A 2 Meter Half-Kilowatt for $1 per Watt

Build this VHF amp using vacuum-tube technology!

by Steve Katz WB2WIK/6

Everybody wants a stronger signal, and those operating 2 meters are no exception. In the car, it is economically feasible to run 170 watts RF output power or so on the 144 MHz band before the law of diminishing returns sets in. Solid-state "brick" amplifiers, which are powered by 13.8 volts DC, abound. These little amplifiers cost about $2 to $2.50 per watt new, and often include a built-in receiver preamp.

For the home station, tube-type amps are much more efficient than solid-state amps. Example: Let's say you intend to use a 170-watt-output "brick" amplifier at home, and its RF drive (input level) requirement is 30 watts to achieve full output. The amplifier requires a regulated source of 13.8 VDC, and draws 27 amperes at full power. To generate this 373 watts of DC power, you use a commercially-manufactured linear power supply that, to deliver 13.8V at 27A, requires an input of 117 VAC at 5 amperes. So, to run a measly 170 watts RF output power you are consuming 585 VA (volt-amperes, the AC equivalent of watts) every time you "push the pickle." To generate that 30 watts RF drive into the amplifier you are probably consuming at least 100 VA more. So, to run 170 watts RF output, you are consuming 685 VA of AC power, which is an overall efficiency level of about *25%*.

The solid-state "brick" amplifier is a convenience which requires no tuning across the band, but its efficiency isn't very good, and gets *much worse* at lower power levels. If you want to run higher power, the overall cost of doing so will skyrocket into the $3+ per watt range as the regulated DC power supply requirements become unwieldly. I can understand using solid-state amps for the car, truck, boat, or RV, since the normal power is 13.8 VDC. But at home, when you use an outboard solid-state amp, you are first down-converting power from 117V (or 234V) AC to 13.8 VDC, then up-converting that to useful RF energy.

While modern "switch-mode" regulated power supplies are 90% efficient, most hams aren't using these because of their cost. Instead, they're using old-fashioned "series regulator" linear power supplies, which are terribly inefficient, wasting a lot of power as heat. Not only that, but the "no-tune" solid-state amps can only be optimized at *one* power level (typically the highest power they can run) and lose efficiency quickly as the power level is reduced. The no-tune solid-state amps will not allow you to transmit into a mismatched load, should you ever need to, because they all have VSWR protection circuits in them that shut down if the SWR gets high. Most also include a thermal overload protection circuit which shuts them off if they get too hot—and they *do* get mighty hot, especially under high duty-cycle service. Yuck! What's a ham to do?

Tube Amplifiers

How about taking a giant step backwards in technology and using a tube amplifier instead? Tubes are still heavily used in modern high-powered transmitters and amplifiers, and for good reason: They tend to develop more gain and operate at higher efficiency levels, especially at higher radio frequencies, than transistors do. Not only that, but reasonably-priced tubes are available that will operate at a linear 1 kilowatt output (per tube) without the need for complicated combining networks and extremely high-current regulated DC power supplies. (To run 1 kW output power at 50% stage efficiency using 28 VDC transistors requires a 71.4 amp power supply, the cost of which could exceed that of the rest of the amplifier.) Sure, tube amps usually require tuning, but in the shack, where the operator has access to a wattmeter and tuning controls, this is not a serious drawback.

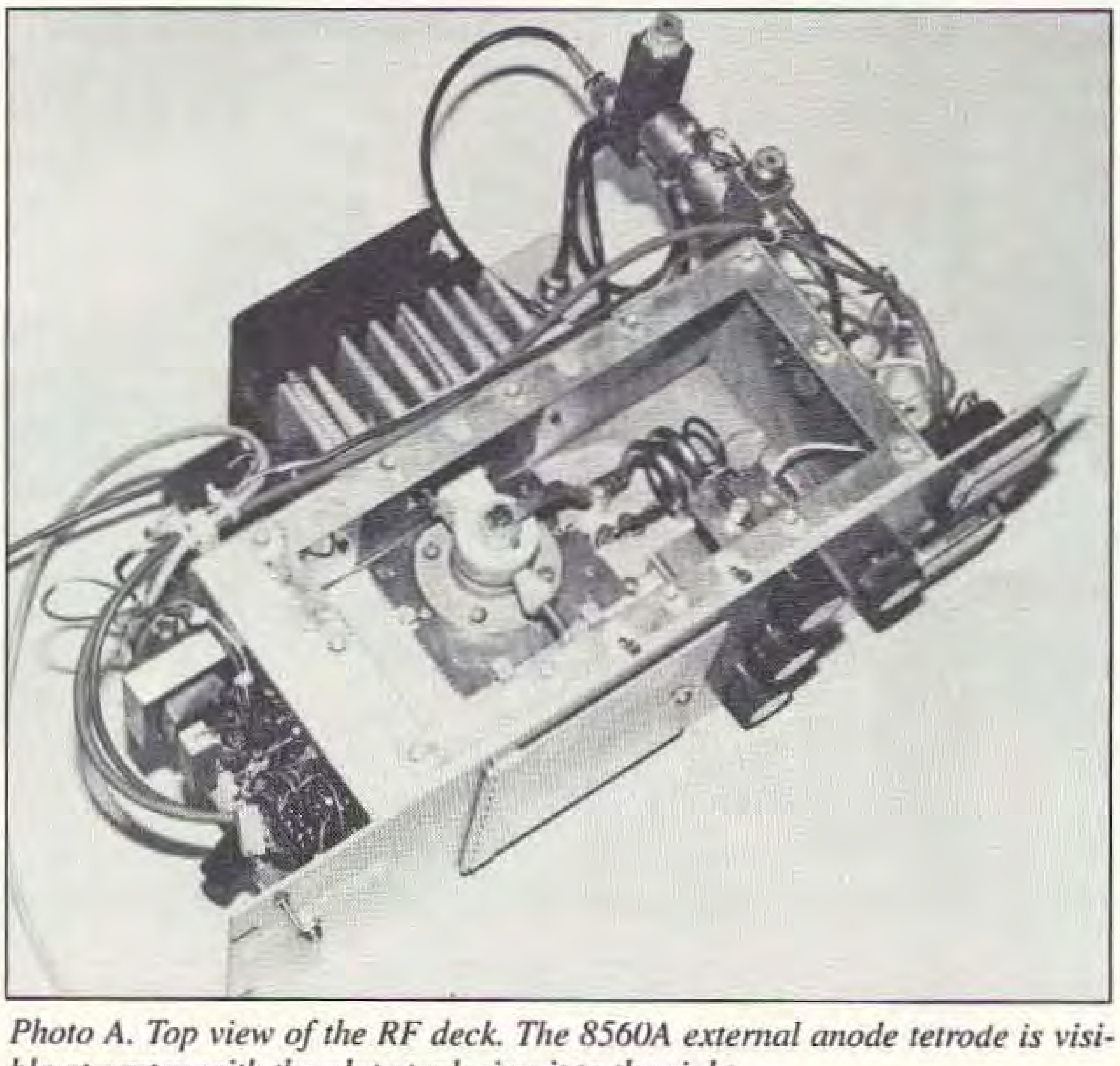

Photo A. Top view of the RF deck. The 8560A external anode tetrode is visible at center, with the plate tank circuit to the right.

How efficient can we make a 2 meter tube amplifier? *Very* efficient. We can use a tube circuit that is about 65% efficient running class AB_2 , and a power supply that is 90% efficient. Under these conditions, that 400 watt amp would consume a mere 684 VA of AC power, an overall efficiency level of *58.5%* (compare this to the 25% solid-state scenario described earlier). This will generate far less heat, and result in a much lower electric bill for the operator. Can this be practical? Surely.

There are two more neat

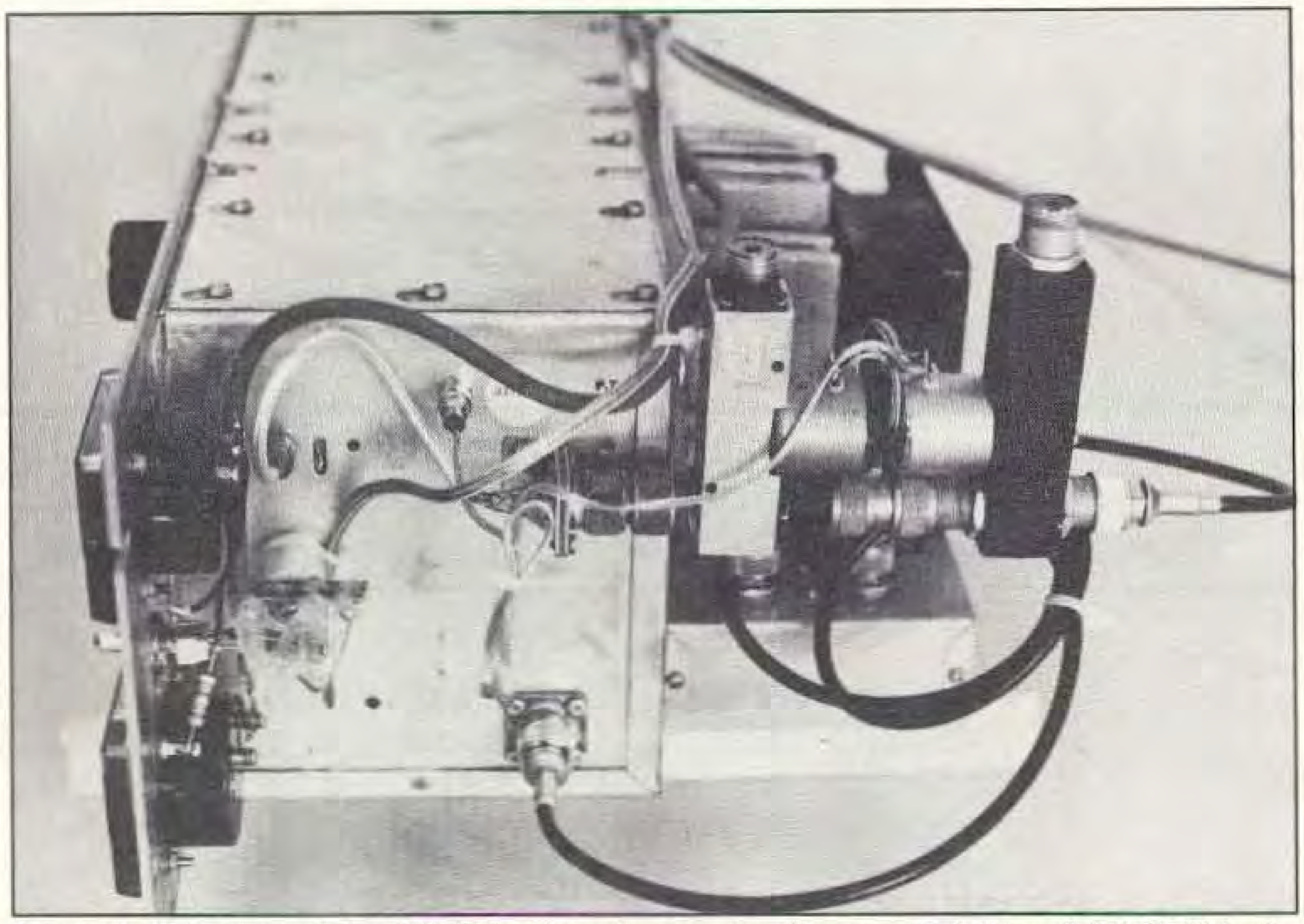

Photo B. Side view of the RF deck. Note the two panel meters, RF IN and RF OUT jacks, meter wiring, and Dow-Key RF relays.

things about tubes. If operated in driven-grid configuration, many power tetrodes will develop about 20 dB gain. Additionally, tubes don't mind heat; in fact, they need it to work. While transistors must be *derated* for operation at high temperatures, and will fail if operated too hot, tubes don't require such derating and most power tubes are intended to be operated at seal temperatures exceeding 200 degrees C, where no normal transistor will survive. Ever see the output power of your solid-state amp start to fall off as it gets hot? This won't happen with tubes.

Finding an Amplifier

We could start "from scratch" and build an amplifier from sheets of aluminum, using a special (and costly) tube socket with spring-finger stock contacts, an air duct chimney, precision-made anode resonators and so forth, but *why*? There are plenty of commercially-made *surplus* RF amplifiers out there which will tune up on 2 meters, available for less than the cost of a single tube. Problem is, most of the surplus comes without documentation, and often without a power supply. Many times a power supply was so big and heavy it was left behind when the amplifier was removed. Sometimes the original power supply was designed to be used on something other than standard 117 VAC power. Still, it is easier to find a high-powered "RF deck" (amplifier without a power supply) than it is a complete unit. So if you find a surplus "RF deck" for a good price, don't hesitate to buy it; the power supply is the easy part and, along with control circuitry, meters, and a relay or two, it can be converted into a great base-station amplifier for little cost or effort.

I stumbled across a beautiful VHF RF deck at the local swap meet. I've seen similar units at the Dayton Hamvention and in the pages of various surplus outlet catalogs. If you want to find a 2 meter RF deck, the key is to look for one that originally covered the 150 MHz band (typically 150-174 MHz) so little or no conversion to the RF circuitry will be required. The deck was unlabeled, but it *looked* like a VHF unit, and a quick check with my trusty Millen 90651 grid-dip meter confirmed that its plate tank circuit resonated at 150 MHz. When I got it home, I checked the tuning range of both the input and output circuits and was pleased to find it tuned right down to 140 MHz without modification.

This deck (see photos) cost me $100, and was worth the price, since it contained an Eimac 8560A conduction-cooled power tetrode that normally retails for about $190; plus, the mating tube socket, beryllium-oxide thermal link, anode heat sink, and all tuning circuitry.

The 8560A is a conduction-cooled version of the famous 4CX250B, and its ratings are identical, but it requires *no* forced-air cooling, blower, air-system socket or chimney. It is rated for literally unlimited anode power dissipation, as long as the anode and base seal temperatures can be maintained below 250 degrees C, and this will be a function of power input, efficiency, and the size of the heat sink used. In the unit pictured, I was able to run 400 watts RF output power for about 20 minutes before the heat sink became uncomfortably warm—that's when I decided to add an outboard "muffin fan" to blow a cooling airstream across the heat sink. If you find a deck with a different tube (e.g., 4X150A; 7034; 4CX250B; 7203; 7580W;

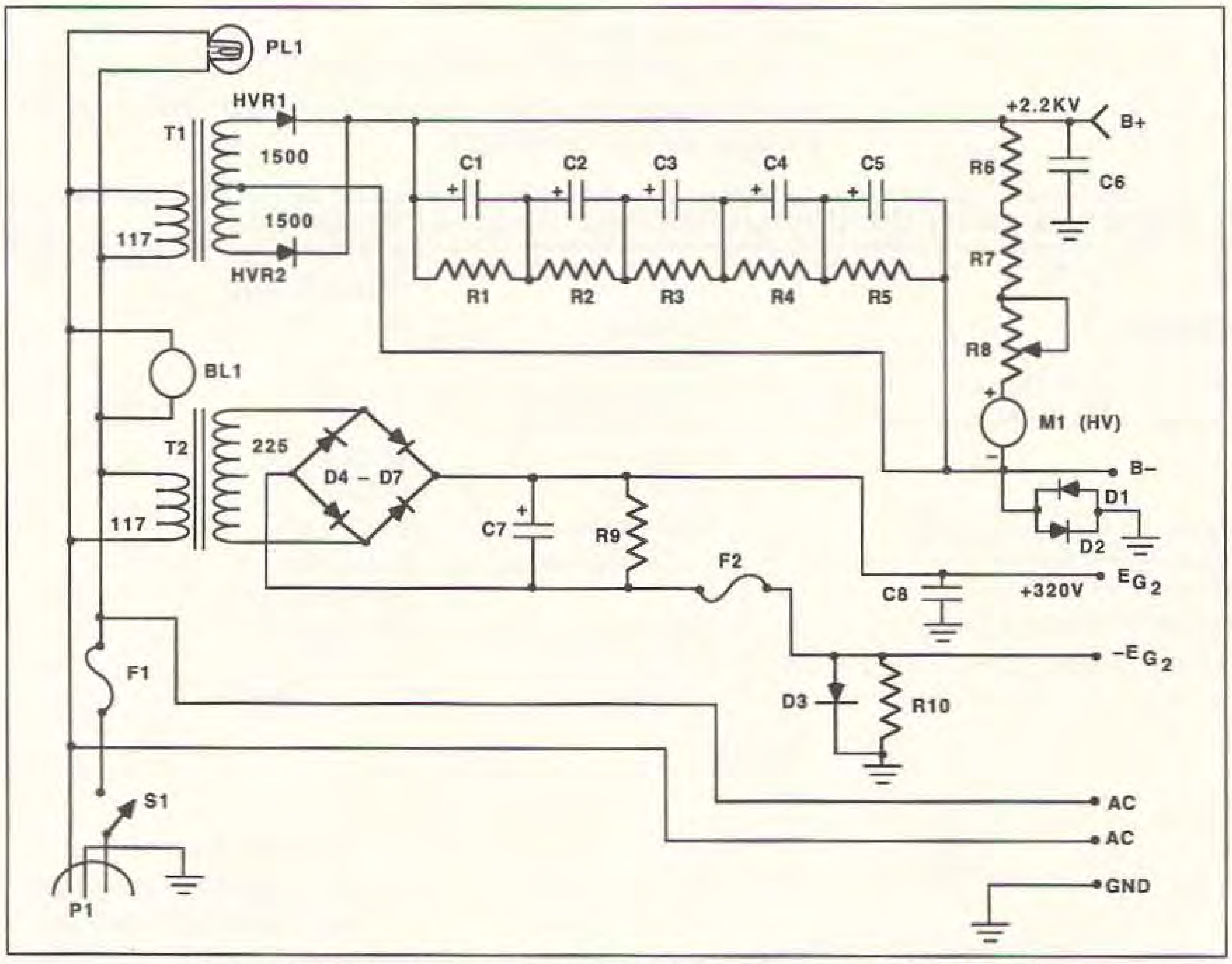

Figure 1. Plate and screen circuit for 2m half kilowatt amp power supply.

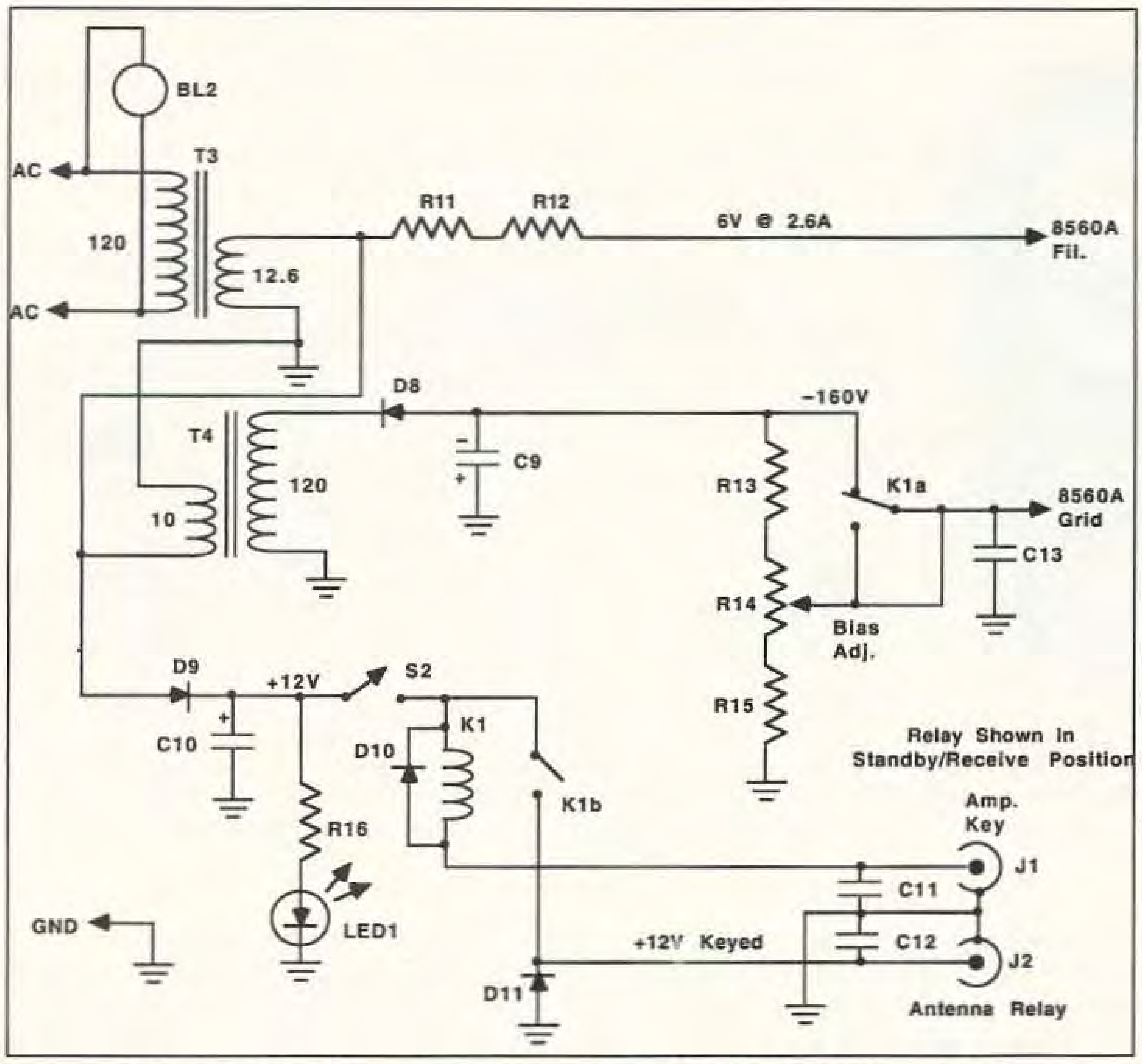

Figure 2. Bias, filament, and control circuit for 2m half kilowatt amp.

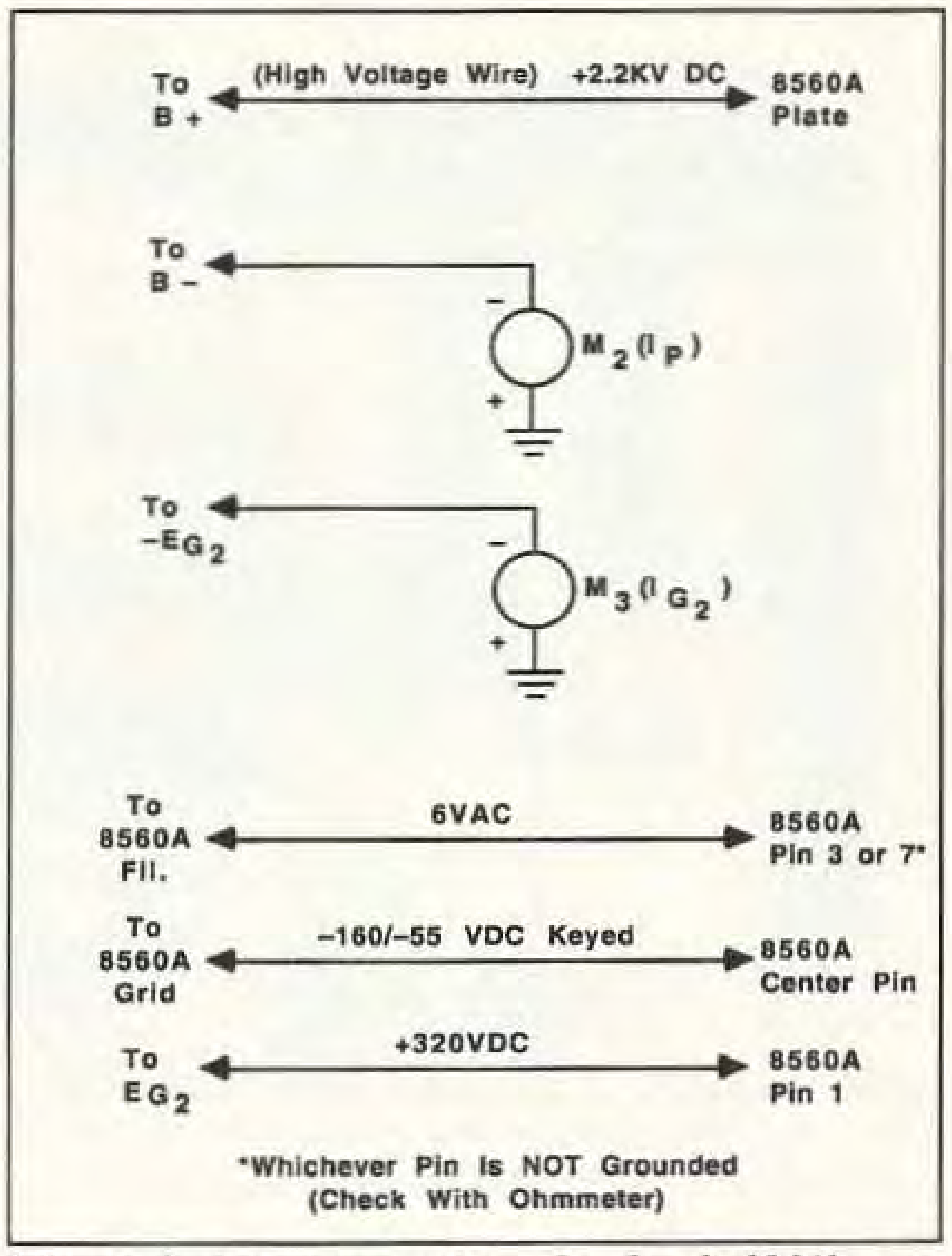

Figure 3. Interconnections for 2m half kilowatt amp.

or 4CX250R) it should still work fine, but if they require air-cooling you'll need to make sure that the original blower, chimney and ductwork are operational.

I decided to make one initial change to the RF circuitry. I noted that the manufacturer used mica chip capacitors to bypass the screen pin of the tube at its socket, but used no further decoupling close to the tube base. This is a huge "no-no" that could result in unstable operation, so I added a 220 ohm, 1 watt *carbon* resistor in series with the screen lead, right at the tube socket, and bypassed the "power supply end" of this resistor with a 0.01 µF, 1 kV ceramic disc capacitor (zero lead length) to ground. This adds considerable RF decoupling for the screen and is recommended for any power tetrode that is not operating grounded-grid. I'd found from many years of experimenting with similar tubes that a carbon resistor works better than an RF choke at this point in the circuit since it offers more wideband decoupling with little fear of resonance and regeneration (instability). It is safe to use a resistor in the screen lead, as it is in the grid bias lead, since the current drawn by these elements is very small.

The Power Supply

The next step was to design and build a modest power supply for the amplifier. The power supply circuit is very simple. The high-voltage (plate) supply is a simple full-wave, center-tap rectifier providing 2200 VDC at 500 mA, filtered by five 250 µF, 450W VDC electrolytic capacitors in series. The total filter capacitance is 50 µF, quite a lot for a 500 mA load. Each capacitor is paralleled by a 50k ohm, 20W wirewound resistor to equalize the voltage across each one. (Please note: Feel free to use something else, if you have it. A single, 20 µF, 2500 to 3000 VDC oil-filled capacitor would serve the purpose here.) The rectifiers are Semtech "Slimpac" type SCH7500, rated 7.5 kV at 500 mA each, found at the local swap meet for $2.50 each. This approach was cheaper and more effective than using big strings of lower-voltage diodes with bridging capacitors and resistors. If you can't find Slimpacs or something similar, "do your own thing" and come up with another solution. In lieu of each Slimpac, four type-1N4007 diodes in series with a 470k ohm, 1/2 watt resistor across each one would work.

To meter the B+ (high voltage), I used a 0-1 mA DC panel meter in series with two 2.4 megohm, 2W resistors and a 250k ohm "calibration" potentiometer, which is used to adjust the meter for accuracy. Because I wanted to meter both high voltage and plate current remotely from the power supply (the meters are on the RF deck), I used a separate "B-" (high voltage return) lead in the power cable between

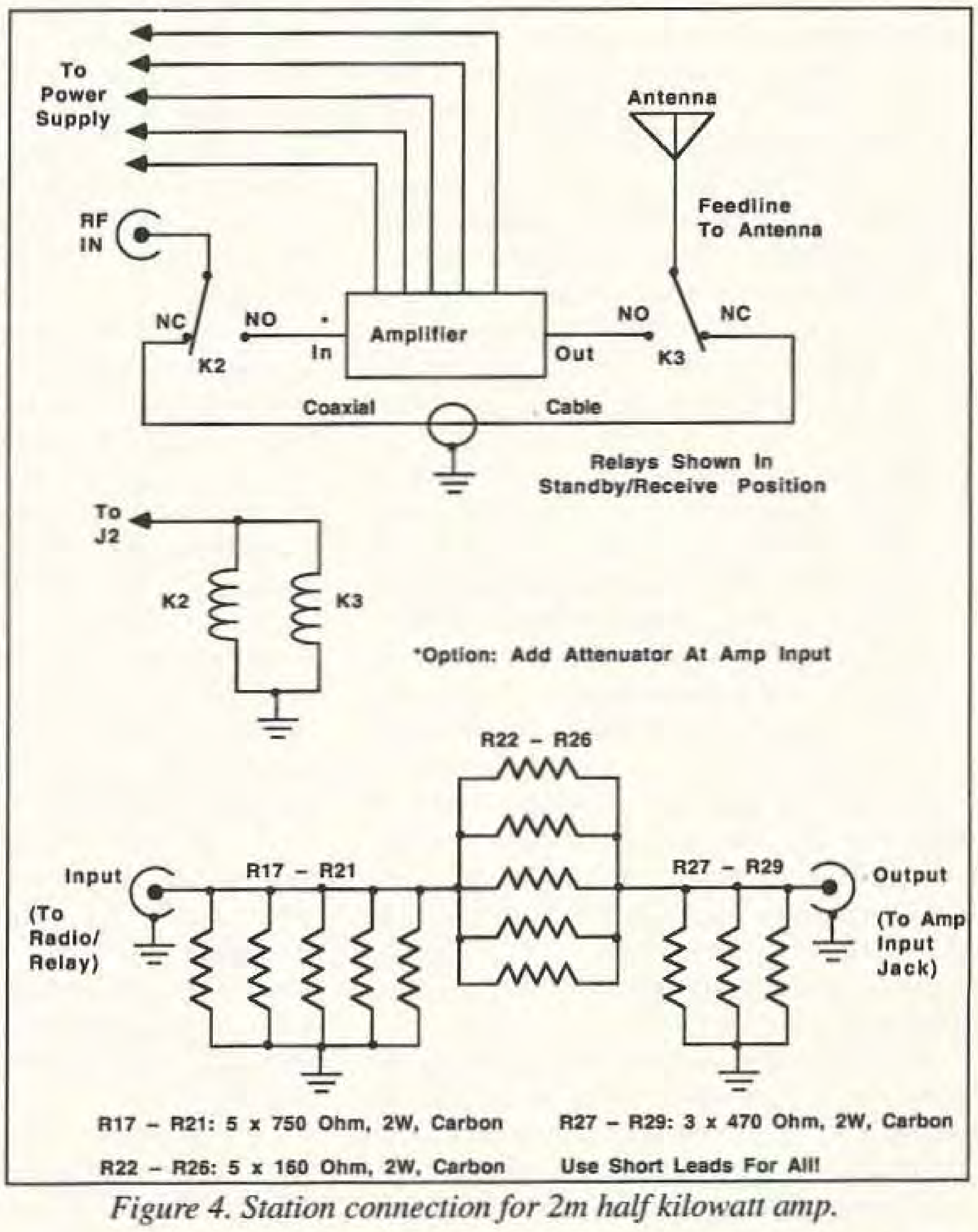

Figure 4. Station connection for 2m half kilowatt amp.

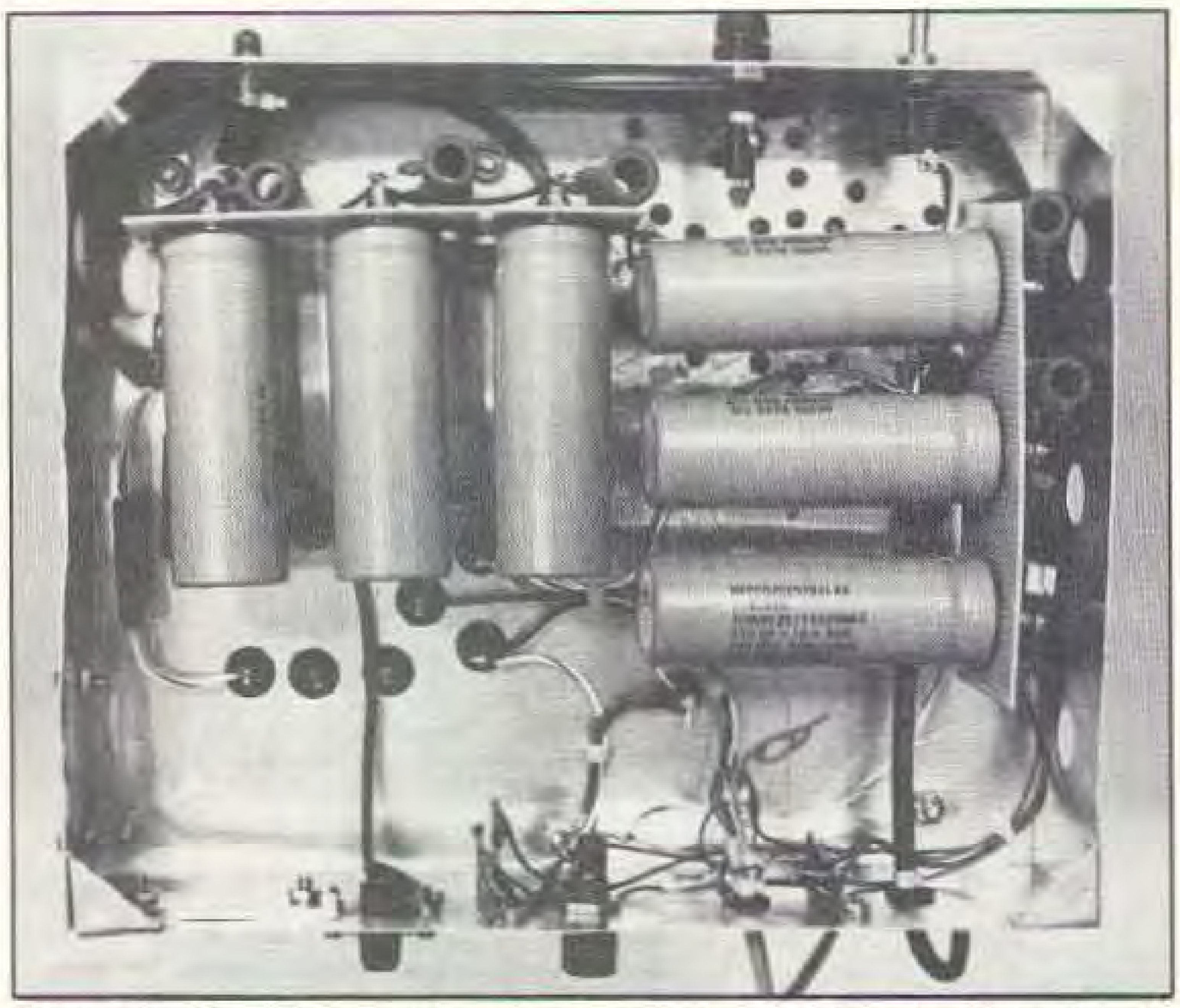

Photo C. View from under the power supply chassis. Note the six high-voltage electrolytics. The bleeder resistors are on the other side of the perf board.

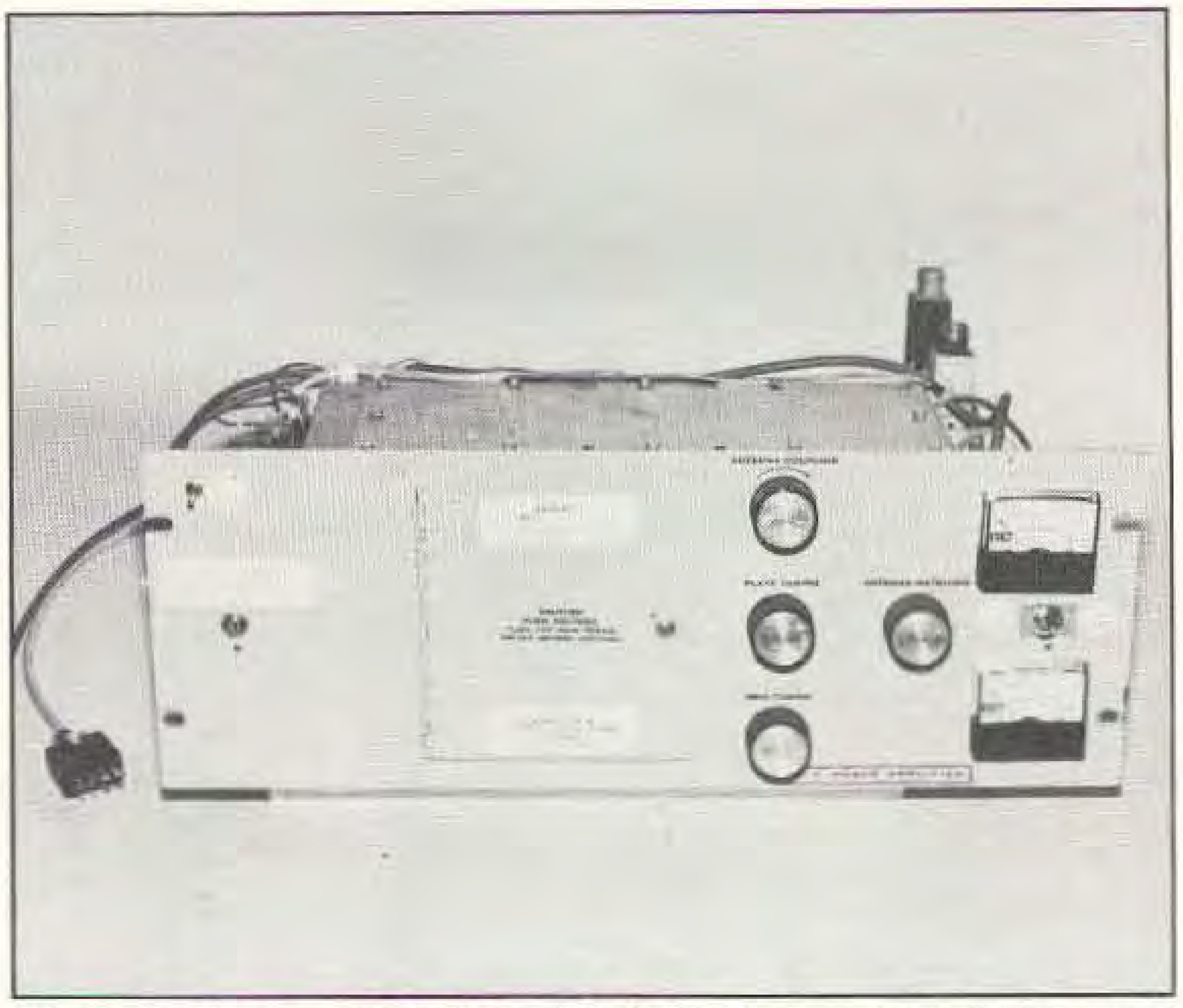

Photo D. The completed, modified RF deck now includes panel meters, a grid bias adjustment pot, and a standby switch.

them, and measured I_P (plate current) in the negative lead—*much* safer than measuring in the "+" lead, which is floating 2200 VDC above ground!

The screen power supply is a full-wave bridge rectifier which develops +320 VDC at about 25 mA. It is not electronically regulated, and many feel that screen supply regulation is key to linearity in tetrode amplifiers. However, it is very stable because the supply is very well filtered by a 250 µF capacitor and a 10k ohm, 20W "bleeder" resistor provides a 32 mA constant load. This load is about 10 times more than the screen current drawn by the tube itself, so the supply voltage doesn't change when the amplifier is run from "key up" to "key down." Electronic regulation with gas tubes or zener diodes wouldn't be much better than this.

For the screen current, negative-lead metering is also used. I used the same 0-1 mA meter that is used for plate current, with a 0.5 ohm, 1 watt precision resistor as a meter shunt. The shunt resistor is located in the power supply, not across the meter itself, to keep the return lead close to ground potential. Possibly the screen current needn't even be monitored, since in operation the amplifier rarely draws any measurable screen current. However, monitoring screen current is useful for tuning the amplifier. You'll also note on the schematic that I used a 1/16 amp, fast-blow fuse in the screen return lead. This will open in the unlikely event the tube tries to draw excessive screen current. (This series of tubes has grid and screen structures which are far more fragile than the cathode or plate, and excessive screen current destroys more power tetrodes than almost any other problem.)

By the time I was finished building the plate and screen power supplies into the little 10" x 12" x 3" chassis, there wasn't much room left for the filament transformer and grid bias power supply. Besides, I wanted to mount a "muffin" fan on the power supply chassis to exhaust the hot air generated by the plate and screen "bleeder" resistors. After all, 35 watts are being dissipated under this power supply chassis, beginning immediately after the "ON" switch is thrown.

No problem: There was sufficient room on and around the RF deck panel to mount the rest of the components necessary for operation. Before mounting sensitive parts like meters and relays, I performed all the drilling and hole-punching. Punching the 1-3/4" holes required for the two meters was a real task because this particular amplifier deck used a solid-steel 1/8"-thick panel. Ugh! Using a "wrench-handle extender" on the socket wrench turning the lead screw to a chassis punch, and after much grunting and groaning, the meter holes were finally completed.

I mounted the filament transformer, bias transformer, relay (to switch bias for the tube and to activate the antenna relays) and other components on the left-hand side of the panel and the rear chassis of the RF deck. Why did I use a 12.6 volt filament transformer for a 6 volt tube filament? Because I *had* one, that's why! And a conventional filament transformer of 6.3 volts would provide excessive voltage for the tube filament, anyway—these tube filaments are rated 6.00 VAC at 2.6 amperes and they do *not* last long with 6.3 volts applied to them. So, a small resistor (or a Variac on the transformer primary) would be required in either case. I used 2.5 ohms total resistance between the 12.6V transformer and the tube filament: one 2.2 ohm, 20W and one 0.3 ohm, 5W wirewound (precision) resistor, both purchased from All Electronics for a total of $2. This results in exactly 6 volts AC at the tube base.

I found a 120V:10V transformer for about a dollar and used it, wired in reverse, to provide grid bias from a half-wave rectifier circuit. The bias rectifier and filter produce -160 VDC (remember, grid bias is *negative*, so the rectifier and capacitor must be wired as shown) which is then adjusted to the proper levels with a three-resistor voltage divider made up of the 3.5k ohm, 10W; 1k ohm, 5W potentiometer; and 1.75k ohm, 5W resistors shown on the schematic. The relay K1 switches the operating bias to the tube from -160 VDC (cutoff, for "standby") to about -55 VDC ("operate") when activated by an outside keying source that simply goes to ground on transmit. Most rigs have such a keying line. The power for the relay coil comes from a small rectifier/filter circuit that is driven by the 12.6 VAC line from the filament transformer. I also used reverse-voltage "spike" suppression (in the form of a diode across the relay coil) to prevent "kick-back" voltage from the relay coil from damaging sensitive keying circuits in the radio used to key the amp.

Even if you don't understand its theory, you can make this amplifier *work*! If you follow instructions and schematics exactly, and have someone check your wiring, the thing *has* to work. It's essentially foolproof.

I used another set of contacts on relay K1 to provide +12 VDC for keying the antenna relays, which are a pair of conventional "Dow Key" (Kilovac Corp., Santa Barbara, California) RF relays which bypass the amp on receive ("standby") and place the RF amplifier circuit in the line on transmit. I also added a "standby" switch. This switch breaks the DC line to the relay K1 so that it will not key, even when the exciter is keyed to transmit. Thus, with the switch in "standby," the exciter will run straight through the antenna relays and run "barefoot"; with the switch in "operate," the amp will be keyed into the line. What could be simpler? (The Kilovac Dow Key relays are extremely high-quality devices offering better performance at VHF than the circuit-board-mounted re-

Construction Tips

(1) *Be careful.* There are lots of hazards associated with construction and operation of this equipment, especially when lethal voltages are involved. Even the mechanical work can be hazardous: You'll be using hacksaw blades, drill bits, chassis punches and other sharp tools. Work slowly and carefully, minding the old saw, "Measure twice, cut once," and you'll be more assured that all the cutting will be on the metal and not on your fingers. Use only high-voltage insulated wire for all the plate voltage wiring; the correct wire isn't expensive or rare.

(2) Don't operate high-powered equipment without all shielding covers in place. Load the amplifier only with a shielded dummy load connected by a well-shielded coaxial cable, or an antenna located at least 20 feet from your operating position and other people.

(3) Don't meter the B+! If you want to measure plate current, meter the B- (plate voltage minus return lead) instead. Plastic-faced meters are not rated to withstand 2200 volts and represent a hazard.

(4) Operate only equipment using three-wire AC power cords, with the ground lead firmly connected to the power supply chassis and the plug installed in a three-wire grounded outlet. When wiring the AC line cord in the power supply, make the ground lead (usually green) the *longest* wire, an inch or two longer than the "hot" lines (black and white), so that in the event the line is pulled very hard from the chassis, the ground lead will be the *last* to break or become disconnected.

(5) Cover or protect all exposed potentially hazardous connections, including the 117 VAC line. Use a generous "glop" of RTV sealant and allow it to cure before turning anything on. And even then, be careful.

(6) Some of the resistors in the schematic will dissipate a lot of power, generating considerable heat. Their surfaces get hot enough to burn your skin, even when operating within their ratings. Conceal these so they are out of reach and be careful not to touch them during and immediately after operation.

(7) Use expert soldering techniques. Don't just wrap stranded wire around or through a terminal point and solder—it's bound to have stray "whiskers" which could short against other surfaces. Pre-tin all stranded wires carefully before wrapping and soldering. This is not just safer, it's more attractive. Take pride in construction—it only takes a little effort to do a professional job.

(8) When measuring the output of this amplifier, use only an instrument which can be trusted at this frequency and power level. The Bird Electronics Model 43 Thruline is an appropriate instrument. Many wattmeters are sold that proclaim very wide bandwidth and power ratings (e.g., 1.8 to 144 MHz, 20 to 2000 watts all in one meter), but these are not precise instruments, and they are not only unlikely to measure accurately but they may even burn up.

(9) Use *real* coaxial relays. The best deals are on surplus "Dow Key" type coaxial relays. Use either two SPDT (single-pole, double-throw) coax relays back-to-back as shown, or a single DK260 type DPST coaxial bypass relay, which is specifically made for this application. I've seen the DK60 variety (SPDT Dow-Key with UHF connectors) at swap meets for $15 each surplus. These are great buys! Very little else has ever been manufactured that works as well for so reasonable a price.

(10) Use coaxial cable capable of handling this power at 144 MHz. RG58/U and similar small-diameter cables will *not* cut it, even for very short jumper connections. RG8X ("Mini 8") might work, but you'd be better off using cable that is well within its ratings at 400W and 144 MHz, such as RG213/U, 9913, etc.

(11) Whichever RF deck you start out with, get a copy of the manufacturer's data sheet on the tube and heed its advice. Most of these external-anode tetrodes require 120 seconds warm-up time before applying operate bias and drive. If you inadvertantly key the amp shortly after turning it on, you risk blowing the tube—and as "cheap" as they are, a new one can cost from $65 to $170, depending on which tube you use.

lays in commercial solid-state amplifers. Unlike the little relays used in solid-state amps, these big units have absolutely *no loss* at 144 MHz, and perform very well up to 500 MHz. They are expensive, but can be found surplus for about $15 each.)

You might notice that I didn't meter the grid current. Feel free to do so! But this amplifier is so easy to drive that I added a 3 dB, 50 ohm attenuator ("pad") in series with its input jack. I still turn the RF drive level on my exciter, a Yaesu FT736R, nearly all the way down when I use it, preventing excessive grid current. I have measured the 8560A grid current during bench tests by breaking into the bias circuit with my trusty VOM, and the grid current for proper operation is just about zilch. It kicks to maybe 1 mA on voice peaks on SSB when running the amplifier at 400W PEP output power. Not bad! Since this tube is rated for 2 watts grid dissipation, the grid current could be as high as 18 mA or so in linear service, but drawing this much grid current means something is very wrong. Believe me, there's no reason for any grid current to flow in order to produce a strong and healthy signal.

I used silicone-based RTV sealant on all exposed potentially hazardous connections, the most hazardous of which is probably the 117 VAC line, which has exposed connections at the fans and on the screen transformer.

Results with this $1 per watt amplifier have been gratifying. (Note: The $1 per watt includes the cost of the original RF deck, plus all power supply components, RF relays, meters, fans, power supply chassis, cables and cords, etc., and still leaves room in the budget for buying QSL cards to confirm all the great contacts you will make. The amplifier has a power gain of about 250:1 until it saturates and requires only 2 watts drive for full (400W) output power. To achieve 200W output, less than 1W drive is required. Driving with my ICOM IC2AT "handie-talkie" just for fun (and keying the amp with a clip-lead to activate the relays), the unit produced more than 50 watts output when using the HT in the *low power* position (rated 150 mW output)! Just try to do *that* with transistors!

I used this amp on-the-air in the "VHF Spring Sprints" 2 meter mini-contest the evening of April 9, 1990, and made contact with every single station heard, including many up in the Bay Area, some 400 miles to the north. I used a little F9FT "Tonna" portable yagi, nine elements on a 10' long boom, temporarily installed on a Radio Shack 19" "slip-up" mast. My location for this four-hour exercise was Saddle Peak, a 2800' hill very close to my home.

Tuning this amplifier couldn't be simpler: Apply power to the amplifier and, after waiting two full minutes for the tube to warm up, key the amp with *no* drive power and adjust the "idling" plate current to about 80 mA using the grid bias adjust potentiometer (1k, 5W resistor in the grid bias circuit). Then apply a *small* amount of RF drive and peak all controls on the amplifier for maximum RF output power. Apply slightly more drive and repeak for maximum output. When the RF output reaches about 400 watts after everything is peaked, reduce the drive slightly until the output drops off just a bit, maybe down to 375W or so. No further tuning is required.

When the amp is properly tuned to resonance and maximum output, the I_P (plate current) should be about 300 mA, screen current anywhere from zero to 5 mA, and grid current nearly zero. If you use my power supply design and are connected to a "stiff" 117 VAC line (normal house wiring should be sufficient), the plate voltage will be 2200 VDC "key up" and 2000 VDC "key down" at full power. Of course, this will depend on exactly what plate transformer you use.

Don't be afraid to experiment! The 4CX250 family of tubes, including the 8560A used here, will perform very nicely with plate voltage anywhere from 1600V to about 2500 VDC. Screen voltage can be from about 275V to 365 VDC, as long as it is stable. The operating bias should be adjustable, as shown, to allow for variations in the other voltages and in the tubes. The amplifier power gain will not be quite as high as I've stated if you use reduced plate and/or screen voltages, but it will still have a *lot* of gain, especially compared with solid-state.

Eimac only rates the tube for a maximum plate voltage of 2000, so using this series of tubes at higher plate voltages is done at the user's risk. However, I've used these tubes for years at 2500 VDC with no ill effects. As stated earlier, filament voltage, screen power and grid power are the critical parameters on these tubes, much more so than plate voltage or even plate power.

Any deck using this series of popular tubes and originally intended for VHF service should work. Try Fair Radio Sales. The military surplus AM-912/GRC is a wonderful unit that Fair has sold for years for about $90 (a great buy!) which tunes 100-225 MHz and uses a single 4X150A. But there's a multitude of commercially-made RF decks out there using these tube types, and many will cover the 2 meter ham band. Since a new tube, socket and chimney for a 4CX250B will cost much more than $100, any amplifier using them and available for about this price is a terrific deal.

A bit of scrounging, and a few hours work building the power supply and control circuitry described here, is all it will take to be a "big signal" on 2. Oh, by the way: I'd stay away from FAA VOR transmitters for use on 2 meters. Since they were designed for frequencies much lower than 144 MHz, my experience has been that most won't tune up to 2 meters, and the conversion to the RF circuitry isn't worth the effort.

Please feel free to write me (21101 Celtic Street, Chatsworth CA 91311; Fax: 818-349-8264) with questions regarding this, or the conversion of other commercial/military gear which will make useful amplifiers for VHF/UHF service. I've converted a lot of them, but many require literally no conversion. Good luck, and good DXing on 2 meters!

Surplus Electronic Outlets Likely to Have RF Decks and Other Required Parts

All Electronics Corp.
14928 Oxnard St.,
Van Nuys CA 91406 (800) 826-5432
(Miscellaneous electronic parts.)

Apex Electronics
8909 San Fernando Rd.
Sun Valley CA 91352
(Miscellaneous electronic parts, especially power transformers, HV capacitors, relays, meters, etc.)

Davilyn Corp.
13406 Saticoy St.,
No. Hollywood CA 91605
(Miscellaneous electronic parts including complete RF decks, power tubes and sockets.)

Fair Radio Sales
1016 E. Eureka, (P.O. Box 1105)
Lima OH 45802 (419) 227-6573
(Miscellaneous electronic parts including complete RF decks, power tubes and sockets, blowers, transformers, capacitors, etc.)

Surplus Sales of Nebraska
1502 Jones St.
Omaha NE 68102 (402) 346-4750
(Miscellaneous electronic parts including complete RF decks, power tubes and sockets, etc.; also Ten-Tec cabinets, Collins parts, etc. to dress up your project!)

Tucker Electronics
1717 Reserve St.
Garland TX 75042
(214) 348-8800, (800) 527-4642
(Sometimes has complete, operational equipment.)

All these dealers publish catalogs or flysheets featuring their current "goodies," and all sell by mail order. Fair Radio has been an excellent source of complete RF decks, with or without power supplies, for a number of years. If you don't see one in their catalog, call them! Also search your local flea markets or swap meets, and contact your local two-way radio shops (found in the Yellow Pages) for possible surplus commercial gear taken out of repeater service.

Parts List

BL1, BL2	Rotron "muffin" fans, 4-1/2" square, 117 VAC
C1-C5, C7	250 µF, 450V electrolytic
C6	0.001 µF, 3 kV ceramic
C8, C11-C13	0.001 µF, 1 kV ceramic
C9	250 µF, 250V electrolytic
C10	1000 µF, 25V electrolytic
D1-D11	1N4007 (1000 PIV, 1A rectifier)
F1	10A 125 VAC "slo-blo" fuse
F2	1/16 125V 3AG fuse (special item)
HVR1, HVR2	Semtech SCH7500 or equivalent (7.5k V PIV, 500 mA rectifier assemblies)
J1, J2	RCA phono receptacles
K1	DPDT relay, 12 VDC coil (non-critical: Radio Shack item or surplus)
K2, K3	DK60 Dow-Key SPDT coaxial relays
LED1	High-intensity LED, panel mount
M1	0-1 mA DC panel meter (will read 0-5000 VDC plate voltage when used with R6-R8)
M2	Plate current meter: Can be 0-500 mA DC used without shunt; or, a 0-50 mA DC meter may be used with a 0.1 ohm shunt resistor; or, a 0-5 mA DC meter may be used with a 0.01 ohm shunt resistor. Use whatever you can find, and select shunt value as appropriate.
M3	0-1 mA DC panel meter (will read 00-100 mA DC screen current when used with R10).
P1	Three-prong (grounding) 125 VAC plug, 15A
PL1	125 VAC pilot lamp assembly, panel mount
R1-R5	40k ohm, 20 watt wirewound
R6, R7	2.4 megohm, 2 watt, 1% or 2% precision high voltage resistors (ceramic or glass insulation)
R8	250k ohm, 1 watt potentiometer (HV meter calibration)
R9	10k ohm, 20 watt wirewound
R10	0.5 ohm 1% or 2%, 1 watt precision
R11	2.2 ohm, 20 watt wirewound
R12	0.3 ohm, 5 watt wirewound
R13	3.5k ohm, 10 watt wirewound
R14	1k ohm, 5 watt wirewound potentiometer (grid bias adjust)
R15	1750 ohm, 5 watt wirewound
R16	680 ohm, 1/2 watt carbon
R17-R21	750 ohm, 2 watt carbon (only): Do *not* use wirewound.
R22-R26	160 ohm, 2 watt carbon (only): Do *not* use wirewound.
R27-R29	470 ohm, 2 watt carbon (only): Do *not* use wirewound.
S1	SPST, 15 amp rated AC toggle (AC power ON-OFF)
S2	SPST, 3 amp rated mini toggle (STBY-OPERATE)
T1	Plate transformer. 117 VAC primary: 3000V C.T. (center-tapped) secondary, 1/2 ampere continuous rated (a 750 mA "intermittent duty" transformer is okay).
T2	Screen transformer. 117 VAC primary: 225V secondary, 100 mA rated.
T3	117 VAC primary: 12.6V secondary, 3 amps continuous rated. Could be different secondary voltage (6.3V, 10V, etc.) but if a different rating is used, this will affect the values for R11, R12, R13, R14, R15, etc. Recommend staying with the original rating shown unless you like to experiment.
T4	117 VAC primary: 10V secondary, 1 amp rated (wired in "reverse" as shown on schematic, with the 10V winding used as the primary for this design).