BUILD THE TUBEHEAD

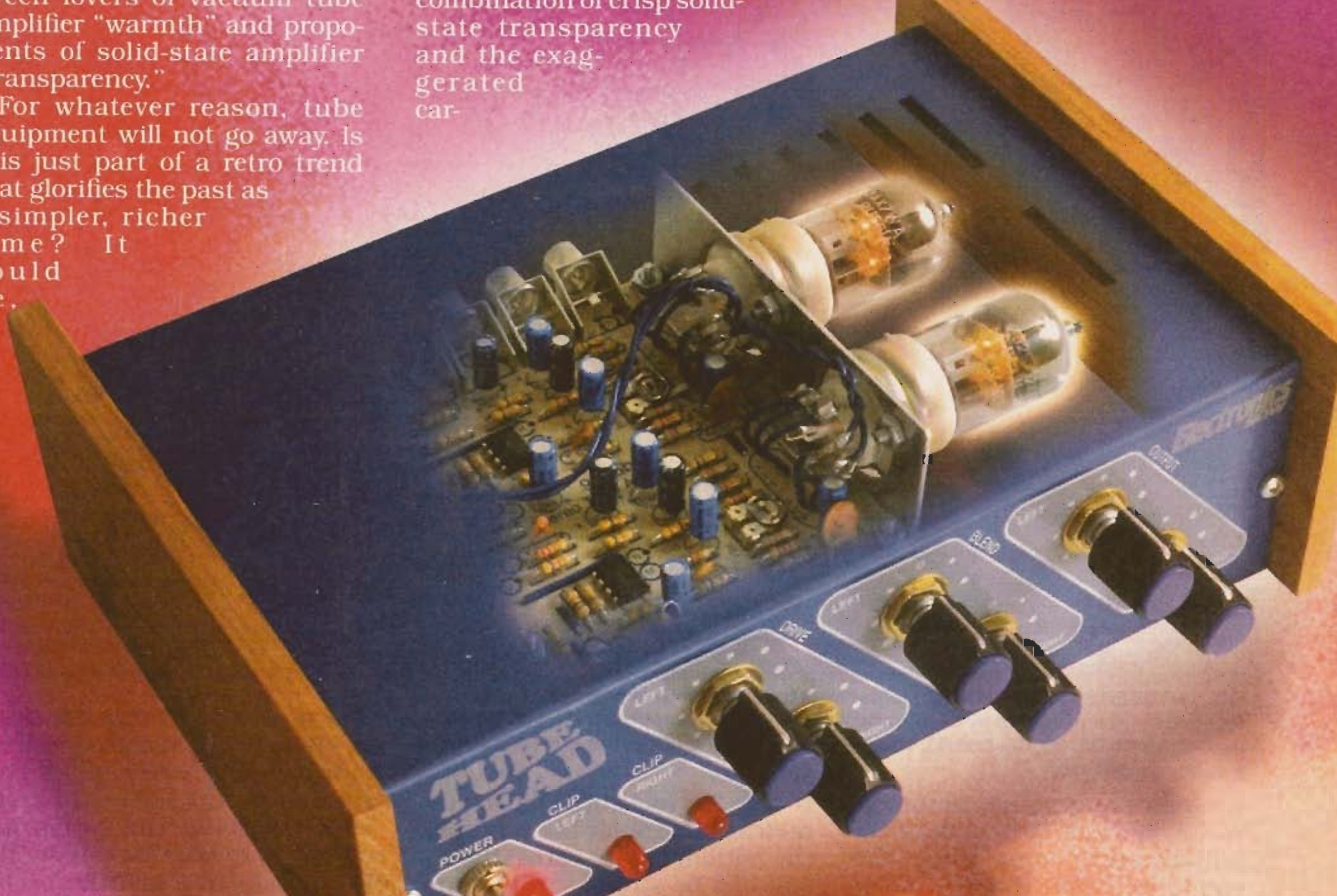
THE OPTICAL PITS ON COMPACT discs that store sound digitally are a remarkable technical accomplishment as far removed from the spiral grooves in vinyl records as ICs are from vacuum tubes. However, many audiophiles believe that compact discs are just the pits—nothing more than over-sampled, error-corrected digital records.

Opinions run so deep on this subject that the arguments rekindle the on-going dispute between lovers of vacuum tube amplifier "warmth" and proponents of solid-state amplifier "transparency."

For whatever reason, tube equipment will not go away. Is this just part of a retro trend that glorifies the past as a simpler, richer time? It could be, but the differences between solid-state and vacuum-tube amplifiers are more than myth—they are real. To see (hear actually) how tube technology might improve the sound of your CDs, read on and take a close look at the TubeHead, a preamplifier with a twist. This hybrid circuit uses both low-noise solid-state op-amps and tubes together, so you can dial in the precise amount of sonic coloring you like—a combination of crisp solid-state transparency and the exaggerated caricature of tube-amp warmth.

Tube sound?

Many people believe that vacuum tube amplifiers sound "warmer," "fuller," or just plain louder than their solid-state cousins. There's wide, but not universal, agreement that those differences originate in the ways that solid-state and vacuum-tube amplifiers overload. Where solid-state circuitry tends to be linear over most of



Mellow the harsh sound of compact discs with the TubeHead preamp.

JOHN SIMONTON

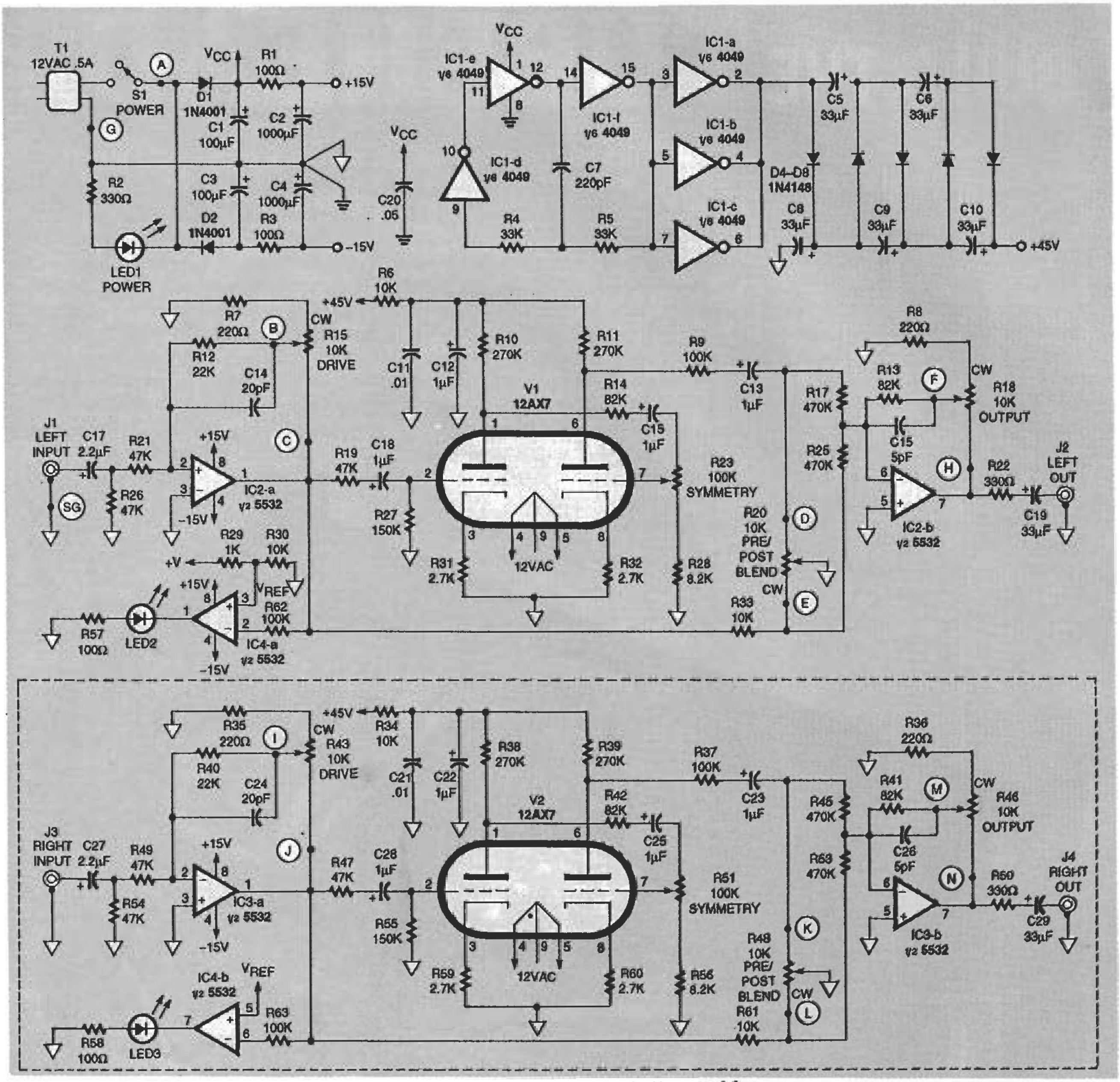


FIG. 1—TUBEHEAD SCHEMATIC. Output from transformer T1 is positive half-wave AC rectified by D1 and filtered by C1, C2, and R1 for a +15-volt supply. A −15-volt supply is available from D2, C3, C4, and R3. The plate supply for the 12AX7 tubes is produced by a voltage multiplier.

its operating range before it suddenly clips, tube amplifiers usually start "squashing" the signal well before they run out of headroom (see the "Clipping and Squashing" sidebar).

Both of those responses produce harmonic distortion, adding frequency components that were not in the original signal, but "squashing" generates much lower order harmonics. The result doesn't have the "buzzy fuzziness" that comes from the high-frequency components produced by clipping.

If the "squashing" is asymmetrical (more on the top than the bottom or vice-versa) the result can be strong second- and fourth-order overtones. These are musically benign in terms of producing dissonance, and more pleasing (though not necessarily more interesting) than the odd harmonics of clipping.

Consider this: All natural instruments generate an increasingly complex harmonic structure when they're played louder. They don't just produce higher sound pressure levels—in a very real way they get "fuller." In fact, the increase in harmonic complexity gives the strongest indication to your ears (actually the brain attached to them) that one sound is louder than another. The squashing distortion of vacuum tubes extends this same principle to amplifiers. This might be the reason why tube amplifiers are so often subjectively judged to be "louder" than solid-state units.

Any preference for the warmer, fuller sound of tubes might be nothing more than habit. After all, even with vacuum tubes out of the picture, analog

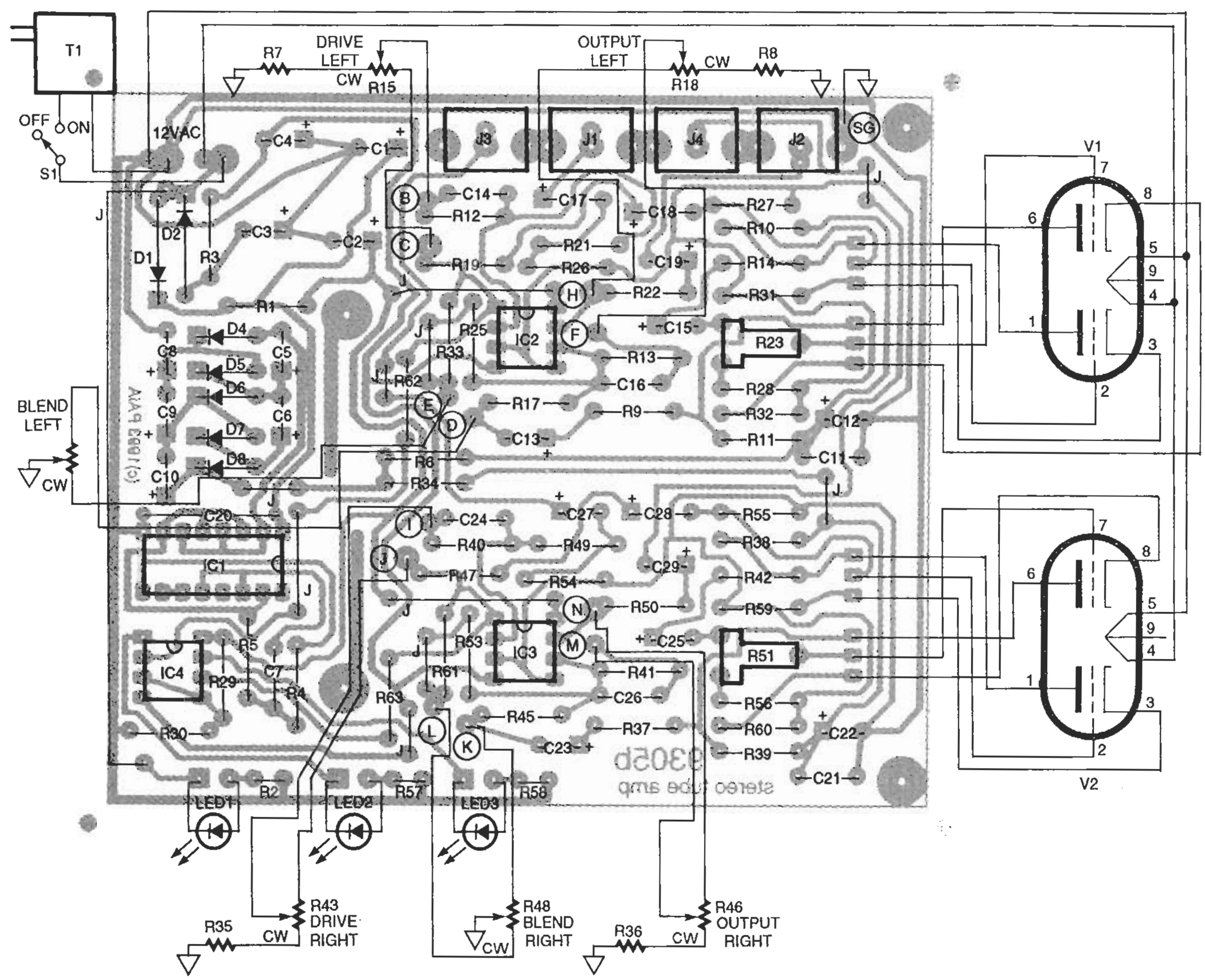


FIG. 2—PARTS-PLACEMENT DIAGRAM. Any accepted assembly technique can be used for the TubeHead, but a PC board is recommended.

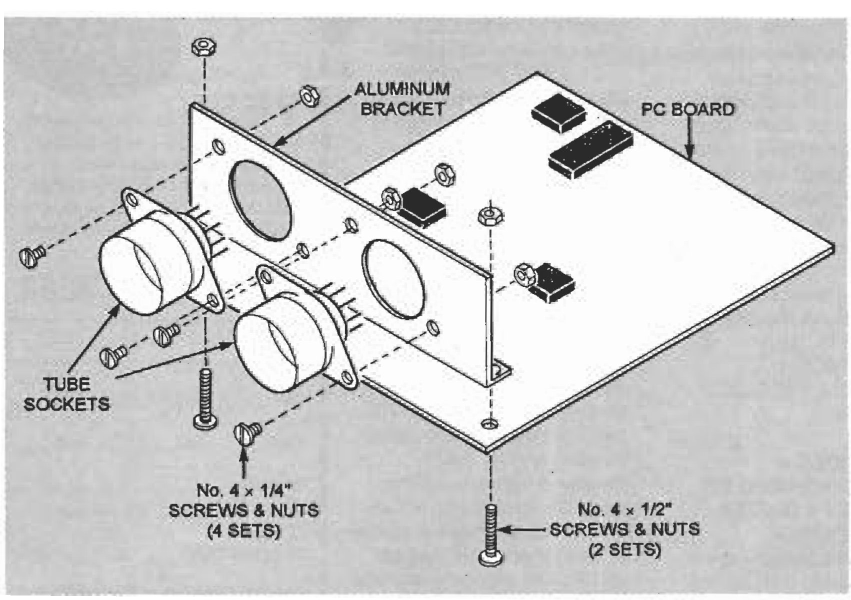


FIG. 3—THE TUBES ARE MOUNTED HORIZONTALLY to fit in a low-profile case. Four No. 4 × ¼ inch machine screws and nuts fasten the tube sockets to their mounting bracket. The right-angled aluminum bracket is fastened to the circuit board with four No. 4 × ½-inch screws and nuts that also hold the assembly in the case.

tape and vinyl records still had the same compressing non-linearities. It's not unusual to find a listener expressing a preference for a taped copy of a CD over the CD itself. It was the general acceptance of CDs and digital sound recording that finally removed the last vestiges of natural "imperfection."

If tube preference is only habit, it is deeply ingrained. Even with the overwhelming editing and duplicating advantages of digital audio tape, many artists and engineers prefer to record on analog tape before transferring the sound to digital audio tape. Also, some of the most expensive condenser microphones used in professional recording have a vacuum-tube preamplifier built into the microphone. And if you don't know that tube amplifiers are *de-rigueur* in rock 'n' roll, it can only be because you don't care.

CLIPPING AND SQUASHING

All amplifiers become non-linear when they're driven hard enough, but tubes and transistors distort in distinctly different ways. An easy way to see these differences is with transfer curves such as those shown here. The input at the bottom responds to the curves to produce the outputs shown at right.

The transfer curve shown in Fig. 1-*a* is typical of a solid-state amplifier. Response is linear and wonderful until you run out of headroom, and then the signal is suddenly clipped. The curve in Fig. 1-*b* shows what happens in the typical vacuum-tube amplifier. Because the ends of the curve roll over gradually rather than suddenly reaching a plateau, an increasing output is gracefully "squashed" rather than suddenly "clipped."

When you refer to the work of Fourier related to this clipping and squashing business, he tells us that a "discontinuity," such as the point where the output of the solid-state amplifier suddenly stops changing, splatters a spectrum of harmonics. These frequency overtones in the original waveform, both odd and even, easily extend into and beyond audible range. Even a guitarist's "fuzz box" doesn't generally produce harmonic structures like this because, in a musical context, the strong odd-order harmonics can lead to unplanned, unpleasant dissonances.

"Squashing," on the other hand, has no discontinuities and, because of this, the harmonics cluster within a few octaves of the fundamental. A particularly interesting observation is that while linear response leaves harmonics unchanged and clipping can only add harmonics, this squashing distortion can actually decrease total harmonic content. In Fig. 2, a triangular waveform is passed through a squashing function to produce a nearly sinusoidal output; the odd-order harmonics that made the input a triangle have been suppressed. Unlike a filter, this harmonic suppression is not frequency sensitive. Ω

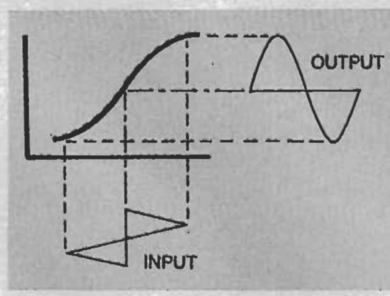


FIG. 2—A "SQUASHING" TRANSFER function can decrease total harmonic content of a signal, such as the triangular wave shown here.

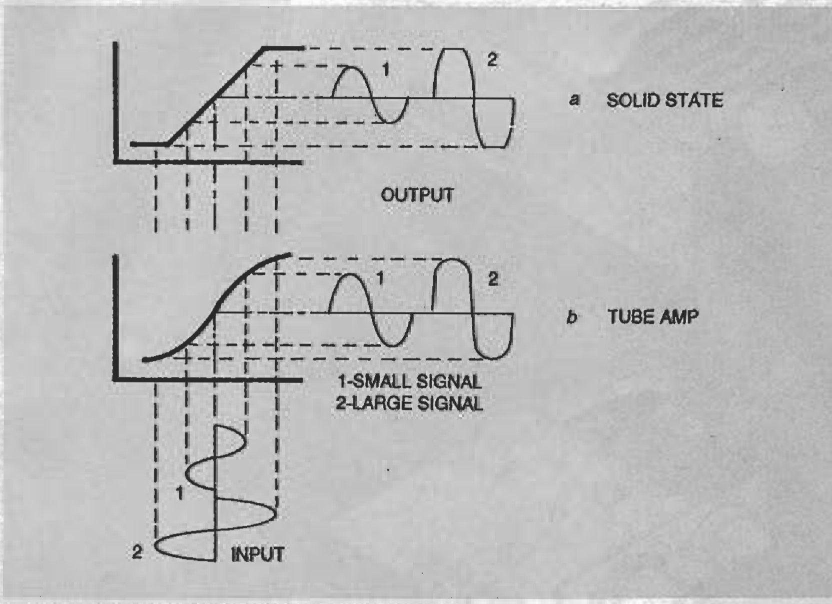


FIG. 1—TRANSFER CURVES show how an input is transformed into an output. The solid-state amplifier (*a*) is linear over most of its useful range before it suddenly plateaus. A tube amplifier (*b*) is never completely linear and goes into saturation gradually.

The TubeHead circuitry exaggerates the natural non-linearities of the tubes by operating them at fairly low voltages and plate currents (see the Vacuum Tube Fundamentals sidebar). In addition to controlling how hard the tubes are driven, and consequently how much the signal is squashed initially, the circuit also features a blend control that sets the relative amounts of pre-tube or post-tube signal in the output.

How it works

The TubeHead schematic is shown in Fig. 1. The output from 12-volt AC transformer T1 is positive half-wave AC rectified by D1 and filtered by C1, C2, and R1 for a +15-volt supply. A −15-volt supply is obtained from D2, C3, C4, and R3.

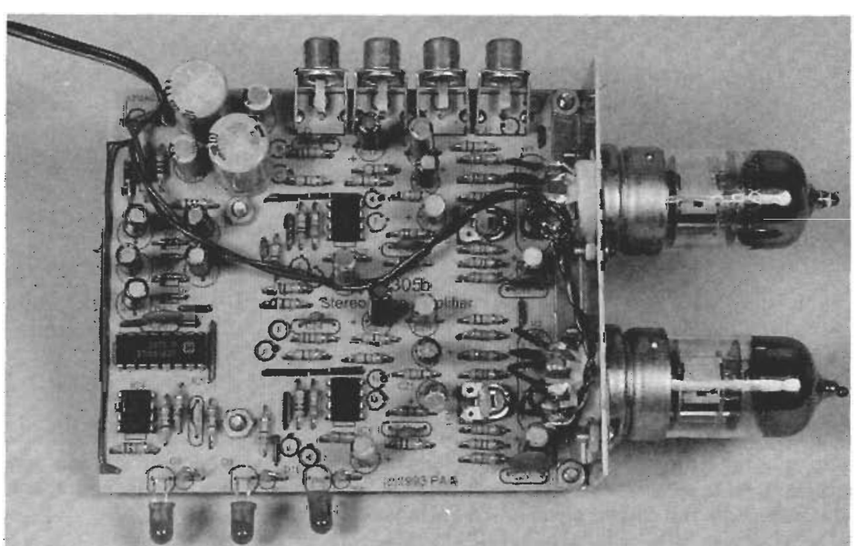


FIG. 4—COMPLETED PC BOARD and tube assembly.

Most tube circuits operate at high plate voltages, often hundreds of volts, and components needed to obtain those voltages

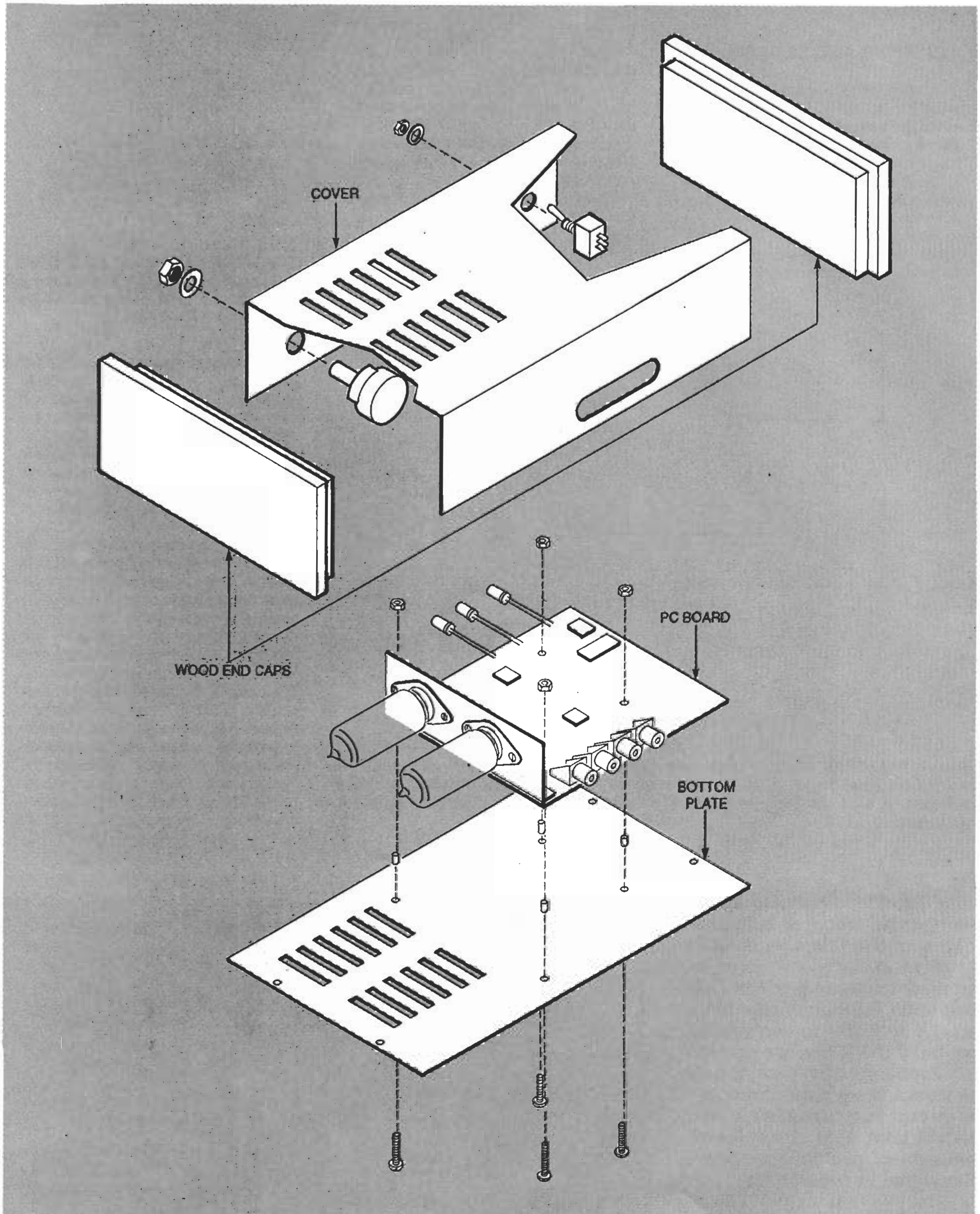


FIG. 5—THE CASE IS FORMED from 0.040-inch sheet aluminum with the top and bottom held together by screws driven into the wooden end caps. You can purchase this case from the source given in the Parts List.

can be expensive and difficult to find as well.

However, the method used to make a tube *really* sound like a tube is to "starve" it with low plate voltage.

The 45 volts required for the TubeHead is higher than would typically be found in solid-state circuitry. In place of an exotic multiwinding power transformer, the tube's plate supply is produced by a voltage multiplier. Capacitor C7 and resistors R4 and R5, together

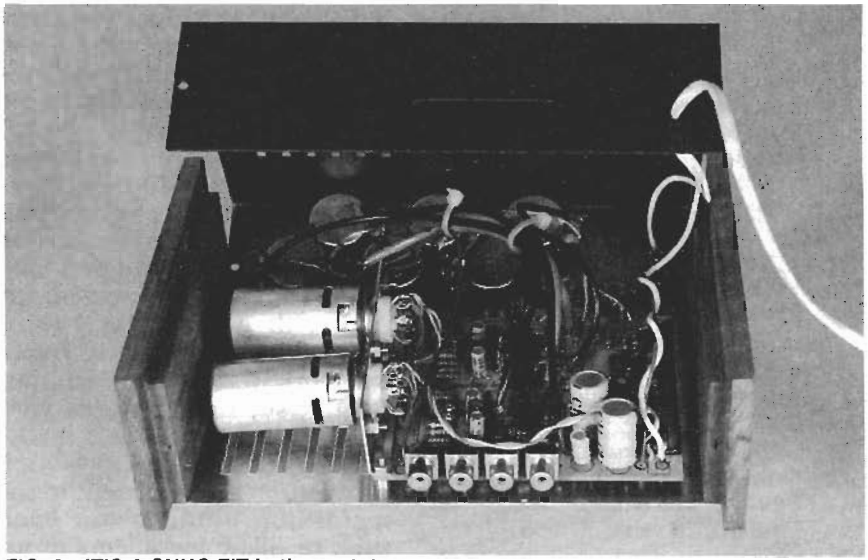
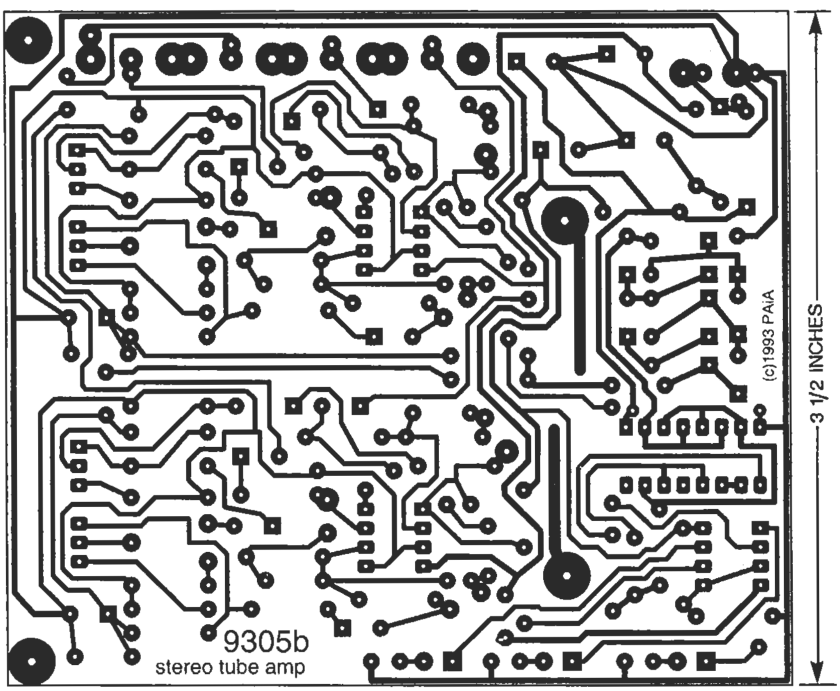


FIG. 6—IT'S A SNUG FIT in the prototype case.



TUBEHEAD FOIL PATTERN.

with three of the six inverters in IC1 form a 60-kHz, 15-volt, peak-to-peak, square-wave oscillator. The remaining three buffers in IC1 are wired in parallel to provide the greater output current necessary for driving a network of diodes (D4 to D8) and capacitors (C5, C6, C8 to C10) that multiply the 15-volt square wave to a DC voltage as high as 45-volts.

The stereo TubeHead consists of two identical preamplifier/tube/final amplifier sections. The left channel is built around a 12AX7 tube (V1) and a 5532 op-amp (IC2). The right channel is identical to this section.

The signal path begins with an adjustable gain stage built around op-amp IC2-a. Input signals are coupled by C17 and appear across R26. When the DRIVE control R15 is fully counter-clockwise, the voltage gain is set to a minimum of ½. At the clockwise end, the voltage gain is set to a maximum of 25. Capacitor C14 rolls off the high frequency response at a corner frequency of about 30 kHz. An op-amp wired as a comparator (IC4-a) turns on LED2 when the output of the gain stage starts to clip.

Two tube stages provide maximum control of the output waveform's asymmetry. Both tube stages are within the envelope of V1, a 12AX7 dual triode. The output of IC2-a is coupled by R19 and C18 to R27, the grid resistor of the first tube stage. The output of the first tube stage appears across plate-load resistor R10, and is coupled by R14 and C15 to SYMMETRY trimmer R23. Trimmer output sets the amount of signal applied to the grid of the second stage. The output of the second stage appears across plate-load resistor R11.

A final output buffer stage built around op-amp IC2-b converts the relatively high impedance output of the tubes to a lower impedance consistent with contemporary audio equipment. Its operation is very similar to that of the circuitry around IC2-a.

Op-amp IC2-b also mixes the dry signal (pre-tube) with the post-tube processed signal using the BLEND potentiometer R20. At the clockwise end of R20's rotation, the final amplifier is fed exclusively with the output of the tube. At the counter-clockwise end, it's fed by the buffered input signal from the first gain stage. At intermediate settings of R20, a mix of the dry signal and the tube output drive the final buffer. The relative values of R37 and R61 compensate for the additional gain of the tubes so that the overall level is fairly constant as BLEND is varied from "pre" to "post."

Building the TubeHead

Any accepted conventional technique can be used for the assembly of the TubeHead electronics. The foil pattern for the PC board in the TubeHead is provided in this article if you want to make your own. However, ready-to-use PC boards and other components are available from the source given in the Parts List. Figure 2 is the parts-placement diagram for the PC board.

If you build the TubeHead from scratch, there are some

PARTS LIST

All resistors are ¼-watt, 5%, unless otherwise noted.

R1, R3, R57, R58—100 ohms
R2, R22, R50—330 ohms
R4, R5—33,000 ohms
R6, R30, R33, R34, R61—10,000 ohms
R7, R8, R35, R36—220 ohms
R9, R37, R62, R63—100,000 ohms
R10, R11, R38, R39—270,000 ohms
R12, R40—22,000 ohms
R13, R14, R41, R42—82,000 ohms
R15, R18, R20, R43, R46, R48—10,000 ohms, panel-mount potentiometer
R17, R25, R45, R53—470,000 ohms
R19, R21, R26, R47, R49, R54—47,000 ohms
R23, R51—100,000 ohms, horizontal-mount trimmer potentiometer
R27, R55—150,000 ohms
R28, R56—8200 ohms
R29—1000 ohms
R31, R32, R59, R60—2700 ohms

Capacitors

C1, C3—100 µF, 25 volts, electrolytic
C2, C4—1000 µF, 16 volts, electrolytic
C5, C6, C8–C10, C19, C29—33 µF, 25 volts, electrolytic
C7—220 pF, ceramic disk
C11, C21—0.01 µF, ceramic disk
C12, C13, C15, C18, C22, C23, C25, C28—1 µF, 50 volts, electrolytic
C14, C24—20 pF, ceramic disk
C16, C26—5 pF, ceramic disk
C17, C27—2.2 µF, 25 volts, electrolytic
C20—0.05 µF, ceramic disk

Semiconductors

D1, D2—1N4001 diode
D3—not used
D4–D8—1N4148 diode
LED1–LED3—Red light-emitting diode
IC1—CD4049 CMOS hex inverting buffer, Harris or equivalent
IC2–IC4—NE5532 dual low-noise op-amp, Signetics or equivalent

Other components

J1–J4—RCA phono jack (PC mount)
S1—SPST switch
T1—12.5-volt AC, 500 milliampere wall-mount transformer
V1, V2—12AX7 dual triode tube

Miscellaneous: tube sockets and mounting brackets, wire, solder, hardware, PC board, case, etc.

Note: The following items are available from PAiA Electronics, Inc., 3200 Teakwood Lane, Edmond, OK 73013, phone (405) 340-6300, fax (405) 340-6378:
- **TubeHead PC board with tube-mounting bracket (9305pc)—$22.50**
- **Complete kit of parts and PC board, less case, for 2-channel TubeHead (9305k)—$78.25**
- **Punched, formed, and anodized case with 2-color legending and wooden end caps (9305cen)—$19.50**

Please add $5 P&H to each order.

precautions to observe: Every ground in the system should return to a single point, but this is not always practical. Nevertheless, it is *very important* that there be separate wires for the ground of the audio circuitry and the power ground to IC1. The frequency of the 60-kHz square wave that drives the voltage multiplier is above the audio range, but if it leaks into the audio path it can cause unpleasant distortion. It is also recommended that you separate the voltage multiplier from the audio components (particularly the tubes and related components) by placing them at opposite ends of the board.

Connect the tube filaments directly to the points where the transformer wires meet the PC board with separate wires. Be sure that no filament power passes through any part of the signal ground. Twist the filament wires together and route them away from all of the audio components.

When installing components, observe the polarity of electrolytic capacitors and diodes. Note that a single-channel version of the TubeHead can be built by eliminating all of the components drawn within the dashed lines on the schematic.

The TubeHead circuitry will fit into a low-profile case if the tubes are mounted horizontally. A right-angle aluminum bracket holds the tube sockets to the component board as shown in Fig. 3, and individual wires connect the socket's solder lugs to the rest of the circuitry. Figure 4 shows the completed PC board and tube assembly.

The prototype case was formed from 0.040-inch sheet aluminum with the top and bottom held together by screws driven into the wooden end caps (see Fig. 5). However, any case with interior dimensions greater than 7 × 5 × 2 inches will work well. If you make your own case, don't forget that tubes radiate a lot of heat. In the prototype, twelve 1 × ⅛-inch ventillation slots were cut in the metal above and below each tube to allow for adequate air flow. Figure 6 shows how all the components fit in the prototype case.

When you have completed the assembly and thoroughly checked your work, it's time for the all important "smoke" test. If any fault shows up, it is most likely to occur at this time.

Plug the wall-mount transformer into an outlet and turn on the power switch. The POWER indicator (LED1) should light; if it doesn't, you should immediately unplug the unit and find out why. Improperly placed components or solder bridges on the circuit board might be the cause. Also check the orientation of the integrated circuits.

When LED1 lights, let the unit idle for a few minutes while you check for passive components that might be getting hot, smoke, or any unusual smell. Observe the tube filaments to be sure they're glowing—if not, check the soldered connections on the tube sockets and the twisted pair that connects the filament circuit to the power supply.

If everything works well after a few minutes of operation, connect a low-impedance, line-level source to the left input (J1), and connect the corresponding output (J2) to an amplifier. Set the left channel DRIVE, BLEND, and OUTPUT controls to midrange and confirm that the signals flow correctly through the unit. Change the settings of the controls and observe that each one affects the sound. Notice that at

VACUUM-TUBE FUNDAMENTALS

Figure 1 shows a typical triode vacuum tube. Because of the Edison Effect, heat from the filament drives free electrons from the oxide coating on the cathode. The positive voltage on the plate attracts the electrons, and the moving electrons produce a current flow. A negative bias voltage on the grid repels some of the electrons and prevents them from reaching the plate, resulting in lower current flow. In this way, a changing negative charge on the grid can modulate the plate current.

One source of non-linearity in vacuum tubes is "space charge;" electrons that are driven from the cathode but don't reach the plate simply accumulate. This cloud of negatively charged electrons has the same effect as a negative voltage applied to the grid—it decreases current flow. This is referred to as "self-biasing." This is a non-linear process because increasing negative grid voltage blocks electrons, which produces more space charge. This has the effect of making the grid even more negative.

Operating a vacuum tube at low plate voltages doesn't significantly affect the number of electrons that leave the cathode; that is primarily set by the filament temperature. So at low plate voltages and currents, space charge becomes a more important factor (just as many electrons are leaving the cathode, but fewer of them are reaching the plate). As a result, the non-linearity which is present in all tubes is exaggerated.

The TubeHead circuitry operates at such low voltage and current that it completely self-biases. To see this, measure the voltage between any of the grids and ground with a high-impedance scope or voltmeter. You will find that the grid is about 1 volt, negative. The negative voltage is the result of electrons boiling off the cathode and clustering around the grid. Ω

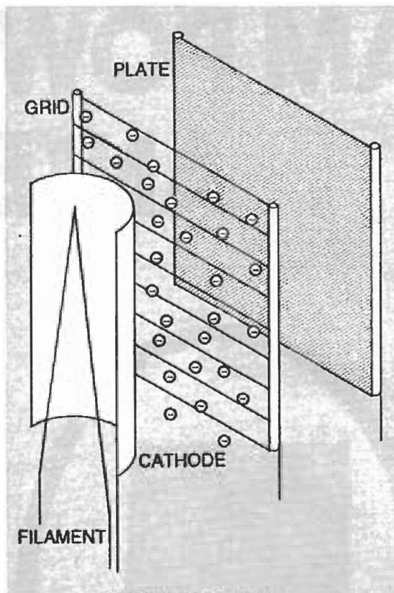


FIG. 1—TYPICAL TRIODE vacuum tube. Heat from the filament causes electrons to boil off the cathode. Any electrons not attracted to the positive plate voltage form a cloud that biases the tube.

some point in the rotation of the DRIVE control potentiometer, CLIP indicator LED2 turns on.

Disconnect the source and amplifier from the left channel and connect it to the right channel. Confirm that this channel behaves the same way as the left channel.

Using the TubeHead

The 50:1 gain range available from the TubeHead's input buffer stage allows a wide range of signal sources to be processed. Typically, the signal source, such as a CD or tape player, can be plugged into the TubeHead inputs, and the outputs can plug into the main amplifier. The tape monitor input and output jacks on your integrated amplifier will provide a handy "effects" loop.

Each channel has three front-panel controls and one internal trimmer. The DRIVE control determines how hard the tube is driven and, as a result, how much it "squeezes" the signal. The circuitry is designed so that with DRIVE set to minimum, the tube begins its non-linear response at about 0 dBV. With DRIVE at maximum, non-linearity onset occurs at about a 20-millivolt input.

The BLEND control sets the relative amounts of pre- and post-tube sound in the output. With the control fully counter-clockwise (the "pre" setting), only the clean signal appears in the output. Turning the control fully clockwise (the "post" setting) provides an exclusive output of tube sound.

The final panel control for each channel is the OUTPUT level. After setting the DRIVE and BLEND controls, set the OUTPUT level as needed for the best balance and lowest overall noise in the signal path.

As with the front panel controls, the SYMMETRY trimmer for each channel should be set to taste. These trimmers (R23 for the left channel and R51 for the right) are arranged so that at the clockwise end of their rotation, the output of the TubeHead is approximately symmetrical. Counter-clockwise rotation of these trimmers increases the asymmetry.

Notice that CLIP indicators LED2 and LED3 light when the first op-amp gain stage begins to clip; they are not intended to indicate distortion in the tube. If the CLIP indicator for a channel lights, reduce the DRIVE until the light goes off. Overloading the tube produces the desired effect, but overdriving the op-amps does not.

If you're involved in the production of music, either as musician or sound engineer, you'll find the TubeHead to be a useful addition to your bag of audio tricks. In addition to its warming ability, the TubeHead's "squashing" action makes it a useful substitute for an audio compressor or sustainer. The compression of an overloaded vacuum tube is not the same as a normal studio compressor. Compressors act on the average level of a signal over a relatively long time period. They affect the envelope of the signal without altering the harmonic structure. The tube's action is on a cycle-by-cycle basis, but with the exception of the subtle harmonic distortion that this produces, other effects are similar.

The nominal input impedance of the TubeHead is about 20 kilohms, consistent with most hi-fi equipment, synthesizers, and sound blasters. However, it is a little low for a proper match with high-impedance sources such as guitar pickups. A few minor changes will overcome this incompatibility; remove R26 and C14 and change the value of R21 to 680 kilohms and R12 to 100 kilohms. This increases the input impedance to 680 kilohms, making it compatible with such instrument transducers as piezoelectric microphones and guitar pickups. Ω