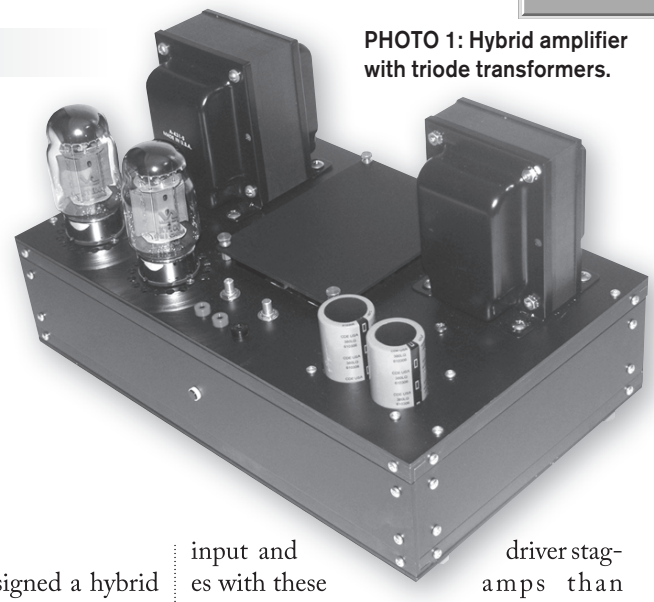


PHOTO 1: Hybrid amplifier with triode transformers.

A Hybrid High-Fidelity Power Amplifier

This patent-pending design features a National Semiconductor IC in a vacuum tube topology.

For years I have thought about building an amplifier with output tubes and transformer driven by a solid-state front end and driver stage. But I put the idea aside because I wanted to use integrated circuit operational amps to avoid the complexity of designing the driver stage with discrete components, and, to my knowledge, there wasn't a suitable IC op amp available. About a year and a half ago, that changed when National Semiconductor introduced the LM4702, a high voltage dual op amp intended for use in high-fidelity amps with solid-state output stages. In the commercial grade you can operate it from a ±75V power supply, which is more than adequate for the driver stage of a tube amp.

When the output devices of a class AB power amp are properly biased, there is a small overlap in the signals delivered by these devices. Class AB amps that employ solid-state devices in their output stages generate extremely fast switching transients when one device switches off and the other switches on. Traditionally these transients are nulled out with large amounts of negative feedback.

But this can cause an effect called transient intermodulation distortion. This is because the input stage where the error correction takes place has a difficult time handling the slew rate of these transients. This effect is difficult to measure, but it is audible. It is my opinion that this phenomenon is what makes tube amps sound different from solid-state amps.

CIRCUIT DESIGN

Using the LM4702, I designed a hybrid audio amp that uses a solid-state input and phase-splitting driver stage feeding a push-pull vacuum tube output stage typical of conventional vacuum tube audio amps. The input stage is composed of a non-inverting operational amp that accepts the input signal and negative feedback signal. The driver stage uses the LM4702 with one amp inverting and the other non-inverting, thereby providing the phase-splitting function with sufficient voltage swing needed to drive the control grids of vacuum tubes in a push-pull output stage. The combined gain of the input and driver amps is set to emulate their counterparts in a conventional vacuum tube amp. The gain is set higher than the overall closed loop gain of the amp by a factor determined by the amount of negative feedback that you desire.

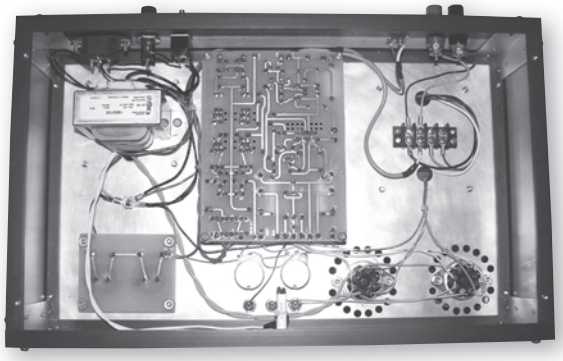


PHOTO 2: Hybrid amplifier chassis wiring.

For the solid-state operational amps I used Burr-Brown's (Texas Instruments) OPA134 for the input stage and National Instruments' LM4702 high voltage dual op amp for the driver stage. You can achieve much lower distortion in the input and driver stages with these amps than you can typically achieve with input and driver stages using vacuum tubes. This combination takes advantage of the strengths of both technologies.

The basic topology of the hybrid amp is shown in **Fig. 1**. It is typical of the topology found in many conventional vacuum tube amps, with the exception that the input amp and phase-splitting amps are solid-state. The input is connected to the non-inverting input of op amp U1, and the output of the feedback network of R7 and C3 is connected to the inverting input of U1. Resistors R1 and R2 form a local feedback loop that sets the gain and stabilizes this stage of the amp.

The output of this stage feeds two operational amplifiers U2a and U2b. U2a is configured as an inverting amp with resistors R3 and R4 setting its gain. U2B is configured as a non-inverting amp with resistors R5 and R6 setting its gain. The gains of U2a and U2b are equal in magnitude but opposite in polarity, thereby producing the required phase-splitting function.

The DC voltage of this stage is isolated from the output stage by capacitors C1 and C2. This is necessary because the control grids of the output tubes must be negatively biased with respect to their cathodes. The DC bias network performs this function. The output tubes are connected to the primary winding of the output transformer.

The secondary winding of the transformer is connected to the load and to a feedback network of resistor R7 and

capacitor C3. Resistor R7 in conjunction with resistor R1 sets the overall closed loop gain of the amp in the audio range. Capacitor C3 is not always necessary, but when it is employed, it will reduce the gain of the amp above the audio range and in some cases may be necessary to stabilize the amp.

THREE EXAMPLES

I've built three amps with this topology. The first, a mono amp, uses the transformers out of an Eico HF-20 integrated amp that I bought at a flea market years ago. The Eico used 6L6GC output tubes, but I was able to upgrade to EL34s because I didn't need to provide filament current to preamp and driver tubes. The result was great. I achieved nearly 40W versus 20 that Eico specified and with less than 0.1% IM distortion. And it sounded great.

The second is a stereo amp that I built around Acrosound TO-330 output transformers, which I had from amps I built using Eico's HF-60 circuitry. I powered the amp with a Toroid of Maryland Transformer, P/N 326.5072, which was large enough to power the two channels. Again, the results were great. I achieved about 70W per channel.

The only problem these amps have is that the output transformers would be nearly impossible to duplicate. Therefore, I decided to build a third amp using readily available parts—transformers from Triode Electronics that are clones of transformers used in the Dyna Mark III. This is the amp that I am describing here. The schematic is shown in **Fig. 2** with the power supply in **Fig. 3**.

Combined gain for the input and driver stage is set to 180. The gain of the driver stage is about 32 or 30dB (National Semiconductor specifies a minimum gain of 26dB for stability). The

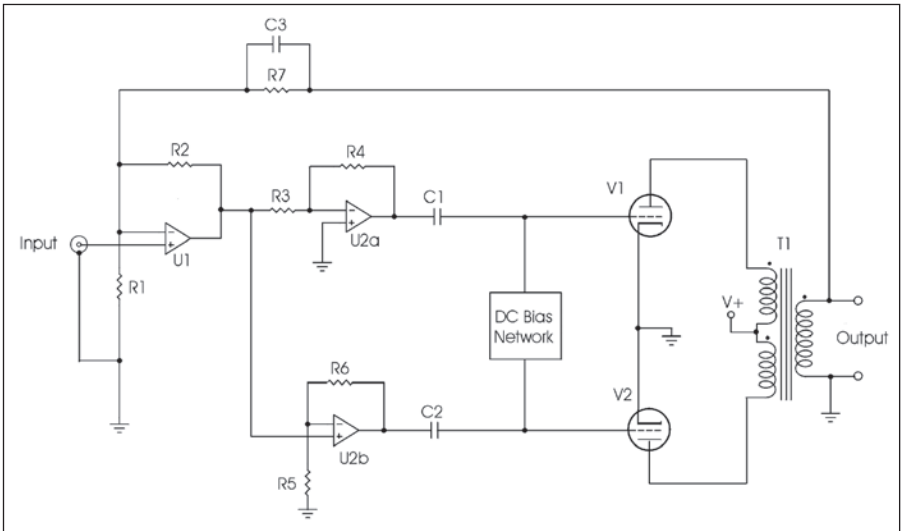


FIGURE 1: Simplified schematic.

closed loop gain of the complete amp with a 16Ω load is set by resistors R3 and R4 which turns out to be about 32. This gives roughly 15dB of negative feedback. Raising the value of R5 would increase the negative feedback and lower the distortion, but the amp sounds so good that I decided not to change it.

IC CONSIDERATIONS

Since it was designed for amps with a solid-state output, the LM4702 has a source and a sink output to facilitate biasing the output transistors. This is not needed in this application, so I've just tied the source and sink together. The LM4702 requires external compensation. C6 and C7 fulfill this requirement.

The LM4702 will dissipate approximately 3W with the power supply used here. Without a heatsink, the temperature rise would be 30° C per watt. You should use a heatsink with a thermal resistance of 7° C per watt or less to keep the rise within reason. I've also put ventilation holes in the PC board under the heatsink.

Provision for wiring a mute switch is provided on the PC board. If you're not going to use one, you should put a jumper on the board in place of the wiring to the switch.

The output stage is pretty typical. It is wired for ultralinear operation to maximize the power output. I put a ¼A fuse between ground and the cathode resistors of the tubes. Tubes do short on occasion and this affords a degree of protection for the high voltage supply and output transformer.

The 10Ω cathode resistors provide a convenient place to measure the bias and balance of the output stage. I included an AC balance pot R8 in series with resistor R8a. This allows the gains of the two driver amps to be set exactly equal. You could substitute a 51k resistor for R8 and R8a with satisfactory results.

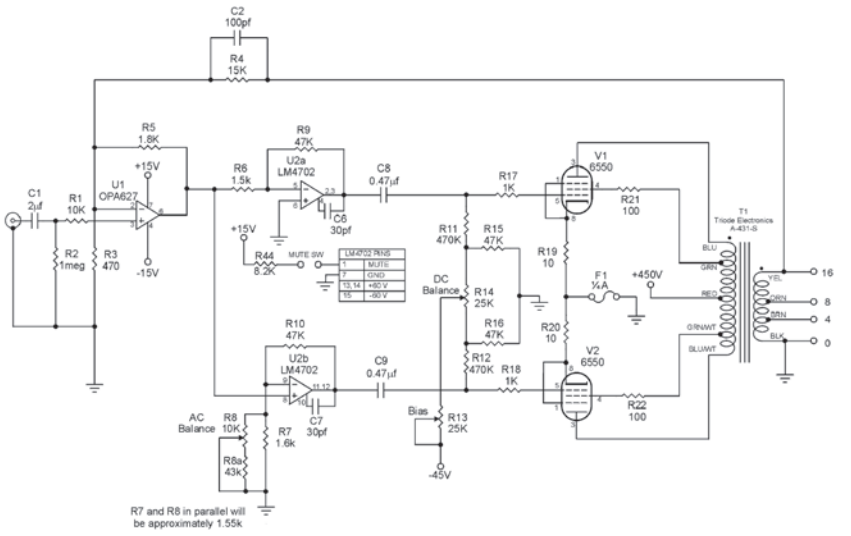


FIGURE 2: Hybrid power amplifier schematic.

POWER SUPPLY DESIGN

The high voltage and bias supplies are not regulated but are highly filtered. I needed to add a second power supply transformer (Hammond 166 G100) for the solid-state input and driver stages. Power to the LM4702s is regulated using adjustable 3-terminal regulators.

I set the driver stage voltage to ±60V, which is higher than the maximum allowed for the LM317 and LM337 regulators, but National Semiconductor outlines a clever technique for overcoming the limitation in its linear brief, LB-47. The zener diodes ZD1 and ZD3 keep the voltages across the regulators well within their voltage limits. The ±15V supplies for the input op amp are derived from the ±60V supplies with simple shunt regulators.

I left space on the PC board for resistors R29 and R36 to dissipate some of the heat that would otherwise be handled by the transistors and regulators. It turned out they weren't necessary, so I just put jumpers in their place. The output voltage of the positive regulator is determined by the equation:

VCC+ = 1.25 * (1+R32/R33) + 0.00005*R32

Similarly, the voltage from the negative regulator is:

VCC- = -1.25 * (1+R40/R39) - 0.00005*R40

The large filter capacitors preceding these regulators are necessary to keep ripple voltage low enough to ensure adequate headroom for the regulators.

MECHANICAL ASSEMBLY

I used a 1/8″ thick aluminum plate for mounting everything. This is thick enough to drill and tap, which facilitates mounting parts under the transformers. I drilled a ring of ventilation holes around each output tube and cut a large hole in the plate where the main printed circuit is mounted. I mounted the lower voltage power transformer under the main power transformer and a terminal block to select the output impedance of the amp under the output transformer. If you do the same, make sure the screws are flush with the top of the plate before mounting the main power and output transformers.

I like using dual banana plugs for connecting the speaker to a pair of 5-way binding posts, and using the terminal block to select the output impedance means that I have only two wires going to the back panel. The large hole has two advantages. First, it allows access to both sides of the PC board, and, second, it allows for ample ventilation.

The PC board is mounted under the hole with spacers, and a cover plate is mounted with spacers above the hole. Mount a smaller PC board containing

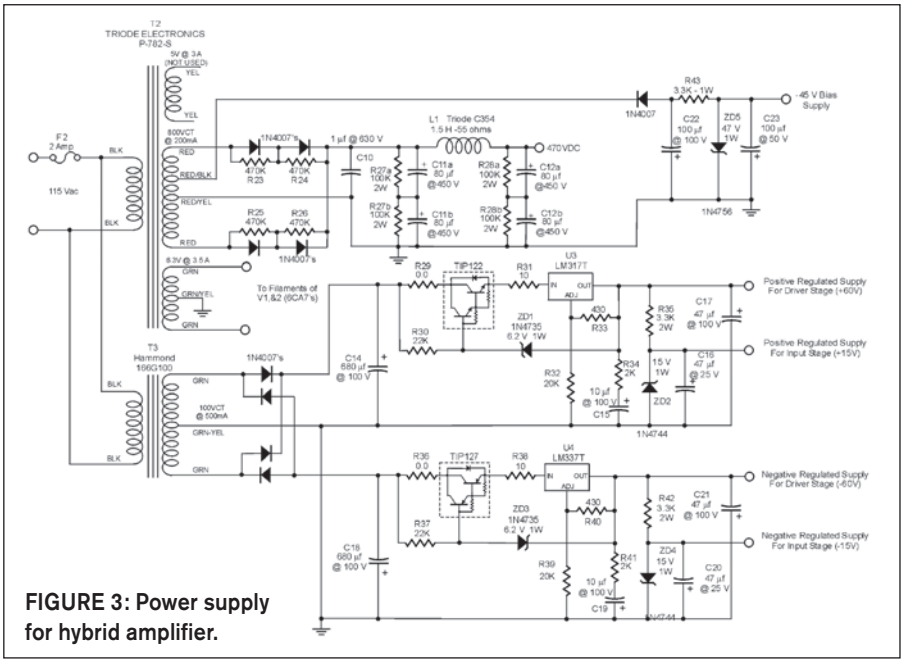


FIGURE 3: Power supply for hybrid amplifier.

the high voltage filter capacitors in front of the power transformer and also mount a number 8 screw next to it to serve as a connection point for a star ground. All grounds are tied to this point.

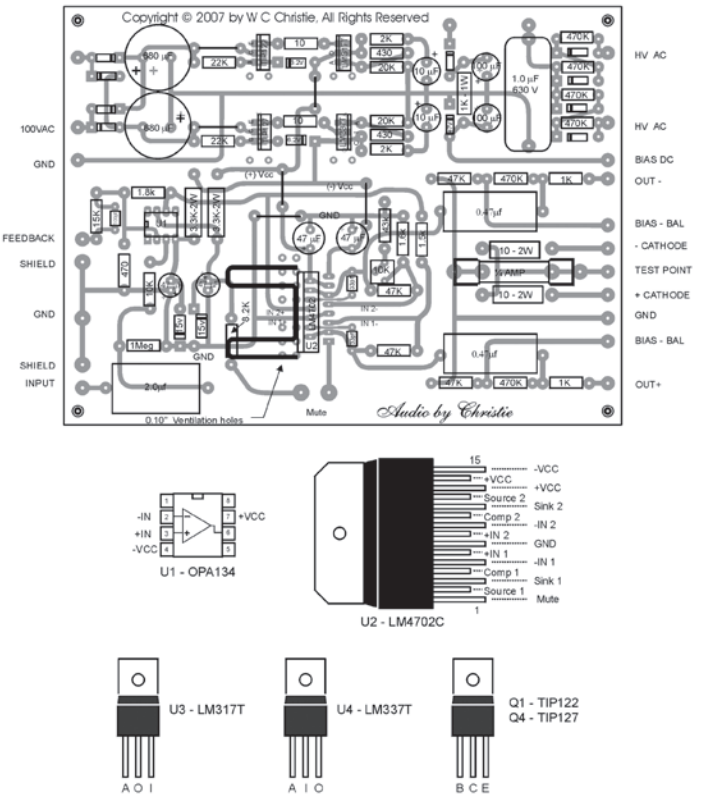
You can mount this assembly in either a wood or metal base. A back panel is used for the main power connector, fuse, switch, and input and output connectors. I made the bottom plate out of 1/8″ thick aluminum and put holes under the tubes and PC board.

FINAL ASSEMBLY AND ADJUSTMENTS

You should use a socket for the input op amp U1, and you need to solder the LM4702 driver IC directly to the PC board. Fully populate the board with the exception of jumpers J1 and J2 and don't insert the input op amp. This will allow checking out the power supplies without risking damage to the op amps.

With the amp otherwise fully wired and the output tubes not yet inserted,

FIGURE 4: PC board with component layout.



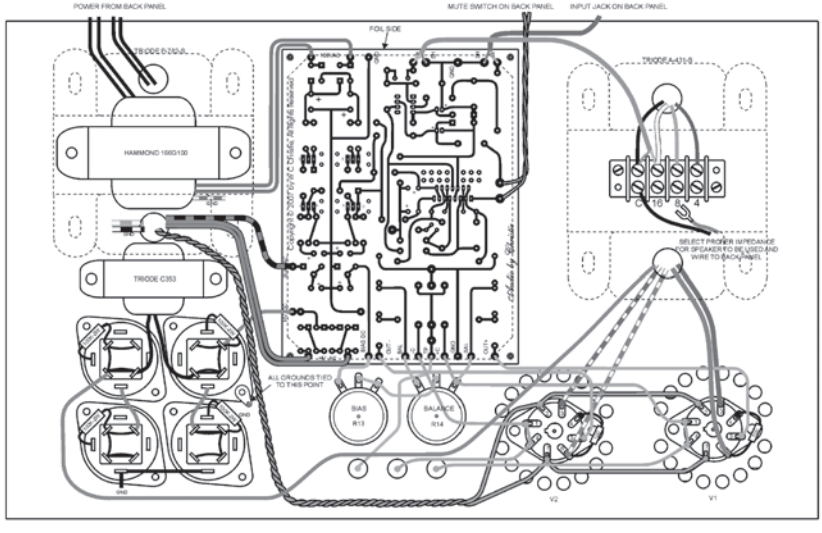


FIGURE 5: Chassis wiring for hybrid amplifier.

you can turn on the amp and measure the voltages. **Table 1** gives the voltages that you should find. Use extreme care when measuring high voltages, which, in this case, are high enough to be lethal.

Once you've checked out the power supplies, remove power and wait about five minutes for the filter capacitors to

PHOTO 3: Hybrid amplifier with cover off.

PHOTO 4: Hybrid amplifier, bottom view.

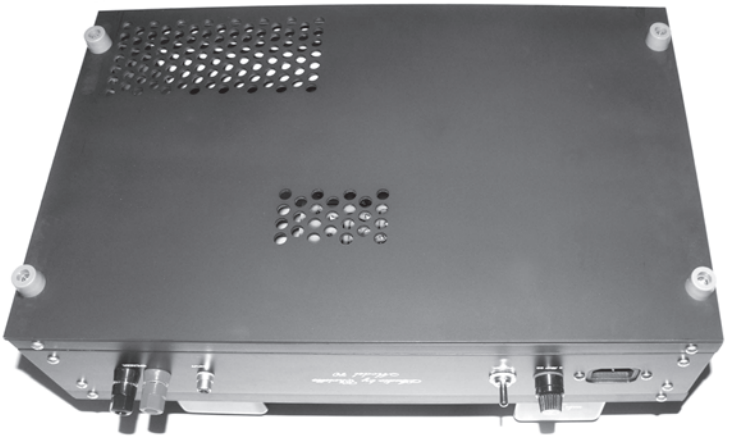


TABLE 1

Preliminary measurements before installing tubes		
High voltage DC	+600V	From C10 to ground
+Vcc	+60V	From J1 to ground
-Vcc	-60V	From J2 to ground
U1+ supply	+15V	From U1 pin 7 to ground
U1- supply	-15V	From U1 pin 4 to ground
Raw bias voltage	-78V	From pot R13 to ground
Bias voltage at V1	-69V	From V1 pin 5 to ground (R13 ccw)
Bias voltage at V2	-69V	From V2 pin 5 to ground (R13 ccw)
Measurement with tubes installed and bias adjustments made		
High voltage DC	+527V	From C10 to ground
+Vcc	+60V	From J1 to ground
-Vcc	-60V	From J2 to ground
U1+ supply	+15V	From U1 pin 7 to ground
U1- supply	-15V	From U1 pin 4 to ground
Raw bias voltage	-75V	From pot R13 to ground
Balance adjust	0V	From TP2 to TP3
V1 plate current	+70mA	+700mV from TP2 to TP1
V2 plate current	+70mA	+700mV from TP3 to TP1

Note: High voltage DC and raw bias voltage will vary with line voltage. Measurements in these tables were with line voltage at 120V AC and no input signal.

TABLE 2

AMPLIFIER PERFORMANCE
Power output: 60W
IM distortion: Less than 0.1% at 1W
Less than 1.0% at 60W

TABLE 3 PARTS LIST

RESISTORS	
R1	10K ½W
R2	1 Meg
R3	470 ½W 1%
R4	15K ½W 1%
R5	3K3 ½W 1%
R6	1K5 ½W 1%
R7	1K6 ½W
R8	10K trimpot
R8a	43k
R9, R10	47K ½W 1%
R11,12,R24-27	470K ½W
R13,R14	25K chassis mount potentiometer
R15,R16	180K ½W
R17,R18	1K ½W
R19,R20	10 1W
R21,R22	100 ½W
R23	8K2 ½W
R28,R29	100K 2W
R30,R37	Jumper
R31,R38	22K ½W
R32,R39	10 ½W
R33,R40	20K ½W
R34,R41	430 ½W 1%
R35,R42	2K ½W 1%
R36,R43	3K3 - 2W
R44	3K3 1W
CAPACITORS	
C1	2µF
C2	100pF
C3,C4	15pF
C5,C6	33pF
C7,C8	470pF
C9	1µF at 630V
C10,C11	820µF at 400V
C12,C16	680µF at 100V
C13,C17	10µF at 100V
C14,C18	47µF at 100V
C15,C19	47µF at 25V
C20,C21	100µF at 100V
TRANSFORMERS	
T1	Triode Electronics A-431-S
T2	Triode Electronics P-782-S
T3	Hammond 546-166G100
DIODES	
ZD1,ZD3	1N4735 (6.2V - 1W)
ZD2,ZD4	1N4744 (15V - 1W)
D1,D2,. . .	1N4007 (1A - 1000 PIV)
TRANSISTORS	
T1	TIP122 (Darlington) (NPN 100V, 3A, 40W)
T2	TIP127 (Darlington) (PNP 100V, 3A, 40W)
ICs	
U1	OPA134PA (Single OP amplifier)
U2	LM4702C (Dual HV OP amplifier)
U3	LM317T (Pos. Adj.,. 1.5A)
U4	LM337T (Neg. Adj., 1.5A)
VACUUM TUBES	
V1,V2	KT88 (Power Tetrode)
FUSES	
F1	¼A
F2	3A Slow Blow

discharge. Plug in the input op amp, install the jumpers installed, and then you can test the input and driver stages. With a small signal applied to the input—say 0.1V RMS at 1kHz—you can adjust the AC balance pot to get equal AC voltages from the output of the amps in the driver stage. (Note that the mute switch must be closed to get anything out of the LM4702.)

Once this is done, you should remove the signal and short the input. Prior to inserting the output tubes, preset the bias and balance pot. You should set the balance pot at its mid point and the bias pot fully counterclockwise (zero ohms). Pins 5 of all the output tube sockets should read –45V or more negative. If they don't, then something is wired wrong and needs to be fixed before proceeding. Output tubes, which are expensive, can easily be damaged if the bias voltage is not negative enough.

With the power supplies checked out and the input and driver stages working properly, and again waiting for the filter capacitors to discharge, you can install the output tubes. You need to put a dummy load across the output terminals before turning on the amp. Without it the amp will be unstable and damage to the output transformer can occur.

Now you can adjust the bias and balance pots. You should short the input jack for this procedure. While the tubes are warming up, monitor the voltage across one of the 10Ω cathode resistors (test points 1 and 2 or test points 1 and 3). If it exceeds 0.8V, turn the amp off and look for wiring problems.

After the tubes have had time to warm up—say 3 or 4 minutes—adjust the balance pot for equal voltage on the cathodes (zero volts between test points 2 and 3). Next measure the voltage between test points 1 and 2 and slowly turn the bias pot clockwise to get a 0.6V reading. Let the amp set this way for an hour or so and then readjust the balance as before, and then adjust the bias for a reading of 0.75V between test points 1 and 2.

The amp should now be functioning. The output tubes will change slightly during a burn-in period. After a few days or a week of use, recheck and adjust the bias and balance if necessary. *aX*