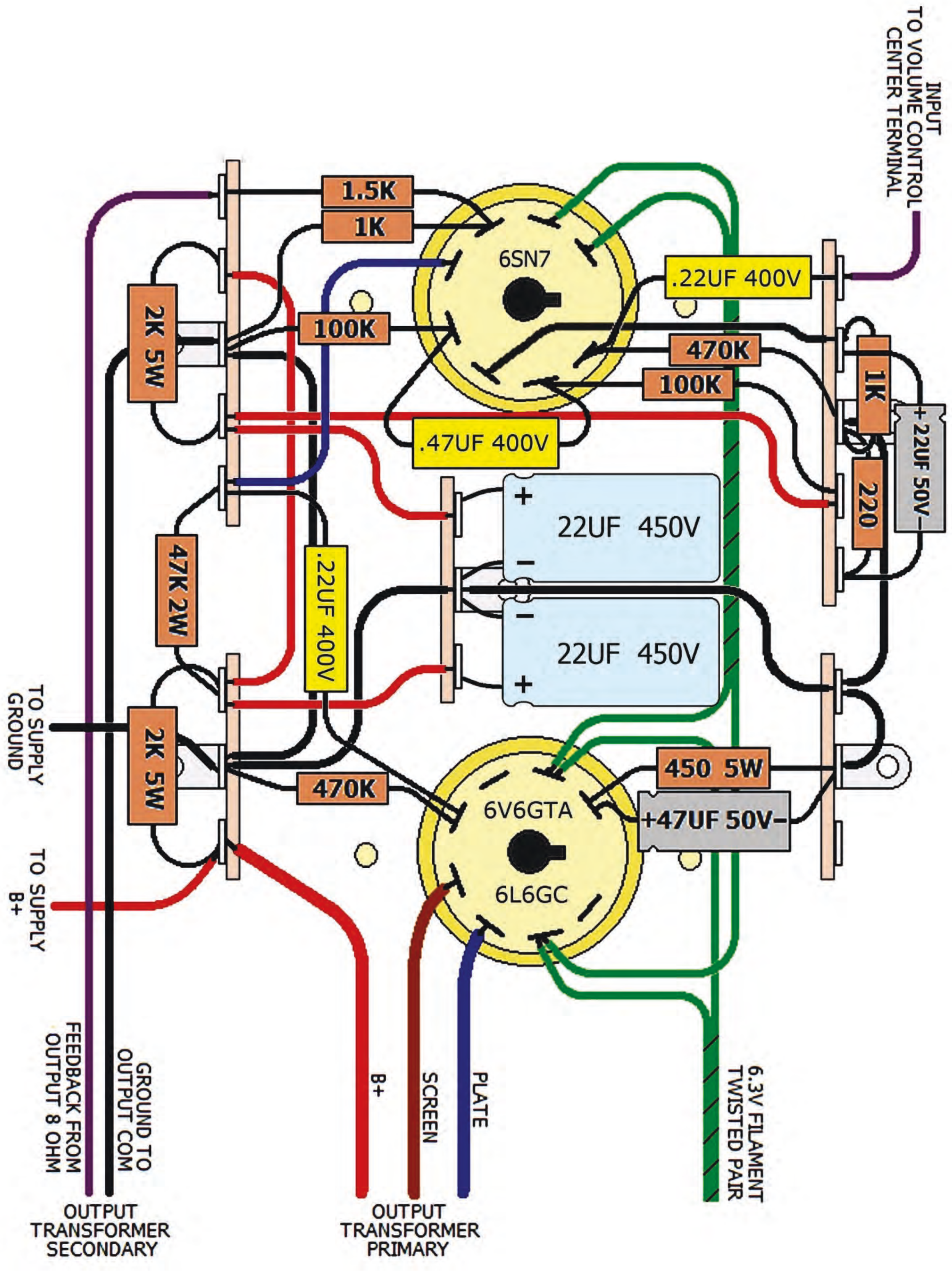
When ordering 1/2-watt resistors, if you choose metal film type resistors, consider increasing the watt rating to 1 or 2 watts. The reason being that 1/2-watt metal film resistors are much smaller and may be awkward to wire onto terminals.

If you ever get the urge to plug in a 6K6 (or similar) output tube, don’t. The 6K6 has a maximum plate voltage of 315VDC. The tube may arc-over and damage components.

6V6GTA/6L6GC MONOBLOCK AMPLIFIER
Circuit drawing



6V6GTA/6L6GC Monoblock Amplifier
Component layout guideline

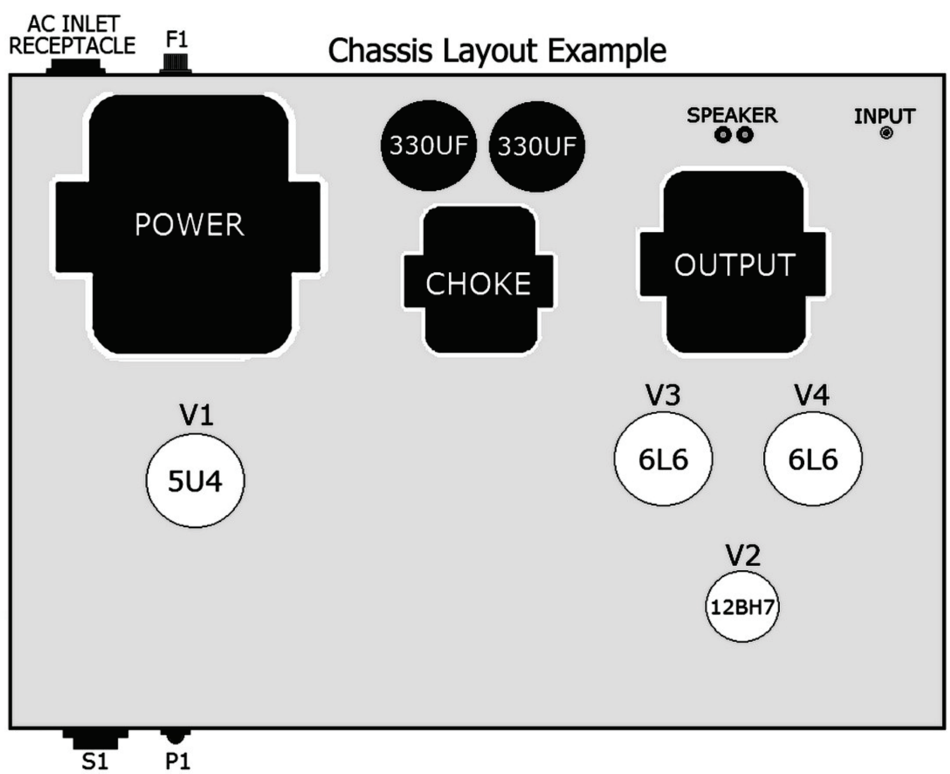


30-Watt 6L6GC/KT66 Monoblock

This project is a 30-watt single-channel power amplifier. Actual amplifier power output will vary depending on the type of output tubes used. This design uses cathode self-bias, eliminating any bias concerns, lending the amplifier to tube rolling. The power supply is designed to provide enough filament and high voltage power for operating various power tubes. Tubes that can be directly plugged in include the 6L6GC, KT66, 5881, 6CA7 (EL34), and 7581. The input/phase inverter can either be a 12AU7 or 12BH7. Voltage amplifier tubes such as the 12AX7 are not suitable for the input/phase inverter because of the output tube drive requirements. An audio control unit typically precedes a monoblock that can provide the two or three volts of audio required by the monoblock.

There are component layout drawings provided for the amplifier circuits that can be used as a guideline, or you can come up with your own layout. The component layout drawings are not to scale, use actual components as a template when machining chassis holes.

An 8-ohm output impedance is recommended. This is because of speaker load impedance variations reflected back to the output transformer primary. Read pages 100 through 105.



This project uses potentially lethal voltages, so be extremely careful. Normal B+ high voltage is around 400 volts. But, until the output tubes warm up completely or are removed from their sockets, the unloaded high voltage can get as high as 540 volts. The power supply current is high enough to lock your muscles should you get a hand across the high voltage.

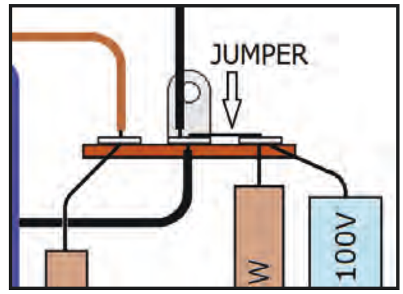
The AC plug third prong ground connects to the chassis near the AC inlet connector. Do not directly connect the AC plug third prong ground to amplifier circuit ground wiring. This helps to avoid current ground loops between the AC mains and sensitive amplifier circuits.

It is customary to wire the power supply before the amplifier circuits. Being careful, you can check B+ after wiring the power supply. Using a clip lead, connect the negative meter probe to B– (chassis). Using a clip lead for the negative meter lead allows you to use one hand for making measurements. Before attempting to power up the supply, double-check your wiring against the power supply circuit drawing.

Set your volt meter to the +1,000VDC scale. Turn on the power supply. Place the meter positive test probe on pin 8 of the 5U4 rectifier. There will be no B+ voltage until the 5U4 rectifier warms up. As the rectifier warms up, voltage will start to rise. If by 8 seconds the meter shows no voltage, shut the power supply off. Check the meter setting and negative connection, being careful not to touch any power supply components. If the meter appears to be set properly, then unplug the power supply from AC power. Manually discharge B+ capacitors to be sure they are safe (see page 2). Check for wiring errors.

If the supply is functioning correctly, your meter should read around 530 to 540VDC. Shut the supply off and, using your test meter, check for charged power supply capacitors. It may take several minutes for capacitors to discharge. Let the chassis sit until the capacitors have discharged. After the power supply capacitors have discharged and the 5U4 has cooled, remove the 5U4 rectifier and continue with wiring the amplifier. There may be a residual voltage of less than 20 volts in discharged capacitors. This is normal and safe to handle.

While wiring the amplifier, pay close attention to the parts layout drawing. Missing a jumper wire can cause problems. For instance, output tubes V3 and V4 socket pins 1 and 8 are connected together. This is required for the 6CA7 output tube. Other tube types do not use pin 1.



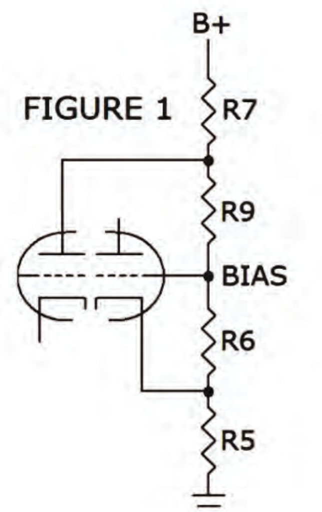
Be sure to put the jumper wire across terminal strip terminals used for the output tube cathodes.

Each output tube has its own cathode resistor; this is required for some tubes such as the KT66.

Filament current limiting resistors R23 and R24 provide an average 6.3V filament for various tube types used. Filament capacitors C15 and C16 help filter AC noise.

The V2 input stage cathode pin 8 has resistor R3 in series with the bypass capacitor C2. This provides sufficient cathode bypass, but still allows applying negative feedback from the T2 secondary back to the V2 cathode.

The second half of V2 is the phase inverter. Resistor R9 across coupling capacitor C3 is part of the phase inverter grid bias. Figure 1 shows how grid bias is set by R7, R9, R6 and R5.



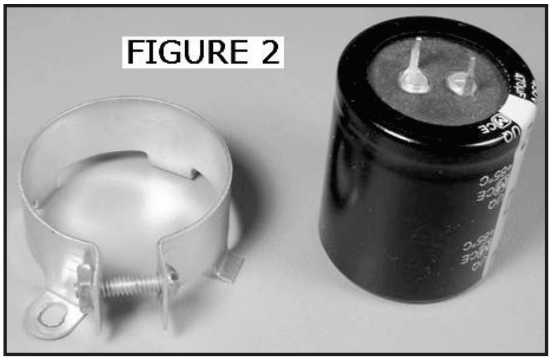
Grid stopper resistors R10 and R11 help prevent high-frequency instability. R16 and R17 are screen suppressors limiting screen current.

R18 helps prevent no-load oscillating if the amplifier should not have a speaker connected.

The amplifier component values are optimized for either 6L6GC or KT66 output tubes. You may want to initially use one of these types for the output tubes. After the amplifier is completed, you should do voltage checks. With 6L6GC or KT66 tubes, the B+ voltage after the L1 choke should measure around 400VDC. At C9A and R19 (the 10K 2W resistor), the voltage should be about 350VDC.

The 5U4 5-volt filament must not be grounded; doing so would short out the high voltage.

When powered on, B+ may get as high as 540VDC until the power output tubes start drawing current. Capacitor voltage ratings should be no lower than those specified in the parts list. B+ is shown as +400VDC, but will vary depending on the type of output tube used.



C13 and C14 should be snap-in type capacitors as shown in Figure 2. The capacitors should have a 35mm diameter to fit a Cornell Dubilier VR3A mounting clamp. Although intended to snap into printed circuit boards, the terminals are easy to wrap wire around and solder.

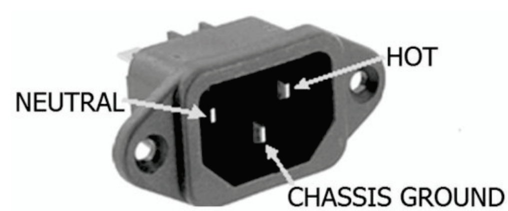
C12A, C12B, R22A and R22B allow the use of low-cost radial electrolytic capacitors instead of traditional axial electrolytic capacitors that are becoming harder to find and are usually more expensive. The same applies to C9A, C9B, R21A and R21B.

R21A, R21B, R22A and R22B should be metal oxide types due to possible current surges. If you search, you should be able to find metal oxide 3-watt resistors rated at least 500 volts. Vishay CPF3150K00GKB14 (150K) and Vishay PR03000204703JAC00 (470K), for instance.

C12 A&B should be long life and have a 1-amp ripple current rating or higher.

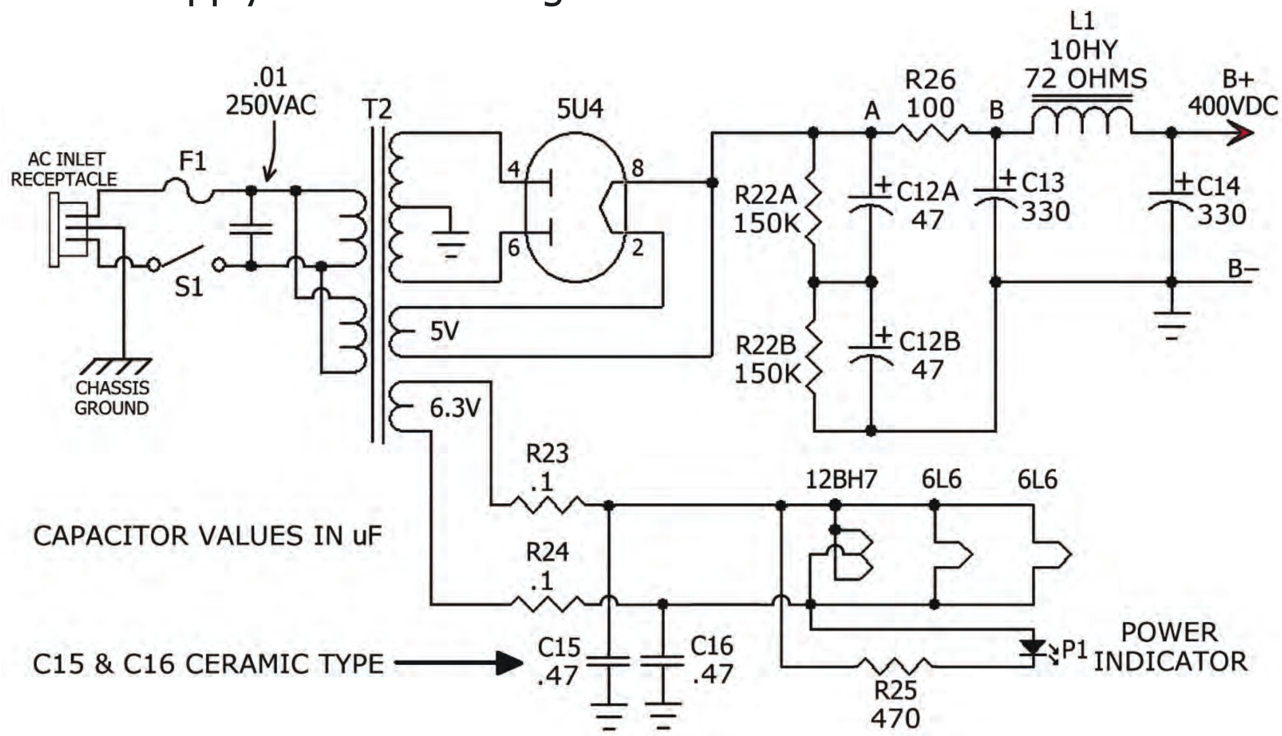
C13 & C14 should be rated for long life, have a ripple current rating of 2-amp or higher, and be 35mm in diameter to fit a VR3A mounting clamp.

The AC inlet receptacle should be wired so that the hot prong connects to the F1 fuse and the neutral prong connects to the S1 power switch. The chassis ground center prong connects to the terminal strip ground lug near the AC inlet connector.



Be aware that wires with PTFE insulation may pose a health problem as some people and animals have an allergic reaction to PTFE.

30 Watt 6L6GC/KT66 Monoblock Power Supply Circuit Drawing



Parts List, for one amplifier, double for two amplifiers.

R22A & R22B – 150K-ohm 3-watt (metal oxide)

R23 & R24 – .1-ohm 5 or 6-watt wirewound

R25 – 470-ohm 1-watt

R26 – 100-ohm 10-watt wirewound

C12A & C12B – 47 uF 450V radial leads TDK B43890A5476M000

C13 & C14 – 330 uF 550V KEMET ALC10A331DH550

(2) – Cornell Dubilier VR3A Capacitor mounting clamp

C15 & C16 – .47 uF 100V ceramic

P1 – LED 20mA (VCC 5100H5)

AC Inlet Receptacle and power cord

S1 – S.P.S.T. power switch

F1 – 3-amp fuse

F1 – Fuse holder

(1) – 5U4GB

(1) – .01 250VAC noise filter VISHAY F17733102000

T2 – Power transformer
EDCOR XPWR010
(has 120V/240V primary)
750VCT @ 175 mA
5.0V @ 3 amps
6.3V @ 6 amps

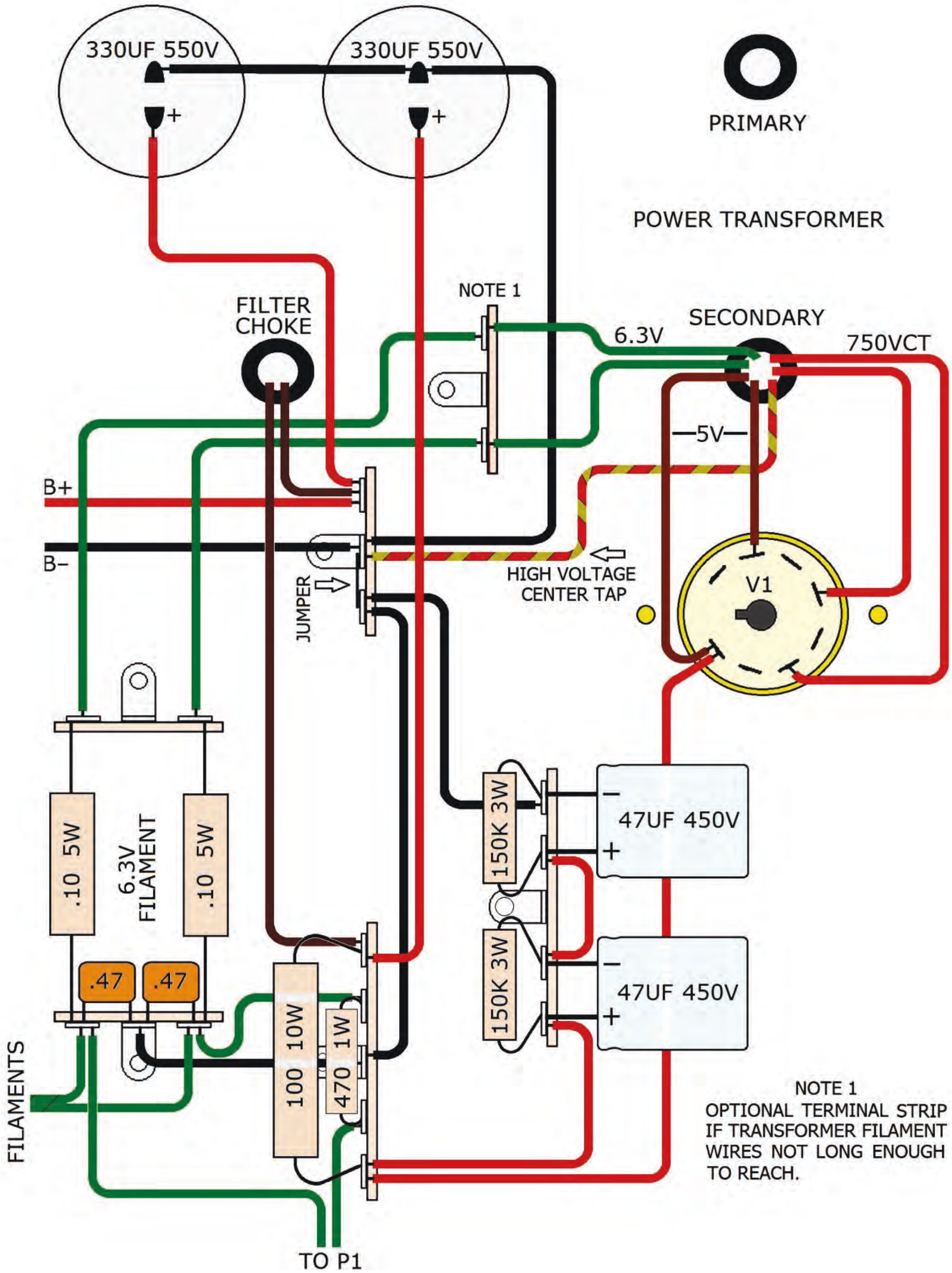
L1 – Filter choke
EDCOR CXC150-10H-300
10 H 300 mA 72 ohms

(4) – Terminal strip
three terminal
center terminal ground

(3) – Terminal strip
five terminal
center terminal ground

(1) – 8-pin octal tube socket

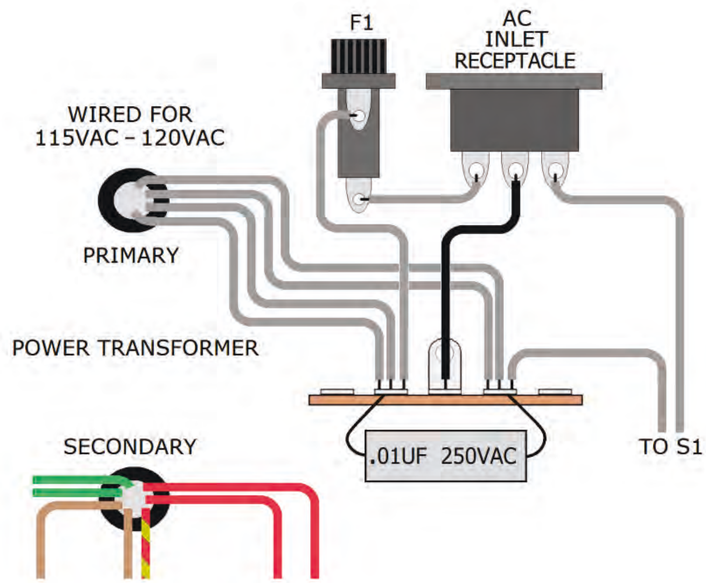
30 Watt 6L6GC/KT66 Monoblock
Power supply component layout guideline



30 Watt 6L6GC/KT66 Monoblock
Power Transformer Primary Wiring

The T2 power transformer specified in the parts list has a dual primary that can be wired for 115VAC – 120VAC or 230VAC – 240VAC.

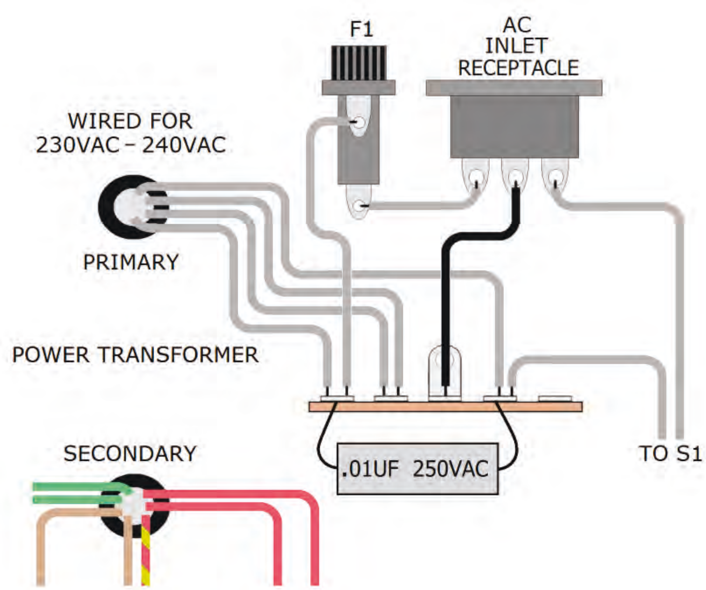
There are four primary wires. For 115VAC – 120VAC, two sets of wires are connected in parallel. The transformer should come with instructions that indicate which wires are tied together.



For 230VAC – 240VAC, two primary wires are tied together. The transformer should have wiring instructions that indicate which wires are tied together.

• • • •

If desired, the .01 uF capacitor across the power transformer primary can be upgraded to a higher 400VAC rating, Vishay MKP18423104000.



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When ordering 1/2-watt resistors, if you choose metal film type resistors, consider increasing the watt rating to 1 or 2 watts. The reason being that 1/2-watt metal film resistors are much smaller and may be awkward to wire onto terminals.

30 Watt 6L6GC/KT66 Monoblock Amplifier Parts List

For one amplifier, double for two amplifiers.

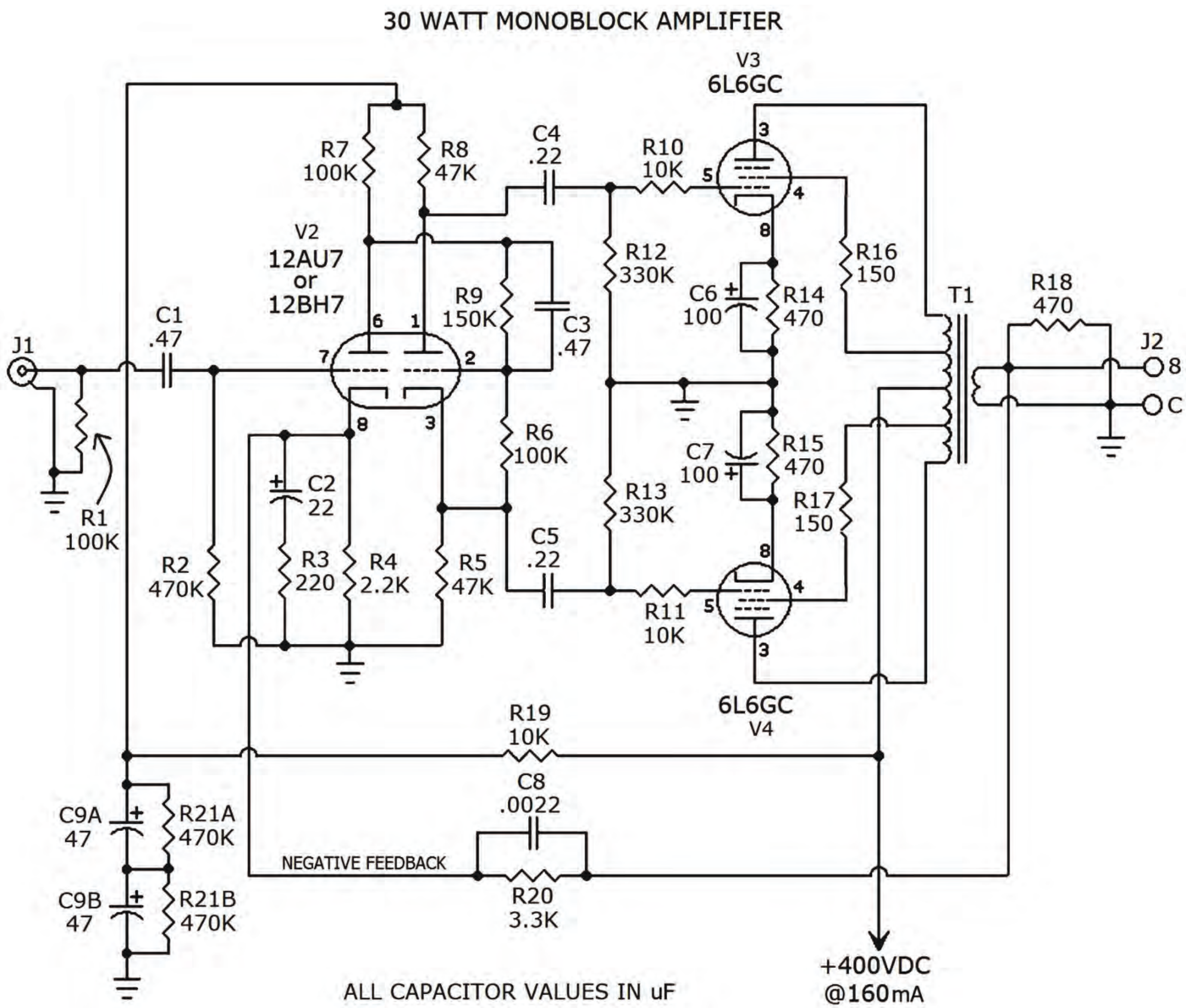
R1 – 100K-ohm 5% 1/2-watt
R2 – 470K-ohm 5% 1/2-watt
R3 – 220-ohm 5% 1/2-watt
R4 – 2.2K-ohm 5% 1/2-watt
R5 – 47K-ohm 5% 1/2-watt
R6 – 100K-ohm 5% 1/2-watt
R7 –100K-ohm 5% 1/2-watt
R8 – 47K-ohm 5% 1/2-watt
R9 – 150K-ohm 5% 1/2-watt
R10 – 10K-ohm 5% 1/2-watt
R11 – 10K-ohm 5% 1/2-watt
R12 – 330K-ohm 5% 1/2-watt
R13 – 330K-ohm 5% 1/2-watt
R14 – 470-ohm 5% 7-watt
R15 – 470-ohm 5% 7-watt
R16 – 150-ohm 5% 3-watt
R17 – 150-ohm 5% 3-watt
R18 – 470-ohm 5% 3-watt
R19 – 10K-ohm 2-watt wirewound
R20 – 3.3K-ohm 5% 1/2-watt
R21A – 470K-ohm 5% 3-watt (metal oxide)
R21B – 470K-ohm 5% 3-watt (metal oxide)
(2) – 8-pin octal tube socket
(1) – 9-pin miniature tube socket
(2) – Output Tubes Matched Pair 6L6GC, KT66, etc
(1) – 12AU7 or 12BH7

C1 – .47 uF 250V
C2 – 22 uF 50V
C3 – .47 uF 400V
C4 – .22 uF 630V
C5 – .22 uF 630V
C6 – 100 uF 100V
C7 – 100 uF 100V
C8 – .0022 uF 400V
C9A – 47 uF 450V radial leads TDK B43890A5476M000
C9B – 47uF 450V radial leads TDK B43890A5476M000
J1 – Input jack
J2 – Speaker binding post
T1 – Output transformer EDCOR CXPP50-6.6K[1] 6,600 ohm P-P primary 8 ohm secondary rated 50 watts
(3) – Terminal strip three terminal center terminal ground
(6) – Terminal strip five terminal center terminal ground

[1] Any transformer with identical specifications can be used, a 50 watt power rating is recommended.

Searching the EDCOR site for CXPP50-6.6K may require search for CXPP50, then scroll down.

30 Watt 6L6GC/KT66 Monoblock Amplifier Circuit Drawing

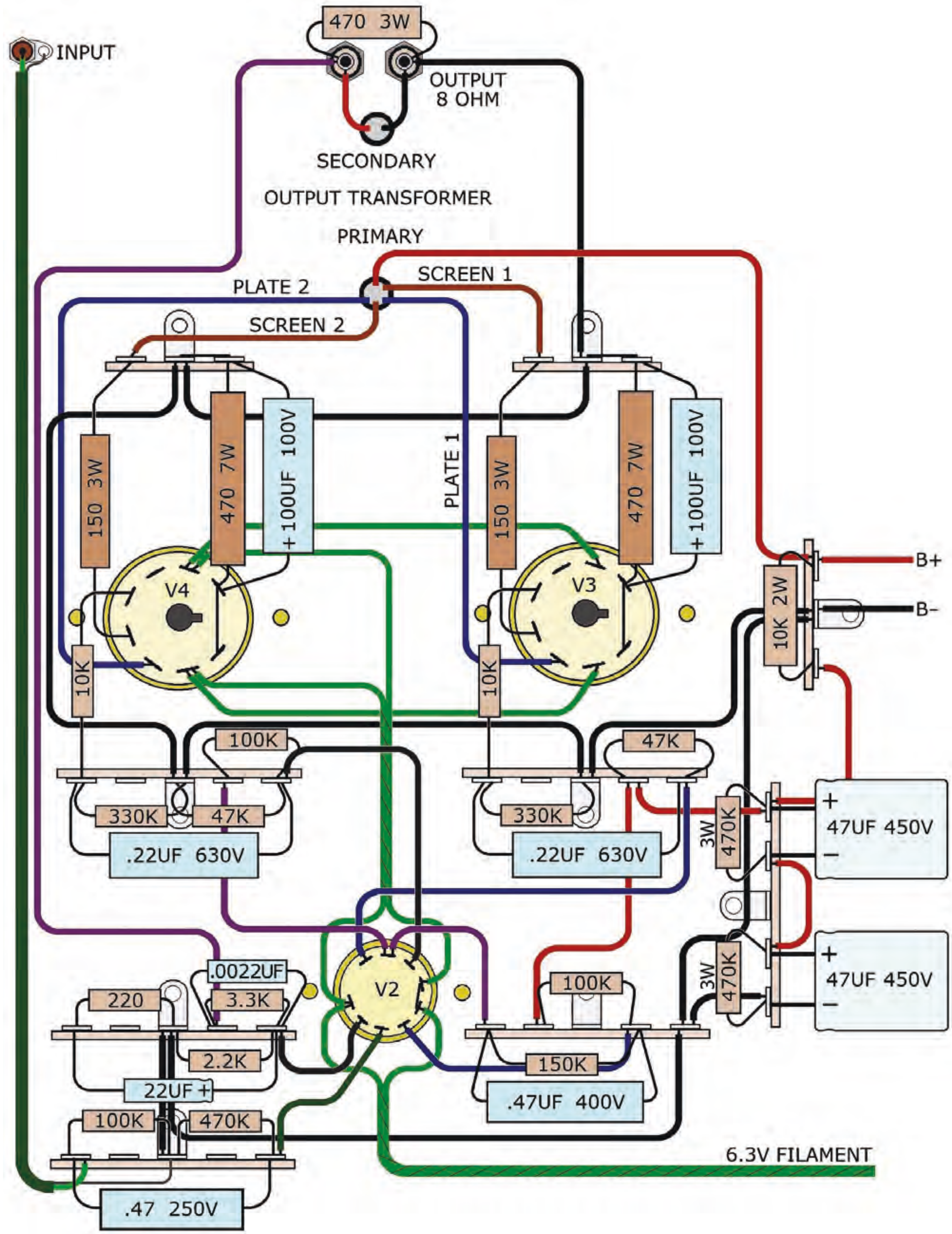


Inverter Loading

The output tubes present a significant load on the phase inverter. The 12AU7 or 12BH7 are able to deliver more drive into such a loading than a 12AX7 or similar voltage amplifier type tube. It's been tried with the result that the inverter goes into distortion before the output tubes reach full output power. However, plugging in a 12AX7 or similar type tube will not cause damage.

30 WATT 6L6GC/KT66 MONOBLOCK

Amplifier component layout guideline



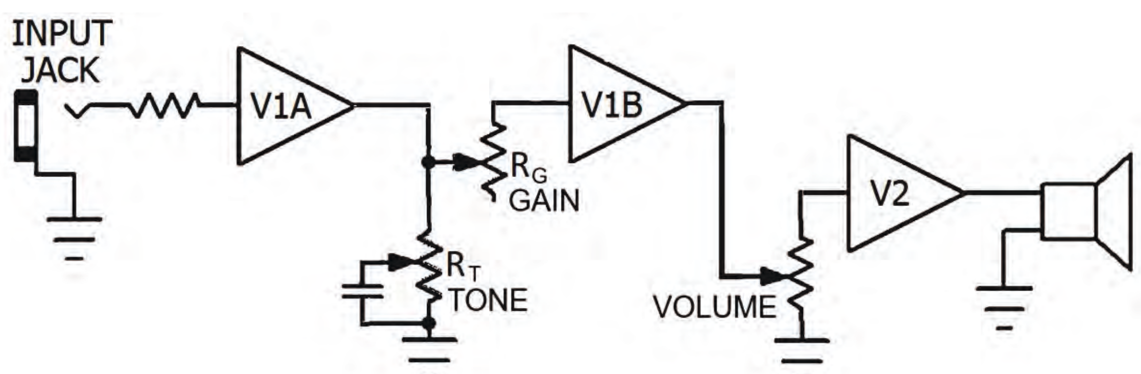
6V6GTA/6L6GC Basic Guitar Amplifier

Updated Dec 2024

A simple guitar amplifier with volume and tone controls. Output tubes that can be directly plugged in include the 6V6GTA, 6V6EH, 6V6S, 6L6GC, 5881 or 7581. The 6V6EH or 6V6S is a custom version of the standard 6V6GTA except with higher maximum voltages. Pre-amplifier tubes that can be directly plugged in include the 12AX7, 12AY7 and 12AT7.

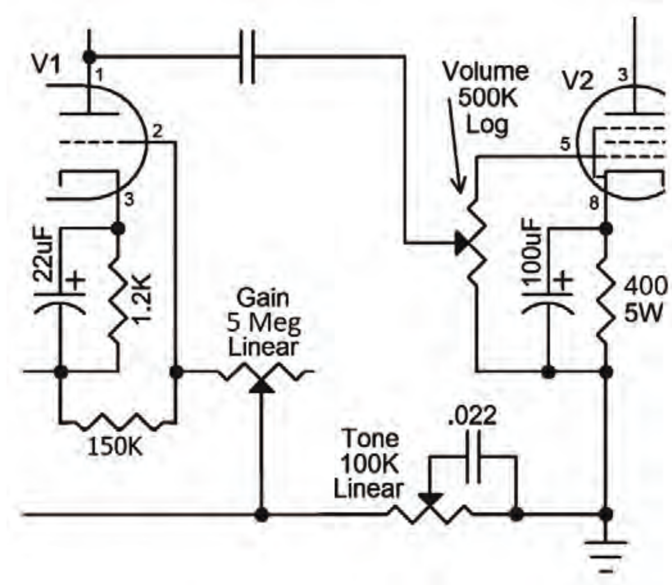
Electric guitars sound best when played through a paper cone speaker that has a paper edge suspension, such as the Jensen™ line of guitar speakers. Besides the quality of sound, paper cone speakers with paper suspension are usually more efficient than full-range Hi-Fi type speakers; it takes less wattage to get more volume. When paired with a high-efficiency guitar speaker, five watts of amplifier power provide appreciable volume. Another advantage of this type of speaker is that they do not need to be in a sealed baffle. Mounting the speaker in an open back cabinet is fine.

Audio Path



Two level controls are used. A volume control is in front of the output tube and a gain control is in the pre-amplifier. The level control in front of the output tube is the master volume. The gain control in the pre-amplifier adjusts the pre-amplifier's gain level. Potentiometer R_T limits the pre-amplifier's low gain setting. R_T is also the tone control. Only the master volume can turn the audio level completely off. Using two level controls allows the option of driving the pre-amplifier hard while still having volume control.

The V2 output stage uses the volume potentiometer as a grid leak resistor.



The grid of the second V1 stage has a 150K-ohm grid leak resistor that also presents a load to the 5 meg-ohm gain control. The tone control is a simple high-end roll-off type. With the tone control at full counter-clockwise position, the .022 uF capacitor is applied from the gain control to ground.

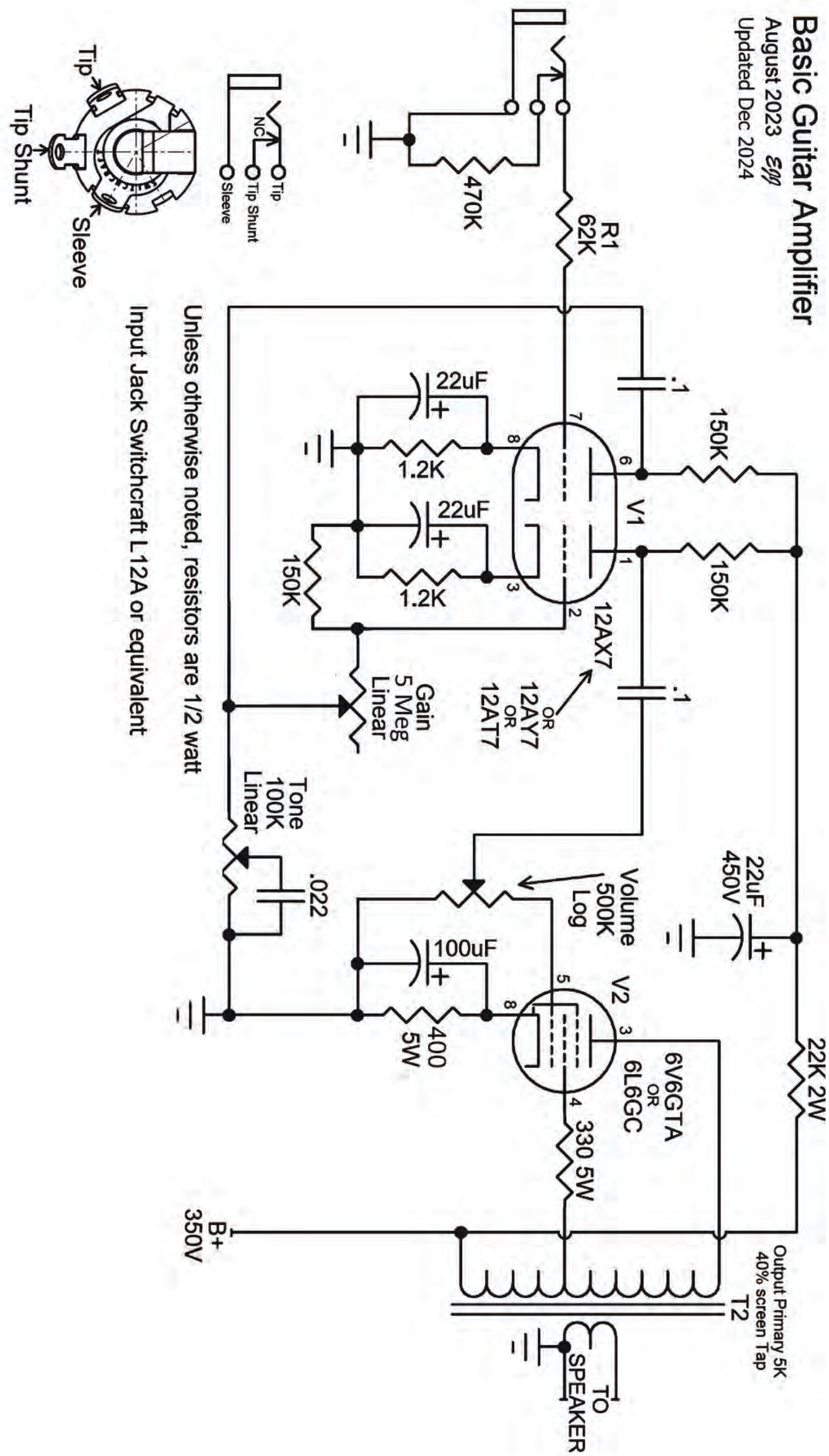
It does not matter what position the 5 meg-ohm gain pot is at, the .022 uF capacitor will still roll-off the higher frequencies. In the full clockwise position, the higher frequencies are at a normal level. There is some reactance between the .022 uF capacitor and the 5 meg-ohm gain potentiometer. The result is a variation in sound depending on the settings of the tone and gain controls. Because the wiper of the volume potentiometer is facing towards the V1 pre-amplifier, the volume control presents a variable load to the V1 output plate. Some variation in sound quality can be achieved by using the volume control to vary loading on the V1 output plate plus adjusting the pre-amplifier gain. Adjustment of sound quality depends on the settings of the gain, tone and volume controls. The cleanest sound is with the gain control set for low gain.

The amplifier parts layout has the gain, tone and volume controls plus the input jack as they would be on a control panel. The power supply layout shows wiring connections; the actual placement of parts is up to the builder.

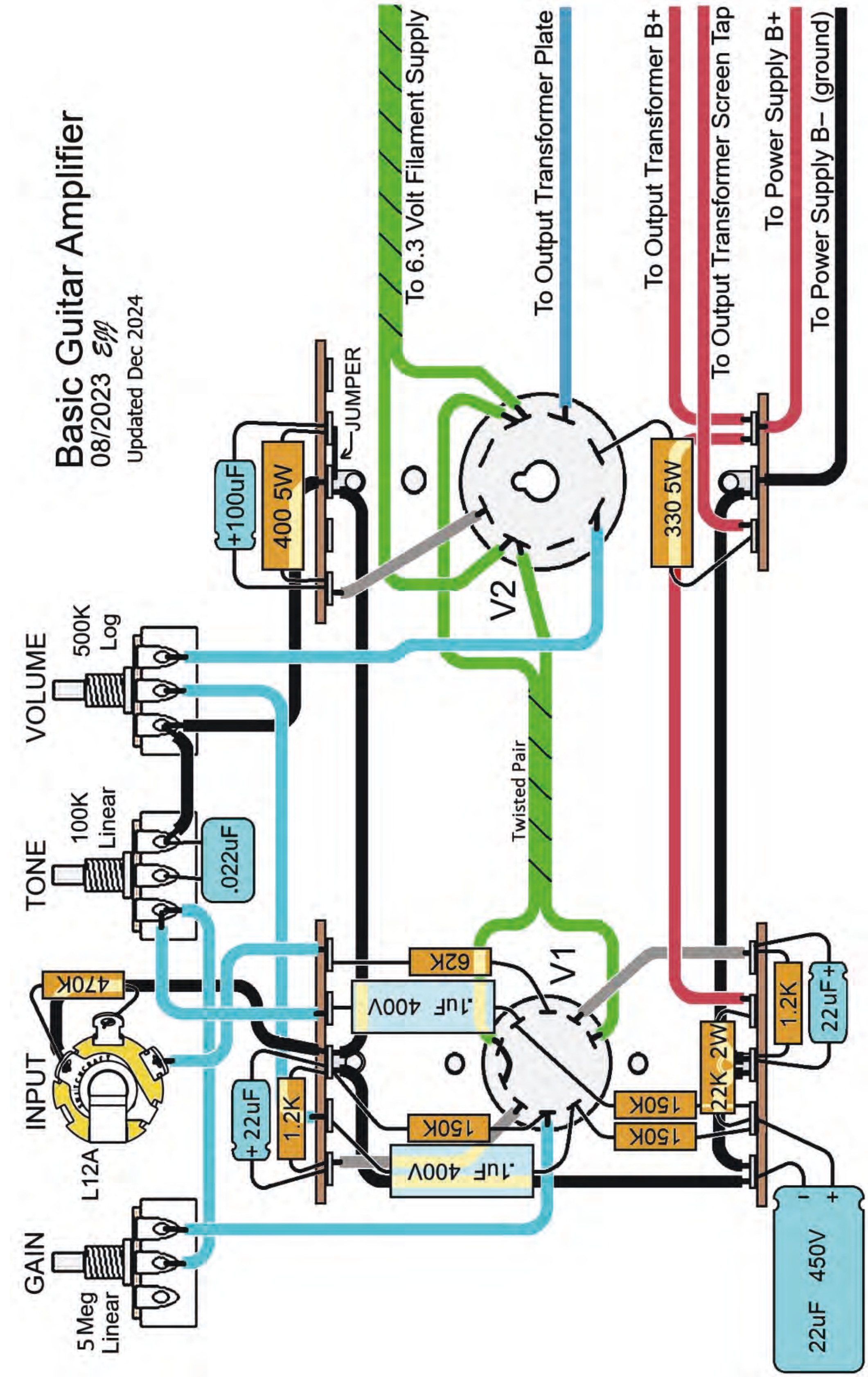
You may have to use an electronics parts source that specializes in guitar amplifier parts to find a 5 meg-ohm linear pot. At present, Mouser Electronics is a good source.

Be aware that wires with PTFE insulation may pose a health problem as some people and animals have an allergic reaction to PTFE.

6V6GTA/6L6GC Basic Guitar Amplifier
Circuit Drawing



6V6GTA/6L6GC Guitar Amplifier
Parts Layout



6V6GTA/6L6GC Basic Guitar Amplifier

Parts List

(1) – 6V6GTA (or 6V6EH or 6V6S) or 6L6GC, 5881 or 7581
(1) – 12AX7 (or 12AY7 or 12AT7)
(1) – 8-pin octal tube socket
(1) – 9-pin miniature tube socket
(1) – T2 output transformer, EDCOR GXSE15-5K
  Power rating 15 watts, 5000 ohm primary, 40% screen tap
  8-ohm secondary (or if you prefer, 4-ohm)
(1) – Dual connection speaker connector (your choice)
(1) – 330-ohm 5-watt resistor wirewound
(1) – 400-ohm 5-watt resistor wirewound
(2) – 1.2K-ohm 1/2-watt resistor 5%
(1) – 22K-ohm 2-watt resistors 5%
(1) – 62K-ohm 1/2-watt resistor 5%
(3) – 150K-ohm 1/2-watt resistors 5%
(1) – 470K-ohm 1-watt resistor 5%
(1) – .022 uF 400VDC capacitor radial leads
(2) – .1 uF 400VDC capacitor axial leads
(2) – 22 uF 25VDC capacitor axial leads (V1 cathode bypass)
(1) – 22 uF 450VDC capacitor radial leads (B+ filter)
(1) – 100 uF 50VDC capacitor radial leads (V2 cathode bypass)
(1) – 500K-ohm potentiometer (volume) audio taper (Log taper)
(1) – 5 meg-ohm potentiometer (gain) linear taper
(1) – 100K-ohm potentiometer (tone) linear taper
(1) – J1 input jack, Switchcraft L12A or equivalent
(1) – Terminal strip, 3-terminal center terminal ground
(3) – Terminal strip, 5-terminal center terminal ground

When ordering 1/2-watt resistors, if you choose metal film type resistors, consider increasing the watt rating to 1 or 2 watts. The reason being that 1/2-watt metal film resistors are much smaller and may be awkward to wire onto terminals.

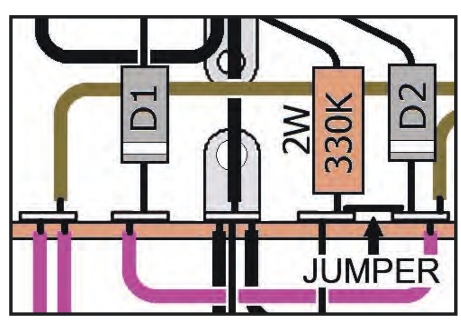
6V6GTA/6L6GC Guitar Amplifier
Power Supply Parts List

A solid state rectifier power supply provides a more solid B+ voltage than that of a tube rectifier. Capacitors in the B+ supply circuits are rated 450VDC to allow for the higher B+ voltage before the tubes warm up and start drawing current. The nominal B+ voltage under load is 350V.

(2) – 1N4007
(1) – 470-ohm 5% 1-watt resistor
(1) – 330K-ohm 2-watt wirewound resistor
(1) – .2-ohm 3-watt resistor
(1) – .01 uF 250VAC capacitor
VISHAY F17733102000
(2) – .47 uF 100VDC ceramic capacitor
TDK FG24X7S2A474KRT06
(1) – 47 uF 450VDC capacitor
radial leads
TDK B43890A5476M000
(or equivalent)
(1) – 470 uF 450VDC capacitor (snap-in)
KEMET ALA7DA471DD450
(or equivalent)
(must be 35MM diameter)
(1) – Capacitor mounting clamp
Cornell Dubilier VR3
(1) – AC power inlet connector
(1) – AC power cord
(1) – Power switch
(1) – Fuse holder
(1) – 1-amp fuse (delayed type)
(2) – Terminal strip, 3-terminal
center terminal ground
(3) – Terminal strip, 5-terminal
center terminal ground
(1) – T1 Power transformer
EDCOR XPWR061
600VCT 300-0-300V @ 120mA
6.3VCT @ 3 amps
5V winding not used
(1) – L1 Filter choke
1.5HY 40 Ohms DC resistance
TRIAD C-17X
(1) – LED panel mount 20mA
VCC 5100H5

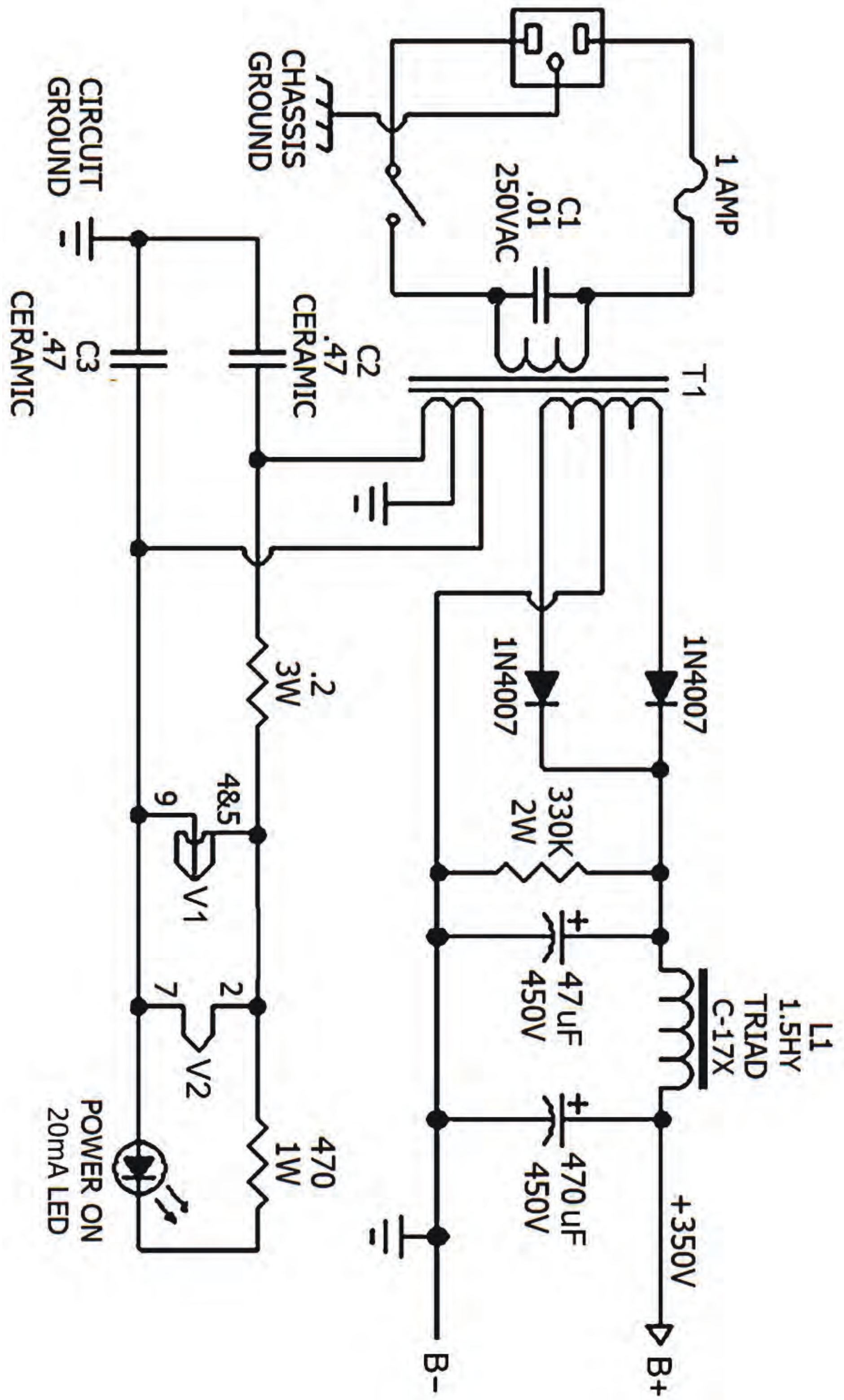
When wiring the power supply, be sure to include the jumper from the 330K ohm resistor to D2.

The EDCOR XPWR061 power transformer only operates on 120V AC mains.



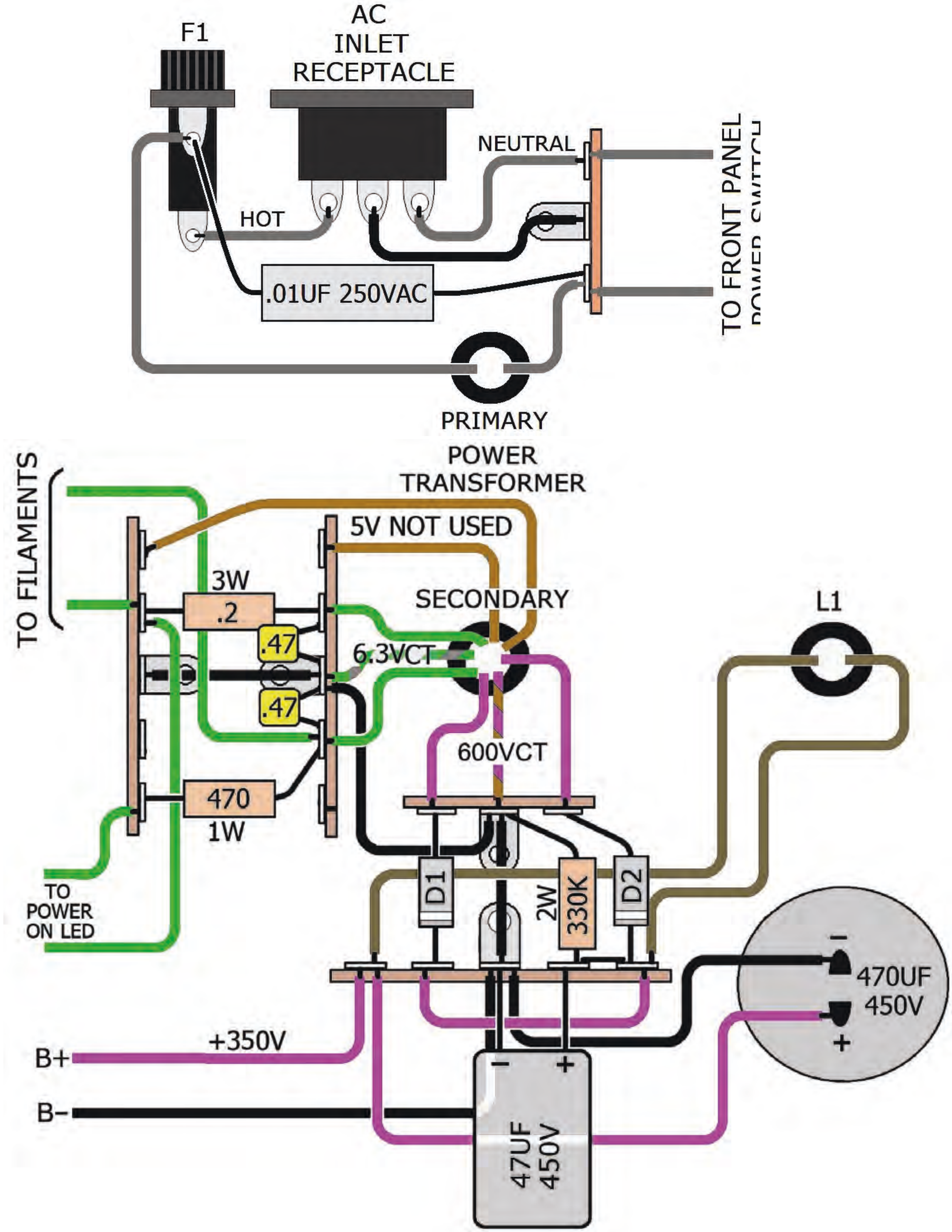
6V6GTA/6L6GC Guitar Amplifier

Power Supply Circuit



6V6GTA/6L6GC Guitar Amplifier

Power Supply Parts Layout



Citations

Lead Free Solder
Preventing the Growth of Metal Whiskers
© 2007
The Aerospace Corporation

Selecting Capacitors to Minimize Distortion in Audio Applications by
Zak Kaye
Texas Instruments Analog Design Journal
Published 2020

Classic Amplifier Kits
Allied Radio catalog 1957
Used as filler on page 44

Series RC circuit Impedance Calculator
mathforengineers.com

Integrated Stages
A process of linking the plates of consecutive stages
Previously used in the output stage of a Revere T-100 tape recorder

CrownAudio.com
Amplifier Power Required Calculator

RCA Receiving Tube Manuals
Graphs and data reference

EJ Jurich
Vacuum tube audio connoisseur since 1957
(Age of audio quality awareness)

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