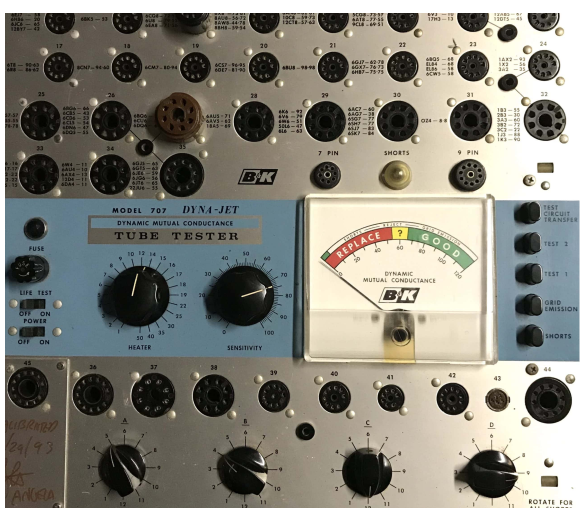
To Test, Or Not to Test, Part Five: Vacuum Tubes

ISSUE 130



Written by Adrian Wu

In a previous article in this series (Issue 128), I discussed measurements that help determine the quality of electronic components such as capacitors and resistors. However, most audiophiles are quite content with the electronic components chosen by the designers of their equipment and have no wish to make changes. That said, one particular electronic component always requires attention, and that is the vacuum tube. Of course, not all audiophiles wish to use vacuum tube audio equipment, but for those who do, the quality and the health of those tubes play an important role in the sound quality of their systems. The quality of the tubes can be determined by testing them.

People often have preconceived ideas about tubes. Tube amplifiers have a reputation for sounding "soft" or "colored," and to have poor frequency extension and flabby-sounding bass. Many of us have in fact experienced tube amplifiers that confirm these biases, but these qualities are not due to the inherent shortcomings of tubes per se, but to poor design and/or poor-quality components.

For those unfamiliar with how vacuum tubes used for signal amplification work, or need a quick refresher: a heated element (usually a *cathode)* releases negatively-charged electrons, which are attracted to the positively-charged *anode* or *plate*. A *grid*, located between the cathode and the anode, and usually kept at a negative voltage relative to the cathode, has the musical signal applied to it, which alters the flow of electrons in accordance with the musical signal (like a valve controlling the flow of water, hence the Brits call vacuum tubes electron valves). This signal current induces a voltage at the plate, and the magnitude of the voltage is dependent on the plate resistance. As the plate voltage is usually larger than the signal voltage applied to the grid, so the tube acts as an amplifier. (A diode, or rectifier tube used in power supplies, operates differently.)

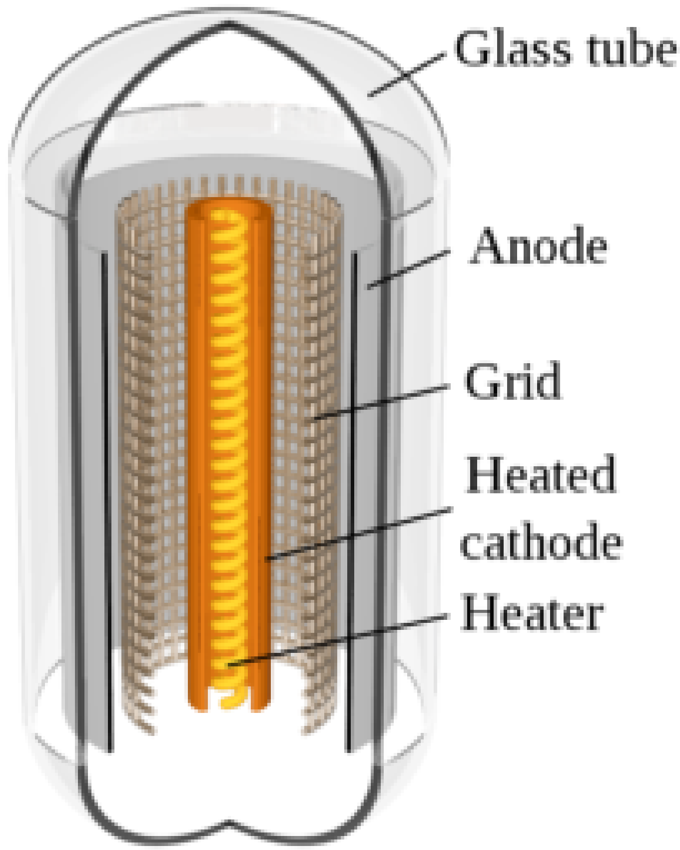


Diagram of a triode tube. Courtesy of Wikimedia Commons/Svjo.

Tube circuit topology can be divided into the self-bias (cathode bias) or the fixed bias type. Self-bias amps rely on a cathode resistor to raise the cathode voltage. The grid of the tube is kept at ground potential, thus ensuring a negative grid-to-cathode potential difference (V_{gk}). The plate current decreases when V_{gk} becomes more negative (the more negatively charged grid repels more of the electrons released from the cathode), and increases when V_{gk} becomes less negative, until the potential difference approaches zero and the grid starts to conduct current. At this point, the input impedance of the tube quickly drops, causing distortion unless the driver stage is designed to supply current to the grid (a so-called Class A2 configuration). When the plate current increases, the current going through the cathode resistor also increases, thus raising the cathode voltage. This causes V_{gk} to become more negative, which in turn reduces the plate current. This is a negative feedback mechanism that ensures the plate current stays fairly constant.

While this negative feedback is useful in the steady state, it also reduces the amplification of the signal (so-called degeneration). Therefore, a bypass capacitor is usually added in parallel to the cathode resistor to avoid incurring negative feedback of the signal. The combination of the resistor and the capacitor forms a high-pass filter, which means the value of the capacitor needs to be sufficiently large to prevent rolloff of the bass frequencies. The quality of these components have an important influence on the sound quality, since they are in the signal path. However, the capacitance usually needed is so large that electrolytic capacitors are often used. The equivalent series resistance (ESR) and dielectric absorption (DA) of such capacitors are orders of magnitude higher than film capacitors, making them poor choices for use in signal circuits. This is one of the reasons why this type of design could compromise performance.

To get around the problems of cathode bias, one can use fixed bias. In this case, the cathode of the tube is connected to ground, and the grid is kept at a fixed negative potential. This means a negative voltage power supply is needed, which increases the cost. This type of power supply also needs to be well-regulated, since it has a big influence on the sound quality. However, this type of design tends to have a cleaner sound and better transient response than cathode biasing.

So what does all this have to do with tube testing? *It is because the circuit design determines how much influence certain electrical properties of the tubes have on sound quality.* That is why some tubes might sound fine when plugged into a particular amplifier, but sound horrible when used in a different amp. What are the reasons for testing vacuum tubes? First, we want to make sure the tubes are performing at or close to their original specifications. Second, we want to match certain characteristics of the tubes so that they will work well together, and can determine how they'll behave in various circuits.

Vacuum tubes are handmade products. In the old days, after the tubes were assembled by skilled technicians, they were burned in (usually for at least 48 hours) and then tested, and those that were not up to specification were rejected. The more expensive premium tubes usually had more stringent requirements during the quality control process. For example, premium tubes such as the E188CC/7308 and 6072a are specially selected low-noise examples of the E88CC/6922 and 12AY7 respectively. Some difficult-to-manufacture tubes such as certain tubes with a frame grid construction had very high rejection rates. Keep in mind that tubes were the mainstay in electronic equipment up to the late 1960s, and were used in many mission-critical applications. The reputable companies such as Telefunken, AEG, Siemens, Valvo, Western Electric, STC, Mullard, Brimar, Amperex, General Electric, Marconi-Osram, Philips, RCA, Sylvania, Tung-Sol and others produced millions of tubes per year and had very strict quality control.

The Western Electric 437A frame grid tube, for example, was used in undersea repeaters for telephone lines crossing the Atlantic and Pacific oceans. These tubes can easily last 20 years with continuous use. Imagine having to change out faulty tubes under these circumstances; just charter a submarine and off you go! This tube has extremely high transconductance; in fact, it is possible to build a power amplifier with just one 437A per channel. I have a stash of these waiting for projects after I retire…

A 1950s Western Electric 437A. It's available at Tube Depot.com for $1,295.

Nowadays, vacuum tubes are produced mostly for guitar amps, where such strict QC is not needed. Many audiophiles therefore like to use tubes produced in a bygone era. New old stock (NOS) of these ancient tubes is becoming increasingly scarce, and many examples being sold as NOS are probably "pulls," or tubes pulled from old equipment.

Is it better to buy NOS tubes or recently manufactured ones? (If you're a manufacturer, it's certainly or almost impossible to use anything other than new-production tubes because of quantity requirements.) I bought most of my NOS tubes from now-venerable electronics distributors in the early 1990s, when they still had a stash of these hidden away in their warehouses, but after eBay came on line, this supply quickly dried up. Except for a few currently-reputable dealers specializing in NOS audio tubes, who have the knowledge to tell the real NOS tubes from those that are not – there *are* counterfeits out there – and are honest enough to only sell the genuine articles, I would be very cautious when buying from other sources. And it is definitely necessary to test the tubes before plugging them into your expensive amplifiers, unless they came from one of the few dealers who test every tube they sell. Even for recently-manufactured tubes, I find the quality quite variable, and rough handling during shipping can cause damage to a tube's internal structure. Tubes should be tested after purchase, and returned to the seller if faults are discovered.

When using NOS tubes, one needs to pay attention to several aspects. First, these tubes can lose their vacuum over time. The air molecules that have seeped into the tube during the years of storage get ionized when the tube is used for the first time, and these positive ions are attracted to the cathode, striking its surface and causing damage, leading to a shortened lifespan. When these positive ions strike the grid, electrons are released from the grid, and this makes the grid more positively charged. This grid current causes a noise voltage that is amplified by the tube; the higher the resistance of the grid circuit, the higher the noise voltage. The positively charged grid increases the plate current, which in turn increases the grid current and makes the grid even more positively charged (so-called thermal runaway) until the cathode is depleted. The plate starts to glow red ("red plating") when this happens, which looks very ominous. Cathode-biased circuits, by virtue of their self-correcting nature, are less prone to this problem.

Morgan Jones, the author of the excellent book *Valve Amplifiers,* recommends baking NOS tubes in an oven at 120ºC (248ºF) for 12 hours and allowing them to cool before use. His experiments showed that the heat reactivates the residual barium present in the tube's *getter*, the structure inside the tube designed to absorb residual gas and maintain the tube's vacuum.

Tubes with metal-oxide cathodes need to be handled carefully. If the cathode is made to pass current before it reaches an adequate temperature, its life will be shortened. This was usually not a problem in the old days when tube rectifiers were used in amplifiers, since the time it takes the rectifiers to warm up and start conducting is adequate to allow the cathode to reach operating temperature, but modern equipment with solid-state diodes needs to have a time delay in the circuit. (Some modern gear, like certain guitar amps, still use tube rectifiers.) Some modern amplifiers have a reputation for eating up NOS tubes, and users should only install current-production tubes in these amps unless circuit modifications have been made.

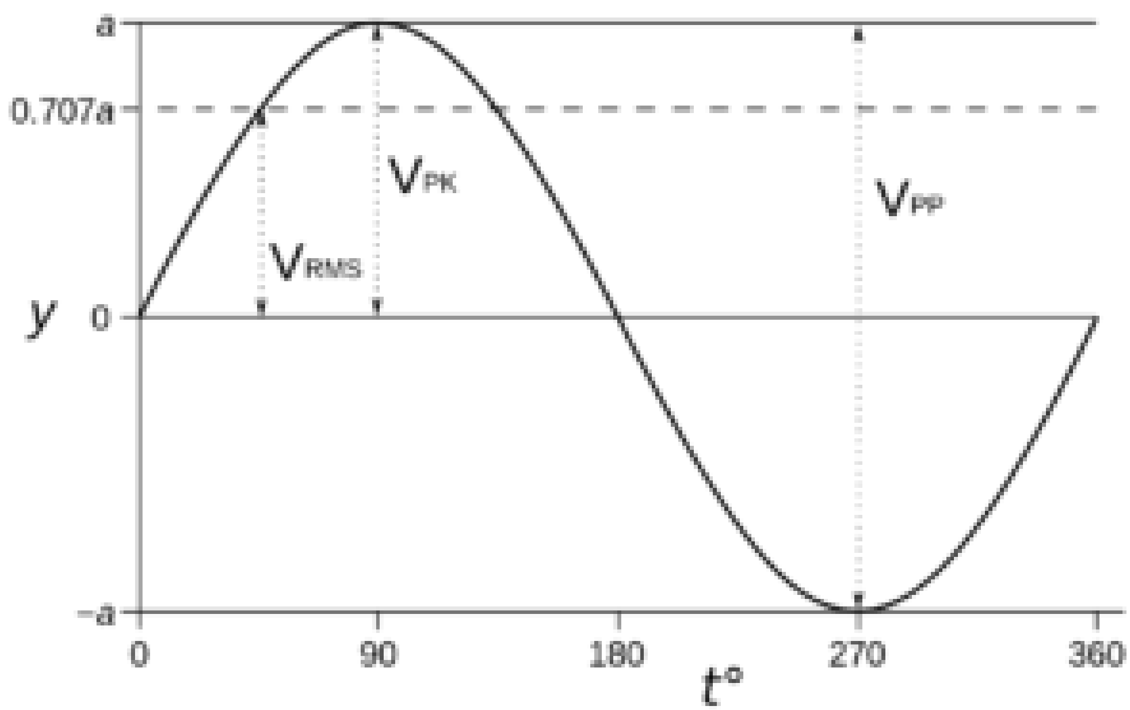
What do we need to test to ensure the tubes are working correctly? Open or shorted filaments can be detected using a multimeter, and should be done before plugging the tubes in. Set the multimeter to measure resistance and connect the meter's test leads to the filament pins. (You can consult on-line tube manuals for the pin configuration. For testing other parameters, a tube tester is needed.)

I have a George Kaye Small Signal Tube Checker that I find very handy for testing smaller tubes for emission, gain, noise and microphonics (the tendency for a tube to literally act as a microphone; you can sometimes hear an audible "clunk" or "ring" when tapping on such a tube when an amp or preamp is on). The tester tests for distortion level when the tube is overdriven; the distortion level rises when the tube's emission falls, due to aging. The gain is measured at one operating point only, but this is adequate for tube matching in less-critical circuit positions. The noise and microphony test is very useful, as the tester allows you to actually listen through headphones as well as see the noise level on a VU meter. I use this function to sort tubes (from least to most noise) for use in the phono stage, the input stage, the driver stage or the output stage of phono stages, preamps, integrated amps and power amplifiers. Unfortunately, this tester is no longer made, and it can only test small-signal tubes like 12AX7s, not bigger power tubes. However, I mention its use in order to outline what to look for when testing tubes, and I'll cover other vintage and current tube testers a bit later.

Adrian's George Kaye Small Signal Tube Checker.

Matching tubes is important if they are to be used in push-pull amplifier output stages, in differential (balanced) circuits, and in outputs that use parallel devices. In all of these cases, the performance of the tubes needs to be matched as closely as possible.

In push-pull output designs, where one tube (or set of tubes) amplifies the positive phase (or half) of the audio signal and the other tube (or tube set) amplifies the negative phase, an imbalance of the current between the two phases will lead to saturation of the transformer core and a rapid drop in inductance. If this is allowed to persist, the transformer core will become permanently magnetized. Many amplifiers allow for adjustment of the plate current of output tubes. If not, or if the amplifier uses cathode bias, matched tubes will be needed. Amplifiers with parallel push-pull output devices often do not have separate adjustments for each tube. Therefore, using matched tubes is essential. In differential circuits, mismatched tubes will result in increased distortion, but the result depends on the circuit design. Many well-engineered modern amplifiers make use of transistor constant-current sources or sinks to control the plate current of the tubes. This ensures a more stable operation and vastly improves the common mode rejection ratio of the differential stage. Such a design is less sensitive to the drift in parameters such as plate resistance, gain and transconductance.



Graph of a sine wave showing the positive and negative halves of the waveform. Courtesy of Wikimedia Commons/AlanM1.

Ideally, tubes should be matched for emission and transconductance (the change in plate current per unit change in grid voltage). However, with most tube testers, transconductance is measured only at a single operating point. To match tubes at a variety of operating points, a curve tracer is needed.

The most popular tube tester in history was the TV-7 Series, which was made for the US military by Hickok and others. At one time these testers could be picked up at the second-hand market for very little money, but they themselves use tubes and need to be restored and calibrated in order to perform correctly. Audio clubs with sufficient funds and expertise should invest in a laboratory-grade tube tester for their members' use. The best vintage examples of these include the British AVO VCM 163 and the German Neuberger RMP370. My recording partner bought two AVO163s and used one as a parts donor to restore the other. The tester is a great piece of British engineering, and a real pleasure to use. Vintage tube testers were also made by B&K, Eico, Knight, Precision Apparatus Company, Sencore, Heathkit and others.

[Copper's *J.I. Agnew refurbishes tube testers. He's located in Europe. Vintage Tube Electronics is located in the US and repairs and calibrates tube testers. – Ed.]*

The most famous tube curve tracer is the Tektronix 570, which is rare and expensive. It displays the testing results on a cathode tube display. However, it only provides up to 300VDC of plate voltage and 150mA of plate current, so some tubes cannot be tested at their typical operating condition. The Tektronix 575 transistor curve tracer is easier to find – and can be modified to measure tubes. In recent years, several curve tracers aimed at audio hobbyists have become available. These devices connect to a computer via a digital interface, and all the information is displayed on the computer screen. These devices can test for emission, gas leaks, short circuit between electrodes, plate resistance, gain and transconductance, and they can also generate tube curves that display plate current vs. plate voltage at different grid voltage steps.

The Amplitrex AT1000 is a self-contained unit that can be used without a computer to measure various tube parameters by means of an LED screen. However, it does have to be used with a computer in order to generate curves. The software is rather clunky and still uses an RS232 interface. Another limitation is that it only measures the parameters at one operating point. Also, it only has a power supply for one grid, and therefore can only measure tetrodes and pentodes wired as triodes. It does have a headphone output that allows the user to assess tube noise and microphony.

Amplitrex AT1000 tube tester.

The RoeTest was designed by a German enthusiast and is a very flexible apparatus. It has three grid power supplies, and can measure tube parameters at different operating points. However, the designer can only supply the software, the blank printed circuit boards, the transformers and the design files for the construction of the chassis. The user must buy all the electronic components, order the chassis from a chassis shop and build the device him or herself. The design is quite complicated, and since it involves voltages of up to 600V, the user must be experienced in building and testing tube amplifiers to tackle such a project.

A newcomer to this space is the eTracer. It was designed by a Taiwanese electronics engineer, and can test tubes at up to a maximum plate voltage of 750V at up to 300mA. This means that even high-powered triodes can be tested. It can measure cathode-heater leakage, which is important for cascode, SRPP and other topologies where one tube is stacked on top of another and the cathode of the upper tube is at an elevated voltage. If the heater filament of the upper tube is kept at ground potential, there will be a large potential difference between the heater and the cathode, leading to a leakage current, which causes noise. The proper way to design such a circuit is to have a separate heater power supply for the upper tube, elevated to the same voltage as the cathode. This will add to the cost and complexity, and not all manufacturers do it. Users should therefore choose the tubes with the lowest leakage to serve as the upper tubes in these circuits.

The eTracer can also detect gas leaks by measuring the change in plate current when a resistor is added to the grid circuit. The grid current caused by ionized gas molecules will raise the grid voltage when the resistor is in place, which can be detected as an increase in plate current. The software is very sophisticated, and parameters (plate current, plate resistance, gain and transconductance) at different operating points are displayed simply by placing the mouse cursor on different areas of the graph. It has a curve-matching facility that helps you find tubes that are the most closely-matched to each other. The eTracer can also calculate distortion with different anode loads, which is helpful if you are designing a circuit.

The device can be bought as a kit or a fully assembled and tested product. The basic model requires the user to hook up the different pins of the tube socket manually using banana plugs, which reminds me of an old telephone switchboard. There is also an optional computer-controlled wire routing module, but I don’t think this is a necessary expense unless you plan on testing many different tube types in one sitting. The fully assembled basic tester costs around $1,200, and I view this as a high-value acquisition if you use tube equipment regularly. To put this into perspective, a new pair of reissue Western Electric 300B is quoted as $1,499 on the manufacturer’s website. Shouldn’t you at least find out if they are working as advertised?

Tube Depot.com also has these Western Electric 300B tubes, New Old Stock from the 1930s! They'll set you back $19,995.

Postscript: A word about output transformers.

The quality of a tube amplifier's output transformer is extremely important. Since it is expensive to build a high-quality transformer, any attempt to cut cost there could seriously undermine the amplifier's sound. This is especially true for single-ended amplifiers, since an air gap in the transformer is needed to prevent transformer core saturation, which would cause audible distortion and other problems. However, having an air gap lowers the inductance, which compromises low-frequency response. To increase the inductance requires adding more windings, which adversely affects the high-frequency response. It is therefore a balancing act when designing such transformers. An obvious solution is to use different amplifiers that are optimized for different frequency ranges to power the different drivers (woofers, midrange and tweeters) of the loudspeakers, using an active crossover, but I digress. (This is just one of the variables that make owning and operating vacuum tube equipment so intriguing.)