Build a Linear 2 Meter 80 W All Mode Amplifier

This solid state amplifier will give your low power VHF transceiver or transverter just the boost you need.

James Klitzing, W6PQL

There are many different 2 meter low power rigs in use, ranging from handheld transceivers for FM to older multimode transceivers and even the newer all purpose types such as the Yaesu FT-817 or the Elecraft 2 meter transverters. Low power (QRP) operation can be fun, but if you're like me, you have the occasional need for a bit more power.

If you have a couple of afternoons to spend on a project, you can build this 80 W multimode amplifier with ease. It's easy because it uses one of the newer Toshiba modules as the heart of the amplifier. The Toshiba S-AV36 provides direct 50 Ω input and output impedances with gain galore — so much gain that less than 50 mW can drive it to full output in any mode. This design will work with any exciter providing 1 to 10 W drive, through the use of a built in attenuator.

My original intent in making this was to have an amplifier capable of boosting an older 10 W multimode radio up to 80 or 100 W. I wanted to keep it low in cost and simple (no preamp or power meters), yet capable of fixed station or mobile operation in any mode and operation from the usual nominal 12 V dc power supply. In this way, the supply that powers a 100 W HF transceiver can likely power the amplifier as well.

After absorbing the specs in the data sheet, it was clear to me that this module could be driven by almost any low power rig; thinking about it a bit more, and keeping in mind the low cost and simplicity requirements, a few more useful features came to mind, such as:

- An output low-pass filter to comply with FCC regulations for harmonic and spurious suppression.
- A low loss antenna relay.
- An RF-sensing TR switch for remote operation, as well as a hard key option.
- TR sequencing to protect the S-AV36 module and prevent hot switching of the antenna relay.
- Indicator LEDs and control switches.
- Reverse polarity protection.

The inside of the final project is shown in Figure 1. Note the simplicity.

The devil is in the details for the designer, though, and it did take a little planning, but the end result was a small PC board made at home using common hobby tools. Add a few interconnecting wires, heat sink, connectors, switches, a couple of sheet metal parts for the enclosure, and that's about it. A schematic and parts list is provided in Figure 2. The input and output power of the amplifier with the built in attenuator for a 10 W exciter shown in Figure 2 is provided in Table 1. This also shows the current required at 13.8 V dc.

Designing the Amplifier

The S-AV36 module is pretty easy to use; aside from RF IN and RF OUT, there are two power connections; one is for BIAS (this turns the module on and off), and the other for main DC POWER, 13.5 V nominal at up to 15 A. Since the input power required to drive it is only about 50 mW, the first thing to do is design an input attenuator to match the output of the driver to the S-AV36. The resistive attenuator (R7, R8 and R9) can adapt the attenuator to drive levels ranging from 1 to 10 W as shown in Table 2. There are some strange values there, but these are not terribly critical,

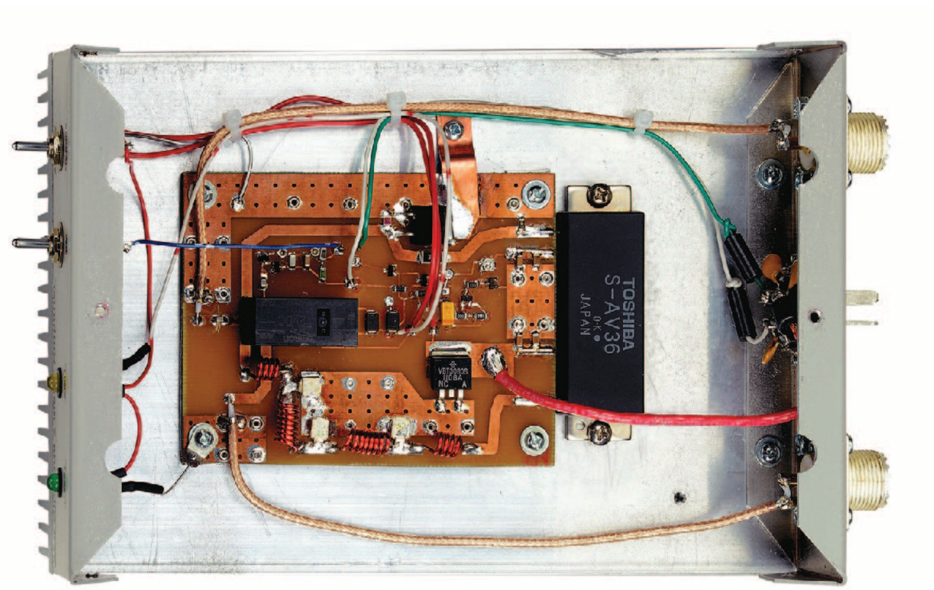


Figure 1 — Inside of the compact amplifier showing the simplicity of the final design. The amplifier module is the black rectangle connected to the right edge of the PC board.

you just have to get within a few ohms to get the job done. For example, a 23 dB attenuator is needed for a 10 W radio. The resistors chosen were those readily available from major distributors, so 58 Ω became 56, and 351 became 360 (close enough). L5 is not really necessary. Its purpose is to compensate for the stray capacitance of R7 at 2 meters (a 35 W tab-mounted resistor). The input SWR was acceptable without it, but it does make the input match almost perfect.

The Low-Pass Filter

Now that the input is taken care of, let's deal with the output. The data sheet says the second harmonic will only be down about 25 dB, and the third about 30. Not good enough for the FCC, so we need an output filter that will put us in good graces with at least 60 dB total suppression. For that 25 dB second harmonic, we need another 35 dB.

The filter shown (L1-L4, C12-C14 in Figure 2) is a standard pi type, Chebyshev filter of seven poles. The design provides the required suppression with very little insertion loss at the operating frequency.

The Antenna Relay and Switching Controls

In the spirit of keeping costs low, a PCB mount type of DPDT general purpose relay was chosen for TR and bypass switching. At less than $5 in cost, the contacts are rated at 8 A. At 2 meters, a bit of reactance is introduced by this part, but compensated for by a small capacitor (C15) in series with its input.

The best way to tell the amplifier to switch on is to use a control line back to the driving radio (PTT). If this is unavailable or inconvenient, the amplifier has an RF sensing circuit that samples a bit of drive from the input connector to provide the transmit trigger.

In another little twist; switching from receive to transmit should be sequenced for two reasons; first, the S-AV36 is tough, but no self-respecting amplifier module likes seeing an open circuit while those lazy relay contacts are moving, even if it only takes 20 ms to happen. It's not good for the module, and just plain rude. For this reason, the module has to be kept off while the relay contacts are settling. The other reason is to protect the relay contacts from that 80 to 100 W the amplifier will generate before they finally settle; it tends to shorten the life of the relay.

C4, D1 and D2 sample the input while C5, C6, R1 and R2 provide filtering and some timing, depending on the position of S1. In SSB mode, the circuit provides a delay on switching to RECEIVE similar to VOX, providing a second or so of delay. In FM mode, the switch back to RECEIVE is much quicker, as the delay is not necessary for FM operation. The circuit is sensitive, and will trigger with less than ½ W drive.

Q1 is the switch that operates the relay. When the relay is turned on by Q1, it also turns on Q2 (the bias switch) after a short delay. This delay is provided by C9 and R4, and is about 50 ms in duration, allowing those relay contacts to settle before the module becomes active.

When switching back to RECEIVE, the bias to the module is cut off before the relay contacts open. This fast cutoff is timed by C9 and R5, and is only about 5 ms in duration.

Another noteworthy component is D6, the reverse-polarity protection diode. This diode's purpose is to blow the in-line fuse in the power cord if you accidentally connect the power cord backwards (come on, we've all done it).

The extra contacts on power connector J3, Pins 3 and 4, provide a means to disable the RF sensing and connect PTT directly to the driver should the RF sensing be deemed unnecessary. If just Pin 4 of J3 is grounded by a PTT line, the amplifier will be switched by the PTT, but all the delays will apply. If Pin 3 is grounded the amplifier the will follow the PTT with only the delays designed to protect against hot switching, as described above.

Building the Amplifier

Here are the recommended steps, in sequence, for constructing the amplifier:

- Mark the heat sink for drilling by using the PC board as a template. You can also position the Toshiba module and mark its two mounting holes; leave a small gap of 2 to 3 mm between the module body and the board for strain relief.

- Drill and tap the module mounting holes for #6-32 screws, and the PCB holes for 4-40 screws.

Install all the PC board components except for the module. The relay should be installed last, and because the pins will protrude through the bottom of the board, they should be cut off flush with the board after soldering.

While I used a PC board and surface mount components, there is no reason leaded components could not be substituted. The PC board is still recommended because the etched transmission lines going in and out of the TR the relay will provide minimum loss on receive — important since any loss adds directly to the receive noise figure.

- Make the enclosure parts and two aluminum spacers as shown in the fabrication drawings available on the *QST* in Depth web page.[1]

- A PC board is available from the author, or can be made from the artwork on the *QST* in Depth web page. Mount the board to the heat sink with four 4-40 screws. The two aluminum spacers must be positioned under the board on either end to elevate the board to a convenient height for the module and keep the back side PCB connections at the relay pins from shorting against the heat sink.

- Some minor tuning of the low-pass filter coils can be made at this time. Connect a dummy load to the output of the board, and a transmitter and SWR meter to the trace at the input of the filter where the module will connect. Apply 12 V across the relay coil to close the relay, and spread or compress L1-L4 for lowest SWR reading. If this is inconvenient to do, the filter can be adjusted after the amplifier is fully constructed, adjusting for max power at about 50 W output. It's best to do it now, though, and you'll probably find that

[1]www.arrl.org/qst-in-depth

Table 1
Output Power and Current Required with Resting Current at 8 A

Drive Power (W)	Output Power (W)	Current (A) at 13.5 V
1	12	8.2
2	29	9.0
3	44	9.5
4	53	10.0
5	66	11.0
6	74	11.5
7	80	12.0
8	85	12.5
9	89	12.8
10	92	13.0

Table 2
Values of R7, R8 and R9 for Different Drive Levels

Drive Power (W)	Attenuation (dB)	R7, R9 (Ω)	R8 (Ω)
1	13.0	79	106
2	16.0	69	154
3	17.8	65	191
4	19.0	63	220
5	20.0	61	248
6	20.8	60	272
7	21.5	59	295
8	22.0	59	313
9	22.6	58	335
10	23.0	58	351

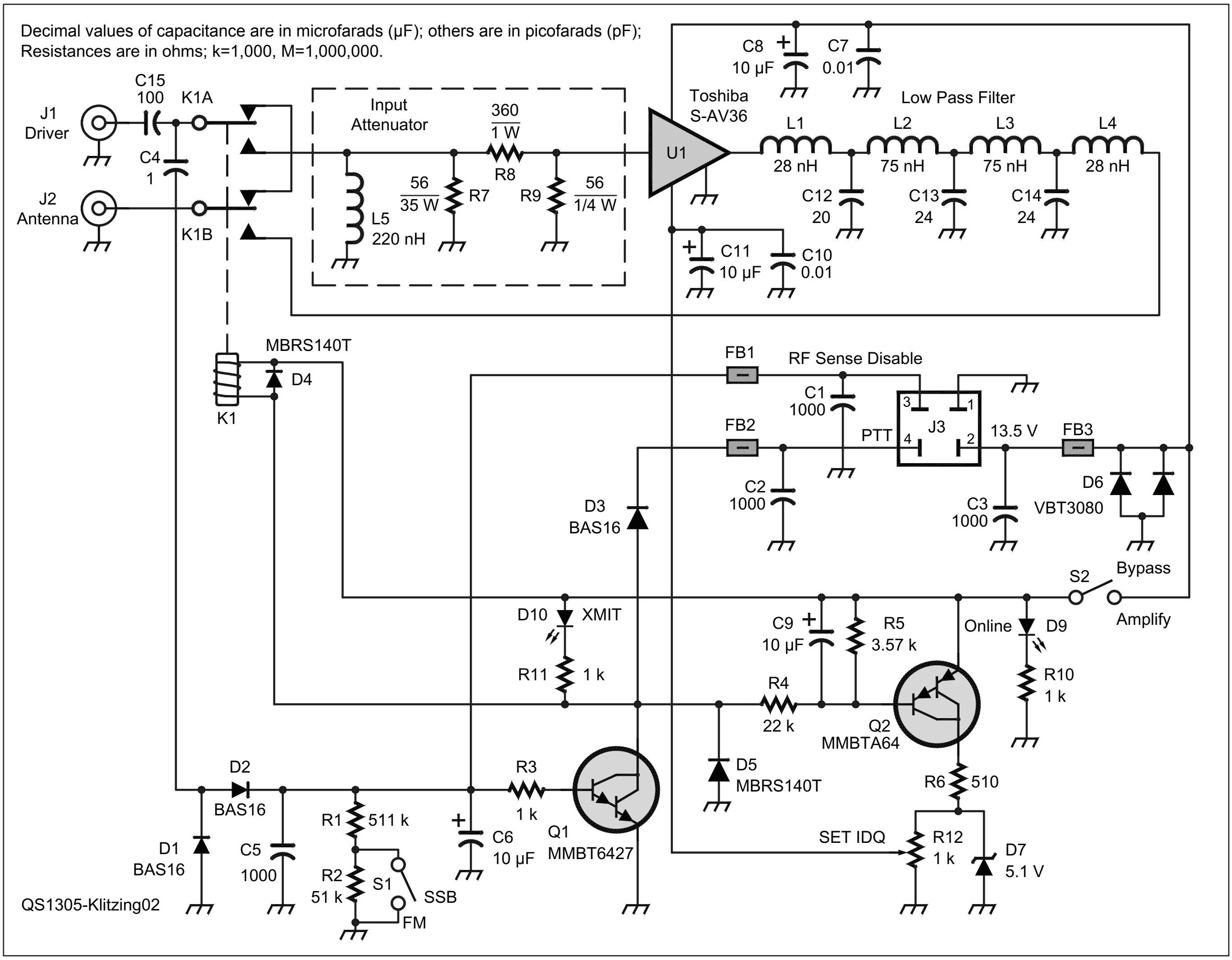


Figure 2 — Schematic diagram and parts list for the amplifier. For parts supplied by Mouser, you can order all of these by ordering the project list from their website, or order individual parts if your prefer. **www.mouser.com/tools/projectcartsharing.aspx**. The access ID code for the project is **c3ad150d1a**. RFPARTS (**www.rfparts.com**) is the supplier for the Toshiba module and coax connectors. Heat Sink USA parts are available at **www.heatsinkusa.com**. Artwork for the PC board is provided on the *QST* in Depth web page, along with fabrication drawings for sheet metal parts. For those not wishing to make their own board, commercially made boards are available from **www.w6pql.com**.

C1, C2, C3 — 1000 pF ceramic capacitor (Mouser S102K29Y5PN6TJ5R).
C4 — 1 pF SMT capacitor (Mouser 12061A1R0CAT2A).
C5 — 1000 pF 1206 (SMT) capacitor (Mouser 12065C102KAT2A).
C6, C8, C9, C11 — 10 µF 1206 (SMT) ceramic capacitor (Mouser 581-TAJA106M016R).
C7, C10 — 0.01 µF 1206 (SMT) capacitor (Mouser VJ1206Y103KXXCW1BC).
C12 — 20 pF metal mica capacitor (Mouser MIN02-20J-F).
C13, C14 — 24 pF metal mica capacitor (Mouser MIN02-24J-F).
C15 — 100 pF metal mica capacitor (Mouser MIN02-100J-F).
D1, D2, D3 — SMT switching diode (Mouser 512-BAS16).
D4, D5 — 1 A surface mount diode (Mouser MBRS140TRPBF).
D6 — SMT dual diode, 30 A (Mouser VBT3080S-E3/8W).
D7 — 5.1 V SMT Zener diode (Mouser MMBZ5231B-V-GS08).
D9 — 5 mm green LED (Mouser 941-C503BGCNCY0C0791).
D10 — 5 mm red LED (Mouser 941-C566CRFSCT0W0BB2).
F1 — 20 A fuse to fit the fuse holder in the power cable called out below.
FB1, FB2 — Small ferrite bead (Mouser 623-2643000701).
FB3 — Large ferrite bead (Mouser 623-2643000801).
J1, J2 — Panel mount SO-239 coax socket.
J3 — Power connector, 4 Pin cable mount (Mouser 38331-8004).
K1 (RL1) — Omron DPDT relay (Mouser G2RL-2-DC12).
L1, L4 — Inductor, 28 nH. 4 turns #18 AWG, 4 mm inside diameter, 8 mm long.
L2, L3 — Inductor, 75 nH. 7 turns #18 AWG, 4 mm inside diameter, 10 mm long.
L5 — Inductor, 220 nH. (Mouser 70-IMC10008ERR22J).
Q1 — NPN Darlington transistor (SMT) (Mouser MMBT6427).
Q2 — PNP Darlington transistor (SMT) (Mouser MMBTA64).
R1 — 511 kΩ 1206 (SMT) resistor (Mouser CR1206-FX-5118ELF).
R2 — 51 kΩ SMT resistor (Mouser CR1206-FX-5102ELF).
R3 — 1 kΩ 1206 SMT resistor (Mouser CR1206-FX-1001ELF).
R4 — 22 kΩ SMT resistor (Mouser CR1206-FX-2202ELF).
R5 — 3.57 kΩ SMT resistor (Mouser CR1206-FX-3571ELF).
R6 — 510 Ω SMT resistor (Mouser CR1206-FX-5100ELF).
R7 — 56 Ω, 35 W SMT resistor (Mouser PWR263S3556R0F).*
R8 — 360 Ω, 1 W SMT resistor (Mouser RK73B3ATTE361J).*
R9 — 56 Ω, ¼ W SMT resistor (Mouser CR1206-FX-56R0ELF).*
R10, R11 — 1 kΩ, ¼ W metal film resistor (Mouser 660-1/4DCT52R1001F).
R12 (VR1) — 1 kΩ potentiometer (Mouser TC33X-2-102E).
S1, S2 — SPST miniature toggle switch (Mouser A101SYZQ04).
U1 — Toshiba S-AV36 amplifier module (RF Parts)
Heat sink extrusion 5.375 × 8 × 1.376 inches (Heat Sink USA A009).
Heat sink extrusion 5.375 × 8 × 1.375 inches (Heat Sink USA A008).
In-line fuse holder (Mouser 441-R-332B-GR).
RG-316 50 Ω Teflon coax to go from J1 and J2 to K1.

*These parts provide the input attenuation required for a 10 W input. For other levels of driving power, see Table 2.

very little adjustment is necessary.

- Using heat sink compound, mount the Toshiba module with #6-32 machine screws. Note that the mounting bar of the module is slightly concave; this is not a defect, the manufacturer makes them this way, as do other module makers. Do not attempt to sand this footing flat or otherwise fill with any material except for heat sink compound. There is still plenty of contact area for heat transfer. I'm just guessing, but I believe the manufacturer makes the footing this way for strain relief in order to protect the mechanical bonds inside. Solder the module wires to the appropriate traces on the PC board (cut off the excess wire length if necessary, see Figure 3).

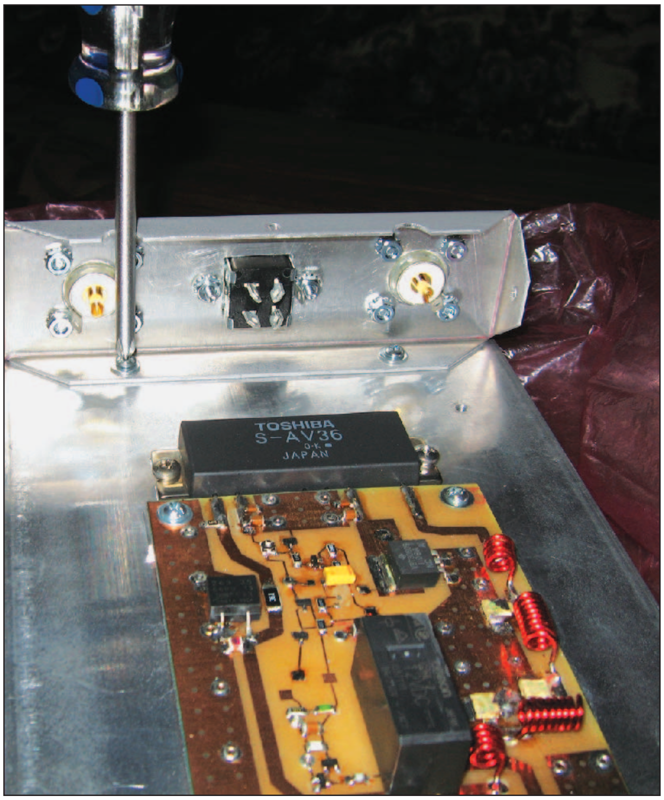


Figure 3 — The rear panel is attached using #6-32 machine screws. The module connections are soldered to the PC board as shown.

- Mount the connectors, switches and LEDs, and complete the chassis wiring (see Figure 4). The LEDs have their 1 kΩ resistors soldered directly to their leads, with the wire connected to the other side of the resistor; heat shrink is used to cover the resistor and connections. Use solder lugs under the mounting screws for the connectors on the rear panel; these are for connecting coax shields, dc chassis ground, and bypass capacitors as shown in Figure 5.

- Make the power cord from #14 AWG wire. Make certain to use an in-line fuse on the positive lead, and fuse it for no more than 20 A. If you will be hard keying your amplifier from your radio, jumper Pin 3 of the connector to ground, and carry Pin 4 back to your keying connection from the radio. The radio's PTT relay contacts or other switching must be capable of sinking 12 V at 50 mA to ground.

Testing the Amplifier

Once everything is wired and in place, you can test the amplifier using the following procedure:

- Connect the output to a suitable wattmeter and dummy load, and the input to your driving radio.

- Connect the power cord to a power supply

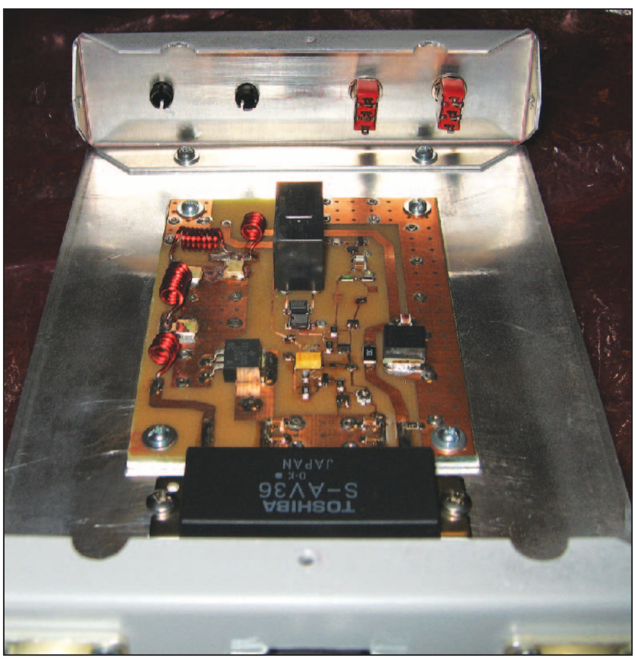


Figure 4 — View of the inside of the front panel before wiring.

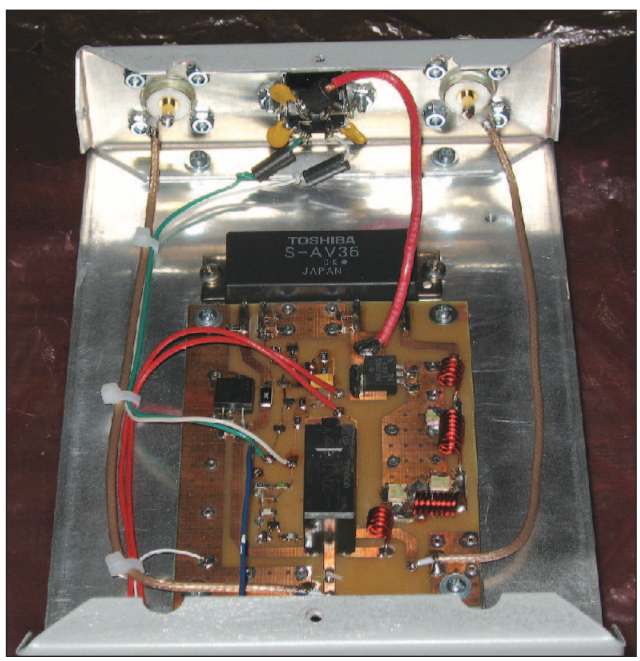


Figure 5 — Details of the rear panel wiring.

A Quest for a More Linear Amplifier

Your editor, in common with many casual VHF operators, uses a transverter with a power output of 10 W. In my case it is an Elecraft K3 HF and 6 meter transceiver with an internal 2 meter transverter. This unit has a very low noise receiver with the result that I can hear many more 2 meter stations than can hear me.

In an effort to put my station on an equal footing with stations with the frequently encountered 100 W multimode radios, I wanted to find an amplifier that could be added to my station to make up the difference. I tested a number of "brick" amplifiers in the hopes of finding one that would provide the needed power with appropriate intermod products for use on SSB.[1,2] While the tested units delivered the desired power, and indicated that they were suitable for SSB, the intermod levels were high enough that I thought they would cause trouble for other stations during contests. These amplifiers work fine on FM, their primary use design goal, as well as on CW. It is only using them in SSB operation that generates the spurious signals due to the multiple simultaneous frequency components.

There was an alternative, a much higher priced, higher powered, amplifier (now discontinued) that showed HF type IMD was indeed possible on VHF.[3] There was also the very nice 2 meter kilowatt amplifier described by Jim Klitzing in a recent *QST* article.[4] That inspired me to commission Jim to put his talents to work designing a lower powered amplifier that would meet my operational objectives, be easy to build and relatively inexpensive.

Jim has met my objectives in this very nice package. The IMD output, as measured in the ARRL Lab were as shown in Table A, and a plot of the input versus output power in Figure A. Note that it closely follows the straight line until 75 to 80 W, at which point the compression is evident.

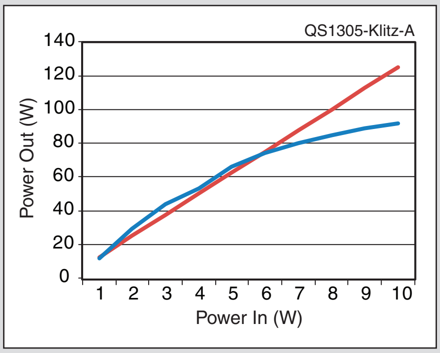


Figure A — Power output versus input, as measured in the ARRL Lab. A straight line (red) is shown for comparison.

Table A
Intermodulation Response as a Function of PEP Output

Power Output	Intermodulation Products (dBc)			
PEP (W)	3rd	5th	7th	9th
55	–27	–44	–46	–56
75	–24	–42	–49	–53
100	–19	–28	–36	–47

[1] J. Hallas, W1ZR, "Product Review —A Pair of Mirage 2 Meter Amplifiers" *QST*, Aug 2010, p 52.
[2] J. Hallas, W1ZR, "Product Review — TE Systems 1410G 2 Meter Linear Amplifier," *QST*, Jan 2012, p 54.
[3] J. Hallas, W1ZR, "Product Review — Tokyo Hy-Power Labs HL. 350VDX 2 Meter Linear Amplifier," *QST*, Mar 2012 p 48.
[4] J. Klitzing, W6PQL, "Solid State 1 kW Linear Amplifier for 2 Meters," *QST*, Oct 2012, p 32.

capable of delivering 13.5 V at up to 15 A.

Place the AMPLIFY/BYPASS switch in BYPASS mode. Transmit, and verify that bypass mode works (most of the driver's power should pass through the amplifier to the load). The bypass mode insertion loss is only about 0.1 dB.

Turn off the driving radio and put the amplifier in AMPLIFY mode. The READY LED should illuminate. Jumper PTT to ground, and the XMIT LED should also illuminate. Adjust the IDQ trimmer (VR1) for 8 A. Place the amplifier back in BYPASS mode and remove the PTT jumper.

Turn the radio back on, place the amplifier in AMPLIFY mode, and transmit. Performance should be similar to the data shown in Table 1.

I experimented some with various IDQ settings, and concluded that Toshiba must have designed the module to operate close to Class A. Setting IDQ too low tended to introduce lower overall gain and crossover distortion in SSB, while setting it too high resulted in higher gain and saturated output power. At 10 A IDQ, for example, the amplifier could be driven to over 100 W output with about half the drive required at 8 A IDQ. This current drawn at this level is close to the manufacturer's absolute maximum ratings for the device, and really doesn't make any difference on the air, so I resisted the temptation to leave it that way. For all mode versatility, leaving IDQ set at 8 A is best.

One last note. At a drive level of 10 W, I noticed R7 (the 35 W attenuator input resistor) ran hot. This was due to the inadequate heat transfer of the PC board I made for the original prototype, which has just a few rivets where there should have been multiple plated through holes surrounding this part. My solution was to use a piece of 0.040 inch copper strip soldered to the ground tab of the resistor. I used this to transfer the heat to the heat sink by fastening the other end to it with a #4 screw. Most of us making our own prototype boards at home don't have the ability to make plated through holes the way the commercial board houses do, so if you make your own board for this project, you'll probably need to implement a similar solution.

ARRL member and Advanced class licensee James Klitzing, W6PQL, was first licensed in 1964 as WB6MYC. He has been a precision measurement specialist for the US Air Force and Hewlett-Packard Company. He retired in 2006 as an engineering manager for Agilent Technologies after 34 years with HP/Agilent. Jim has always enjoyed building his own equipment and is active on HF through 3456 MHz.

You can reach him at 38105 Paseo Padre Ct, Fremont, CA 94536, or at **jim@w6pql.com**. Jim's website, **www.w6pql.com**, has all current updates to this and many other projects.

For updates to this article, see the *QST* Feedback page at www.arrl.org/feedback.

2 Watt RF Power Amplifier for 10 GHz

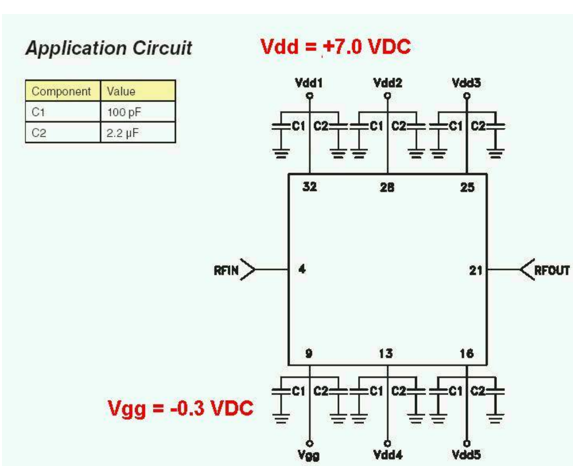
Overview

Generating RF power above a few milliwatts in the 10 GHz band used to be very difficult. Thankfully, Hittite Microwave Corp. has the HMC487, which is an easy−to−use X−band amplifier chip that requires no complicated external RF circuitry or weird voltage biasing. The HMC487 costs around $60 in single quantities and the evaluation board − which is *highly* recommended − is a couple hundred dollars. The project shown here will be based around the HMC487 evaluation board to help make construction of the final amplifier very easy, even for a beginner microwave experimenter.

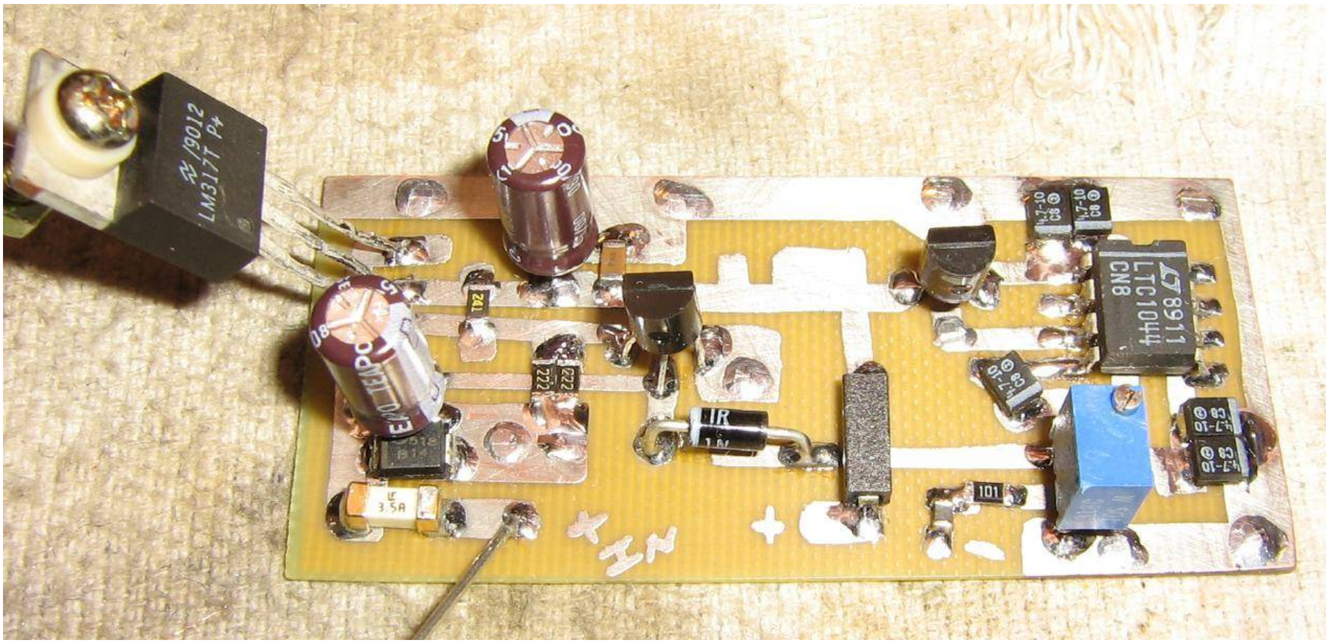
The Hittite HMC487 is a remarkable little chip. It has around 20 dB of gain from 9 to 12 GHz and is internally matched to 50 ohms on both the RF input and output. This means no fussing with complex tuning lines or sliding solder flakes! It will do an easy 1 watt (+30 dBm) RF output with a 10 mW (+10 dBm) RF input over most of the X−band. It saturates at around 2 watts (+33 dBm) and I've heard it can reach 3 watts (+35 dBm) if you run it with a little higher drain voltage and fiddle with the input return loss matching a bit. The only real drawback to the HMC487 is the large amount of heat it needs to dissipate. Its RF efficiency is only around 20% and the rest of the this energy will need to be dissipated as heat. To properly do this, a small block of aluminum will need to be milled out in order to securely hold the HMC487 evaluation board. This new aluminum block can act as a heatsink alone, or it can be further attached to a larger heatsink in order to improve cooling. This entire process may be difficult to accomplish if you don't have access to a milling machine, but some type of additional heatsinking, or probably even fan cooling, for the HMC487 evaluation board will be *required*. This is especially true if you plan on operating the amplifier for an extended period of time.

To power the HMC487, a +12 VDC input will be regulated down to +7 volts using a LM317 adjustable voltage regulator. The HMC487 does require a small negative voltage for its gate bias which will be generated with a LTC1044 negative voltage converter and controlled via a 500 ohm multiturn potentiometer. A simple 4.7 volt Zener diode / 2N3904 transistor circuit will "power down" the LM317 voltage regulator until the negative gate voltage is applied to the HMC487. This little Zener voltage pre−conditioning circuit is a requirement to protect the HMC487 when voltage is first applied. When the HMC487's negative gate bias is set (at around −0.3 VDC), the amplifier's supply current (1.3A) will not change whether RF input power is applied or removed.

HMC487 Application Circuit



Pictures & Construction Notes



Overview of the Hittite HMC487 evaluation board power supply circuit.

Nothing too complicated is required, but try to have a good ground plane on the PC board.

The +12 VDC input is from the lower−left and goes through a little surface−mount 3 amp fuse. The LM317's tab will need to isolated from the project box with a mica washer or thermal pad and a plastic feed−through on the mounting screw. High−quality capacitors can be salvaged from old computer motherboards.

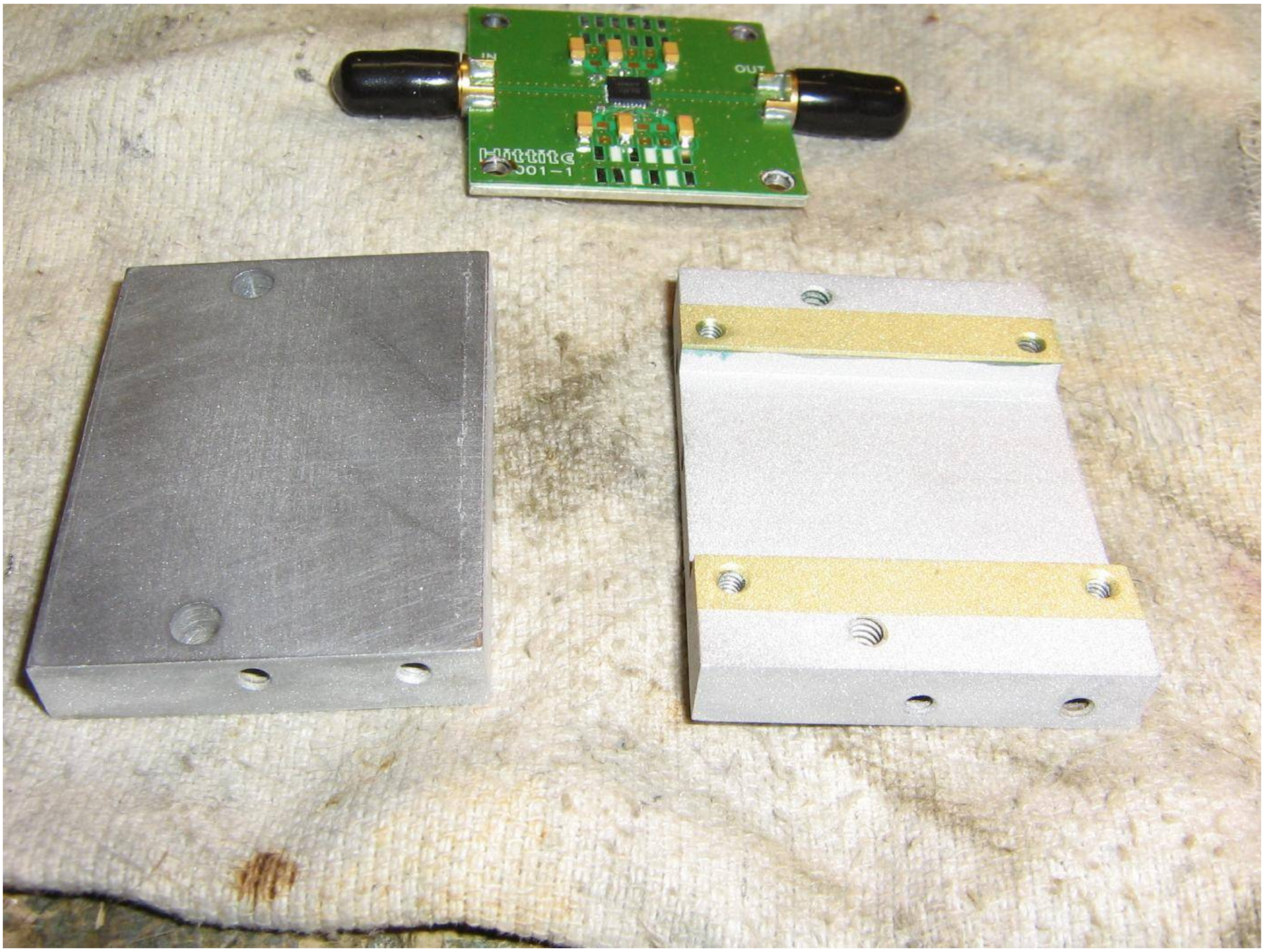
The blackish rectangle thing in the middle is a high−current surface−mount ferrite bead.

The LTC1044 negative voltage converter is on the upper−right and takes its input from a 78L05 voltage regulator. The −5 VDC output of the LTC1044 is then feed to a multiturn 500 ohm potentiometer. This is used to adjust the HMC487's gate bias for a final quiescent current draw of 1.3 amps. The negative voltage going to the HMC487 should never exceed −2.0 volts.

For additional protection, the +12 VDC power supply feeding this circuit should be current−limited to around 2 amps.

Installing the power supply circuit in the project box.

This old project box was found at a hamfest and already had a bunch of holes drilled in it, so it may look a little funny and is probably a tad too small to house everything.



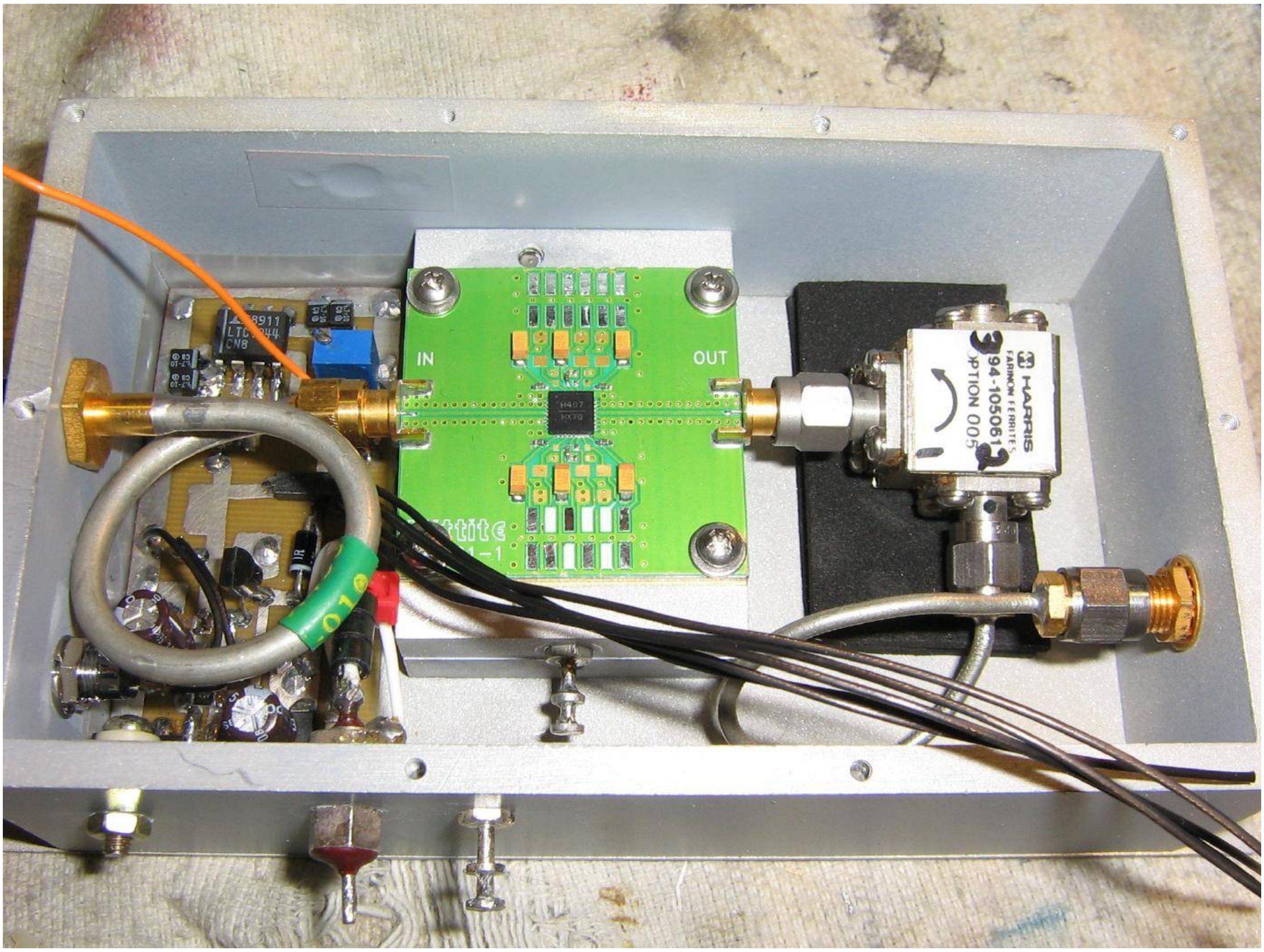
Overview of the Hittite HMC487 evaluation board and the milled aluminum mounting block.

The aluminum blocks where salvaged from other projects, hence the holes in the sides. Two were used in order to make room for an optional RF isolator attached to the RF output of the HMC487.

The block on the right−side has a slot milled to accept the little heatsink on the bottom of the HMC487 evaluation board. Thermal grease was lightly applied to each piece and then the entire assembly is bolted to the bottom of project box.

The brass inserts on that one aluminum block were added when I machined the aluminum down a little too much.

The HMC487 evaluation board has a little 1/4−inch thick aluminum square attached to its bottom to act as a makeshift heatsink, but it's far too small for continuous operation. The idea here is to mill out a slot for this stock heatsink to fit in, then mount this entire assembly to a larger heatsink.



Mounting the evaluation board in the project box.

Four holes where also drilled in the HMC487 evaluation board and the top aluminum block. The holes in the aluminum block were then tapped with #3−48 threads and the evaluation board was secured to the aluminum blocks with #3−48 hardware.

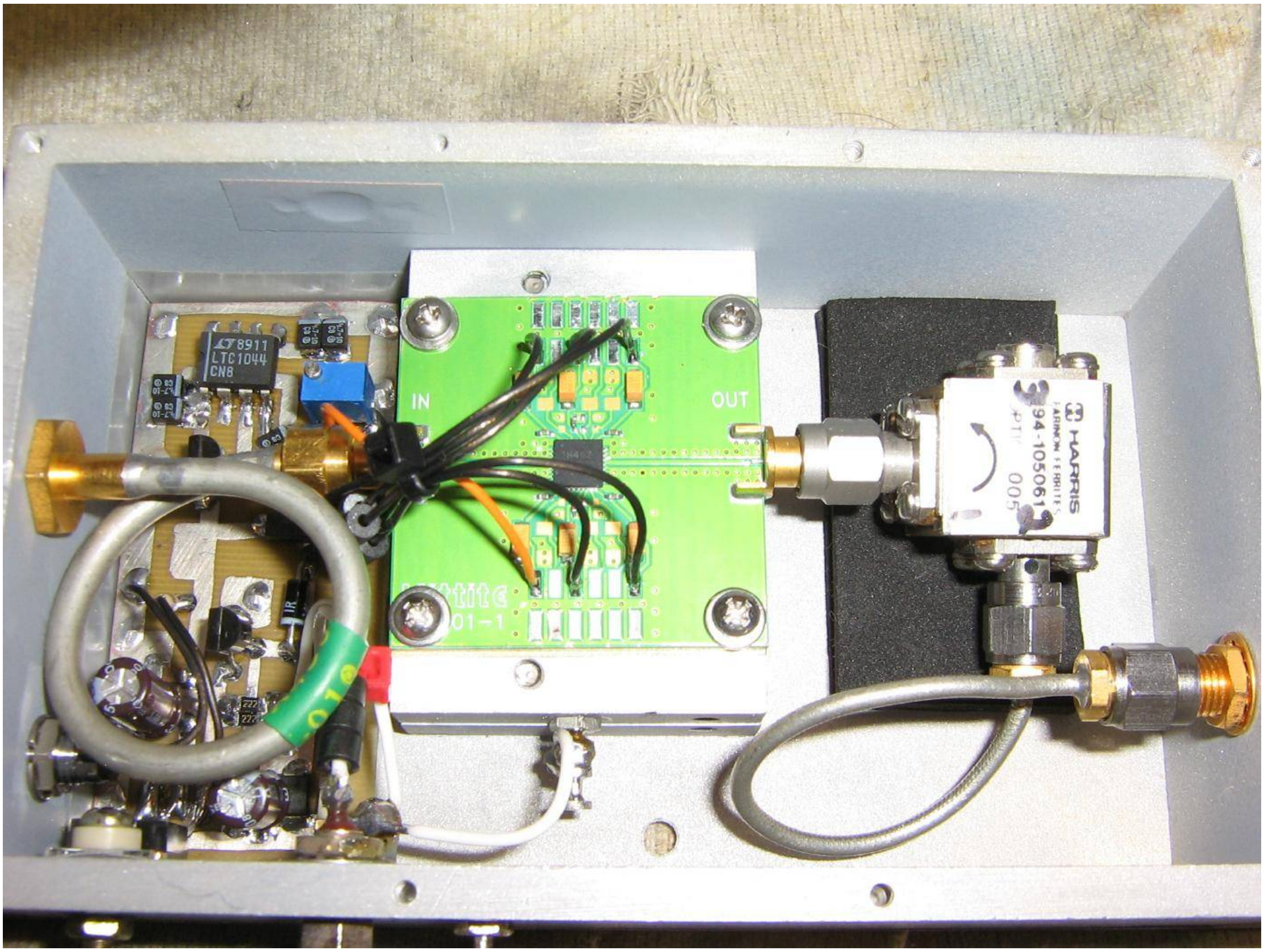
Two #6−32 screws come up from the bottom and secure two aluminum blocks together.

The pin headers were removed from the HMC487 evaluation board to allow the drain and gate wires to be soldered directly to the board. A solder terminal was added to one of the aluminum blocks for the ground.

The +12 VDC input is via the feed−through capacitor on the lower−left. Ground is the solder terminal to the right. There are a couple extra ferrite beads on the incoming +12 VDC wire.

The RF input is on the left−side and comes in via a panel−mounted SMA connector on a salvaged piece of UT−141 coax. The RF output goes through and optional 10 GHz RF isolator (Harris/Farinon 94−105061) to protect the HMC487 in the event of an impedance mismatch downline. The final RF output is via a panel−mounted SMA bulkhead.

The RF connectors and conformable coax were all hamfest finds, so it may look a little rough, but everything checked out fine.



Finished overview.

The **BROWN** wires carry the +7 VDC drain voltage. The **ORANGE** wire carries the approximately –0.3 VDC gate bias. The **WHITE** wire is a common ground for everything.

A few pieces of art foam are underneath the 10 GHz isolator to relieve any strain.

Extra ferrite beads where slipped over the wires carrying the drain and gate bias voltages.

Setting the HMC487's negative gate bias and drain quiescent current.

First, attach good 50 ohm loads to the RF input and output of the amplifier.

Then power the amplifier with a quality current meter inline with the incoming +12 VDC power line. Slowly adjust the 500 ohm gate bias potentiometer until the quiescent current reads around 1.3 amps.

The final gate voltage will be around −0.3 VDC. The meter in the above picture is reading −0.256 VDC. Don't exceed −2.0 volts on the gate bias line or the HMC487 will be damaged.

Finished case overview.

RF input is via the SMA connector on the left side.

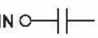
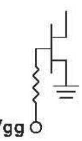
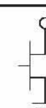
RF output in on the right side. It passes through an optional 10 dB directional coupler for power monitoring or local oscillator drive on an external mixer.

+12 VDC power is applied via the feed−through capacitor.

For linear operations, you'll want to avoid running the amplifier into compression but for FM, or other constant−envelope modulations, you can let this amplifier hit 2 watts (+33 dBm) of RF output.

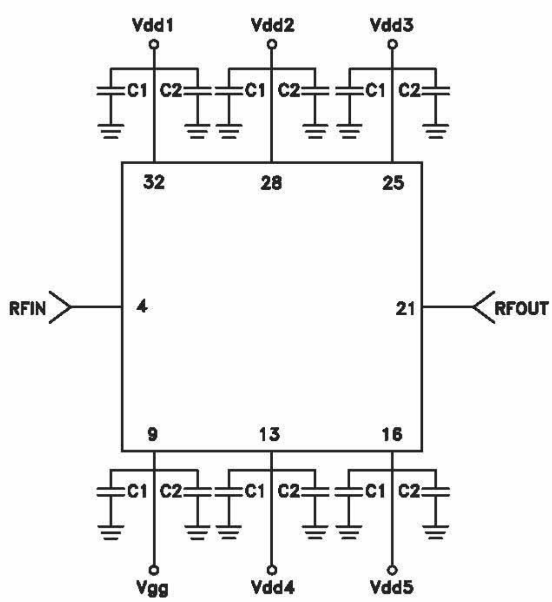
Doing this, when combined with a simple 18−inch DSS satellite dish, will make your ERP at least 2,000 watts − at 10 GHz!

Pin Descriptions

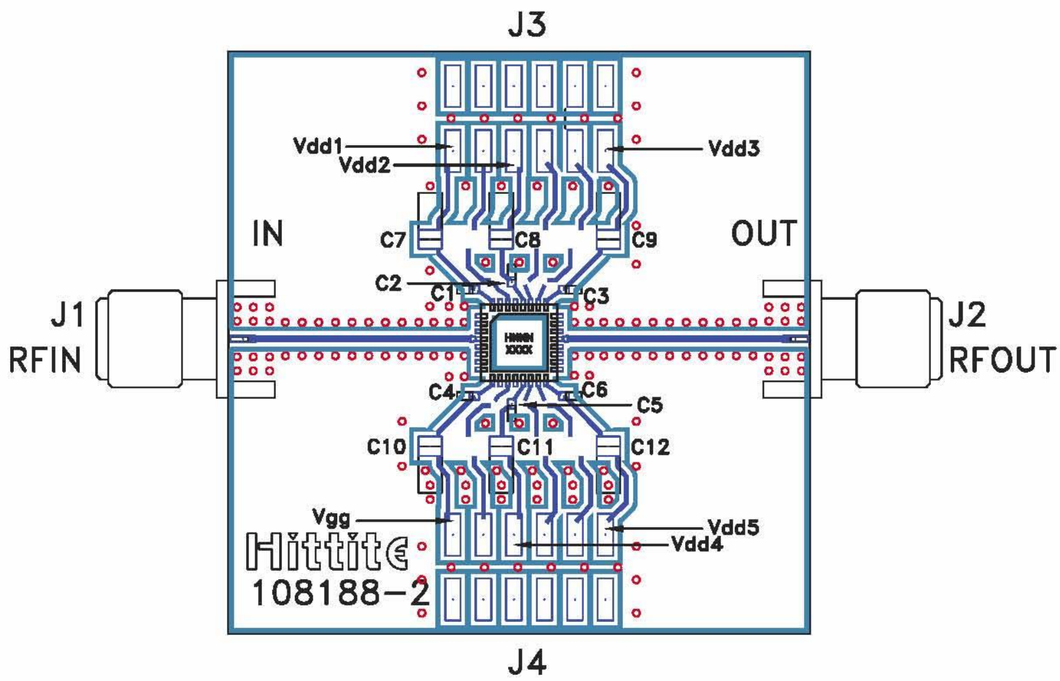
Pin Number	Function	Description	Interface Schematic
1-3, 5-8, 10-12, 14, 15, 17-20, 22-24, 26, 27, 29-31	N/C	No connection required. These pins may be connected to RF/DC ground without affecting performance.	
4	RFIN	This pin is AC coupled and matched to 50 Ohms from 9 - 12 GHz.	
9	Vgg	Gate control for amplifier. Adjust to achieve Idd of 1300 mA. Please follow "MMIC Amplifier Biasing Procedure" Application Note. External bypass capacitors of 100 pF and 2.2 µF are required.	
21	RFOUT	This pin is AC coupled and matched to 50 Ohms from 9 - 12 GHz.	
32, 28, 25, 13, 16	Vdd1, Vdd2, Vdd3, Vdd4, Vdd5	Power Supply Voltage for the amplifier. External bypass capacitors of 100 pF and 2.2 µF are required.	
	GND	Ground: Backside of package has exposed metal ground slug that must be connected to ground through a short path. Vias under the device are required	

Application Circuit

Component	Value
C1	100 pF
C2	2.2 µF



Evaluation PCB



List of Materials for Evaluation PCB 108190 [1]

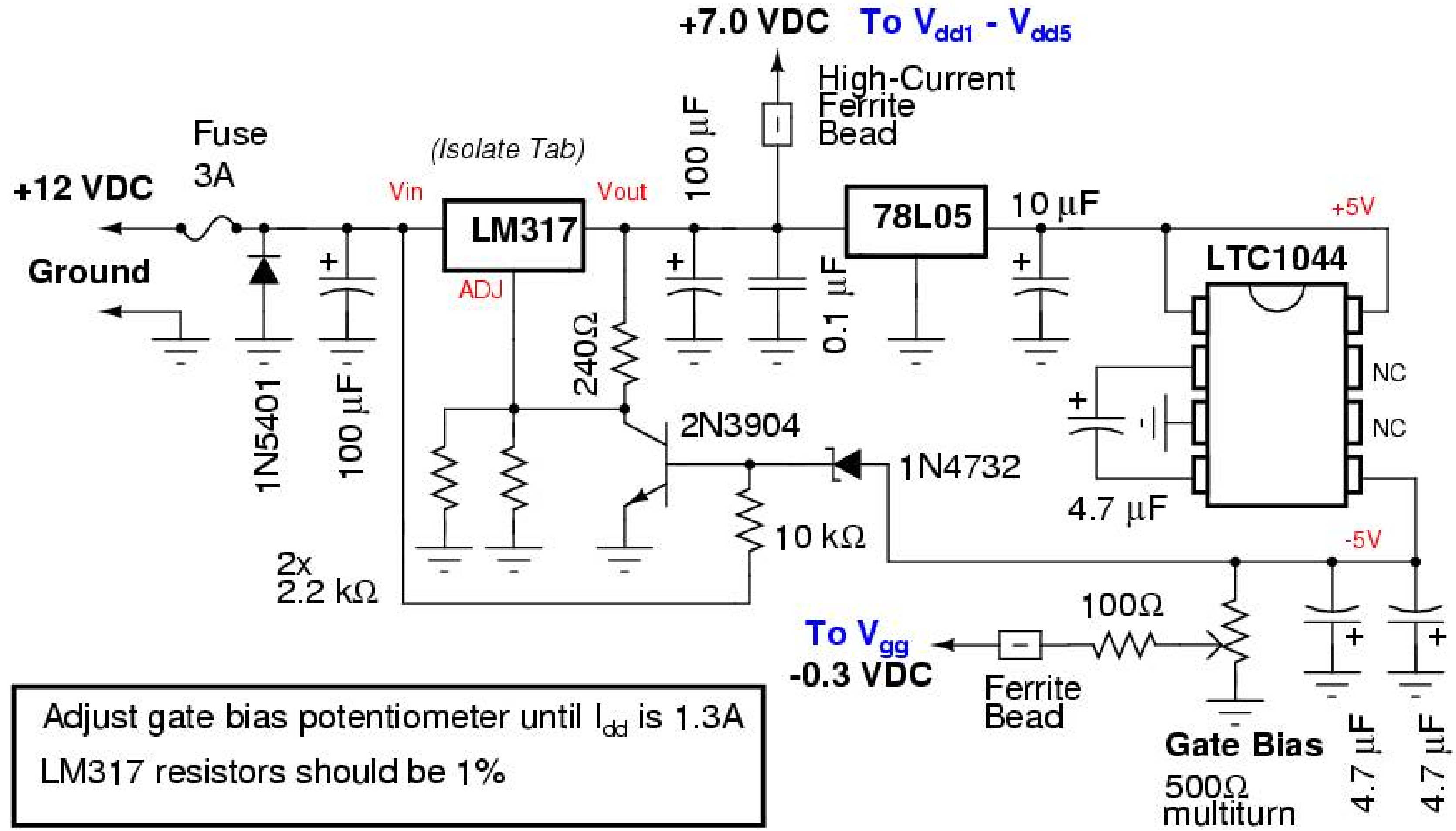
Item	Description
J1, J2	SRI PC Mount SMA Connector
J3, J4	2mm DC Header
C1 - C6	100 pF capacitor, 0402 pkg.
C7 - C12	2.2μF Capacitor, Tantalum
U1	HMC487LP5 / HMC487LP5E Amplifier
PCB [2]	108188 Evaluation PCB

[1] Reference this number when ordering complete evaluation PCB

[2] Circuit Board Material: Rogers 4350.

The circuit board used in this application should use RF circuit design techniques. Signal lines should have 50 ohm impedance while the package ground leads and exposed paddle should be connected directly to the ground plane similar to that shown. A sufficient number of via holes should be used to connect the top and bottom ground planes. Copper filled vias under the device are recommended. The evaluation board should be mounted to an appropriate heat sink. The evaluation circuit board shown is available from Hittite upon request.

HMC487 Power Supply Circuits



Adjust gate bias potentiometer until I_{dd} is 1.3A

LM317 resistors should be 1%

A 3CX1500D7 RF Linear Amplifier

Editor's note: Section and figure references in this article are from the 2013 edition of the ARRL Handbook. *Although a 3CX1500D7 tube is used in this design, the 3CX1200D7 tube may be more affordable and the design can be adapted to use it with somewhat less plate dissipation.*

The following describes a 10-to-160-meter RF linear amplifier that uses the new com-pact Eimac 3CX1500D7 metal ceramic triode. It was designed and constructed by Jerry Pittenger, K8RA.

The amplifier features instant-on operation and provides a solid 1500 W RF output with less than 100 W drive. Specifications for this rugged tube include 1500-W anode dissipation, 50-W grid dissipation and plate voltages up to 6000 V. A matching 4000-V power supply is included. The amplifier can be easily duplicated and provides full output in key-down service with no time constraints in any mode. **Fig 17.56** shows the RF deck and power supply cabinets.

DESIGN OVERVIEW

The Eimac 3CX1500D7 was designed as a compact, but heavy-duty, alternative to the popular lineup of a pair of 3-500Z tubes. It has a 5-V/30-A filament and a maximum plate dissipation of 1500 W, compared to the 1000-W dissipation for a pair of 3-500Zs. The 3CX1500D7 uses the popular Eimac SK410 socket and requires forced air through the anode for cooling. The amplifier uses a conventional grounded-grid design with an adjustable grid-trip protection circuit. See the RF Deck schematic in **Fig 17.57**.

Output impedance matching is accomplished using a pi-L tank circuit for good harmonic suppression. The 10 to 40-meter coils are hand wound from copper tubing, and they are silver plated for efficiency. Toroids are used for the 80- and 160-meter coils for compactness. The amplifier incorporates a heavy-duty shorting-type bandswitch. Vacuum variable capacitors are used for pi-L tuning and loading.

A unique feature of this amplifier is the use of a commercial computer-controlled impedance-matching module at the input. This greatly simplifies the amplifier design by eliminating the need for complex ganged switches and sometimes frustrating setup adjustments. The AT-100AMP module kit available from W4RT Electronics (**www.w4rt.com**) is an acceptable tuning unit.

An adjustable ALC circuit is also included to control excess drive power. The amplifier metering circuits allow simultaneous monitoring of plate current, grid current, and a choice of RF output, plate voltage or filament voltage.

Fig 17.56—At the top, front panel view of RF Deck and Power Supply for 3CX1500D7 amplifier. At bottom, rear view of RF Deck and Power Supply.

The blower was sized to allow full 1500-W plate dissipation (65 cfm at 0.45 inches H_2O hydrostatic backpressure). The design provides for blower mounting on the rear of the RF deck or optionally in a remote location to reduce ambient blower noise in the shack. The flange on the socket for connecting an air hose was ground off for better air flow. (This is not necessary.).

The power supply is built in a separate cabinet with casters and is connected to the RF deck using a 6-conductor control cable, with a separate high voltage (HV) cable. The power transformer has multiple primary taps (220/230/240 V ac) and multiple secondary taps (2300/2700/3100 V ac). No-load HV ranges can be selected from 3200 to 4600 V dc using different primary-secondary combinations. The amplifier is designed to run at 4000 V dc under load to maintain a reasonable plate resistance and component size. A step-start circuit is included to protect against current surge at turn on that can damage the diode bank. The power supply schematic is shown in **Fig 17.58** and a photo of the inside of the power supply is shown in **Fig 17.59**.

Both +12-V and +24-V regulated power supplies are included in the power supply. The +12 V is required for the computer-controlled input network and +24 V is needed for the output vacuum relay. The input and output relays are time sequenced to avoid amplifier drive without a 50-Ω load. Relay actuation from the exciter uses a low-voltage/low-current circuit to accommodate the amplifier switching constraints imposed by many new solid-state radios.

Much thought was put into the physical appearance of the amplifier. The goal was to obtain a unit that looks commercial and that would look good sitting on the operating table. To accomplish the desired look, commercial cabinets were used. Not only does this help obtain a professional look but it eliminates a large amount of the metal work required in construction. Careful attention was taken making custom meter scales and cabinet labeling. The results are evident in the pictures provided.

GENERAL CONSTRUCTION NOTES

The amplifier was constructed using basic shop tools and does not require access to a sophisticated metal shop or electronics test bench. Basic tools included a band saw, a jig saw capable of cutting thin aluminum sheet, a drill press and common hand tools. Some skill in using tools is needed to obtain good results and insure safety, but most people can accomplish this project with careful planning and diligence.

Metal work can be a laborious activity. Building cabinets is an art within itself. This part of the project can be greatly simplified by using commercial cabinets. However, commercial cabinets are expensive (~$250 each) and could be a place where some dollars could be saved.

The amplifier is built in modules. This breaks the project into logical steps and facilitates testing the circuits along the way. For example, modules include the HV power supply, LV power supply, input network, control circuits, tank circuit and wattmeter. Each

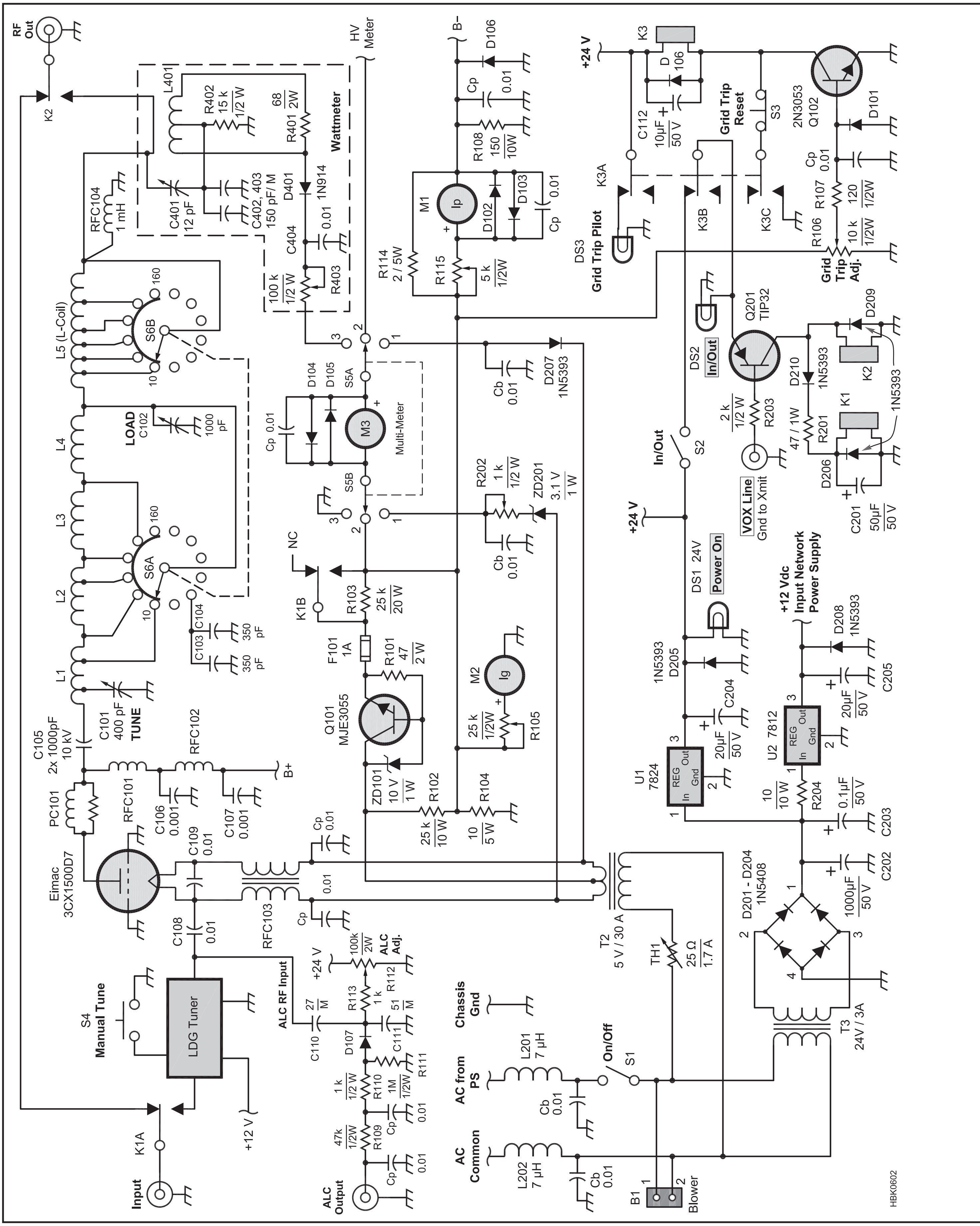

RF Out
K2
HV Meter
B–
D106
+24 V
K3
Wattmeter
L401
R402 15 k 1/2 W
R401 68 2W
D401 1N914
C401 12 pF
C402, 403 150 pF/M
C404 0.01
R403 100 k 1/2 W
RFC104 1 mH
Cp 0.01
R108 150 10W
M1 Ip
D102
D103
R114 2 / 5W
R115 5 k 1/2W
C112 10µF 50 V
Grid Trip Reset
S3
2N3053 Q102
D101
K3A
K3B
K3C
R107 120 1/2W
R106 10 k 1/2W
Grid Trip Adj.
DS3 Grid Trip Pilot
L5 (L-Coil)
S6B
S5A
D104
D105
M3
Multi-Meter
S5B
D207 1N5393
Cb 0.01
Q201 TIP32
D209
DS2 In/Out
D210 1N5393
K2
R203 2 k 1/2 W
R201 47 / 1W
K1
1N5393
D206
C201 50µF 50 V
VOX Line Gnd to Xmit
In/Out S2
+24 V
R202 1 k 1/2 W
ZD201 3.1 V 1 W
LOAD C102 1000 pF
L4
L3
L2
L1
S6A
NC
K1B
R103 25 k 20 W
DS1 24V Power On
+12 Vdc Input Network Power Supply
D208 1N5393
C104 350 pF
C103 350 pF
F101 1A
R101 47 2 W
M2 Ig
1N5393 D205
C204
C205 20µF 50 V
Q101 MJE3055
R105 25 k 1/2W
C101 400 pF TUNE
C105 2x 1000pF 10 kV
RFC102
B+
ZD101 10 V 1 W
R102 25 k 10 W
R104 10 5 W
U1 7824
REG In Gnd Out
20µF 50 V
U2 7812
R204 10 10 W
C203 0.1µF 50 V
PC101
RFC101
C106 0.001
C107 0.001
Eimac 3CX1500D7
C109 0.01
C108 0.01
RFC103
D201 - D204 1N5408
C202 1000µF 50 V
T2 5 V / 30 A
TH1 25 Ω 1.7 A
S4 Manual Tune
LDG Tuner
ALC RF Input
+24 V
100k 2W ALC Adj.
R113 1 k
R112 51 M
C110 27 M
D107
C111
R111
Chassis Gnd
T3 24V / 3A
R110 1 k 1/2 W
1M 1/2W
R109 47k 1/2W
Cp 0.01
AC from PS
L201 7 µH
On/Off S1
+12 V
K1A
Input
ALC Output
AC Common
L202 7 µH
Cb 0.01
B1
Blower
HBK0602

Fig 17.57 — Schematic of the RF deck and control circuitry.

B1 — Dayton 4C763 squirrel-cage blower.
Cb, Cp — 0.01 µF, 1 kV disc ceramic.
C101 — 400 pF, 10 kV Jennings vacuum variable, UCSL-400.
C102—1000 pF, 5 kV Jennings vacuum variable, UCSL-1000.
C103, C104—350 pF, 5 kV ceramic doorknob.
C105—two parallel 1000 pF, 10 kV ceramic doorknob capacitors (Ukrainian mfg).
C106, C107—0.001 µF, 7.5 kV disc ceramic.
C108, C109—0.01 µF, 3 kV transmitting mica (1 kV disc ceramics can be used).
C401—12 pF piston trimmer.
C403, C403—150 pF silver mica.
D101, D107, D205-D210—1N5393 (200 V, 1.5 A).
D102-D106, D201-D204—1N5408 (1 kV, 3 A).
K1—4PDT, 24 V dc KHP style (gold contacts).
K2—SPST vacuum relay, Kilovac H8/S4.
K3—4PDT, 24 V dc KHP style (gold contacts).
L1-L5—See Table 17.8.
L201, L202—Line chokes, 7 µH.
L401—24 t #22 enamel wire, center tapped on T50-6 core.
M1-M3—Simpson Designer Series, Model 523, 1 mA movement.
PC101—2 t ¾-inch diameter × 2-inch long, ½-inch brass strap with two 150 Ω, 2 W non-inductive carbon resistors in parallel.
Q101—MJE3055 TO-220 case on heat sink.
Q102—2N3053 TO-18 case.
R103—25 kΩ, 25 W wire-wound.
R104—10 Ω, 5 W.
R108—150 Ω, 10 W wire-wound.
R112—100 kΩ, 2 W potentiometer
R403—100 kΩ, 0.5 W trim pot.
RFC101—90 µH, 3 A Plate Choke, Peter W. Dahl p/n CKRF000100, (see text).
RFC102—14 t #18 enamel wire wound on 100 Ω, 2 W resistor.
RFC103—Bifilar 30 A filament choke, Peter W. Dahl p/n CKRF000080, (see text).
RFC104—1 mH, 300 mA RF choke.
S1-S2—Alco 164TL5 DPDT switch (only SPST contacts are used), www.alliedelec.com/.
S3-S4—Alco 164TL2 momentary DPDT (only SPST contacts are used; S3 wired as normally closed, S4 as normally open), www.alliedelec.com/.
S5—2 pole, 3 position rotary switch.
S6—RadioSwitch model 86, double-pole 12-position (30° indexing) with 6-finger wiper on each deck, p/n R862R1130001, www.multi-tech-industries.com.
T2—5 V, 30 A center-tapped transformer, Peter W. Dahl EI-150 × 1.5 core, primary 115/230 V ac, (see text).
TH1—Thermistor, Thermometrics CL-200 (Mouser 527-CL200).
ZD101—10 V, 1 W Zener 1N4740A.
ZD201—3.1 V, 1 W Zener.
Other parts:
Cabinet—Buckeye Shapeform DSC-1054-16 (10×17×16-inch H×W×D), www.buckeyeshapeform.com.
Chimney (Teflon)—A. Howell, KB8JCY, PO Box 5842, Youngstown, OH 44504.
LDG Tuner—AT-100AMP autotuner, see text.
Tube socket—Eimac SK-410.

module can be tested prior to being integrated into the amplifier.

The project also made extensive use of computer tools in the design stage. The basic layout of all major components was done using the *Visio* diagramming software package. The printed-circuit boards were designed using a free layout program called *ExpressPCB* (**www.expresspcb.com**). Masks were developed and the iron-on transfer technique was used to transfer the traces to copper-clad board. The boards were then etched with excellent results. The layout underneath the RF Deck is shown in **Fig 17.60A** and the top side of the RF Deck is shown in Fig 17.60B.

Meter scales were made using an excel-lent piece of software called *Meter* by Jim Tonne, W4ENE (**www.tonnesoftware.com**). Also, K8RA wrote an *Excel* spread-sheet to calculate the pi-L tank parameters. A copy of the spreadsheet, *Meter Basic* software and *Express PCB* files for the PC boards are all included on the CD-ROM that accompanies this book.

Although using computer tools simplifies the design step, all design work can be done without the use of a computer. Be creative and use the tools and resources at hand! There are many different ways to construct this design. The key secret is diligence and not compromising until it is done right. Note that the tank coils in this amplifier were wound at least three times, the inside side panels were cut twice and many printed circuit boards ended in the trash before acceptable boards were fabricated.

Since this project was built, Peter W. Dahl has discontinued business, Dahl transformers are now available from Harbach Electronics (**www.harbachelectronics.com**). Contact Harbach to cross-reference the Peter Dahl part numbers in the parts list for T1, T2 and RFC103 with current Harbach stock or equivalent designs.

CABINET METAL WORK

By purchasing commercial cabinets, metal work required was minimized but not eliminated. The power supply components are very heavy. The transformer weighs about 70 pounds by itself. Therefore the base plate of the power supply cabinet needed to be reinforced. The original base plate for the cabinet was not used. One-eighth-inch plate was purchased from a local aluminum scrap company. Two pieces were sandwiched to provide a ¼-inch plate. Of course ¼-inch material could have been used but it was not available at the time of purchase.

The plate can be cut on a metal band saw using a guide or on a radial arm saw. Metal blades are readily available from Sears for both saws. If using a radial arm saw, multiple passes are required, lowering the blade slightly with each pass. Be sure to wear eye protection because the metal chips fly. The edges were then cleaned and straightened using a 4-inch belt grinder. If a belt sander is not available, a large file will work.

The two metal plates were held together with the mounting bolts on the four casters. The power supply base plate exactly matches the original base plate and fastened to the cabinet using the original tapped screw holes. All the heavy components are mounted on the base plate. The power supply must always be handled by lifting the base plate, since the cabinet does not have the structural integrity to bear the weight by itself.

The RF deck needed both a chassis plate and a front sub-panel. See Fig 17.60B. The sub-panel is used to mount the load and tune capacitors, the bandswitch and also provides RF shielding for the meters. Side plates were needed because of the cabinet configuration. The side plates, chassis plate and sub-panel all use 1⁄16-inch aluminum plate. After the side plates are cut and mounted to the cabinet sides, the chassis plate and front sub-panel are mounted using ½-inch aluminum angle to join the edges.

Cutting holes can often be a challenge. If a drill bit is the correct size, drilling a hole is easy, of course. But large-size round holes and square holes can be a challenge. This was especially true in this project since the front and rear panels are ⅛-inch aluminum plate.

The large meter holes can be cut using a hole saw on a drill press. For odd sizes, a "fly cutter" can be used. Fly cutters are available from Sears but a special warning is in order. These devices work well but are extremely dangerous. Make sure the cutting bit andthe placement into the drill chuck are secure.

Large square holes are required for the turn counters. Mark the square hole to be cut. Drill a hole in each corner. The hole must be at least the size of the saw blade if a jigsaw is used to finish the hole. Note that the jigsaw must have a removable straight blade. If a metal-cutting jigsaw is not available, a series of small holes can be drilled in a straight line on all four sides and the edges smoothed with a file. Almost any hole can be custom cut by making a hole the approximate size and finishing it to the exact dimension with a file. It is slow and laborious but it works. When using a file on panels, be very careful that the file does not slip out of the hole and put an undesired scratch in the panel!

Once panel holes are cut, carefully label the panels before mounting the components. Dry transfers are used on both the power supply and the RF deck. Dry transfers of all sizes and fonts are available at graphics art stores and hobby shops. The author has found that hobby shops carry an excellent selection of dry transfers in the model railroad section.

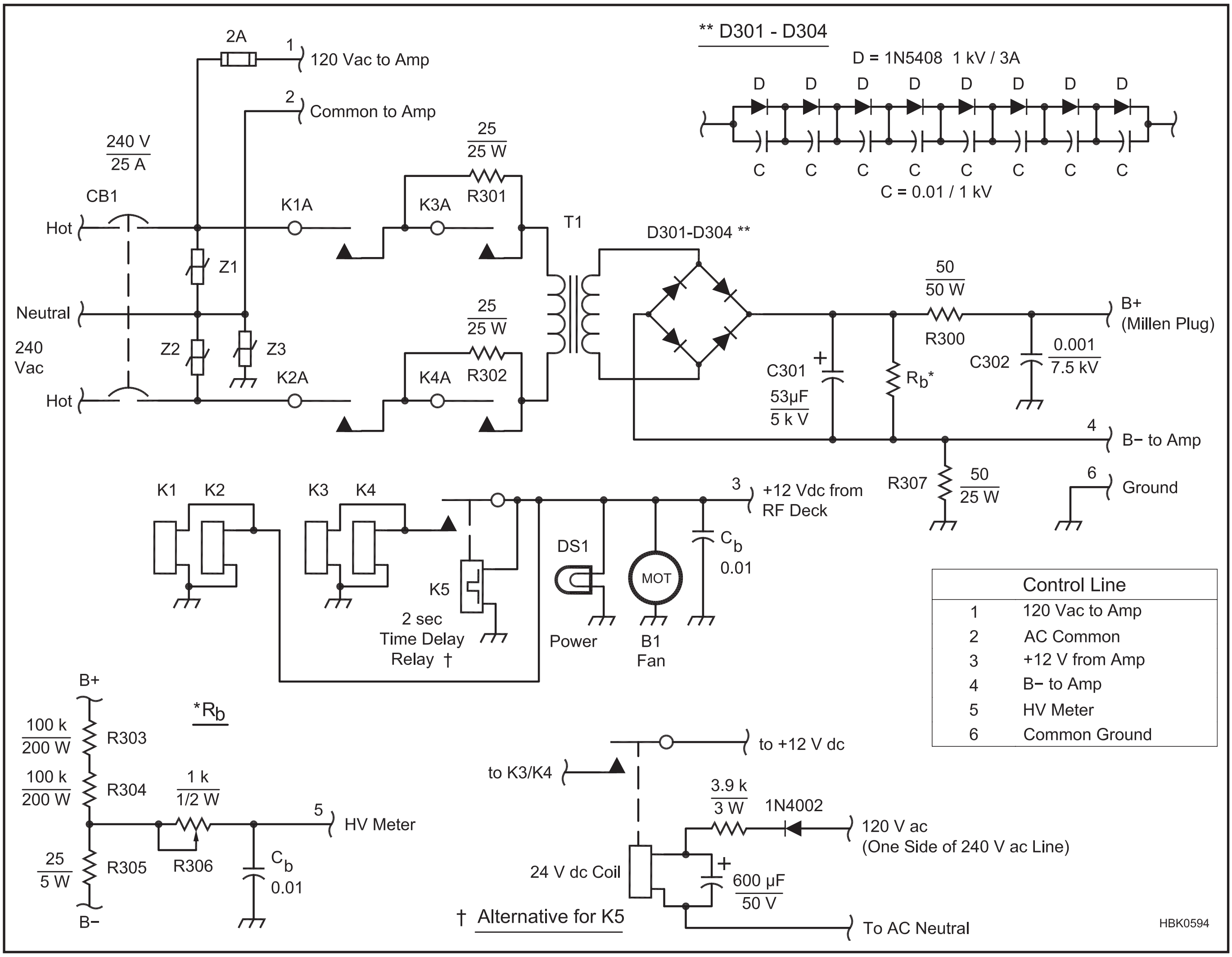


Fig 17.58—Schematic for power supply for 3CX1500D7 amplifier.

B1—12 V dc brushless fan, 2¼ inch (Mouser 432-31432).
DS1—12 V dc pilot lamp (Alco 164-TZ).
Cb—0.01 µF, 1 kV disc ceramic bypass capacitor.
C301—53 µF, 5 kV oil-filled.
CB1—2 pole 25 A, 240 V circuit breaker.
K1-K4—SPST solid-state relay 240 V ac, 25 A line voltage with 12 V dc input (the author used surplus Crydom relays but a readily available substitute is the Tyco/P&B SSR-240D25R).
K5—2 second trimpot time delay relay (surplus Bourns 3900H-1-125 or equiv; or FTD-12N03 3 second glass timer relay from Surplus Sales of Nebraska). Note: This part may be difficult to find. You can build the equivalent from a 24 V dc SPST relay, diode, resistor and capacitor as shown in the drawing inset. This technique is borrowed from the K6GT HV supply shown later in this chapter (Fig 17.63).
R303, R304—100 kΩ, 200 W wirewound resistor).
T1—Plate transformer, primary 220/230/240 V; secondary 2300/2700/3100 V at 1.5 A CCS (Peter W. Dahl Co P/N Pittenger PT-3100, see text).
Z1-Z3—130 V MOV.
Cabinet—Buckeye Shapeform DSC-1204-16 (12×18×16 inches HWD), www.buckeyeshapeform.com.

RF DECK CONTROL CIRCUITS

The control circuits in the amplifier are not complex due to the simplicity of the grounded-grid design and the instant-on capability of the 3CX1500D7 tube. 120 V ac is routed from the HV power supply to the RF Deck in the 6-conductor control cable. When the on/off switch (S1) is pressed, 120 V ac is sent to the primary of the low voltage transformer (T3) and the filament transformer (T2). The surge current to the filament of the tube is suppressed by the thermistor (TH1) in one leg of the filament transformer primary. These are excellent current limiting devices that have a resistance of approximately 25 Ω cold but decrease to less then 1 Ω as they heat. Keep the thermistor in open air away from other components since they are designed to run hot.

The low voltage supply provides regulated +12 V dc and +28 V dc. The voltages are regulated using simple three-terminal regulators. Pilot lights are included in each push button switch, S1-S4, and a power indicator on the HV power supply. When the low-voltage power supply first comes on, +12 V dc is directed through the control cable back to the HV supply. High voltage is applied immediately to the instant-on tube. Therefore the amplifier is turned on and ready to go instantly—You don't have to listen to your friends working that rare one for three or four tense minutes while you wait for your amplifier to time in!

The amplifier is switched in and out of the circuit using a 4PDT KHP style relay (K1) for the input and a SPDT vacuum relay (K2) for the output. It is important to select the timing constants for the input relay (C201

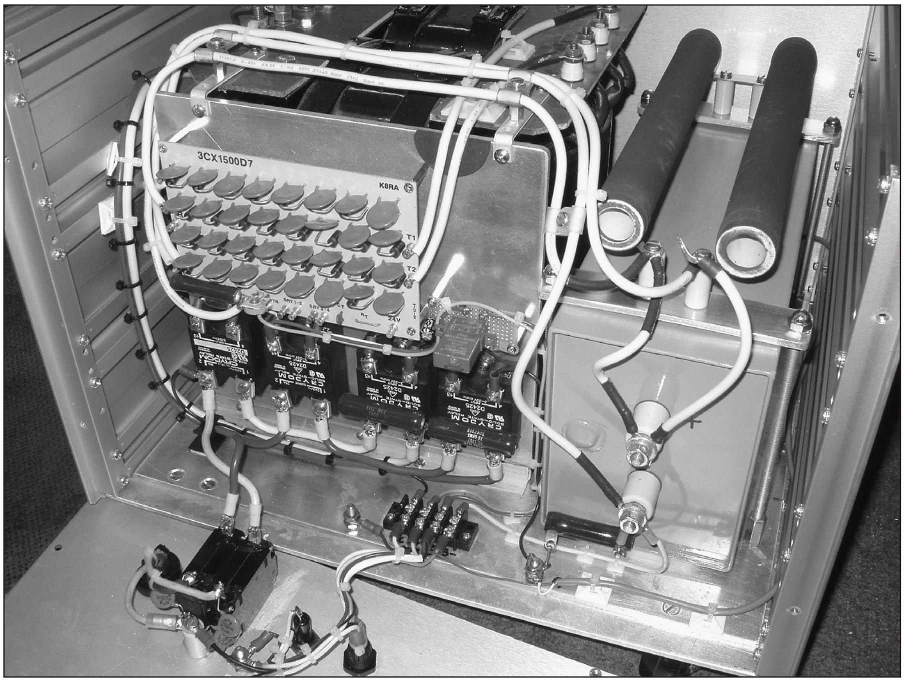


Fig 17.59—Inside view of the power supply, showing rectifier stack, control relays and HV filter capacitor with bleeder resistors. The heavy-duty high voltage transformer is at the upper left in this photo.

and R201) so the input relay closes a few milliseconds after the vacuum relay. This avoids hot switching the output, which could fuse the vacuum-relay contacts. This is a balancing act since the brief time the input relay is open will present an open circuit to the exciter. Many modern radios now have exciter-timing circuits that close the amplifier relay circuit a few milliseconds before RF is transmitted.

It is recommended that timing components for the input relay be located in a place where they can be easily changed. Another approach is to build a breadboard circuit that feeds the relay coils in parallel but places the contacts in series. Feed a low voltage through the contacts of the two relays and monitor the timing with a dual-trace oscilloscope. This technique allows precise timing of contact closure as the two relays work together. Note that different relays will need different timing-circuit component values. A set of contacts on input relay, K1, is used to short across bias resistor, R103. The resistor biases the tube to cutoff in standby.

Approximately +10 V bias is provided to the center tap of the filament transformer to limit the idle current of the tube to approximately 125 mA. The bias is developed using the three components D101, R101 and Q101. These components could be replaced with a single 10-V/50-W Zener diode. However, 50-W zeners are expensive and they are difficult to obtain. Using the circuit shown, the bias is provided by a common NPN transistor (Q101) and a one-watt zener (D101) you can obtain from RadioShack.

TUBE PROTECTION CIRCUIT

The main protection for the tube is a plate-current surge resistor and a grid-trip circuit. The current surge resistor (R308, 50 Ω/50 W) is in series with the B+ line and acts as a fuse should excessive current be drawn from the HV power supply. Ohm's law says that up to 1-A plate current can be drawn through the resistor and still stay within the 50-W rating of R308. However, let's assume a problem occurs and 5 A flows through the resistor. Resistor R3 must now dissipate 1250 W. The resistor will quickly fail and will shut down the HV to the 3CX1500D7 tube.

Q102 is a grid-trip circuit that snaps the amplifier offline if the grid current exceeds 400 mA. The grid current is drawn through the 10-Ω resistor (R104) connected between the B– line and chassis ground. The current creates a voltage across R104 that is fed to the grid-trip adjustment potentiometer, R106. Q102 is turned on when the base voltage reaches 0.6 V and actuates the grid-trip relay K3. K3 contacts break the +28 V dc input and output relay lines (K3B), locks the relay closed (K3C) and extinguishes the pilot bulb (K3A) of the GRID-TRIP RESET normally closed push-button switch (S3) located on the front panel. Pushing the GRID TRIP RESET switch (S3) breaks the current path for the grid-trip relay K3 and resets the relay. The reason the grid trip was actuated should be determined prior to attempting to use the amplifier again. Usually, this is caused by improper setting of the load capacitor or transmitting into the wrong antenna.

INPUT NETWORK

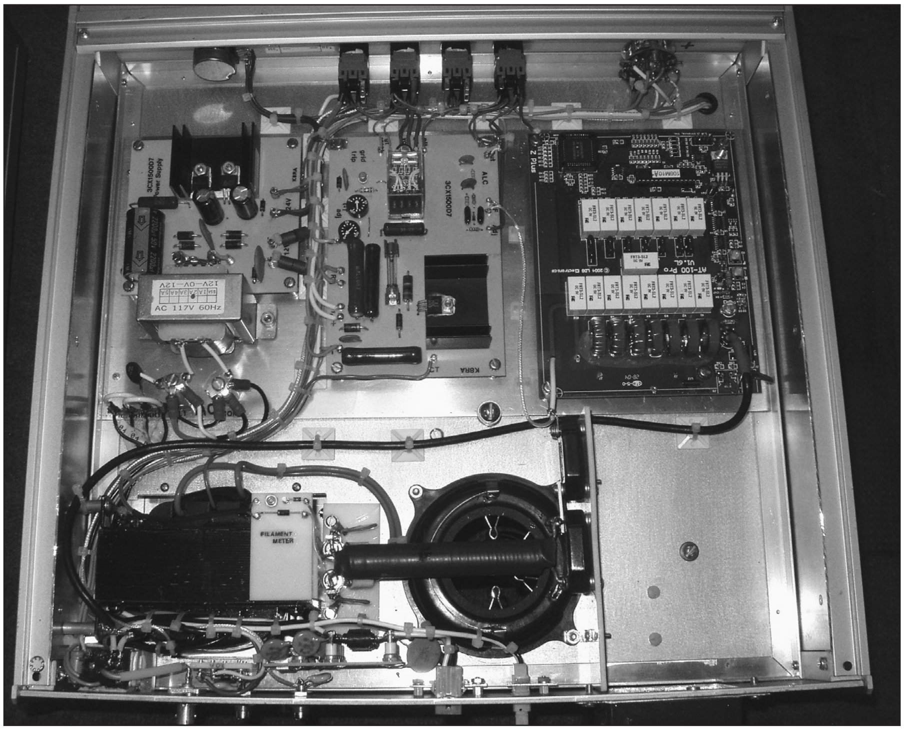
As mentioned before, this amplifier uses a unique concept for the input-matching network, getting rid of a switched network mechanically ganged to the main band-switch. Not only can such a switching arrangement be awkward mechanically, but obtaining a reasonable network Q and a low SWR over an entire band can be difficult.

Thus the author decided to use a commercial automatic tuner integrated into the RF deck (see Fig 17.60A). The tuner is a kit from W4RT Electronics based on the AT-100 autotuner by LDG Electronics (discontinued as standalone equipment). The kit is supplied without the enclosure and switches. This application is simple but elegant. The unit automatically initiates a retune if the input SWR exceeds approximately 1.5:1. The tuning cycle takes three to five seconds to execute. But retuning does not happen often because the tuner has over 4000 memories and remembers the settings for different frequency ranges. As the amplifier is used on each band, the tuner *learns* and stores settings into the memory. When switching bands, it only takes milliseconds to retrieve the data from memory and actuate the correct tuner relays.

Integration of the tuning network requires connections for RF input and output, +12 V and ground. RF input goes to the center of T1 and ground goes to J2 (clearly marked on the board). RF output goes to J3 and ground goes to J6. The + 12-V dc connection is the larger of the three holes at J10 (next to L10). The other two holes are grounds for dc connections.

A momentary contact switch (S4) is mounted on the front panel to provide manual control of the tuner. A normally open contact on S4 is connected to the input pin J9 (next to L12) and ground. (The pin is marked as the ring for the connector that is not installed.) The correct hole is on the C56 side. If the switch is pushed for less than ½ second, the tuner alternates between bypass and in-line modes. If S4 is pressed between 0.5 to 2.5 seconds, it does a memory tune from the stored data tables. If S4 is pressed for more than 2.5 seconds with RF applied, it skips the memory access, retunes and stores the new settings into the memory table. The manual retune function is seldom, if ever, used.

The tuner works perfectly and it really simplified the input-network design and construction. The SWR never exceeds 1.5:1 (typically it is 1.2:1).



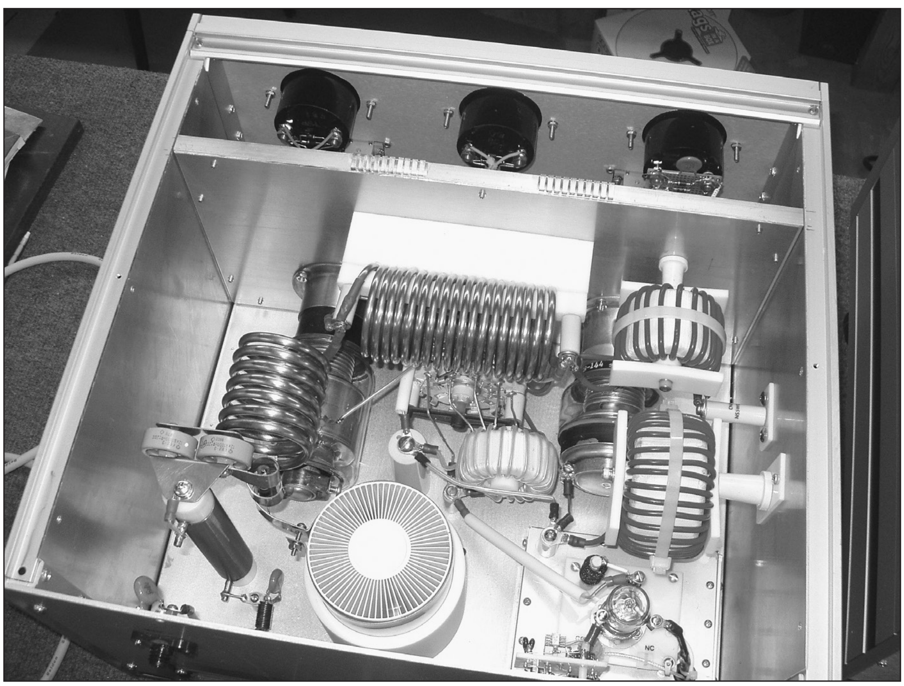


Fig 17.60—At the top, under the chassis of the RF Deck. The autotuner used as the input network for this amplifier is at the upper right. At bottom, view of the Pi-L output network in the RF Deck.

PI-L NETWORK

A pi-L network is used to insure good harmonic attenuation. The pi-L circuit is actually a pi-network, followed by an L-network that provides additional harmonic attenuation. The L-section transforms the load of 50 Ω up to an intermediate resistance of 300 Ω. The pi section then transforms 300 Ω up to the desired plate load resistance of 3100 Ω. The plate load is calculated using the following formula:

$$R_L = \frac{E_p}{1.7 \times I_p} = \frac{4000}{1.7 \times 0.750} = 3137\Omega$$

A nominal Q of 12 is used for the network. But as with most RF amplifiers, the capacitance needed for the higher-frequency bands is less than is physically possible using variable capacitors. For Q = 12, the tune capacitance (C101) for 10 meters is 14 pF. Using a vacuum variable capacitor for C1 helps because the minimum achievable capacitance (12 pF) is substantially less than with an air variable. But the tune capacitance is the sum of variable C101, 7.1 pF for the output capacitance of the 3CX1500D7 tube and any stray capacitance resulting from the physical layout of the amplifier.

The minimum obtainable capacitance is thus on the order of 30 pF, which yields a higher value of loaded Q than optimum. The solution is two fold. First, connect the plate-tune capacitor (C101) one turn into the 10-meter coil. This actually forms an L-pi-L circuit. Second, accept a higher value of loaded Q so that the variable capacitor can still be tuned. **Table 17.8** shows the loaded Q finally used for each band setting. The disadvantages of higher loaded Qs are high circulating currents in the tank circuit and the need to retune during excursions across the higher-frequency bands. This amplifier works fine on all bands, delivering a solid 1500 W output even on 10 meters.

Another pi-L tank circuit design constraint in this amplifier is the bandswitch. Many amplifiers use a single-pole, 12-position, non-shorting switch. Although this type of switch is easier to find, it can be problematic because high voltages are generated that could result in arcing in the bandswitch—usually from the wiper to the high frequency taps. You should use a switch with a multiple-finger wiper (see Fig 17.57) that shorts out lower-frequency coil taps not being used. For example, when the amplifier is used on 20 meters, the 40-, 80- and 160-meter taps are shorted to the wiper.

However, shorting switches only allow for six connections with 30° indexing. The common shorting wiper consumes 180° of switch deck on 160 meters. This results in having to design the 10/12-meter and 15/17-meter bands to use single taps for each frequency pair. Again, this is accomplished by adjusting the loaded Q for each band so that shared bands so they require nearly the same inductance. From Table 17.8, the same band switch position is shared on the 10/12-meter bands (1.4 µH) and the 15/18-meter bands (2.2 µH).

In actual construction of the tank circuit, it is very useful to have access to both a capacitance meter and an inductance meter. The author used an Elenco LCM-1950 meter that measures both capacitance and inductance and is available for under $100 (**www.elenco.com**). With the tune and load capacitors mounted and connected to calibrated knobs or turns counters, make a table of capacitance verses knob settings. This is useful to estimate the initial setting for each band during setup

Table 17.8
Pi-L Component Values

Frequency (MHz)	*C1 (pF)*	*C2 pF*	*L1 µH*	*L2 µH*	*Q*
1.850	211	1262	44.3	9.6	12
3.700	105	631	22.2	4.8	12
7.150	65	364	9.7	2.5	14
14.150	33	184	4.9	1.26	14
18.100	45	208	2.23	0.98	23
21.200	33	159	2.21	0.84	20
24.900	36	161	1.48	0.71	25
28.250	29	133	1.43	0.63	23

Tank Circuit Coils

Coil	*Band*	*Inductance*	*Construction*
L1	10/12-15/17 m	2.3 µH	7½ t, ¼-in. copper tube, 2-in. ID silver-plated 10/12-m tap @ 3½ t 15/17-m tap @ 7½ t
L2	20-40 m	7.4 µH	19 t, 3⁄16-in. copper tube, 2-in. ID silver plated 20 tap@ 8 t 40 tap @ 19 t
L3	80 m	12.4 µH	17 t on 3×T225-2 cores, #10 Teflon silver wire
L4	160 m	22.0 µH	23 t on 3×T300-2 cores, #10 Teflon silver wire
L5	L-Coil	9.6 µH	19 t on 2×T225-2 cores, #12 tinned wire w/Teflon sleeve 10/12-m tap @ 2 t 15/17-m tap @ 4 t 20-m tap @ 5 t 40-m tap @ 7 t 80-m tap @ 12 t 160-m tap @ 19 t

and test. Also, measure the inductance of each coil turn to determine initial coil taps for each band. On this amplifier, only the 10-meter tap had to be adjusted from the predetermined settings.

As mentioned above, the pi-L tank circuit was designed for 3100-Ω plate-load resistance. Such a high plate resistance demands higher inductance values to obtain reasonable tank circuit Qs. Table 17.8 shows that 160 meters requires 42 µH. If air-wound coils were used exclusively, the coils would require many turns and would take up a lot of cabinet space. To maintain a reasonable physical coil size, therefore, toroidal coils were used for 80 (L3) and 160 (L4) meters in addition to the output coil (L5) (see Fig 17.60B). You should use substantial core material for high-power operation to avoid core heating. Core sizes were increased by using multiple cores taped together. Each ferrite core is wrapped with three layers of high temperature fiberglass tape, available from RF Parts (**www.rfparts.com**). Teflon-insulated #10 wire was wound to obtain the desired inductance in L3 and L4. Both coils are mounted on ceramic standoffs and held in place with Teflon blocks.

The output coil is wound on a pair of T225-2 cores using #12 tinned wire covered with a Teflon sleeve. Taps onto the coil are made by carefully trimming a small ⅛-inch space from the Teflon sleeve on the inner edge of the core facing the bandswitch. Taps are then made from the back section of the 2-pole bandswitch using #12 tinned wire. The proper placement of each tap is determined by first winding #12 insulated wire around the core. A small slit is carved into each turn and the inductance was measured. The copper wire is removed and the final Teflon-covered #12 tinned wire is wound onto the core. Using the output L-coil (L102) design values in Table 17.8, permanent taps were made.

Note that the taps for the output coil are not extremely critical. Select the closest turn to the value needed. The output coil is mounted on the back of the bandswitch on one of the switch wafer screws using a threaded 1-inch diameter Teflon rod. The Teflon rod holds the position of the coil. The weight is carried by the wire taps from the coil to the bandswitch contacts. Table 17.8 also gives the inductance and construction instructions for each coil.

L1 and L2 (10-40 meters) are silver plated. They were wound using a 2-inch aluminum pipe as a form. Clean the copper tubing with #0000 steel wool prior to winding. Wind the copper tubing close spaced on the pipe. Leave plenty of pigtail on each end of the coil. The ends can be trimmed to fit the mounting positions precisely. After winding the desired number of turns, plug the ends by closing the tube ends with a hammer, spread the coil windings and rinse the coil in acetone to remove any oil. Allow a few minutes to dry. The coil is now ready to plate.

Go to any photo shop and beg/buy a gallon of used photographic fixer solution. Note that used fixer solution has silver remnant. The more the solution has been used, the more the silver content. The coils can be silver plated by dipping the clean coil into the solution. Do not leave the coil in the solution too long or it will turn black. A thin but bright silver coat will be deposited on the copper tube. This is called *flash plating*. After dipping the coil into the solution, immediately rinse in a bath of clean water and blow dry under pressure with an air compressor, heat gun or hair dryer. If a thicker silver coat is desired, electroplating is necessary, a subject beyond the scope of this article.

A #10 lug is crimped and soldered onto the end of each coil and used to mount the coil. The L2 coil is mounted using a Teflon block that is held in place to the front sub-panel with small screws. The block is carefully drilled with 3⁄16-inch holes the desired spacing of the coil about ¾-inch from one edge. The block is sawed down through the holes creating two matching blocks. At each end of the block a hole is drilled and tapped (6-32 tap). The silver plated coil is sandwiched between the two blocks for secure support. The tapped screws serve as the connecting points for the ends of the coil.

METERING

The amplifier uses three separate meters to simultaneously monitor plate current, grid current and a choice of plate voltage, power output or filament voltage. Each meter is identical with a 1-mA full-scale movement. As mentioned previously, the custom scales for each movement were designed using the *Meter Basic* software from Tonne Software. This allows up to three scales on each meter. Scales can be designed as either linear or log and the number of major and minor tick marks can be specified. Each scale can be labeled using different font size and color. The author printed the scales using a color inkjet printer onto glossy photo paper. The scales were carefully cut to match the meter faceplate and glued into place using a thin coat of adhesive.

Plate current is measured by M1 in series in the B– line using a current divider (R114 and R115) as shown in Fig 17.58. Adjust R114 to obtain full scale with 1-A of plate current. The meter was calibrated prior to installation using a low-voltage power supply with adjustable current limiting in series with an accurate digital meter.

M2 monitors grid current by measuring the voltage drop created by grid current flow through the 10-Ω resistor, R104. Connecting a voltage source (ie, small variable power supply) across R104 and measuring the actual current flow with an external meter provides a way to set the calibration pot, R105.

M3 is a multimeter that reads HV, RF power or filament voltage. The metering circuit is selected using a 2P3T rotary switch (S5). The HV metering circuit is in the HV power supply and fed to the RF deck through the control cable. The filament-voltage detect circuit is shown on the control circuit diagram (Fig 17.57: D207, D201 and R202). Adjust R202 for the proper reading on Meter M3. The 3.1-V zener (D201) expands the meter scale for more precise reading.

The RF wattmeter circuit is also shown in Fig 17.57. Only forward power is measured and potentiometer R403 is used for calibration. The wattmeter is not a precise instrument but gives a relative output reading. It is adequate for peaking power output when tuning. The meter provides good accuracy through 40 meters and then begins to read lower on the higher-frequency bands. This is due to the simplicity of the circuit and the toroid used. Quite honestly, don't expect much accuracy from this wattmeter.

HV POWER SUPPLY

The matching HV Power Supply (Fig 17.58) provides approximately 4000 V under load. It uses a full-wave bridge rectifier and is filtered using a single 53 µF/5000-V oil filled capacitor (C301). Whenever the HV supply is plugged into the 240-V line, live 120 V ac is routed to the RF deck through the control cable. The 120-V ac line is obtained from L1 and neutral of the 240-V ac line. The neutral line is isolated from ground for safety.

Actuating the on/off switch S1 on the front panel of the RF deck provides ac power to the low-voltage power supply. In turn, +12 V is returned to the power supply through the control cable and routed to a pair of solid state power relays (K1, K2). Also, +12 V is routed to a timer relay that provides a two-second delay in applying +12 V to the second pair of solid-state relays (K3, K4). During the two-second delay, each leg of the 240-V ac primary voltage is routed through a 25-Ω resistor (R301, R302) to reduce the current surge when charging the filter capacitor, C301.

HV is metered at the bottom of the two series 100,000-Ω bleeder resistors (R303, R304). A current divider is created using a small potentiometer (R306) in parallel with a 25-Ω/5-W resistor (R305). The current divider is in series with the bleeder resistors and tied to the B– line. R306 is set to allow 1 mA of current to flow to the HV meter located on the front panel of the RF deck with 5000 V HV dc. The potentiometer R306 and the paralleled fixed resistor R305 need handle only a small amount of power, since the voltage and current flow is quite small at this point in the circuit.

The HV cable between the RF Deck and power supply is made from a length of automotive-ignition cable that has a #20 wire and 60,000-V insulation. Be sure to get a solid-wire center conductor and not the resistive carbon material. Also use high-quality HV connectors that are intended for such an application. Millen HV connectors (50001) were used in this amplifier. Coax boots intended for coaxial cable are used on each connector for added insulation and physical strength. The mounting holes for the Millen connectors are oversized and plastic screws were used for safety.

TUNING AND OPERATION

The amplifier is very easy to tune after the initial settings of the tune (C101) and load (C102) controls are determined. The correct settings are determined with a plate current of 700 mA with a corresponding grid current of 200 mA. The turn counters provide excellent resetability once the proper settings have been found initially. Required drive power is about 75 W for 1500 W output.

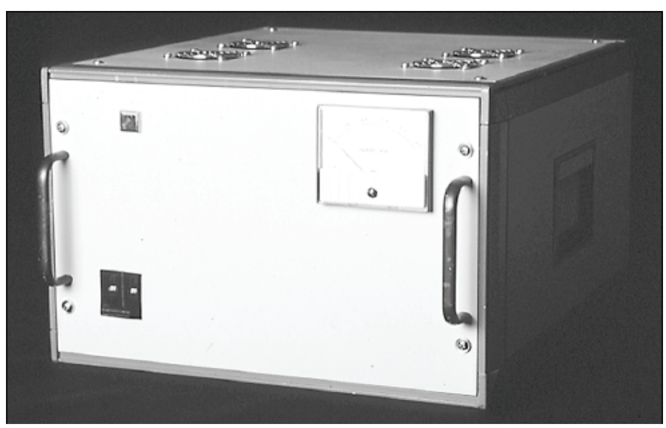
Thanks to CPI Eimac Division, LDG Electronics, and MTI Inc (Radio Switch) for their support in this project.

The Sunnyvale/Saint Petersburg Kilowatt-Plus

This article describes a modern 1500-W output linear amplifier for the amateur HF bands. It uses a relatively recent arrival on the transmitting tube scene in the US, a 4CX1600B power tetrode made by Svetlana in Saint Petersburg, Russia. The amplifier was designed and constructed by George T. Daughters, K6GT, who lives in Sunnyvale, California—hence the name “Sunnyvale/Saint Petersburg” for this project. **Fig 18.28** shows the completed amplifier and the power supply cabinet.

Power tetrodes such as the 4CX1600B feature higher power gain than do the power triodes (such as the 3-500Z or 8877) often used in linear amplifiers. The increased power gain gives the designer additional flexibility, at the expense of a

(A)



(B)

Fig 18.28—At A, photo of Sunnyvale/Saint Petersburg Kilowatt-Plus amplifier RF Deck. At B, the Power Supply cabinet.

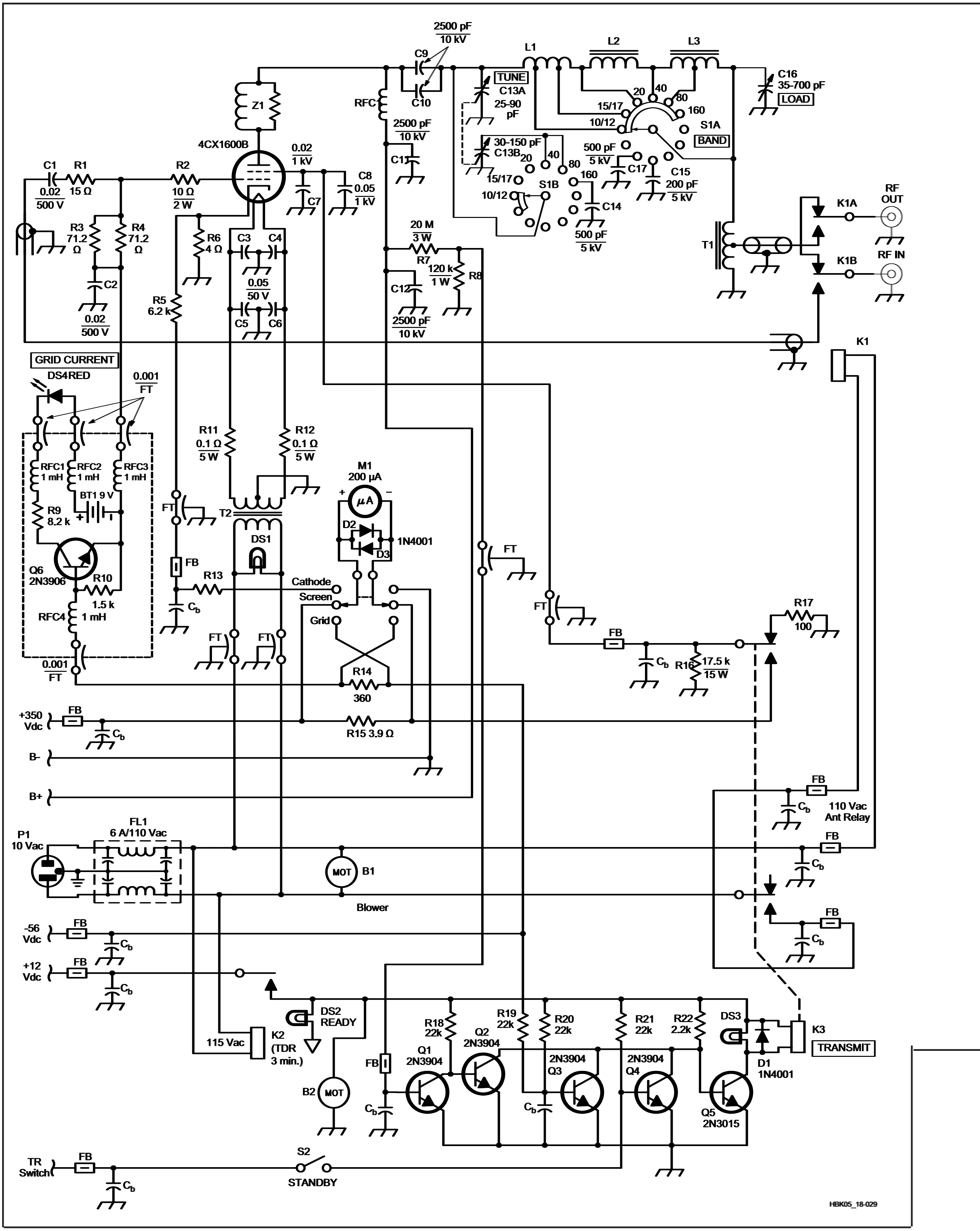

2500 pF
10 kV
C9
C10
L1
L2
L3
C16
35-700 pF
LOAD
TUNE
C13A
25-90
pF
RFC
Z1
4CX1600B
20
40
80
15/17
160
10/12
S1A
BAND
2500 pF
10 kV
C11
30-150 pF
C13B
500 pF
5 kV
C17
C15
200 pF
5 kV
S1B
C14
500 pF
5 kV
C1
R1
0.02
500 V
15 Ω
R2
10 Ω
2 W
0.02
1 kV
C7
C8
0.05
1 kV
R3
71.2
Ω
R4
71.2
Ω
R6
4 Ω
C3
C4
0.05
50 V
C5
C6
C2
0.02
500 V
R5
6.2 k
20 M
3 W
R7
120 k
1 W
R8
C12
2500 pF
10 kV
T1
K1A
RF
OUT
K1B
RF IN
K1
GRID CURRENT
DS4RED
0.001
FT
R11
0.1 Ω
5 W
R12
0.1 Ω
5 W
M1
200 µA
µA
RFC1
1 mH
RFC2
1 mH
RFC3
1 mH
BT1 9 V
R9
8.2 k
FT
T2
D2
1N4001
D3
DS1
FB
Q6
2N3906
R10
1.5 k
R13
Cathode
Screen
Grid
RFC4
1 mH
Cb
FT
FT
FT
FT
R14
360
0.001
FT
R17
100
FB
R16
17.5 k
15 W
+350
Vdc
FB
R15 3.9 Ω
B-
B+
P1
10 Vac
FL1
6 A/110 Vac
MOT
B1
Blower
FB
110 Vac
Ant Relay
-56
Vdc
+12
Vdc
115 Vac
K2
(TDR
3 min.)
DS2
READY
B2
MOT
R18
22k
Q1
2N3904
Q2
2N3904
R19
22k
R20
22k
2N3904
Q3
2N3904
Q4
R21
22k
R22
2.2k
DS3
K3
TRANSMIT
D1
1N4001
Q5
2N3015
TR
Switch
S2
STANDBY
HBK05_18-029

Fig 18.29—Schematic diagram of the RF Deck of the 4CX1600B linear amplifier. Resistors are 1/2 W unless noted. Capacitors are disc ceramic unless noted and those marked with a + are electrolytic.

B1—Squirrel-cage blower capable of 36 cfm at 0.4 inches of water back pressure (Dayton 4C753 or similar).
B2—"Biscuit" blower, 12 V dc, 130 mA (Rotron BD12A3 or similar) mounted inside the pressurized RF deck to aid cooling the input grid resistor R1.
BT1—9 V transistor radio battery.
C1, C2—0.02 µF, 500 V disc ceramic.
C3, C4, C5, C6—0.05 µF, 50 V disc ceramic.
C7—Screen bypass capacitor (0.02 µF, 1 kV disc ceramic at the screen terminal on the socket in parallel with the internal bypass capacitor, which is part of the Svetlana SK-3A socket).
C8—0.05 µF, 1 kV disc ceramic.
C9, C10—Parallel 2500 pF, 10 kV ceramic doorknob.
C11, C12—2500 pF, 10 kV ceramic doorknob.
C13—Plate tuning capacitor; front section is 30-150 pF; rear section is 25-90 pF (Command Technologies P/N 73-2-100-41).
C14, C17—500 pF, 5 kV ceramic doorknob.
C15—200 pF, 5 kV ceramic doorknob.
C16—Plate loading capacitor, 35-700 pF (Command Technologies P/N 73-1-45-65).
D1—1N4001.
DS1, DS2, DS3—Indicator lamps (green: 120 V ac; amber: 12 V; and red: 12 V).
DS4—Jumbo red LED.
FL1—IEC 110 V ac connector with 6 A line filter.
FT—0.001 µF, 1000 V feedthrough capacitors.
FB, —RF decoupling components used in multiple places; ferrite beads FB-43-1801 and 0.01 µF, 1 kV disc-ceramic capacitors.
K1—110 V ac DPDT antenna changeover relay.
K2—115 V ac 3-minute time delay (Macromatic SS-6262-KK).
K3—12 V dc relay, DPST.
L1—Plate tank inductor; 1/4-inch diameter, silver-plated copper tubing, 6 turns with inside diameter of 1 1/4 inches, followed by 4 1/2 turns with inside diameter of 1 3/4 inches. Tap for 10 (and 12) m is 4 turns from small-diameter end; tap for 15 (and 17) m is 2 turns further down. All of L1 is used for 20 m.
L2—Toroid coil; 5 turns #10 PTFE wire (40 inches long, overall) on two T-225-8 cores.
L3—Toroid coil; see text; 3 each #10 PTFE wires (150 inches long, overall) on three T-225-28 cores.
M1—200 mA meter movement, internal resistance 2000 Ω.
P1—IEC power cable to J1 on Fig 18.30.
Q1 to Q6—2N3904 or similar (Silicon, general purpose, NPN).
Q5—2N3015 or similar (Silicon, low (Sat), NPN).
R1—15 Ω, Caddock MP-850, mounted on heat sink with R3 and R4.
R2—10 Ω, 2 W composition.
R3, R4—71.2 Ω Caddock MP-850, mounted on heat sink with R1.
R5, R13—6.2 kΩ, 1 W. (R5 is part of the cathode current meter multiplier, as is R13. Their values were chosen to provide 1.3 A full-scale reading on the meter used.)
R6—4 Ω, 12 W (4 each 16 Ω , 3 W, noninductive metal-oxide-film, in parallel on 4CX1600B tube socket).
R7—20 MΩ, 3 W (Caddock MX430).
R8—120 kΩ, 1 W composition.
R11, R12—Filament dropping resistors; 0.1 Ω, 5 W.
R16—Screen bleeder; 17.5 kΩ, 15 W (two 25 kΩ, 5 W in parallel, in series with 5 kΩ, 5 W).
RFC—1 mH RF choke.
RFC1—Plate choke, 91 turns #26 enamel on 1-inch diameter × 3.75 inch Delrin form (Command Technologies P/N RFC-1).
T1—Broadband 2:1 transformer; 13 bifilar turns #12 PTFE (120 inches, overall) on three FT-240-61 cores. Note that plate tank inductors, bandswitch, plate RF choke, and toroidal RF transformer are part of Command Technologies HF-2500 plate tank circuit.
T2—Filament transformer, 12.6 V ac (center-tapped), 6A (Triad F-182).
V1—Svetlana 4CX1600B power tetrode in modified Svetlana SK-3A socket. The anode connector is a Svetlana AC-2, and the chimney and the chimney extension are each a Svetlana CH-1600B.
Z1—Parasitic suppressor; two turns of tinned copper strap (0.032-inch thick × 0.313-inch wide) over three 91 Ω, 2 W composition resistors in parallel.

somewhat more complex dc supply design. This amplifier operates in the grounded-cathode configuration, with a 50-Ω resistor from control grid to ground. This provides a good load for the transceiver driving the amplifier, promotes amplifier stability and also eliminates the need for switched-input tuned circuits. The advantages of such a passive-grid, grounded-cathode design outweigh the cost and complication of the screen-grid supply needed by the tetrode tube.

The Svetlana 4CX1600B is designed with a "striped-cathode," where emission takes place mainly in the spaces between parallel control-grid wires. This reduces the number of electrons intercepted by the control grid under normal drive conditions. (The Eimac 4CX1500B is also designed this way.) However, the linearity of such a high-gain tetrode falls off rapidly if the control grid is allowed to draw any current at all. Even a small positive voltage at the control grid can cause a large current to flow in the grid.

Note that the control grid in this type of high-gain tetrode is only rated at 2 W dissipation. (The first versions of the data sheet for the 4CX1600B specified the grid dissipation as 100 milliwatts!) By comparison, the control grid dissipation of the venerable, but much lower-gain, 4-1000A tetrode is 25 W. Any circumstance where measurable control grid current flows in the 4CX1600B will result in nonlinear operation, resulting not only in splatter, but also in possible damage to the control grid. It is thus important to provide some sort of grid current prevention scheme or, at the very least, a grid current warning alarm, for an amplifier using the 4CX1600B.

The grid of the 4CX1600B in this amplifier is tapped down on the input resistor. With 100 W of drive, the grid voltage cannot swing positive enough to result in significant grid current. Deliberate cathode degeneration (negative feedback) is also used to help prevent grid-current flow. This is accomplished by placing a noninductive resistor between the cathode and ground. In addition, a sensitive grid-current meter is provided, reading 1.3 mA at full-scale deflection. Finally, a simple, yet sensitive, grid-current-activated warning is also included in this design, using a red LED on the front panel as a warning lamp.

In receive, a 100 Ω resistor is switched into the screen grid circuit to chassis ground. This removes the screen voltage and keeps the tube cut off to avoid the generation of any shot noise. In transmit, a 17.5-kΩ, 15-W resistor to ground is switched into the screen grid circuit to keep a constant load of 20 mA on the series regulator. This allows the regulator to function properly with up to –20 mA of screen current. (Negative screen current is a condition common to these types of power tetrodes under some load conditions.) The 20-mA constant load is indicated on the screen-current meter as "zero," so that the meter reads actual screen current from –20 to + 80 mA.

Building It

The heart of the amplifier consists of the RF deck, the control and metering circuitry and the cooling system. These are

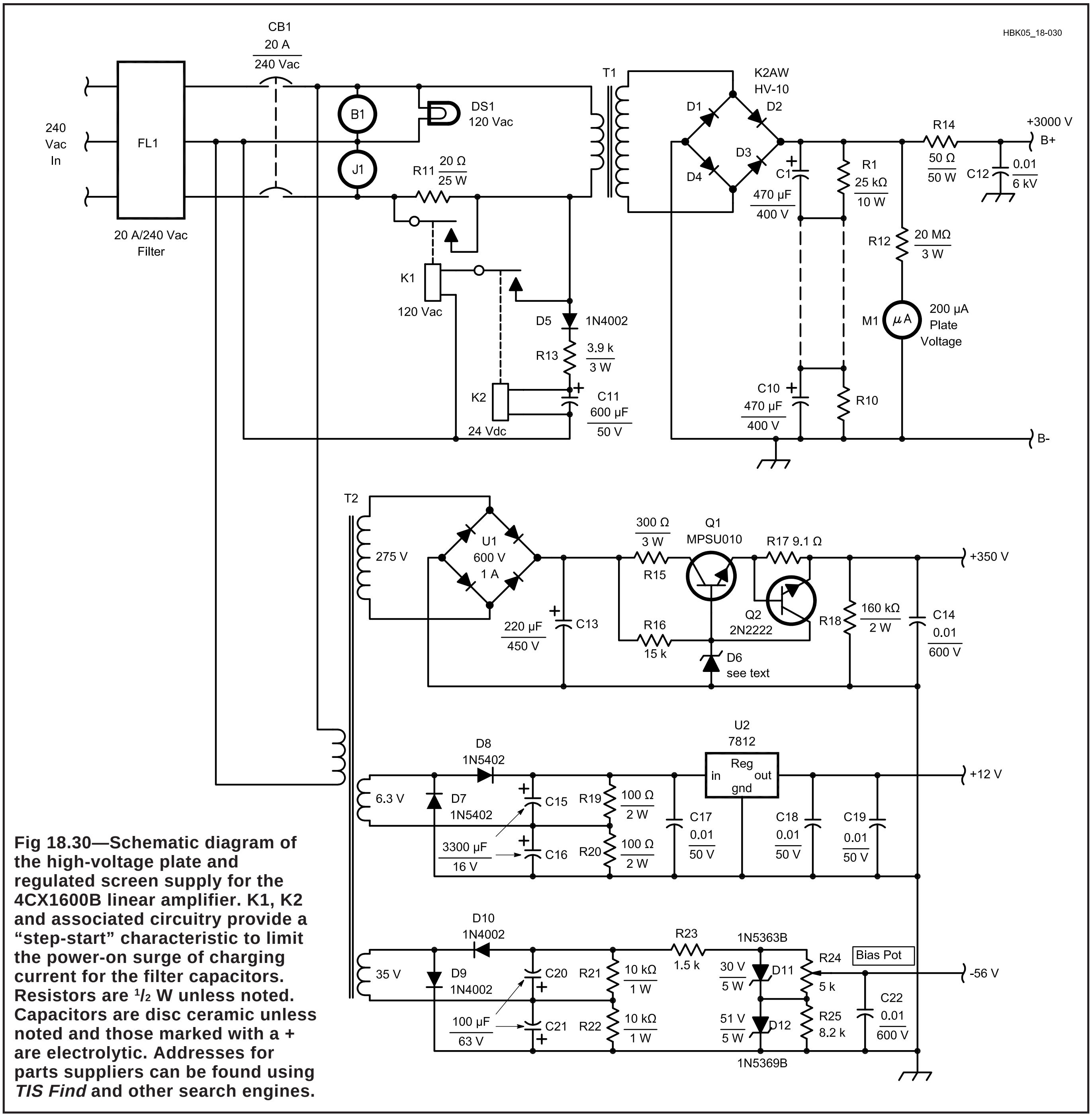


Fig 18.30—Schematic diagram of the high-voltage plate and regulated screen supply for the 4CX1600B linear amplifier. K1, K2 and associated circuitry provide a "step-start" characteristic to limit the power-on surge of charging current for the filter capacitors. Resistors are ½ W unless noted. Capacitors are disc ceramic unless noted and those marked with a + are electrolytic. Addresses for parts suppliers can be found using *TIS Find* and other search engines.

B1—Muffin fan (Rotron SU2A1 or similar).
C1 to C10—Filter capacitors; 470 µF, 400 V electrolytic.
C11—600 µF, 50 V electrolytic.
C12—0.01 µF, 6 kV disc ceramic.
C13—220 µF, 450 V electrolytic.
C14, C22—0.01 µF, 600 V disc ceramic.
C15, C16—3300 µF, 16 V electrolytic.
C17, C18, C19—0.01 µF, 50 V disc ceramic.
C20, C21—100 µF, 63 V electrolytic.
CB1—2 Pole, 20 A, 240 V ac circuit breaker.
D1 to D4—K2AW's HV-10 rectifier diodes.
D5—1N4002.
D6—Zener diodes, three 1N4764A and one 1N5369B to total approximately 350 V dc.
D7, D8—1N5402.
D9, D10—1N4002.
D11—Zener diode, 1N5363B (30 V, 5 W).
D12—Zener diode, 1N5369B (51 V, 5 W).
DS1—120 V ac indicator lamp (red).
FL1—240 V ac/20 A EMI filter.
J1—110 V ac, 15 A receptacle for plug P1 on Fig 18.32.
K1—120 V ac DPDT relay; both poles of 240 V ac/15 A
(Figure 18.30 continued)
contacts in parallel.
K2—24 V dc relay; 120 V ac/5 A contacts.
M1—200 mA meter movement.
Q1—MPSU010.
Q2—2N2222.
R1 to R10—Bleeder resistors; 25 kΩ, 10 W.
R11—20 Ω, 25 W.
R12—20 M Ω, 3 W (Caddock MX430).
R13—3.9 k Ω, 3 W.
R14—50 Ω, 50 W mounted on standoff insulators.
R15—300 Ω, 3 W.
R18—160 k Ω, 2 W composition.
R19, R20—100 Ω, 2 W composition.
R21, R22—10 k Ω, 1 W composition.
R24—5 kΩ potentiometer; sets control grid bias for desired no-signal cathode current.
T1—Plate transformer (Peter W. Dahl No. ARRL-002).
T2—Power transformer, 120 V / 275 V at 0.06 A, 6.3 V at 2 A, 35 V at 0.15 A.
U1—600 V, 1 A rectifier bridge.
U2—7812, +12 V IC voltage regulator.

all mounted in a surplus 19-inch rack-mount cabinet of the sort picked up at surplus stores and hamfests. The power supply is built into another cabinet.

Fig 18.29 shows the schematic diagram of the RF deck. The 4CX1600B is mounted in the Svetlana SK-3A socket, modified as described below (to allow the cathode to operate above ground potential for negative feedback). Svetlana's CH-1600B chimney routes the cooling airflow through the anode cooling fins. An additional CH-1600B acts as a chimney extension, discharging the air through the top of the RF deck's cabinet. The cooling fan is a squirrel-cage blower. According to the 4CX1600B data sheet at 1600 W of plate dissipation, the blower should deliver at least 36 cfm (cubic feet per minute) of cooling air at an ambient temperature of 25°C, at a back pressure of 0.4 inches of water.

The low-cost filament transformer specified in Fig 18.29 produces 18.5 V ac (with nominal mains voltage), so two 0.1-Ω, 5-W resistors were added to drop the voltage at the filament terminals of the 4CX1600B to the 12.6 V ac recommended by the tube manufacturer.

The input grid resistor is 51.6 Ω, with a dissipation capability exceeding 100 W. It consists of three Caddock MP850 resistors—two 71.2-Ω resistors in parallel, in series with 15 Ω, all mounted on a surplus heat sink (5.0 × 5.5 × 0.75 inch or 12.7 × 14.0 × 2.0 cm). This passive grid resistor is mounted below the chassis, near the SK-3A socket, and has its own small cooling "biscuit" fan. While the air below the chassis is pressurized by the main blower to provide cooling of the tube, the auxiliary fan cools the input resistors and keeps the air stirred up to prevent any stagnant hot air below the chassis.

The grid of the 4CX1600B is tapped at the 35.6-Ω point of the input resistive divider. As a further aid to stability, a 10-Ω, 2-W composition resistor is placed in series with the control-grid lead. This arrangement results in an input SWR of 1.0:1 at 1.9 MHz, increasing to just over 1.6:1 at 29.6 MHz, mainly due to the reactance of the 86 pF input capacitance of the 4CX1600B. No frequency compensation was deemed necessary. The cathode resistor is made up of four 16-Ω, 3W non-inductive metal-oxide film resistors from the cathode terminal ring on the socket to each of the four socket mounting screws.

The plate tank circuit components include a heavy-duty bandswitch, a silver-plated inductor for the high bands, powdered iron toroidal inductors for the low bands and a plate choke wound on a Delrin form. These components are those used in a Command Technologies HF-2500 amplifier but other suitable components could be utilized. (As it is currently configured, the plate tank cannot be tuned to 30 m. Operation at full power on this band would require another position on the bandswitch and another tap on the tank coil or compromises on other bands. These are options that the author considered to be unnecessary and undesirable, since US hams have a power limit of 200 W on 30 m.)

To construct L3, stack the three T-225-28 cores, side-by-side and hold them together with Teflon tape, making a really thick core. Start with a 150-inch long piece of Teflon-insulated #10 stranded wire and begin to wind the core with close-wound turns. When you have three turns in the first "group" of turns, leave a space (about 20º of the circle) before winding the fourth turn. Then wind the next three turns, making the second group of three turns. Make another blank space of 20º and then continue in this fashion until you have six groups of three turns spaced evenly around the core. The tap for the 80-meter position is at nine turns—halfway around.

The anode connector is a Svetlana AC-2, and the plate parasitic choke is two turns of tinned copper strap (0.032-inch thick × 0.188-inches wide, or 0.8 mm × 4.8 mm) over three 91-Ω, 2-W composition resistors in parallel. (Any value from 47 to 100 Ω will be satisfactory.) The antenna change-over relay has a 115 V ac coil (12 V dc would be fine also). The author's relay had wide, gold-plated contacts.

Control Circuitry

The control circuitry is shown in Fig 18.29. The amplifier is turned on with the main switch/breaker on the power-supply cabinet. When the switch is thrown, all voltages are ready (after the step-start delay in the plate supply). The 4CX1600B filament begins to heat; the cooling fans go on; the time delay starts and anode voltage is applied to the 4CX1600B. After the mandatory three minutes for filament warm up, the +12 V dc control voltage is enabled by the time-delay relay. At this time, the control circuitry (consisting of transistors Q1 to Q5) determines whether screen voltage can be applied to the 4CX1600B and whether to activate the antenna changeover relay. Q5 is the main switch activating T/R relay K2 whenever 12 V is available (that is, after the 3-minute warm up period). Screen voltage will thus be supplied to the tube only when all of the following conditions are met:

1. The anode voltage for the 4CX1600B is available. This is sensed in the RF deck by the resistive divider R7/R8 shown in Fig 18.29. If the HV sense line is low, then Q1 and Q2 hold the base of Q5 at a low level.
2. The negative control-grid bias is present. If this voltage is near zero, transistor Q3 is saturated, and again Q5 is turned off.
3. The T/R switch from the exciter has pulled the base of Q4 low, allowing its collector to rise.

The Power Supply

Remember that almost every voltage inside a power supply for a high-power linear amplifier is lethal! Turn it off, unplug it, and short it out before you touch anything! Always apply the "one hand in the pocket" principle when working on anything above 24 V!

The high-voltage power supply uses a Peter W. Dahl ARRL-002 transformer, weighing 46 pounds. As shown in **Fig 18.30**, a simple step-start circuit using K1 and K2 limits the current surge charging the filter capacitors when power is first applied. The transformer's output is rectified by a bridge of K2AW's Silicon Alley 10-kV diode arrays, and the filter capacitor is made up of a string of ten 470 μF, 400-V electrolytic capacitors. These were removed from a laser power supply board, which was available at a local surplus store (Alltronics, Santa Clara, CA) for $14.95. The voltage is divided equally across the capacitor string by 25-kΩ, 25-W resistors that also serve as the power supply bleeder. (This divider results in a considerably higher bleeder current than the typical 100 kΩ resistors often seen. The result is a stiffer power supply, but more heat is generated.)

The author's junk box produced a transformer with output windings of 275 V ac at 60 mA, 6.3 V ac at 2 A, and 35 V ac at 150 mA. These windings were dedicated to a regulated 350-V screen supply, a regulated 12-V dc supply for relay and indicator lamps (using a full-wave doubler and a three-terminal IC regulator), and the control-grid bias supply. The circuitry for these supplies is very straightforward. These supplies were built in the same cabinet as the plate high-voltage supply.

All power supplies are cooled by a muffin fan on the rear panel of the cabinet. Although the fan probably isn't necessary, cool components are sure to last longer. The major source of heat in this cabinet is the bleeder-resistor chain, which dissipates about 36 W when the plate voltage is 3000 V. High voltage is monitored with a 200 mA surplus meter movement through a Caddock MX430 20-MΩ multiplier

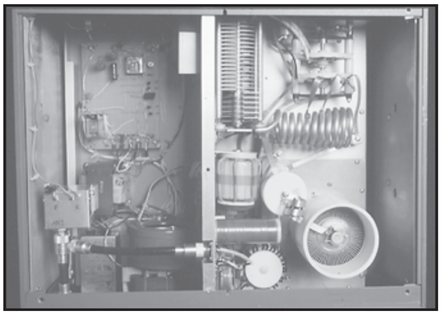


Fig 18.31—Inside view of RF deck. Tank components are from a Command Technologies HF-2500 amplifier.

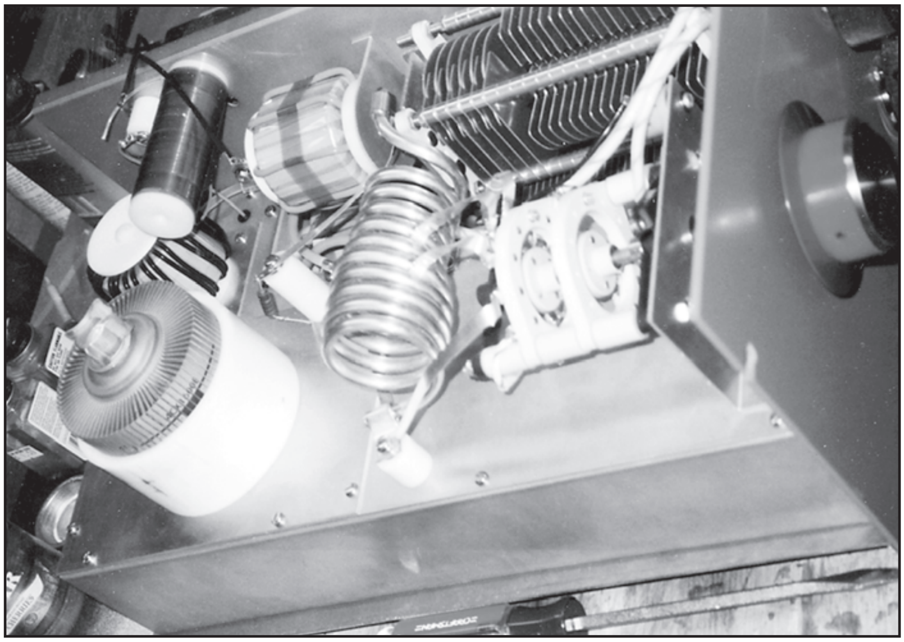


Fig 18.32—Another view of RF deck during construction.

resistor.

All power to the RF deck is supplied from the power supply cabinet. There is a standard IEC 120-V ac cable for the 4CX1600B filament transformer and the antenna changeover relay, an auxiliary power cable and a high-voltage line for the anode voltage. The shielded auxiliary power cable carries the screen and control-grid bias voltages and the 12-V dc and the ground. The high-voltage line is a 40-kV #18 wire obtained from a local surplus store, with Millen 37001 connectors at each end.

In this design it is possible to plug in and turn on the HV supply without any connection to the RF deck. If you should forget to connect the ground wire and only connect the HV cable by itself, then a potentially unsafe condition exists, with high voltage on the RF deck chassis with respect to the power supply chassis. You can avoid this in several ways: Use a special high-voltage cable/connector that incorporates a chassis ground connection together with the HV lead. Or you could use an interlock system, with an additional high-current relay in the 240 V ac line that is activated only when an interlock cable is connected. (The interlock cable would contain a direct inter-chassis ground connection.) Finally, a simple but effective approach is to bundle the HV cable with the other inter-cabinet cables, with a distinctive bright warning label to remind the operator to make sure all connections are made between the power supply and the RF deck.

Because no control-grid current flows, the control-grid bias voltage (nominally –56 V) is provided by a simple half-wave voltage doubler, with low-power zener diodes and a potentiometer to allow grid bias adjustment for the desired no-signal cathode current. The common practice of using a zener diode in the cathode circuit to provide operating bias was rejected because of the need for actual resistance between the cathode and ground for negative feedback.

The screen supply provides a dc voltage of 350 V by means of a series electronic regulator. The regulator has a current-limiting feature, where the output voltage falls if the screen draws more than 60 mA. This prevents the screen grid dissipation from exceeding its maximum rating of 20 W.

Again, please take the time to review the *Safety* chapter in this *Handbook* to familiarize yourself with the lethal dangers present in any high-powered amplifier—and the proper procedures to use in accessing such equipment.

Modifying the SK-3A Socket

Because the stock Svetlana socket has the cathode tied directly to chassis ground (through the socket's mounting plate) and because an internal bypass capacitor for the screen grid is placed between the screen grid and the cathode, you must modify the socket for this application. You will need four insulating shoulder washers (Teflon or other insulating material), made for 4-40 screws.

1. Drill out the four rivets holding the screen ring to the screen contactors at the very top of the socket.
2. At the bottom of the socket, remove the four nuts from the machine screws holding the socket assembly together.
3. Disassemble the socket:
   a) First remove the cathode contact ring. Be sure to mark its position relative to the underlying bakelite layer.
   b) Remove the bakelite socket layer, which has the factory markings and serial number, also marking its position relative to the socket mounting plate. (This is the 0.060-inch [1.5-mm] silver-plated brass plate.)
   c) Carefully remove the screen contactor assembly, freeing the contactor "ears" by springing them outward. Don't drop the screen capacitor! It is the ceramic annulus with silver plating on each side, and it is very brittle.
   d) Finish removing the spring plate, the capacitor and the other spring plate, if they didn't already come out with the screen contactor assembly in step (c) above.
   e) Remove the mounting plate assembly, marking its position relative to the remaining socket assembly.
4. Drill out the four holes in the mounting plate assembly using a #14 drill (0.180 inches). These are the second set of holes in from the outer edge, through which the socket assembly screws pass. (The screws should still be in the top layer of the socket, with heater, grid, and cathode contactors.)
5. Put the new Teflon shoulder washers on the screws. When the socket is reassembled, the cathode will be isolated from the main mounting plate and the screen bypass capacitor.
6. Replace the capacitor assembly in the following order: spring, capacitor and spring. Now replace the screen contactor assembly and the bakelite bot-

tom section, taking care to align this section with your previous mark. Carefully guide the socket solder tabs through the bakelite bottom without bending them.

7. Cut the outer tabs off the cathode ring contact. After all of this work, you don't want this ring (the cathode terminal) to be grounded when you mount the socket in the chassis! Place the modified cathode contact ring over the screws.
8. Replace the washers and nuts on the socket assembly machine screws and tighten each a little at a time, until the assembly is snug.

This completes the socket conversion. The screen ring on the 4CX1600B is contacted exactly as before. The internal screen bypass capacitor still appears between the screen grid and ground (through the socket mounting plate). The heater, control grid, and screen contacts function exactly as in the original.

The cathode annulus on the 4CX1600B is contacted exactly as before, but the electrical connection for the cathode is now isolated from the chassis. The cathode contact on the socket is now made through the thin cathode ring on the bottom of the socket. (The ring is silver-plated and easily soldered, convenient for an application like the present one, which requires multiple contacts.)

Metering

The author obtained some attractive meters with 200 μA movements from a local surplus store. The internal resistance was 2000 Ω. One meter became a voltmeter on the anode power supply (0 to 4 kV); one became a triple-purpose multimeter to measure anode current (0 to 1.3A), screen-grid current (–20 to +80 mA), and control-grid current (0 to 1.3 mA). The third meter, not shown in the schematic, indicates forward (0 to 1500 W) and reflected power (0 to 150 W) at the output connector. After dc calibration against a digital multimeter, he carefully removed the cover and face of each movement and attached a homemade laser-printed scale.

Grid Current Warning

The circuitry for the grid-current warning indicator light is very simple and is shown in Fig 18.29 also. When control-grid current flows, it develops a voltage across R10. This causes the collector current of Q6 to light a red LED indicator brightly when grid current is about 1.0 mA. (Although the battery is always connected to the circuit of transistor Q6, the current drain due to collector-emitter leakage current is negligible, so battery life should be very long. If you don't like the floating 9-V battery, a small dc power supply could be included or a small "wall-wart" type of dc supply could be built right into the cabinet. It must however, be capable of floating at the grid potential, about 60 V away from chassis ground potential.)

When the grid-current warning LED flickers on voice peaks, it's time to back off the transceiver's RF output control to reduce the drive. In CW mode, many transceivers will put out a high-power spike on initial key closure, even when the RF output control is set to quite low values. If this happens with your transceiver, the warning blink from the LED will alert you to the problem. The circuitry for the grid-current warning indicator is built into a small aluminum minibox that uses feedthrough capacitors and RF chokes to eliminate stray RF.

Results

The zero-signal plate current is about 280 mA, resulting in a zero-signal plate dissipation of about 900 W. At full 1.5 kW output on 40 m, the plate current is about 0.8 A and the anode dissipation is less than 1000 W. (Until the TR switch is activated, the screen voltage is zero and the tube is effectively cut off, so there is no plate dissipation except during transmit periods.) After a heavy period of operating the amplifier, let the fan run for a few minutes in standby mode to cool the tube before turning the amplifier off.

Performance figures for the amplifier are presented in **Table 18.7**.

Table 18.7
4CX1600B, Class AB1, Passive Grid-Driven Service

	Zero Signal	*Maximum Signal*
Plate Voltage	3200 V	3040 V
Control Grid Bias Voltage	–56 V	–56 V
Screen Grid Voltage	350 V	350 V
DC Plate Current	280 mA	800 mA
Approx. Plate Load	—	2400 W
Drive Power	0 W	66 W
Power Output	0 W	1500 W
Intermodulation Distortion Products		
3rd order	—	–35 dB
5th order	—	–43 dB
7th order	—	–47 dB

A 6-Meter Kilowatt Amplifier

Editor's note: Section and figure references in this article are from the 2013 edition of the ARRL Handbook. *Although a 4CX1600B tube is used in this design, the currently available model is the 4CX1600U.*

The Svetlana 4CX1600B tube has attracted a lot of attention because of its potent capabilities and relatively low cost. Because of its high gain and its large anode dissipation capabilities, the tube has relatively large input and output capacitances—85 pF at the input and 12 pF at the output. Stray capacitance of

Fig 17.61—Photo of the front panel of the 6-meter 4CX1600B amplifier.

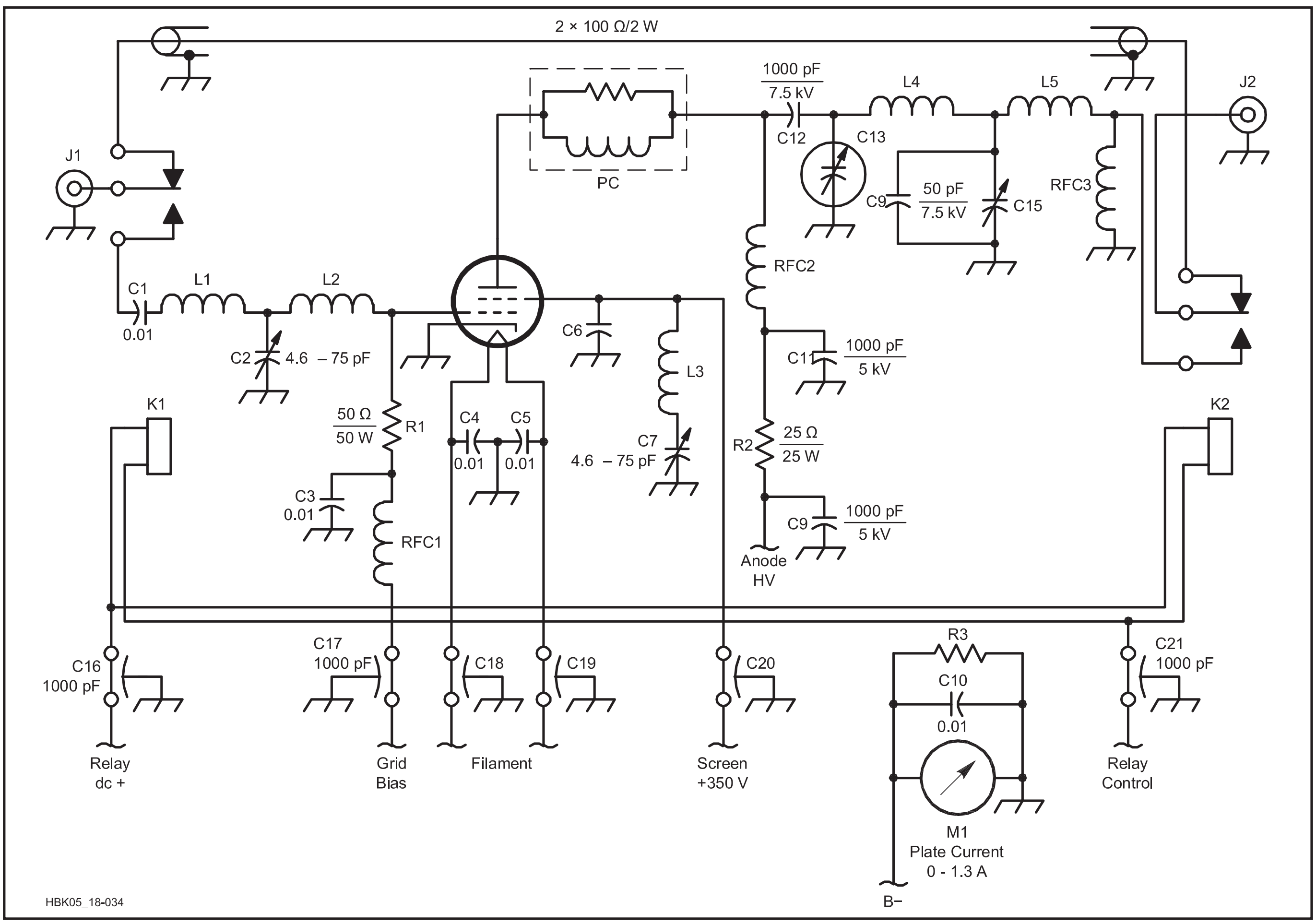


Fig 17.62—Schematic for the RF deck for the 6-meter 4CX1600B amplifier. Capacitors are disc ceramic unless noted.

C2, C7—4.6-75 pF, 500-V air-variable trimmer capacitor, APC style.
C6—Screen bypass capacitor, built into SK-3A socket.
C13—1-45 pF, 5 kV, Jennings CHV1-45-5S vacuum-variable capacitor.
C14—50 pF, 7.5 kV, NP0 ceramic doorknob capacitor.
C15—4-102 pF, 1100V, HFA-100A type air-variable capacitor.
C16, 17, 18, 19, 20, 21—1000 pF, 1 kV feedthrough capacitors.
L1—11 turns, #16, ⅜-inch diameter, 1-inch long.
L2—9 turns #16, ⅜-inch diameter, close-wound.
L3—8 turns #16, ⅜-inch diameter, ⅞-inch long.
L4—¼-inch copper tubing, 4½ turns, 1¼ inches diameter, 4½ inches long.
L5—5 turns #14, ½-inch diameter, 1⅜ inches long.
M1—0-1.3 A meter, with homemade shunt resistor, R3, across 0-10 mA movement meter.
PC—Parasitic suppressor, 2 turns #14, ½-inch diameter, shunted by two 100-Ω, 2-W carbon composition resistors in parallel.
RFC1—10 μH, grid-bias choke.
RFC2—Plate choke, 40 turns #20, ½-inch diameter, close-wound.
RFC3—Safety choke, 20 turns #20, ⅜ inch diameter.

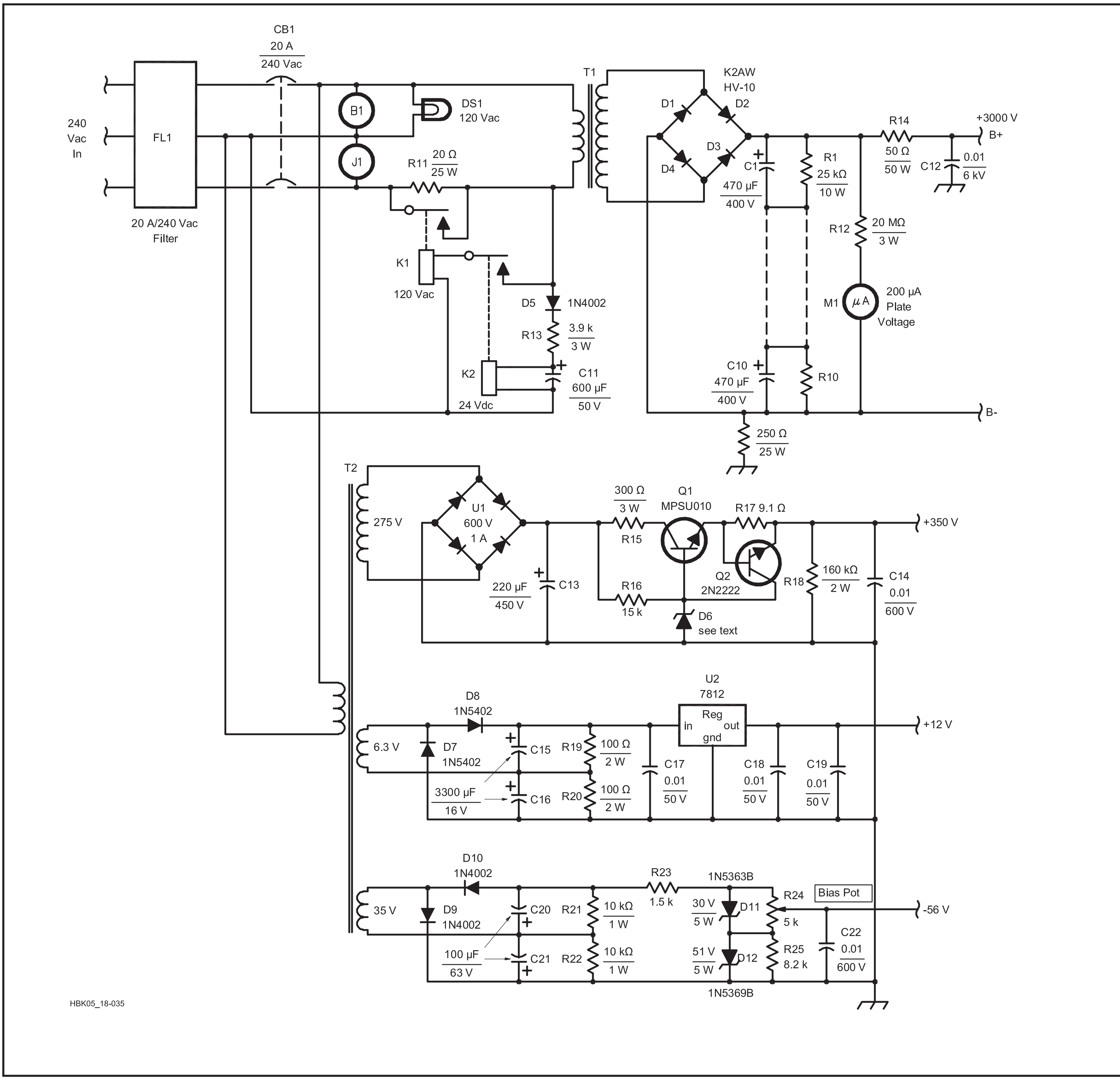


Fig 17.63— Schematic diagram of the K6GT high-voltage plate and regulated screen supply for the 6 meter 4CX1600B linear amplifier. K1 , K2 and associated circuitry provide a "step-start" characteristic to limit the power-on surge of charging current for the filter capacitors. Resistors are ½ W unless noted. Capacitors are disc ceramic unless noted and those marked with a + are electrolytic.

about 10 pF must be added in as well. On bands lower than 50 MHz, these capacitances can be dealt with satisfactorily with a broadband 50-Ω input resistor and conventional output tuning circuitry.

See the article by George Daughters, K6GT, "The Sunnyvale/Saint Petersburg Kilowatt-Plus" in 2005 and earlier Handbooks and included in the Templates section of the *Handbook CD* for details on suitable control and power-supply circuitry. This 6-meter amplifier uses the same basic design as K6GT's, except for modified in-put and output circuits in the RF deck. See **Fig 17.61**, a photograph of the front panel of the 6-meter amplifier built by the late Dick Stevens, W1QWJ.

On the 50-MHz band the tube's high input capacitance must be tuned out. The author used a T network so that the input impedance looks like a nonreactive 50 Ω to the transceiver. To keep the output tuning network's loaded Q low enough for efficient power generation, he used a 1.5 to 46 pF Jennings CHV1-45-5S vacuum-variable capacitor, in

B1 — Muffin fan (Rotron SU2A1 or similar).
C1-C10 — Filter capacitors; 470 µF, 400 V electrolytic.
C11 — 600 µF, 50 V electrolytic.
C12 — 0.01 µF, 6 kV disc ceramic.
C13 — 220 µF, 450 V electrolytic.
C14, C22 — 0.01 µF, 600 V disc ceramic.
C15, C16 — 3300 µF, 16 V electrolytic.
C17, C18, C19 — 0.01 µF, 50 V disc ceramic.
C20, C21 — 100 µF, 63 V electrolytic.
CB1 — two pole 20 A, 240 V ac circuit breaker.
D1-D4 — K2AW's HV-10 rectifier diodes.
D5, D9, D10 — 1N4002.
D6 — Zener diodes, three 1N4764A and one 1N5369B to total approximately 350 V dc.
D7, D8 — 1N5402.
D11 — Zener diode, 1N5363B (30 V, 5 W).
D12 — Zener diode, 1N5369B (51 V, 5 W).
DS1 — 120 V ac indicator lamp (red).
FL1 — 240 V ac, 20 A EMI filter.
K1 — 120 V ac DPDT relay; both poles of 240 V ac/15 A contacts in parallel.
K2 — 24 V dc relay; 120 V ac, 5 A contacts.
M1 — 200 µA meter movement.
Q1 — MPSU010.
Q2 — 2N2222.
R1-R10 — Bleeder resistors; 25 kΩ, 10 W.
R11 — 20 Ω, 25 W.
R12 — 20 M Ω, 3 W (Caddock MX430).
R13 — 3.9 k Ω, 3 W.
R14 — 50 Ω, 50 W mounted on standoff insulators.
R15 — 300 Ω, 3 W.
R18 — 160 k Ω, 2 W.
R19, R20 — 100 Ω, 2 W.
R21, R22 — 10 k Ω, 1 W.
R24 — 5 kΩ potentiometer; sets control grid bias for desired no-signal cathode current.
T1 — Plate transformer (Peter W. Dahl No. ARRL-002, contact Harbach Electronics, www.harbachelectronics.com, for equivalent parts).
T2 — Power transformer, 120 V / 275 V at 0.06 A, 6.3 V at 2 A, 35 V at 0.15 A.
U1 — 600 V, 1 A rectifier bridge.
U2 — 7812, +12 V IC voltage regulator.

a Pi-L configuration to keep harmonics low. You should use a quarter-wave shorted coaxial stub in parallel with the output RF connector to make absolutely sure that the second harmonic is reduced well below the FCC specification limits.

To guarantee stability, the author had to make sure the screen grid was kept as close as possible to RF ground. This allows the

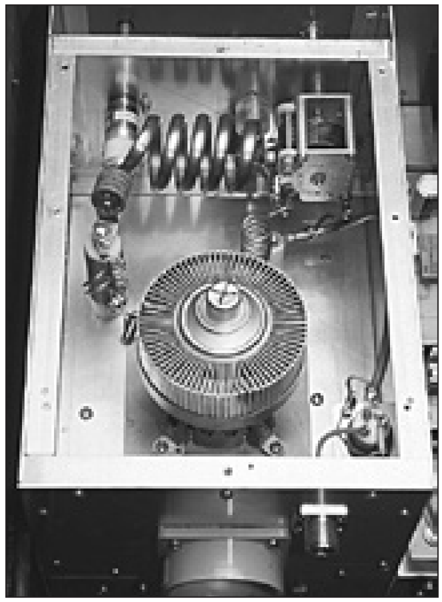


Fig 17.64—Close-up photo of the anode tank circuit for 6-meter kW amplifier. The air-cooling chimney has been removed in this photo.

screen to do its job "screening"—this minimizes the capacitance between the control grid and the anode. He used the Svetlana SK-3A socket, which includes a built-in screen bypass capacitor, and augmented that with a 50-MHz series-tuned circuit to ground. In addition, to prevent VHF parasitics, he used a parasitic suppressor in the anode circuit.

Unlike the K6GT HF amplifier, this 6-meter amplifier uses no cathode degeneration. The author wanted maximum stable power gain, with less drive power needed on 6 meters. He left the SK-3A socket in stock form, with the cathode directly grounded. This amplifier requires about 25 W of drive power to produce full output.

Fig 17.62 is a schematic of the RF deck. The control and power supply circuitry are basically the same as that used in the K6GT HF amplifier, except that plate current is monitored with a meter in series with the B– lead, since the cathode in this amplifier is grounded directly. The K6GT power supply is modified by inserting a 250-Ω, 25-W power resistor to ground in place of the direct ground connection. See **Fig 17.63**. In Fig 17.62, C1 blocks grid-bias dc voltage from appearing at the transceiver, while L1, L2 and C2 make up the T-network that tunes out the input capacitance of V1. R1 is a non-reactive 50-Ω 50-W resistor.

C6 is the built-in screen bypass capacitor in the SK-3A socket, while L3 and C7 make up the series-tuned screen bypass circuit. RFC3 is a safety choke, in case blocking capacitor C12 should break down and short, which would otherwise place high voltage at the output connector.

CONSTRUCTION

Like the K6GT amplifier, this amplifier is constructed in two parts: an RF deck and a power supply. Two aluminum chassis boxes bolted together and mounted to a front panel are used to make the RF deck. **Fig 17.64** shows the 4CX1600B tube and the 6-meter output tank circuit.

Fig 17.65 shows the underside of the RF deck, with the input circuitry shown in more detail in **Fig 17.66**. The 50-Ω, 50-W noninductive power resistor is shown in Fig 17.66. Note that the tuning adjustment for the input circuit is accessed from the rear of the RF deck.

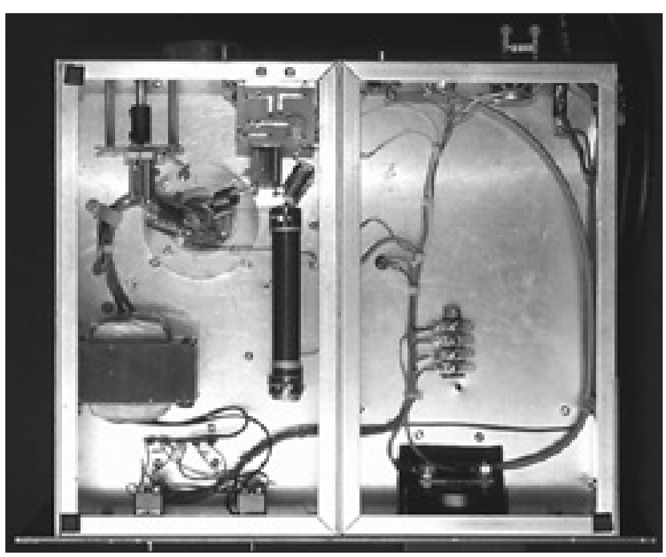


Fig 17.65—Underneath the 6-meter kW amplifier RF deck, showing on the left the tube socket and input circuitry.

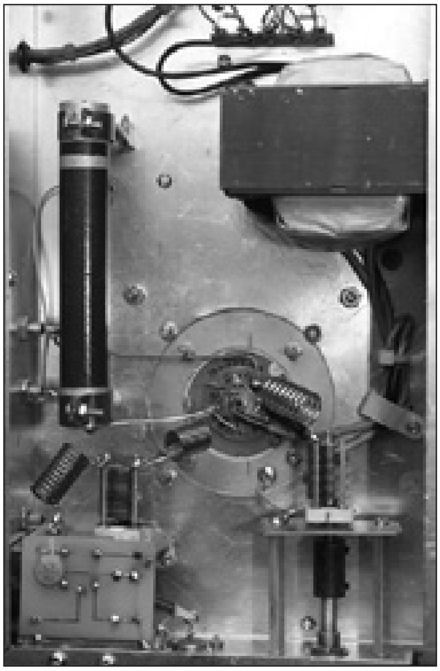


Fig 17.66—Close-up photo of the input circuitry for the 6-meter kW amplifier. Input tuning capacitor C2 is adjusted from the rear panel during operation, if necessary. The series-tuning capacitor C7 used to thoroughly ground the screen for RF is shown at the lower right. It is adjusted through a normally plugged hole in the rear panel during initial adjustment only.

AMPLIFIER ADJUSTMENT

The tune-up adjustments can be done without power applied to the amplifier and with the top and bottom covers removed. You can use readily available test instruments: an MFJ-259 SWR Analyzer and a VTVM with RF probe.

1. Activate the antenna changeover relay, either mechanically or by applying control voltage to it. Connect a 2700-Ω, ½-W carbon composition resistor from anode to ground using short leads. Connect the SWR analyzer, tuned to 50 MHz, to the output connector. Adjust plate tuning and loading controls for a 1:1 SWR. You are using the Pi-L network in reverse this way.
2. Now, connect the MFJ-259 to the input connector and adjust the input T-network for a 1:1 SWR. Some spreading of the turns of the inductor may be required.
3. Disconnect the Pi-L output network from the tube's anode, leaving the 2700-Ω carbon composition resistor from the anode still connected. Connect the RF probe of the VTVM to the anode and run your exciter at low power into the amplifier's input connector. Tune the screen series-tuned bypass circuit for a distinct dip on the VTVM. The dip will be sharp and the VTVM reading should go to zero.
4. Now, disconnect the 2700-Ω carbon resistor from the anode and replace the covers. Connect the power supply and control circuitry. When you apply power to the amplifier, you should find that only a slight tweaking of the output controls will be needed for final adjustment.

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Title: Quarter-Kilowatt 23-cm Amplifier--Part 1, A
Author: E.R. "Chip" Angle, N6CA

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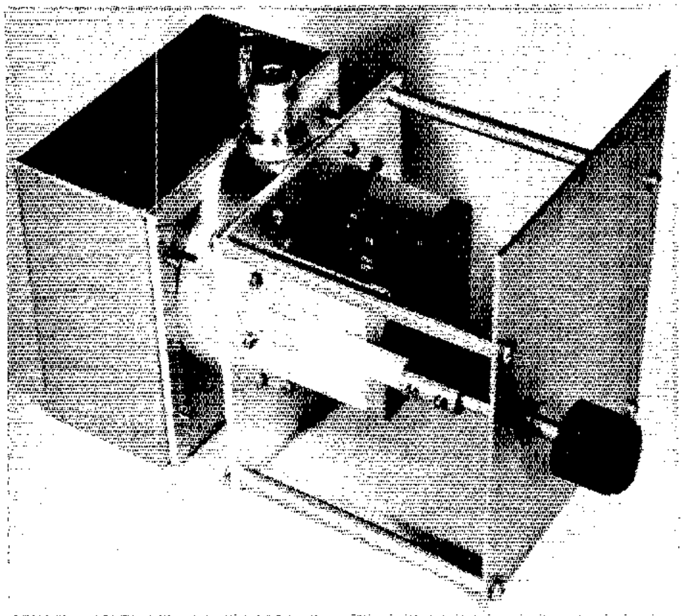

A Quarter-Kilowatt 23-cm Amplifier

Imagine, a linear amplifier with great efficiency and long-term stability that is super quiet and small in size. Sounds like HF? Not exactly . . .

By E. R. "Chip" Angle,* N6CA

To me, there is nothing more frustrating than having to dig through a construction article to find out exactly what performance you can expect from the finished product. So here it is:

1) Grounded-grid 7289/2C39 cavity amplifier, single tube.

2) Linear operation (what you put in, you get out, only more of it).

3) Covers 1240 to 1300 MHz.

4) Power gain ranges from 12-20 dB depending on output power, input power, loading, anode voltage and grid bias voltage.

5) 50-ohm input and output — no stub tuner required.

6) Power output greater than 200 W with about 12-W drive.

This is Part 1 of a two-part article. In this installment, I describe the design and construction of the RF deck. Part 2 describes power-supply construction, testing and operation.

This amplifier is a tried and proven design. Much development work has gone into this project. The amplifier works well, is reliable and can be duplicated. More than 50 of these amplifiers have been built to date. I have successfully worked many 1296-MHz EME (earth-moon-earth) stations with one of these amplifiers and a 384-element loop-Yagi array during the past year. Amplifiers of this design were used on both ends of the first California-to-Hawaii QSO on 1296 MHz. Another unit has logged more than 20,000 hours of continuous operation at the KH6HME beacon.

General Design Approach

A cavity amplifier is similar to a conventional amplifier designed for lower frequencies. The tube anode excites a resonant circuit, and power is in turn coupled into a load, usually 50 ohms. Instead of using coils and capacitors, as at lower frequencies, the cavity provides the resonant circuit necessary to tune the amplifier output.

The anode cavity of this amplifier is a squat cylinder. Cylinder height is set by mechanical tube requirements. The inside diameter of the cylinder sets the highest resonant frequency. Any capacitance added from the top to the bottom of the cavity will lower its resonant frequency, as will increasing the cavity diameter.

This amplifier uses 1/8-inch-thick copper plates for the cavity top and bottom, and a thick-wall aluminum ring, cut from tubing, for the walls.[1] This heavy construction virtually eliminates all resonant-frequency variations caused by thermal and mechanical changes.

Fig. 1 is a schematic diagram of the cavity amplifier. The circuit is simple. Filament voltage and cathode bias enter the RF deck through feed-through capacitors (C4, C5) and RFC1 and 2. High voltage is fed to the anode through RFC3. C8, the anode bypass capacitor, is homemade from Teflon® dielectric sandwiched between a copper plate and the chassis.

The input pi network easily tunes the entire band at any power level. It is made from two Johanson piston trimmer capacitors and a "coil" made from copper wire. An input cavity is not necessary at 23 cm.

Output coupling is through a rotatable loop that serves as a variable loading control. This allows amplifier-tuning flexibility; it may be tuned for maximum gain or for maximum power. Light loading can pro-

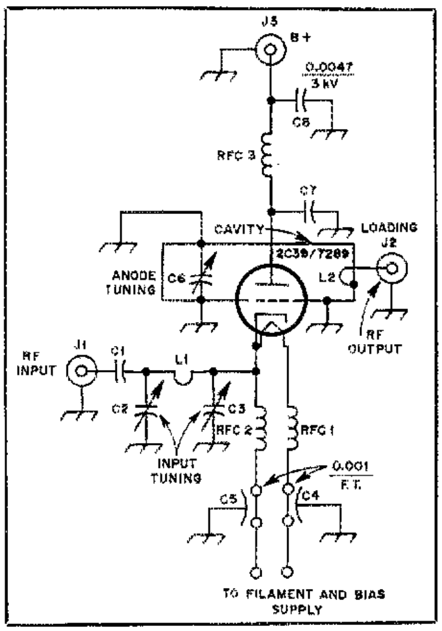

Fig. 1 — Schematic diagram of the 23-cm amplifier.

C1 — 3-pF dipped mica capacitor.
C2, C3 — 1- to 10-pF piston trimmer capacitor (Johanson no. 3957, 5201 or equiv.).
C6 — Anode-tuning capacitor. See text and Fig. 11.
C7 — Anode-bypass capacitor, 90 pF. Homemade from copper plate and Teflon sheet. See text and Figs. 5, 12 and 15.
C8 — Disc ceramic, 0.0047-µF, 3-kV capacitor.
J1 — 5-mm SMA connector, chassis mount, female.
J2 — Modified Type-N connector. See text and Fig. 7.
J3 — Female chassis-mount BNC connector.
L1 — Loop of no. 18 bus wire soldered between C2 and C3. See Fig. 15.
L2 — Output-coupling loop. Part of output-connector assembly. See text and Fig. 7.
RFC1, RFC2 — 5 turns no. 20 bus wire, 3/16-inch ID.
RFC3 — 3 turns no. 20 bus wire wound on a 20-ohm, 1-W carbon-composition resistor.

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[1]Notes appear on page 20.

duce stable power gains of up to 20 dB.

Amplifier tuning is accomplished with a homemade cylindrical coaxial capacitor with Teflon dielectric (C6). There are no moving metal parts to cause erratic performance. The Teflon rod/tube screws in and out of the coaxial capacitor, increasing or decreasing the capacitance by changing the amount of Teflon dielectric inside the cylinder. With the rod all the way in, the dielectric is all Teflon; with the rod all the way out, the dielectric is all air.

Teflon has a relative dielectric constant (relative to air = 1) of 2.05, which means that the value of the capacitor with the rod all the way in is twice the value of the capacitor with the rod all the way out. Full capacitance will pull the resonant frequency of the amplifier down to 1240 MHz. Use of only one tuning adjustment means the amplifier will have more gain because cavity shunt capacitance has been minimized.

Thermal Considerations

The cavity walls are formed by a thick-wall aluminum ring, which is sandwiched between two thick copper plates. RF and thermal properties of these two metals are reasonably close, whereas brass is rather poor in both respects. The 7289/2C39 tube used in this amplifier is being run at 2-2½ times its normal dissipation rating; therefore it's important to have a cavity that remains thermally stable.

Most previously described amplifiers have used sheet brass in their construction. This has usually meant constant retuning of resonance to maintain output power at or near maximum.

The copper and aluminum construction in this amplifier has solved all thermal stability problems. The amplifier can easily be run key down for over an hour at 200-W output without retuning. This, of course, is obtained only with a good tube and water cooling. A practical water cooling system will be described in Part 2 of this article.

Water cooling keeps the internal structure of the tube thermally stable. When air cooling is used for output levels of 100 to 150 W, output power fluctuations are a direct result of internal tube changes. These changes vary from tube to tube and must be tested for. In some cases, otherwise perfectly good RF tubes have had poor thermal stability. Such tubes can make good drivers at lower power levels.

"Using Simple Hand Tools Will . . ."

Hand tools are great if you are skilled and patient. Most people want to hurry up and finish their new project. If that's you, then have a machine shop make all of the parts, leaving you only the final assembly. It should cost about $200. The parts are not difficult to fabricate, but the process is time consuming. If you have the time and patience to do it yourself, this amplifier can be very inexpensive.

Gathering the Materials

All of the materials used in this amplifier are fairly common and should be available from suppliers in most metropolitan areas. Some suppliers have "short sale" racks, where they sell odd pieces cut off standard lengths or sheets at reduced prices. The parts for this project are small enough to be fashioned from cutoff stock. Surplus-metal houses have some great buys, so start there if one is nearby.

The key to successfully completing this project is careful layout work before cutting or drilling any parts. Invest in a can of marking dye, a sharp scribe, an accurate rule, vernier calipers and several center punches. These tools are available at any machinists' supply shop. The marking dye will make cutting and filing lines much easier to see. Measure all dimensions as carefully as you can and then recheck them before cutting. Mark with a sharp scribe because the sharper the scribe, the finer the marked line, and the finer the marked line, the closer your cut will be to where it should be. Remember — the accuracy of your drilled holes is only as good as your center-punching ability, so use a fine punch for the first mark and then a bigger one to enlarge the mark enough for drilling.

Access to a drill press is a must. It's extremely difficult to drill holes accurately with a hand drill. Although they are not absolutely necessary, you should have access to a lathe or milling machine.

Other tools that will aid you with this project are a nibbling tool, a set of punches, a new set of files and some sharp drill bits. If you don't already have one, purchase a file card to clean metal shavings out of your files as you work. Clean, sharp files are faster and more accurate to work with. You'll also need an assortment of sandpaper for the final finish work.

The Template Approach

I highly recommend fabrication of a single template for marking and drilling the anode plate, anode bypass capacitor, cavity ring, grid plate and front panel. The template shown in Fig. 2 has all of the holes for these parts. If you use the template, you'll only have to make the careful measurements once — after that, it's simple to mark and drill the rest of the parts.

The template approach offers several other advantages. A template makes it much easier to maintain accuracy between the anode plate, cavity ring, grid plate and front panel; these parts will fit perfectly because they were all drilled from the same master. The template approach also makes it possible to set up a small production line if you decide to build more than one of these amplifiers and combine them for higher power, or if a friend wants to build an amplifier along with you.

See Fig. 2 for complete template dimensions. Start with a piece of 1/16-inch-thick aluminum stock that is larger than you need and degrease it with soap and water. Dry it off and spray it with marking dye. Scribe

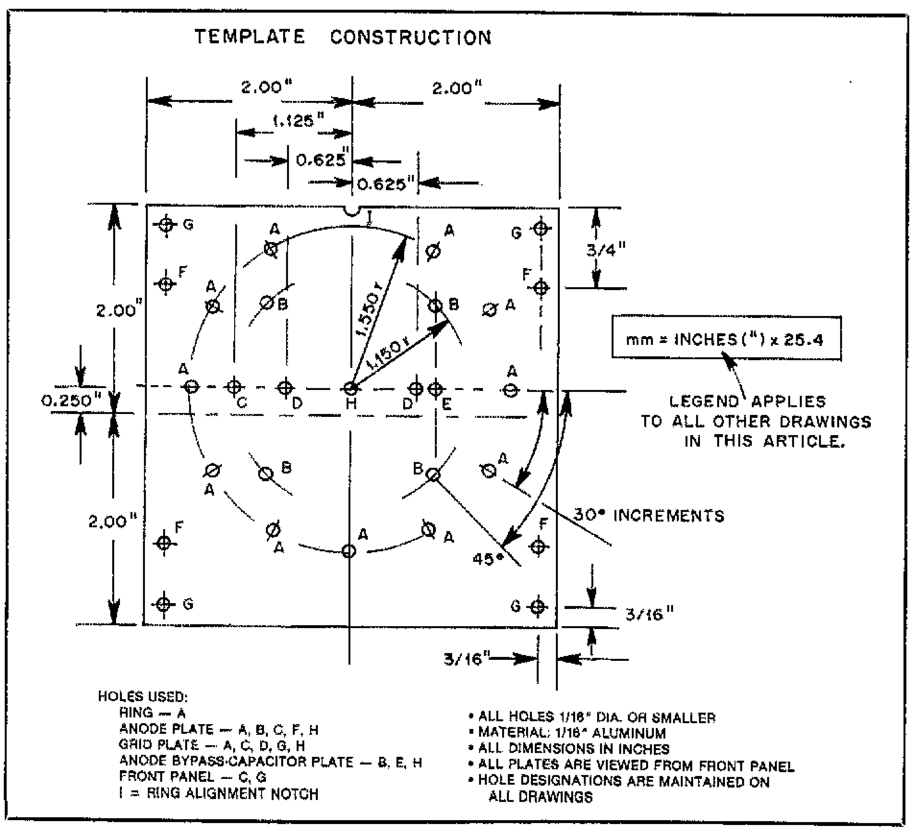


Fig. 2 — Complete dimensions for the aluminum template.

a 4-inch square on the stock and cut the template to size. A shear will make this job much easier, but it can be cut with hand tools and filed to size.

Carefully measure and scribe all holes. Note that holes A and B are on the circumference of circles. Use a compass to scribe the circles, and then locate the holes. After you have marked and checked all holes, centerpunch and drill them. The holes should be drilled with a 1/16-inch or smaller bit. Recheck all measurements. If you goof, start again. The time you spend making the template as perfect as you can will save you much time and aggravation when you make and assemble the other parts.

When you finish the template, mark the front side for future reference. All plates made from the template are marked and drilled from the front side (as viewed from the front panel).

Making the Copper Plates

Once you have completed the template, it will be easy to make the copper plates. The anode plate, grid plate and anode-bypass-capacitor plate are all made from 1/8-inch-thick copper. See Figs. 3, 4 and 5 for the dimensions of these pieces.

Measure and cut the three plates to the proper dimensions. Carefully break (deburr) all sharp edges to avoid small cuts to your fingers and hands.

Clean the plates with alcohol and spray them with marking dye. Clamp the aluminum template to each plate, and carefully scribe the correct holes. Remember that all plates do not have the same holes. The anode plate uses holes A, B, C, F and H; the grid plate uses holes A, C, D, G and H. The anode-bypass-capacitor plate uses holes B, E and H.

Use a small center punch to punch all holes lightly. If they then look accurate, enlarge them enough for drilling.

Copper isn't the easiest metal to work with. It's very stringy, and drilling it can be frustrating. You'll need the proper drill bits for best results. Special drills can be purchased, or you can use a grinder to carefully remove the sharp points on the outer edge of the cutting surface of each side of a standard drill bit. This will eliminate any tendency for the copper to grab. Practice on an old bit and be sure to grind it symmetrically. Modified drill bits can still be used on aluminum and other metals.

Always start with a smaller drill and work up to the final hole size. It's safer and more accurate. The larger holes can be cut with a flycutter, or you can drill a series of smaller holes around the inside of a larger hole and file to finish. Either way is fine. Use lots of cutting fluid to lubricate the drill bit, and wear safety glasses and an old shirt. Remember, some cutting fluids are not to be used on aluminum.

Start with a no. 50 (0.070-inch) or smaller bit and drill pilot holes at each of your punched marks. The details for finishing each hole are listed in the drawings. Some holes are countersunk or tapped. Pay attention to the details, and take your time.

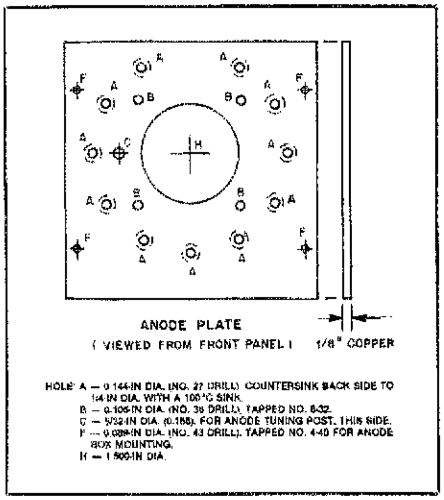


Fig. 3 — Drilling details for the anode plate. See Fig. 2 for additional information on hole location.

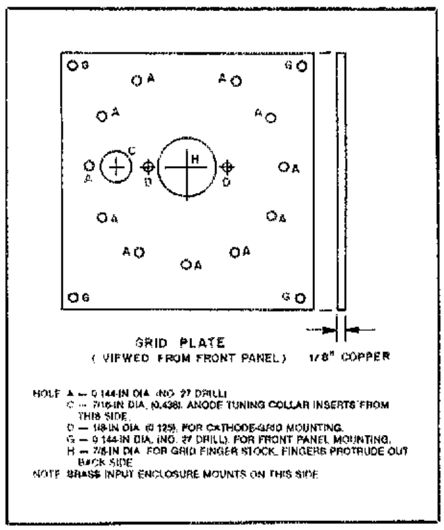


Fig. 4 — Drilling details for the grid plate. See Fig. 2 for additional information on hole location.

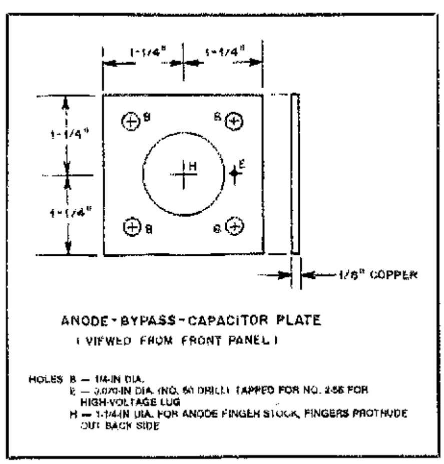


Fig. 5 — Drilling details for the anode bypass capacitor plate. See Fig. 2 for additional information on hole location.

When you are through drilling, you must deburr each hole. Copper is soft, so it tends to rise up around the hole during drilling and deburring. Use a flat file for the initial cut, and then remove any remaining material with a countersink. File the copper plates flat again; a flush fit on both sides of the aluminum ring is important.

When all copper work is done, you should be able to stack the plates and see all pertinent holes align correctly. Enough tolerance is included in the dimensions to accommodate minor errors. After the holes are drilled, it can be difficult to tell which side of each plate is which, so mark the front side of each plate with a permanent marker.

Machining the Ring

The aluminum ring that forms the cavity wall is cut (sliced) from a length of 3½-inch-OD tubing with a 3/8-inch wall thickness. See Fig. 6. The tubing ID is about 2¾ inches. The dimensions of the ring are the most critical in this amplifier. Tolerance of the ring thickness is ±0.005 inch to maintain full band coverage.

The ring can be hacksawed or bandsawed out of the tubing, but take extreme care to be accurate. Cutting tubing straight isn't easy. Clamp the tubing to prevent rotating on the band saw. The final finish cut is best done on a lathe or milling machine, but careful filing will work.

Once the ring is the correct thickness, deburr the sharp edges and spray it with marking dye. Notice that the outside and inside diameters are not concentric. This is normal for large tubing. Lay the ring flat and find the thickest wall section. Scribe a line across the wall at this point, across the center of the ring and across the wall on the other side. The scribed lines on each side of the ring will be used to align the template. The output connector will be placed at the thick wall section.

Carefully align notch I on the template with the line scribed on the thickest wall section on the ring. Clamp the template onto the ring. Mark each of the 11 holes labeled A on the template. After you mark the holes and remove the template, check alignment with the copper plates just in case. If everything lines up, center punch all eleven holes on one side of the ring only, and drill each hole completely through the ring. Use lots of cutting fluid. File the ring flat before and after deburring, taking care not to change the wall thickness. Tap each hole to accept no. 4-40 machine screws. Each hole will have to be tapped to a depth of at least 3/8 inch from both sides because long taps don't exist. The inside of the ring doesn't need to be polished.

The hole for mounting the output connector can now be drilled. There are two ways to mount this connector, and either scheme works fine. Read ahead to the sec-

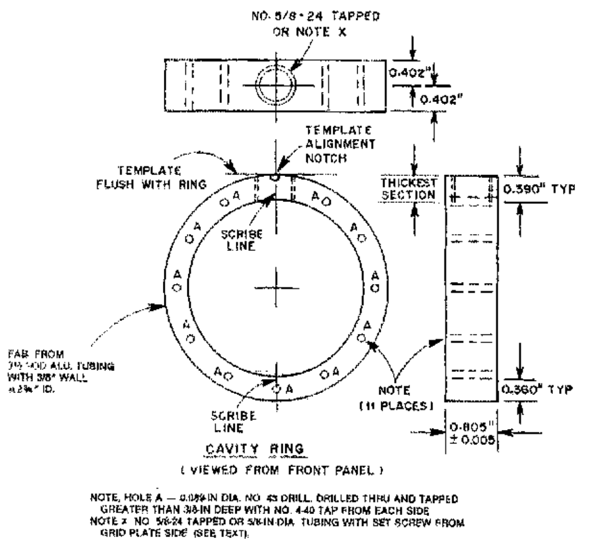


Fig. 6 — Details of the cavity ring. See Fig. 2 for additional information on hole location.

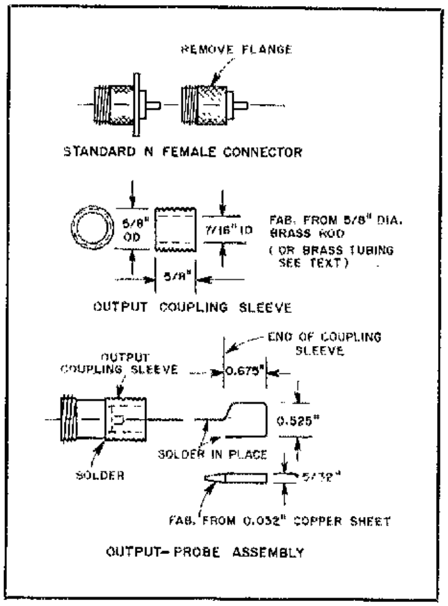


Fig. 7 — Output-probe/connector assembly details.

tion on making the output connector for more information. The first method of mounting the connector involves tapping the ring with a no. 5/8-24 tap and using a lathe to cut matching threads on the output connector coupling sleeve. Large taps are expensive, but a tap and die for Type-N connectors are handy if you do much building.

If you don't have access to a lathe or a large tap, the second method is easier. Make the output connector coupling sleeve from 5/8-inch-OD brass or copper tubing, and drill the ring to just clear it. Then drill and tap the grid-plate side of the ring above the output connector to accept a setscrew. Also, drill a clearance hole in the grid plate for the setscrew. Use the setscrew to secure the output connector.

Output Connector

A standard Type-N chassis-mount female connector (silver plated) is used for the output probe/connector. See Fig. 7. First, remove the flange with a hacksaw and file flush with the connector body. Next, make the output-coupling sleeve that is right for your application (threaded or unthreaded, depending on how you fabricated the ring). The sleeve will be the same length in either case. The output-coupling loop is fashioned from a piece of 0.032-inch-thick copper sheet that is 5/32 inches wide. Bend it to the dimensions shown in Fig. 7. We will solder the output connector together later.

Grid Compartment

The grid compartment measures 2 inches square by 1½ inches high. See Fig. 8. It is made from brass and can be sawed out of square tubing or bent from sheet. The cover can be made from any material.

I use two small PC boards (Fig. 9) for holding the finger stock that makes contact with the filament pin and cathode ring on the 2C39 tube. These boards are cut from 1/16-inch-thick, double-sided G-10 glass-epoxy stock. The copper pattern is identical for both sides of each piece. Mark and drill or file the holes first, and then cut the boards to size. Small boards are difficult to hold while drilling them. Mark each side of each board and score the copper foil with a sharp knife.

The unwanted copper can be removed easily by heating the foil with a soldering iron and lifting it off. Use a flat file to deburr the boards. Do not use a countersink because the copper foil must be as close to the holes as possible to facilitate soldering the finger stock in place.

The input connector that I use is a 5-mm SMA type. This is an excellent RF connector, especially for low-power UHF applications. I highly recommend use of an SMA,

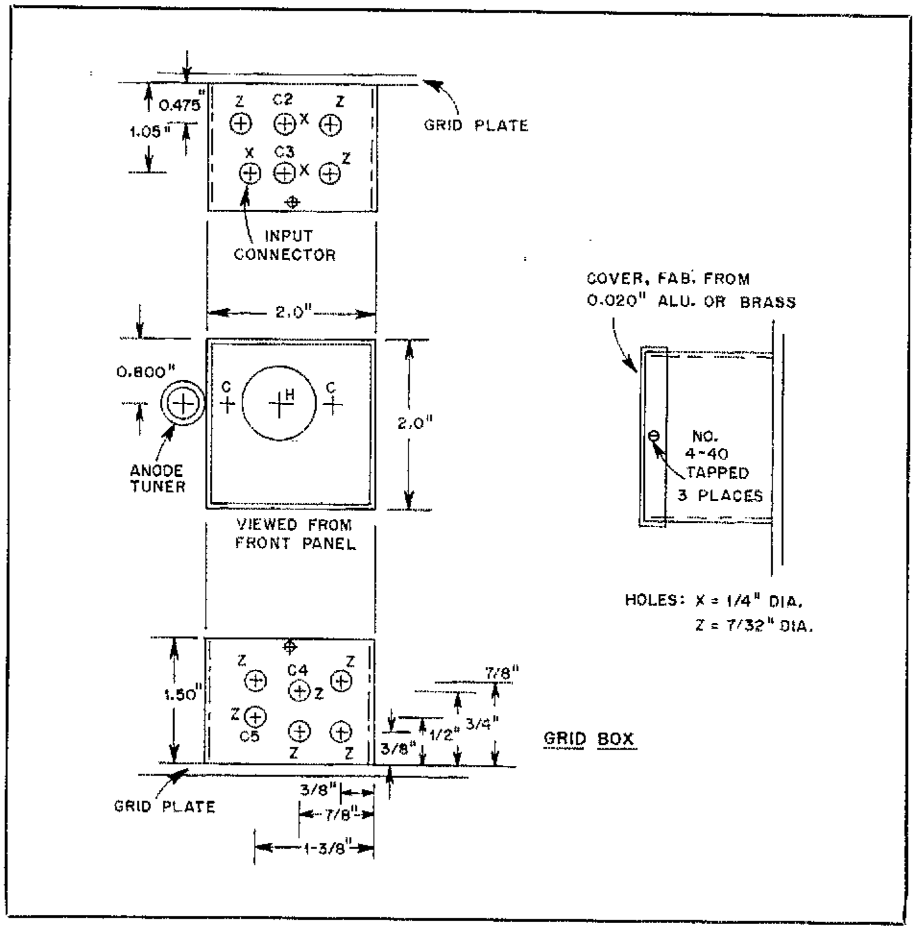


Fig. 8 — Input-compartment details.

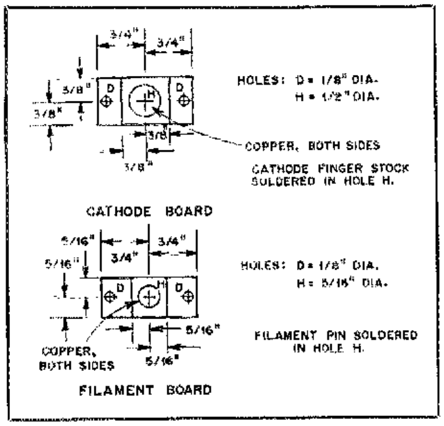


Fig. 9 — Cathode and filament PC-board details.

but any small screw-on connector will do. If you really feel you have to use a BNC then do so, but it's a lousy connector at frequencies above 200 MHz. Remember to move the connector hole to accommodate its larger size.

The input connector must be as close as possible to the first input capacitor. The lead length of the input dc blocking capacitor must be as short as possible. The 3-pF capacitor is series resonant at 1200 MHz only with short (1/16-inch or less) leads.

Miscellaneous Bits and Pieces

There are still several small, but very important parts to fabricate. The front panel I use is shown in Fig. 10. It is made from a piece of 1/8-inch-thick aluminum sheet. Some builders may wish to mount the amplifier on a rack panel. Wash and dry your front-panel material and spray it with marking dye. Clamp it to the template and mark the holes. Check the hole alignment with the copper grid and anode plates. If all lines up correctly, center punch and drill the holes. The only front-panel control is for the anode tuning capacitor, which is adjusted by a 1/4-inch shaft protruding through a 3/8-inch panel bushing in hole C.

The anode tuning collar, shown in Fig. 11A, is made from a piece of 1/2-inch-OD brass rod. This rod has a 3/8-inch hole drilled through its center, and it is turned down to 7/16-inch OD for half its length. The inside of the 1/2-inch-OD end is tapped to a depth of 1/4 inch to accept 3/8-24 threads. This collar will be inserted into hole C on the grid plate.

Fig. 11B also shows the anode tuning post. It is simply a length of 5/32-inch-OD brass rod that inserts into hole C on the copper anode plate. This rod will form one plate of the anode tuning capacitor.

The anode tuner (Fig. 11C) is machined from a piece of 3/8-inch-OD Teflon rod. One end of the rod is drilled out with a no. 21 drill. The outer wall of this end is threaded with a no. 3/8-24 tap. This is the end that will thread into the anode tuning collar and slip over the anode tuning post. The other end is turned down to fit inside a ¼-inch shaft coupler.

Fig. 12 shows the remaining parts. The tuning shaft (A) is made from a piece of ¼-inch brass rod. A coupler (B) to connect the tuning shaft to the anode tuner may be purchased or made. This also applies to the front-panel spacers (C). The Teflon dielectric for the anode bypass capacitor (D) is made from 0.010-inch-thick Teflon sheet. Use the template to locate holes B and H. Teflon washers and inserts (E) are used to insulate the mounting hardware for the anode bypass capacitor from the chassis. The inserts are made from ¼-inch-OD Teflon rod. The washers are made from Teflon sheet. Sharpen a piece of 3/8-inch aluminum tubing and chuck it up in a drill press. This tool will cut neat, round washers from the sheet.

The box that encloses the anode compartment (Fig. 13) is fabricated from a Bud AU-1083 utility cabinet. Clean the chassis and spray it with marking dye. Secure the template to the side of the enclosure that contacts the anode plate and scribe the holes labeled F. Make sure that these holes line up with the holes on the copper anode plate. If they do, center punch and drill them to size. If air cooling is used, the blower will mount to this box.

Soldering the Subassemblies

Once all copper and brass parts are drilled and deburred, they should be cleaned with alcohol and Scotch-Brite®, a nonmetallic pot cleaner, and washed in alcohol again. Set the pieces aside and avoid touching them. Fingerprints will inhibit soldering.

I have found that the best way to solder the heavy brass and copper parts is to first build the soldering fixture shown in Fig. 14. This soldering fixture, made from ½-inch-thick aluminum plate, will evenly heat the entire assembly to be soldered. Even heating

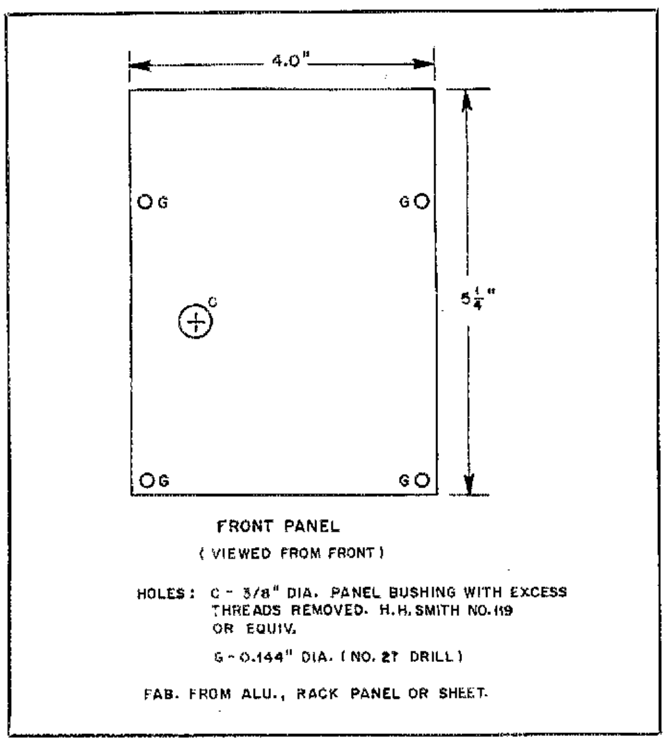


Fig. 10 — Front-panel details.

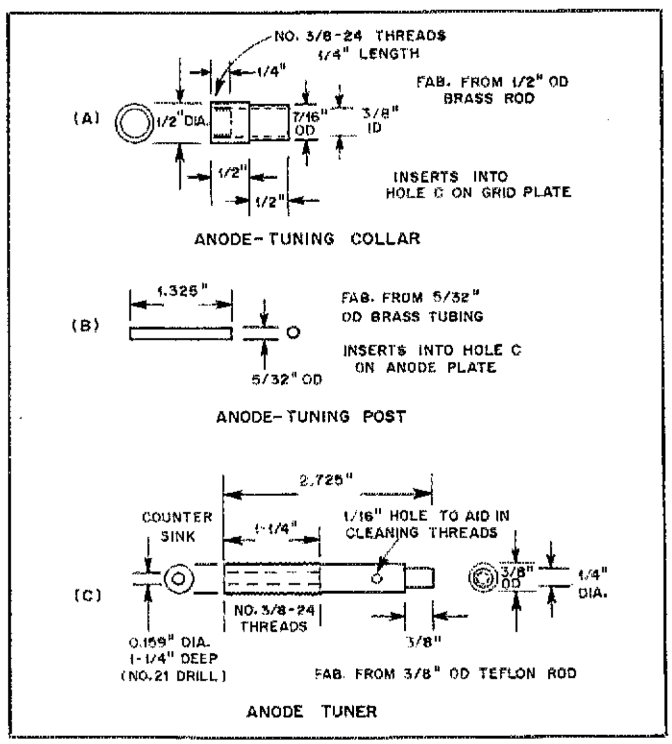


Fig. 11 — Anode-tuning capacitor details.

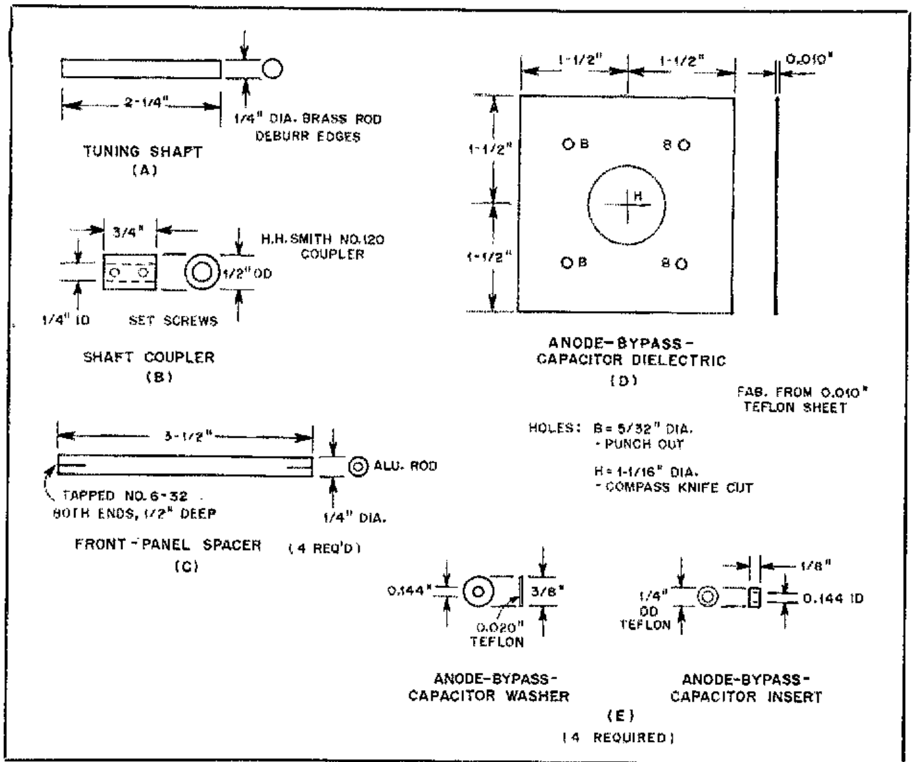


Fig. 12 — Miscellaneous parts necessary to complete the amplifier.

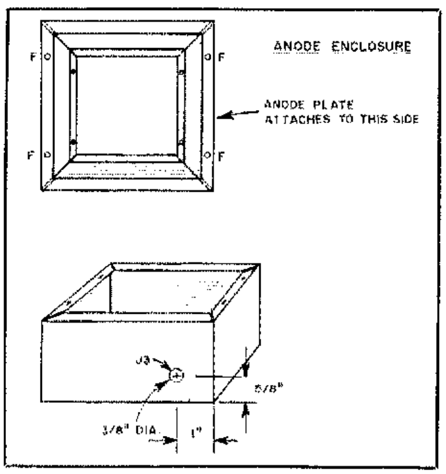


Fig. 13 — Anode-enclosure details.

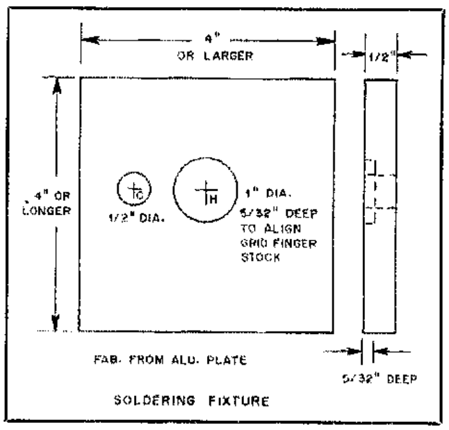


Fig. 14 — Dimensions of the soldering fixture. See Fig. 2 for more information on hole location.

will allow you to do a much better soldering job than you could otherwise.

The soldering fixture should be preheated on a stove or hot plate until bits of solder placed on its surface just melt. At this point, reduce the heat slightly. Avoid excessive heat. If the copper parts placed on the fixture suddenly turn dark, it's too hot.

Solder the grid plate assembly first. You will need the copper grid plate, grid finger stock, anode tuning collar and brass input compartment.[2] Look at the drawings again to be sure that you know which parts go where. Insert the grid finger stock into hole H on the grid plate. As viewed from the front-panel side, the curved fingers will protrude out the back side, away from you. Apply liquid or paste flux and set the grid plate in the soldering fixture. The finger stock will fit in hole H in the fixture, allowing the grid plate to rest flush with the surface of the fixture. Next, apply flux to the anode tuning collar and insert it in hole C of the grid plate. Part of the tuning collar will slip into hole C in the soldering fixture. Make sure the collar seats flush with the grid plate. The flux should start to bubble.

Carefully apply solder directly to the joints of the installed parts. The solder should melt almost immediately and flow bright and smooth. Next, place the square brass input compartment in place and apply flux. In a few seconds, it can be soldered by running solder around the joints, inside and outside. If you have trouble getting it to flow on both sides, merely tap the brass box aside (1/16 inch) and return it to its original position.

Now comes the hard part — getting the soldered assembly away from the heat without disturbing the alignment. A pair of forceps is recommended, but long pliers will do. Carefully lift the assembly off the soldering fixture and set on a cooling rack. Do this without moving any part. The cooling rack can be any two pieces of metal that will allow clearance for the protruding parts. You can expedite cooling by using an ordinary hair dryer in the "cool" position to gently blow air across the assembly.

While the grid assembly is cooling, assemble the output connector. See Fig. 7. Place the modified Type-N female connector, threaded end down, on the soldering fixture. Apply flux to the top and install the output coupling sleeve. Allow both parts to heat before applying solder. Carefully remove the soldered output connector from the fixture. When it has cooled, solder one end of the loop to the center pin of the N connector and the other to the output coupling sleeve.

Now place the anode plate on the soldering fixture and allow to heat. Apply flux to hole C. Insert the anode tuning post (5/32-inch-OD brass tube) and allow to heat; apply solder. Remove the parts and cool. Next, solder the finger stock in hole H on the anode bypass capacitor plate.[3]

This completes the work with the soldering fixture. Be sure to let it cool off before handling! Save the fixture for future construction; you never know when you might want it again.

The anode plate and the anode-bypass-capacitor plate must be filed and then sanded flat on their butt surfaces to assure that there are no solder bumps or sharp points to puncture the Teflon dielectric. This must be done after soldering. The Teflon sheet is adequate insulation for many times the anode potential of this amplifier, but only if the surfaces it separates are smooth!

Next, clean the cathode and filament PC boards. Install the finger stock in hole H of the cathode board. Apply flux to both sides of the board. Heat with a hot iron and apply solder around the circumference of hole H, soldering the finger stock on both sides of the board. Use the same technique to install the filament pin.[4]

After all parts have cooled, use a spray can of flux remover to clean them. Slight scrubbing with Scotch-Brite pot cleaner will finish them nicely. Congratulations: You have finished the pieces and are now ready to bolt the amplifier together.

Silver Plating

Over the years, many people have pushed silver plating as the only way to go. You may wish to silver plate the amplifier components before soldering them together, but

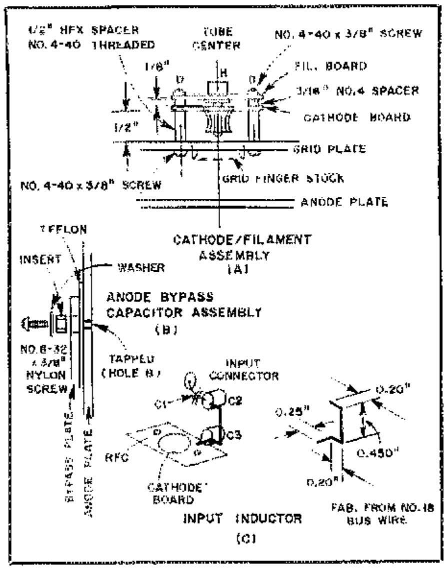
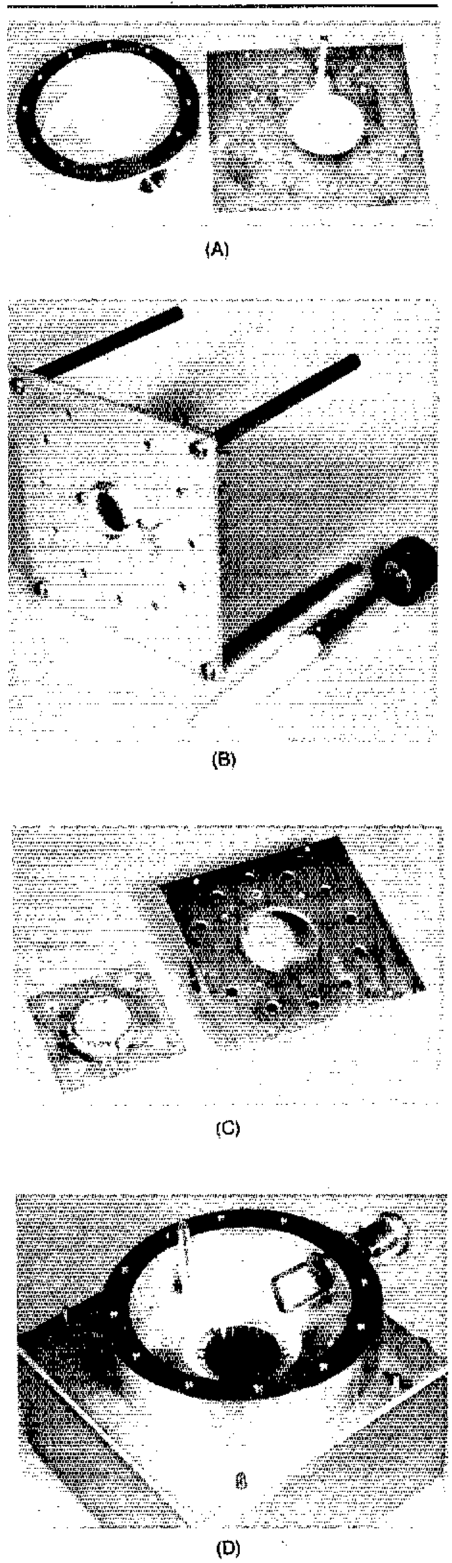


Fig. 15 — Assembly details for the filament and cathode boards (A), the anode-bypass capacitor (B) and the input pi network (C).



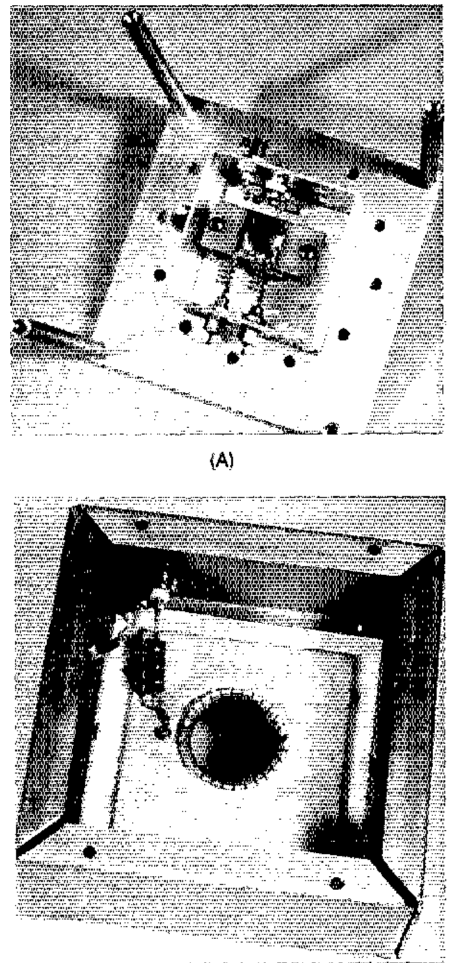
(A)

(B)

(C)

(D)

Fig. 16 — The completed cavity ring and anode plate with anode tuning post soldered in place are shown at A. The photo at B shows the grid plate with finger stock, input compartment and anode tuning collar soldered in place. The completed anode tuner is at the right. C shows the cavity ring attached to the anode plate. The anode-bypass capacitor is ready for installation. At D, the interior of the cavity as seen from the grid plate side is visible. The output probe/connector assembly is installed. The anode bypass capacitor and anode enclosure have been installed on the anode plate.



(A)

(B)

Fig. 17 — At A, the interior of the completed input compartment is visible. The photo at B shows the interior of the anode compartment with the anode bypass, RFC3, C8 and J3 installed.

I do not think it's necessary. I ran several tests to prove how much various types of plating affect performance of this amplifier. Remember that the RF skin conductivity of aluminum and copper is pretty good at 23 cm; they are much better than brass.

Four amplifiers were built for this test. They were plated as follows:

1) Nickel plated
2) Tin plated
3) Silver plated
4) Unplated

There was no difference in performance among the tin-plated, silver-plated and unplated versions. The nickel-plated amplifier exhibited 3-dB less gain.

In other words, it is not necessary to silver plate this amplifier; however, it does improve appearance by making the parts a similar color. Silver does tarnish, especially with fingerprints. The decision to plate or not to plate is up to you.

Assembly

After fabrication of all parts, assembly is simple. Figs. 15 through 17 show assembly details. Loosely fasten the grid and anode plates to the ring. Mount the input connector and capacitors on the input compartment. Loosely install the cathode and filament boards and their respective spacers. See Fig. 15A.

Now insert a 7289/2C39 tube. This will center up all finger stock. Place the Teflon anode tuner in its collar on the grid plate and screw it most of the way in. Now tighten all of the screws. The 7289/2C39 tube should slide in and out snugly, and the anode tuner should screw in and out smoothly.

The Teflon sheet and anode bypass capacitor plate can be installed now (Fig. 15B). Assemble the remaining input components, the filament feed-through capacitors and RFCs (Fig. 15C). Screw the output probe into the cavity ring (or push in the probe and tighten the setscrew, depending on which method you chose). Install the high-voltage connector and other parts in the anode box. Mount the amplifier on the front panel and install the anode tuner shaft. This completes the assembly.

Part 2 of this article will describe a complete power supply for the amplifier, a practical water cooling system, testing procedures, microwave radiation safety hazards, and amplifier tune-up and operation.

Notes

[1]mm = in × 25.4.

[2]The finger stock for this project is manufactured by Instrument Specialities, P.O. Box A, Delaware Water Gap, PA 18237. Contact them for the name of the closest distributor. The part numbers for this amplifier are: anode bypass capacitor plate, no. 97-70A; grid plate, no. 97-74A; cathode board, no. 97-420A; filament board, no. 97-280A.

[3]See note 2.

[4]See note 2.

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QST Issue: Apr 1985
Title: Quarter-Kilowatt 23-cm Amplifier, A--Part 2
Author: E.R. "Chip" Angle, N6CA

A Quarter-Kilowatt 23-cm Amplifier

Part 2: Last month, we described the design and construction of a 23-cm cavity amplifier. This installment describes the rest of the components needed to put it on the air

By E. R. "Chip" Angle,* N6CA

After you complete construction of the cavity amplifier described in March *QST,* you are ready to assemble the rest of the components needed to put it on the air. This month, I will discuss the filament, bias and high-voltage supplies; a whisper-quiet, high-efficiency water-cooling system; testing and hookup; and, finally, tune-up and operation.

Power Supplies

The filament and bias supplies for the cavity amplifier are shown schematically in Fig. 1. The manufacturer's specification for the 7289/2C39 filament is 6.0-V ac at 1 A. I have found that the use of a standard 6.3-V ac, 1-A transformer only slightly increases the tube emission without much loss of tube life. The filament should be allowed to warm up before operating the amplifier, so the filament, bias and high-voltage supplies incorporate separate primary switches.

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Biasing

Many biasing schemes have been published for grounded-grid amplifiers. Fig. 1 shows a bias network that satisfies all of the following operating requirements:

1) external bias supply referenced to ground
2) low-power components
3) variable bias to accommodate tube-to-tube variations
4) TR switchable with relay contact or transistor to ground
5) bias-supply protection in case of a defective or shorted tube.

U2 provides a variable bias-voltage source, adjustable by R1. The output of U2 drives the base of Q1, which is used to increase the current-handling capability of the bias supply. Q1 must be mounted on a heat sink. J1 is connected to the station TR switching system so that R1 is grounded on transmit and disconnected on receive. The approximate range of the bias supply is 6 to 20 V. Z1 and Z2 provide protection for Q1 in case of a shorted tube. The amplifier can be run without Z1 and Z2 if you keep the anode voltage below 1100 V.

High-Voltage Power Supply

A safe, reliable high-voltage power supply is described here. Of course, you can use any readily available HV supply; keep in mind, however, that the 7289/2C39

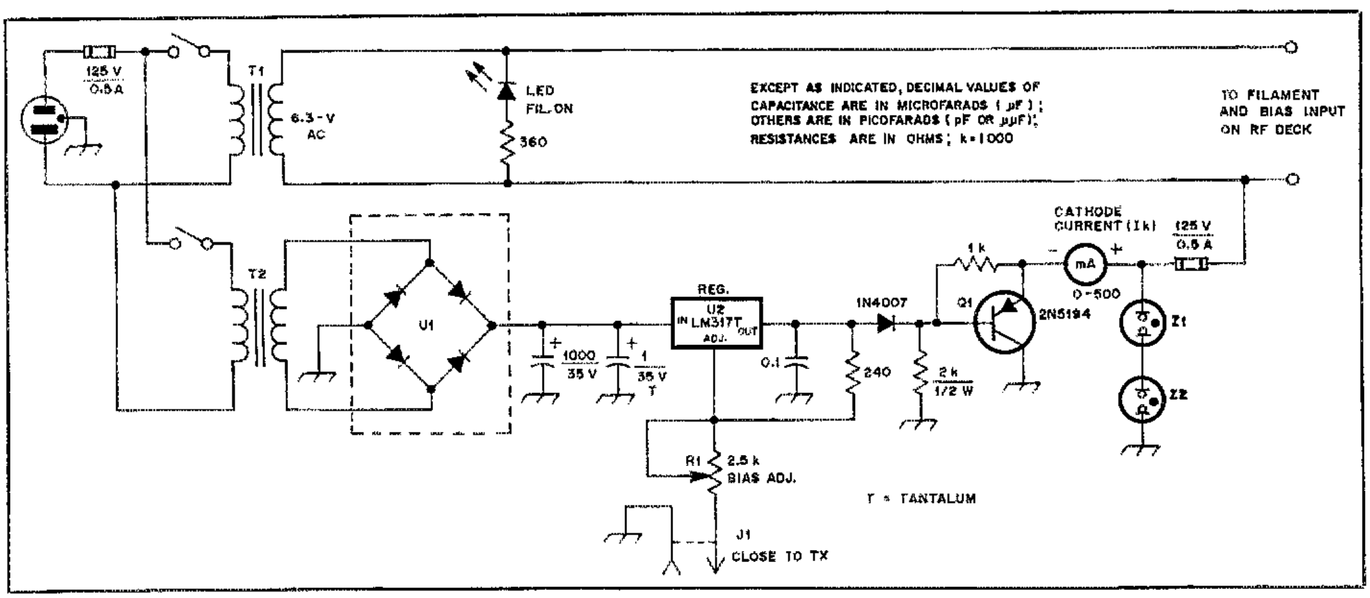

Fig. 1 — Schematic diagram of the cavity-amplifier filament and bias supplies. All resistors are ¼-W carbon types unless otherwise noted.

J1 — Female chassis-mount phono connector.
T1 — Filament transformer. Primary, 117 V; secondary, 6.3 V at 1 A.
T2 — Power transformer. Primary, 117 V; secondary, 24 to 28 V at 50 mA or greater.
U1 — Bridge rectifier, 50 PIV, 1 A.
U2 — Adjustable 3-terminal regulator (LM317T or equiv.).
Z1, Z2 — 20-V unipolar metal-oxide varistor (General Semiconductor SA20 or equiv.) or two 20-V, 1-W Zener diodes.

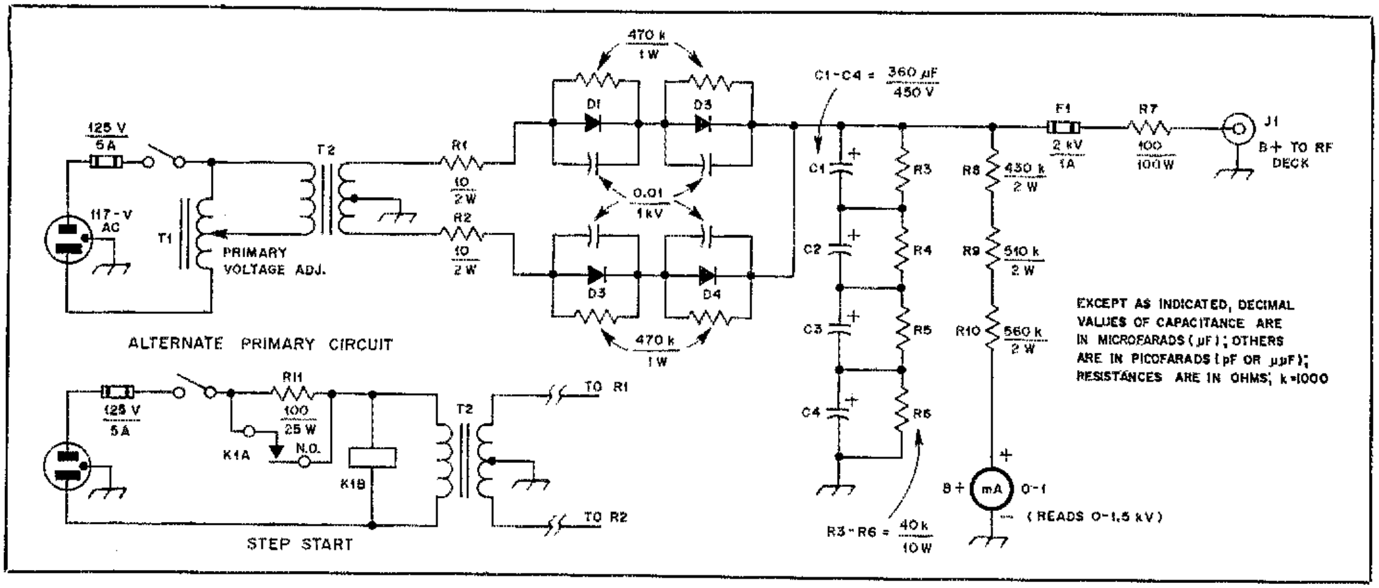

Fig. 2 — Schematic diagram of the amplifier high-voltage supply.

C1-C4 — Electrolytic capacitor, 360 μF, 450 V.
D1-D4 — Silicon rectifier, 1000 PIV, 3 A.
F1 — High-voltage fuse, 2 kV, 1 A.
J1 — Chassis-mount female BNC or MHV connector.
R3-R6 — Wirewound resistor, 40 kΩ, 11 W.
T1 — Variable autotransformer, 500 VA.
T2 — High-voltage transformer. Primary, 117 V; secondary, 900 to 1050 V at 500 mA.

anode potential should never exceed 1400-V dc at full load and that the amplifier will withstand 1900-V dc at low cathode current and cut-off-bias conditions. For maximum power output, assuming adequate drive power is available, anode voltage under full load should be about 1200- to 1400-V dc.

Fig. 2 is a schematic diagram of the high-voltage supply. A power transformer (T2) that delivers 900- to 1050-V ac is ideal. The type of rectifier circuit used will depend on the type of transformer chosen. Each leg of the rectifier is made from two 1000-PIV, 3-A silicon diodes connected in series. Each diode is shunted with a 0.01-μF capacitor to suppress transient voltage spikes, and a 470-kΩ equalizing resistor.

Filtering is accomplished with a string of four 360-μF, 450-V electrolytic capacitors connected in series. R3-R6 equalize the voltage across each capacitor in the string and serve as bleeder resistors. Of course, a single oil-filled capacitor may be used here if available. Whatever type of filter you use, the total capacitance should be about 80 μF at a voltage rating of at least 1500-V dc. This value allows adequate "droop" of the anode voltage under high-current loads to protect the amplifier in case of RF overdrive or a defective tube.

Protective Circuitry

Some type of start-up protection should be incorporated in the primary. Fully discharged filter capacitors look like a dead short at supply turn-on. Initial surge current (until the capacitors charge) may be high enough to destroy the rectifiers. R1 and R2 provide some surge-current limiting, but either of the two primary configurations shown in Fig. 2 should be used. T1, a variable autotransformer (Variac and Powerstat are two common trade names), is ideal. In addition to allowing you to bring the primary up slowly (and charging the capacitors gradually), it also allows full control of amplifier output power by varying anode voltage.

The second method, a "step-start" system, uses a resistor in the T2 primary to limit the turn-on surge current. When the capacitors have charged, K1 is energized, shorting out R11 and applying full voltage to the T2 primary.

F1 and R7 protect against high-voltage arc-overs or short circuits. If sustained overcurrent is drawn, F1 will open and remove B+ from the RF deck. Use a high-voltage fuse here; standard fuses may arc when blown and not interrupt the B+. R7 provides current limiting to protect the amplifier and power supply in case of a high-voltage arc.

Safety

An HV meter should always be used to monitor the status of the power supply. The values for R8-R10 shown in Fig. 2 will give a 1500-V dc full-scale reading on a 0-1 mA meter. RG-58 or -59 coaxial cable should be used for the high-voltage interconnection between the power supply and the RF deck. Ground the shield at both ends for safety and a good dc return.

Safety must be observed when working with all power supplies. These voltages are lethal! Always disconnect ac power and then discharge the filter capacitors before working on the power supply. Never guess or make assumptions about the status of a power supply. Assume it is hot.

Metering

Cathode-current monitoring is all that's really necessary for observing amplifier dc performance. Cathode current (I_K) is the sum of the plate (I_P) and grid (I_G) currents. Normally, when this amplifier is driven to 300- or 400-mA I_K, the grid current will be around 40 to 50 mA. The inclusion of a grid-current meter is not really necessary and only makes biasing and TR switching complicated.

Cooling

Desired output power and the level of drive power available will dictate what type of cooling to use. For intermittent duty (SSB, CW) at output levels less than 50 W, air cooling is satisfactory. Any small blower may be easily mounted to the aluminum box surrounding the tube anode. For high-duty-cycle modes and/or output levels greater than 50 W, water cooling is highly recommended. Greater than twice the normal air-cooled output power can be obtained from a water-cooled tube, and water cooling is quiet.

Tube Modification and Water Jacket

The first step is to remove the air radiator from the tube. The air radiator screws on, so it may simply be unscrewed without damage to the tube.

First, place a hose clamp around the tube anode. Secure the radiator fins in a vise and grip the hose clamp with a pair of large pliers. Gently unscrew the tube from the radiator. If the hose clamp slips slightly, tighten it.

Some 7289/2C39 tubes use an air radiator that is attached with setscrews. To remove the radiator, simply remove the setscrews and pull the radiator off.

The air radiator will be replaced with a water jacket that allows water to be circulated past the tube anode and through a radiator, where it is cooled and circulated

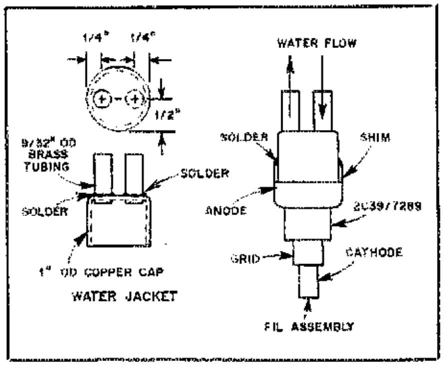

Fig. 3 — Details of the solder-on water jacket.

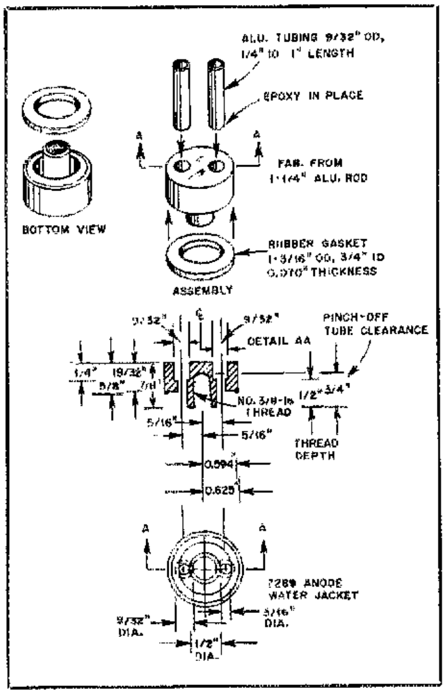

Fig. 4 — Details of the screw-on water jacket.

past the tube anode again. I have successfully used two different types of water jackets; both are described here.

The water jacket shown in Fig. 3 will work with any type of 7289/2C39. It is fabricated from a 1-inch-OD copper tubing cap and two short pieces of 9/32-inch-OD brass tubing. The copper tubing cap should be available from a local hardware store or plumbing supply house. Brass tubing is available from many hobby stores and metal supply houses.

Mark and drill the copper cap so that the brass tubing is a snug fit. Thoroughly clean the parts until they shine. Push the tubing into the holes in the end cap and degrease the assembly with alcohol. Using plenty of flux, solder the seam around each section of tubing. Allow the jacket assembly to cool.

Meanwhile, thoroughly clean the 7289/2C39 anode to a bright finish. Check the water jacket for fit. In some cases, you'll have to use a 0.005- to 0.010-inch-thick copper shim to fill the gap between the copper cap and the tube anode. This shim helps eliminate pin holes in the solder.

Using plenty of flux, solder the water jacket to the tube anode. Solder it quickly with a hot, high-wattage iron. Allow the tube to cool in the air after soldering to avoid thermal shock and possible breakage. After the tube has cooled, use plenty of alcohol to remove all traces of flux from the tube and water jacket.

The second type of water jacket is shown in Fig. 4. This jacket will work only with 7289/2C39 tubes that have a screw-on air radiator. It is designed to thread onto the tube anode just like the air radiator did. This jacket is machined from a piece of 1¼-inch aluminum rod. The water inlet and outlet tubes are made from 9/32-inch-OD, ¼-inch-ID aluminum tubing that is epoxied in place. A rubber gasket seals the jacket against leaks.

If you have access to a lathe, you should have no trouble duplicating the jacket. You could have one made up at a local machine shop. Complete screw-on water jackets are also available from the author.[1]

After you unscrew the air radiator from the 7289/2C39, check for and remove any burrs from the tube anode. The anode surface must be flat if the rubber gasket is to be effective. Screw the water jacket onto the tube. Tighten by hand only. Do not use any tools, or you could damage the tube or jacket! Do not use the water inlet and outlet tubes for leverage—they have thin walls and break easily.

Water System

Fig. 5 depicts the complete water-cooling system. Recommended pumps and accessories that have proven reliable and effective are listed in the caption.

Any small pump, such as a fountain pump, that can deliver 160 to 200 gallons per hour can be used here. Most inexpensive pumps are not self-priming, which means that they won't pump water if they have air in the rotor. Although water can be forced through the pump for the initial prime, my system uses gravity priming. The water reservoir is a 2-foot length of 3-inch-OD plastic pipe that is available from hardware or plumbing stores. The outlet is at the bottom, and the inlet about halfway up the column. The inlet is located here to eliminate aeration that ionizes the water and reduces its effectiveness. The outlet directly feeds the pump. The pump and the reservoir outlet port should be mounted in the same plane. The pump should be

[1]The price is $17 plus $2 shipping. The ARRL and *QST* do not warrant this offer.

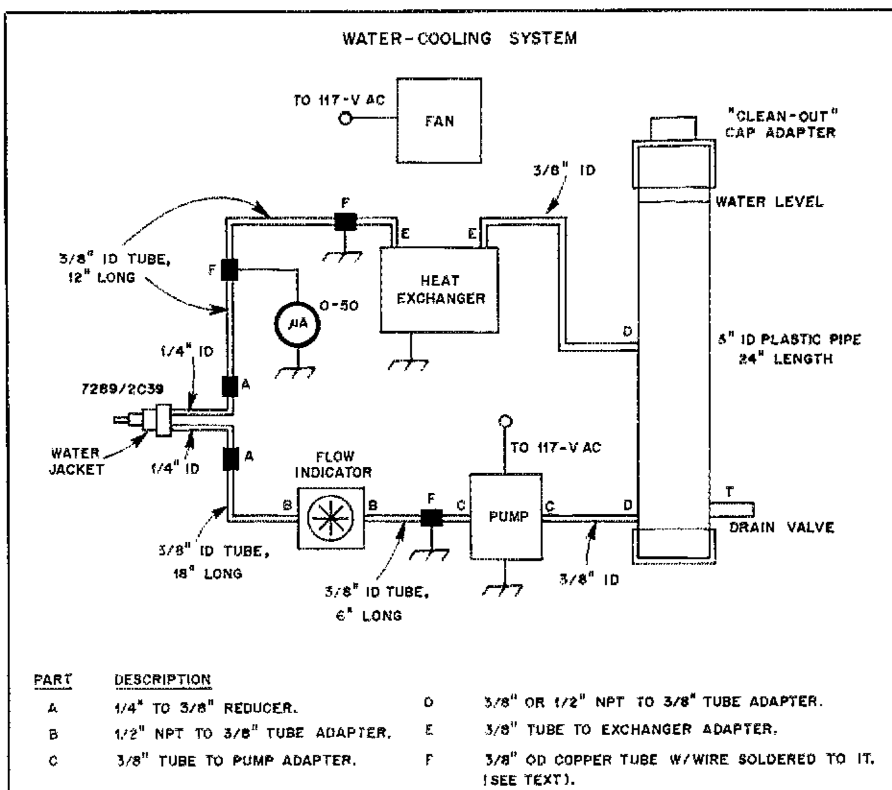

Fig. 5 — Details of the water-cooling system. Recommended pumps are: (1) Little Giant Pump Co. Model 1-42A or larger, available from most hardware stores; or (2) Calvert Engineering, Cal Pump Model 875S (160 gal/h), available from Calvert, 7051 Hayvenhurst Ave., Van Nuys, CA 91406, tel. 213-781-6029. The flow indicator (Model 15C; requires two ½-inch NPT adapters) is available from Proteus Industries, 240 Polaris Ave., Mountain View, CA 94043 tel. 415-964-4163.

Microwave Radiation Safety

Intense RF radiation concentrated on body tissues can produce heat damage; the extent and penetration will depend on the radio frequency in use and on exposure duration. You should be aware of the approximate intensity of RF radiation of the transmitting equipment and antennas you come in contact with.

RF intensity is commonly expressed in milliwatts per square centimeter (mW/cm²), which is the power flowing away from a source through a unit sampling or interception area at some specified distance. Although the United States as yet has no federal RF protection standard, a useful interim guide is the 1982 standard of the American National Standards Institute (ANSI '82). The most stringent level in this standard is 1 mW/cm² for frequencies between 30 and 300 MHz. Above 300 MHz, the protection level rises until it reaches 5 mW/cm² at 1500 MHz. Beyond 1500 MHz, the recommended level remains at 5 mW/cm². These levels represent the average power density allowed over any six-minute period and are for the sum of all polarizations from a given source.

At 1296 MHz, where one wavelength (λ) equals 23 cm, a thick resonant dipole feeding a calibrated power meter with matched coaxial cable (itself free of pickup) may be used to obtain an indication of power density. A reasonably lossless resonant dipole has an effective aperture of $\lambda^2/8$; at 23 cm this is 66 cm². The power meter reading in milliwatts, divided by 66, is the indicated power density. For this to be a reliable indication, the dipole must be positioned far enough from the RF source to be in its far field. For a small source, the distance should be at least λ/2, and here that would be about 12 cm (4.5 inches). The dipole should be oriented for alignment with the dominant polarization. Note that the power meter must be capable of readings well below 1 mW.

This arrangement would be useful for checking leaks along the coaxial route that the high power (here 250 W) takes to a load, be it dummy load or antenna. Cable connectors may not be tightly secured, or they may be faulty. For equipment operating in the SHF region, waveguide flanges may not be clamped properly.

Direct measurement of electric field strength near an antenna (with a calibrated instrument, preferably one with the indicating meter shielded and possibly positioned at the center of the sampling dipole) is another way to check for adequate protection. A field strength of 60 V per meter (V/m) corresponds to 1 mW/cm²; 134 V/m corresponds to 5 mW/cm². At a distance 60 cm (2 feet) from an isolated dipole fed with 26 watts, the field strength would be about 60 V/m. This is a far-field field strength for all frequencies where the half wavelength is less than 60 cm, or for frequencies above 250 MHz. For full 250 watts applied to the dipole, the 60 V/m level occurs at a distance of 1.8 meters (6 feet), and at this distance this holds for all frequencies above 80 MHz.

With SSB or CW keying, the fields during Amateur Radio operation are highly intermittent, and usually include considerable pauses or intervals for listening. These factors reduce the average power density over the six-minute averaging period.

Further information on RF safety and protection estimates can be found in Chapter 7 of *The Satellite Experimenter's Handbook*, published by the ARRL. The following rules of good practice for RF protection are recommended:

- Never operate an RF amplifier with equipment shielding removed.
- Never handle antennas with RF power applied.
- Never guess that RF levels are safe. Take the time to consult a reliable reference for an estimate, or measure levels carefully. Allow a "cushion" of about 6 dB (factor of four in power density). If possible, borrow an RF radiation monitor (after learning how to use it), or consult with a ham who is well informed on RF protection.
- Never look into an open end of a power waveguide; never point a powered directive antenna (a beam or a paraboloid, for example) toward people. Keep all VHF and UHF transmitting antennas as high as possible, distant from humans.
- Use good-quality, well-constructed coaxial cable and connectors to avoid RF leaks.
- Think RF and electrical safety first; test later!
- Watch *QST* for news on RF measurement techniques and progression, protection standards and proposed federal and state RF regulations. — *David Davidson, W1GKM*

oriented so that air bubbles will rise into the impeller output port and can be blown out once the pump starts running.

Flow Indicator and Heat Exchanger

Water cooling is best described as "super quiet." There is no noisy fan to reassure you that the tube is receiving adequate cooling. If water flow is reduced or cut off during amplifier operation, tube damage is virtually assured.

Flow interlocks and switches to shut down the amplifier if water flow is reduced are hard to find and expensive. Flow indicators, however, are inexpensive and reliable. A flow indicator has a spoked rotor that turns as water passes through the unit. If the wheel is turning, there is water flow; if not, you have a problem. Changes in flow rate can be observed by watching for speed changes in the rotor. A small lamp illuminates the flow indicator, making it easy to see rotation. The flow indicator should be mounted where it can be seen from the operating position and monitored during operation.

Heat exchangers, or radiators, remove the heat from water as it passes through. For this application, a small automobile transmission-oil cooler works great. Most auto- parts stores and speed shops have a good selection. Pick one that is similar in size and aspect ratio to a whisper fan (approximately 4 × 4 × 1 inches). Some come with mounting brackets. Look for a cooler with the input and output ports on the top so air bubbles will rise to the top and move on without becoming trapped. Trapped air degrades cooler performance.

If you use the amplifier for high-duty-cycle modes such as ATV or FM, or for long, slow-speed CW transmissions (EME, for example), you should use a small axial whisper fan to increase the effectiveness of the heat exchanger. A fan isn't necessary during normal operation, or even for sustained operation at moderate power levels, but I highly recommend one if you plan prolonged operation at maximum power. Locate the fan so the warm exhaust air won't heat up other equipment.

Hoses and Fittings

Most hardware stores carry a complete line of brass fittings and adapters that can be used for this project. Brass, however, will eventually corrode and pollute the water supply. Plastic fittings are cheaper and don't corrode, but they are harder to find. Recreational vehicle suppliers are my main source for these parts. They are used extensively in drinking water systems for mobile homes and travel trailers. Procure the fittings when you have the rest of the parts in hand, as there are many variables to consider.

You can use any relatively soft, thin-wall vinyl tubing for all water lines. The main runs are made from 3/8-inch-ID hose, while 1/4-inch-ID stock is used to connect to the 7289/2C39 water jacket. The 1/4-inch-ID tubing fits snugly over the 9/32-inch-OD inlet and outlet tubes on the water jacket, so no clamps are required. All other hose connections should be secured with stainless-steel clamps to prevent leaks. Any leaks mean air in the system and deterioration of cooling performance.

Safety

The tube anode, and hence the water jacket and water, are in direct contact with the high-voltage supply, so some safety precautions must be observed. Approximately 12 to 18 inches of tubing should run between the 7289/2C39 jacket and any other component in the cooling system. This will allow enough resistance in the water to provide adequate current limiting, should the water contact any components that are grounded.

It is best to ground the water supply at the pump. Do this by replacing a short section of the tubing that runs to the flow indicator with a piece of brass or copper tubing. Solder a wire to this metal tubing and connect the other end of the wire to your station ground. Use at least 24 inches of vinyl tubing between the anode cooling jacket and the ground point.

On the warm-water side of the 7289/2C39, run 12 inches of vinyl tubing to a small metal fitting or short section of metal tubing, and then another 12 inches of vinyl tubing to a grounded point (this can be at the heat exchanger). You can measure the water leakage current to ground by placing a microammeter between the metal fitting that connects the two vinyl hoses and ground. Leakage current should be less than 10 μA with clean water and an anode potential of 1 kV. As the water ages, the leakage current will rise; when this happens, replace the water.

Grocery stores carry distilled water for use in steam irons. It may be deionized and not truly distilled, but it works fine for about four to six months in this application. Filters can be purchased from scientific supply houses, but they're not really worth buying because deionized water is so cheap.

Do not use tap water under any circumstances! When you turn on the water system for the first time, run a gallon of water through it for half an hour to wash out fabrication impurities. Replace with clean water before using the system to cool the amplifier.

Water was chosen because it's inexpensive, nontoxic, nonflammable and easy to clean up if you have a leak. Better liquid coolants are available, but they are toxic. Don't use them!

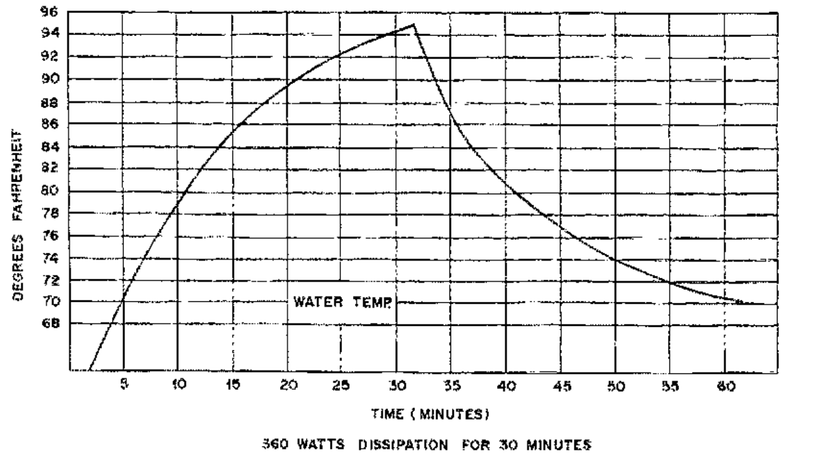

Fig. 6 — Performance graph of the water-cooling system.

Cooling Performance

I have used water-cooling systems for several years with no problems whatsoever. Fig. 6 is a graph of several transmit/receive cycles on a water-cooled, 500-W output, 23-cm power amplifier. For this test, I used two of the amplifiers described in this article coupled with a pair of hybrid combiners. This particular cooling system used 1 gallon of water. Experiments indicate that, during extended operation, the water temperature rises only 30° to 35°F above ambient room temperature. Typically, the tube anode and water average 10° to 15°F above ambient during casual operating.

Flow rates in this system are typically 1/3 gallon per minute per tube, which is more than adequate. At this rate, more than 300 W of dissipation from a single inefficient 7289/2C39 were required to boil the water in the water jacket. The water should not be allowed to boil because this will heat the rubber gasket.

Tubes

It is not really necessary to buy a new 7289/2C39. Used tubes can be found surplus for around $1 to $5 and, in many cases, will perform as well as a new tube. Most used tubes have been sitting around for several years, so it's a good idea to run them through the dishwasher to clean them up and then run the filaments for about 24 hours. This will restore operation in many cases.

If you buy a new tube, you should be aware that the 7289/2C39 is being run far in excess of its ratings in this amplifier. The manufacturer's warranty will not cover tubes run in this application.

Contrary to popular opinion, glass tubes will work. Physically, they are not as rugged as the ceramic version, but the glass-to-metal seal seems to provide better shelf life than the ceramic seal. The glass tubes make great driver tubes and will work fine for power levels up to 100-W output. Pulse tubes (7815, 7211) are not recommended because of their poor thermal stability at high power levels. Also, they generally are 30 to 40 MHz lower in resonant frequency in this amplifier compared to the 7289/2C39. Some 7289 tubes can be as much as 30 MHz lower in frequency. Minor length adjustment of the anode-tuning post may be required to accommodate amplifier and tube differences.

Tube Insertion

Extreme care must be exercised when inserting the 7289/2C39 tube. Never force the tube in place, as damage (bending) of the cathode finger stock may result. Observe the layout of the finger stock to get an idea of how the tube inserts. Carefully position the tube so it is straight as you gently push. It should slide in snugly without any solid resistance.

Testing

After you have completed all of the parts for the amplifier, it's time to test everything before hooking it all together. Test the water-cooling system by turning it on and watching for steady water flow as indicated on the flow meter. The tube and water jacket can be removed from the cavity amplifier for this test.

Check all of the power-supply voltages first without connecting them to the RF deck. Then, without the tube in place, hook the bias and filament supplies to the cavity and check the voltages again at the tube finger-stock connections. Connect the high-voltage supply to the RF deck and bring the voltage up slowly with a variable autotransformer. Monitor the high voltage on the anode-bypass-capacitor plate, and look and listen for any possible arcing between the anode-bypass-capacitor plate and ground. Use extreme care when measuring and testing the high-voltage supply. If everything looks okay with the power supplies, shut them off and disconnect them.

You can make a safe, low-power test of the cavity resonance without applying any voltage. With the tube in place, insert a 2-inch-long coupling loop on the end of a piece of coaxial cable between the spring fingers of the anode down into the cavity. Connect the amplifier output probe/connector to a device capable of detecting low-level RF at 23 cm (for example, a spectrum analyzer or microwattmeter). Feed a signal from an L-band signal generator into cable attached to the wire coupling loop that you inserted into the cavity. Set the signal generator for various frequencies in the 23-cm band and tune the amplifier anode tuner. There will be sharp peak in output at cavity resonance.

This testing method can be used to determine cavity tuning range, anode-bypass-capacitor effectiveness and resonance of various tube types for use in this amplifier. Any cavity amplifier can be tested completely without ever applying high voltage. The better your test equipment, the easier the amplifier is to test. If all dimensions were followed strictly, the amplifier will tune as designed.

Amplifier Hookup

Installation and operation of this amplifier is relatively straightforward, but as with any amplifier, several precautions must be followed. If these are adhered to, the amplifier will provide years of reliable service.

The amplifier is designed to be operated in a 50-ohm system and should never be turned on without a good 50-ohm load connected to the output connector. *Never* operate it into an antenna that has not been tuned to 50 ohms!

Drive power to the amplifier should *never* exceed 15 W. *Never* apply drive power in excess of 1 W unless all operating voltages are present and the tube is biased on. Otherwise, the tube grid-dissipation rating will be exceeded and you will probably ruin it.

•As in all TR-switched systems, some type of interlock or sequencing of transmit and receive functions should be incorporated. In most systems, the sequence for going into transmit is something like this: First, switch the antenna changeover relay from the receiver to the power amplifier. Next, bias the power amplifier on. Last, key the exciter and apply drive to the amplifier. To go to receive, unkey the exciter, remove operating bias from the amplifier and switch the antenna relay back to the receiver.

If the antenna relays are switched while the power amplifier is operating and putting out power, damage to the relay contacts and/or the amplifier is likely. If there is a momentary removal of the antenna while the power amplifier is biased on, oscillation may occur. This can damage the TR relay, the tube or even the receive preamplifier.

Tune-up and Operation

This is it — the big moment when you will see your project come to life! Connect an accurate UHF power meter and a 50-ohm antenna or load to the amplifier output connector. A Bird Model 43 wattmeter with a 100- or 250-W, 400-1000 MHz slug will give reasonable accuracy, depending on the purity of the drive signal. Apply filament power and tube cooling, and allow 3 to 5 minutes for the filaments to warm up. Turn on bias supply (the amplifier will draw maximum current if the anode voltage is applied without bias). Apply 300 to 400 V to the anode. There should be no current flowing in the tube as indicated on the cathode-current meter. Ground J1 on the bias supply to apply transmit bias and observe cathode current. As R1, the bias control, is turned clockwise, quiescent idling current should increase. Set for about 25 mA.

Apply 1 W of RF drive power. Turn the anode tuner while observing the RF output power meter and tune for maximum output. The output should go through a pronounced peak at cavity resonance. Adjust C2 and C3 on the input tuning network for maximum amplifier output. If possible, use a directional wattmeter between the driver and the amplifier input to check that best input SWR and maximum amplifier output occur at roughly the same setting.

Depending on the amount of drive power available, you may want to tune the amplifier for maximum power output or maximum gain. Fig. 7 shows what you can expect from different drive levels.

Once the amplifier is tuned for best input SWR and maximum output with 1 W of drive, anode voltage and drive power can be increased. Increase both in steps; be sure to keep the anode tuner peaked for maximum output power. When you get to the 100-W output level, very carefully readjust the input circuit for maximum output. The input capacitor closest to the cathode is critical and should need to be rotated less than 90 degrees maximum. Maximum output power will be roughly coincident with best input SWR.

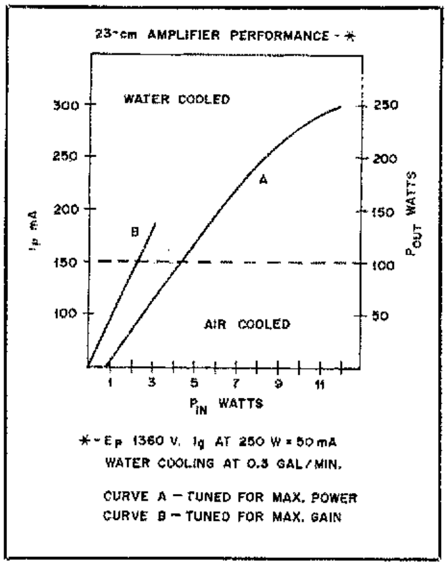

Fig. 7 — Performance of the cavity amplifier under different drive and plate-current conditions.

Increase the drive power and keep the anode tuner peaked for maximum output. Increase the drive until you reach the desired output level, but *do not exceed 400-mA I_K!* At 1400-V dc and 350-mA I_K, output power with a good tube should be about 230 to 250 W. At lower anode voltages, I_K will be higher for the same output power. Higher anode voltages result in higher gain, lower drive levels, lower grid current and lower plate current for a given output power.

The anode tuner's tuning rate is approximately 5 MHz per turn. Clockwise rotation of the tuner lowers the resonant frequency of the cavity. This control will require readjustment as you make large frequency excursions within the 23-cm band (for example, if you go from 1296 weak-signal work to the 1269-MHz satellite segment). You should also check the input SWR if you move more than 15 MHz. Generally, amplifier tuning does not change much after initial setup. You should be able to turn it on and use it without retuning as it heats up. Slight adjustments may be necessary, however, depending on cooling, inherent thermal differences from tube to tube and duty cycle of the operating mode. Always keep the anode tuner peaked for maximum output, and check it from time to time, especially while you are first learning how the amplifier operates.

The output loading control is the output connector and probe assembly. Loading is changed by minor rotational adjustment of the N connector. First loosen the jam-nut (or setscrew) slightly. While observing output power and keeping the anode tuner peaked, rotate the loading control ±30 degrees maximum for greatest output power. This should be done only once and should not need repeating unless another tube is installed. Even then it may not be required.

Conclusion

This cavity amplifier for the 23-cm band is capable of safe, reliable operation at output powers in excess of 200 W. More than 50 of these amplifiers are in operation, and you can build one, too. I would like to thank Mike Stahl, K6MYC, Bill Troetschel, K6UQH, William Jungwirth, AA6S, Lem Moeschler, W6KGS and Joseph Cadwallader, K6ZMW, for their help and encouragement during the development of this project.

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Strays

QEX: THE ARRL EXPERIMENTERS' EXCHANGE

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• David Arbogast, NV4G, revealed how to eliminate duplicate contest contacts with his "TI 99/4A Contest Dupe Program"

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• A list of Product Review items, 1976 to 1984.

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A 144-MHz Amplifier Using the 3CX1200Z7

This 2-meter, 1-kW amplifier uses the Eimac 3CX1200Z7 triode. The original article by Russ Miller, N7ART, appeared in December 1994 *QST*. The tube requires a warm up of about 10 seconds after applying filament voltage—no more waiting for three agonizingly long minutes until an amplifier can go on-line!

The 3CX1200Z7 is different from the earlier 3CX1200A7 by virtue of its external grid ring, redesigned anode assembly and a 6.3-V ac filament. One advantage to the 3CX1200Z7 is the wide range of plate voltages that can be used, from 2000 to 5500 V. This amplifier looks much like the easily duplicated W6PO design. The RF deck is a compact unit, designed for table-top use (See **Fig 18.39** and schematic in **Fig 18.40**.).

Table 18.8 gives some data on the 3CX1200Z7 and **Table 18.9** lists CW operating performance for this amplifier.

Fig 18.39—This table-top 2-meter power amplifier uses a quick-warm-up tube, a real plus when the band suddenly opens for DX and you want to join in.

Input Circuit

The author didn't use a tube socket. Instead, he bolted the tube directly to the top plate of the subchassis, using the four holes (drilled to clear a #6 screw) in the grid flange. Connections to the heater pins are via drilled and slotted brass rods. The input circuit is contained within a 3$^1/_2$ × 6 × 7$^1/_4$-inch (HWD) subchassis (Fig 18.40).

Control Circuit

The control circuit (**Fig 18.42**) is a necessity. It provides grid overcurrent protection, keying control and filament surge control. To protect the tube filament from stressful surge current, a timer circuit places a resistor in series with the primary of the filament transformer. After four seconds, the timer shorts the resistor, allowing full filament voltage to be applied. C2 and R4 establish the time delay.

Another timer inhibits keying for a total of 10 seconds, to give the internal tube temperatures a chance to stabilize. C1 and R3 determine the time constant of this timer. After 10 seconds, the amplifier can be keyed by grounding the keying line. When the amplifier is not keyed, it draws no plate current. When keyed, idle current is approximately 150 mA, and the amplifier only requires RF drive to produce output. A safety factor is built in: The keying circuit requires +12 V from the high-voltage supply. This feature ensures that high voltage is present before the amplifier is driven.

The grid overcurrent circuit should be set to trip if grid current reaches 200 mA. When it trips, the relay latches and the NORMAL LED extinguishes. Restoration requires the operator to press the RESET switch.

Plate Circuit

Fig 18.43 shows an interior view of the plate compartment. A 4 × 2$^1/_4$-inch tuning capacitor plate and a 2 × 2-inch output coupling plate are centered on the anode collet. See **Fig 18.44**. Sufficient clearance in the collet hole for the 3CX1200Z7 anode must be left for the fingerstock. The hole diameter will be approximately 3$^5/_8$ inches. **Fig 18.45** is a drawing of the plate line, **Fig 18.46** is a drawing of the plate tuning capacitor assembly, and **Fig 18.47** shows the output coupling assembly.

Cooling

The amplifier requires an air exhaust through the top cover, as the plate compartment is pressurized. Fashion a chimney from a 3$^1/_2$-inch waste-water coupling (black PVC) and a piece of $^1/_{32}$-inch-thick Teflon sheet. The PVC should extend down from the underside of the amplifier cover plate by 1$^1/_8$ inches, with the Teflon sheet extending down $^3/_4$ inch from the bottom of the PVC.

The base of the 3CX1200Z7 is cooled using bleed air from the plate compartment. This is directed at the tube base, through a $^7/_8$-inch tube set into the subchassis wall at a 45° angle. The recommended blower will supply more than enough air for any temperature zone. A smaller blower is not recommended, as it is doubtful that the base area will be cooled adequately. The 3CX1200Z7 filament draws 25 A at 6.3 V! It alone generates a great deal of heat around the tube base seals and pins, so good air flow is critical.

Construction

The amplifier is built into a 12 × 12 × 10-inch enclosure. A 12 × 10-inch partition is installed 7$^1/_4$ inches from the rear panel. The area between the partition and the front panel contains the filament transformer, control board, meters, switches, Zener diode and miscellaneous small parts. Wiring between the front-panel area and the rear panel is through a $^1/_2$-inch brass tube, located near the shorted end of the right-hand plate line.

High voltage is routed from an MHV jack on the rear panel, through a piece of solid-dielectric RG-59 (not foam dielectric!), just under the shorted end of the left-hand plate line. The cable then passes through the partition to a high-voltage standoff insulator made from nylon. This insulator is fastened to the partition near the high-voltage feedthrough capacitor. A 10-Ω, 25-W resistor is connected between the insulator and the feedthrough capacitor.

The plate lines are connected to the dc-blocking capacitors on the plate collet with 1$^3/_4$ × 2-inch phosphor-bronze strips. The bottom of the plate lines are attached to the sides of the subchassis, with the edge of the L-shaped mounting bracket flush with the bottom of the subchassis.

When preparing the subchassis top plate for the 3CX1200Z7, cut a 2$^{11}/_{16}$-inch hole in the center of the plate. This hole size allows clearance between the tube envelope and the top plate, without putting stress on the envelope in the vicinity of the grid flange seal.

Exercise care in placing the movable tuning plate and the movable output coupling disc, to ensure they cannot touch their fixed counterparts on the plate collet.

Operation

When the amplifier is first turned on, it cannot be keyed until:

- 10 seconds has elapsed.
- High voltage is available, as confirmed by presence of +12 V to the keying circuit.

Connect the amplifier to a dummy load through an accurate power meter capable of indicating 1500 W full scale. Key the amplifier and check the idling plate current. With 3200-V plate voltage, it should be in the vicinity of 150 mA. Now, apply

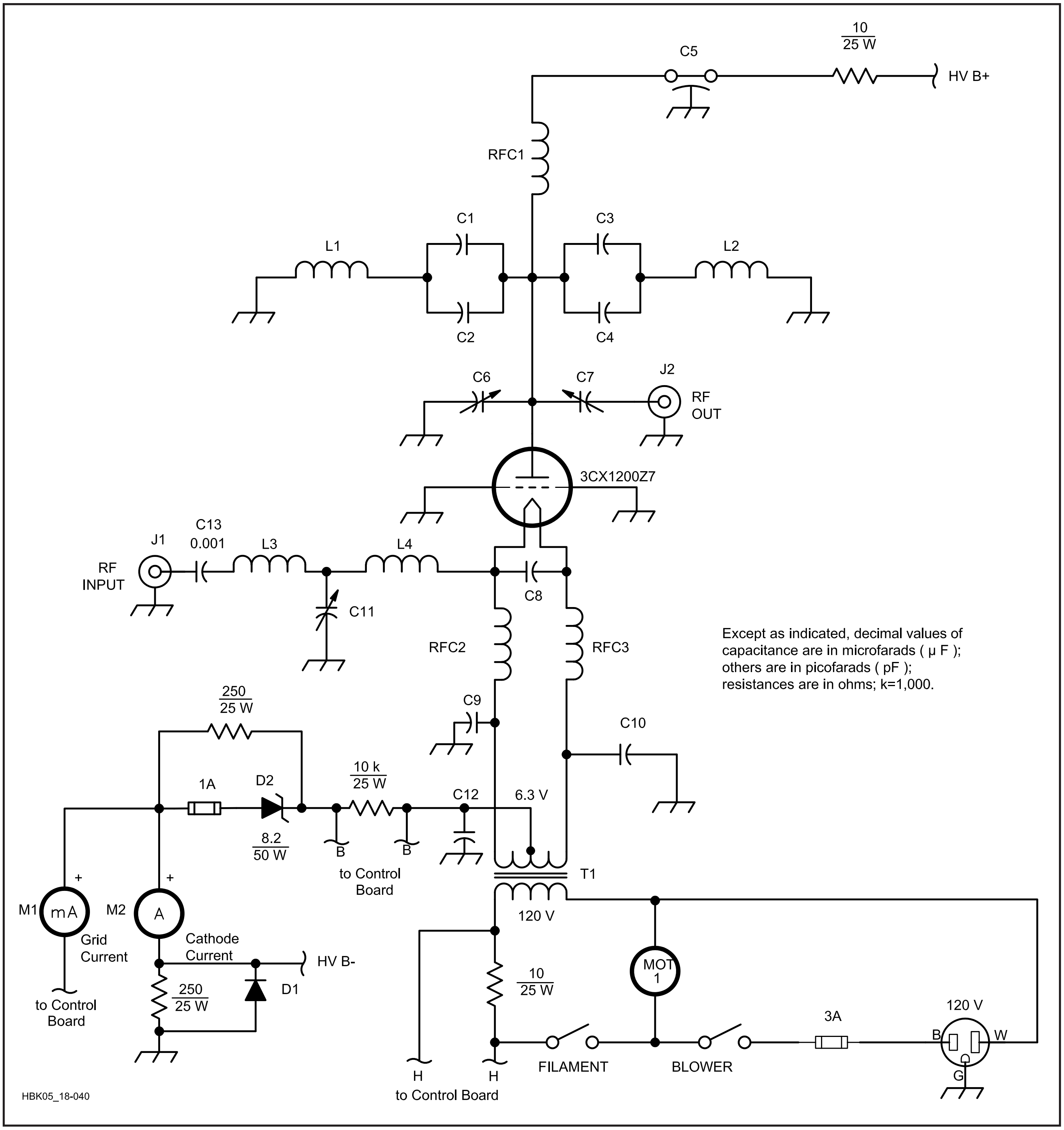


Fig 18.40—Schematic diagram of the 2-meter amplifier RF deck. For supplier addresses, use *TISFind* (www.arrl.org/tis) or other search engines.

C1-C4—100 pF, 5 kV, Centralab 850.
C5—1000 pF, 5 kV.
C6—Anode-tuning capacitor; see text and Fig 18.46 for details.
C7—Output-loading capacitor; see text and Fig 18.47 for details.
C8-C10, C13—1000-pF silver mica, 500 V.
C11—30-pF air variable.
C12—0.01 µF, 1 kV.
D1—1000 PIV, 3-A diode, 1N5408 or equiv.
D2—8.2-V, 50-W Zener diode, ECG 5249A.
J1—Chassis-mount BNC connector.
J2—Type-N connector fitted to output coupling assembly (see Fig 18.47).
L1, L2—Plate lines; see text and Fig 18.45 for details.
L3—5 t #14 enameled wire, $^1/_2$-inch diameter, close wound.
L4—3 t #14, $^5/_8$-inch diameter, $^1/_4$-inch spacing.
RFC1—7 t #14, $^5/_8$-inch diameter, 1$^3/_8$ inch long.
RFC2, RFC3—10 t #12, $^5/_8$-inch diameter, 2 inches long.
T1—Filament transformer. Primary: 120 V; secondary: 6.3 V, 25 A, center tapped. Available from Heritage Transformer Co.; part number AV-539.
M1—Grid milliammeter, 200 mA dc full scale.
M2—Cathode ammeter, 2 A dc full scale.
MOT1—140 free-air cfm, 120-V ac blower, Dayton 4C442 or equivalent.
Sources for some of the hard to get parts include Fair Radio Sales and Surplus Sales of Nebraska.

Table 18.8

3CX1200Z7 Specifications

Maximum Ratings

Plate voltage: 5500 V
Plate current: 800 mA
Plate dissipation: 1200 W
Grid dissipation: 50 W

Table 18.9

CW Operating Data

Plate voltage: 3200 V
Plate current (operating): 750 mA
Plate current (idling): 150 mA
Grid current: 165 mA
DC Power input: 2400 W
RF Power output: 1200 W
Plate dissipation: 1200 W
Efficiency: 50%
Drive power: 85 W
Input reflected power: 1 W

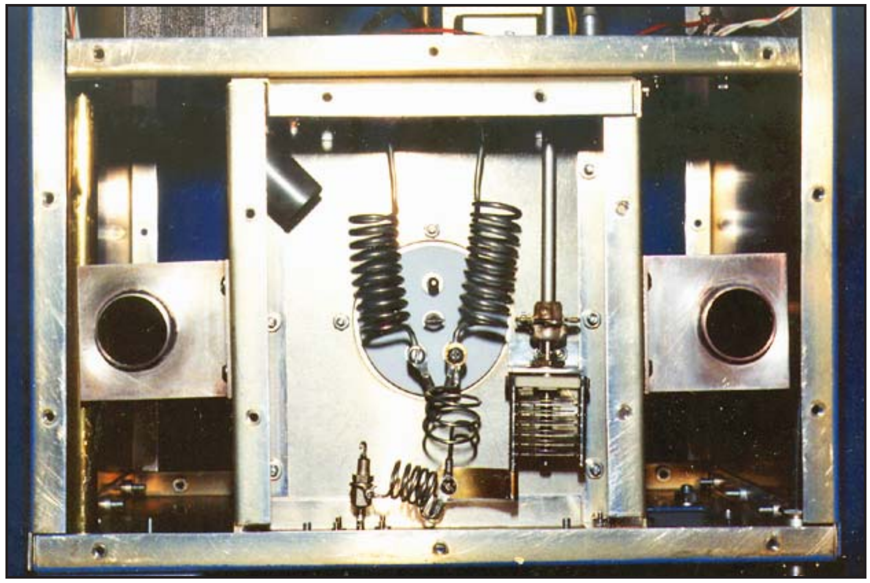
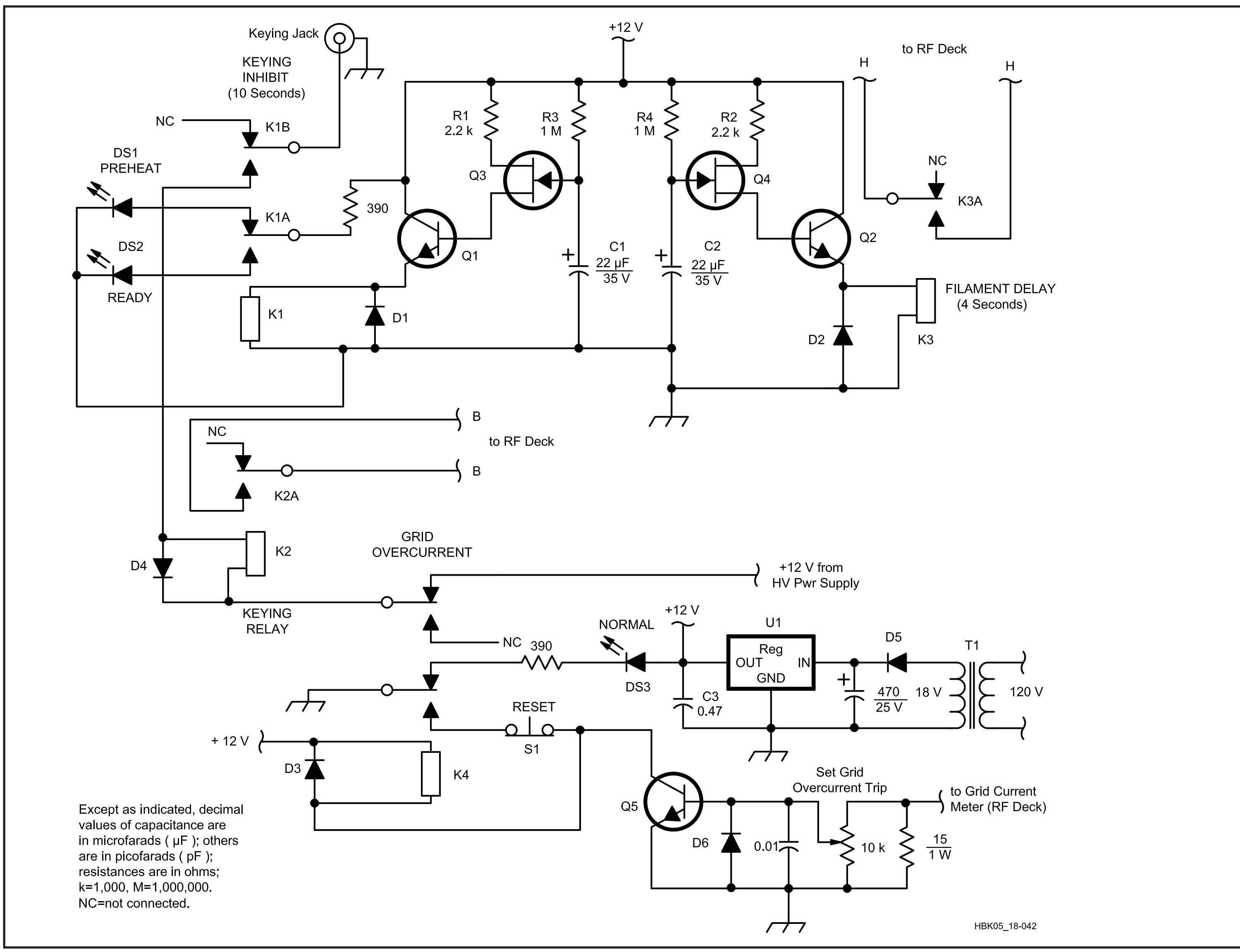


Fig 18.41—This view of the cathode-circuit compartment shows the input tuned circuit and filament chokes.



a small amount of drive and adjust the input tuning for maximum grid current. Adjust the output tuning until you see an indication of RF output. Increase drive and adjust the output coupling and tuning for the desired output. Do not overcouple the output; once desired output is reached, do not increase loading. Insert the hold-down screw to secure the output coupling capacitor from moving. One setting is adequate for tuning across the 2-meter band if the SWR on the trans-mission line is reasonably low.

When you shut down the amplifier, leave the blower running for at least three minutes after you turn off the filament voltage. The 3CX1200Z7 is an excellent tube. The author tried it with excessive drive, plate-current saturation, excessive plate dissipation—all the abuse it's likely to encounter in amateur applications. There were no

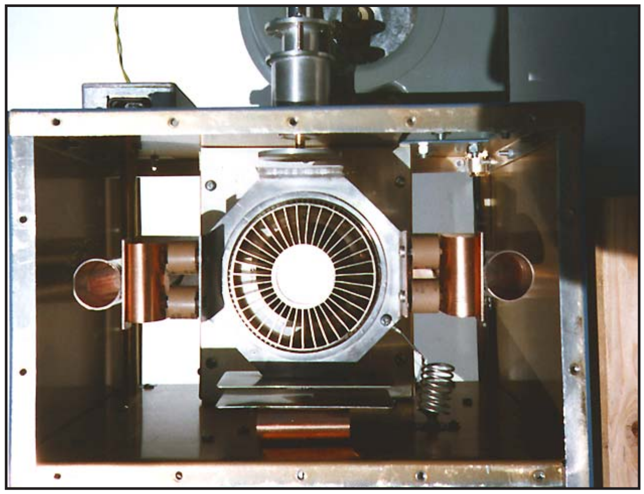


Fig 18.43—This top view of the plate compartment shows the plate-line arrangement, C1-C4 and the output coupling assembly.

Fig 18.42—(Schematic diagram of the amplifier-control circuits.
C3—0.47-µF, 25-V tantalum capacitor.
D1-D5—1N4001 or equiv.
D6—1N4007 or equiv.
DS1—Yellow LED.
DS2—Green LED.
DS3—Red LED.
K1—Keying-inhibit relay, DPDT, 12-V dc coil, 1-A contact rating (RadioShack 275-249 or equiv).
K2—Amplifier keying relay, SPDT, 12-V dc coil, 2-A contact rating (RadioShack 275-248 or equiv).
K3—Filament delay relay, SPST, 12-V dc coil, 2-A contact rating (RadioShack 275-248 or equiv).
K4—Grid-overcurrent relay, DPDT, 12-V dc coil, 1-A contact rating (RadioShack 275-249 or equiv).
Q1, Q2, Q5—2N2222A or equiv.
Q3—MPF102 or equiv.
Q4—2N3819 or equiv.
S1—Normally closed, momentary pushbutton switch (RadioShack 275-1549 or equiv).
T1—Power transformer, 120-V primary, 18-V, 1-A secondary.
U1— +12 V regulator, 7812 or equiv.

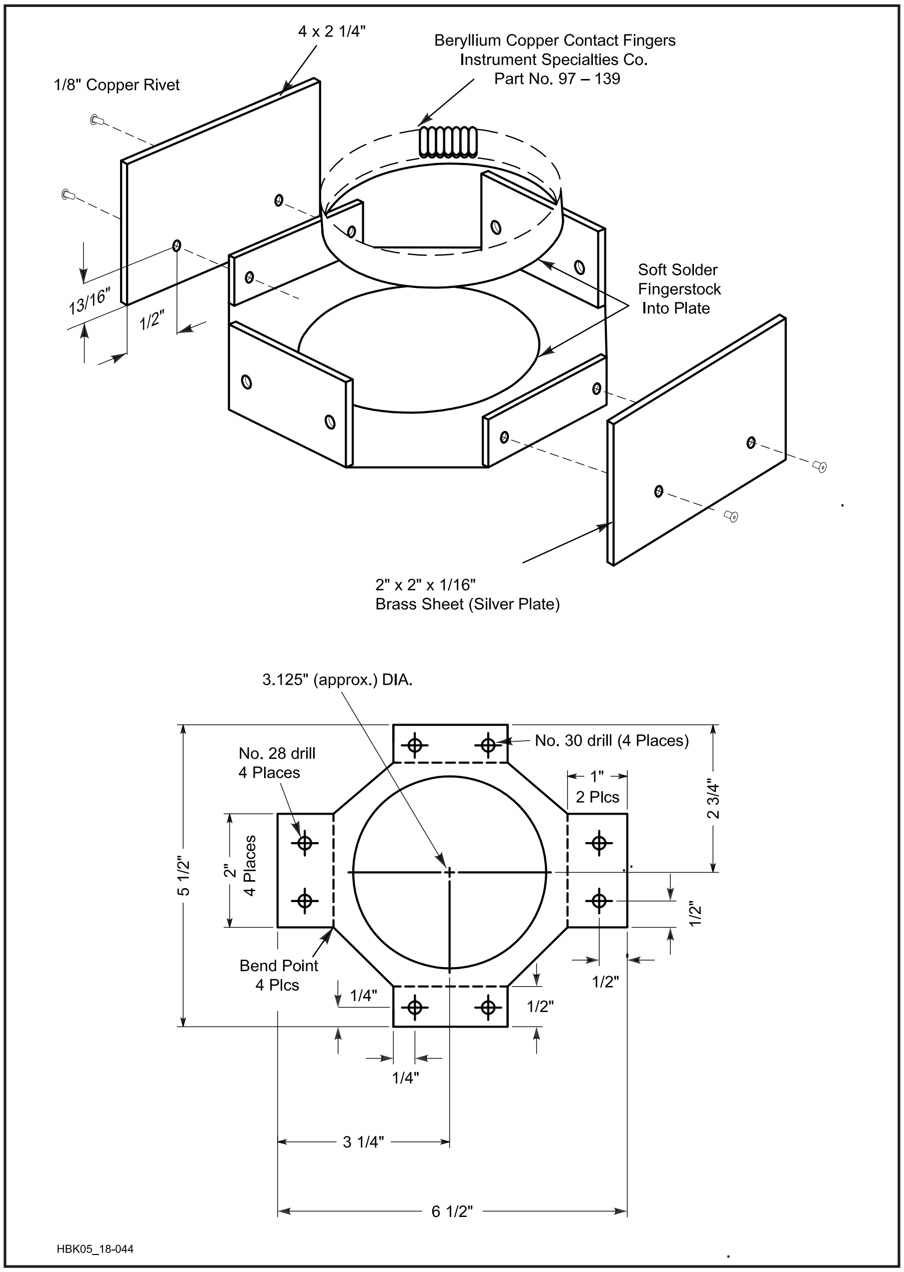


Fig 18.44—Anode collet details.

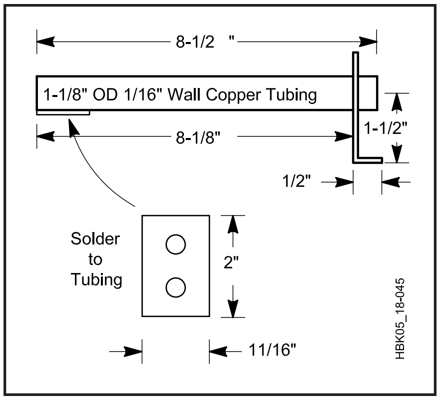


Fig 18.45—Plate line details.

Table 18.10
Power Supply Specifications

High voltage: 3200 V
Continuous current: 1.2 A
Intermittent current: 2 A
Step/Start delay: 2 secs

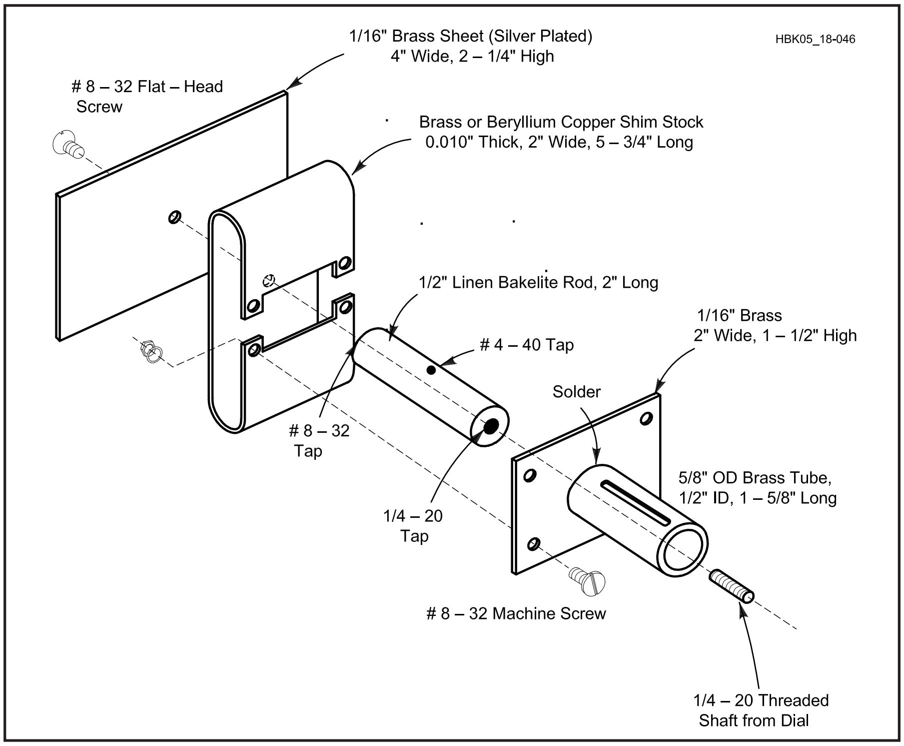


Fig 18.46—Plate tuning capacitor details.

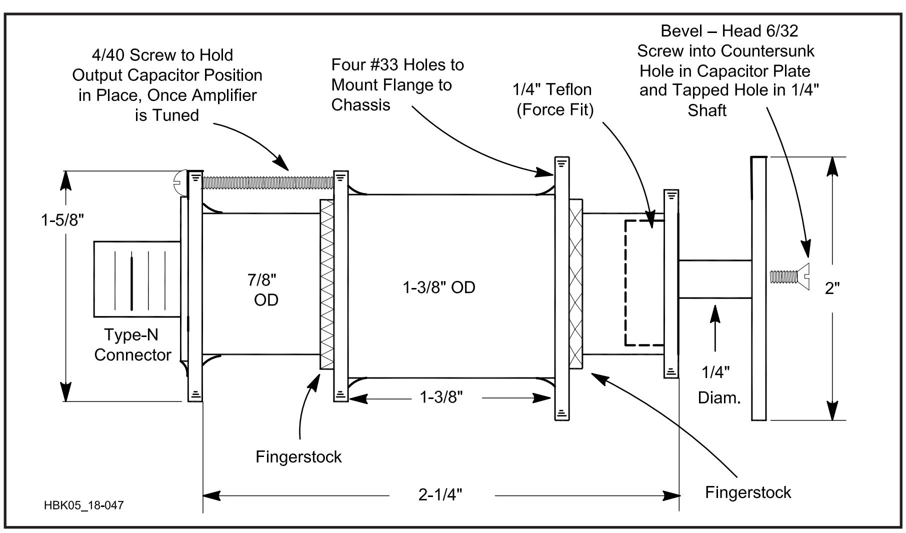


Fig 18.47—Details of the output coupling assembly.

problems, but that doesn't mean you should repeat these torture tests!

A Companion Power Supply

A well-designed and constructed high-voltage power supply is necessary to ensure linearity in SSB operation. Specifications of the power supply for this amplifier are given in **Table 18.10**. A schematic and parts list for a rugged power supply—usable with this project—are in the **Power Supplies** chapter. Although bi-level, it is otherwise similar to the author's design described in the December 1994 issue of *QST*.

Conclusion

This amplifier is a reliable and cost-effective way to generate a big 2-meter signal—almost as quickly as a solid-state amplifier. To ensure that the output of the amplifier meets current spectral purity requirements, a high-power output filter, as shown in **Fig 18.48**, should be used. The author reports that he can run full output while his wife watches TV in a nearby room.

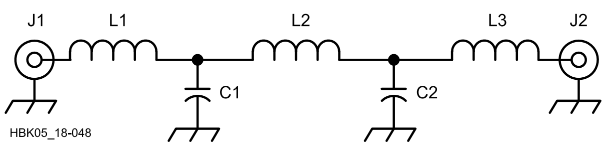


Fig 18.48—Schematic diagram of output harmonic filter.
C1, C2—27-pF Centralab 850 series ceramic transmitting capacitor.
J1, J2—Female chassis-mount N connector (UG-58 or equiv).
L1, L3—2 t #14 wire, 0.3125 inch ID, 0.375 inch long.
L2—3 t #14 wire, 0.3125 inch ID, 0.4375 inch long.

high-performance grounded-grid 220-MHz kilowatt linear

The Eimac 8877 is a high-mu ceramic-metal triode rated for use up to 250-MHz and several successful amplifier designs using this tube have been constructed for hf through vhf.[1,2,3] The 220-MHz amplifier described here has proven to operate very well during the last year, including several successful Earth-Moon-Earth (EME) contacts.

This 220-MHz 8877 linear amplifier is designed for the serious vhf DXer who demands reliable service combined with good linearity and efficiency. The amplifier requires no neutralization, is completely stable and free of parasitics, and is very easy to operate.

The amplifier is designed for continuous duty operation at the 1000-watt dc input level, and can develop 2000-watts PEP input for SSB operation with ample reserve. For operation at 2000-watts PEP the plate supply should be between 2500 and 3000 volts; under these conditions the amplifier will deliver 1230 watts output. With the higher plate-voltage supply, up to 14-dB gain can be obtained with an amplifier efficiency of 61 per cent; see **table 1.**

The 8877 triode has very good current division; that is, the grid current is quite low in comparison to the plate current. The grid current is typically about 15 per cent of the value of the plate current. the 8877 also has good gain and intermodulation distortion characteristics. The plate dissipation rating is 1500-watts. The cathode is indirectly heated; filament requirements are 5.0-volts at 10.5 amperes. The tube base mates with a standard septar socket.

the circuit

In the amplifier circuit shown in **fig. 1** the 8877 grid is operated at dc ground. The grid ring at the base of the tube provides a low-inductance path between the grid element and the chassis. The plate and grid currents are measured in the cathode return lead. A 12-volt, 50-watt zener diode in series with the negative return sets the desired value of idling current. Two additional diodes are shunted across the meter circuit to protect the instruments in case plate voltage arcs over to ground, or if there is an internal tube arc.

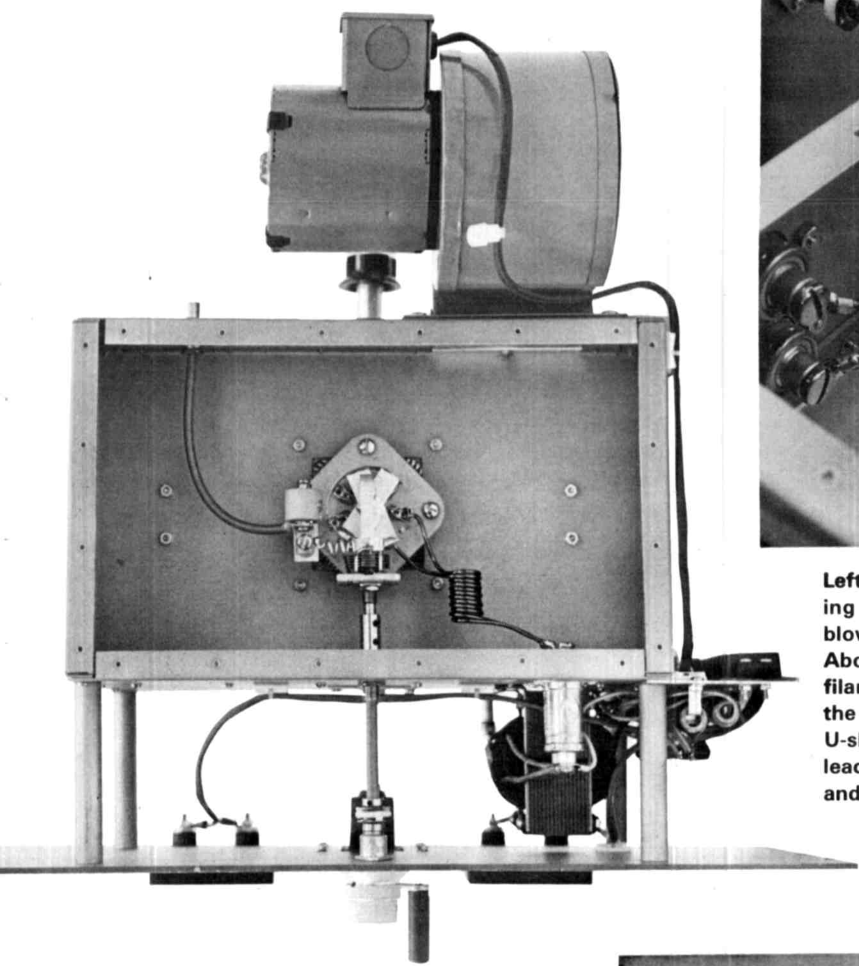
Standby plate current of the 8877 is reduced to a very low value by a 10,000-ohm cathode resistor. This resistor is shorted out in the transmit mode by the station control circuit. The resistor must be in the cathode circuit when receiving to eliminate the noise generated in the station receiver if electron flow is permitted within the 8877 tube.

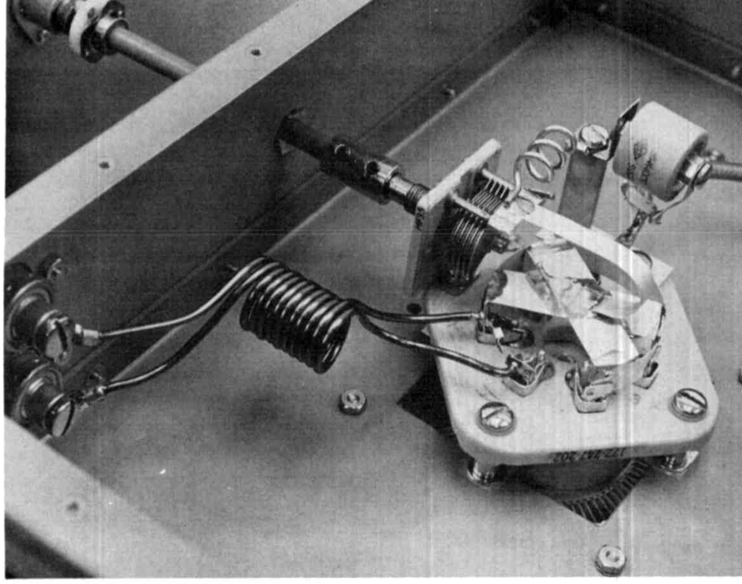
A 200-ohm safety resistor insures that the negative side of the power supply does not go below ground potential by an amount equal to the plate voltage if the positive side is accidentally grounded. A second safety resistor across the 1N3311 zener diode prevents the cathode potential from rising if the zener should accidentally burn open.

input circuit

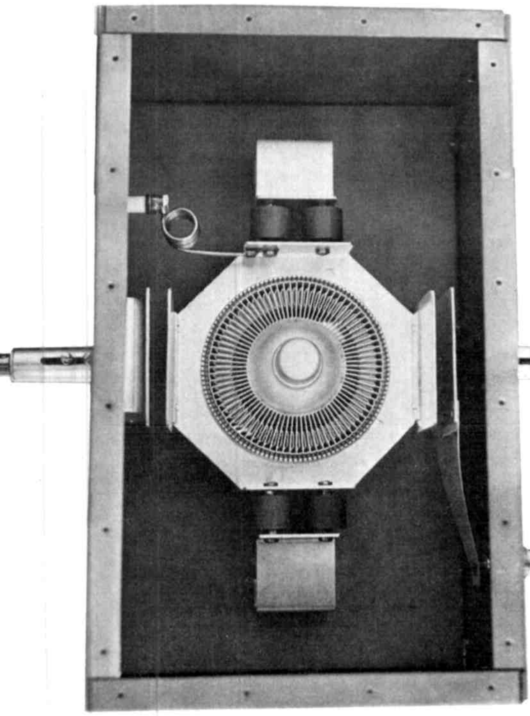
The cathode matching circuit is a T-network which transforms the input impedance of the tube (about 54 ohms in parallel with 40 pF) to 50 ohms at the coaxial input connector; the network consists of two series inductors and a shunt variable capacitor. The inductors are fixed and have a very low value of inductance; in fact, the rf return path through the chassis has about the same inductance value. To design the input circuit, many values of circuit *Q* were tried in the calculations. When the design equations yielded physically realizeable inductance values, then several combinations were tried in the actual amplifier. Since the stray inductances in the chassis and connecting leads in the socket were not included in the calculations, the final inductors were smaller in value than the calculated size. The actual inductors which resonated and provided a reasonable input match are specified in fig. 1 and are shown in some of the photographs. For those who build this amplifier I would expect that some minor variations in these coils might be required to attain an adequate input match.

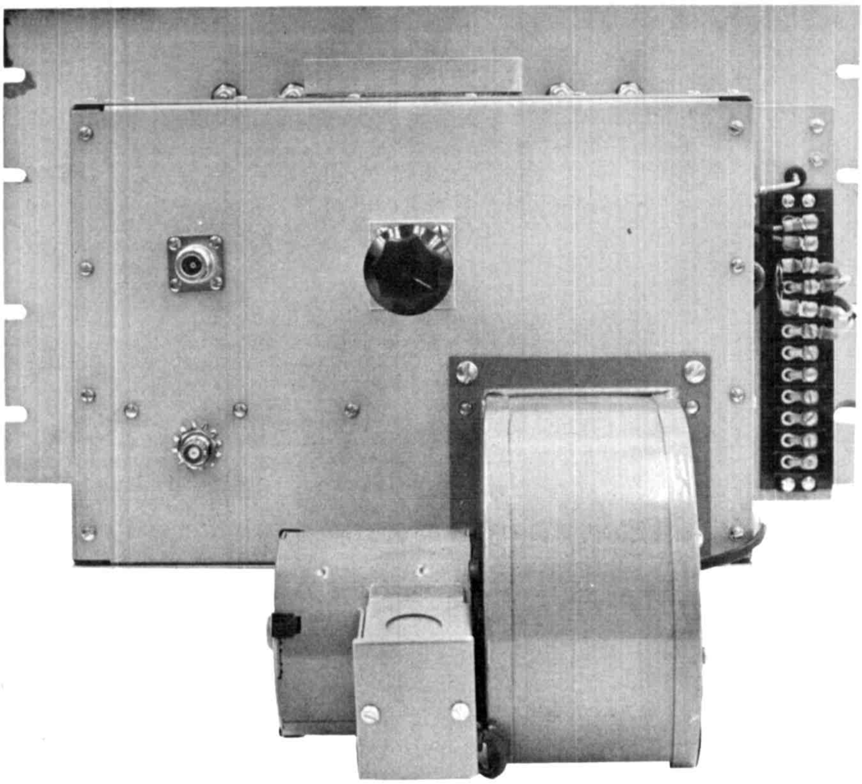
By Robert I. Sutherland, W6PO, EIMAC Division of Varian, 301 Industrial Way, San Carlos, California 94070





Left, underside view of the 220-MHz power amplifier showing the blower location as well as the input circuit. The blower is a Dayton 4C446.
Above, close-up view of the input circuit shows the bifilar filament choke L3 and L4 and the matching network. C2 is the 35-pF air variable mounted on the 8877 socket. L2 is the U-shaped strap connecting the capacitor to the cathode leads. L1 is the coil going between the variable capacitor and input line blocking capacitor C1.





Left, top view of the amplifier plate compartment. The 8877 tube is in the center with L5 and L6 to the left and right. The plate tuning capacitor C5 is at the bottom and the loading capacitor C6 is at the top.
Right, back view of the amplifier. The type-N connector is the rf power output; the BNC fitting is the connection for drive power. The knob is the loading adjustment. The terminal strip to the right is for the input voltage and control circuit connections. A Millen high-voltage connector is used for the plate voltage.

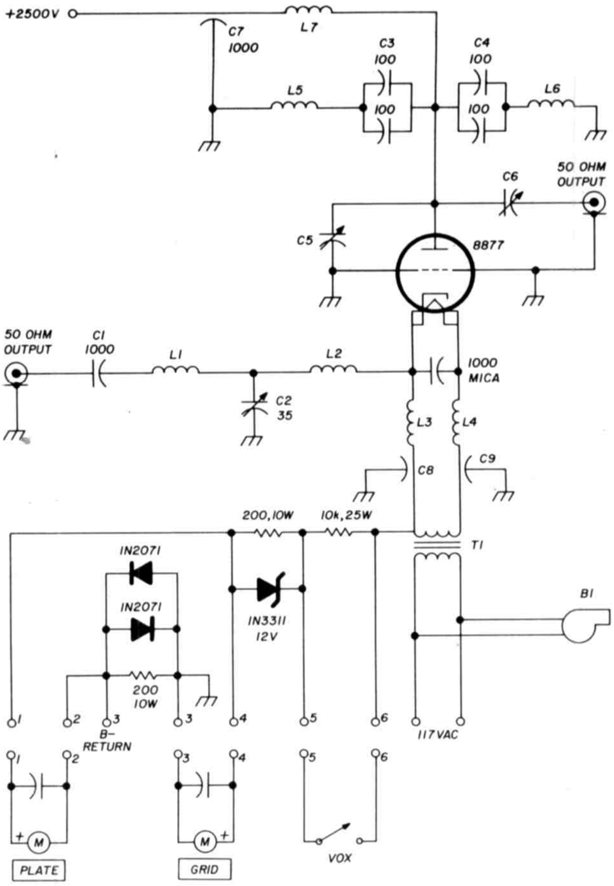


fig. 1. Schematic of the grounded-grid 220-MHz triode amplifier. Operating bias for the 8877 is supplied by a 12-volt zener diode in the cathode lead.

table 1. Performance of the 220-MHz grounded-grid 8877 rf power amplifier.

Plate voltage	3000 V	2500 V	2500 V
Plate current (single tone)	667 mA	800 mA	400 mA
Plate current (idling)	54 mA	44 mA	44 mA
Grid voltage	– 12 V	– 12 V	– 12 V
Grid current (single tone)	48 mA	50 mA	29 mA
Power input	2000 W	2000 W	1000 W
Power output	1230 W	1225 W	621 W
Efficiency (apparent)	61%	61%	62%
Drive power	48 W	69 W	20 W
Power gain	14 dB	12.4 dB	15 dB

C1	1000 pF ceramic transmitting type (Centralab 858S-1000)
C2	35 pF air variable (Hammarlund HF35 or Millen 22035)
C3,C4	Each consists of two parallel connected 100 pF, 5000 volt ceramic transmitting capacitors (Centralab 850S-100)
C5	Plate tuning capacitor (see **fig. 2**)
C6	Output loading capacitor (see **fig. 7**)
C7	1000 pF, 4000 volt feedthrough (Erie 2498)
C8,C9	0.1 uF, 600 volt feedthrough capacitor (Sprague 80P3)
L1	3 turns no. 14 (1.6 mm) wire, 1/4 inch (6.5 mm) inside diameter, 5/8 inch (16 mm) long
L2	Copper strap 1/4 inch (6.5 mm) wide, 2-1/2 inches (64 mm) long, bent into a U 5/8 inch (16 mm) wide
L3,L4	7 bifilar turns no. 12 (2 mm) enamelled wire, bifilar wound on 1/2 inch (12 mm) inside diameter
L5,L6	Plate resonators (see **fig. 5**)
L7	6 turns no. 14 (1.6 mm) wire, 1/2 inch (12 mm) diameter, 1 inch (25 mm) long
T1	Filament transforrmer rated at 5 volts, 10 amps (Stacor P-6433)

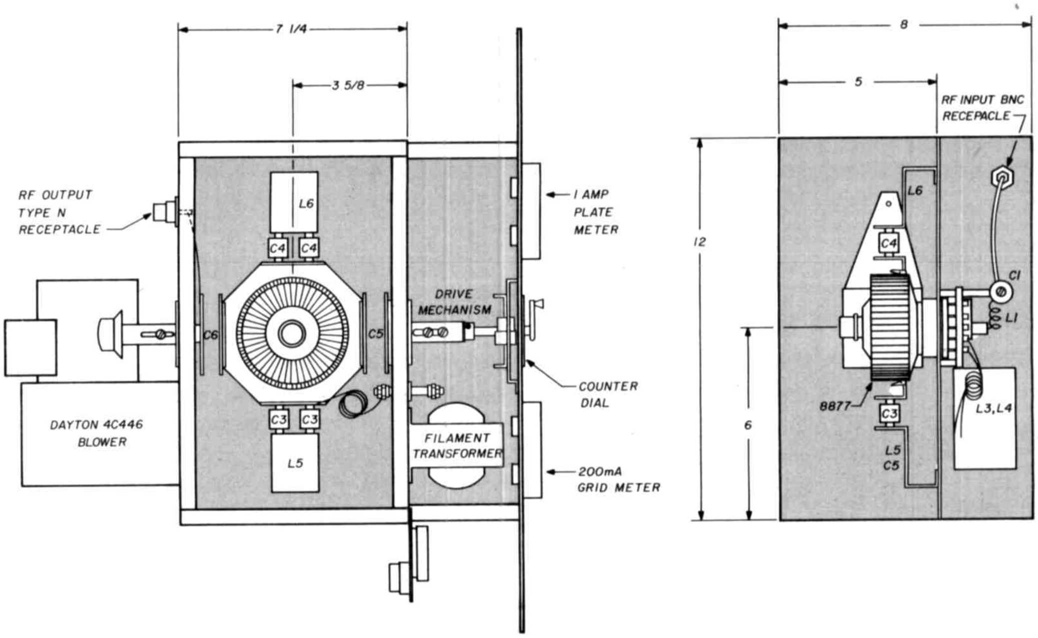


fig. 2. Structural details of the amplifier showing relative size and position of the various components. Assembly is made of aluminum panels.

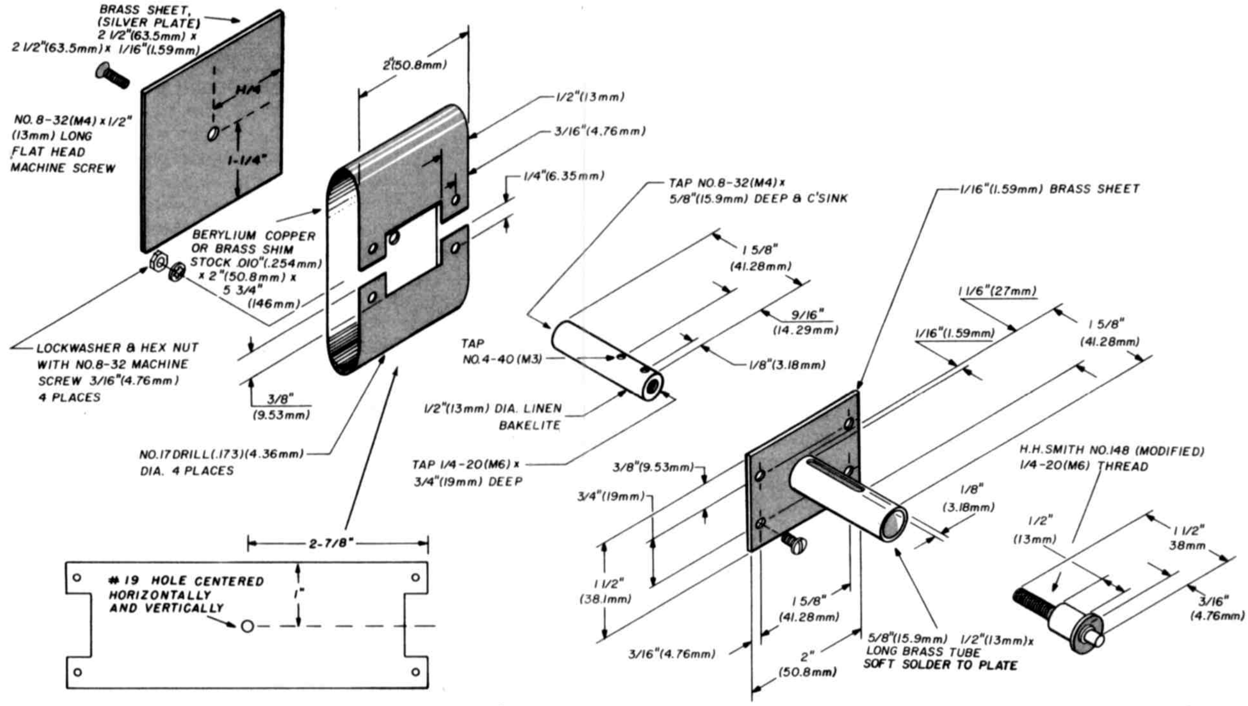


fig. 3. Variable plate portion of plate-tuning capacitor C5. Since there are no moving or sliding contacts which carry heavy rf current, this arrangement permits the capacitor to be adjusted under full power without erratic tuning.

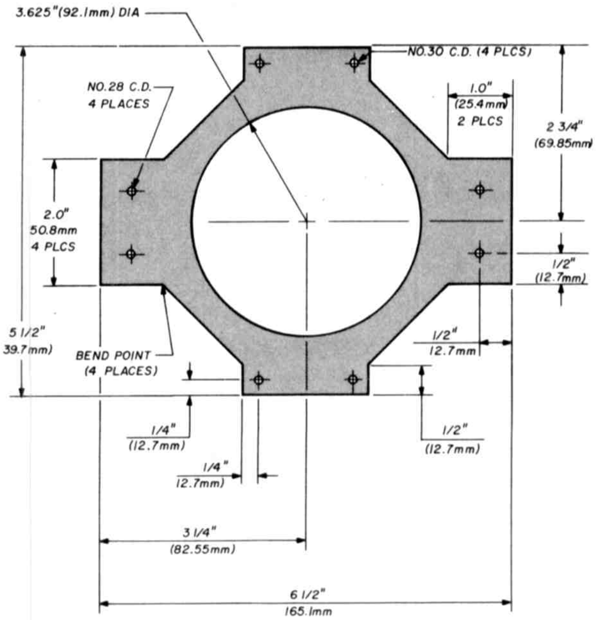
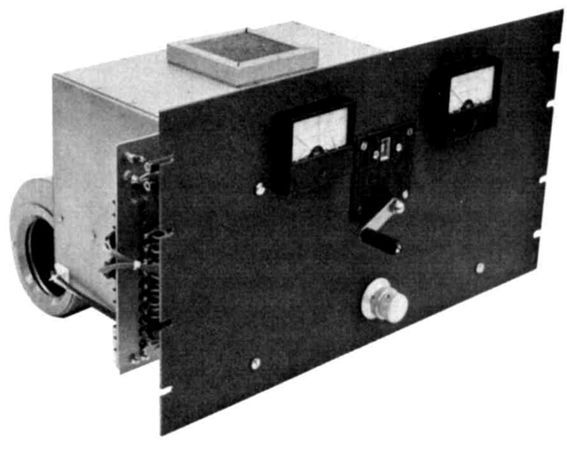


fig. 4. Anode collet and capacitor plate support pattern.

The underchassis layout of components is shown in the photographs. In the close-up view the bifilar wound coil in the foreground is the filament choke. The variable capacitor is C2, and L2 is the U-shaped strap connecting C2 with the cathode terminal. All the cathode leads and one filament lead are connected together with low inductance copper straps. Note that L2 is connected to the center point of all the cathode leads in an effort to equally balance rf drive to all sides of the cathode. At the frequency of 220-MHz, lead length and residual inductance are very important.

The inductor L1 connects capacitor C2 with the input blocking capacitor C1 at the top of an insulating piller. A section of RG-142B/U teflon-insulated coax connects the other side of C1 to the BNC coax input connector. It is difficult to see in the picture, but there is a 1000-pF chip ceramic capacitor connected from one heater pin to the other on the socket.

The socket for the 8877 is the Eimac SK-2210, the version with the grounded grid clips. The filament transformer is located between the aluminum enclosure and the panel. The filament voltage is fed



through the enclosure wall using 0.1 μF Sprague *Hy-Pass* feedthrough capacitors.

plate circuit

The plate circuit of the amplifier is a transmission-line type resonator. The line (L5 plus L6) is one half-wavelength long with the tube placed at the center. This type of circuit is actually two quarter-wavelength lines in parallel. One of the advantages is that each of the quarter-wavelength lines is physically longer than if only one is used. This is because only half of the tube output capacitance loads each quarter-wavelength section. Another advantage to this layout is a better distribution of rf currents around the tube seals.

The dc blocking capacitors are surplus Centralab 100-pF, 5000-volt ceramic capacitors. Two are used on each line to handle the rf current. The homemade variable capacitor C5 tunes the plate circuit. Note that this type of capacitor structure has no wiping contacts. All the rf currents flow through a fixed path which provides very smooth tuning with no jumping meter readings. The load capacitor C6 is constructed in a similar manner.

The plate choke L7 is visible in the photograph of the plate compartment. It is connected to the plate collet assembly with the Erie high voltage feed-through capacitor C7.

construction

The 220-MHz power amplifier is built in an enclosure measuring 8 × 12 × 7-1/4 inches (20 × 30 × 18 cm). The 8877 socket is centered on an aluminum deck 5 inches (12.7 cm) from the top of the enclosure. A centrifugal blower* forces cooling air into the under chassis area; the air escapes through the air-system socket, the teflon chimney (SK-2216), and then the tube. The warm air is exhausted through a "waveguide beyond cut-off" air outlet. This is an assembly which has expanded metal about 1/2 inch (12 mm) thick, mounted in a frame. A perforated aluminum cover may suffice in most cases, although restricts air flow slightly more and is not a very good rf shield at 220 MHz.

The plate tuning mechanism is shown in **fig. 3**. This simple apparatus will operate with any variable plate capacitor, providing a back-and-forth movement of about one-half inch. It is driven by a counter dial and provides a quick, inexpensive, and easy means of driving a vhf capacitor. The ground return path for the grounded capacitor plate is through a wide, low inductance beryllium-copper or brass shim stock which provides spring tension for the drive mechanism.

The variable output coupling capacitor is located at the side of the 8877 anode. The type-N coaxial

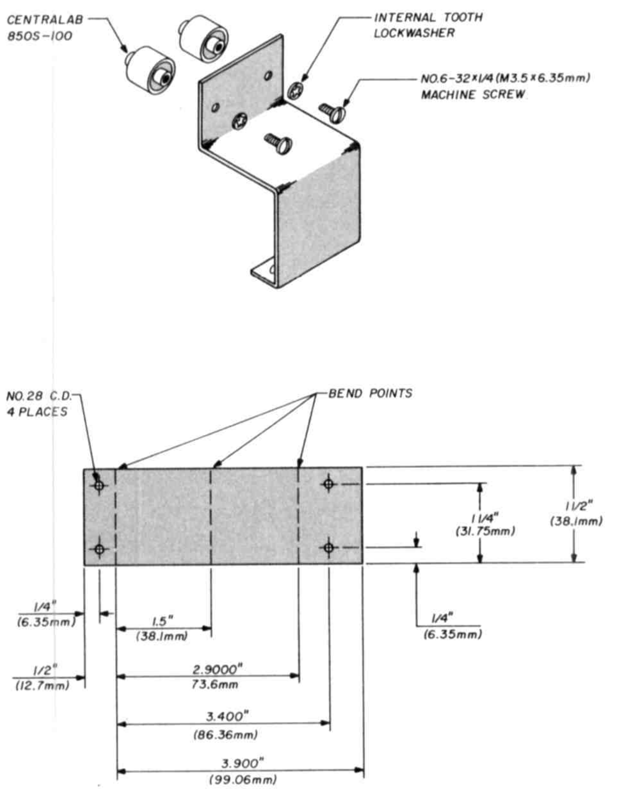


fig. 5. Plate line inductor pattern and bending layout for L5 and L6. Two assemblies are needed for the plate circuit.

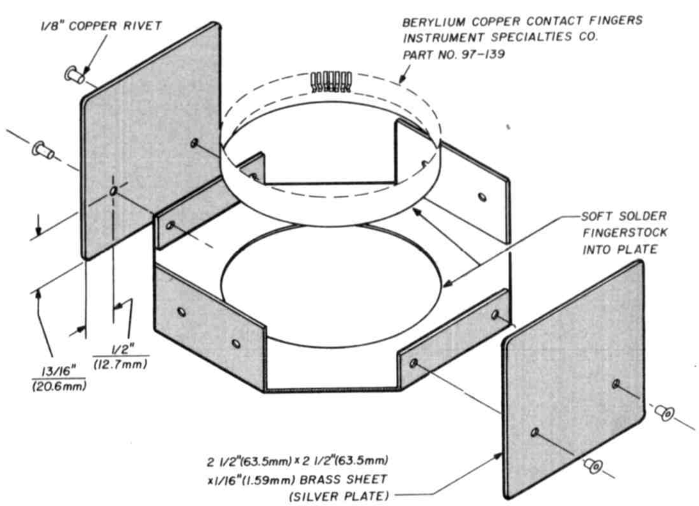


fig. 6. Anode collet and capacitor plate support assembly. The two fixed capacitor plates for C5 and C6 are mounted to the assembly using copper pop-rivets and then soldered. The two remaining bent-up edges are for mounting the blocking capacitors C3 and C4. The finger-stock is soft-soldered into the large hole in the center. A tight fitting aluminum disc helps to hold the finger stock in place while soft soldering with a hot plate.

*Recommended blower is the Dayton 4C446, a 115-Vac unit rated to deliver cooling air at 135 cubic feet per minute (3.8 cubic meters) with a static pressure equivalent to 0.2 inch (5 mm) of water.

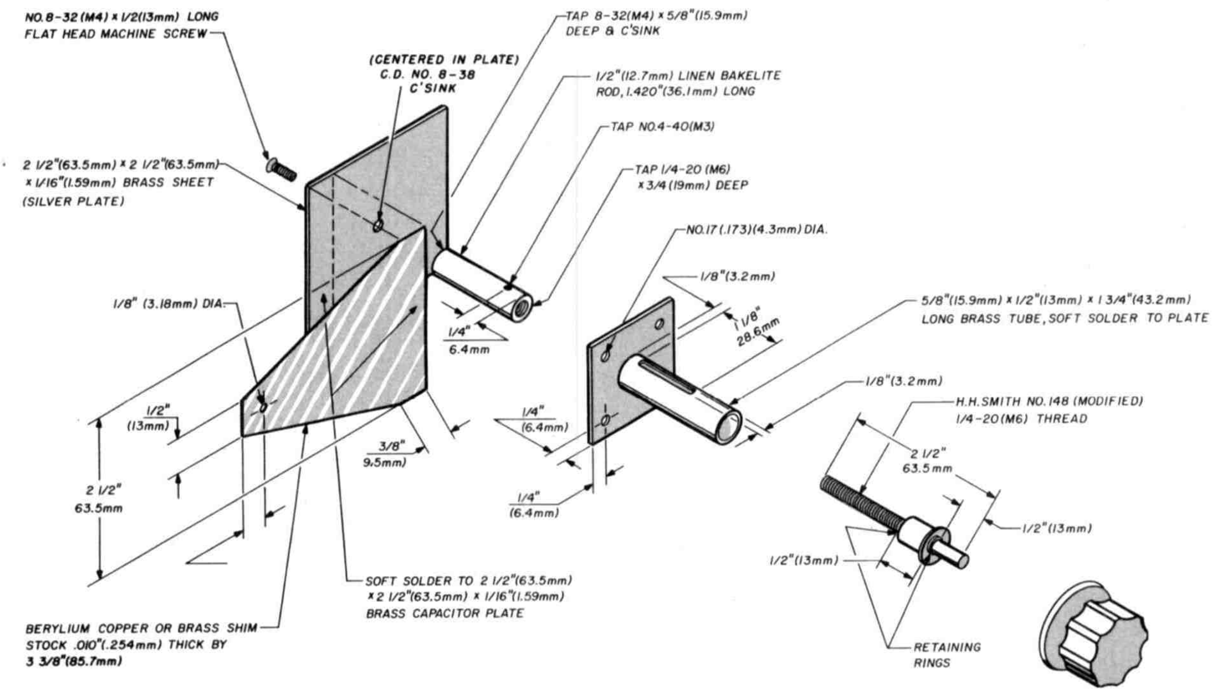


fig. 7. Variable plate portion of the loading capacitor C6. The beryllium-copper portion carries the rf current to the type-N coaxial connector as well as providing spring tension on the tuning mechanism. Because of the constant rf conducting path, the loading is very smooth with no jumpiness.

output connector is connected to the moveable capacitor plate by a wide beryllium-copper strap. The capacitor plate is driven in a manner similar to the tuning capacitor as shown in **fig. 7.**

The plate line is made up of two inductors L5 and L6 (see **fig. 5**) and the anode collet and capacitor assembly shown in **fig. 6**. With the inductor sizes given, the amplifier can be tuned from 220 to 222.5-MHz; no tests were run above 222.5-MHz.

The plate rf choke is mounted between the junction of the anode collet and a pair of the dual blocking capacitors. The high-voltage feedthrough capacitor is mounted on the front wall of the plate compartment. The blocking capacitors are rated for rf service, and inexpensive television-type capacitors are not recommended for this amplifier.

operation

Amplifier operation is completely stable with no parasitics. The unit tunes up exactly as if it were on the hf bands. As with all grounded-grip amplifiers, excitation should never be applied unless the plate voltage is on the amplifier.

The first step is to grid-dip the input and output circuits to near-resonance with the 8877 in the socket. An SWR meter should also be placed in series with the input line so the input network may be adjusted for lowest SWR.

Tuning and loading follows the same sequence as any standard grounded-grip amplifier. Connect an SWR indicator at the output and apply a small amount of rf drive. Quickly tune the plate circuit to resonance; the cathode circuit should now be resonated. The SWR between the exciter and the amplifier will not necessarily be optimum. Final adjustment of the cathode circuit for minimum SWR should be done at full power because the input impedance of a cathode-driven amplifier is a function of the plate current of the tube.

Increase the rf drive in small increments along with the output coupling until the desired power level is reached. By adjusting the drive and loading together it will be possible to attain the operating conditions given in the performance chart in **table 1**. Always tune for maximum plate efficiency: maximum output power combined with minimum input power. It is easy to load heavily and underdrive to get the desired power input but power output will be reduced if this is done.

references

1. R. Sutherland, W6UOV, "Two Kilowatt Linear Amplifier for Six Meters," *ham radio*, February, 1971, page 16.
2. R. Sutherland, W6UOV, "High Performance 144-MHz Power Amplifier," *ham radio*, August, 1971, page 22.
3. M. Partin, K6DC, "Custom Design and Construction Techniques for Linear Amplifiers," *QST*, September, 1971, page 24.

ham radio

A 250 W Broadband Solid-State Linear Amplifier

By Dick Frey, K4XU

Editor's note: Section and figure references in this article refer to the 2013 edition of the ARRL Handbook.

Additional files, photos and other information mentioned in this article are available elsewhere on the CD-ROM. The amplifier described here and shown in **Figure 17.43** is neither revolutionary nor daring. It uses commonly available parts — no special parts and no "flea market specials." It is based on well-proven commercial designs and "best design practices" acquired over the past 30 years as solid-state technology has matured. This design project was undertaken for the 2010 Handbook as a detailed design example as well as a practical solid-state amplifier you can build. It is a continuing project.

Fig 17.43 — This 250-W amplifier for 160 through 6 meters provides a detailed design example as well as a practical project. Additional photos and information about the interior layout may be found elsewere on the CD-ROM.

A block diagram for the project is given in **Figure 17.44**. The amplifier is built on three PC boards — a PA module, a low-pass filter assembly, and a board for control, protection and metering circuitry. The *Handbook* CD includes *ExpressPCB* files for these boards, and the artwork can be used to have boards made in small quantities (see **www.expresspcb.com** for details).

The basic PA configuration has been in the *Handbook* since the 2010 edition. It is intended to be a "ham-proof" external amplifier for QRP transceivers that put out 15 W or less. It is designed for a gain of 30×, or 15 dB. Drive power of less than 10 W will provide 250 W output from 1.8 through 51 MHz. The amplifier provides exceptionally linear performance, necessary for high quality SSB and PSK modes, and is rugged enough to withstand the most rigorous contest environment.

Amplifier design tends to focus on the RF section, but a successful stand-alone solid-state amplifier is equally dependent on its control system. The control requirements for a tube amplifier are well known, while those for solid-state amplifiers are not. This is mostly because the functions of a solid-state amplifier's control system are generally transparent to the user. Parameters are monitored and protection is applied without any operator intervention. This must be. While tubes are fairly forgiving of abuse, semiconductors can heat so quickly that intervention *must* be automatic or they can be destroyed.

Transistors are sensitive to heat, so cooling and temperature compensation are critical to a successful design. Transistors require a heat sink. Power amplifier tubes have large surface areas and are cooled by air blown on or through them. Transistors are small. Mounting them on a heat sink increases their thermal mass and provides a much larger surface area so the heat dissipated in the devices can be removed either by convection or forced air. The thermal design of an amplifier is just as important as the electrical design. More information on thermal design may be found in the **Analog Basics** chapter.

Silicon's thermal coefficient causes the bias current to increase as the device heats up if the bias source is fixed. The increased current causes even more heating and can lead to thermal runaway. For stable Class AB linear operation, the gate bias for a MOSFET or bipolar transistor must track the temperature of the device. The control circuit typically uses another silicon device such as a diode thermally coupled to the amplifier heat sink near the transistor to sense the temperature and adjust the bias to maintain a constant bias current.

Transistor power amplifiers are designed to operate into 50 Ω. Operation into a VSWR other than 1:1 will cause an increase in device dissipation and other stress. The success of the solid-state transceiver is due to its integrated PA protection system. The temperature of the heat sink, the load VSWR, the output power and the supply current are all monitored by the control system. If any of these exceed their threshold limits, the RF drive is reduced by the transceiver's ALC system.

An external solid-state PA protection system must perform the same functions, but the driver's ALC circuit is not always available so other means must be used to protect the PA. This is usually accomplished simply by taking the amplifier out of the circuit. An indicator then tells the operator which condition caused the fault so appropriate action can be taken. Access to the driver's ALC system would make this protection task more automatic, smoother and less troublesome, but no two transceiver models have the same ALC characteristic. This makes the design of a universal ALC interface more difficult.

17.11.1 The 1.8 to 55 MHz PA — Detailed Description

Figure 17.45 shows the power amplifier (PA) schematic. Two Microsemi VRF151 MOSFETs are used in this amplifier. The circuit topology is a 4:1 transmission line transformer type, rather than a "tube and sleeve" type common in many PA designs and discussed earlier. This style offers more bandwidth, necessary to provide performance on 6 meters. Typical gain is 15 dB; 10 W drive will easily provide 250 W output with a 48 V supply. There is a lot of latitude in this design. It can even be operated on an unregulated supply. As long as the maximum unloaded voltage does not exceed 65 V, the transistors will not be overstressed. Other devices such as the MRF151, SD2931 or BLF177 would probably also work but have not been tested. They will require a regulated power supply, however.

FEEDBACK — TWO KINDS

The amplifier's gain is controlled by two kinds of feedback. Shunt feedback (from drain to gate) is provided by the link on T2 through resistors R5 and R6. It tends to lower the input impedance but it also helps to keep the gain constant over frequency and improve the linearity. Series feedback is provided by the 0.05 Ω of resistance in each source. This increases the input impedance, cuts the gain by 3 dB, and most importantly, it has a huge effect on the linearity.

Without any feedback at all, the amplifier would have more than about 30 dB gain (×1000) at some frequencies, tending to make it unstable — prone to parasitic oscillation. And the linearity would be terrible, –25 dBc or so IMD products. It would also be very sensitive to load changes. The input SWR is 1.2:1 on 160 meters and rises to 1.5:1 on 6 meters. The amplifier's gain is 15 dB ±0.5 dB over the same frequency range.

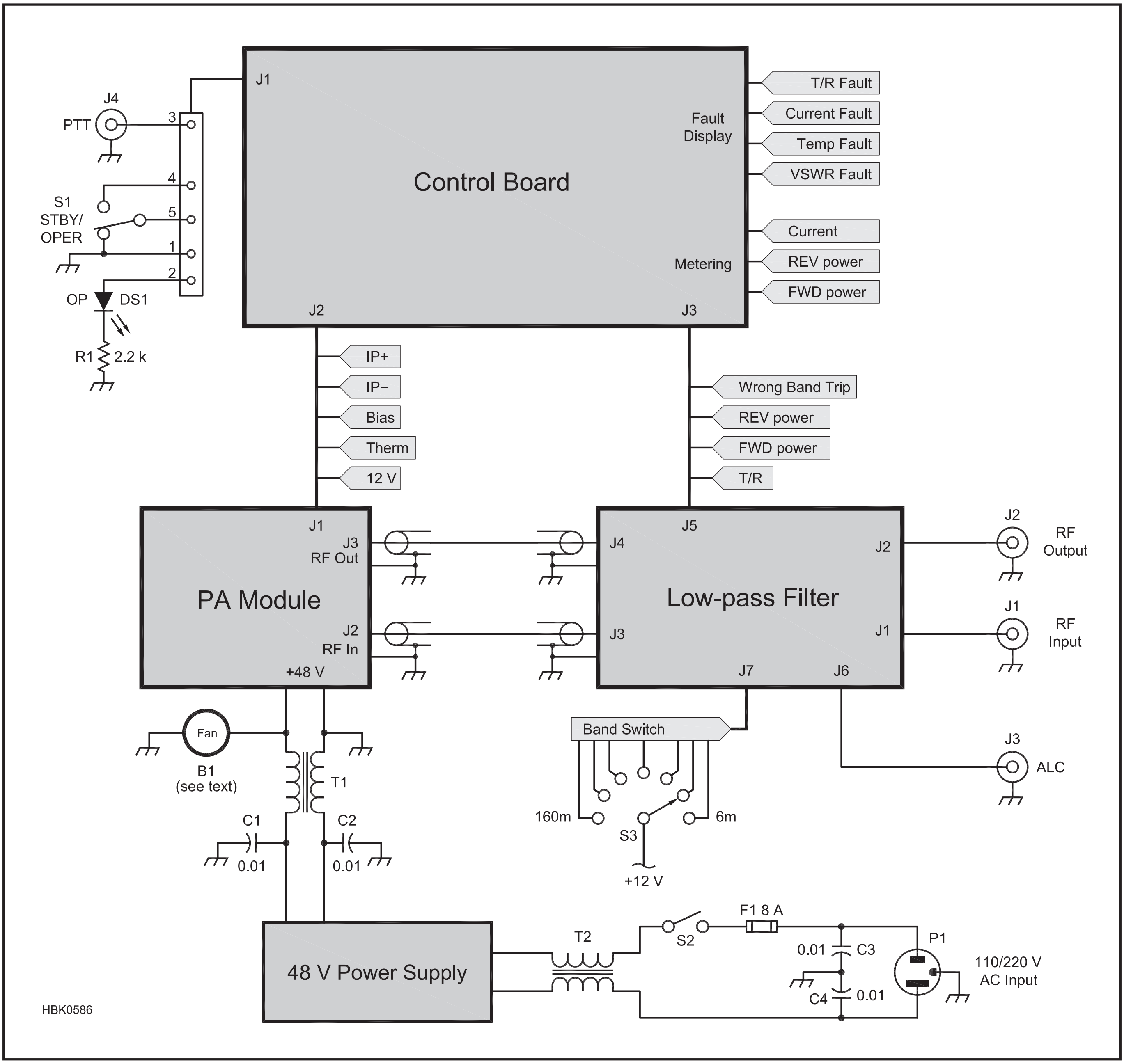


Fig 17.44 — Block diagram of the 250-W solid-state amplifier. It is built on three PC boards, which are described in the text and accompanying diagrams. T1 and T2 are 2 turns through a Fair-Rite 2643540002 ferrite bead if needed to suppress RFI from the switching power supply.

PA INPUT

On the input side, T1 is a sleeve-and-tube RF transformer. Its small size and tight coupling make it suitable for very wide bandwidth operation. When properly compensated, this type is able to provide a match to a 12.5-Ω load over a very wide frequency range from 1 to 100 MHz. The problem is that the input impedance of the two transistors is not a flat resistive load.

The gate of a MOSFET is essentially a high-Q capacitor. A voltage greater than its threshold (V_{th}) applied between the gate and source will control the conductivity of the drain-to-source path. No power can be dissipated in a purely reactive element, so we cannot match to a capacitor. Fortunately, all real reactive elements have losses and it is this loss that we would match to in a MOSFET gate for single-band operation. But that is no good here because we want a broadband match.

There are several ways to match a MOSFET over a broad frequency range. The most common is to swamp the gate capacitors with resistors. If the resistor value is lower than the impedance of the transistor gate capacitance, it dominates what the transformer sees as a load at the lower end of the bandwidth. The gate capacitor impedance decreases at higher frequency so some series resistance is added, R3 and R4, so that there is always a minimum real part to the load on the secondary of T1.

For a 1:1 input SWR, T1 wants to be terminated by a 12.5 Ω load. More than half of this is provided by R3 and R4. The rest is through shunt loads R7 and R8, plus the impedance of the output passed through the

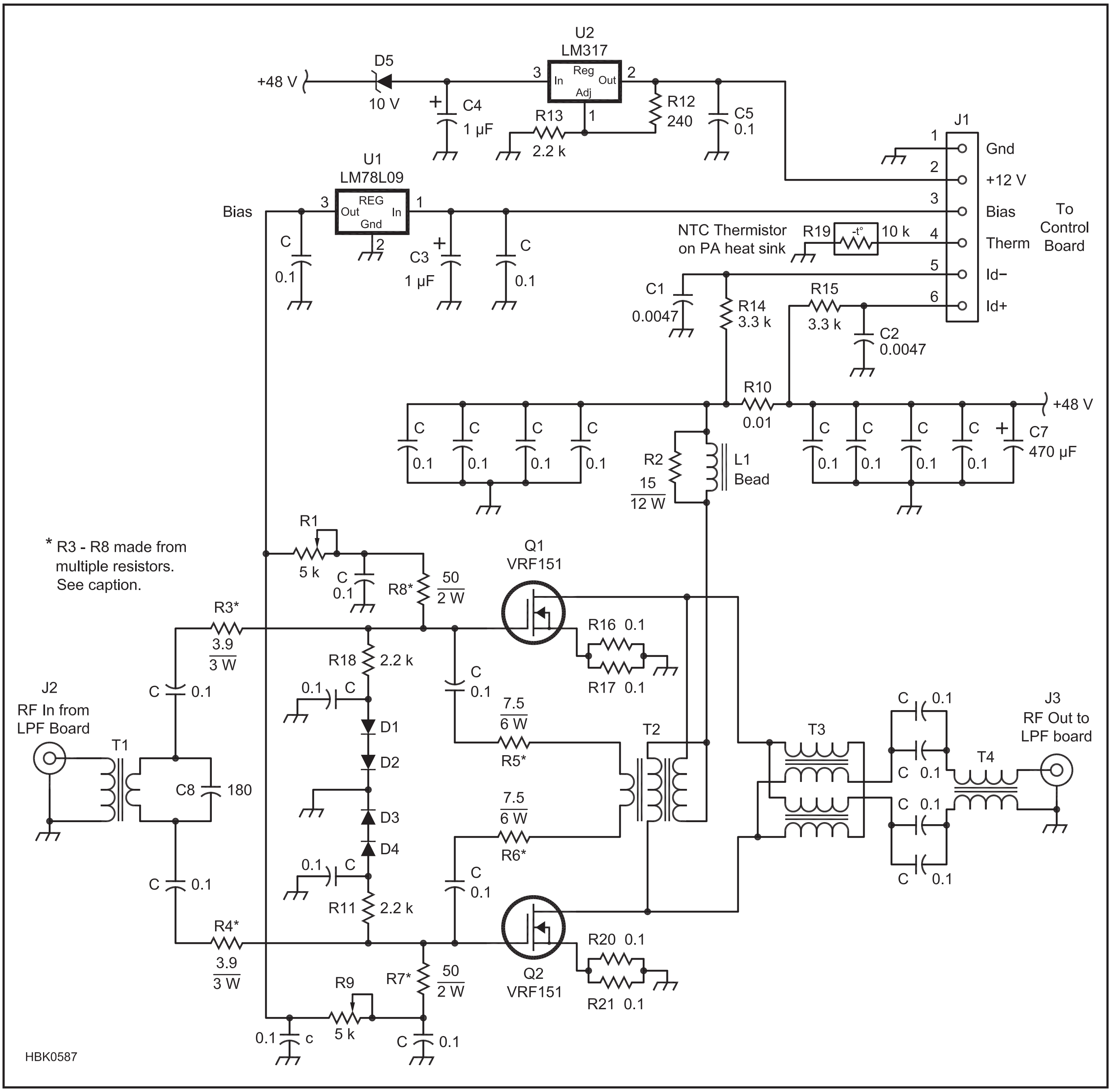


Fig 17.45 — Schematic diagram of the 250-W amplifier PA module. A complete parts list may be found elsewhere on the CD.

C — 0.1 µF, 100 V X7R 1206 SMT.
D1-D4 — SMT silicon PN-junction diodes such as 1N4148 or equivalent.
L1 — 2t on Fair-Rite 2643480102 ferrite bead.
R2 — 15 Ω, 12 W.
R3, R4 — Three 12 Ω, 2 W SMT resistors in parallel.
R5, R6 — Two 15 Ω, 3 W resistors in parallel.
R7, R8 — Two 100 Ω, 1 W SMT resistors in parallel.
R19 — 10 kΩ, 5% NTC thermistor, SMT (DigiKey 541-1150-1-ND).
T1 — 2t #22 wire on CCI RF400-0 core (or two Fair-Rite 2643006302 cores)
T2 — Primary, 1t #22 wire; secondary 8t #22 wire bifilar wound, on Fair-Rite 5961004901 core.
T3 — 2 × 3t 25 Ω coax on Fair-Rite 2861010002 core (see text).
T4 — 3t RG-188 coax on Fair-Rite 2643665802 core (on cable to LPF board, not on PC board).
Q1, Q2 — Microsemi VRF151 MOSFET.

feedback network. T1 has no center tap so a balanced load is forced by the action of resistors R7 and R8. Having "soft" center taps on both the input and output absorbs any differences between transistors and greatly improves the network's RF balance. This in turn improves the cancellation of even harmonics at the output. The gate impedance is raised by the effect of the source resistors, further improving the match.

DC FEED TRANSFORMER

In addition to providing the link for the feedback, T2 also acts as the dc feed choke. It is wound with two parallel bifilar #22 wires and a single turn for the feedback. At dc, the current flows in opposite directions through each #22 wire so the net current is zero and the core does not saturate with dc. At RF, the choke with its ferrite core provides at least 50 Ω of inductive reactance making it essentially invisible to the RF signals across it. As the feedback transformer it provides a 1⁄16 sample of the drain-drain voltage to the gate feedback loop.

It is not often mentioned in the literature, but the dc feed transformer T2 acts as a 180° hybrid combiner (**Figure 17.46**). A hybrid combiner has four ports: two inputs, the sum port and the difference port. The sum of the two input signals appears on the sum port and the difference between them (differences due to voltage or phase) appears at the difference port. In this case T2 is terminated with a 1:4 balanced transformer that brings the output impedance up to 50 Ω. The sum port is across the whole secondary. The two input ports are between each end of the secondary and ground. The difference port is between the center tap and ground.

No two transistors or their circuit layouts are exactly equal. In a push-pull circuit these slight differences gives rise to imbalance between sides which gives rise to even harmonics at the output. By not placing the usual heavy RF bypassing at the center (the difference port) of the bifilar winding in T2 the difference between the two drain voltages shows up across L1 and is dissipated in the parallel resistor R2. This enables the amplifier to achieve better than 40 dB suppression of even harmonics, helps the efficiency, and greatly improves its stability when driving mismatched loads.

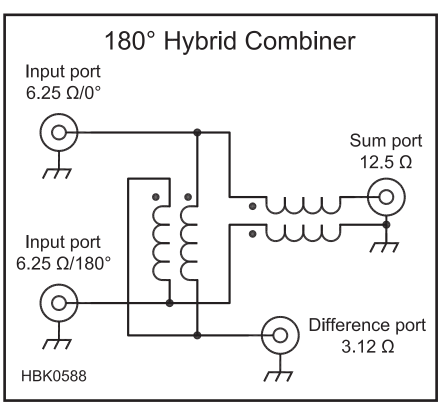


Fig 17.46 — Dc feed transformer T2 acts as a 180° hybrid combiner.

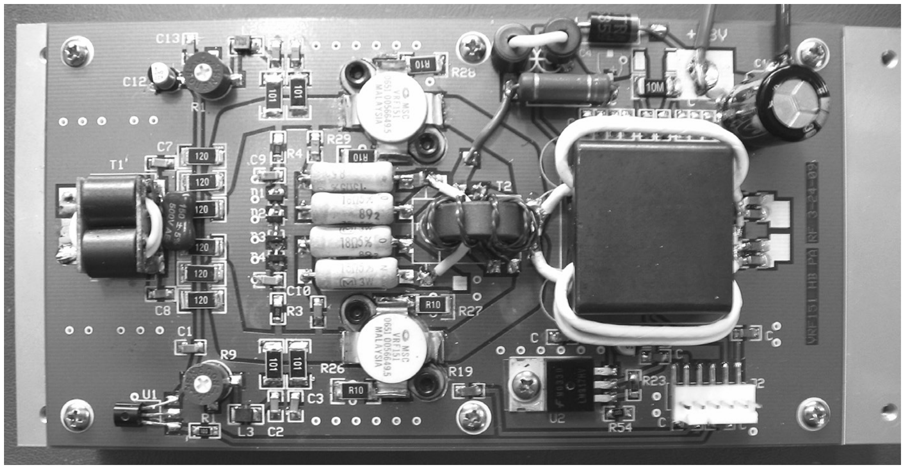


Fig 17.47 — The power amplifier module PC board assembly mounted on the heat sink.

THE PA OUTPUT TRANSFORMERS

The output circuit of the PA uses a 4:1 impedance transformer. We have two VRF151 transistors that will each put out 150 W if properly cooled. That means 300 W output power for the pair operating on 48 V. The classic formula relating drain-to-drain load impedance to the supply and output power is

$$R_L = \frac{2\ V_{dd}^{\ 2}}{P_O} \qquad (10)$$

For 48 V this gives 15.36 Ω. But the drain cannot swing all the way to zero because of the finite on-resistance of the MOSFET. The actual available swing is typically 90% of the supply voltage so a more practical formula is

$$R_L = \frac{2\ (0.9\ V_{dd})^2}{P_O} \qquad (11)$$

A 4:1 transformer gives 12.5 Ω. This is a nice load for these devices.

The 4:1 impedance ratio is performed by a simple transmission line transformer. The impedance of the coax used should be the geometric mean between the two impedances to be matched:

$$Z_0 = \sqrt{50 \times 12.5} = 25\ \Omega$$

Coax with this characteristic impedance is not a common stock item but it is available as p/n D260-4118-0000 from Communications Concepts, Inc. (**www.communication-concepts.com**). Two feet are required. An acceptable alternative is #22 shielded 600 V Teflon-insulated wire such as Belden 83305-E whose physical dimensions result in approximately the same characteristic impedance.

These two coax lines are connected in parallel on the drain end and in series on the 50 Ω output end. Any voltage on the input is put in series at the output, giving a 2× voltage ratio or a 4× impedance ratio, exactly what we want. If coiled up in separate coils, the transformer will work without any ferrite. The two coils cannot be allowed to couple so they cannot be on the same form.

In order to get a wider frequency response, the inductance of these coax coils is increased by winding them on a ferrite core. The core used here has two holes, so independent coils can be wound on each side without any coupling between them and it makes a nice neat package. Separate cores would work just as well. The ferrite core is type 61 material with a permeability of μ_i = 125. It is a binocular bead but could be replaced by two 0.5 dia × 1-inch long sleeves of the same material. The ferrite "load" on the coax makes its outside shield a high impedance from end to end, while inside the shield the coax maintains its 25 Ω characteristic impedance between center and shield. As long as the coax lines of T3 are wound as two non-coupled coils, the amplifier will operate from 21 to 80 MHz without any ferrite at all.

The advantage of the transmission line type of RF transformer is that it does not have the leakage reactance that plagues the tube-and-sleeve type of transformer used on many solid-state amplifiers. Simply stated, a parasitic leakage inductance is introduced in series with the primary due to incomplete coupling of the flux between the primary and secondary winding. This increases the apparent impedance of the low-Z side of the transformer as the frequency increases. The output impedance of the transistors decreases with frequency — a double hit of mismatch that causes the gain to drop off quickly.

There is one disadvantage to the transmission line transformer. It has a balanced input and output. Sometimes designers will ground one side of the output and rely on the ferrite loading to decouple the ground side of the output. This has a negative effect on the balance of the amplifier, and on those even harmonics we want to minimize. It also doubles the flux stress in the ferrite causing it to heat more. The solution is T4, a simple current balun — four passes of the 50 Ω output line through a toroid of type 61 ferrite. With T4 in place, a balanced load on the output of T3 is maintained, the even harmonics are suppressed, and the efficiency is 5 to 10% better on most bands.

PA LAYOUT

The PA board (**Figure 17.47**) was designed with all parts mounted on the top surface — no through-hole parts at all. The back side of the PC board is a continuous ground plane and is mounted directly to the heat sink without spacers.

17.11.2 Control and Protection

The control board appears far more complicated than the PA but in reality, it is just a few analog and logic ICs. The various control and protection circuits are shown in **Figure 17.48** and the LED displays and drivers (also on the control board) are shown in **Figure 17.49**.This circuitry monitors several parameters, displays them, and if necessary, puts the amplifier into standby if one of them goes out of range. This control system could be used on any amplifier. All solid-state amplifiers need similar protection. The amplifier is protected for:

1. Over temperature, by a thermistor on the heat sink and setting a limit.
2. Over current, by measuring the PA current and setting a maximum limit.
3. High SWR, by monitoring the reflected power and setting a maximum limit.
4. Selection of a low-pass filter lower than the frequency in use.

Each of these fault trips results in forcing the amplifier into the standby position and out of the RF path, and lighting an error LED. There is also an ALC level detector that generates a negative-going feedback voltage for the driver when the RF drive goes above the level corresponding to maximum power. If this PA were part of a transceiver, the several faults described above would generate inputs into the ALC system and turn back the drive rather than taking it off the air. We do not always have that luxury so the best course is to take it off line until the cause can be fixed.

THERMAL COMPENSATION

MOSFETs are sensitive to temperature. If a fixed bias is used on the gate to set the quiescent bias at 100 mA when the device is cold, the current will increase as the device heats up. In some devices, it will cause thermal runaway. The hotter it gets, the more current it draws, causing even more heating and so on. The solution is to sense the temperature of the device and reduce the gate bias as it heats up. The VRF151 is relatively insensitive compared to similar high power RF MOSFETS.

The compensation system is quite simple, effective and foolproof. It relies on the thermal characteristic of silicon diodes that as a diode heats up, the forward voltage across it goes down approximately 2.4 mV/°C. Two diodes in series are used at the bottom of each gate voltage divider (D1-D4, any silicon PN-junction diode in a suitable SMT package will work). Mounted on the PA board, they heat up along with the transistors and reduce the gate voltage by a proportional amount. The 100 mA of bias at 25 °C is less than 150 mA at 200 °C. This compensation system may not work as well if other MOSFET types are substituted because they have different thermal coefficients of V_{th} and may require more aggressive thermal compensation. Gate bias voltage is provided via a PTT-activated 9 V regulator.

A simple way to check or adjust compensation is to place the amplifier module, board and heat sink, on an electric frying pan. Set it to 212 °F (100 °C) and monitor the drain current. It should stay within 150% of the cold setting. Be patient. This takes a while because the response time of this arrangement is quite long. Under some operating conditions, it is possible for the transistor to get very hot before the heat travels to the diodes. For this reason, we have additional means to protect the transistors.

OVER-CURRENT PROTECTION

One simple protection method is to limit the power into the PA module by limiting the maximum supply current. The drain current is sensed across shunt resistor R10. The sense voltage is amplified by U2A and sent to the current meter. It also goes to comparator U2B where it is monitored and compared to the limit voltage set by R13. If it exceeds this limit, the comparator trips the fault latch U1, lights the OC LED, and opens the PTT.

OVER-TEMPERATURE PROTECTION

The heat sink temperature is monitored directly by a negative temperature coefficient thermistor, R19, mounted on the PA assembly. It is the lower half of a voltage divider sensed by U3A and fed to comparator U3B. When the thermal sense voltage exceeds the limit set by R14, the U1 fault latch is tripped and the PTT line opened. Any time the fault latch is tripped it lights an LED to indicate the cause of the fault so the operator can address the problem. Cycling the OPERATE - STANDBY switch resets the fault latch and restores normal operation.

VSWR PROTECTION

The amplifier is protected for high VSWR. The amplifier is designed to operate into 50 Ω. It acts somewhat like a constant voltage source. It will dutifully try to put the same voltage across whatever load it is given, even a short. The SWR bridge produces a voltage proportional to both the output power and the relative mismatch between the load and 50 Ω.

T1 on the LPF board is the heart of a dual directional coupler that provides both the VSWR detection and the forward power monitoring. It is really two transformers on one two-hole core, Fair-Rite # 2843010402. Each has 17 turns of #28 AWG as the secondary and a single "turn" of #22 AWG Teflon hookup wire as the primary.

T2 is a single directional coupler that looks at the power reflected from the low-pass filter. Its secondary has 20 turns of #28 AWG wire, and the primary is a single pass of #22 AWG wire. In order to minimize the impedance bump it places in the RF signal path between the PA and the LPF, the core is mounted in a small window cut in the board. This allows the toroid to be mounted so the primary wire can go straight through the center of the toroid. Detailed photos of all the transformers are contained elsewhere on the CD.

Several load conditions can produce the same value of indicated VSWR. At one mismatch load condition the amp might be trying to put out way too much power. At a different reflection coefficient, it might see a very high reflected voltage. This could raise the peak voltage on the drains past the voltage breakdown limit of the MOSFET. The voltage from the detector on the reflected power port of the SWR bridge is brought to the meter and to a comparator that will trip the fault latch when the voltage is past a limit. Again the PTT is opened. The operator can either lower the SWR by improving load match or reduce the output power to limit the reflected power from the bad match. The amplifier is happy either way.

Transformer T1 on the LPF board is the heart of the directional coupler used for VSWR protection and power metering. It consists of identical transformers wound on each side of a two-hole ferrite core. The secondary is formed from 17 turns of #28 AWG enameled wire. The primary is a single pass of #22 AWG insulated hookup wire though the hole. A picture of the transformer is contained elsewhere on the CD.

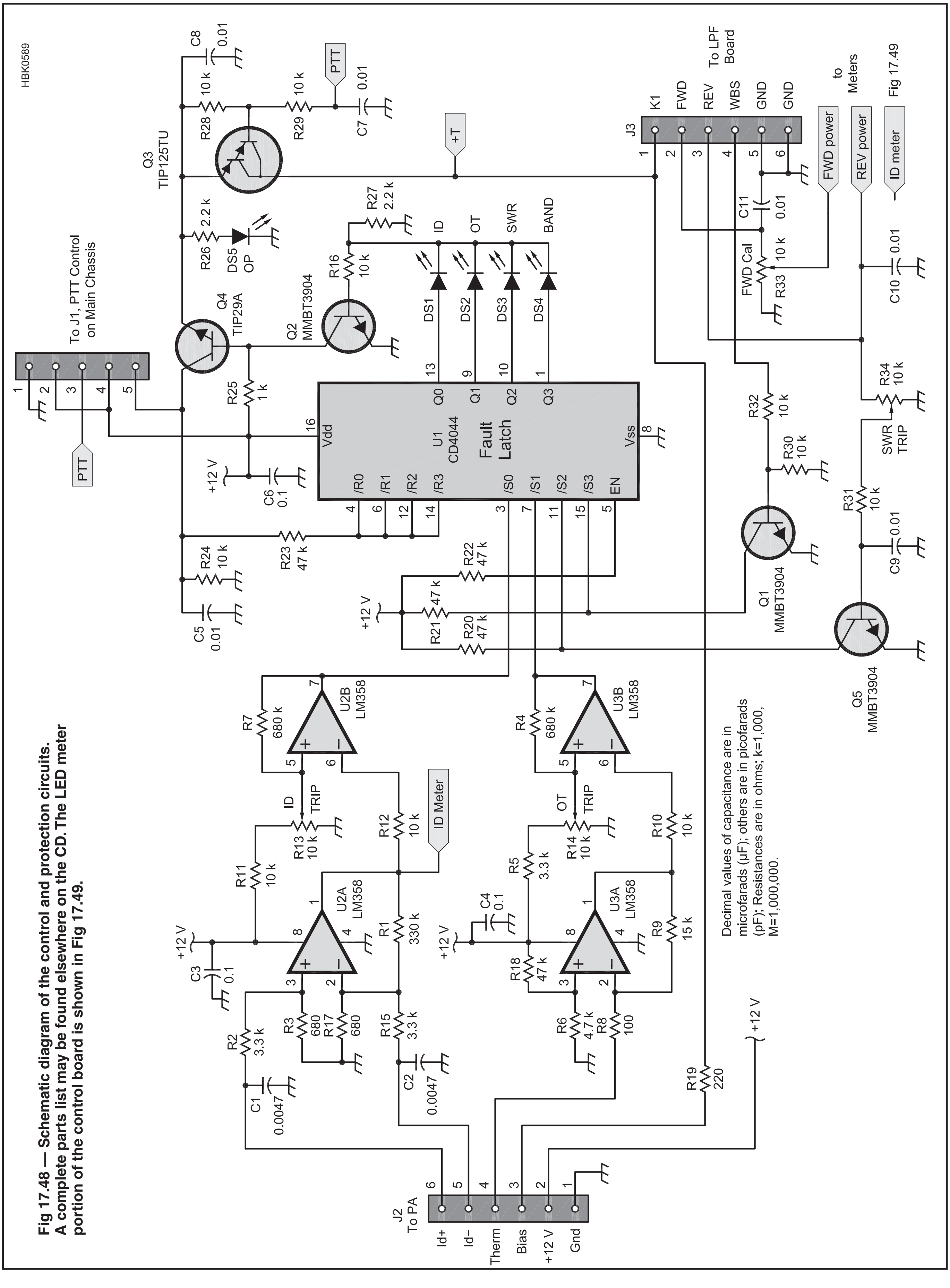


Fig 17.48 — Schematic diagram of the control and protection circuits. A complete parts list may be found elsewhere on the CD. The LED meter portion of the control board is shown in Fig 17.49.

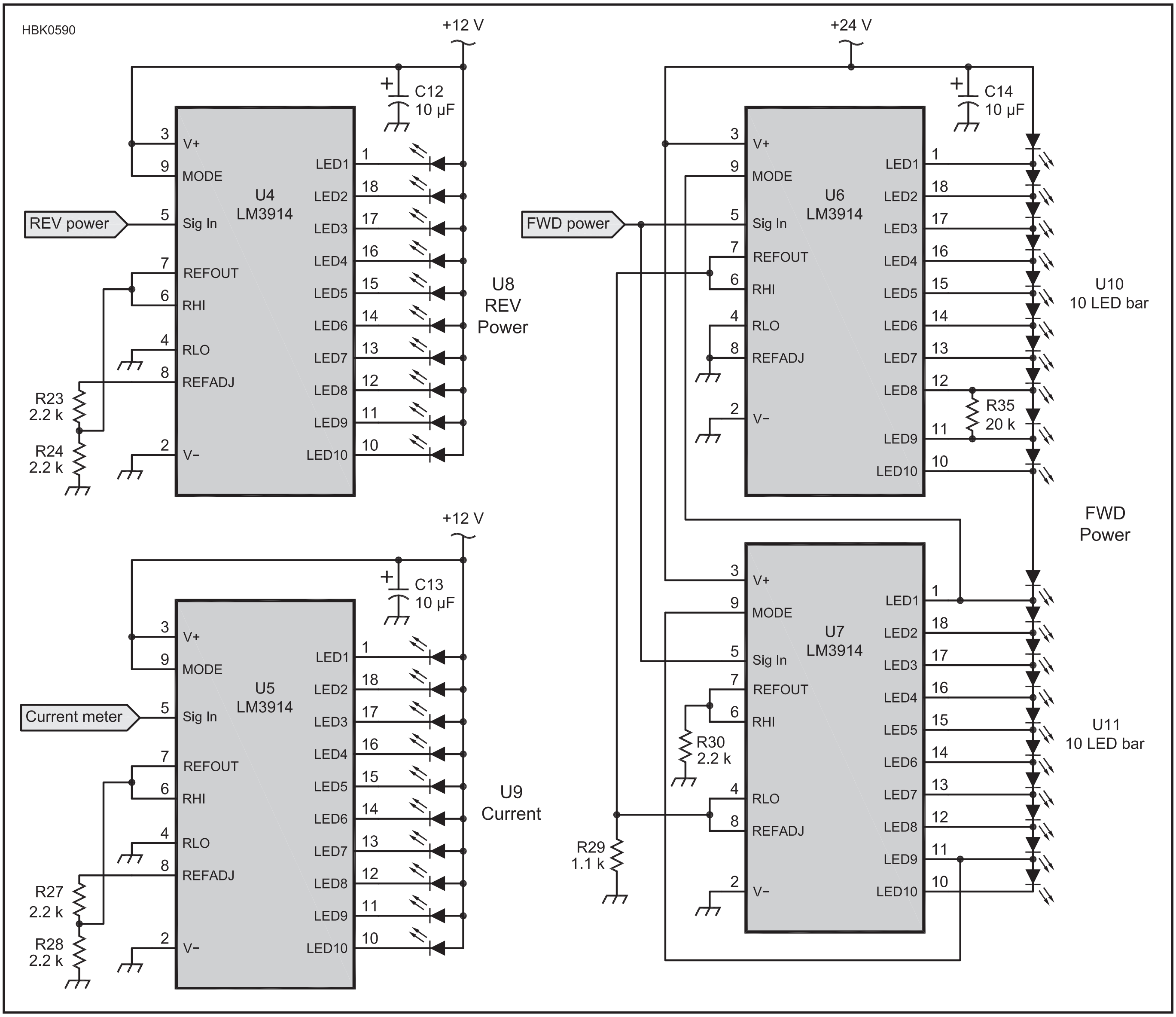


Fig 17.49 — Schematic for the LED meters, which are also located on the control board with the circuitry shown in Fig 17.48. A complete parts list may be found elsewhere on the CD.

BAND FAULT PROTECTION

One problem unique to external broadband amplifiers is that they generally do not care what frequency they amplify, but their low-pass filters on the output certainly do. The problem arises when the operator forgets to change the band switch on the amplifier when moving to a higher band. All the power from the amp is reflected back from the LPF and the amplifier is distressed — all that power with no load. The solution is to place a reflected power sensor between the PA and LPF. A monitor will see this condition and trip the fault latch for Wrong Band Selection.

T2 is single directional coupler used for reflected power only. The transformer is mounted in a small window cut in the board that allows the primary wire to go straight through the center of the toroid. This coupler normally sees all the reflected harmonic power from the LPF. The maximum harmonic power from the PA output is down 13 dB from the fundamental. See Figure. 17.50. When the wrong filter is selected, all of the power is reflected by the filter so the threshold is set to detect this 20× (13 dB) difference.

17.11.3 Low-Pass Filter

For amateur use, FCC §97.307(d) requires that harmonics be suppressed at least 43 dB for operation below 30 MHz, and at least 60 dB on 6 meter and higher frequency bands. The output signal from a broadband ampli--fier itself contains harmonics and needs to have a separate filter to meet the FCC's requirements for harmonic suppression. **Figure 17.50** shows the harmonic output of this amplifier without any low-pass filtering.

In a well designed solid-state push-pull amplifier, the second harmonic is 30 to 40 dB below the fundamental if the balance is good, but the third harmonic is only down 13 dB. This means the low-pass filter needs to supply about 10-13 dB of attenuation at the 2nd harmonic and 30 dB or more to the rest. On 6 meters the filter must provide at least 35 dB attenuation at the 2nd harmonic and 50 dB to the rest. None of this is difficult for a properly designed low-pass filter. In a commercial application, all harmonics must be at least 60 dB down. This usually

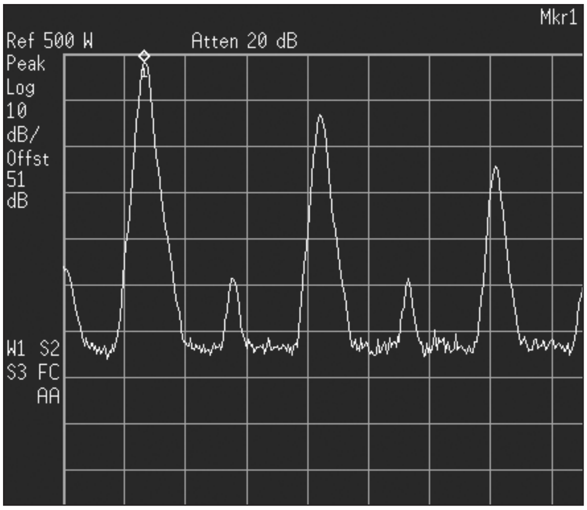


Fig 17.50 — The output of the 250 W amplifier without a low-pass filter. The even harmonics are suppressed by more than 40 dB. The odd harmonics are not suppressed by the push-pull balance and must be attenuated in the LPF. Harmonics after the LPF are all greater than 60 dB down.

requires a more complicated filter, especially if continuous coverage is desired.

The largest board in the amplifier, shown schematically in **Figure 17.51**, contains the low-pass filters, TR antenna relay, SWR bridge and the ALC detector. Amateur bands are harmonically related, so a filter for 40 meters will not do anything to reduce the second harmonic on 80 meters. If an amplifier is going to cover 160 to 10 meters, it will need at least five filters. With 30, 17 and 12 meters, the number of filters is usually increased by one to provide better suppression of harmonics. When 6 meters is added another filter is required, and it must be able to bring all 6 meter harmonics to –60 dB. This requires a more complicated filter.

FILTER DESIGN

The HF band filters can easily meet their requirements with simple five-element, 0.044-dB ripple Cauer filters. These filters use an elliptic topology. The nulls can be arranged to provide specific treatment of the third harmonic. Also, the insertion loss is the lowest of the several common filter types. The *SVC Filter Designer* software provided on the CD was used to design the LPFs used here. (See the **RF and AF Filters** chapter for more information on Cauer and other filter types.).

Low-pass filters are precision-tuned circuits. If the values are not right, the filter will have high loss and/or high VSWR in the passband. The calculated capacitor values are rounded to the closest 5% standard values. This is done by the *SVC Filter Designer* program. In a 5th order Cauer filter, there are two parallel resonant circuits that set the nulls in the response. If the exact calculated C value is not used, its paired L must be adjusted so the desired null still hits at the proper frequency. **Table 17.6** gives all the LPF capacitor and inductor values, the corner frequency (F_c), and the frequencies of the nulls (F1 and F2). L1-C2 resonate at F1 and L2-C4 resonate at F2.

LPF Inductors

Inductor winding details are given in **Table 17.7**. The low-frequency coils are wound on Micrometals T80-2 powdered iron toroid cores. For 20/30 and 15/17 meters the mix is changed to T80-6. Use of toroid cores keeps the Q of the coils high, makes physically smaller coils and provides magnetic shielding. This construction also helps to prevent the various sections of the filter from "talking to each other" and causing "suck-outs" in the passband or "lumps" in the stop band.

The 10/12 and 6 meter coils are self-supporting air-wound types with no cores which gives the highest possible Q. Coil

Table 17.6
Low Pass Filters
5th order Cauer
Ap = 0.044, As = 40 dB

Band (m)	*Fc (MHz)*	*C1 (pF)*	*L1 (µH)*	*C2 (pF)*	*F1 (MHz)*	*C3 (pF)*	*L2 (µH)*	*C4 (pF)*	*F2 (MHz)*	*C5 (pF)*
6	57.4	36	0.1571	6.8	154	75	0.1245	20	100.85	27
10/12	30.9	68	0.307	12	82.9	150	0.2387	36	54.3	51
15/17	22.265	120	0.424	22	52.09	220	0.338	62	34.771	91
20/30	15.053	180	0.619	33	35.217	330	0.458	100	23.508	130
40/60	8.837	300	1.058	56	20.674	560	0.831	160	13.801	240
80	4.778	560	2.027	100	11.177	1000	1.517	300	7.461	430
160	2.243	1200	4.181	220	5.248	2200	3.329	620	3.503	910

Table 17.7
Low Pass Filter Inductor Winding Details

Band (m)	*L1 (nH)*	*Core Type*	*Wire Size (AWG)*	*No. of Turns*	*Inside Dia. (in.)*	*L2 (nH)*	*Core Type*	*Wire Size (AWG)*	*No. of Turns*	*Inside Dia. (in.)*
6	157	—	16	5	0.312	124	—	16	4	0.33
10/12	307	—	16	7	0.35	238	—	16	3	0.33
15/17	424	T80-6	18	10	—	338	T80-6	18	9	—
20/30	619	T80-6	18	12	—	458	T80-6	18	10	—
40/60	1058	T80-2	18	14	—	831	T80-2	18	12	—
80	2027	T80-2	20	19	—	1516	T80-2	20	17	—
160	4180	T80-2	20	28	—	3329	T80-2	20	24	—

All of the cores are wound with enameled copper wire. The size is as large as will fit to maximize coil Q.

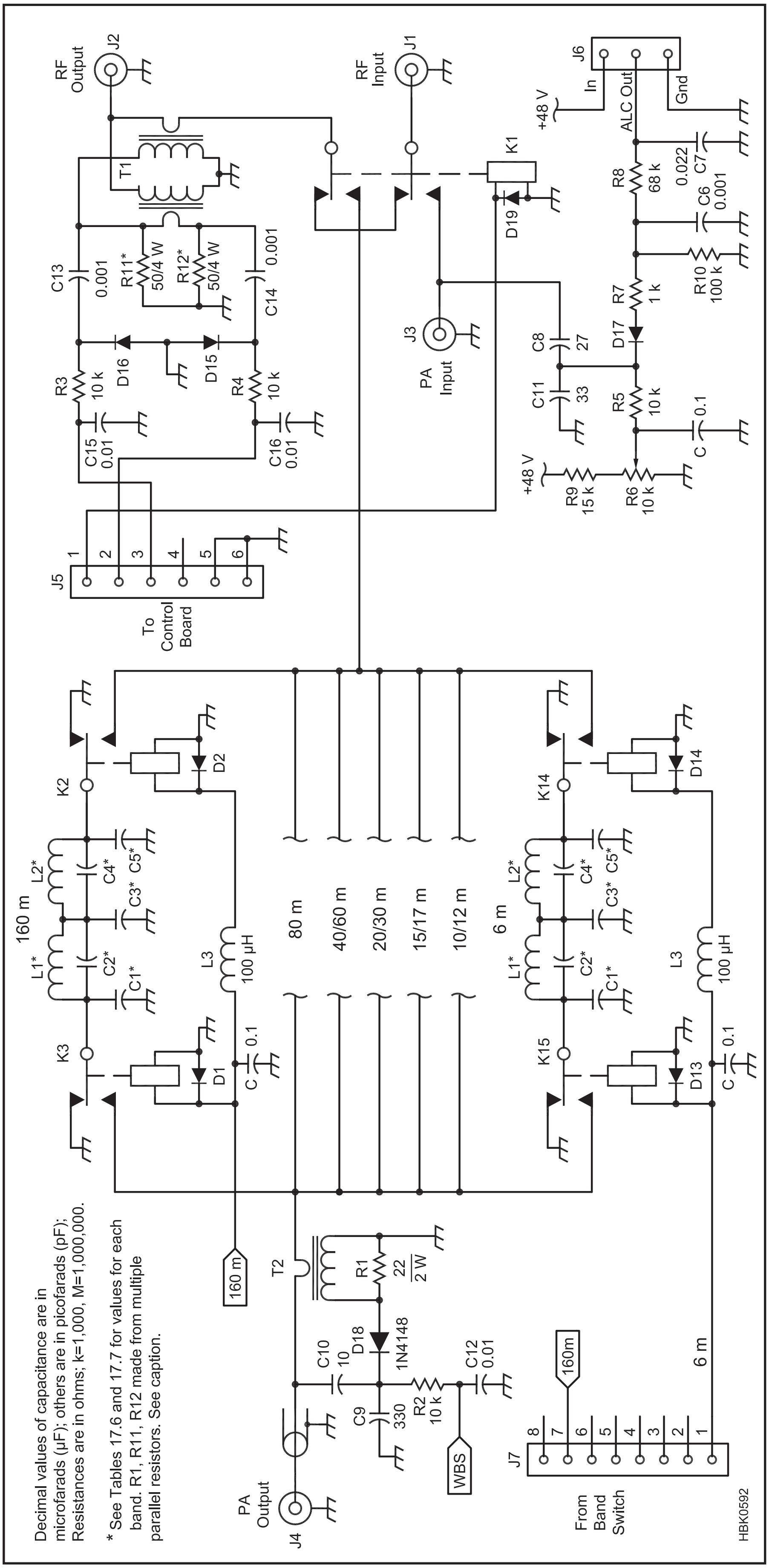


Fig 17.51 — Schematic for the low-pass filter board. The filters are described in detail in the text, and values are shown in Tables 17.6 and 17.7. This board also contains the TR relays, directional couplers and ALC circuitry. A complete parts list may be found elsewhere on the CD.

K1 — DPDT, 12 V coil, 8 A contacts (Potter & Brumfield RTE24012F).

K2-K15 — SPDT, 12 V coil, 10 A contacts (Omron G5LA-14-12DC).

R1 — Two 47 Ω, 2 W resistors in parallel.

R11, R12 — Two 100 Ω, 2 W resistors in parallel.

T1 — Dual transformer (see text).

T2 — Secondary: 20t #28 AWG on Fair-Rite 5961000201 toroid. Primary: 1t #22 AWG (see text).

adjustment is done by compressing or spreading turns on the cores. On the high bands, the coils are 5% high when wound tight. Spreading the coils slightly brings them to the proper value.

As mentioned before, it is important that the nulls in the Cauer filter response occur at the right frequency. Since the capacitor values have been rounded to the closest 5% values, the value of each parallel inductor has to be tweaked to set the null on the proper frequency. This is easy to do with a network analyzer but rather difficult for the home builder because the nulls are at various frequencies up to 154 MHz.

LPF Capacitors

Selecting capacitors for the LPF is a bit trickier. At 300 W of RF, the requirement is 123 V RMS or 174 V peak. A 500 V capacitor will easily handle this. We are also looking for RF current handling capability. At 300 W of RF, the requirement is 2.5 A RMS into 50 Ω. If a capacitor carrying this current has an equivalent series resistance (ESR) of 0.4 Ω it will dissipate 2.5 W. Harmonic currents can increase the heating dramatically.

Ceramic capacitors come in several grades of dielectric quality — X7R, Z5U and NP0 (or C0G). The NP0 is called a "Class 1" dielectric (see the **Component Data and References** chapter for more on capacitor characteristics). NP0 (C0G) capacitors are more expensive and harder to find, but they are the only type suitable for use in RF power filters. The best way to make capacitors for a PA low-pass filter is to use several in parallel. This spreads the RF current across several units and permits obtaining odd values by combining standard value parts.

RF capacitors are very difficult to find, and all the required values are never in the dealer's stock. Several capacitor manufacturers were tried and most quoted 6 to 14 week lead times and had minimum order quantities of $100 to $500 of each value! The best ceramic RF capacitors are made by ATC. Fortunately they also had most of the values in stock and in reasonable minimum quantities. Several values were paralleled when a particular value was not available. They are quite expensive, about $3 each for 500 V units below 200 pF and $8 each for the larger units. The filter set uses 29 different values. A commercial amplifier manufacturer would have to make a large capital investment to stock an LPF production line, another barrier for a solid-state legal-limit amplifier.

An alternative capacitor solution would be to use 500 V silver-mica capacitors. These are suitable for all but the 10 meter and 6 meter filters where a single unit's RF current rating might be exceeded and the lead parasitics changes the net value considerably. While SMT silver-micas are available, they are also hard to find in all the values needed. The leaded versions are far more common and are made by several companies. The downside is that the LPF board was laid out for surface-mount capacitors, all mounted on the bottom side of the board. Using leaded through-hole parts will require laying out a new LPF board and it will have to be larger.

With the capacitors used, the filter is suitable for a full kW output in a system with an SWR protection circuit as implemented in this amplifier. The coils might need to be implemented on the next larger size core.

LPF Construction

The LPF board, shown in **Figure 17.52**, has a continuous ground plane on the top side. All the coils are mounted through the board. As noted, all the capacitors are leadless SMT types mounted on the bottom side. Plated-thru vias complete the circuit to the top side ground. This arrangement with the coils on the top and capacitors on the bottom provides the best space efficiency and gives repeatable filter performance. Repeatability is not so much a concern for the home builder, but critical for commercial equipment.

To prevent coupling between bands, the filters are not in order across the board. On the two high band filters, the axis of each coil is perpendicular to the next to prevent coupling between them. Finally, each filter is shorted out by the selection relays when not in use, which helps prevent "sneak paths" around the selected filter.

The filter selection relays are used in pairs. Each is rated for 10 A, overkill for this application. They are quite inexpensive, around $1 each in quantities of 25, and have very low loss and parasitic inductance. The 10/12 meter and 6 meter filter values were tweaked for lowest loss and best efficiency after the whole filter was built. Computer modeling of the stray capacitances and inductances proved tricky and in the end it was better to temporarily replace the end capacitors with trimmers and tune for best performance to find the final values and then replace them with fixed units.

ALC DETECTOR

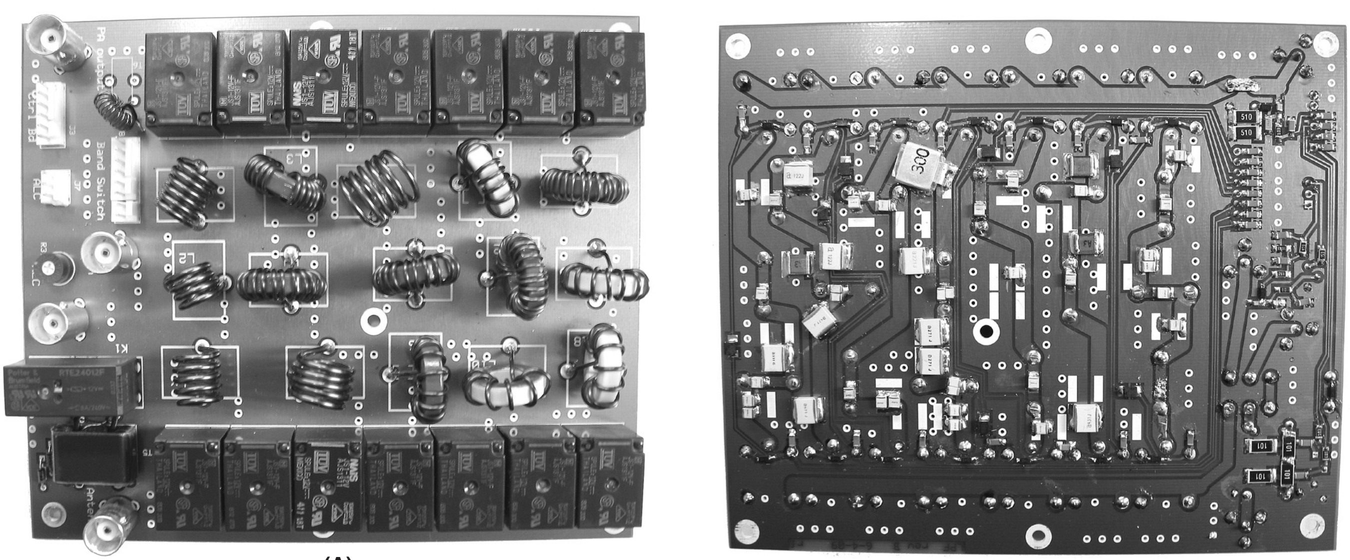
There is also an automatic level control (ALC) detector on the LPF board. ALC provides a feedback signal to the exciter to prevent overdriving the amplifier, and it was once a very common connection between the exciter and amplifier. Now that most solid-state transceivers have an output power control, it is used less often but still useful.

ALC interfacing is difficult because there is no standard ALC system specification among different transceiver brands and models. The detector here is a generic circuit with median values that generates a negative-going ALC signal. D17 rectifies the drive signal after a detection threshold, set by R6, has been exceeded. The attack time and filtering time constants are set by the RC network following the diode. Some adjustment of the R/C values may be required to work with a particular model of transceiver because of loop dynamic stability issues.

17.11.4 Power Supply

The PA requires 48 V at 10 A peak. It does not have to be regulated provided the following conditions are met. The maximum no-load voltage of 55 V is preferred, and it cannot exceed 60 V under any condition to provide a suitable safety margin. It must have at least 10,000 μF of filtering to prevent noticeable hum modulation. A simple power transformer feeding a 20 A bridge rectifier and a filter capacitor is sufficient. It may require a step-start circuit to ease the high current surge on the line power switch. See the **Power Supplies** chapter for more information.

The alternative is to use a switching supply. Supplies rated for 48 V and 500-600 W supplies regularly go for less than $100 at online auction. They are small and light. You may have to deal with RFI issues on some of the cheaper models, though. This usually just requires a ferrite bead and additional bypass



(A)

(B)

Fig 17.52 — The assembled low-pass filter board with the coils, relays and other components mounted on the top side (A) and the LPF capacitors mounted on the bottom (B). The prototype used available capacitors — two sizes of ATC ceramic RF chip capacitors, a metal clad mica and three unencapsulated SMT mica units. All are serviceable, but the ATC ceramics work best.

capacitors on both the ac input lines and the dc output lines as well.

Power output varies with the square of supply voltage. The amplifier will put out 75 W if run from 25 V. The gain changes very little, just the output power. This squared relationship makes it more sensitive to ripple modulation, so make sure that the power supply, no matter how it is made, has reasonable filtering. It does not need to be current-limited since the PA control has this built-in. It does need a suitable fuse, however. A 15 A low-voltage fuse will do nicely.

The power supply used in the test amplifier was purchased on eBay. It was called "500 W 48 V 10.4 A Switching Power Supply for Radio" and was less than $100 including shipping. It is 8.5 inches long, 2 inches high and 5.54 inches wide. It was the best value of all power supply options investigated. However, as in all compromise decisions, it was not without a downside as will be described later.

17.11.5 Amplifier Cooling

Cooling is the single most important requirement for a transistor's reliability. Tubes can get hot and angry, but they are made from high-melting-point materials so they can stand the heat. Transistors cannot. They will melt. The active area of a VRF151 die is 0.034 square inch, about the area inside the letter P on a computer keyboard. It must dissipate up to 150 W when key down. The heat dissipated in the transistor die is conducted through to the transistor's package base. Here it is conducted to the heat sink which, because of its large surface area, can effectively couple the dissipated heat into the surrounding air.

Figure 17.53 shows the VRF151s on the PC board and heat sink. There is no substitute for ensuring a good mechanical fit before mounting the transistors. The heat sink surface must be as flat as possible and the transistors must also be flat. A sheet of 600 grit sandpaper on a glass plate makes a good way to check the flatness of high power metal-backed transistors. A couple of light strokes across the paper will reveal any high spots on the bottom of the device. Keep rubbing until the back is all the same color. The plating on the back is not necessary once it is mounted — bare copper is fine.

Similarly, the heat sink must also be flat. Extruded aluminum heat sinks are notoriously "lumpy." A careful swipe across the width of the sink with a large flat file, perpendicular to the direction of the fins, will reveal any ridges and valleys. File it until they disappear. Be careful to keep the file clean or you can do more harm than good. In commercial practice, extruded heat sinks are usually milled flat before use.

The interface between the transistor and the heat sink is always greased with thermal heat sink compound. Thermal grease is a suspension of zinc oxide powder in silicone or mineral oil. It is very similar to the white sun screen paint used to protect your nose at the beach. Here it is the oil that does the work. The zinc oxide is simply a filler to keep the oil from running away. Oil is not a good conductor of heat but is much better than air. The thermal grease is used to fill any microscopic gaps and scratches between the sink and the transistor. Use only as much grease as needed to fill the gaps. Spread an even thin coat of grease on the bottom of the transistor with a knife blade then put the part on the sink. Before putting in the screws, wiggle the part around on the sink to force out any trapped air and to make the layer of grease is as thin as possible. You should be able to feel the sink grab the part as you move it. It does not want to "float" on the grease!

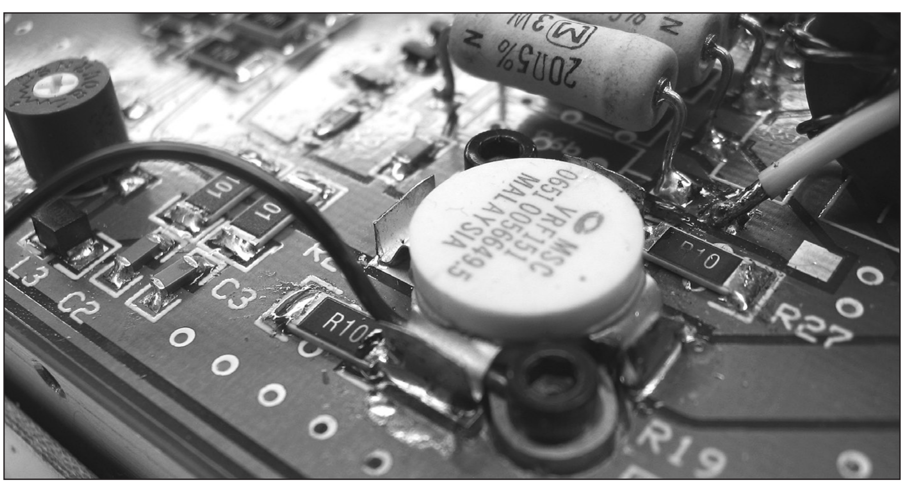


Fig 17.53 — It's important to make sure that the VRF151 power transistors mount flush to the heat sink, without gaps or air pockets that would impede heat transfer (see text for details). Once the transistors are mounted, a piece of wire is used as a lead forming device to bend the transistor leads down to the PC board pads for soldering.

THERMAL DESIGN

The VRF151's maximum junction temperature rating is 200 °C, but device lifetime is seriously degraded at this temperature. Industry design standards typically aim for 150 °C absolute maximum, and typical operating temperature about 130 °C. The heat sink chosen for this amplifier is a 7-inch length of aluminum extrusion 3.25 inches wide and 1 inch high with nine longitudinal fins. This provides a lot of surface area, but in order to remove the 250 W of heat dissipated when the amplifier is running at maximum CW power, the heat sink must have air forced through it. It is impossible to dissipate this much heat by convection alone. The forced air cooling keeps the junction temperature below 150 °C at all times. The combination of a fairly large heat sink area and a relatively small fan allows the amplifier to "keep its cool" without making a lot of noise.

A single 3-inch 24 V dc fan (47 CFM) provides pressurized air across the sink. The closed chassis forms a pressurized plenum. The air comes in through the fan but can only leave the chassis after traveling down the length of the heat sink and out the 3 × 1 inch opening in the rear panel. Ducting the air this way makes very effective use of the fin area on the heat sink.

The original prototype of the amplifier had two smaller cooling fans mounted on the rear panel. When the amplifier was put in its place on the operating table, it was overheating because both the air intake and exhaust were on the same end of the chassis. It was sucking in its own hot air. A new chassis was bent up and this time the fans were mounted on one side of the cover. This eliminated the self-heating problem and allowed a much cleaner layout of the rear panel. It provided enough space to mount the fuse holder outside rather than inside. The final version uses a single high capacity 24 V fan. A 24 V 5 W Zener diode is placed in series to run it from the 48 V supply. A 48 V fan would be a better choice, but a suitable unit was not available from distributor stock, only by special order.

Note of caution: The amplifier cannot be run at power without the top cover in place because the chassis must be pressurized in order to force the cooling air thorough the fins of the heat sink.

The fan runs at full speed all the time. It would be more "operator friendly" to run the fan at a very low speed to start off with and use the temperature sensing circuit to increase the fan speed when the heat sink reaches a moderate temperature, say 100 °F. A second threshold point would run the fan at full speed when the sink temperature reaches 120 °F. This is a project for the next version. As it is, the fan does not require any controls. It will continue to run after the supply is switched off until it bleeds down the filter capacitors.

17.11.6 Metering and Calibration

The cost of quality moving-needle meters has gone beyond reasonable, in part because digital panel meters have become more popular. However, you need to be able to assess the health of the amplifier at a glance and digital meters are not good for this. LED bar graphs are very inexpensive and are used for metering in this amplifier. They are easy to read and because of their low cost we can have one for each parameter being measured. Output power is displayed on a 20 LED string (made from two 10 LED bars). There is a "hang" built in so the SSB voice peaks can be seen easily. The drain current and reflected power are each shown on 10 LED bars. The output of the thermistor on the heat sink is also available for display by changing a jumper or incorporating a selector switch.

Absolute meter calibration is not so important in an amplifier like this. As long as none of the displays overflow in normal operation, they will serve as a way to easily monitor the operation of the amplifier.

Calibration of the meters will require using external standards. An ammeter in series with the power supply will be enough to calibrate the current meter. It should be set to display 15 A at full scale. R1 is adjusted to light bar #10 at 15 A. It would work out exactly right if all the resistors were 1% values. Forward power similarly requires a calibrated power meter on the output. R33 should be adjusted for 250 W when 18 bars of the 20 are lit. The top two LEDs are red and the others green so the operator can readily tell when the drive is too high.

Calibrating the reflected power is a little more difficult. The simplest method requires a calibrated external wattmeter. Run 30 W of RF power from another source backward through the amplifier, from antenna to input, *with the operate switch in the standby position*. Set R34 so the SWR LED trips at this point. This corresponds to an SWR of 2:1 at 250 W output. The amplifier should be stable and totally reliable up to this mismatch. If your load has a higher VSWR than 2:1, you can back off on the drive and continue to operate. As long as the reflected power is less than 30 W, the amplifier is happy.

Protecting the amplifier from damage requires a combination of careful attention to the operating conditions and reliance on the automatic limits in the control system.

17.11.7 Chassis

As seen in **Figure 17.54**, the chassis is a double clamshell configuration made from aluminum sheet stock. The top cover is 0.031-inch thick and the chassis bottom is 0.062-inch thick. This provides both adequate strength and workability with simple hand tools. Aluminum 12 × 24 inch sheets are available from several suppliers. They were sheared to size and bent into U-shaped parts at a local sheet metal shop.

The power supply and the fans are mounted on the cover. It overhangs the chassis base by 1⁄16 inch on all sides. The top is attached by 4-40 threaded L-brackets, DigiKey part 612K-ND, that are riveted to the main chassis. A drawing of the chassis layout and front and rear panels is included elsewhere on the CD.

17.11.8 Performance

The maximum for the PA design itself is 300 W. Increasing its output past 300 W to make up for filter loss quickly degrades the IMD performance. It needs some headroom. So, in very un-amateur fashion, this amplifier is conservatively rated at 250 W output. This provides a clean signal and plenty of margin for wrong antenna selection, disconnected feed lines, and all the other things that can kill amplifiers that are run too close to their limit.

The PA will provide 250 W PEP for sideband or PSK and 250 W CW. The design goal for this PA was to make it reliable and at least as good as any competitive transceiver. The harmonics are –60 dB on HF and –70 dB on 6 meters. Transmit IMD is >38 dB down from either tone as shown in **Figure 17.55**.

Parasitics are not usually a problem in broadband amplifiers because of the feedback used. The prototype was tested into a 3:1 SWR load at all phase angles without breaking into parasitic oscillation anywhere.

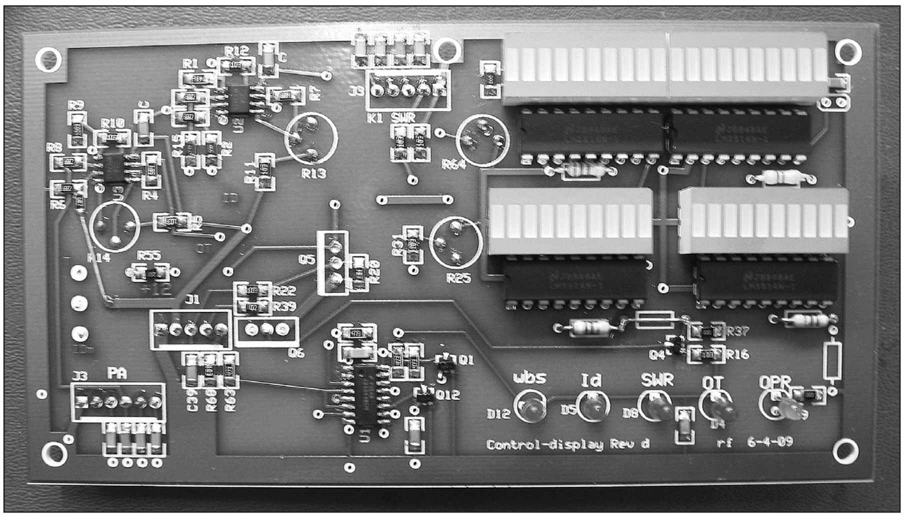


Fig 17.54 — The control and display circuitry mounts on a PC board that attaches to the front panel. LED bar graphs show forward and reflected power and current.

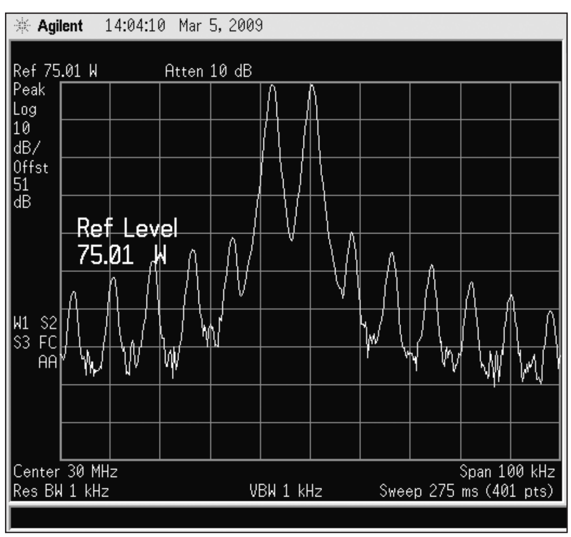
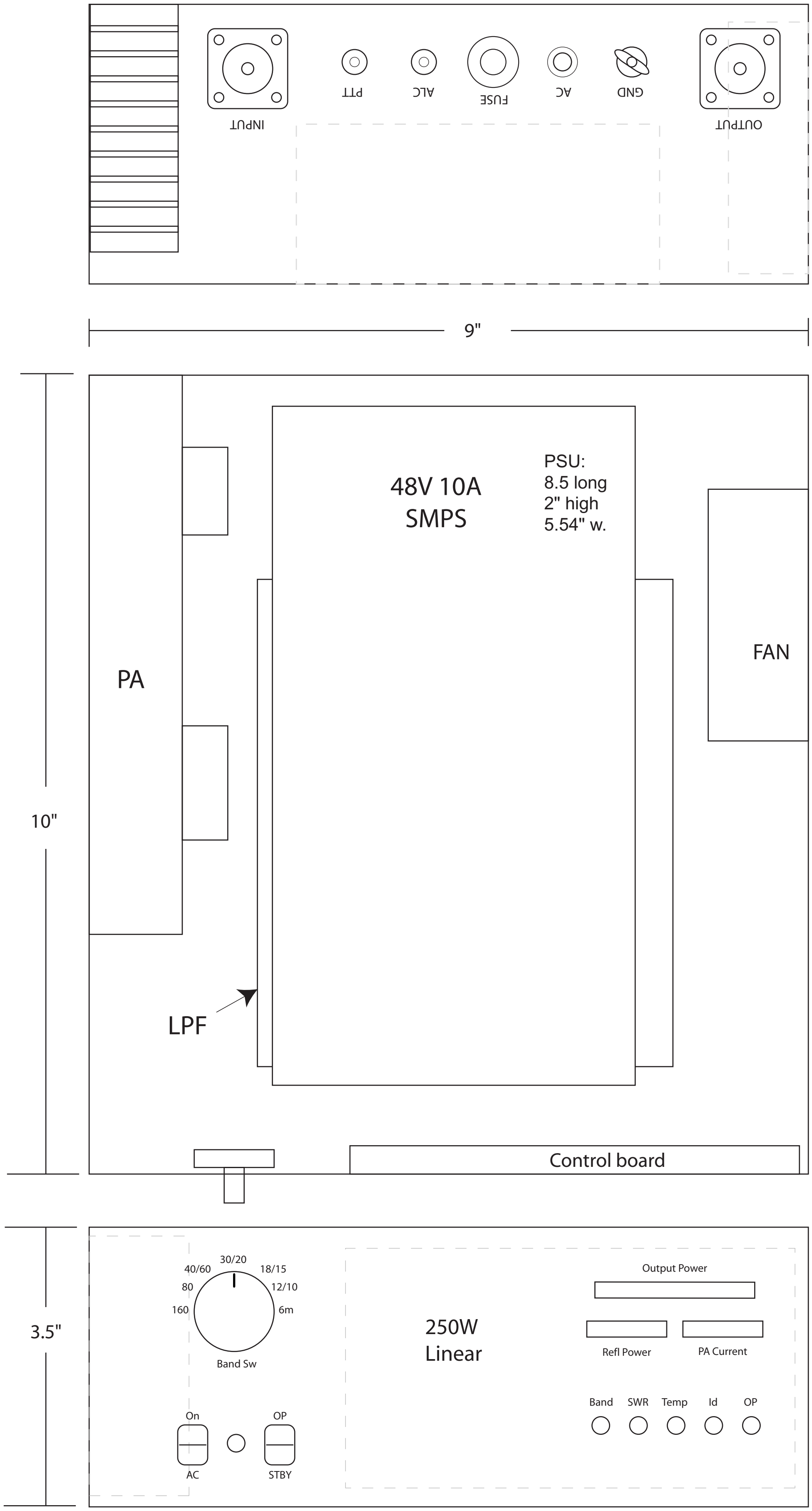


Fig 17.55 — Output of the 250 W amplifier during two-tone IMD testing. All IMD products are better than 38 dB down from either tone.

250 Watt Amplifier Chassis Layout



A 3CX800A7 Amplifier for 432 MHz

By Steve Powlishen, K1FO

In 1979, I described a 432-MHz power amplifier using a single 8874 tube.[1] The popularity of the amplifier far exceeded my expectations. While stable, linear and efficient, the 8874 amplifier had several drawbacks:

1. Construction required considerable metal fabrication, as the RF enclosure dimensions didn't correspond to a standard chassis size.

2. At 432 MHz, the 8874 requires over 35-W drive for full output—more than current 25-W transceivers can provide.

The introduction of the EIMAC 3CX800A7, essentially an improved 8874, provided the inspiration to build a new and improved amplifier. I wanted higher gain and simplified construction. In addition, this amplifier has TR switching voltages and currents compatible with low-power solid-state transceivers, and tube-protection circuitry.

The IMD performance of this amplifier is almost an order of magnitude better than some 432-MHz exciters! While this point may appear insignificant, operators may have to contend with local signals that are 80 to 100 dB above the noise and only a few kHz away. Any serious 432-MHz operator can attest to near loss-less propagation periods when signals 300 miles away are 80 to 90 dB above the noise. Under such conditions, this amplifier will not aggravate other operators.

While expensive when purchased new, the 3CX800A7 may still be a bargain. When you consider that in intermittent service a properly operated 3CX800A7 still may be cooking long after another operator has gone through several sets of 4CX250-class tubes, the initial price appears more reasonable.

The amplifier described in this article will deliver about 620 W with 25-W drive. At maximum ratings, the 3CX800A7 generates 730 W. Efficiency and maximum power output are better than with the 8874 amplifier.

Construction Details

To minimize metal work, the amplifier uses 4 standard aluminum chassis. The RF plate enclosure is made from a 5- × 13- × 3-in. chassis. The cathode circuit is housed in a 4- × 5- × 2-in. chassis. The RF enclosures are attached to the EIA standard 5¼ in. high, 19-in. rack panel by 2 standard 5- × 7- × 2-in. chassis. Using the smaller chassis in this way makes it unnecessary to fabricate mounting brackets for the RF deck, while also providing space to mount the control circuits. Heavy gauge (0.062-in. or thicker) cover plates are preferred on the RF chassis to assure RF sealing and provide mechanical rigidity.[2]

The construction of this amplifier has the RF deck mounted on its side, relative to the construction of most amplifiers. This mounting method has several advantages. The tuning controls can be positive-actuating lead screws, while still providing front-panel access. Alternately, the fish-line tuning arrangement can be used, as I did. Fish-line actuated controls allow the front-panel knobs to be placed for convenience and esthetics. The mounting arrangement used in this amplifier accommodates a convenient control arrangement while minimizing the length and bends in the fish line. As a result, the plate tuning controls operate smoothly and repeatably. An additional benefit to the mounting method is that tube hot air exhaust exits to the rear of the amplifier. Other equipment can be mounted above or below this amplifier, without leaving cooling space. I built matching 3CX800A7 amplifiers for 50, 144, 222 and 432 MHz. All four amplifiers and their 2200-V power supply can be mounted in a single 28-in. high desktop rack.

I took care to make this amplifier easy to duplicate with readily available parts. Complete metal cutting and drilling drawings are provided for the RF sections. If you accurately follow the drawings and use all parts specified in Table 1, the amplifier should go together and tune up like a commercial kit. I don't discuss the layout of the control circuits as they are not critical, and you may wish to tailor them to your station. Some of the specified parts are priced higher than junk-box substitutes. With some ingenuity you may be able to use cheaper parts, but you do so at your own risk. I'm unable to offer advice about finding and using substitute parts.

Plate Circuit Details

The plate circuit is the now-standard half-wave stripline with the tube located at one end. A "flapper" tuning capacitor is mounted at the other end. The stripline (Fig 1) is larger than

Table 1
Parts List for the Single 3CX800A7 Amplifier

Chassis and Hardware Components

RF deck enclosure: 5×13×3-in. chassis, Bud AC-422 or equiv.
Cathode compartment: 4×5×2-in. chassis, Bud AC-1404 or equiv.
Side chassis (2 req.): 5×7×2-in. chassis, Bud AC-402 or equiv.
Rack panel: 5 1/4×19×1/8-in., Bud SFA-1833 or PA-1103 or equiv.
Tube socket: 11-pin EIA, Eimac SK-1900 or Johnson 124-0311-100.
Grid collet: Eimac 720359 assembly (Eimac 882931 can be used).
Anode collet: Eimac 720829.
Grid collet insulator: Eimac 720518.
Chimney: Eimac SK-1906.
Panel bearings: 1/4-in. diam., Millen 10066 (2 req.).
Reduction drives: Jackson 4511/DAF (2 req.).

Components Referenced On Schematic Diagram

C1—1.5-5 pF miniature air variable (butterfly); Cardwell 160-0205.
C2—1.8-8.7 pF miniature air variable; Cardwell 160-0104.
C3-C5—1000-pF, 300-V feedthrough capacitor; Tusonix 327-005-C5UO-102M.
C6—Plate tuning flapper. See text.
C7—Plate loading flapper. See text.
C8—1000-pF, 4000-V feedthrough capacitor; Tusonix 2498-001-X5UO-102M.
C9-C10—1000 mF, 25-V electrolytic.
C11—0.15 mF, 25-V disk or epoxy.
C12-C19—0.01-mF, 50-V monolytic ceramic; Sprague 1C105Z5U103M050B.
D1—5.6-V, 10-W Zener, mounted on RCA SK122/5178A heatsink.
D2—10-A, 400-PIV.
D3-D4—2.5-A, 1000-PIV; R170 or equiv.
D6-D14—1-A, 1000-PIV; 1N4007 or equiv.
F1—2-A, AGC or 3AG fast-blow.
F2—3/4-A, AGC or 3AG fast-blow.
I1—120-V neon, amber; GC Electronics 38-282.
I2—120-V neon, red; GC Electronics 38-280.
J1—Chassis-mount BNC female, UG-1094/U.
J2—Chassis-mount N female, UG-58A/U.
J3—Chassis-mount MHV female, UG-931/U.
J4—6-pin male chassis mount; Cinch P306AB.
J5—6-pin miniature chassis connector; Waldom Molex 03-06-1061.
J6-J8—Phono connector; Switchcraft 3501FR.
K1—180-sec. thermal time-delay relay, 115-V heater, SPST-NO; Amperite 115NO180B.
K2—Control relay, DPDT, 24-V dc coil; Potter and Brumfield R10-E1-X2-V700.
K3—Control relay, 4PDT, 24-V dc coil; Potter and Brumfield R10-E1-X4-V700.
K4—Coaxial relay, SPST, BNC connectors, 28-V dc coil.
K5—Coaxial relay, SPST, high-power, N connectors, 28-V dc coil.
L1—2 turns no. 16 copper, 1/4-in. diam., 3/4-in. long.
L2—Brass strip 1/4-in. wide × 1-3/16-in. long.
M1—Dc milliammeter, 600 or 1000 mA fullscale.
M2—0-1 milliammeter with shunt resistors to give full-scale deflections of 60 mA (grid current); 3 kV (high voltage); 30 V ac (filament voltage).
MOT1—54 cfm blower; Dayton 4C012 or equiv.
Q1-Q2—2N2222A, 2N3903 or equiv.
Q3—2N3053 or equiv.
Q4—2N4037 or equiv.
Q5—2N2904, 2N3905 or equiv.
R1—200-Ω, 25-W wirewound.
R2—1000-Ω, 12-W wirewound.
R3—10-kΩ, 25-W wirewound.
R4—1-Ω, 1-W, 1%.
R5-R10—499-kΩ, 1/2-W, 1% metal-film, type RN-60 preferred.
R11—820-Ω, 1/2-W, metal film. Select value to calibrate HV meter.
R12—1.5-kΩ, 1/2-W metal film. Select value to adjust HV relay trip point.
R13—9-Ω, 1/2-W metal film. Select value to calibrate grid meter.
R14—10-Ω, 2-W, metal film
R15—10-kΩ, 1/4-W miniature trimmer.
R16—1200-Ω, 2-W. Select value to set K1 time delay.
R17—50-Ω, 12- or 25-W adjustable slider wirewound.
R18—1-Ω, 5-W wirewound.
R19—12-kΩ, 1/2-W, film.
R20—2-kΩ, 1/4-W, miniature trimmer.
R21, R22, R25, R27—2.7-k, 1/2 W.
R23, R28—10-kΩ, 1/4 W.
R24—4.7-kΩ, 1/4 W.
R26—2.2-kΩ, 1/4 W.
R29—330 Ω, 1/4 W.
R30—500-Ω, 25-W wirewound.
RFC1—8 turns, no. 18 enameled, 1/4-in. diam., closewound.
RFC2, RFC3—8 turns, no. 16 enameled, 1/4-in. diam., closewound.
RFC4, RFC5—7 turns, no. 18, 3/4-in long, 1/4-in. diam.
S1—DPST toggle.
S2—SPST toggle.
S3—2-pole, 4-position rotary.
S4—SPDT miniature toggle.
T1—Filament transformer: 14-V, 2-A secondary, 120-V primary; Stancor P8556 or equiv.
T2—Control transformer: 10-V, 2-A secondary, 120-V primary; Stancor P8653 or equiv.
W1—Plate stripline.
W2—Cathode stripline.

the one used in the 8874 amplifier, both to fill the larger plate compartment and to accommodate the larger (2.5-in.) diameter of the 3CX800A7 anode radiator. The larger stripline allows for better placement of the tuning controls. The preferred material for the stripline is 1/16-in. brass, which is silver plated after the collet is soldered in place. Copper is also suitable, but

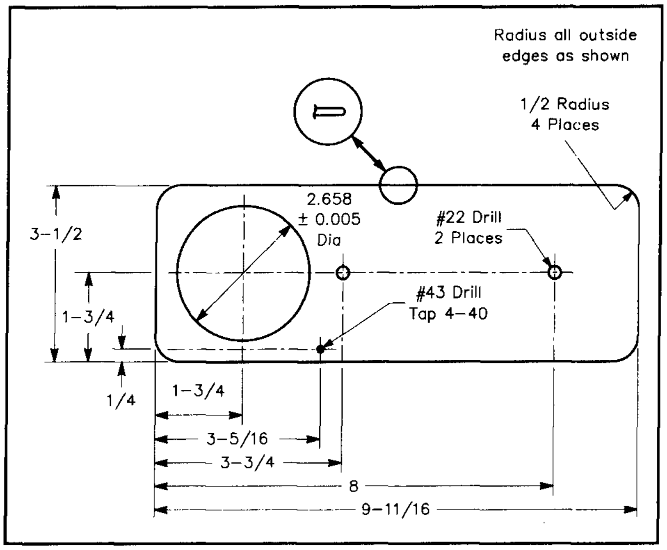


Fig 1—Plate line of the single 3CX800A7 amplifier. Except as noted on the drawing, dimensions are ± 1/32 in. Material is 1/16-in. copper or brass. Anode hole is sized for the EIMAC 720829 collet. Dull-finish (nickle-less) silver plating is recommended after the collet is soldered in place.

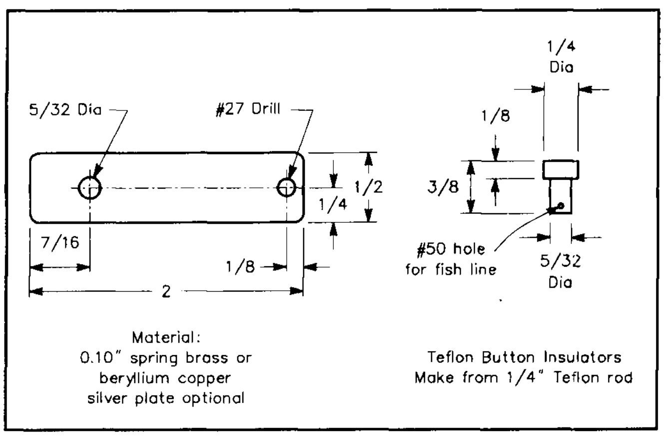


Fig 3—Plate loading capacitor C7 is made from 0.010-in. spring brass or beryllium copper. The button insulator is made of 1/4-in. Teflon rod.

harder to machine. If you have your line professionally plated, specify a "dull" finish; that is, without nickel content. A plater experienced in RF work will know what you mean. He will copper flash the line before plating it. Specify a minimum silver thickness of 0.001 in. In 1986, the cost to silver plate all parts (W1, W2, L2, C6 and C7) was $63, of which $60 was for setup and only $3 was for material. For minimal additional cost, you and other hams can collect a wide assortment of RF parts and have them all plated at once.

Silver plating is *not* necessary for proper operation. The difference in efficiency between a clean, polished but unplated stripline and a silver-plated line was nearly impossible to measure. Experience with the 8874 432-MHz amplifier has shown that an unplated line begins to tarnish after a few years. When the oxidation is heavy enough, the amplifier tuning drifts as it heats up. Polishing the stripline returns the amplifier to

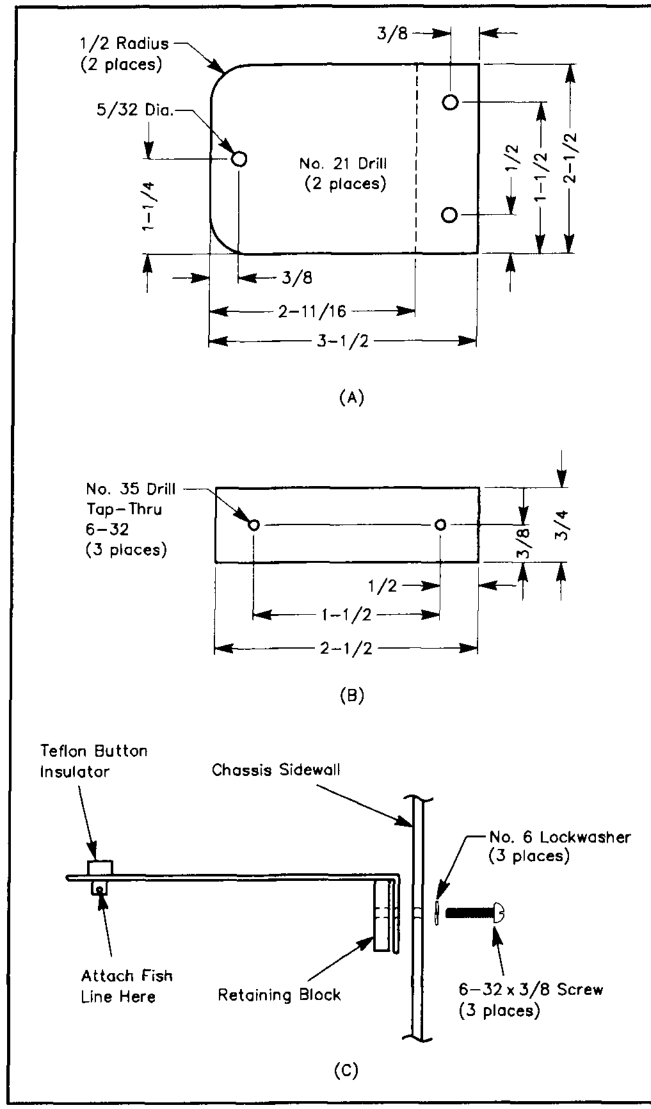


Fig 2—Plate tuning capacitor C6 (A); retaining block (B); mounting of the capacitor and retaining block (C). The capacitor is made from 0.010-in. hard brass or beryllium copper. Silver plating is optional. The mounting block is made from 1/8-in. aluminum.

like-new operation with no thermal drift.

The plate line is held in place with two 1½ in. high × ⅜-in. diameter ceramic standoff insulators. Homemade Teflon insulators are even better. They can be made ⅜ or ½ in. diameter. Tap the ends for 6-32 screws. Use brass screws to hold the stripline in place. Steel (and especially stainless steel) can cause unwanted tuning effects. Also use a brass screw to attach the plate RF choke (RFC4). The screws used to attach the standoff insulators to the chassis bottom can be steel. The hole in the plate line for the anode is sized for an EIMAC 720089 collet. Finger stock may be used if you prefer. If you use finger stock significantly larger than the EIMAC collet, the position of the plate-tuning capacitor will be different. Try to obtain finger stock with contacts that are rolled over 180°, sized about ⅛ to 3/16 in. high, with the fingers rolled over about ⅛ in. Be careful to size the anode hold in the plate line correctly.

The tuning and loading capacitors are made from 0.010-in. thick brass shim stock. This material has a spring temper

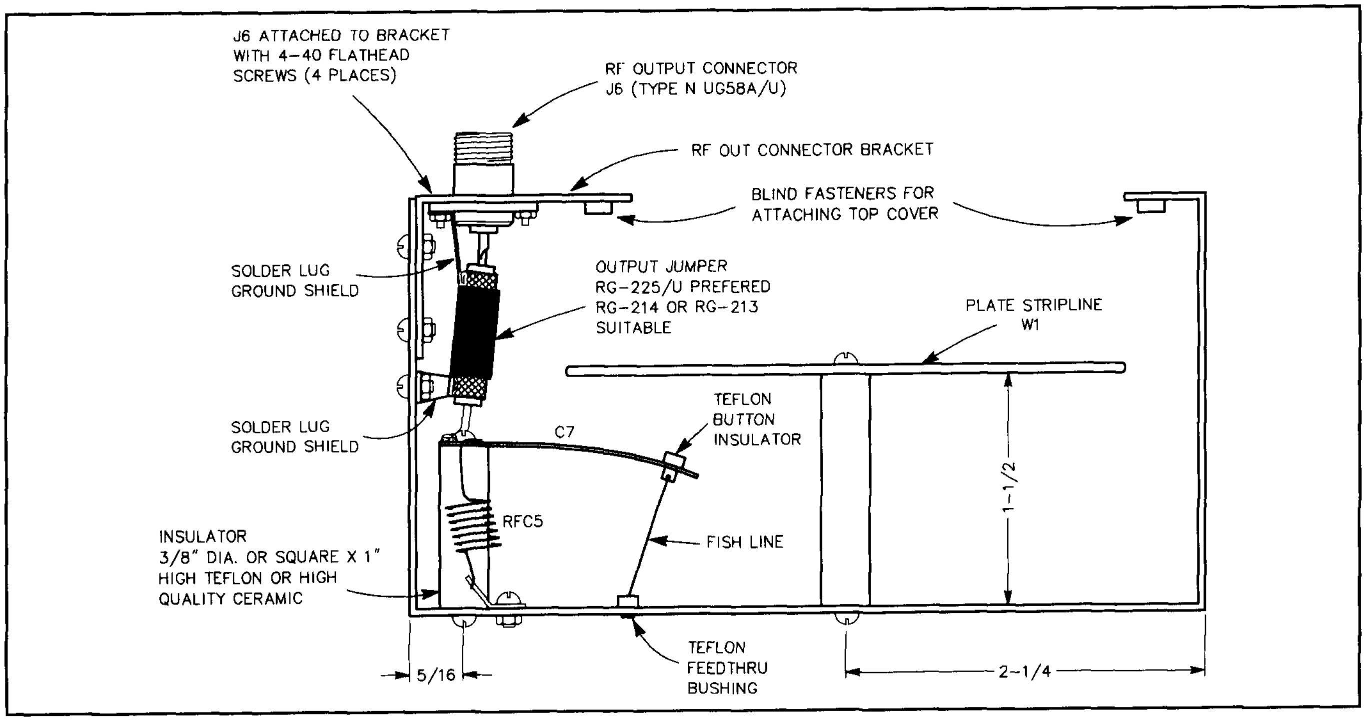


Fig 4—RF output compartment details. The plate line is not centered in the enclosure. See Fig 5 for construction details of the RF output jumper.

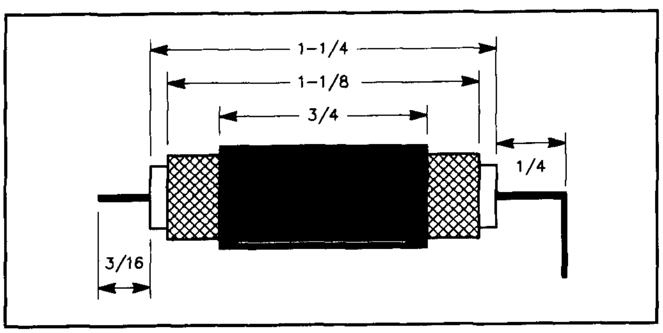


Fig 5—RF output jumper details. RG-225 Teflon-dielectric cable is preferred, but RG-214 or RG-213 cable may be used. Alternately semi rigid solid copper sheathed cable such as UT-141 or UT-250 may be used.

and works well. You can also use beryllium copper. Don't use material thicker than 0.010 in. Thicker stock is more likely to take a set and not spring back to its original position. In addition, thicker material may place too great a load on the fish line and tuning controls. The strain may stretch the fish line or move the tuning control positions, affecting tuning.

The plate flapper (Fig 2) is held in place by an aluminum block ¾-in. wide × 2½ in. long × ⅛-in. thick. Tap the holes for 6-32 thread, for easy installation and removal. The loading flapper (Fig 3) is mounted on a 1-in. tall, ⅜-in. dia. Teflon or ceramic insulator. Both flappers use small Teflon button insulators to secure the fish line. These homemade insulators serve the dual purpose of providing an attachment point for the fish line and preventing the flappers from accidentally contacting the plate stripline.

The preferred fish line is braided Dacron fly line. I used Specialist 18-lb Fly Line Backing, made by Berkley. Be sure

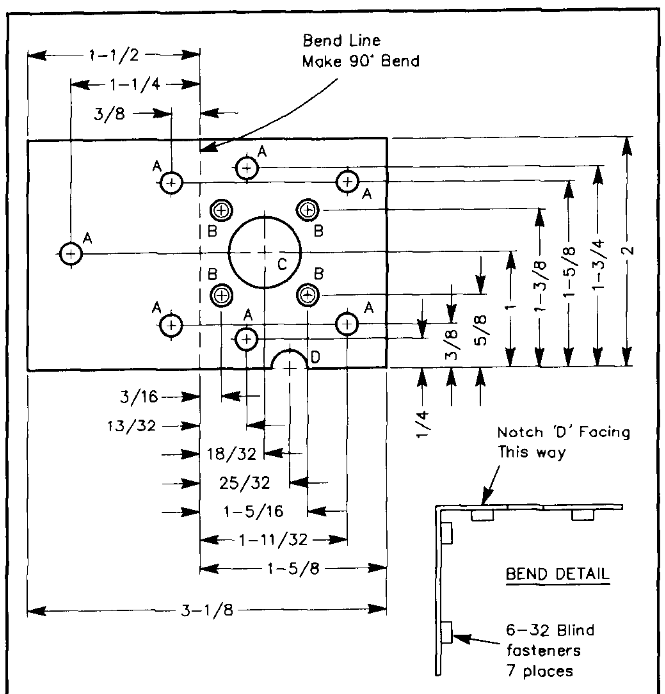


Fig 6—RF-output connector bracket is made from 0.062.-in. aluminum. Holes marked A are 3/16-in. diam., for 6-32 blind fasteners. Asterisks (*) indicate holes that should be located using the top cover as a template when the bracket is mounted. Holes marked B are No. 30, countersunk for flush mount with 4-40 screws. The connector mounting holes may also need to be countersunk. Hole C is 5/8 in. diam. Hole D is a 5/16-in. diam. notch to clear the blower mounting plate.

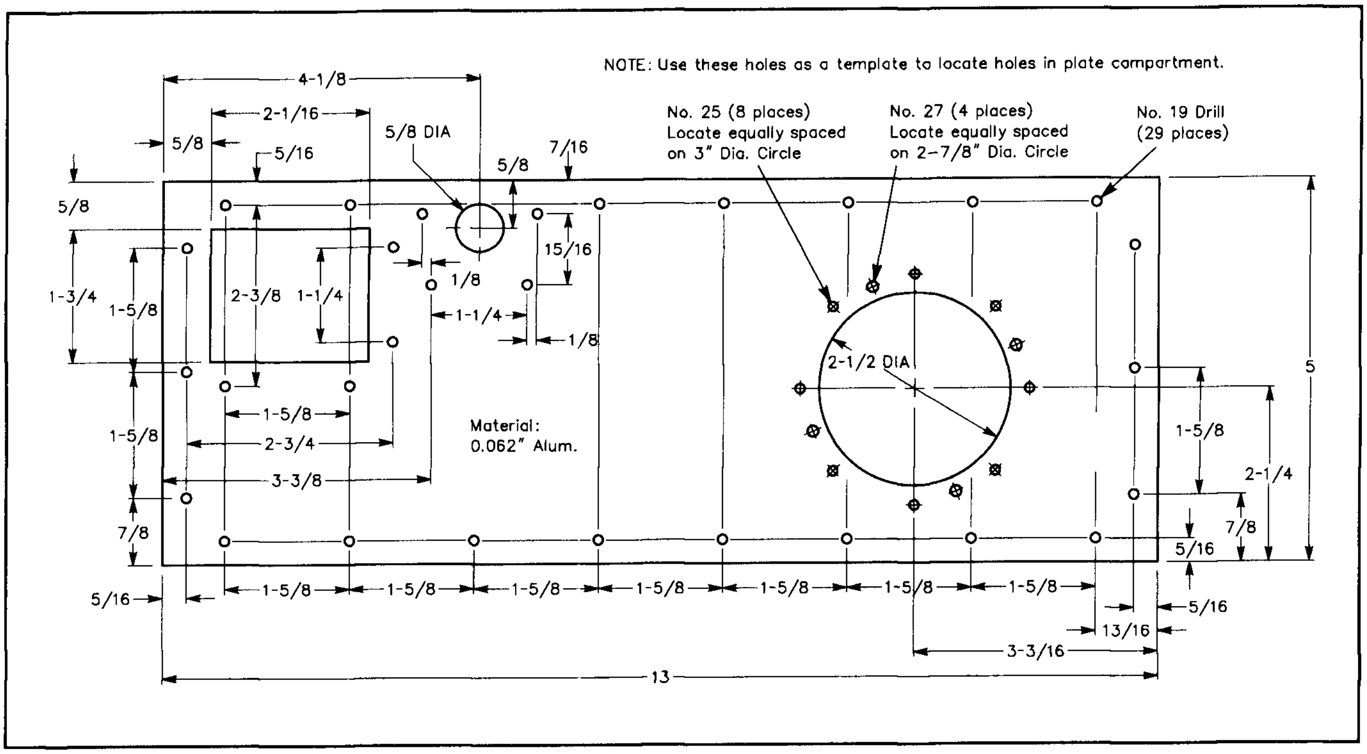


Fig 7—Top cover of the amplifier is made from 0.062-in. aluminum. Use the cover as a template to mark holes in the chassis.

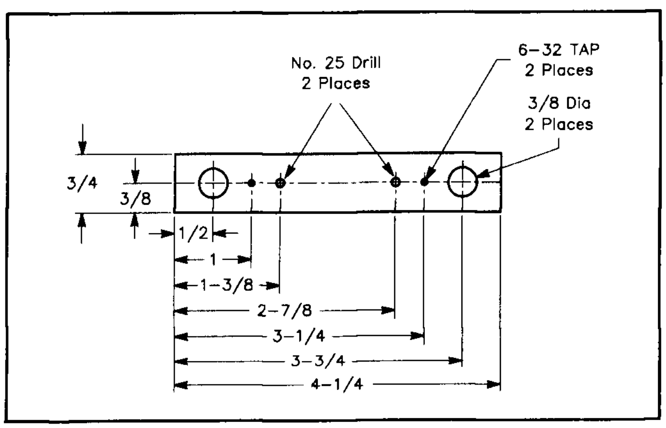


Fig 8—Plate tuning control bracket is made from 0.062-in. aluminum.

all edges on the flappers are smooth and free from burrs. Also make sure the flappers are mounted parallel to the stripline. These precautions assure RF or dc doesn't arc from the plate line to the flappers.

A small piece of RG-225 coax connects the loading capacitor to the RF-output Type-N connector (J2). Fig 4 details assembly of the loading capacitor (C7) and Fig 5 gives dimensions for the coax jumper. RG-225 is similar to RG-214, but uses Teflon dielectric and jacket, along with double silver-plated shields. You can also use RG-213 or RG-214 if you're careful not to melt the dielectric while soldering it in place. Both ends of the shield are grounded through solder lugs. Be sure that the jumper is mounted close to the chassis wall and away from the stripline. The output connector is mounted on a small bracket to allow for rear-panel RF-output connection, while not requiring any disassembly when the plate-compartment cover is removed. Fig 6 gives the layout of the output connector bracket.

Be very careful when notching the plate chassis for the RF- output-connector bracket. Once the lip is cut out it is very easy to bend the chassis if the bracket is not secured in place. The top cover (Fig 7) should be drilled first. Then you can use it as a template to locate the holes in the chassis that will hold the top cover in place. Next, install the blind fasteners (PEM nuts). Once the fasteners are in place, you can notch the chassis for the output-connector bracket. Cut the bracket to size and bend it 90°, as shown in Fig 6. Drill the 3 holes for the bracket mounting screws and install the bracket. Now use the top cover again as a template to locate the output-connector hole and the 4 top-cover mounting holes. You can use the UG-58 output connector as a template to locate its mounting holes.

The plate tuning and loading fish lines are brought through the chassis through small homemade Teflon bushings. The lines run over small pieces of ¼-in. Teflon rod, giving nearly friction-less 90° transition of the tuning controls. Brass shafts, which run through panel bearings that are mounted on a support bracket (Fig 8), control the tuning lines. This bracket is supported by standard 1¼ in. long steel standoffs. To impart a slow, smooth feel to the plate tuning and loading controls, 6:1 ball-reduction drives are used. The drives I used are Jackson Bros. 4511/DAF, and is available from Radiokit or Surplus Sales of Nebraska.[3] The ball drives are

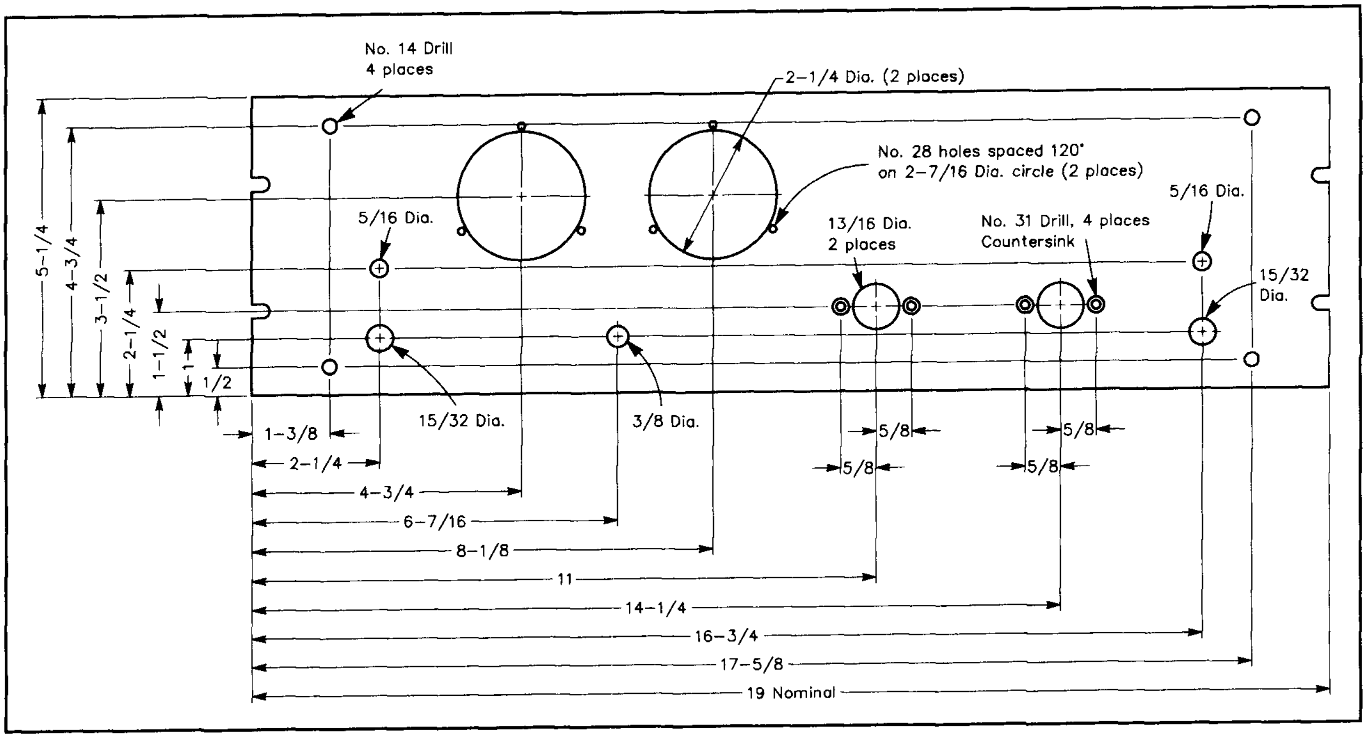


Fig 9—Front-panel layout. The panel is made from a standard 5-1/4 in. aluminum EIA rack panel.

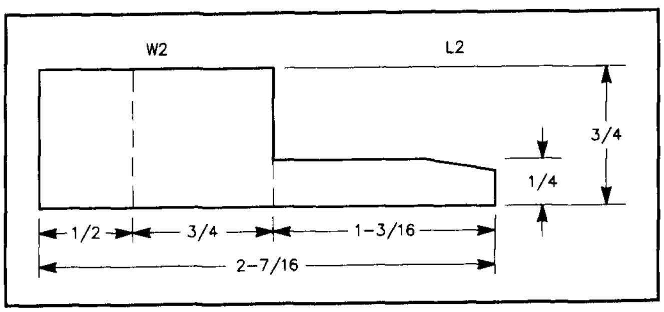


Fig 10—Cathode stripline is made from 0.015-in. brass. Silver plating is optional.

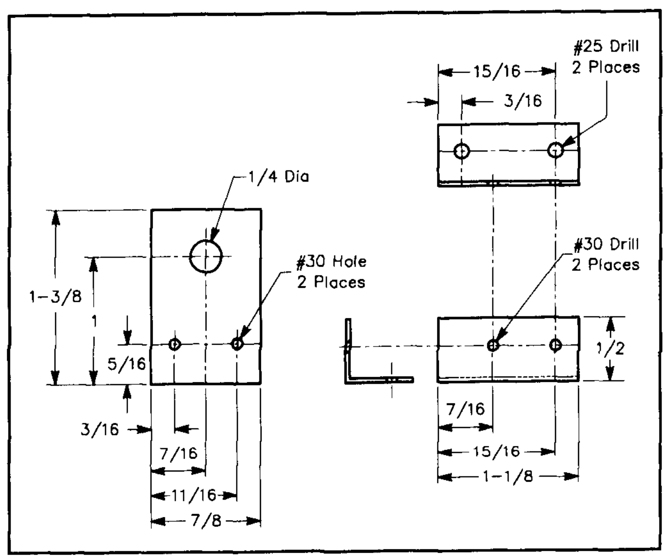


Fig 11—C1 mounting bracket is made from 0.062 X 1/2-in. aluminum angle or 0.062-in. aluminum sheet. The mounting insulator is made from 1/16-in. G10 circuit-board material from which the copper has been removed.

mounted to the front panel with 4-40 flat-head screws. Fig 9 shows the front rack-panel hole sizes and locations for the ball drives and other holes. Use 4-40 nuts to secure the screws, so they act as mounting studs for the ball drives. The nuts also serve as spacers to position the ball drives nearly flush with the front panel. Homemade pointers attached to the ball drives serve as control position indicators.

The specified high-voltage feedthrough capacitor may be hard to find. It may be available from Microwave Components of Michigan.[4] You can also construct a bypass capacitor from 1/16-in. thick brass plates and 0.005-in. Teflon or Kapton sheets. A two-plate capacitor with one plate inside the RF enclosure and another plate on the outside is recommended. Plates sized approximately 2½ × 3¼ in. are suitable. The plates should be flat, polished so they are smooth and free from any burrs, and have rounded edges. If you use Teflon, spread silicone grease on the Teflon to fill in any imperfections. You don't have to coat Kapton, as it doesn't have the porosity or cold-flow characteristics of Teflon.[5]

Cathode Circuit Assembly

The cathode circuit consists of a quasi-half-wave line, similar to that used in the original 8874 amplifier. Changes have been made, due to the higher input capacitance of the 3CX800A7 and to make the circuit more repeatable when duplicated. Fig 10 gives the layout of W2 and L2. Most of the first quarter wave of the half-wave input line is actually inside the tube and socket. W2 forms the rest of the first quarter wave and part of the second quarter wave. L2 completes the second

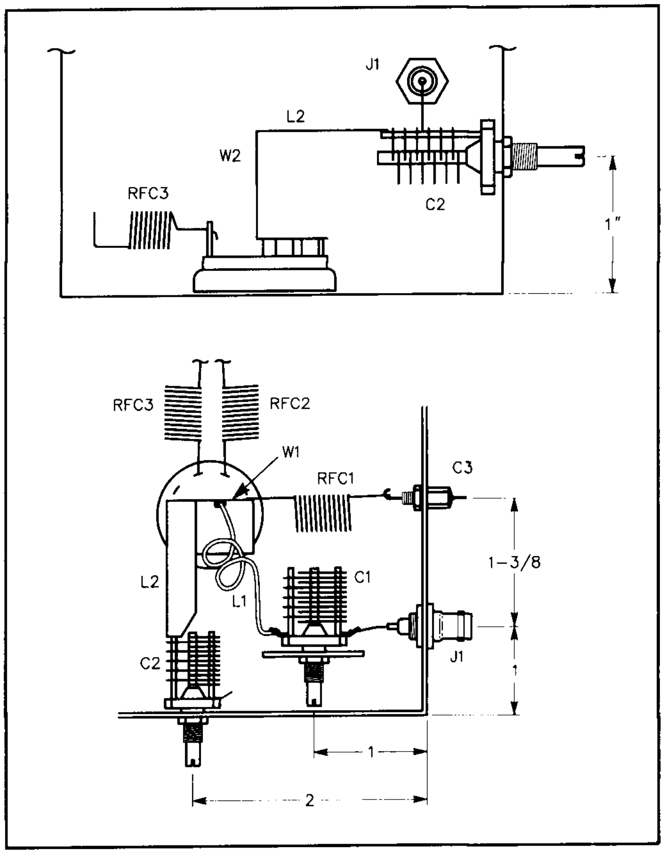


Fig 12—Side and bottom views of the cathode circuit.

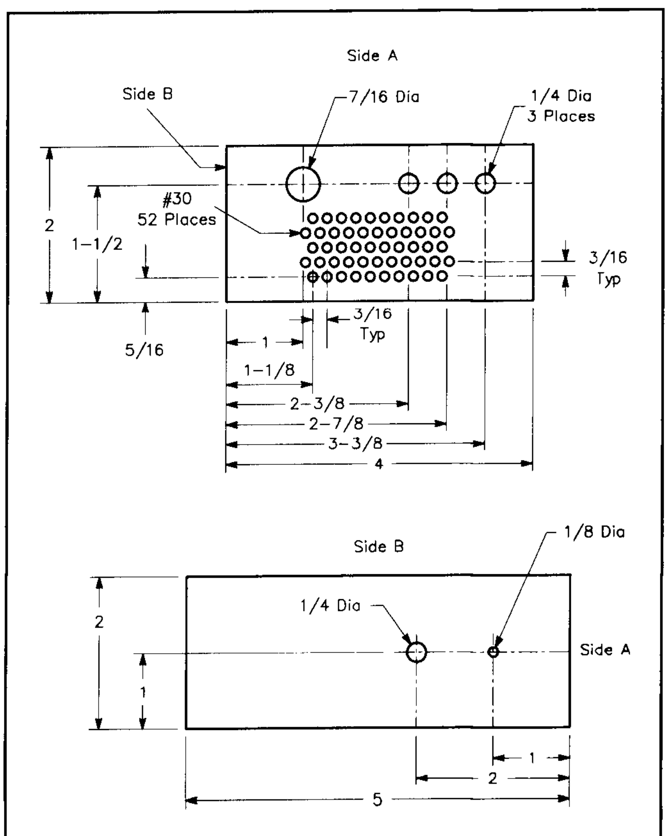


Fig 13—Cathode compartment details. The compartment is made from a 5 X 4 X 2-in. chassis.

half of the line. C2 is simply used to tune the line to resonance. L1 is a series inductance to match the 50-Ω input impedance to the input impedance of the tube. L2 has slightly too much inductance so the series capacitor C1 is used to adjust the total reactance for a proper match. Note that the rotor of C1 must be insulated from ground. A small piece of G-10 epoxy PC board material serves as a mounting insulator. The circuit board is held in place by a small aluminum bracket (Fig 11).

To assemble the cathode circuit, first remove the unused grid pins (4, 7, 11) from the tube socket. Next bend the 6 cathode pins (1, 2, 3, 8, 9, 10) in toward the center of the socket, forming a 90° angle. The bend is made just above the dimple that keeps the pins in place in the socket. The socket is then mounted in place on the grid collet. Note how the 2 filament pins point to the top of the amplifier and the 6 cathode pins point toward the bottom. Mount the rest of the cathode components, C1, C2 and J1. If the layout has been followed, when W2 is soldered to the 6 cathode pins, L2 should line up right on the stator wires of C2. Fig 12 gives 2 views of the cathode-circuit layout. Fig 13 covers the hole-drilling patterns in the cathode compartment. If you follow the layout, the input circuit should tune up easily and you'll obtain an input SWR less than 1.2:1.

Tube Socket Mounting

The recommended EIMAC 720359 grid-collet assembly simplifies construction. It consists of an EIMAC 882931 collet that has been soldered to a 1/16 in.-thick brass mounting ring. The mounting ring has three 4-40 studs that are positioned to match the mounting holes of the 11-pin tube socket. An alternate method of construction is to use the 882931 collet and attach it to a homemade mounting ring. Although the 720359 collet assembly is more expensive, it will save you considerable construction time.

To cut the hole for the tube socket, first punch a 1¼ in. diameter hole in the chassis bottom, located as shown in Fig 14. Next use the tube socket to locate 3 no. 28 holes, orienting the socket per the hole layout in Fig 14. Put the EIMAC 720359 collet in place and use it as a template to drill its 4 mounting holes in the chassis with a no. 27. Remove the collet and socket. Next, drill out the 3 #27 holes with a 9/32-in. drill. Then file out the holes until they form one hole that matches the shape shown in Fig 14. The socket should be able to pass through the hole. Drill a series of 6 no. 43 holes in the collet, matching the pattern shown in Fig 22. Again use the collet as a template to drill 6 no. 42 holes in the chassis. These holes are for bleeding air into the cathode compartment for cooling the tube base. The tube socket may then be mounted to the collet, using 4-40 nuts and lock washers. The collet is then mounted to the chassis with 4 6-32 screws. With everything properly assembled the tube socket will mount flush with the collet.

Additional air is let into the cathode compartment through a series of cooling holes. A metal plate (Fig 15) is used to make an RF filter to prevent leakage from the plate compartment into the cathode compartment. The cathode box is perforated on the side away from the cooling holes. In this way, the air passing into the cathode box is forced across the tube base, to maximize its cooling effect.

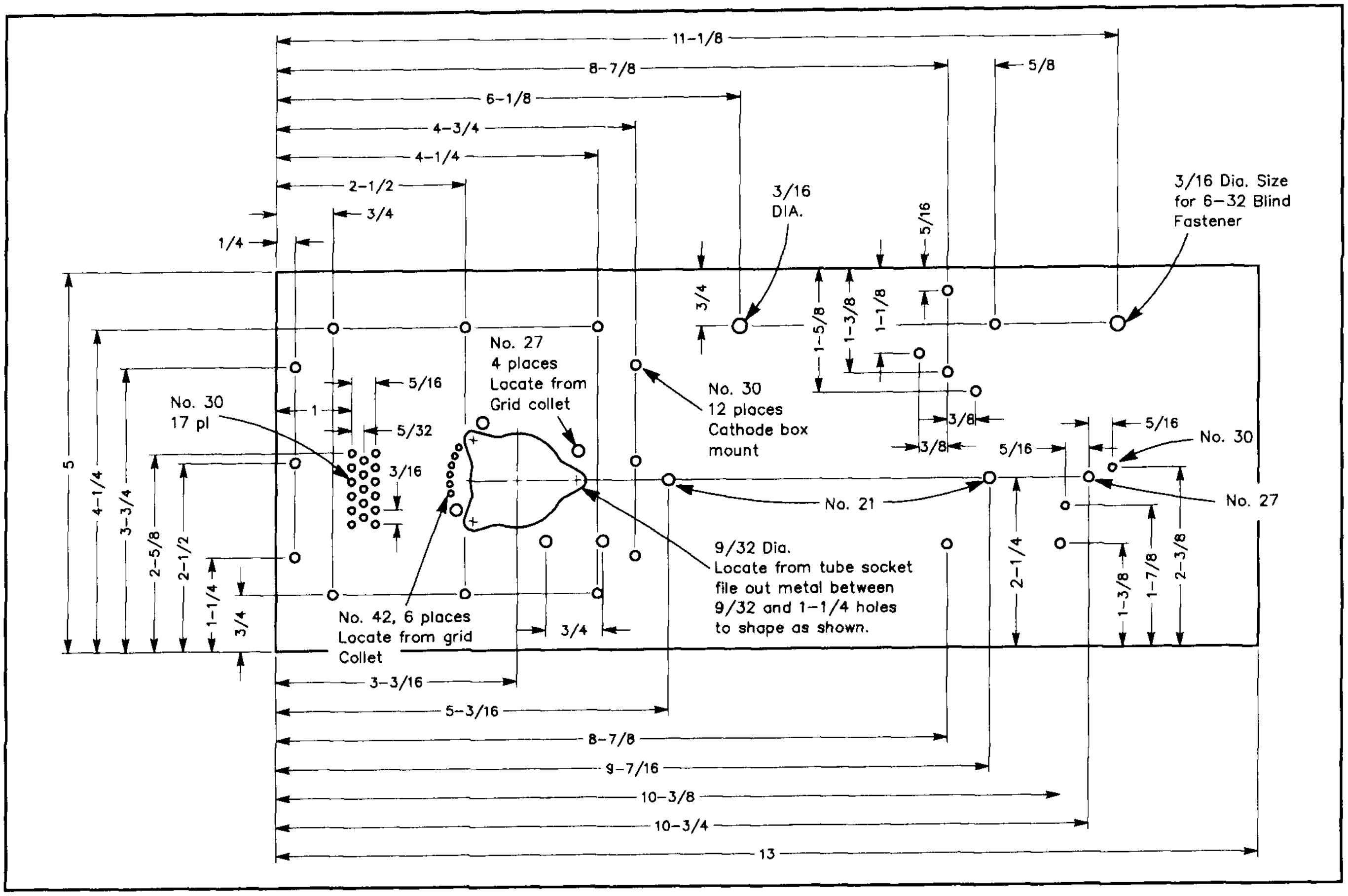


Fig 14—Bottom cover of the plate RF enclosure is made from 0.062-in. aluminum.

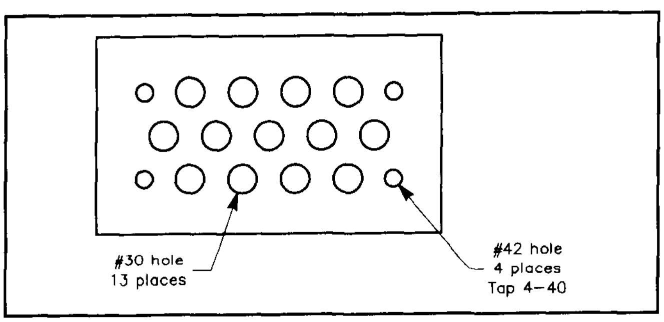


Fig 15—Cathode air vent waveguide is made from 3/16-1/4 in. aluminum.

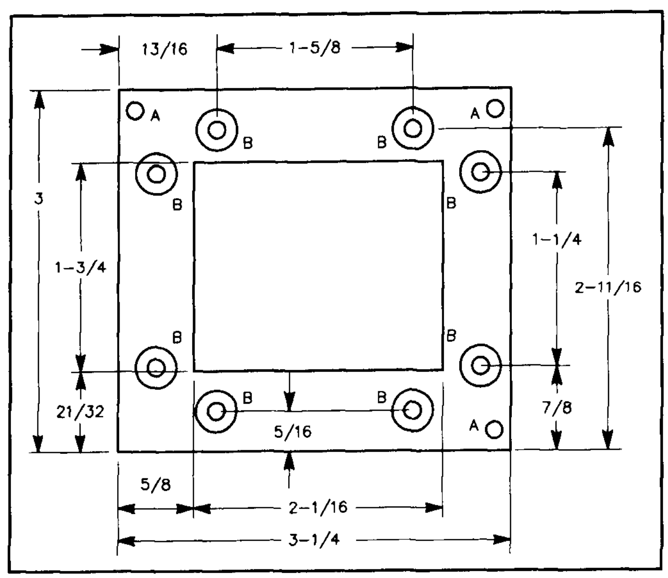


Fig 16—Air inlet retaining plate is made from 3/16-1/4 in. aluminum. Hard alloys, such as 6061-T6 or 2024-T6 are preferred. Holes marked A are No. 7, tapped 1/4-20. Use the blower itself as a template to locate the holes. Holes marked B are No. 25, countersunk for 6-32 flathead screws. Use the top cover to locate these holes.

Cooling Considerations

The air inlet and outlet are RF shielded by means of aluminum cooling screen, sandwiched between the RF deck top cover and ¼-in.-thick retaining plates. Matching hole patterns are cut in the top cover and the retaining plates. For best alignment, use the top cover as a template for drilling the plates. Although these plates may look complicated to make, they were fabricated with hand tools. The large air inlet and outlet holes were first scribed. Then, a series of small holes was drilled along the inside of the marks. The holes are then drilled out with a larger drill so the hole slug can be knocked out. The holes are then simply filed to shape. Fig 16 gives the inlet plate layout and Fig 17 shows details of the outlet plate.

The air-outlet plate is mounted on the inside of the chassis sandwiching the screen between it and the cover plate. The plate also serves to space the chimney down to the plate line. The EIMAC SK-1906 chimney is held in place with 4, ½-in.-

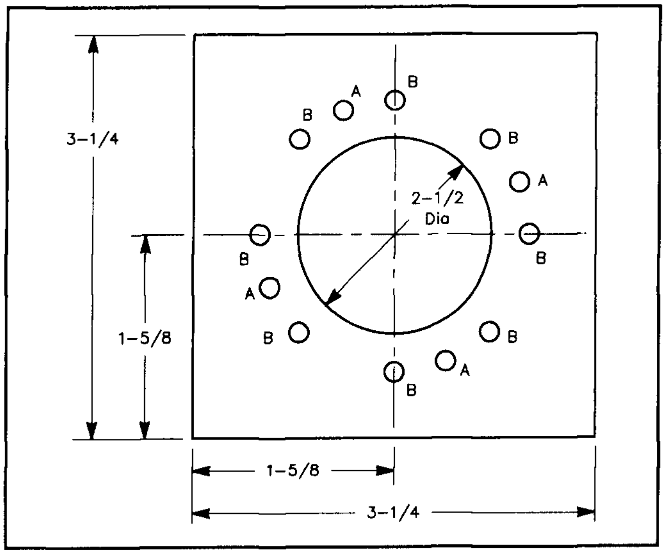


Fig 17—Air outlet retaining plate is made of 1/4-5/16 in. aluminum. Hard alloys, such as 6061-T6 or 2024-T6 are preferred. Holes marked A are No. 27. Locate the 4 holes equally spaced on a 2-7/8 in. diam. circle. Holes marked B are No. 35, tapped 6-32. Locate the holes equally spaced on a 3-in. diam. circle.

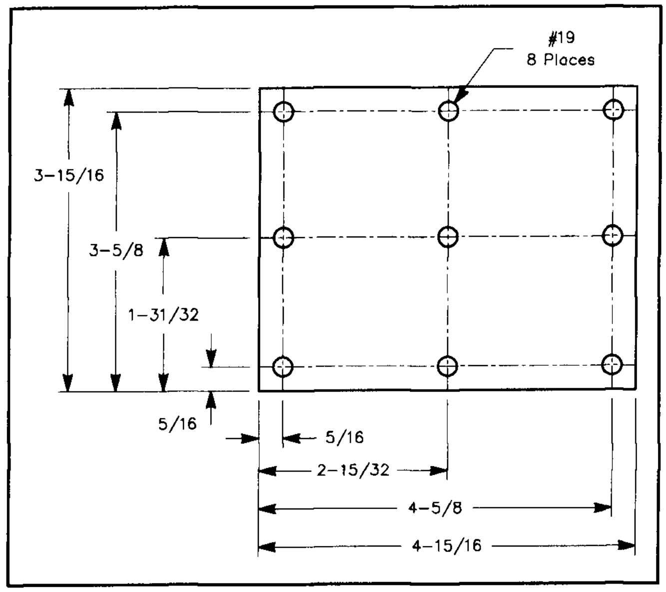


Fig 19—Cathode compartment cover plate is made from 0.062-in. aluminum. Use the finished cover as a template to locate holes in the cathode compartment.

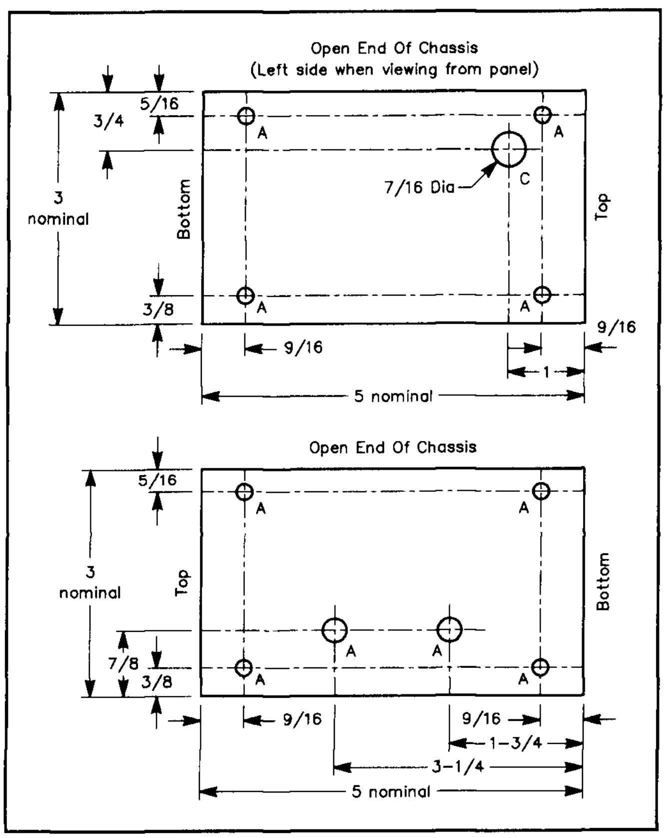


Fig 18—RF deck. At top, tube end; at bottom, flapper end. Holes marked A are chassis mounting holes, No. 23.

long 4-40 screws, which pass through the cover plate and retaining plate. The threaded metal inserts in the chimney should be removed from the plate line side of the chimney. Alternately, you can use a homemade Teflon chimney. The air-inlet plate and screen are mounted on the outside of the top cover. Tap three ¼-20 blower-mounting holes in the plate. Note that 4 of the inlet plate hold-down screws also secure the top cover. Since the blower covers all 8 of the mounting screws, their holes are countersunk and flat head screws are used. The blower must be removed to take the plate compartment top cover off.

To ensure that adequate RF shielding is maintained, the air inlet retaining plate and the top cover must be fastened tightly. The 5- × 13- × 3-in. chassis is made from 0.040-in.-thick soft aluminum. Sheet-metal screws will easily strip out the thin aluminum after being removed and replaced several times; it's essential to use blind fasteners (PEM nuts or Rivnuts). They are readily available from Small Parts Inc. I used 6-32 fasteners. When installing the fasteners, be very careful not to distort the chassis lip. It is easy to make ripples in the metal, which will cause RF leakage.

The amplifier operates quietly with the specified blower, in combination with effective shock mounting. A ⅛-in.-thick gasket made from high-density foam rubber is placed between the blower and its mounting plate. The blower is attached with three ¼-20 nylon screws, ½-in. long. Rubber grommets are placed on the screws before they are installed. This arrangement assures that there are no solid mechanical contacts to transmit blower noise and vibration.

Metal Finishing

The professional finish on the amplifier is gold-irridite applied by a plating company. Irridite provides a hard and conductive finish. Don't confuse irridite, which is sometimes known as chromate finish, with anodizing. Anodize is not a conductive finish and may contribute to RF leakage and improper operation of the amplifier. All aluminum was wet sanded with 320-grit wet-sanding paper. Sand in one direction in a straight motion. You are sanding the aluminum to remove

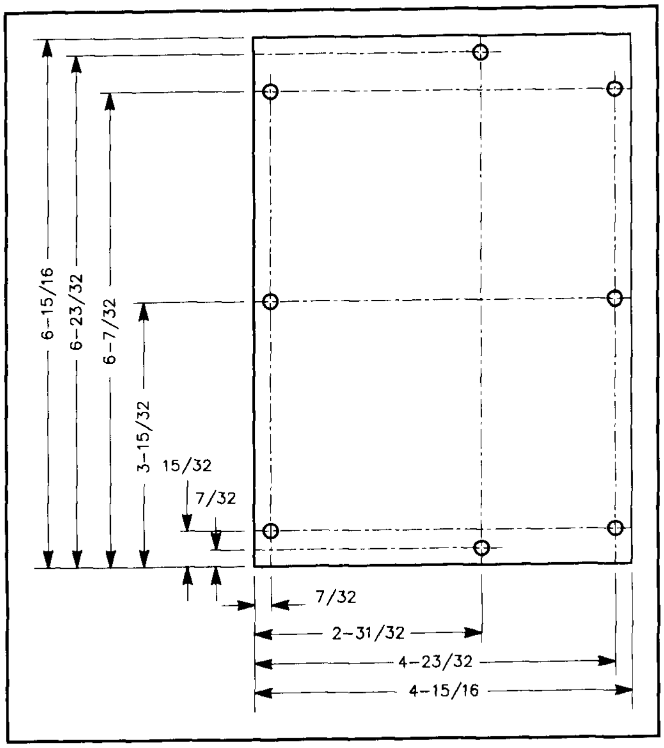


Fig 20—Side-chassis cover plates (2 required). Holes are No. 19. Use cover plates as templates to drill side chassis.

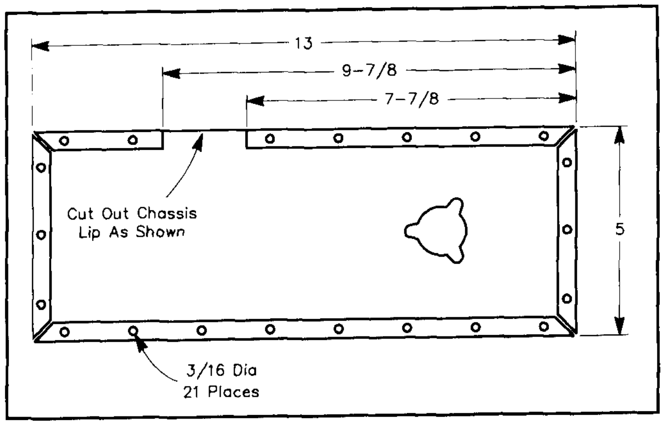


Fig 21—RF plate enclosure. Install blind fasteners in the 21 3/16-diam. holes.

scratches and burrs made during construction. At the plater's specify a deep etch, which will remove any remaining scratches, unless they are very deep. While you can apply irridite at home, I don't recommend you try, though. The aluminum must be absolutely free of contaminants, and the chemicals necessary to ensure it is are not readily available and are dangerous to use. I paid only $32 to have all the amplifier parts irridite plated, in 1986.

The drill work done to make the various air-vent holes (cathode compartment and side chassis) may look as if it was done by magic, to achieve their near-perfect patterns. In truth, these vent holes are simple to create. A piece of standard perforated steel was used as a drilling template, so the many holes do not even have to be marked! After drilling, the burrs are sanded smooth to create the clean, sharp holes. Figs 18 to 21 give additional metalwork drilling and cutting information.

Protection Circuits

The specified filament warm-up time for the 3CX800A7 is 3 minutes. Follow this specification to obtain maximum tube life. As the cathode is heated, the areas directly in front of the filament wires get hot first, and become the first areas to emit cathode current. If you operate the amplifier in this condition, the cathode hot spots will emit all the cathode current, and may vaporize.

An Amperite thermal time-delay relay is used to prevent operation of the amplifier for 3 minutes. A solid-state timing circuit was considered, but the thermal time-delay was chosen because it is simple and heats just like the tube filament. There's no need to wait another three minutes if filament power is only interrupted momentarily. Brief interruptions may be caused by power failures or HV arcing. This kind of flexibility is hard to design into a solid-state circuit.

A 120-second time-delay relay was used because it is the longest delay available in the 9-pin miniature size. I extended its turn-on time to 180 seconds by placing a resistor in series with the heater element. Even if you obtain a 180-second unit, you should check the turn-on time. Most units are specified for use on a nominal 115-V ac circuit. With US line voltage now typically 118 to 120 V, some timers will warm up 15 to 20% faster than the specified time. If necessary, use a series resistor to adjust the warm-up time. Since I built this amplifier, the Amperite 115NO120T (9-pin) and 115NO180 (octal) have become hard to get and very expensive. An inexpensive sealed-plastic-case model (115NO180B) can be used instead.

A small but significant point is the use of a 14-V transformer for the filament. Since the filament voltage is backed off to 13.0 V for operation, you may be tempted to use a commonly available oversized 12.6-V transformer. Doing so will be detrimental to the life of the tube. A well-cared-for tube used in intermittent service may first fail with an open filament. A cold filament has very low resistance (1.5 Ω for the 3CX800A7). Unless some protection is used, the turn-on surge may be as high as 10 A. By using a higher-voltage transformer and series resistors, automatic surge limiting is easily achieved. I used a 1-Ω resistor in series with the secondary of the transformer. A 50-Ω, 12-W variable resistor is used in the primary circuit to set operating filament voltage.. This combination limits turn-on surge to just over 2 A.

To achieve high gain and efficiency, the 3CX800A7 uses a grid structure constructed of small wires. This construction limits grid dissipation to 4 W. It is common practice for HF amplifier designers to include a circuit to sense excessive grid current. Such sensing circuits are not always useful at UHF, as transit-time effects may cause negative grid currents vastly different from real grid absorption and secondary emission. In testing the 3CX800A7 at 432 MHz, the grid current was found to behave predictably, that is positive current which corresponded directly to drive levels was observed. Because of this desirable behavior, a grid-current-sensing circuit was included in this amplifier. R14, in combination with grid shunt R4 develops a voltage sufficient to switch on the grid-trip relay K3, through switching transistor Q2. Contacts on K3 lock in the over-current relay and turn off the OPERATE pilot lamp. No reset switch is used. The circuit is reset by setting STANDBY/OPERATE switch (S2) to STANDBY, then back to OPERATE.

An additional protection circuit senses high voltage. It consists of Q1, which senses the presence of high voltage through the HV metering circuit. Q1 allows the T/R relays to switch on transmit. This circuit prevents the amplifier from keying should plate voltage not be present. While just the grid-trip circuit may seem adequate, the absence of plate voltage will cause the tube to draw excessive grid current when drive is applied. The HV sensing circuit protects against such an occurrence.

Many high-performance 432-MHz stations use a single T/R relay at the array, in combination with an antenna-mounted receive preamplifier. In these stations, in-out RF relays are not used at the amplifier. This could cause a problem if the amplifier ac fuses blow. Since the grid-trip circuit requires that power be present to operate, ac-power loss to the amplifier but not the exciter can result in damage to the tube, unless a driver-to-amplifier interlock is provided. The HV-sensing circuit will protect the tube. Simply unshorting the cathode-bias resistor (R3) will provide sufficient protection for the tube from drive power, but it is better to remove all drive power when plate voltage isn't present.

Another feature of the switching circuitry is provided by S4. This switch, located on the rear panel, allows the operator to determine whether the RF relays actuate every time he transmits, or lock in when the amplifier is switched from standby to operate. This feature can be used if the station includes a tower-mounted preamp with a separate feed line. It eliminates the noise generated by switching the relays in the shack. If an in-out tower preamp is used (with a single transmission line) or a transceiver without an external preamp, this locking feature is not usable. Note though, even if the RF relays are locked in, either an excessive grid-current trip or loss of plate voltage will still drop out the RF relays.

Metering Circuits

The metering circuit has one anomaly: The resistor string is used both for the high-voltage meter and for the high-voltage sensing circuit. Since the HV sensing circuit is referenced to ground, the current from the circuit will return to the HV supply B– lead through the grid-meter shunt. The grid meter will read this current. At idle conditions, the grid-current meter will read negative by about 0.8 mA. If you find this to be a problem, use separate resistor strings for the HV meter and HV sensing. The HV meter would then be connected to the B– line, not to ground.

Note also that the HV meter also reads plate voltage relative to ground. Since the actual power input is determined by plate-to-cathode voltage, the bias voltage must be subtracted to obtain the true plate voltage and power input. As the bias voltage on the 3CX800A7 is only 5.6 V, so the correction is only 0.2%. To obtain a true plate-to-cathode voltage reading, you must reference the HV meter circuit to the tube side of the Zener bias diode. This would again require separate HV meter and sensing resistor strings. Arranging the meter circuit in this way also causes the plate meter to indicate the metering string resistor current.

Many operators will want to build 3X800A7 amplifiers for other bands, and share a common HV supply. This would place the grid shunts in parallel. Grid-current meters on the unused amplifiers will indicate a portion of the operating amplifier's plate and grid currents, uncalibrating all the metering circuits. There are two methods to reduce this problem. One is to place a resistor in series with the grid-sensing resistor (R21). Alternately, you can install a resistor in series with the B– line. T/R relay K2 would short out these resistors on transmit. Use the lowest-value resistors which eliminate the problem. This value depends on the number of amplifiers connected to the same power supply, but a value of 500 Ω is typical. A word of warning: These resistors increase the possibility of damage to the metering circuits when a HV arc occurs. Also note that the 11-Ω effective grid-shunt value (due to the grid over-current sensing circuit) causes a portion of the grid current to flow through the B– safety resistors (R1 on the amplifier and any similar resistors at the HV power supply). R13 can be adjusted to make the grid meter read the correct value when connected to the power supply.

Keying Circuits

A transistorized relay-switching scheme is used. The circuit can be switched by either grounding J6 or by supplying +12 V to J8. Current sinking or supplying capability is only 15 mA, which should be compatible with current 432-MHz exciters. If you are using conventional switching circuits, make sure your relays will reliably contact at only 15 mA of current. As described in the protection-circuit section, a loss of high voltage will prevent the relays from switching, or drop them if they have already switched.

The coaxial relays you use should have dc coils. Dc coils switch faster, have less contact bounce and run cooler than ac types. The coils don't have to be 28 V, as are most available military surplus relays. Several types of suitable coax relays with 12-V coils are available. The switching circuitry can be made to work with 12-V coils but you'll have to change T2. If you have relays with 120-V ac coils, don't despair. Many 120-V ac relays work better on 12 to 28 V dc, so try them on a dc supply.

Amplifier in-out switching relays don't need high isolation. If you use separate input and output relays, the input relay can be a low-power type.

Power Supply Considerations

The high performance of the 3CX800A7 at VHF and UHF is partially a result of the close internal spacings of the tube elements. These close spacings increase the possibility of a plate-to-grid arc over. To protect the tube, power supply, metering circuits and the operator, a 50-Ω 50-W resistor is connected in series with the HV power lead. This resistor substantially reduces the energy dissipated in the tube during an arc over, yet only reduces the full-load plate voltage by 30 V. EIMAC specifies that idle plate voltage should not exceed 2500 V.

I built a modern capacitor-input power supply, which uses a solid-state bridge rectifier in combination with a low-resistance plate transformer. My supply uses a Peter Dahl Hypersil transformer (1800 V at 700 mA, CCS). The electrolytic-capacitor string has a total capacitance of 22 µF. An oil-filled capacitor is preferred. Adequate regulation and ripple filtering can be obtained with less than 25 µF of filter capacitance. No-load voltage is approximately 2510 V. At 600 mA, the plate voltage is 2250 V. Out of the 259-V drop, over 100 V is due to line-voltage sag and the protection resistor. In no case should you use more than 50 µF of filter capacitance. Higher values will not significantly improve regulation, but will greatly increase the possibility of damage during an arc over.

Avoid choke-input filters. I have seen many improperly designed amateur supplies that were made from surplus components haphazardly cobbled together. These supplies can have bad transient-voltage-spike problems, induced from the chokes. These transients will blow rectifier diodes and cause tube arcs. They can also severely reduce the IMD performance of the amplifier. Finally, be sure to use MOV transient suppressors on the ac-input leads.

I highly recommend MHV-type HV connectors. The most dangerous condition to the operator is when high voltage is present and the power-supply-to-amplifier ground connection open. If this happens and you touch the amplifier and power supply (or any other grounded object if the power supply was grounded), you become the ground return. MHV connectors prevent this possibility as the shield makes contact along with the center conductor. RG-59 cable can comfortably handle the 2500-V power that this amplifier uses.

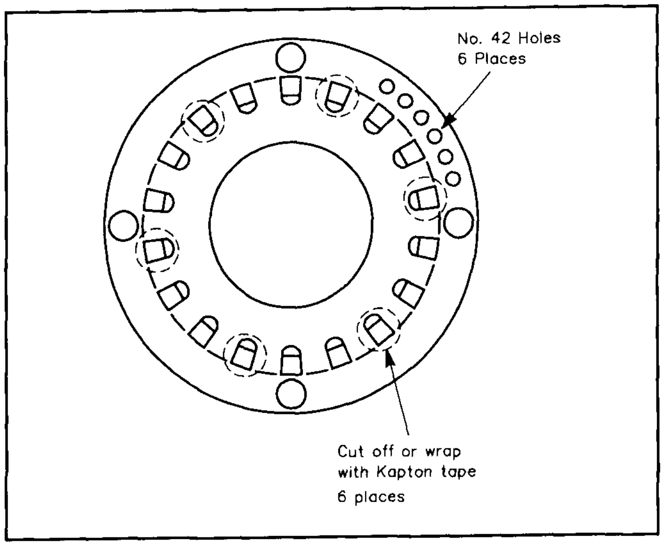


Fig 22—Grid collet modification. The EIMAC 720359 collet is supplied with 36 fingers. Break off every other finger. Wrap 6 of the remaining fingers (as shown) with Kapton tape or break them off. Removing the fingers adjusts grid-circuit capacitance and helps neutralize the amplifier.

Amplifier Stabilization

Many amateurs mistakenly believe that neutralization of a grounded-grid amplifier is not required. Although operation of this amplifier is possible without neutralization, the simple neutralization procedure used provides for improved tuning, more stable operation and greater apparent efficiency. In addition, tube life may be increased due to the elimination of unwanted higher frequency circulating currents. The amplifier was neutralized by adjusting the grid inductance until the plate current dip matched the maximum output point. The amplifier operates so well that it can be tuned up without a power-output indicator. By dipping the plate current and adjusting the loading for proper grid current one can obtain output power that will be within a few watts of tuning it up for maximum output on a directional wattmeter!

Since the 3CX800A7 is operating below its self-neutralized frequency, neutralization is easily accomplished by breaking off grid collet fingers. The so-called self-neutralizing frequency of a tube is simply the frequency at which the combination of tube and socket have the right combination of feedback capacitance and inductance as to create the maximum input-to-output isolation. It should be noted that not all tube and socket combinations have any frequency where their isolation will be acceptable.

By breaking off some of the grid-collet fingers, the effective grid inductance is raised and the maximum reverse isolation point is lowered to 432 MHz. Fig 22 shows the proper pattern for breaking off the grid-collet fingers. Tube characteristics appear to be close enough among different 3CX800A7 tubes such that neutralization for a specific tube is not required. If you want to be safe, however, break off every other finger on the grid collet. There will be 18 remaining fingers. Tape over 6 of them with Kapton tape, spacing the taped fingers equally around the tube. These taped fingers will then allow future tuning adjustments without replacing the grid collet.

An even more scientific approach to neutralization is to look at the reverse isolation of the amplifier. This is done by connecting the output of a signal generator or network analyzer to RF-output connector and measuring the fed-through power with a power meter, spectrum analyzer or network analyzer. Ideally, this test is performed after tuning up the amplifier with all voltages in place. If isolators are not available, there is a danger that the amplifier can oscillate during the test procedure and put out enough power to destroy your signal generator.

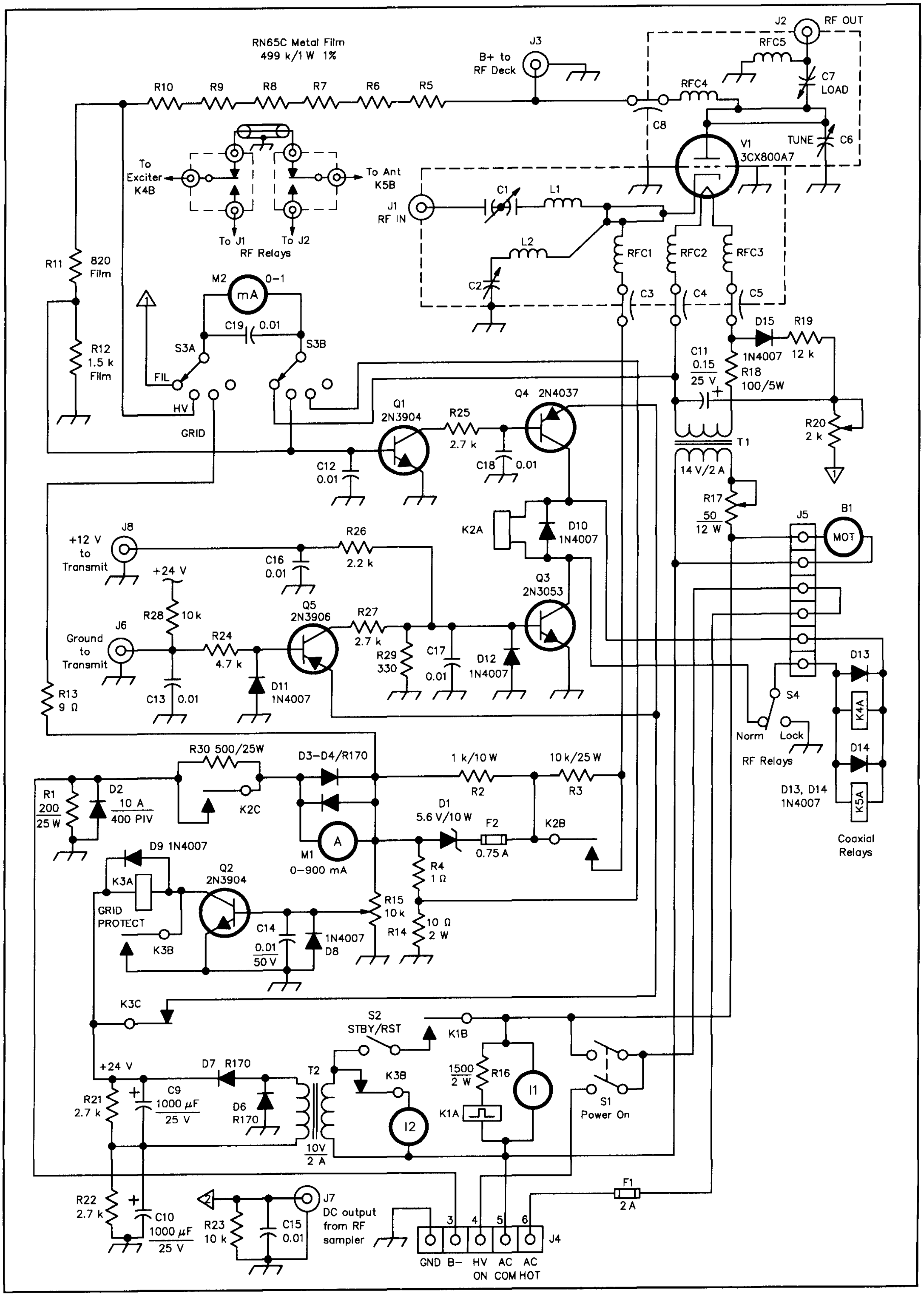
The reverse isolation of the amplifier should be a minimum of 20 dB greater than its power gain. Since the 3CX800A7 amplifier has a gain of 14.2 dB, you should see over 34-dB reverse isolation when it is neutralized. This amplifier had less than 20-dB reverse isolation before neutralization and over 30 dB after the collet was modified.

After neutralization, power drift became almost nonexistent. Power output will slowly rise by only 20 to 30 W from a cold start to full operating temperature. This represents a less than 0.2 dB of power drift, certainly an acceptable amount.

Initial Tuning Adjustments

Tune up of the amplifier is quite straight forward. If the dimensions and layout of the amplifier have been closely followed, the following initial settings will place the amplifier very close to optimum tuning at 432 MHz and full power output.

C1: Plates approximately 50% meshed


RN65C Metal Film
499 k/1 W 1%
R10
R9
R8
R7
R6
R5
B+ to
RF Deck
J3
J2
RF OUT
RFC5
C7
LOAD
RFC4
C8
TUNE
C6
V1
3CX800A7
To
Exciter
K4B
To Ant
K5B
To J1
To J2
RF Relays
J1
RF IN
C1
L1
L2
C2
RFC1
RFC2
RFC3
C3
C4
C5
R11
820
Film
M2
mA
0–1
C19
0.01
S3A
S3B
R12
1.5 k
Film
FIL
HV
GRID
D15
R19
1N4007
12 k
C11
0.15
25 V
R18
100/5W
Q1
2N3904
Q4
2N4037
R25
2.7 k
C18
0.01
C12
0.01
R20
2 k
T1
14 V/2 A
R17
50
12 W
K2A
D10
1N4007
J5
B1
MOT
J8
+12 V
to
Transmit
R26
2.2 k
C16
0.01
+24 V
R28
10 k
Q3
2N3053
Q5
2N3906
R27
2.7 k
J6
Ground
to
Transmit
R24
4.7 k
R29
330
C17
0.01
D12
1N4007
D13
K4A
D11
1N4007
C13
0.01
R13
9 Ω
S4
Norm
Lock
RF Relays
D14
D13, D14
1N4007
K5A
Coaxial
Relays
R30 500/25W
D3–D4/R170
1 k/10 W
10 k/25 W
R2
R3
R1
200
25 W
D2
10 A
400 PIV
K2C
D1
5.6 V/10 W
F2
0.75 A
K2B
M1
A
0–900 mA
R4
1 Ω
D9 1N4007
Q2
2N3904
K3A
GRID
PROTECT
K3B
C14
0.01
50 V
1N4007
D8
R15
10 k
R14
10 Ω
2 W
K3C
S2
STBY/RST
K1B
+24 V
D7 R170
T2
K3B
1500
2 W
R16
I1
K1A
S1
Power On
R21
2.7 k
C9
1000 µF
25 V
D6
R170
I2
10V
2 A
F1
2 A
R22
2.7 k
C10
1000 µF
25 V
J7
DC output
from RF
sampler
R23
10 k
C15
0.01
3
4
5
6
J4
GND
B–
HV
ON
AC
COM
AC
HOT

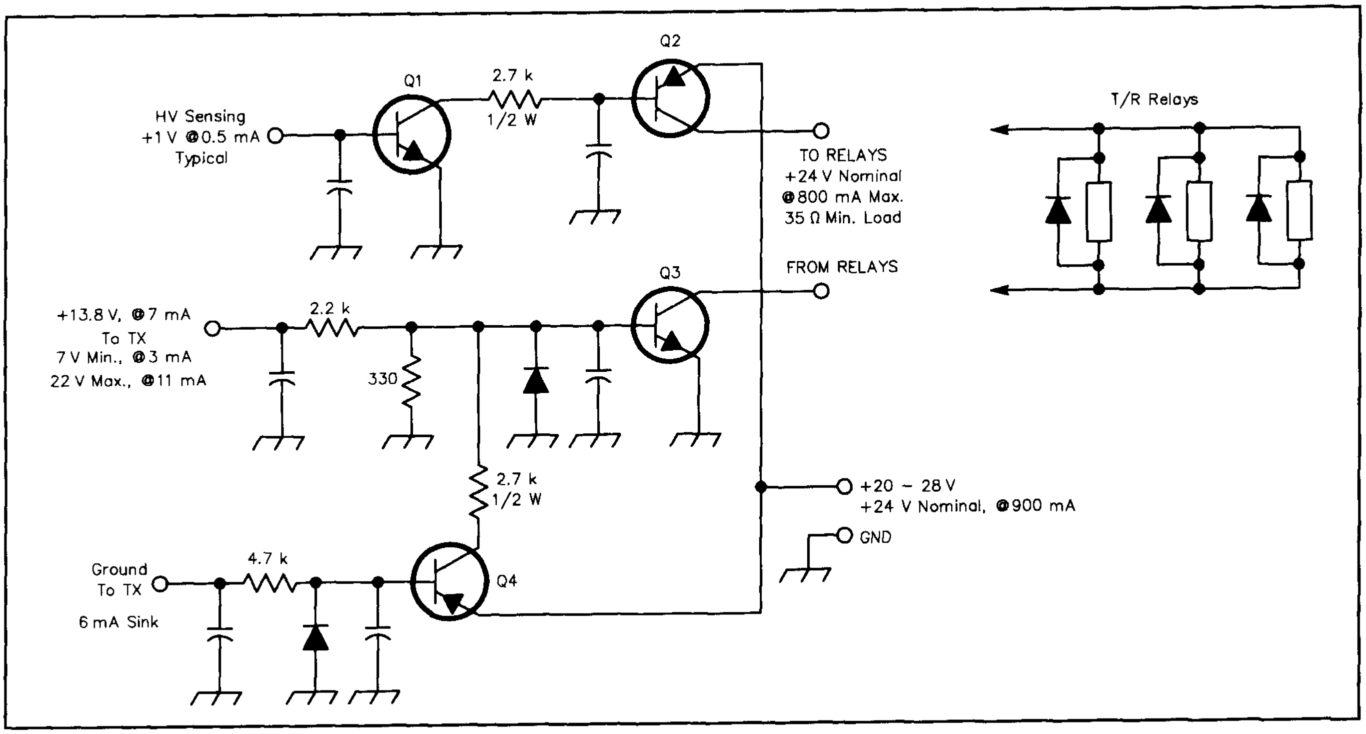


Fig 24—TR switching circuits for use with 24-Vdc relays. These components are mounted on the PC board shown in Fig 25.

←

Fig 23—Schematic diagram of the amplifier. Control circuits protect the tube and amplifier from potentially catastrophic events, such as overdrive, loss of high voltage or loss of heater voltage.

C2: Plates approximately 25% meshed
C6: Fixed end of flapper 1¼ in. above bottom of chassis
Moving end of flapper ¾ in. above bottom of chassis
C7: Fixed end of flapper 1 in. above bottom of chassis
Moving end of flapper ⅞ in. above bottom of chassis

After all wiring has been checked, set R17 (filament adjust) to maximum resistance. Attach an accurate RMS voltmeter to the filament feed-through capacitors. After the filament has warmed up for 3 minutes, adjust R17 until the filament voltage is 13.0 V. Next, adjust R29 such that the filament meter indicates 13.0 V. If the meter cannot be calibrated, change R19.

Apply high voltage and verify the tube draws proper idling current when J6 is shorted to ground (approximately 55 mA at 2400 V). Remove high voltage. Short out cathode resistor R3. Apply a very small amount of drive, increasing drive until the grid current reads 60 mA. Adjust R15 so the grid overcurrent trips at 60 mA. If you are unable to obtain 60 mA of grid current, adjust the cathode tuning controls (C1 and C2) for maximum grid current. After adjusting the grid-trip, reduce drive power and peak C1 and C2 for maximum grid current, being sure not to exceed 60 mA.

Remove the shorting jumper from R3 and turn the high voltage back on. Apply drive power so the plate meter reads 200 to 300 mA. Start adjusting C6 and C7 (plate tuning and loading) maximum power output. As the power output comes up you can increase drive until you are operating at the desired power level. If the amplifier cannot be driven to full power, C1 and C2 may need to be adjusted.

Final adjustments to the cathode circuit must be made at full power. With an in-line power meter connected as close to J1 as possible, alternately adjust C1 and C2 for minimum SWR. You may find that there are combinations of the cathode capacitors that allow the amplifier to be driven but the input SWR is poor. There will be a unique combination of the capacitors that will adjust the amplifier such that the lowest input SWR (less than 1.2:1) corresponds to maximum plate current (lowest drive-power requirement). To obtain this condition will require alternately adjusting C1 and C2 several times. If you cannot obtain a good input SWR, check to see if C1, C2 or both are at minimum or maximum capacitance. If C1 is at minimum capacitance, shorten L1. Lengthen L1 if C1 is at maximum capacitance. If C2 is at minimum or maximum capacitance, it is most likely because you didn't follow the cathode-circuit layout. Using a Bird 43 wattmeter with a 50D element (50 W, 200 to 500 MHz), I can completely null out the reflected power, so that with 30-W drive the wattmeter indicates no reflected power. (This only indicates that reflected power is lower than the directivity of the element, not that I have obtained a perfect match.)

With the input circuit properly adjusted, final adjustments to the plate tuning and loading controls may be made. There will be many settings of C6 and C7 that will deliver lots of power output. There will be a unique combination that will deliver that power output at maximum efficiency. Grid current is an excellent indicator of proper tuning. At full power output the grid current will range from 15 to 30 mA (varies from tube to tube). If the amplifier is properly tuned, grid current should increase as you increase drive. The plate-current dip should

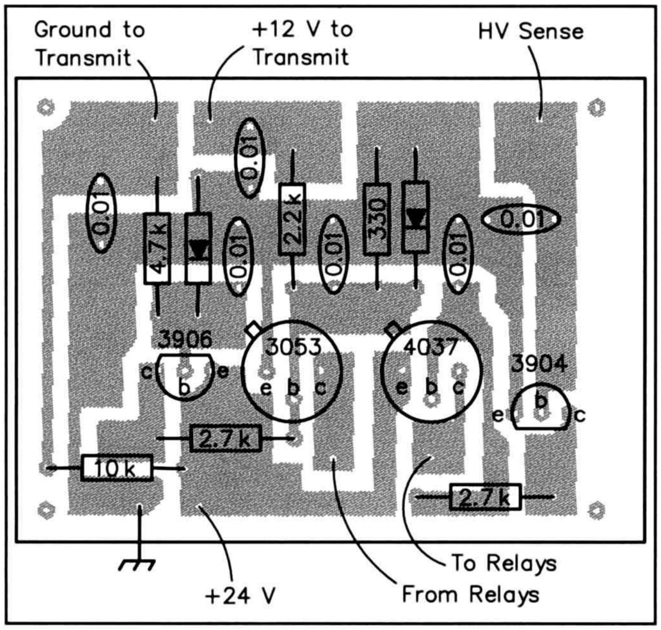


Fig 25—TR switching PC board, component side. While board layout is not especially critical, the board itself must be 1.75 X 3.25 in. or smaller in size.

Table 2

Full Power CW Operating Conditions

Keyed CW and SSB PEP Operation

Plate voltage, full load:	2250 V
Plate current:	600 mA
Dc Input power:	1350 W
RF Output power:	730 W
Apparent efficiency:	54%
Power gain:	14.2 dB
Grid current:	26 mA (will vary from tube to tube)
Drive power:	28.5 W
Input VSWR:	1.16:1
Filament voltage:	13.0 V
Idling current: to tube)	55 mA (@ 2400 V; will vary tube
Bias voltage:	5.6 V

Note: These conditions are for SSB and keyed CW service. Key-down time not to exceed 1 minute. For maximum continuous duty ratings, see text.

also match very closely (within 20 W) of maximum power output. There should also be minimum thermal drift. After letting the fish lines stretch for a few days, power should drift less than 30 W from a cold start.

Amplifier Operation

Efficiency of the amplifier is about 54%. If you are measuring higher efficiency you either have an inaccurate power meter or your high voltage and plate meters aren't calibrated. Use a Bird 1000D element with the Bird 43 wattmeter; 1000E elements typically read about 10% high at 432 MHz. An antenna or dummy load with a high SWR can cause inaccurate power meter readings. This can be verified by placing ¼-wavelength coax sections in series with your feed line, and checking to see if the SWR or indicated power change. Power measurements were made with a directional coupler in combination with a microwave power meter. The directional coupler was measured on a network analyzer to verify the amount of coupling it has at 432 MHz. If your efficiency is below 50%, you may have any of the previously mentioned measurement accuracy problems, a bad tube or just a mistuned amplifier.

At full rated output (about 730 W) the 1-dB bandwidth of the amplifier is 1.3 MHz. The 3-dB bandwidth is 3.9 MHz. The amplifier was designed to operate between 430 and 440 MHz. With the specified plate line and tuning capacitor sizes, the amplifier will operate efficiently at output levels from 300 to 730 W over that frequency range. If operation is desired at higher or lower frequencies, you'll have to adjust the length of W2 or C6.

Maximum CCS ratings of the 3CX800A7 are 2250 V at 600 mA. The specified highest frequency for maximum ratings is 350 MHz. No problems have been experienced running the tube at those ratings in keyed CW and SSB service at 432 MHz. I recommend, however, limiting CW key-down tuneup time to under 1 minute. If the amplifier is to be used in continuous-duty service, such as FM repeater or ATV, limit maximum plate current to 500 mA and reduce full-load plate voltage to 2000 V or less. In continuous service the filament voltage should be reduced to 12.2 V during transmit. A switching circuit should be added to raise the filament voltage to 13.5 V during warmup and standby periods. Maximum CCS output will be 500 W at a drive level of 22 W and 50% efficiency (2000 V at 500 mA). Continuous-duty service at elevations above 2000 feet may also require a larger-capacity blower. When shutting off the amplifier, be sure to let the tube completely cool down. The amplifier should be left powered up (blower running) for at least 5 minutes after the last transmission. The cathode compartment can still be warm after the anode air exhaust is blowing cool air.

Note that in addition to the grid dissipation value of 4 W, the maximum grid current is 60 mA. Under linear service the grid dissipation will be far under the rated value (less than 0.5 W). The grid-current restriction therefore becomes a matter of a total limit of cathode current, which is normally 600 mA of plate current and 60 mA of grid current. At 432 MHz, transit time effects, secondary emission by the grid and back bombardment of the cathode start to occur. The amplifier can be loaded so that negative grid current will be indicated. These conditions require that you be even more careful about grid and cathode current. In general, the amplifier should never be operated with an indicated grid current over 40 mA. An indication of these back-heating effects is grid-current drift. If you are seeing the grid current drift upward at a constant drive and plate-current level, you are running the amplifier too hard (or you may have a bad connector or cable in the system).

You should also be very careful not to overdrive the amplifier. Cathode-driven triodes such as the 3CX800A7 will not exhibit the gain-compression phenomena shown by solid-state amplifiers. That is, the power gain of the tube is just as high at full power as it is at low power. The station should have an exciter that has stable output power. In addition, make provisions to limit the available drive power to 35 W or less.

Table 2 gives full power operating conditions. For SSB operation the conditions represent the PEP point. There is little

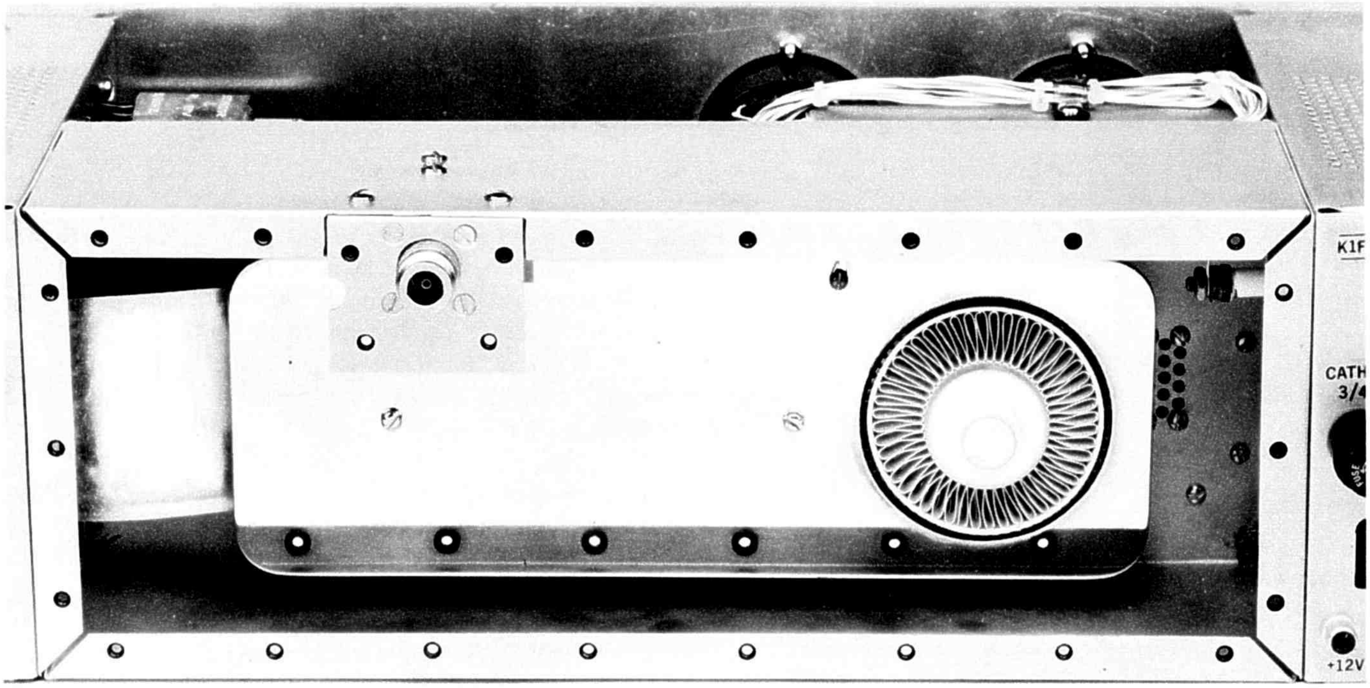
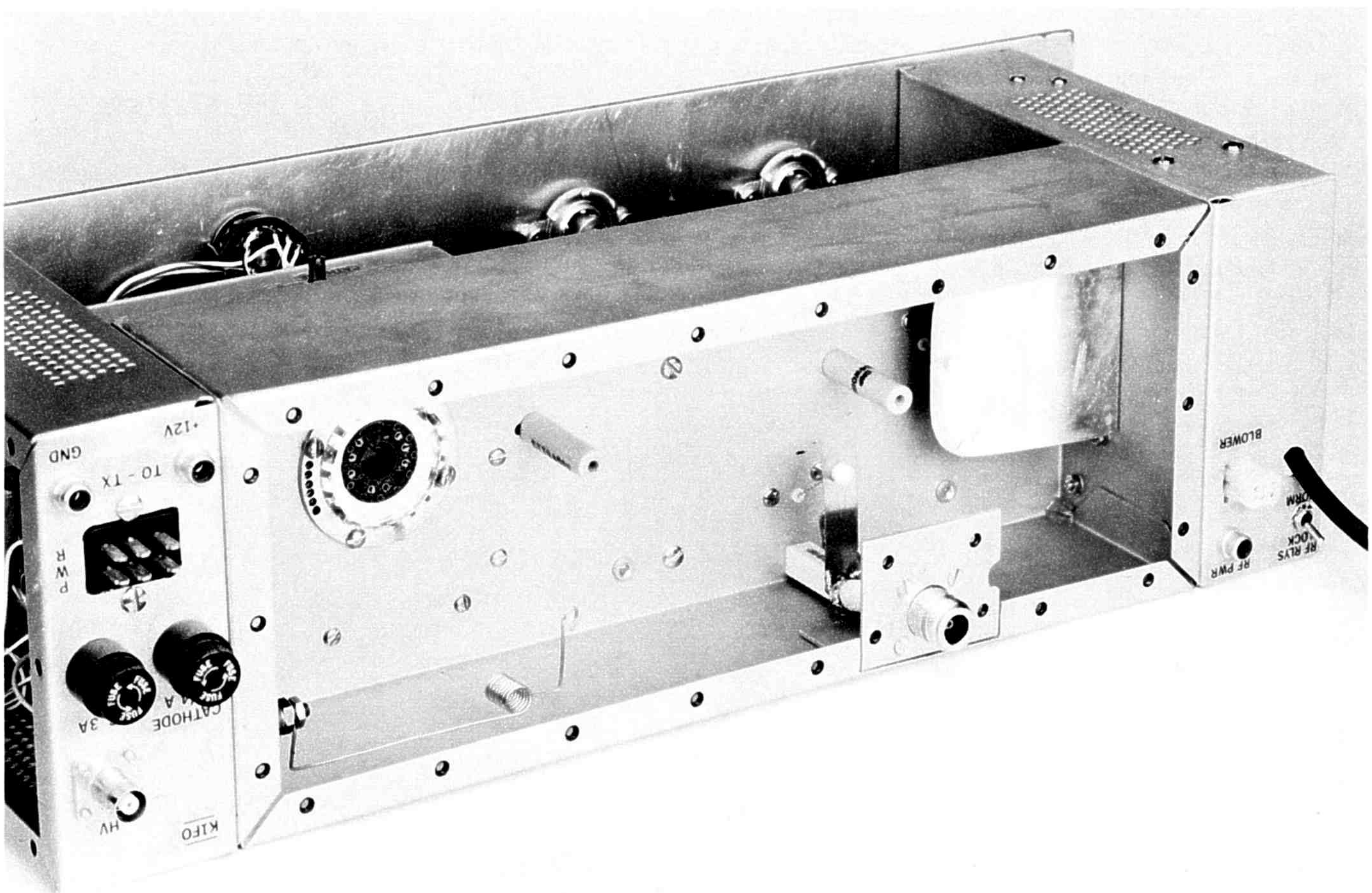
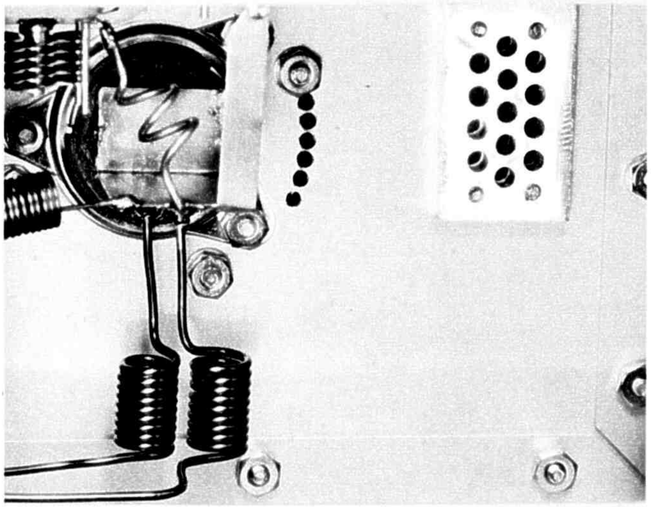


Plate compartment of the single 3CX800 amplifier. Plate tuning capacitor is shown to the left. The RF-output connector is at top.



This inverted view of the plate compartment shows the output loading capacitor, which is adjusted by means of a non-conducting cord fastened to its lower edge.



Interior of the cathode compartment. The filament RF chokes are at bottom.

sense in investing in a tube of this quality if you are going to overdrive or mistune the amplifier. During proper SSB operation, without speech processing, indicated plate current on *voice peaks* should be less than 250 mA. Power output as indicated on a slow-responding average-power meter (such as the Bird 43) should be less than 200 W on peaks. If an effective RF peak clipper is used (10 dB of compression and clipping), indicated plate current on voice peaks can approach 400 mA. Average-power watt meters may indicate up to 325 W on peaks. While driving the amplifier harder may give you the satisfaction of seeing higher meter readings, the additional power will be transmitted primarily as distortion products, and won't make your on-frequency signal any stronger.

Pay attention to the cable, connectors and relays you use. All high-power connections should use Type-N connectors. Assemble each connector properly so the shield has good contact and the center pin is aligned and at the proper depth. This much power at 432 MHz will destroy poorly assembled connectors. Use ½-in. or larger Hardline for the antenna feed line. For flexible jumpers, use RG-225 coax.

Using An 8874

This amplifier will also work with an 8874 tube. To use an 8874, set the filament voltage to 6.0 V RMS. Substitute a 6.3-V, 3-A transformer for T1 and eliminate R18. Make the hole in the plate line (W1) 1.75-in. diameter. An EIMAC 008294 collet makes for a simple connection between the plate line and the 8874 anode radiator. Make the air-outlet hole 1⅝ in. diameter, You'll have to make a chimney (sheet Teflon). In the input circuit, L1 and L2 may need to be made longer. Neutralization of an 8874 is slightly different.

The maximum ratings of an 8874 are 2200 V at 500 mA, in intermittent amateur service (keyed CW and SSB). Peak power output will be 570 W. Drive power for that output level will be 35 to 38 W. In continuous duty, limit the 8874 plate current to 350 mA.

Conclusion

This amplifier is easy to build and requires minimal special metal fabrication. Performance is excellent. The investment in parts and careful assembly time will pay off with years of trouble-free operation.

Notes

[1]The 8874 432-MHz amplifier appears in ARRL *Handbook* editions from 1981 through 1986.

[2]Aluminum sheet cut to size is available from Chassis Kit. Charles Byers, K3IWK, 5120, Harmony Grove Road, Dover, PA 17315. Tel 717-292-4901.

[3]Surplus Sales of Nebraska, 1315 Jones St., Omaha, NE 68102. Tel. 402-346-4750.

[4]Microwave Components of Michigan, P.O. Box 1697, Taylor MI 48180. Tel 313-753-4581.

[5]S. Powlishen, "Improving the K1FO 8874 432-MHz Amplifier," *QST,* Jun 1987, pp 20-23.

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QST Issue: Nov 1982
Title: High-Power Cavity Amplifier For The New 900-MHz Band, A
Author: Robert Sutherland, W6PO

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A High-Power Cavity Amplifier for the New 900-MHz Band

Be ready for the new 900-MHz amateur band when it's ours to use! The road to QRO is paved with resonant cavities and other forms of uhf plumbing.

By Robert I. Sutherland,* W6PO and William I. Orr,* W6SAI

The 1979 WARC (World Administrative Radio Conference) assigned a portion of the 900-MHz region to the Amateur Service in Region 2, which includes the United States, Mexico, Canada and the Central and South American countries. As of this writing, the band has not yet been positioned in the spectrum nor authorized for amateur use in the U.S. Even so, knowing that it will eventually be available raises questions of interest to vhf-minded amateurs.

What will the propagation characteristics of the new band be? Will it resemble 432 MHz or 1296 MHz, the companion bands? Or neither? What circuit techniques apply to the new band? How can power be generated at this frequency to make "tropo" and "moonbounce" (earth-moon-earth) communications practical?

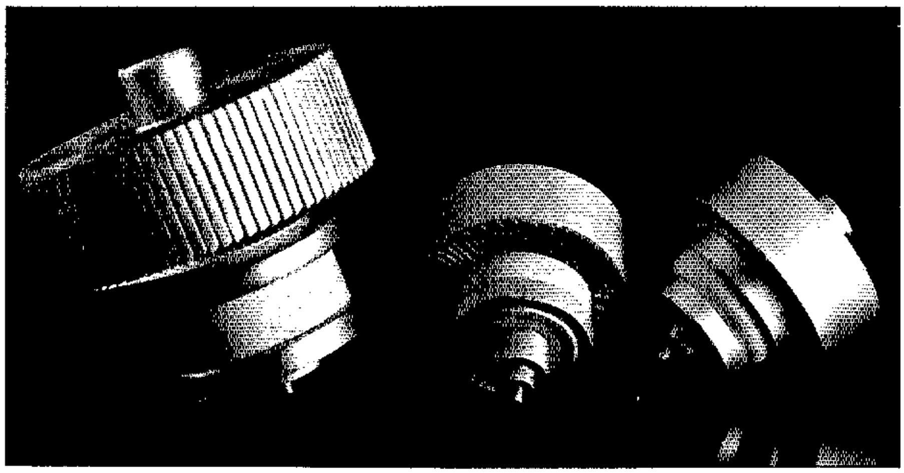


Fig. 1 — Uhf tubes, left to right: 8938 triode with a plate dissipation of 1500 W and rated for more than 1500 W of output at 400 MHz; the 3CX400U7, used in the CV-2805 cavity at 900 MHz; and a 3CX600U7, for over 380 W of output at 800 MHz (rated to 1000 MHz).

The 900-MHz Band Looks Good!

At first glance, the proposed 900-MHz band has a lot going for it. A given antenna type is about half as large as it would be at 432 MHz. That's good news for the enthusiast with the small back yard. Receiver noise figure can be as good at 900 MHz as it is at 432 MHz. Coaxial lines are less lossy at 900 MHz than they are at 1296 MHz. Standard antenna designs work well at 900 MHz, whereas some of them become "squirrely" at 1296 MHz. As every 1296-MHz enthusiast knows, generation of appreciable transmitter power at that frequency is a formidable task. Not so at 900 MHz.Several uhf transmitting tubes will deliver the goods at 900 MHz (Fig. 1), and circuit design is straightforward.

Taking everything into consideration, it seems as if the forthcoming 900-MHz assignment is a "natural" for radio amateurs, since the equipment required to make use of this portion of the rf spectrum is available now. All amateurs require is the *authority* to use this new, interesting band.

A 900-MHz Power Amplifier

Described in this article is a simple power amplifier that is intended for moonbounce communication at 900 MHz. In fm or cw service it provides over 200-W output, and in ssb service it provides over 300-W PEP output. Drive power is about 20 W peak in either case. For those interested, a block diagram of the complete EME station is given in Fig. 2.

The amplifier is essentially a quarter-wave rectangular resonator used in conjunction with a 3CX400U7 high-mu power triode. The tube operates at 1500 to 2000 V. A three-quarter-wave coaxial line assembly is used for the input circuit. Drive power is obtained from a solid-state circuit and a 3CX100A5 cavity amplifier. This is a basic uhf cavity amplifier design that was pioneered by EIMAC and used with success at frequencies above and below the forthcoming amateur band.[1]

The general operating characteristics of the 3CX400U7 tube are listed in Table 1. A combination of high amplification factor and minimum grid interception provide good power gain in cathode-driven service. Coaxial terminals and continuous cone-shaped internal supports for the grid

[1]Notes appear on page 16.

Table 1

Operating Characteristics of 3CX400U7 at 900 MHz

Tube Parameters	*Ssb*	*Fm/Cw*
Plate voltage	2000-V dc	1500-V dc
Cathode bias†	12.0-V dc	12.0-V dc
Filament voltage	6.3-V ac	5.0-V ac
Plate current	400-mA dc	400-mA dc
Grid current††	– 10 mA dc	– 10 mA dc
Useful power output	320 W	230 W

†Varies with class of service
††Approximate

*Varian/EIMAC Division, San Carlos, CA 94070

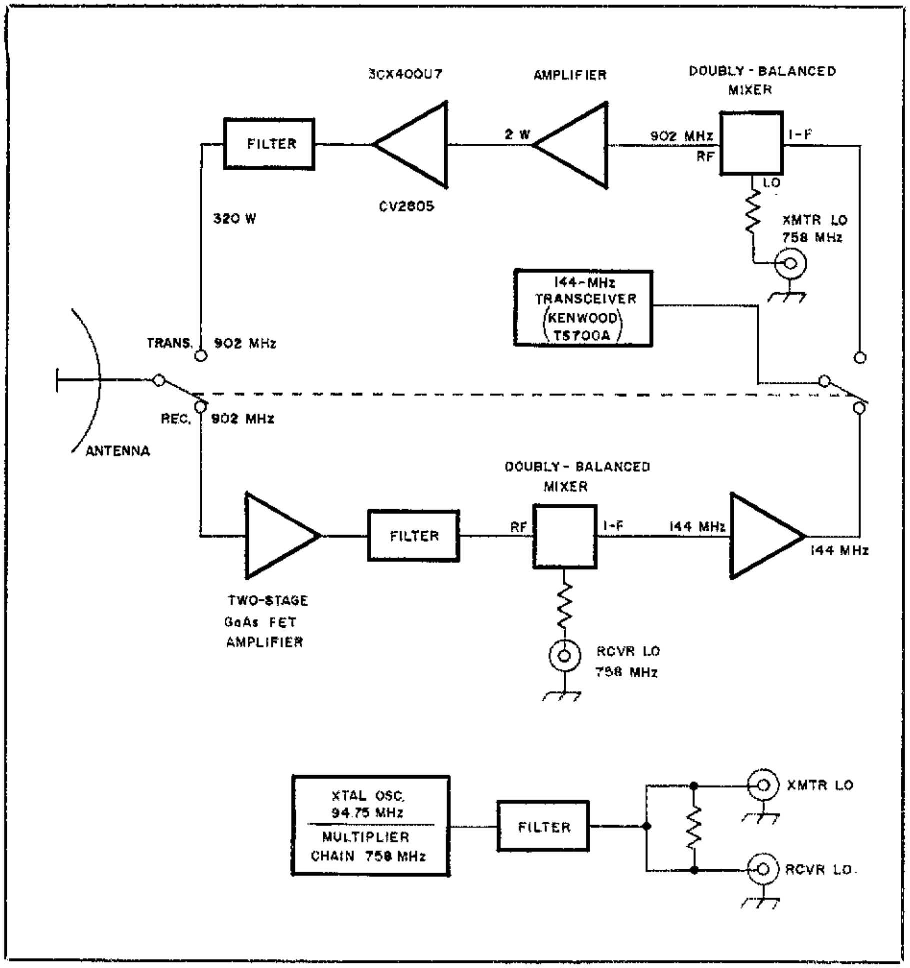


Fig. 2 — Block diagram of the planned EME station at W6PO. A 144-MHz transceiver is used as the station control unit.

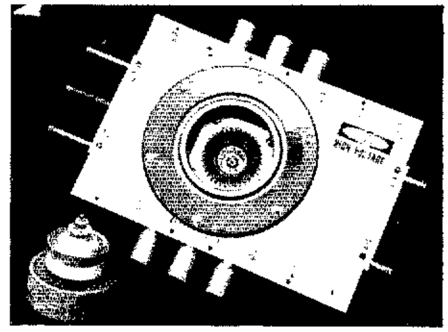


Fig. 3 — Top view of the CV-2805 cavity for 900 MHz. A 3CX400U7 provides more than 300 W of ssb output power. A phenolic ring surrounds the tube-anode collet and holds the circular plate-bypass capacitor (see text).

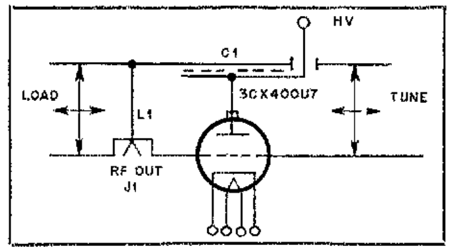


Fig. 4 — Plate circuit of the 1/4-wavelength rectangular resonator. Tuning is by means of sliding walls. The left wall (marked *load*) varies the output coupling by changing the cavity area between L1 and the wall. Resonance is obtained by moving the right wall *(tune)*, which varies the volume of the cavity. The two walls are adjusted in unison, much like the tuning and loading controls of an hf-band amplifier. A large plate is separated from the top of the resonator by means of a thin insulating sheet. It serves as a plate bypass capacitor.

and cathode elements of the 3CX400U7 provide the lowest possible inductance between tube elements and the external circuitry.

The Cavity Plate Circuit

The plate circuit of the CV-2805 amplifier (Fig. 3) is a quarter-wave adjustable cavity. Output coupling is magnetic. A loop is formed between the cavity walls and a post that terminates in the coaxial output connector. Coupling between the output loop and the cavity is varied by moving a wall of the cavity. A simple threaded drive shaft does the job. The degree of coupling is determined by the cavity area enclosed by the post and the cavity walls (Fig. 4). Plate-circuit resonance is established by changing the volume of the cavity by means of a second sliding wall. Contact between the movable walls and the cavity is maintained by preformed finger stock. The two walls are adjusted in unison, much like the conventional loading and tuning controls of an hf amplifier.

The Input Circuit

A simplified drawing of the input circuit is shown in Fig. 5. As shown at A, the circuit is a 3/4-wavelength-long coaxial line. Nearly a quarter wavelength of the circuit is inside the tube, loaded by the tube input capacitance, so that the use of a quarter-wave line is out of the question; insufficient line exists outside the tube to couple to or to effectively tune. An additional half wavelength of line is added to provide room for the tuning capacitor (C1) and the coupling capacitor (C2), which are both placed near the high-impedance portion of the line. The rf short at the bottom of the line is reflected one-half-wavelength up the line, placing the cathode and grid of the tube at a high-impedance point, with the proper 180° phase difference betwen the elements. Since the outside of the assembly is at dc ground potential (Fig. 6), the rf short at the bottom end of the line is made up of a very-low-impedance bypass capacitor, which provides dc isolation for the cathode-return circuit. Fig. 5B shows the same circuit folded back upon itself to conserve length. This is the configuration used in the CV-2805 cavity. The filament leads are brought out through concentric tubes at the center of the assembly; the tubes act as rf chokes to isolate the filament circuit.

Cooling The Cavity

Air for anode cooling is introduced from a cowl or chamber through the three short tubes on each side of the output cavity. The air then exhausts through the finned anode. The short tubes are dimensioned to serve as a "waveguide beyond cutoff" rf filter in the air openings. This prevents the loss of rf power through these ports. Approximately 11.5 cfm of air is required when the tube is operating at sea level and at the full anode dissipation rating of 400 W. The pressure drop across the anode cooler at this flow rate is about 0.2 inch of water. These figures are based on an incoming air temperature of 50° C and a maximum tube-anode temperature of 225° C.

Heater-Cathode Operation

The nominal heater voltage for the 3CX400U7 is 6.3. For operation above 300 MHz and at full power or key-down cw service, the voltage should be reduced as the cathode receives additional heat from rf charging currents and transit-time effects. In this cavity, operating heater voltage is 5.0 for continuous service. During warmup and standby periods, heater voltage is held at 6.3. Nominal heater voltage is applied for a minimum of 60 seconds before plate voltage is applied and operation commences. For best life expectancy and the most stable performance, it is suggested that the heater voltage be held to the final desired value with ±2%. For ssb service and low duty cycle cw, heater voltage is maintained at 6.3.

The Metering Circuits

Conventional grid- and plate-metering circuits are used, with protection provided for the meters by means of reverse-parallel shunt diodes. A zero-center meter is used in the grid circuit because a normal grid-current indication can be negative, depending on plate-circuit loading. This negative current is the result of tube characteristics and transit-time effects at the frequency of operation. A simplified metering diagram is shown in Fig. 7.

Amplifier Adjustment

Before operation is attempted, the cavity-amplifier controls should be set by means of a preturning chart. The cavity frequency rises as the tuning wall is moved inward toward the tube. During tuneup, an rf directional coupler should be placed in the drive line from the exciter. A Thruline® wattmeter, or equivalent monitor, is placed in the output line to the dummy load. Filament and bias voltages, and cooling air, are applied to the cavity. A filament voltage of 6.3 is applied for 60 seconds, followed by the anode voltage of 2000, maximum. Plate current with no drive signal will be approximately 50 mA. When about 10 W of drive is applied, the plate current should rise to 300 to 400 mA. There should be an indication of output power on the Thruline® wattmeter. Under no circumstances should there be rf drive with no plate voltage, as the full drive power will be dissipated in the grid. The tuning and loading controls are now adjusted for maximum output, and both of them are varied until maximum output is achieved. The filament voltage is now dropped to 5.0 for continuous duty or fm operation. It is held at 6.3 for ssb service.

The next step is to adjust the input tuning and matching controls under full-power conditions. The input probe capacitor and the tuning control are adjusted for minimum reflected power. These adjustments are interlocking, so they must be done alternately, tuning for minimum power reflection in the drive line. When this is achieved, the output tuning control should be reset for best power output.

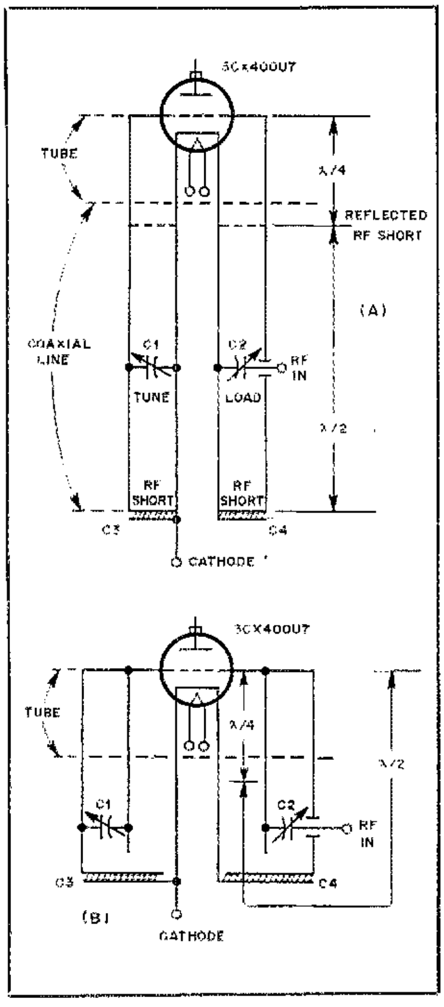


Fig. 5 — At A, the circuit is a 3/4-wavelength coaxial line. Nearly a quarter wavelength of the line is inside the tube — loaded by the tube input capacitance. It is difficult to couple to the short line section, which is external to the tube, so an additional half wavelength of line is added to provide room for tuning capacitor C1 and coupling capacitor C2. The rf short at the bottom of the line (C3, C4) is reflected a half wavelength up the line. This places the cathode and the grid at high impedance, with the proper phase difference between the elements. At B, the same circuit is folded back on itself to conserve length.

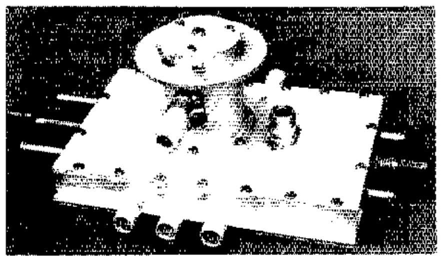


Fig. 6 — View below the CV-2805 cavity. Input-loading capacitor C2 is adjusted by sliding the coaxial fitting in and out of a sleeve. A clamp around the joint locks the adjustment. The plate rf connector is at the side of the input cavity. Filament and cathode connections are made at the end of the input cavity. The assembly is made from heavy silver-plated brass stock to limit thermal expansion.

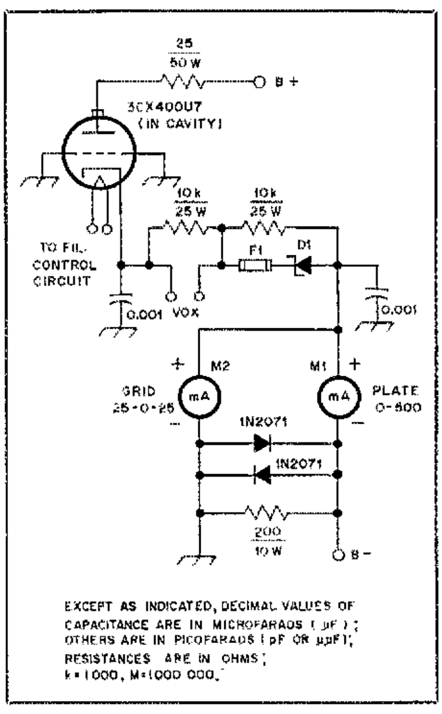


Fig. 7 — Amplifier metering circuit. Metering is done in the power supply return lead. The high-voltage negative line is a few mV above ground to allow insertion of the meters. Reverse-connected diodes protect the meters from overload.

Operation Notes

The tube anode is bypassed effectively in the cavity, so no special precautions are required for application of high voltage to the tube. Connection is made most easily to the center cap of the anode, and it is recommended that a 25-ohm, 50-W current-limiting resistor be used in the high-voltage lead to protect the tube in the cause of a fault condition.

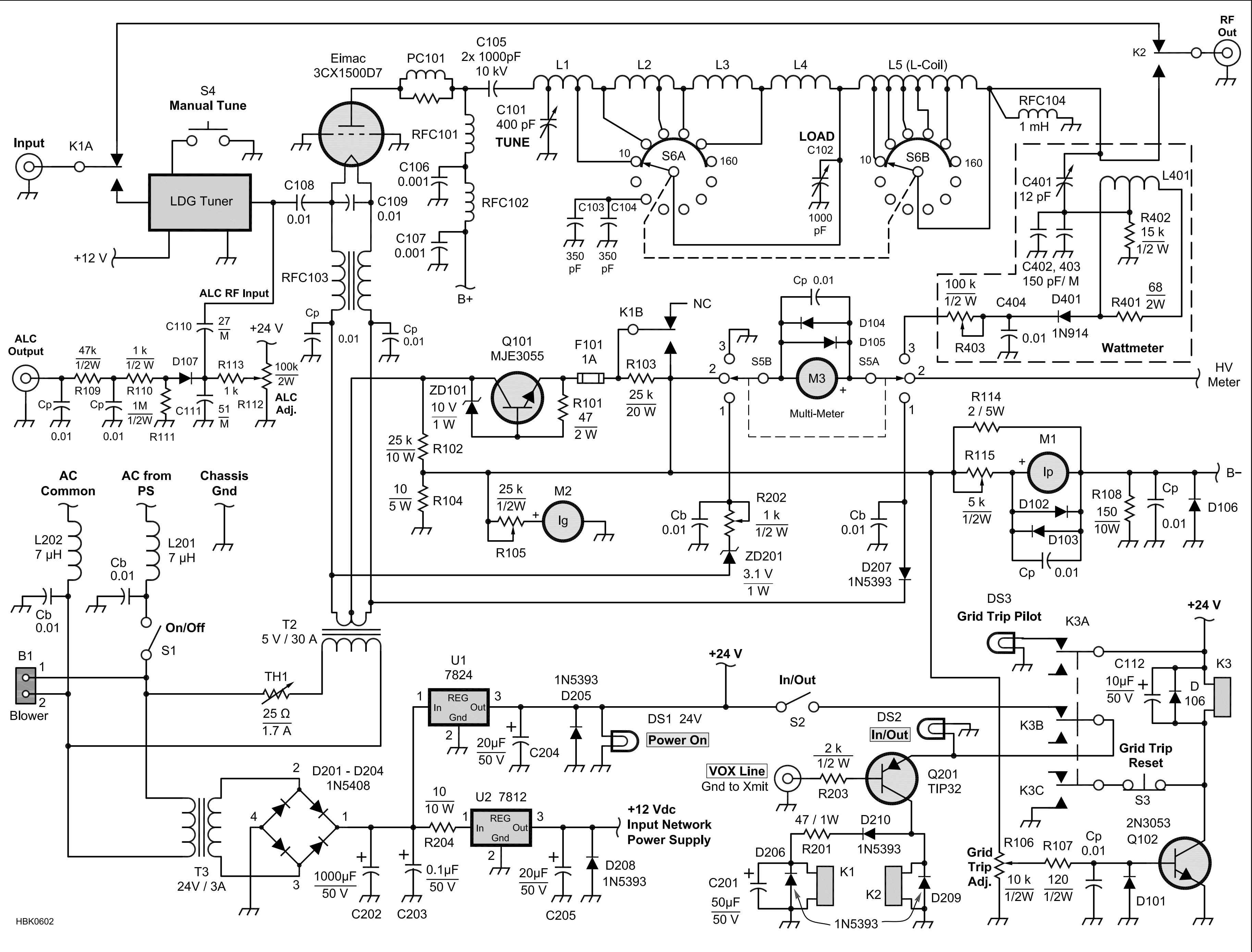
Application of plate voltage should be interlocked with the rf drive in a suitable manner so that the drive signal cannot be applied to the cavity in the absence of plate voltage. It is suggested also that the equipment include an air interlock, so no voltages can be applied to the cavity unless there is an adequate flow of cooling air. For ssb service, the bias should be a fixed value and may be obtained with Zener diode(s) in the cathode circuit.

Finally, it must not be forgotten that absorption of rf energy by human tissue is dependent on frequency. Under 300 MHz, most of the energy will pass completely through the human body with little attenuation or heating effect. At 900 MHz, however, a noticeable heating effect exists, and a prudent operator will stay clear of the antenna field. More information on rf effects on the human body can be found in note 2. QST

Notes

[1]The brochure entitled "EIMAC Cavity Amplifiers," and data sheets for the CV-2805 and the 3CX400U7 are available at no cost by writing to: Application Engineering Dept., Varian/EIMAC Division, 301 Industrial Way, San Carlos, CA 94070.

[2]The following references should be helpful to those seeking further information:
ANSI C95.1-(1982). *Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields (300 kHz to 100 GHz)*. (New York: American National Standards Institute, 1982).
"ARRL Comments on the Biological Effects of RF Energy," Oct. 1982 *QST*, p. 53.
"How Dangerous is RF Radiation?" Technical Correspondence, Sept. 1978, p. 31.
Proceedings of the IEEE, Special issue on Biological Effects and Medical Applications of Electromagnetic Energy, Jan. 1980 (New York: IEEE, 1980).



RF Out
K2
Input
K1A
S4
Manual Tune
LDG Tuner
+12 V
Eimac
3CX1500D7
PC101
C105
2x 1000pF
10 kV
C101
400 pF
TUNE
L1
L2
L3
L4
L5 (L-Coil)
RFC104
1 mH
RFC101
C106
0.001
RFC102
C107
0.001
B+
C108
0.01
C109
0.01
RFC103
Cp
0.01
S6A
S6B
10
160
LOAD
C102
1000 pF
C103
C104
350 pF
350 pF
C401
12 pF
C402, 403
150 pF/ M
L401
R402
15 k
1/2 W
R401
68
2W
D401
1N914
C404
100 k
1/2 W
R403
Wattmeter
ALC RF Input
C110
27 M
+24 V
100k
2W
ALC Adj.
R112
R113
1 k
C111
51 M
D107
ALC Output
47k
1/2W
R109
R110
1M
1/2W
R111
Q101
MJE3055
F101
1A
K1B
NC
R103
25 k
20 W
ZD101
10 V
1 W
R101
47
2 W
R102
25 k
10 W
R104
10
5 W
S5B
S5A
M3
Multi-Meter
D104
D105
HV Meter
R114
2 / 5W
R115
5 k
1/2W
M1
Ip
D102
D103
R108
150
10W
D106
B–
M2
Ig
R105
25 k
1/2W
R202
1 k
1/2 W
ZD201
3.1 V
1 W
Cb
D207
1N5393
AC Common
AC from PS
Chassis Gnd
L202
7 µH
L201
7 µH
On/Off
S1
B1
Blower
T2
5 V / 30 A
TH1
25 Ω
1.7 A
U1
7824
REG
In
Out
Gnd
1N5393
D205
20µF
50 V
C204
DS1 24V
Power On
In/Out
S2
DS2
In/Out
VOX Line
Gnd to Xmit
2 k
1/2 W
R203
Q201
TIP32
D201 - D204
1N5408
T3
24V / 3A
1000µF
50 V
C202
0.1µF
50 V
C203
10
10 W
R204
U2 7812
20µF
50 V
C205
D208
1N5393
+12 Vdc
Input Network
Power Supply
47 / 1W
R201
D210
1N5393
D206
K1
K2
D209
C201
50µF
50 V
DS3
Grid Trip Pilot
K3A
K3B
K3C
C112
10µF
50 V
K3
D 106
Grid Trip Reset
S3
Grid Trip Adj.
R106
10 k
1/2W
R107
120
1/2W
2N3053
Q102
D101
HBK0602

Contents

Design Example: A High Power Vacuum Tube HF Amplifier Using the 8877 Triode

Editor's note: Section and figure references in this article are from the 2013 edition of the ARRL Handbook. This material was originally contributed to the Handbook by John Stanley, K4ERO.

Most popular HF transceivers produce approximately 100 W output. The EIMAC 8877 can deliver 1500 W output for approximately 60 W of drive when used in a grounded grid circuit. Grounded-grid operation is usually the easiest tube amplifier circuit to implement. Its input impedance is relatively low, often close to 50 Ω. Input/output shielding provided by the grid and negative feedback inherent in the grounded-grid circuit configuration reduce the likelihood of amplifier instability and provide excellent linearity without critical adjustments. Fewer supply voltages are needed in this configuration compared to others, often just high-voltage dc for the plate and low-voltage ac for the filament.

17.9.1 Tube Capabilities

The first step in the amplifier design process is to verify that the tube is actually capable of producing the desired results while remaining within manufacturer's ratings. The plate dissipation expected during normal operation of the amplifier is computed first. Since the amplifier will be used for SSB, a class of operation producing linear amplification must be used. Class AB2 provides a very good compromise between linearity and good efficiency, with effective efficiency typically exceeding 60%. Given that efficiency, an input power of 2500 W is needed to produce the desired 1500 W output. Operated under these conditions, the tube will dissipate about 1000 W — well within the manufacturer's specifications, provided adequate cooling airflow is supplied.

The grid in modern high-mu triodes is a relatively delicate structure, closely spaced to the cathode and carefully aligned to achieve high gain and excellent linearity. To avoid shortening tube life or even destruction of the tube, the specified maximum grid dissipation must not be exceeded for more than a few milliseconds under any conditions. For a given power output, the use of higher plate voltages tends to result in lower grid dissipation. It is important to use a plate voltage that is high enough to result in safe grid current levels at maximum output. In addition to maximum ratings, manufacturers' data sheets often provide one or more sets of "typical operation" parameters. This makes it even easier for the builder to achieve optimum results.

According to typical operation data, the 8877, operating at 3500 V, can produce 2075 W of RF output with excellent linearity and 64 W of drive. Operating at 2700 V it can deliver 1085 W with 40 W of drive. To some extent, the ease and cost of constructing a high-power amplifier, as well as its ultimate reliability, are enhanced by using the lowest plate voltage that will yield completely satisfactory performance. Working with various load lines on the characteristic curves shows that the 8877 can comfortably deliver 1.5 kW output with a 3100 V plate supply and 50 to 55 W of drive. Achieving 1640 W output power at this plate voltage requires 800 mA of plate current — well within the 8877's maximum rating of 1.0 A.

Parameter	Result
Grid Current (mA)	34.2
Screen Current (mA)	0.00
Plate Current (A)	0.800
Input Power (Watts)	2470
Output Power (Watts)	1640
Plate Dissipation (W)	831
Plate Load (Ohms)	2210
Efficiency (%)	66.3
Grid Swing (Volts)	80.0
Resting Dissipation (W)	620
Input Resistance (Ohms)	62.5
Power Passed (Watts)	48.8
Total drive power (W)	51.6

Fig 17.35 — Typical operating parameters for the 8877 triode used in the design example detailed in the text.

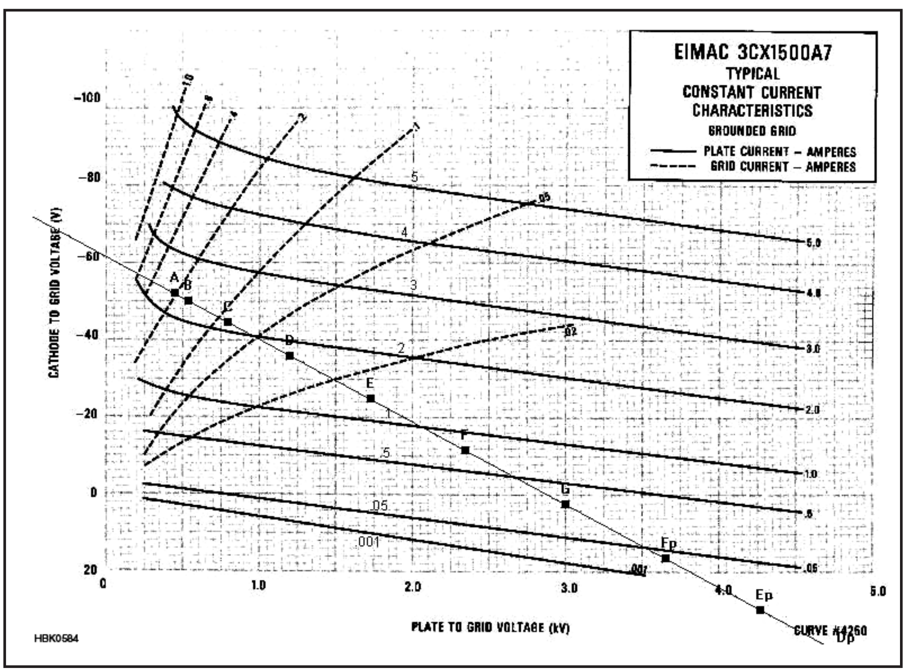


Fig 17.34 — Characteristic curves for the 8877 triode used in the design example detailed in the text.

17.9.2 Input and Output Circuits

The next step in the design process is to calculate the optimum plate load resistance at this plate voltage and current for Class AB2 operation and design an appropriate output-matching network. Using the operating line shown in **Fig 17.34**, the *TubeCalculator* program gives these values (**Fig 17.35**). The simple formula for load resistance shown earlier in this chapter (equation 1) gives a similar value, about 2200 Ω.

Several different output networks might be used to transform the nominal 50-Ω resistance of the actual load to the 2200-Ω load resistance required by the 8877, but experience shows that pi and pi-L networks are most practical. Each can provide reasonable harmonic attenuation, is relatively easy to build mechanically and uses readily available components. The pi-L gives significantly greater harmonic attenuation than the pi and usually is the better choice — at least in areas where there is any potential for TVI or crossband interference. In a multiband amplifier, the extra cost of using a pi-L network is the "L" inductor and its associated band switch section.

The input impedance of a grounded-grid 8877 is typically on the order of 50 to 55 Ω, shunted by input capacitance of about 38 pF. While this average impedance is close enough to 50 Ω to provide negligible input SWR, the instantaneous value varies greatly over the drive cycle — that is, it is nonlinear. This nonlinear impedance is reflected back as a nonlinear load impedance at the exciter output, resulting in increased intermodulation distortion, reduced output power, and often meaningless exciter SWR meter indications. In addition, the tube's parallel input capacitance, as well as parasitic circuit reactances, often are significant enough at 28 MHz to create significant SWR.

A tank circuit at the amplifier input can solve both of these problems by tuning out the stray reactances and stabilizing (linearizing) the tube input impedance through its flywheel effect. The input tank should have a loaded Q of at least two for good results. A Q of five results in a further small improvement in linearity and distortion, but at the cost of a narrower operating bandwidth. Using the *PI-EL Design* software, one can quickly determine values for C1, L1 and C2 for the various bands as well as the bandwidth that various values of Q will provide. Since the 3.5 to 4 MHz band is the widest in terms of percentage bandwidth, using a lower Q for that band seems wise. If we wish to cover two bands with the same switch position, for example the 24 and 28 MHz bands, that will also call for a lower Q. For the 40, 30 and 20 meter bands alone, a rather high Q would work fine. Remember to subtract the input capacitance of the tube from the calculated value of C2.

Fig 17.36 illustrates these input and output networks applied in the amplifier circuit. The schematic shows the major components in the amplifier RF section, but with band-switching and cathode dc return circuits omitted for clarity. C1 and C2 and L1 form the input pi network. C3 is a blocking capacitor to isolate the exciter from the cathode dc potential. Note that when the tube's average input resistance is close to 50 Ω, as in the case of the 8877, a simple parallel-resonant tank often can successfully perform the tuning and flywheel functions, since no impedance transformation is necessary. In this case, it is important to minimize stray lead inductance between the tank and tube to avoid undesired impedance transformation.

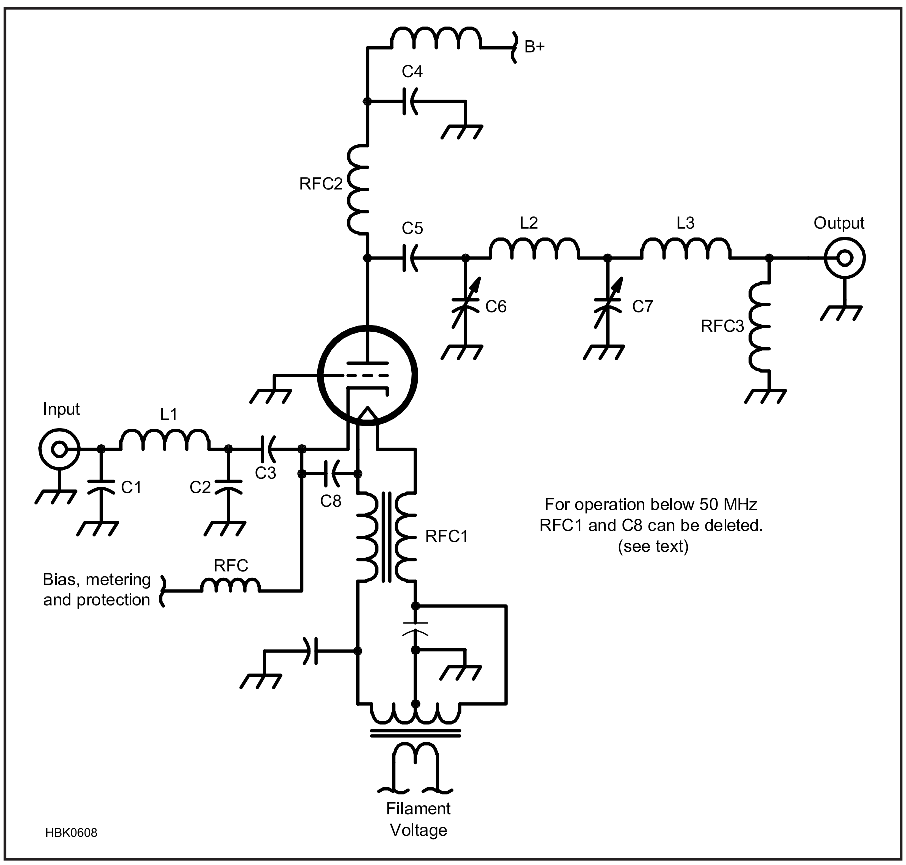


Fig 17.36 — A simplified schematic of a grounded-grid amplifier using a pi network input and pi-L network output.

17.9.3 Filament Supply

The filament or "heater" in indirectly heated tubes such as the 8877 must be very close to the cathode to heat the cathode efficiently. A capacitance of several picofarads exists between the two. Particularly at very high frequencies, where these few picofarads represent a relatively low reactance, RF drive intended for the cathode can be capacitively coupled to the lossy filament and dissipated as heat. To avoid this, above about 50 MHz, the filament must be kept at a high RF impedance above ground. The high impedance (represented by choke RFC1 in Fig 17.36) minimizes RF current flow in the filament circuit so that RF dissipated in the filament becomes negligible. The choke's low-frequency resistance should be kept to a minimum to lessen voltage drops in the high-current filament circuit.

The choke most commonly used in this application is a pair of heavy-gauge insulated wires, bifilar-wound over a ferrite rod. The ferrite core raises the inductive reactance throughout the HF region so that a minimum of wire is needed, keeping filament-circuit voltage drops low. The bifilar winding technique assures that both filament terminals are at the same RF potential.

Below 30 MHz, the use of such a choke seldom is necessary or beneficial, but actually can introduce another potential problem. Common values of cathode-to-heater capacitance and heater-choke inductance often are series resonant in the 1.8 to 29.7 MHz HF range. A capacitance of 5 pF and an inductance of 50 μH, for example, resonate at 10.0 MHz; the actual components are just as likely to resonate near 7 or 14 MHz. At resonance, the circuit constitutes a relatively low impedance shunt from cathode to ground, which affects input impedance and sucks out drive signal. An unintended resonance like this near any operating frequency usually increases input SWR and decreases gain on that one particular band. While aggravating, the problem rarely completely disables or damages the amplifier, and so is seldom pursued or identified.

Fortunately, the entire problem is easily avoided — below 30 MHz the heater choke can be deleted. At VHF-UHF, or wherever a heater isolation choke is used for any reason, the resonance can be moved below the lowest operating frequency by connecting a sufficiently large capacitance (about 1000 pF) between the tube cathode and one side of the heater. It is good practice also to connect a similar capacitor between the heater terminals. It also would be good practice in designing other VHF/UHF amplifiers, such as those using 3CX800A7 tubes, unless the builder can ensure that the actual series resonance is well outside of the operating frequency range.

17.9.4 Plate Choke and DC Blocking

Plate voltage is supplied to the tube through RFC2. C5 is the plate blocking capacitor. The output pi-L network consists of tuning capacitor C6, loading capacitor C7, pi coil L2, and output L coil L3. RFC3 is a high-inductance RF choke placed at the output for safety purposes. Its value, usually 100 μH to 2 mH, is high enough so that it appears as an open circuit across the output connector for RF. However, should the plate blocking capacitor fail and allow high voltage onto the output matching network, RFC3 would short the dc to ground and blow the power-supply fuse or breaker. This prevents dangerous high voltage from appearing on the feed line or antenna. It also prevents electrostatic charge — from the antenna or from blocking capacitor leakage — from building up on the tank capacitors and causing periodic dc discharge arcs to ground. If such a dc discharge occurs while the amplifier is transmitting, it can trigger a potentially damaging RF arc.

17.9.5 Tank Circuit Design

The output pi-L network must transform the nominal 50-Ω amplifier load to a pure resistance of 2200 Ω. We previously calculated that the 8877 tube's plate must see 2200 Ω for optimum performance. In practice, real antenna loads are seldom purely resistive or exactly 50 Ω; they often exhibit SWRs of 2:1 or greater on some frequencies. It's desirable that the amplifier output network be able to transform any complex load impedance corresponding to an SWR up to about 2:1 into a resistance of 2200 Ω. The network also must compensate for tube C_{OUT} and other stray plate-circuit reactances, such as those of interconnecting leads and the plate RF choke. These reactances, shown in **Fig 17.37**, must be taken into account when designing the matching networks. Because the values of most stray reactances are not accurately known, the most satisfactory approach is to estimate them, and then allow sufficient flexibility in the matching network to accommodate modest errors.

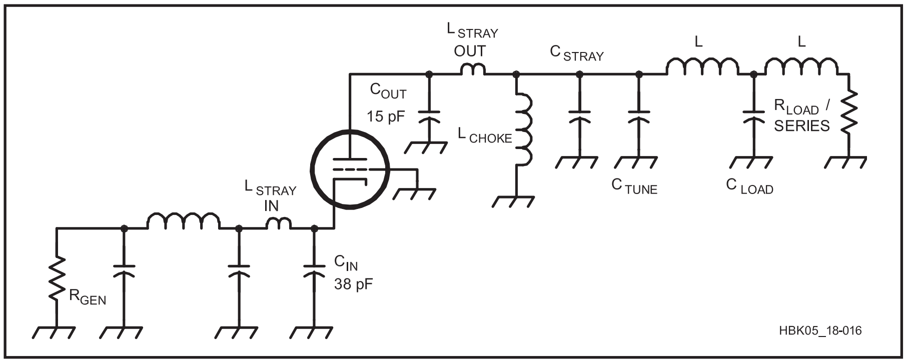


Fig 17.37 — The effective reactances for the amplifier in Fig 17.36.

Fig 17.37 shows the principal reactances in the amplifier circuit. C_{OUT} is the actual tube output capacitance of 10 pF plus the stray capacitance between its anode and the enclosure metalwork. This stray C varies with layout; we will approximate it as 5 pF, so C_{OUT} is roughly 15 pF. L_{OUT} is the stray inductance of leads from the tube plate to the tuning capacitor (internal to the tube as well as external circuit wiring.) External-anode tubes like the 8877 have essentially no internal plate leads, so L_{OUT} is almost entirely external. It seldom exceeds about 0.3 μH and is not very significant below 30 MHz. L_{CHOKE} is the reactance presented by the plate choke, which usually is significant only below 7 MHz. C_{STRAY} represents the combined stray capacitances to ground of the tuning capacitor stator and of interconnecting RF plate circuit leads. In a well-constructed, carefully thought out power amplifier, C_{STRAY} can be estimated to be approximately 10 pF. Remaining components C_{TUNE}, C_{LOAD}, and the two tuning inductors, form the pi-L network proper.

The values for the output network components can be calculated using the *PI-EL Design* software, taken from the graphical charts in Figs 17.17 to 17.19, or from tables included on the *Handbook* CD. For pi networks, a Q of 12 is a good compromise between harmonic suppression and circuit losses. In practice, it often is most realistic and practical with both pi and pi-L output networks to accept somewhat higher Q values on the highest HF frequencies — perhaps as large as 18 or even 20 at 28 MHz. When using a pi-L on the 1.8 and 3.5 MHz bands, it often is desirable to choose a moderately lower Q , perhaps 8 to 10, to permit using a more reasonably-sized plate tuning capacitor.

CIRCUIT REACTANCES

The calculated output network values must be adjusted to allow for circuit reactances outside the pi-L proper. First, low-frequency component values should be examined. At 3.5 MHz, assuming that total tuning capacitance C1 is 140 pF, we know that three other stray reactances are directly in parallel with C_{TUNE} (assuming that L_{OUT} is negligible at the operating frequency as it should be). The tube's internal and external plate capacitance to ground, C_{OUT}, is about 15 pF. Strays in the RF circuit, C_{STRAY}, are roughly 10 pF.

The impedance of the plate choke, X_{CHOKE}, is also in parallel with C_{TUNE}. Plate chokes with self-resonance characteristics suitable for use in amateur HF amplifiers typically have inductances of about 90 μH. At 3.5 MHz this is an inductive reactance of +1979 Ω. This appears in parallel with the tuning capacitance, effectively canceling an equal value of capacitive reactance. At 3.5 MHz, an X_C of 1979 Ω corresponds to 23 pF of capacitance — the amount by which tuning capacitor C_{TUNE} must be increased at 3.5 MHz to compensate for the effect of the plate choke.

If the pi-L network requires an effective capacitance of 140 pF at its input at 3.5 MHz, subtracting the 25 pF provided by C_{OUT} and C_{STRAY} and adding the 23 pF canceled by X_{CHOKE}, the actual value of C_{TUNE} must be $140 - 25 + 23 = 138$ pF. It is good practice to provide at least 10% extra capacitance range to allow matching loads having SWRs up to 2:1. So, if 3.5 MHz is the lower frequency limit of the amplifier, a variable tuning capacitor with a maximum value of at least 150 to 160 pF should be used.

PERFORMANCE AT HIGH FREQUENCIES

Component values for the high end of the amplifier frequency range also must be examined, for this is where the most losses will occur. At 29.7 MHz we can assume a minimum pi-L input capacitance of 35 pF. Since C_{OUT} and C_{STRAY} contribute 25 pF, C_{TUNE} must have a minimum value no greater than 10 pF. A problem exists, because this value is not readily achievable with a 150 to 160-pF air variable capacitor suitable for operation with a 3100 V plate supply. Such a capacitor typically has a minimum capacitance of 25 to 30 pF. Usually, little or nothing can be done to reduce the tube's C_{OUT} or the circuit C_{STRAY}, and in fact the estimates of these may even be a little low. If 1.8 MHz capability is desired, the maximum tuning capacitance will be at least 200 to 250 pF, making the minimum-capacitance problem at 29.7 MHz even more severe.

There are three potential solutions to this dilemma. We could accept the actual minimum value of pi-L input capacitance, around 50 to 55 pF, realizing that this will raise the pi-L network's loaded Q to about 32. This results in very large values of circulating tank current. To avoid damage to tank components — particularly the band switch and pi inductor — from heat due to I^2R losses, it will be necessary to either use oversize components or reduce power on the highest-frequency bands. Neither option is appealing.

A second potential solution is to reduce the minimum capacitance provided by C_{TUNE}. We could use a vacuum variable capacitor with a 300-pF maximum and a 5-pF minimum capacitance. These are rated at 5 to 15 kV, and are readily available. This reduces the minimum effective circuit capacitance to 30 pF, allowing use of the pi-L values for a Q of 12 on all bands from 1.8 through 29.7 MHz. While brand new vacuum variables are quite expensive, suitable models are widely available in the surplus and used markets for prices not much higher than the cost of a new air variable. A most important caveat in purchasing a vacuum capacitor is to ensure that its vacuum seal is intact and that it is not damaged in any way. The best way to accomplish this is to "hi-pot" test the capacitor throughout its range, using a dc or peak ac test voltage of 1.5 to 2 times the amplifier plate supply voltage. For all-band amplifiers using plate voltages in excess of about 2500 V, the initial expense and effort of securing and using a vacuum-variable input tuning capacitor often is well repaid in efficient and reliable operation of the amplifier.

A third possibility is the use of an additional inductance connected in series between the tube and the tuning capacitor. In conjunction with C_{OUT} of the tube, the added inductor acts as an L network to transform the impedance at the input of the pi-L network up to the 2200-Ω load resistance needed by the tube. This is shown in **Fig 17.38A**. Since the impedance at the input of the main pi-L matching network is reduced, the loaded Q for the total capacitance actually in the circuit is lower. With lower Q, the circulating RF currents are lower, and thus tank losses are lower.

C_{OUT} in Fig 17.38 is the output capaci-tance of the tube, including stray C from the anode to metal enclosure. X_L is the additional series inductance to be added. As determined previously, the impedance seen by the tube anode must be a 2200 Ω resistance for best linearity and efficiency, and we have estimated C+ of the tube as 15 pF. If the network consisting of C_{OUT} and X_L is terminated at A by 2200 Ω, we can calculate the equiva-lent impedance at point B, the input to the pi-L network, for various values of series X_L. The pi-L network must then transform the nominal 50-Ω load at the transmitter output to this equivalent impedance.

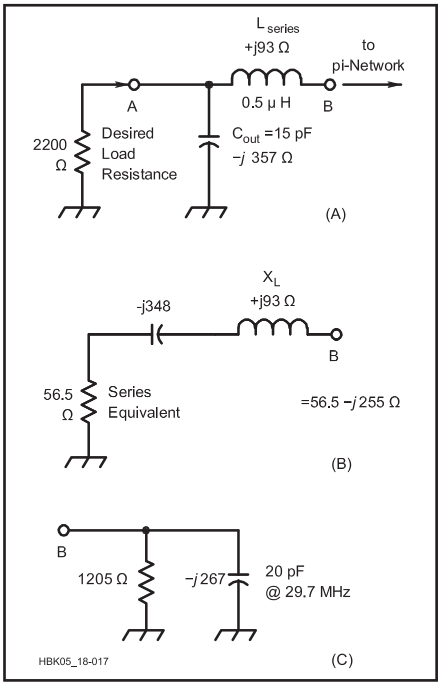


Fig 17.38 — The effect of adding a small inductor in series with the tube plate to aid matching at high frequencies. See text for details.

IMPEDANCE TRANSFORMATIONS

We work backwards from the plate of the tube towards the C_{TUNE} capacitor. First, calculate the series-equivalent impedance of the parallel combination of the desired 2200-Ω plate load and the tube X_{OUT} (15 pF at 29.7 MHz = $-j$ 357 Ω). The series-equivalent impedance of this parallel combination is 56.5 – j 348 Ω, as shown in Fig 17.38B. Now suppose we use a 0.5 µH inductor, having an impedance of + j 93 Ω at 29.7 MHz, as the series inductance X_L. The resulting series-equivalent impedance is 56.5 – j348 + j93, or 56.5 – j255 Ω. Converting back to the parallel equivalent gives the network of Fig 17.38C: 1205 Ω resistance in parallel with – j267 Ω, or 20 pF at 29.7 MHz. The pi-L tuning network must now transform the 50-Ω load to a resistive load of 1205 Ω at B, and absorb the shunt capacitance of 20 pF.

Using the *PI-EL Design* software or pi network formulas on the *Handbook* CD, R1 = 1205 Ω and Q = 15 at 29.7 MHz, yields a required total capacitance of about 67 pF at 29.7 MHz. Note that for the same loaded Q for a 2200-Ω load line without the series inductor, the capacitance was about 36 pF. When the 20 pF of transformed input capacitance is subtracted from the 67 pF total needed, the amount of capacitance is 47 pF. If the minimum capacitance in C_{TUNE} is 25 pF and the stray capacitance is 10 pF, then there is a margin of 47– 35 = 12 pF beyond the minimum capacitance for handling SWRs greater than 1:1 at the load.

The series inductor should be a high-Q coil wound from copper tubing to keep losses low. This inductor has a decreasing, yet significant effect, on progressively lower frequencies. A similar calculation to the above should be made on each band to determine the transformed equivalent plate impedance, before calculating the network values. The impedance-transformation effect of the additional inductor decreases rapidly with decreasing frequency. Below 21 MHz, it usually may be ignored and pi-L network values calculated for R1 = 2200 Ω.

The nominal 90-µH plate choke remains in parallel with C_{TUNE}. It is rarely possible to calculate the impedance of a real HF plate choke at frequencies higher than about 5 MHz because of self-resonances. However, as mentioned previously, the choke's reactance should be sufficiently high that the calculations are not seriously affected if the choke's first series-resonance is at 23.2 MHz.

This amplifier is made operational on multiple bands by changing the values of inductance at L2 and L3 for different bands. The usual practice is to use inductors for the lowest operating frequency, and short out part of each inductor with a switch, as necessary, to provide the inductance needed for each individual band. Wiring to the switch and the switch itself add stray inductance and capacitance to the circuit. To minimize these effects at the higher frequencies, the unswitched 10-m L2 should be placed closest to the high-impedance end of the network at C6. Stray capacitance associated with the switch then is effectively in parallel with C7, where the impedance level is around 300 Ω. The effects of stray capacitance are relatively insignificant at this low impedance level. This configuration also minimizes the peak RF voltage that the switch insulation must withstand.

17.9.6 Checking Operation

After the input and output networks are designed, cold tuning as described earlier will confirm that all of the tuned circuits are working properly. These tests are well worth doing before any power is applied to the amplifier. The band switch itself will have significant inductance especially on the higher frequencies. To determine the proper taps for the various bands on the tank inductor, start with the highest frequency and verify that the calculated number of turns gives the frequency range desired, moving the tap as needed to allow for the inductance of the band switch. As each tap is located, it should be securely wired with strap or braid and the process repeated for successively lower bands. Once the cold tuning looks good, proceed to the tests for parasitics.

You should now be ready to apply full power to the amplifier and see how it performs.

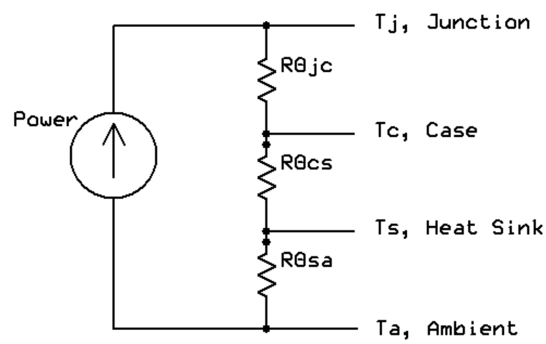
Design Example: MOSFET Thermal Design

By Dick Frey, K4XU

A transistor cannot be run at its maximum rated junction temperature without impacting its long-term reliability. A safe design limit would be 150 °C for a gold-metalization device with a maximum operating junction temperature rating of 200 °C. This will provide a reasonable margin for disastrous events – wrong or no antenna, for instance. The device can then have the thermal margin to withstand the error for the time it takes for the over-current or high SWR protection circuits to react to the fault and shut it off.

Heat sinks come in many forms. Each is rated by its manufacturer for thermal resistance under specified conditions. The thermal rating is called $R_{\Theta SA}$, the thermal resistance between the sink and the ambient environment, i.e. room temperature. For extruded aluminum heat sinks, $R_{\Theta SA}$ is determined, among other things, by the length, depth, number of fins, and the volume and speed of air passing over the fins, if any. The thickness of the base, conductivity of the particular alloy, and whether the fins are part of the extrusion or bonded to it also play on its thermal conductivity. Aluminum is not a particularly good thermal conductor but it's relatively cheap, light and easily extruded into finned shapes. Many amplifier heat sink assemblies employ a copper plate under the transistors as a *thermal spreader* to more effectively distribute the thermal load over the whole area of the sink.

The whole thermal system can be described as shown in the following figure:



The thermal system of a transistor and its heat sink.

The three resistances represent the thermal path of the dissipation power flowing from the transistor's junction out into the ambient environment. The device's $R_{\Theta JC}$ is fixed for a particular device. The case-to-sink $R_{\Theta CS}$ impedance is determined by the surface conditions of the sink and device, and the grease used. The heat sink and its cooling determine the magnitude of $R_{\Theta SA.}$ The temperature drop across any of these thermal impedances can be calculated as $\Delta T = P_D \times R_{\Theta xx}$.

Thermal design starts with the device. Say we want 100 W of RF output from a linear amplifier to be used in the output stage of a mobile radio, operating from 13 V. The amplifier is 50% percent efficient so it takes 200 W of dc input power to get it. 100 W goes to the antenna, the other 100 W goes into the heat sink. We look at devices and see that there are none that can do it alone but the RD100HHF1 will give 100 W, half what is needed. De-rated for the real world, we will use two. This is a good idea since a push-pull amplifier is actually easier to make and has less harmonic content to deal with, and since the two transistors are in parallel thermally, their $R_{\Theta JC}$ is cut in half. These transistors are aluminum LDMOS parts so we decide to aim at 150°C for absolute max T_J.

The amplifier will operate mobile and will experience ambient temperatures much higher than normal room temperature of 25°. A hot day in the car could be 130°F or 55°C. If the amplifier is mounted in a confined space where the heat sink does not get full ambient circulation, it could be even hotter than that. The good news is that you are not going to be operating RTTY at 100% duty cycle. It will be more like 50% or even lower for a low duty cycle mode like SSB. So now we have an average dissipation of 50 W at a maximum ambient temperature of 55°C. The RD100HHF1 has a published $R_{\Theta JC}$ of 0.85 °C/W. Two of them in a push-pull circuit places their thermal resistances in parallel so overall thermal resistance is cut in half. The thermal drop at 50 W of dissipation is 50 W x 0.85/2 °C/W = 21.25 °C. With a limit of 150 °C for the maximum junction temperature, this puts the case of the transistors at 150 – 21.25 = 129 °C. A heat sink must now be found to match the remaining thermal drops of $R_{\Theta CS}$ + $R_{\Theta SA}$ = (129-55°C) / 50 W < 1.48 °C/W

This means the sum of the case-to-sink interface plus the sink-to-ambient resistances must be less than 1.48 °C/W or else the junction temperature will go higher than the allowed 150 °C. A quick check of heat sinks [see AAVID or Wakefield] leads us to the conclusion that a simple convection-cooled aluminum extrusion will need to be larger than the amplifier! The solution is to use forced-air cooling.

We find a piece of extrusion that provides 1.3 °C/W of thermal resistance with 2 cfm of air flow. A small 12V fan can force air over the sink making it far more effective. To control noise and reduce dust build-up on the heat sink, a thermal control circuit is used to monitor the sink temperature. It will turn the fan on when the sink reaches 50 °C and disable the PA if it ever reaches 80 °C, meaning something is wrong like a blocked air intake. This is how most small 100 W radios like the Yaesu FT-100, Icom IC-7000, and Elecraft K3 work.

Application Note
APT-0401
23 March 2004

Determining a Transistor's Maximum RF Output Power Rating

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There is a fairly wide variation between manufacturers in the method used to specify a device's rf output power. There are many factors to be considered and the foregoing explains the cause of those differences and provideds a guide to a successful design.

There are several basic principles involved plus a few intangibles to make it less precise. We define drain (or collector) efficiency as

$$\eta = \frac{P_o}{P_{in}} \quad (1)$$

and then define

$$P_{in} = P_o + P_d \quad (2)$$

We can then define rf output power (P_o) in terms of efficiency and power dissipation:

$$P_o = P_d \frac{\eta}{1-\eta} \quad (3)$$

In cases where the rf gain of the device is low and the drive power is a significant portion of the input power, i.e. G < 10 dB, P_{in} should include the drive power. In this case it is called power-added efficiency, PAE.

The rest of the exercise, the more difficult part, involves determining a reasonable value for P_d. This is not the value given on the data sheet. That one is based on the theoretical and unrealizable conditions of holding the junction at Tj(max) and the case at 25°C. Regardless of the output power specification, every manufacturer's data sheet provides a value for the junction-to-case thermal resistance, $R\theta_{jc}$. This is determined by several methods including infrared measurement and then is derated to a maximum value to cover the range of typical manufacturing variations. This quantity must then be added to the other thermal interface resistances to determine the total thermal impedance from the semiconductor junction out to thermal ambient.

A power transistor is typically mounted on a heat sink with thermal grease to reduce the effects of gaps in the mechanical interface between its mounting surface and the heat sink. Every effort should be made to insure that both mating surfaces are as flat and smooth. The greased interface will typically add about 0.1 °Cin^2/W. That means a device with 0.5 sq in of package base area will have a case-to-sink thermal impedance ($R\theta_{cs}$) of 0.2 °C/W, half the area, twice the resistance.

The heat sink has a thermal impedance too and it is generally the largest design variable in the system. Depending on the construction and method of cooling, the heat sink's thermal resistance, $R\theta_{sa,}$ from sink-to-ambient can range from 0.1°C/W for a water-cooled copper block to 25°C/W or more for a clip-on sink in still air. Regardless of the heat exchange medium transferring the heat from the sink to the ambient environment, it is important to consider the maximum temperature specified. If the air-cooled sink will operate inside a car in the sun, 50°C should be the ambient design temperature.

Thermal impedances add in series so for a total system the thermal resistance between the transistor junction and the ambient is the sum of all the interface impedances:

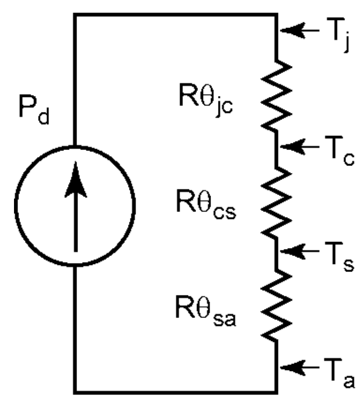
$$R\theta_{ja} = R\theta_{jc} + R\theta_{cs} + R\theta_{sa} \quad (4)$$

All manufacturers specify a maximum operating junction temperature for their devices, Tj(max). This is typically 200°C for air-cavity ceramic-metal packaged parts and 150°C for plastic-encapsulated parts. This is the maximum transistor junction temperature before irreparable damage is done. However, it has been shown in many studies that high operating temperatures are very detrimental to the operational life and reliability of semiconductor devices. Most companies have design guidelines that define the maximum and typical operating junction temperatures for semiconductor parts within a system. 130°C is a good value for a typical design.

Power and thermal resistance are related in a similar way to Ohm's Law where current is replaced by power dissipation and voltage drop is replaced by temperature differential.

$$\Delta T_{ab} = R\theta_{ab} \times P_d \quad (5)$$

For a given amount of power dissipated by a device, each thermal impedance develops a temperature drop across itself. The higher the thermal resistances, the higher the junction temperature rises above a given ambient.



The transistor manufacturer sets the absolute limit on maximum junction temperature, which is then lowered by the designer to meet system reliability goals. The maximum ambient temperature is set by the system specifications. The designer must then provide the minimum heat sink impedance to satisfy these conditions.

As an example, assume we are designing an amplifier using a device with $R\theta_{jc}$ of 0.5°C/W. Though it is rated for use to up to a Tj(max) of 150°C, we will use 130°C as the maximum allowed to improve reliability and provide some "distress margin". The amplifier will be mounted on a large air-cooled heat sink with an $R\theta_{sa}$ rating of .8°C/W. The part will be mounted on the sink using high quality thermal grease that gives a mounting resistance of 0.2°C/W. Thus the total resistance, $R\theta_{ja}$, is 1.5°C/W. If the maximum ambient within the system's operating environment is 50°C, we have enough information to calculate the available device dissipation. From equation (5) we calculate

$$P_d = \frac{\Delta T}{R\theta_{ja}} = \frac{130 - 50}{1.5} = 53.3 \text{ Watts.}$$

Now we can return to the original question – how much output power? That depends on the type of amplifier, its class of operation and efficiency. For a typical class C amplifier, 75% is a reasonable static efficiency when operated into a matched load. If the output is a 100% CW carrier, equation (3) gives

$$P_o = 53.3 \times \tfrac{.75}{1-.75} = 160 \text{ Watts.}$$

This assumes a flat load. If any additional dissipation is required to meet the ruggedness requirements of a non-matched load, typically resulting in a lower operating efficiency, that must be factored in as well.

If the waveform is not CW higher peak power is possible provided the pulse width is less than the thermal time constant of the junction and package and the average power calculated for CW is not exceeded. Most data sheets show a relationship between pulse width, duty cycle and effective $R\theta_{jc}$, the transient thermal impedance.

At this point it should be easier to understand the manufacturers' difficulty specifying an output power. There are many variables that must be set to get to a final answer. Most manufacturers use the performance numbers provided in their standard test circuit. The class of operation and duty cycle are specified as well as a minimum efficiency into a matched load, and sometimes a ruggedness rating (pass/fail) at some higher load VSWR, but nothing is ever said about mounting or cooling.

Therefore when comparing the output power capability of several devices the most important number on the specification sheet is $R\theta_{jc}$. This number is fixed by the device construction and means the same thing for all devices regardless of the manufacturer. All of the other operating conditions that determine the device's maximum output power are defined by the user's application.

rf 3-22-04

rev 11-2-04

The Everyham's Amplifier

By John Stanley, K4ERO

How much power is appropriate for your first HF amplifier? Remember that the effect of RF power is logarithmic, not linear. In terms of S units, 375 W is halfway between 100 W and 1500 W. The 400 to 500 W range for your first linear is a sensible choice that will get you more than halfway to the legal limit at a fraction of the cost.

Many hams have an interest in building a linear amplifier. It may be the most common "homebrew" device in the amateur community other than antennas. Since SSB operations began in the 1950s, every edition of *The ARRL Handbook* has included a design for a linear amplifier. There is interest in a very basic design that will still satisfy the need for more power and provide the joy of building, while providing only the bands and features you want. This amplifier, or family of amplifiers, is an attempt to satisfy that need.

In the February 1966 issue of *QST*, Lew McCoy, W1ICP described "A Low Cost 700 Watt (Input power) Linear Amplifier," which used parts from an old TV set to allow the builder to keep the total cost at between $50 and $75. In October of 1970, he followed up with a "Junker Amplifier" that expanded on the concept with additional tube options and added TR switching. Allowing for inflation, $50 in 1970 would be, perhaps, $400 today. Since $400 is about the lowest price for a working used amplifier, and since the lowest priced new amplifiers are about $800, $300 to $400 seemed like a good target for the homebrewer for whom cost is at least one factor in the decision. Of course, labor costs will not be considered since the joy of building your own equipment is a major motivation, too, but you shouldn't have to pay too much extra for that joy! So, like Lew in 1966, we hope to discover some cost savings.

Project Overview

The design presented here is based on a modular approach. Each of the three major sections (tubes, tuning network, power supply) is somewhat independent and can be changed out separately. In addition, the starting design is "bare bones," containing nothing that is not absolutely essential for the amplifier to work and provide a minimum level of safety against overloads, abuse or accidents. TR switching is included in the most basic design because it gives significant advantages at low cost. For the basic design, each part will be described and its purpose explained.

Several options for the major components are presented with the builder being able to choose what best meets his or her needs and best uses the components available in junk boxes, online, or at hamfests. Many small parts such as resistors and diodes are cheap enough that one need not buy them used. Control transformers and tubes are easy to find through online auction sites. Be sure to check shipping costs on heavy items such as transformers. A parts list for any of the three tube combinations is included at the end of the article.

By shopping carefully, you can avoid the budget being busted by that one essential component costing lots more than expected. Don't overlook acquiring a damaged commercial amplifier or a "basket case" homebrew project — the parts and enclosure hardware available from these are often worth many times the asking price! The sidebar "Using "Surplus" Parts for Your Amplifier" in the **RF Power Amplifiers** chapter of the *Handbook* contains more information about purchasing used and surplus amplifier parts.

The basic amplifier shown in **Figure 1** will get you on the air. Additions and modifications that will improve performance are described at the end of this article. Each of these will stand on its own so that the builder can make changes with a minimum of downtime. Most can be installed in a day, so you need not discontinue using the amp in order to upgrade.

In addition to the material in this article, the CD-ROM also includes photographs of the author's implementation of the amplifier with 811As, a 3-500Z, and a pair of GI-6B tubes.

This article doesn't provide step-by-step kit-style instructions. Instead, there are guidelines and examples that will help you construct your amplifier from the parts you can acquire — this is part of the fun! The basic design is quite tolerant and if you are just getting started, why not try a single-band amplifier first? You can then add and modify and expand the amplifier's capabilities as your own expertise and confidence grow. The path to a homebrew amplifier is never a straight line, but the journey is very rewarding!

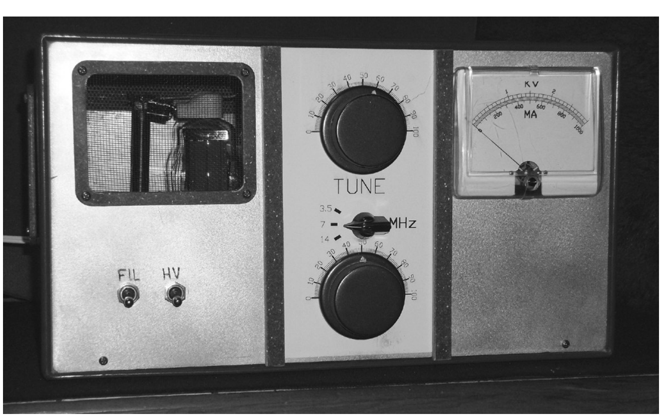


Figure 1 — The front panel of the Everyham's Amplifier. This version is designed to cover three bands (80, 40, and 20 meters). A window is included at left to allow viewing of the tube.

Design Details

The circuit for the amplifier is shown in **Figure 2**. The tubes used in this design are triodes, connected in a grounded-grid configuration. The amplifier can be constructed to use a single 3-500Z or a pair of 811A, 572B, GI-6B or GI-7B tubes. All of these are currently available new or surplus at reasonable cost. The input grid circuit input is driven directly. Tuned input circuits are discussed later as an option.

C3, L1 and C4 form an impedance-matching pi network which transforms the 50-Ω load at the output to the several-thousand-ohm impedance presented by the tube. In addition, this "tank" filters out the harmonics from the tube while passing the desired fundamental signal. An optional band switch, S3, is shown. In its simplest form it shorts out sections of L1 as the operating frequency increases. A single-band design doesn't need S3.

Finding suitable capacitors and coils and the band switch will be a significant part of the total procurement process. This is where you can save a lot by using surplus parts. The parts list specifies certain types, mainly so you will know what to look for, but if you simply buy new parts from the list, you will spend your entire budget on these items alone. You don't need exact values for the circuit to work. Limiting the bands to be covered can greatly relax the coil, capacitor and switch requirements.

When the amplifier is OFF or the trans-

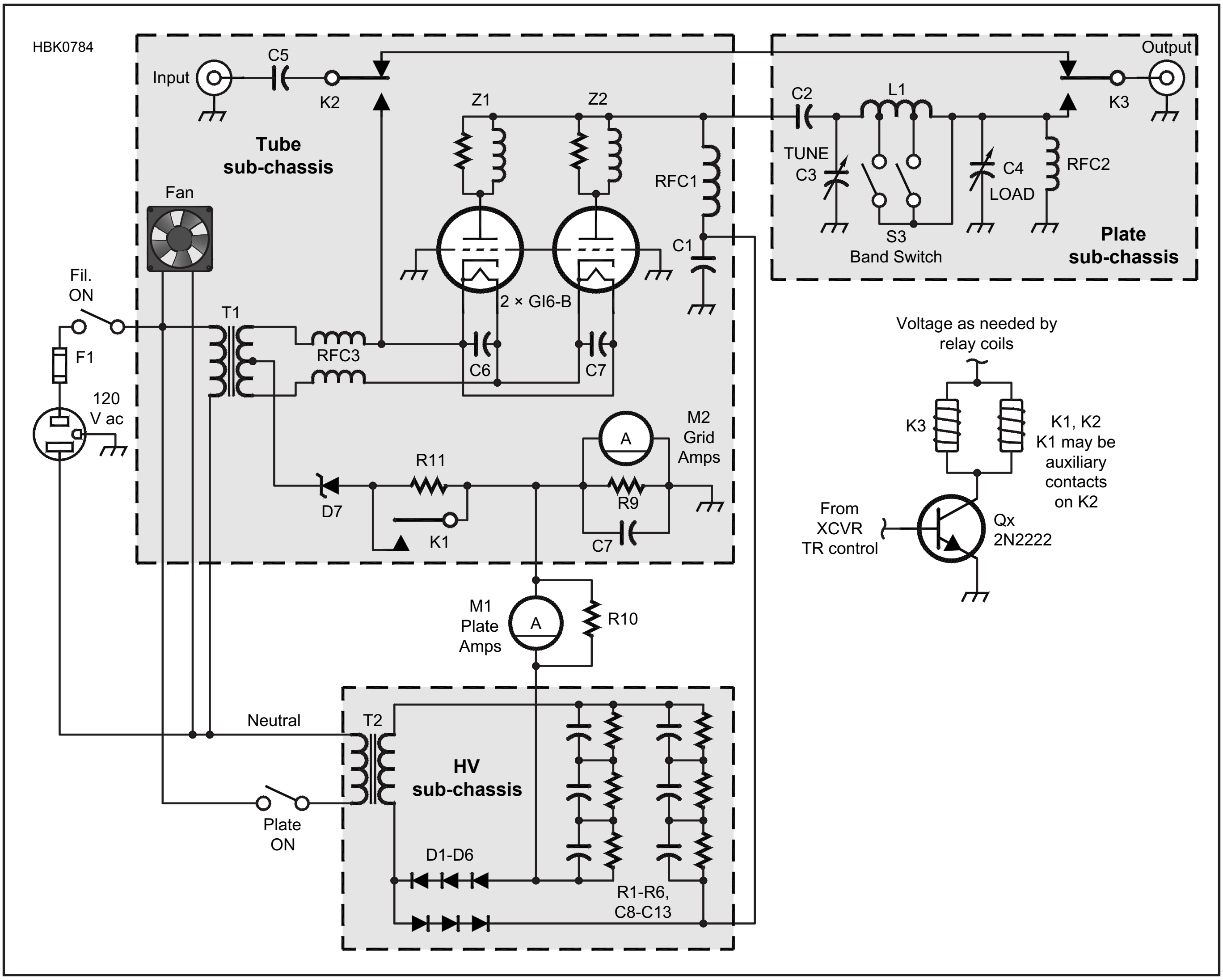


Figure 2 — The schematic of the basic amplifier. The parts list is shown in Table 2 at the end of this article.

ceiver is in receive, the antenna connects directly to the transceiver antenna jack via the two relays as shown in **Figure 3** (K2 and K3 in the main schematic). When the transceiver is in transmit and the amplifier turned on, the transceiver output is routed through the amplifier and amplified.

As part of the TR process, we will want to bias the amplifier off during receive. This saves energy, cools the tube(s) and also removes any RF noise the tube(s) might produce that could get into the receiver. When opened during receive, K1 in Figure 2 lifts the center tap of the filament transformer (tube cathode) from ground. K1 can be a separate relay or an additional set of contacts on the TR relays K2 and K3 if they are internal

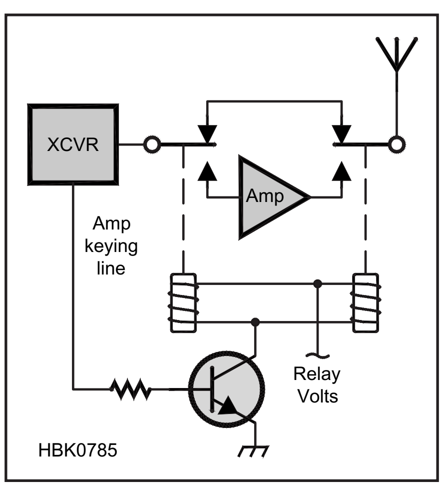


Figure 3 — The TR switching of transmit and receive signals for the basic amplifier is controlled by the transceiver's amplifier keying output signal, assumed here to be a positive voltage to key the amplifier with a suitable current-limiting resistor and relay drive transistor installed in the amplifier.

to the amplifier. Usually a resistor (R11), perhaps 47 kΩ or so, is left between the center tap and ground to provide a dc current path.

The power supply shown is a basic voltage doubler. (See the **Power Sources** chapter of the *Handbook* for information on rectifier and voltage multiplier circuits, as well as an alternative power supply design.) If a high-voltage secondary transformer is available, a rating of 500 VA is required for intermittent service up to 1 kW output. 250 VA ratings are sufficient for intermittent service to 500 W with a voltage quadrupler. Originally, TV transformers were often used for amplifiers of this size. However, they are becoming hard to find and their age leads to insulation breakdown, thus they are not recommended for this project.

For T2, the main power transformer, the basic circuit uses a 480/240 to 120 V "control" transformer with the 480 V winding used as a secondary. Control transformers are used in industry to reduce the plant's 480 V or 240 V equipment wiring to 120 V for the purpose of operating instrumentation and control electronics. These typically have two 240 V windings that can be connected in series for 480 V or run in parallel for higher current. These transformers are commonly available at online auction sites.

Filter capacitors C8-13 are 100 µF, 450 V electrolytics. Avoid capacitors rated for photoflash use. Best of all are "computer grade" types, but they are larger and more expensive. The audiophile tube equipment market has made capacitors available that are rated for continuous power supply duty. (See the section "Optimum Filter Capacitor Size" at the end of this article.)

C8-C13 require voltage-equalizing resistors, which also serve as bleeder resistors to discharge the capacitors when the supply is turned off. The bleeder resistors shown are 47 kΩ, 3 W units although lower resistance, higher wattage resistors will enhance safety by bleeding the voltage more quickly.

The rectifiers are rated at 3 A and 1 kV PIV. Modern rectifiers do not need equalizing resistors and capacitors as seen in older articles and designs. Today, it is cheaper to overrate the diode stack instead.

A meter in the negative lead of the supply monitors the plate current. Several inexpensive options are included in the parts list. A grid current meter is shown with R9 as the sensing resistor and C7 acting as an RF bypass to keep RF out of the meter. Some way to indicate RF output voltage or current is needed, but if you have an external SWR or forward/reflected power meter already, it need not be included in the amp.

Z1 and Z2 are parasitic-suppression chokes that incorporate a lossy element (resistor). These have been proven necessary to prevent VHF parasitic oscillations which can destroy an amplifier. RFC1 feeds dc to the tubes while blocking RF. It is bypassed with C1 to prevent any RF power that gets through the choke from entering the power supply. C2 is the plate dc blocking capacitor which passes RF to the output tank without passing dc.

The circuit works fine without RFC2, but its presence is cheap insurance against the failure of the blocking capacitor, which could put HV dc on the antenna output with deadly results. It and the fuse F1 are the two components not strictly needed, except for safety.

The input is driven directly. Tuned input circuits will be discussed as an option later. We do need C4 and C5 to keep the filament voltage from feeding back into the transceiver or tuner, and to put the RF drive voltage on both ends of the filament. RFC3 feeds filament voltage to the cathode without shorting RF to ground. C6 and C7 keep RF out of the filament transformer. T1 provides the filament voltage for the tube. Zener diode D7 may be needed, depending on the tube type and plate voltage, to keep the resting current below the allowable plate dissipation. A stack of forward biased diodes could work also. See the parts list for the type of Zener required for the tubes chosen.

Construction Notes

Safety First! YOU CAN BE KILLED by coming in contact with the high voltages inside a commercial or homebrew RF amplifier. Please don't take foolish chances. Remember that you cannot go wrong by treating each amplifier as potentially lethal. In addition, do not measure high voltages with test meters and probes that are not rated for those voltages. A flashover can destroy the meter and electrocute you!

For a more thorough treatment of this all-important subject, please review the applicable sections of the **Power Sources** and the **Safety** chapters in the *ARRL Handbook*. This is particularly important for first-time amplifier builders who are not experienced in working around high voltages.

ENCLOSURE AND COOLING

The type of construction chosen will depend on the enclosure (chassis), which is required for good RF performance and for safety reasons. Having a spacious enclosure and an oversized chassis will make construction easier and upgrades simple. If your situation dictates, you can certainly build everything on a single chassis.

If you find an old piece of equipment you can reclaim, that may dictate the layout. Hamfests usually provide a choice of obsolete tube-type lab or medical instrumentation with high quality cabinets at low cost. They may include desirable items such as a blower or meter in addition to the enclosure. The author chose to use a cabinet from an old piece of Heathkit gear, which had no chassis, and so built a front panel and several sub-chassis sections for the various parts of the amplifier. This allows changing out various parts of the circuit easily and even to maintain several different sub-sections to allow experiments with different tubes, frequency ranges or power supply types.

The tube circuit layout will depend on which tube type is chosen. The 811A/572B option is a great place to start. There is just no other option that can compete in price, counting the tubes and sockets. A pair is recommended for this design although up to four tubes in parallel are common in ham-built amplifiers. A single 3-500Z is another popular choice and, for higher power, a pair of them if the power supply is adequately rated. Ceramic sockets are available for the 3-500Z. Surplus Russian triodes such as the GI-6B and GI-7B are becoming popular and one or a pair is commonly used. The sockets will have to be built as described in the construction details or purchased from ham sources.

External anode tubes such as the Russian GI-6B or GI-7B will need a blower. With the 811A or 3-500Z options, a muffin fan blowing on the tubes will allow them to work much harder. This fan also keeps the other components cooler for extended operation. (See the section Tube Amplifier Cooling in the *Handbook* chapter on **RF Power Amplifiers** for additional information on choosing fans and blowers.)

TUBE SUB-CHASSIS

In this design, the tubes and a few closely associated parts are mounted on their own sub-chassis. RFC3 goes under the chassis along with the input circuits. Filament voltage required will depend on which tube(s) are chosen. A dedicated filament transformer is

Figure 4 — Parasitic suppression chokes eliminate VHF oscillation by adding some resistance to the plate circuit at VHF. They consist of a few turns of wire over a resistor. The wire forms an inductor which passes signals at HF but forces VHF and higher-frequency signals through the resistor.

preferred, but if you find a plate transformer with a suitable filament winding, that is okay. RFC1 and C1 are logically located on this same sub-chassis.

The parasitic suppressors, Z1 and Z2, shown in **Figure 4**, are nothing more than 4 turns of wire wound over a 47 Ω resistor. They are attached directly to the tube plate. This point connects to the output tank circuit via C2, the plate dc blocking capacitor.

TUNING NETWORK SUB-CHASSIS

The second sub-chassis carries all of the plate tuning components; C3, C4 and L1 and S3, if used. This is a pi network with a band-switched coil, enabling operation on the 80 to 10 meter bands, or fewer if you choose.

POWER SUPPLY SUB-CHASSIS

The third section is the HV power supply consisting of the power transformer, rectifiers and filter capacitors along with bleeder resistors. The power supply should be included in the enclosure and not built as a separate piece of equipment. Constructing safe high voltage connections between pieces of equipment requires experience and strict attention to safety-related details that may not be obvious to the beginning amplifier builder. For that reason, this basic design assumes an internal power supply.

Rectifiers and filter caps can be mounted on an insulated board, either Plexiglas, other plastic, or an etched PC board. Install that board on top of the transformer for a neat and compact installation. See the Power Supply Notes folder on the *Handbook* CD-ROM for photos and drawings of suggested construction methods. PCB layouts for the *ExpressPCB* fabrication service are also included on the CD-ROM for both the voltage doubler and quadrupler circuits.

Design Options

SAFETY OPTIONS

Including interlocks that will shut off the transmitter when the enclosure or sub-chassis panels are removed to expose high voltage may be desirable. Microswitches in series with the ac power circuits and/or shorting bars that will ground the HV circuits are options.

An interlock on the blower consisting of a pressure switch or air vane that will shut off the amplifier if cooling fails provides good insurance against loss of an expensive tube. Depending on the tube type, this may be highly desirable.

Since your construction method will dictate how interlocks would be applied, you should inspect commercial amplifiers for ideas suitable for adapting to your project. The advice of an experienced amplifier builder would be particularly helpful here.

POWER SUPPLY OPTIONS

The HV power transformer (T2) can be costly. Suitable used power transformers designed for amateur power supplies are available at typical prices between $100 and $200, with new ones even higher. Depending on the voltage of the transformer and that required for the tubes, these may call for a full-wave bridge, a doubler (as shown in Figure 2) or a full-wave center-tapped connection. Each of these circuits are described in the **Power Sources** chapter of the *Handbook*.

Another solution that still uses the simple doubler circuit is to use two control transformers for T2 with the two 480 V windings in series as shown in **Figure 5**. A 500 VA (0.5 kVA) total rating will work fine for intermittent voice service up to 1 kW and a single 250 VA (0.25 kVA) unit will supply 500 W output by quadrupling the output as in the next circuit.

The circuit in **Figure 6** uses a single control transformer with separate 240 V secondary windings. The secondary windings are each connected to their own voltage quadrupler, which are then connected in series. While a

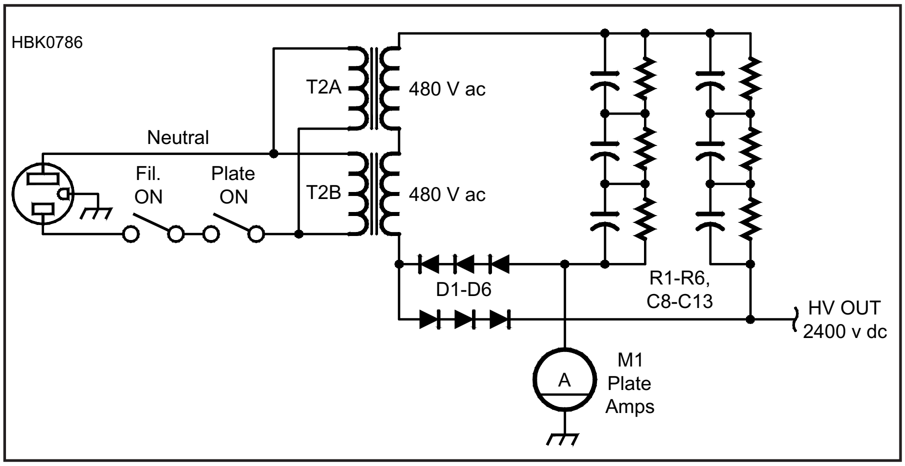


Figure 5 — An alternative power supply using two control transformer secondary windings in series and a voltage doubler.

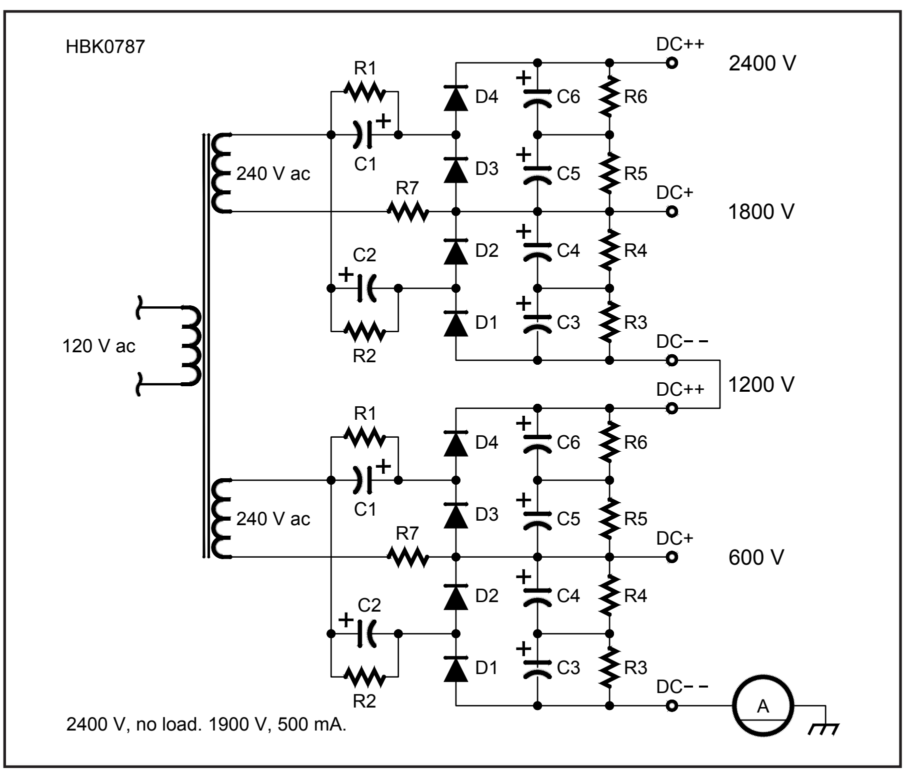


Figure 6 — An alternative power supply using two separate control transformers.

bit more complicated than the simple doubler circuit, it supplies ¼, ½, ¾ or full voltage, which is handy in testing and when substituting different types of tubes. R1 and R2 are optional bleeders — C1 and C2 will discharge through the regular bleeder string. R7 limits the filter inrush current at turn on and may not be needed if the primary fuse does not open from the temporary surge. Each quadrupler could be constructed on its own board or all on one.

FILAMENT OPTIONS

An otherwise ideal filament transformer or a filament winding on a HV transformer may have no center tap. It is possible to use two resistors in place of the center tap as shown in **Figure 7**. A pair of 22 Ω, 2 W resistors works well.

A switching power supply with suitable voltage and current ratings is another option for providing filament voltage as shown in **Figure 8**. It may be cheaper than a transformer and also weighs less. Running filaments from a dc supply reduces hum but with some tubes it causes one side of the cathode (filament) to get hotter than the other. One might want to reverse polarity from time to time. Use a clean dc supply, as one with switching harmonics on the output voltage could produce unwanted sidebands in the amplifier output.

BAND SWITCHING

Some amplifier builders will need only one or, perhaps, two bands. For example, net operators may need only 80 or 40 meters and a single tank coil, L1, for those two bands with a simple switch or even none at all. Some DXers might use only 14, 18 and 21 MHz — a single coil could cover those bands, as well. Many amplifier users however, particularly contesters, will want a quick and convenient way to select all HF bands. This is accomplished by shorting out part of L1 or switching another coil in parallel with it or in place of it.

Figure 9 shows typical band switches that are rated to handle the RF currents and voltages typical of amplifiers. Due to the Q of the tank circuit, the RF current in the switch is much higher than the dc current in the tubes. A good band switch should have contacts rated at 10 amps or more. Clearance between the contacts should be able to sufficient to withstand several thousand volts. Lighter switches will quickly burn up or arc over.

The need for short leads, especially on 12 and 10 meters, will determine parts layout and some compromises may be necessary. Willingness to limit the number of bands (for example, leaving out 160, 30, 17 and/or 12/10 meters) will simplify the design. For those who need unusual frequency coverage (MARS, for example) and who don't need to switch bands quickly, a shorting strap with a movable clip as shown in **Figure 10** is simple and inexpensive. It would be wise to include the safety options mentioned above because changing taps gives access to HV dc or RF voltages inside the amplifier.

TUNED INPUT CIRCUITS

Using tuned inputs to the cathode of the grounded grid linear as shown in **Figure 11** has three advantages:

- It presents a lower SWR to the transceiver.
- It makes it possible to drive the amplifier to full output with lower power.
- It improves the IMD (distortion) of the amplifier.

Nevertheless, there have been successful amplifiers that used untuned inputs as in the basic amplifier circuit. With some tube combinations, such as a pair of GI-6Bs or GI-7Bs you can drive the grids directly with acceptable SWR at the input. With a pair of 811As

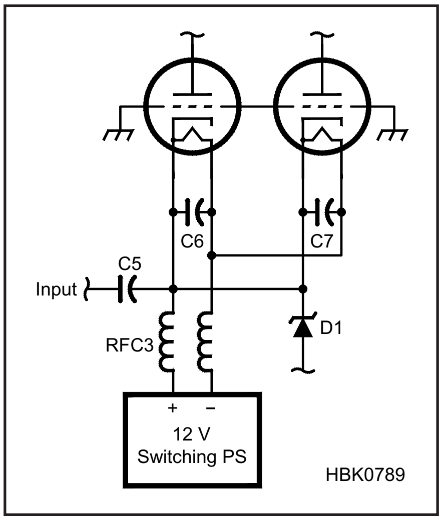


Figure 8 — Using a switching power supply for filament power.

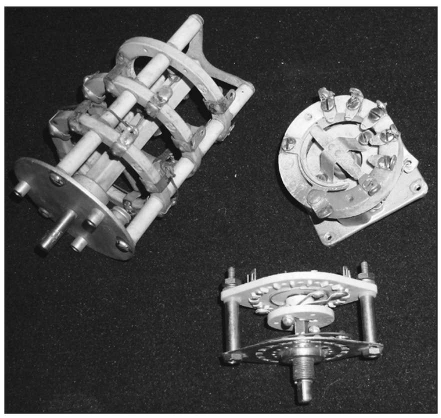


Figure 9 — Heavy-duty ceramic band switches rated for use in an amplifier's output tank circuit.

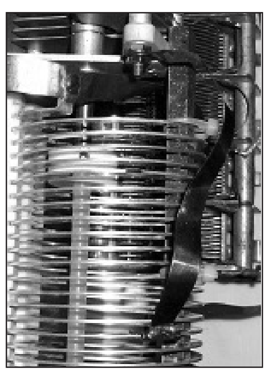


Figure 10 — A movable strap can be used for band switching if rapid band changes are not required. Using this method of changing bands requires strict attention to safety!

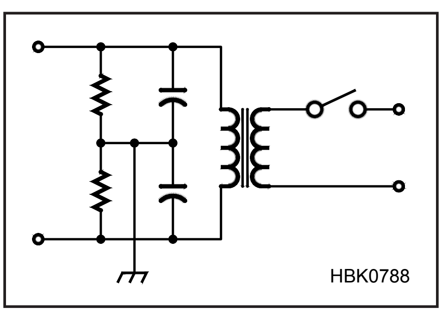


Figure 7 — A method of using two low-value resistors to replace a missing center tap on a filament transformer.

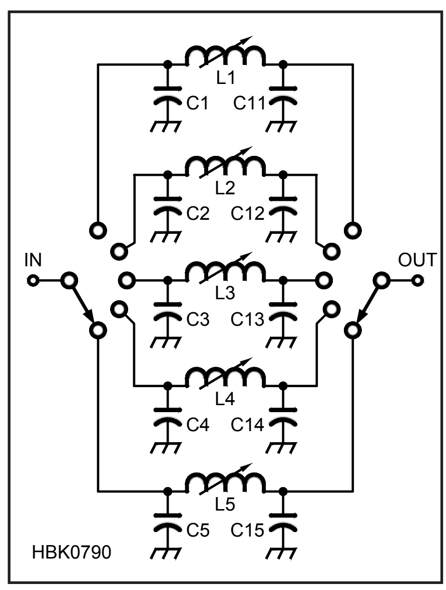


Figure 11 — Typical input tuned circuits using pi networks.

or a single 3-500, adding a resistor of about 120 Ω from input to ground improves the match. Your transceiver may have either a built in or external antenna tuner and if so, you may not need tuned inputs at all and your transceiver can probably supply enough power to drive the cathode directly.

For a few closely spaced bands a single somewhat-broad tuned circuit can work. Tuned inputs in an amplifier covering widely spaced bands will require band switching. It is desirable, but not necessary, to have the input band switch ganged with the main band switch to avoid having the two switches accidentally set to different bands.

The input power levels, combined with lower Q mean that this switch can be much lighter duty than the main band switch. Commonly used circuits are the pi network, shown here, and the tapped coil. In both cases, the input network tunes out the capacitance of the tube input, and it may also transform the resistive input impedance of the tube's cathode circuit to 50 Ω. Suitable values for the components with various tube combinations are included on the CD-ROM.

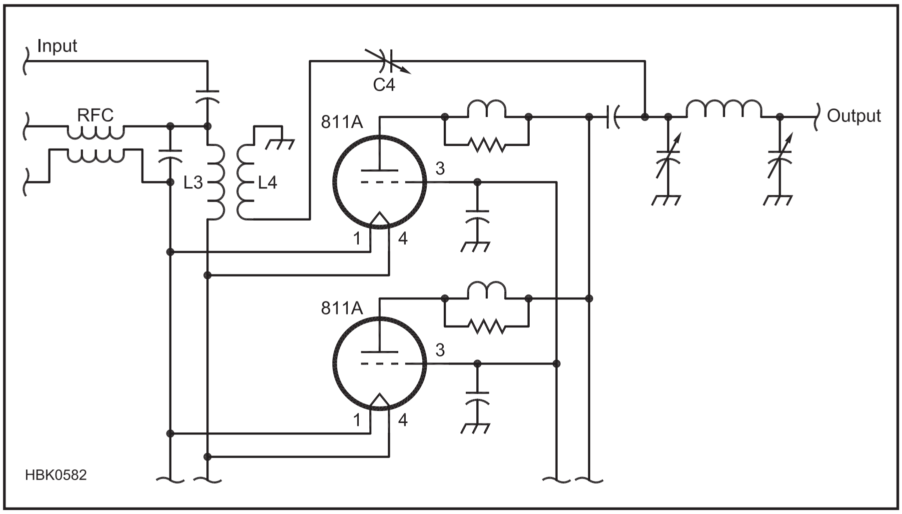


Figure 12 — In this neutralizing method, a broadband transformer (L3, L4) provides the needed out-of-phase signal. L3 is 6 close-wound turns of #14 wire, ½ in. dia. L4 is 5 turns of insulated wire over L3. C4 is 6 pF with 0.06 in. spacing. This circuit was originally featured in June 1961 *QST* and is still found in modern amplifiers using 811A tubes.

BETTER METERING

In addition to the supply current meter shown in the above circuit, metering of the output power (or RF voltage), SWR, and supply voltage are often included. These can each be assigned a separate meter or measured with a single one with a suitable switch and multiple scales. The **Test Measurements and Equipment** chapter of the *Handbook* contains a wealth of information about metering circuits, including how to make custom scales.

Metering the output power, essential for tuning the amp, can be done with an external directional wattmeter, or a similar circuit can be built into the amplifier. The external wattmeter has the advantage of working when you are running without the amplifier and so may be the better choice. Or, if you want that feature, install it in the amplifier, but on the antenna side of the TR relay. Find a published design or copy one from a manufacturer's manual.

NEUTRALIZATION

Many grounded grid amplifiers have been built without neutralization, including the famous Collins 30L-1. However, suitable circuits have long been available and the tuning on the highest frequency bands will be smoother if the neutralization circuit is added. For those using only the lower bands, it may not be worth it. **Figure 12** shows a suitable circuit for this amplifier that is discussed in the Tube Amplifier Stabilization section of the *Handbook* **RF Power Amplifier** chapter. Be aware that if you are receiving through the amplifier without TR switching, neutralization will reduce the receive signal further. It is not recommended to add neutralization without TR switching for that reason.

BETTER PROTECTION AGAINST OVERLOADS

The basic amplifier is protected by fuse F1 in the power supply. Other methods would include circuits to monitor plate and grid currents, air flow, temperature, SWR and turn off the plate supply as needed. This requires that the plate HV switch operate a latching relay. The protection circuits then unlatch the relay and light an indicator indicating the cause of the trip. Check the K8RA amplifier design in the *Handbook* or take a look at what the commercial amplifiers feature.

STEP-START

As part of the overload protection circuits, one can also add a step-start or soft-start for the HV supply as well as a time delay to prevent turning on the HV until the filaments have warmed up. A step-start applies voltage to the HV supply via a resistor for a second or so and then shorts out the resistor. This reduces the peak inrush current in the rectifier diodes and other components at turn on. A legal limit amplifier operating from 240 V is more likely to need this feature than a smaller amplifier.

AUTOMATIC LEVEL CONTROL (ALC)

An ALC circuit detects when grid drive to the tube exceeds a certain level and generates a signal to the transceiver that causes it to reduce output power. If the transceiver itself has ALC, which most do, and if the levels are properly set at maximum output power, there may be no advantage in using ALC. However, when changing bands, etc., the setup may change and the ALC will help to protect against overdrive and distortion while keeping the average power up. Check existing designs and the ALC requirements of the transceiver you are using.

Component Selection

OPTIMUM FILTER CAPACITOR SIZE

When looking at amplifier power supply designs, one finds various sizes of capacitors with the right capacitance and voltage rating for the HV filter capacitors. Here are the tradeoffs between them.

Advantages of using smaller capacitors:

1. The higher the capacitance, the greater the cost. Imported 100 μF, 450V capacitors

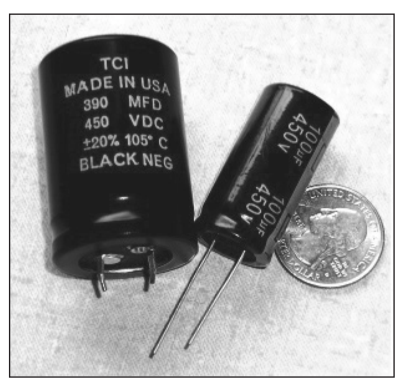


Figure 13— A 390 μF capacitor (left) and a 100 μF capacitor for size comparison.

are about $1 to $1.50 each, from various suppliers. A US-made 390 µF, 450 V capacitor is available from at around $2.50 to $2.75 depending on quantity. (The two capacitors are shown in **Figure 13** for comparison.) Other values at comparable prices can be had from many sources. This price difference is not huge, but with a large string can be significant.

2. Larger capacitors put a greater strain on the rectifier diodes at turn on. The inrush current with the larger caps shown here is at least twice that with the smaller ones, and this could eventually cause the diodes to fail unless a step-start circuit is used (discussed above). In either case, using diodes with an average forward current rating of 3 A is cheap insurance.

3. The stored energy available to do damage in case of a short circuit either in the tube or any of the high voltage circuits is greater with the larger capacitors. Hopefully this will never happen, but tubes do flashover from time to time, as do other circuits. Four times the capacitance makes four times the spark!

4. The larger the capacitors, the longer the discharge time at turn off or else one must use smaller bleeder resistance values so the power loss is greater. Thus, one must sacrifice safety, economy or some of each if the larger caps are used.

5. The larger capacitance units take up more space so the overall size of the supply may have to be bigger. Note that modern electrolytics are smaller than older ones so for replacement purposes, either size will usually fit nicely.

Advantages of the larger capacitors:

1. If the capacitors are too small, the supply voltage and RF output power will drop. At 500 W, 100 µF is sufficient. At a full 1500 W, one may need the larger size to prevent excess voltage drop. These values refer to a string of eight capacitors giving either 12.5 or 48 µF total at 2400 V.

2. With less capacitance, the ripple will be greater. For a typical 500 W linear, the ripple under load will be about 15 V RMS with 100 µF capacitors and about 5 V with the 390 µF capacitors. Transmitting a steady, full-power carrier, one can see the ripple on an oscilloscope with the smaller capacitors, but it isn't a problem with the on-air SSB or CW signal. This ripple value applies to the same eight-capacitor string mentioned above.

Thus, it can be seen that larger is not always better. There is an optimum value for filter capacitors which, while not overly critical, is important. As always, quality is also important. Cheap, tiny capacitors made for photoflash use are not suitable for continuous power supply operation. Nor is it good economy to operate the capacitors very near their rated voltage. Add a few more capacitors to the series string and reduce the voltage across each one. This allows for aging and voltage surges.

TYPICAL VALUES FOR TUNING COMPONENTS

The following values will be about right for a tube amplifier with a plate voltage of 2200 V at a plate current of about 400 mA. Using the *Tube Calculator* and *PI-EL* programs (supplied with the *ARRL Handbook*) will give more exact values based on tube types, voltages and currents. Calculations assume a Q value of 10 below 18 MHz, increasing progressively at higher frequencies to keep plate capacitance values at least as high as the stray capacitances plus tube output capacitance (see **Table 1**).

The plate tune capacitor should have a voltage rating at least equal to the plate voltage. The load capacitor should have a voltage rating of 500 V. Both the tune and load capacitors may consist of a variable capacitor in parallel with some fixed capacitance for the lower bands. The variable capacitance should be at least ⅓ of the total capacitance. Use transmitting type mica or ceramic caps for the fixed capacitors. The table values are the total capacity needed.

Stray capacitance and the tube output capacitance will provide part of the needed plate tuning capacitance. Having some extra capacitance is a good idea, so the components chosen may need to be a bit higher than the values listed to insure sufficient tuning range. For a single-band design it is a good idea to have more than the required capacitance so that actual operation doesn't fall near the extreme setting of the component.

Table 1
Typical Component Values

Freq (MHz)	*1.9*	*3.8*	*7.2*	*10.1*	*14.2*	*18.1*	*21.3*	*24.9*	*28.5*	*50.3*
C3 (Plate Tune, pF)	230	120	65	45	35	30	30	28	27	18
C4 (Plate Load, pF)	950	475	250	180	125	160	180	180	190	120
L1 (µH)	31	16	8.5	6	4	3	2.1	1.6	1.3	0.65

Table 2
Parts List

R1 to R6	Bleeder resistors:	47 kΩ, 3 W metal film
R7, R8	see PS1, PS2	47 Ω, 3 W metal-oxide
R9	Grid current meter shunt:	as needed for full-scale value of M2*
R10	Plate current meter shunt:	as needed for full-scale value of M1*
C1	Plate supply bypass:	0.01 µF, 5 kV ceramic
C2	Plate blocking capacitor:	1000 pF, 5 kV, 5 A, ceramic doorknob
C3	Plate tune capacitor:	10-250 pF, 2 kV variable
C4	Plate load capacitor:	three to five section variable, 20-350 pF/section, sections connected in parallel, 1050-1750 pF total
C5 to C7	Bypass capacitors:	0.0068 µF, 600 V, disc ceramic
C8 to C13	Filter capacitors:	100 µF, 450 V electrolytic
L1	Tank coil:	16 µH for 3.5 MHz 32 µH for 1.8 MHz tapped for other bands (details in text)
Z1,Z2	Parasitic suppressor:	3 turns, ⅜ inch dia. ½ inch long wound on R7 and R8
RFC1	Plate choke:	3.5 -28 MHz: 50 µH, 160 turns #24 AWG wire, ½ inch ceramic form, 3.5 inches long 1.8 -21 MHz: 100 µH, 320 turns #24 AWG wire, ½ inch ceramic form, 7 inches long The Barker & Williamson model 802 plate choke is suitable for use over the entire 1.8-28 MHz range.
RFC2	Safety choke:	25 turns #24 wire on ⅜-inch ferrite rod, #43 mix, 1.5 inches long
RFC3	Filament choke:	bifilar-wound with the winding filling a 4 inch × ⅜ inch ferrite rod (#43 mix) GI-6B or GI-7B: 4 amps, #18AWG wire 811A or 572B: 8 amps, #16AWG wire 3-500Z: 15 amps, #14 AWG wire The Amidon FLC-10 kit is a suitable equivalent.
D1-D6	Rectifiers:	3 A, 1 kV, 1N5408 or equivalent
D7	Cathode bias control:	GI-6B or GI-7B: 30 V, 1 A, Zener diode made of 5 ea 1N5340B (6 V, 5-W Zener) diodes connected in series 811A or 572B: 6.8 V, 10 W Zener diode (1N3999A or NTE5181A) 3-500Z: 6.8 V, 10 W Zener diode (1N3999A or NTE5181A)
M1	Grid current meter:	See text for options, R8 is the meter shunt GI-6B or GI-07B: 1 A 811A or 572B: 500 mA 3-500Z: 500 mA
M2	Plate current meter:	See text for options, R9 is the meter shunt GI-6B or GI-07B: 1 A 811A or 572B: 500 mA 3-500Z: 500 mA
T1	Filament transformer:	See text for options GI-6B/GI-7B: 120 V to 12 V, 4 A 811A/572B: 120 V to 12 V, 8 A 3-500Z: 120 V to 5 V, 15 A
T2	Plate supply transformer:	120 V to 480 V control transformer, 250 to 500 W (VA) (see text for options)
S1, S2	On/Off switches:	SPDT toggle, rated 10 A @ 120 VAC
F1	Primary fuse:	10 A (for tubes described) cartridge fuse Cartridge fuse holder
V1, V2	Vacuum tubes:	Pair of GI-6B or GI-7B triodes Pair of 811A or 572B triodes Single 3-500Z (V1 only)

Tube sockets: 811A or 572B: 4-pin ceramic, 2 required; 3-500Z: 5-pin ceramic, 1 required; GI-6B or GI-7B, see separate article “Constructing Substitutes for GI-6B and GI-7B Sockets - K4ERO” on the CD-ROM
Input and output RF connectors: SO-239 chassis mount
120V blower or muffin fan
2 feet of High Voltage or test lead wire (5 kV insulation minimum)
Heavy-duty, three-wire ac power cord
Strain relief for power cord
*To determine values of meter shunts, see the ARRL Handbook’s Test Equipment and Measurements chapter. The procedure is described in the section “Panel Meters”

Design Notes for "A Luxury Linear" Amplifier

Here are some of the design considerations that went into a recent amplifier project, along with an additional experimental circuit and some interface suggestions.

By Mark Mandelkern, K5AM

This article is a companion to the article "A Luxury Linear," which included a general description of the circuits, performance specifications and all the schematics for a 1500-W 2-m linear amplifier.[21] But it gave few particulars explaining the functioning of the circuits or the special roles of the various components. This article will fill in most of these details. One circuit in the amp, of a more experimental nature, was omitted from the previous article and will be described here. This is the heater idle circuit, which drops the heater voltage 12% during very long standby periods—aiming to dramatically increase tube life. Finally, some problems of interface with other station components will be discussed, including driver IMD, coax relay sequencing and ALC.

[1]Notes appear on page 20.

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RF Circuits

Most of the details for the RF circuits are given in the caption to Fig 4.[22] Here are a few additional suggestions. There can be quite a bit of RF voltage in the plate tank. The swinging link with its Teflon sleeving should stay, throughout its travel, at least 6 mm away from the tank coil. For avoiding excessive RF voltage and arcing, it is most important to keep the loading sufficiently heavy, especially on initial tune-up. The dc-grounded link is a major safety feature. There is no sliding connection at any point of the output circuit; this is important for efficiency and to prevent erratic tuning.

The only difficult item in the output circuit is the link tuning capacitor. There was arcing in the first capacitor I tried, which had less spacing. If you find a capacitor as specified, except with wider spacing, so much the better. But you don't want less capacitance—that would mean more RF voltage. Too much capacitance would limit the effectiveness of the link tuning capacitor as a loading control. To minimize the RF voltage across the plates, I try to keep the link tuning capacitor near maximum capacitance. I use the swinging link for coarse-loading adjustment and the link tuning capacitor for fine-loading adjustment. This works well. Use the link tuning capacitor for loading; if you approach maximum, nudge the link in a bit, and if you find you are down towards half capacitance, ease the link out a bit. Sounds complicated. but I haven't touched the swinging link in the past six months. Another advantage of this loading procedure is that adjusting the link tuning capacitor has very little detuning effect on the tank coil, whereas swinging the link has a noticeable effect.

The voltage divider for HV metering provides a 10,000 to 1 sampling ratio at the HV2 point. The 20-MΩ resistor in Fig 4 consists of two 10-MΩ special glass HV types, with neat spiral resistive traces wound inside the glass tubes. These types are found now and then in the surplus catalogs. A string of twenty 1-MΩ, ¼-W, 1% metal-oxide resistors would be suitable (Digi-Key #1.00MXBK).[20] The resistors are specified as 1% types not because accuracy is required here, since there is a calibrating adjustment in the metering circuit (Fig 10), but because the precision types will be more stable, thermally and over time.

Don't miss the note on C5 in Fig 4, about not connecting any additional bypass capacitor at the screen terminal. The 100-Ω resistor has an important decoupling function.

It may be possible to reduce input drive requirements below 30 W. Owners of 25-W transceivers might be especially interested. A heavy, wide silver-plated strap for the T-match coil would be the first thing to try. I did try a heavier wire in a hairpin loop, with no improvement. That's when I concluded that most of the loss was inside the tube. My driver is capable of 200-W output. So, except for trying to hit the magic 25-W input spec, I had little motivation to work further on the input circuit. The T-match tuning capacitors might be one place to try for improvement. Glass piston trimmers might be better. Trying to read RF voltages at each of the three terminals was wild! One high, one middling (the one fed), one almost nothing. Adding a heavy wire connecting the three grid terminals didn't help. Feeding just one grid terminal doesn't seem to make the other two jealous. The geometry of the socket and the tube base indicates that it may be pointless to worry about this asymmetry; the solid grid ring built into the tube base has less inductance than anything that could be built around the socket. This amp shows a noticeable improvement over the old 1000-W amp; I heard my EME echoes with a horizontal single Yagi at moonset—this is not a first, but it might be for an all-homebrew station.

Power-Supply Circuit

Most of the power supply is straightforward and routine. The heater regulator uses the ubiquitous 723 IC. A minor complication arises from having both sides of the heater above ground, due to the cathode current shunt and the construction of the tube, with the cathode internally connected to one side of the heater. The heater voltage is applied to the A+/A– points, while the S+/S– points provide heater voltage sensing at the socket. Thus the entire regulator circuit is referenced to the S– point. Current for the 723 does flow through the cathode metering shunt, but it hardly moves the plate meter. The heater power supply is returned to the A– point. As noted in "A Luxury Linear" (Note 21), the heater supply did not reach the 90- to 130-V ac operating goal, dropping out at 98 V. I was content with that and did not try to improve it, but it should be easy to do so. I used #18 wire for the A+/A– leads. Since the regulator senses voltage at the socket, drop in these leads is of no concern; but heavier wire could be used to improve low-line-voltage performance. I think, though, that the greatest drop may be in the heater fuse holder, an ordinary 3AG type—it gets pretty hot! An automotive type blade fuse and socket will probably have less voltage drop.

The choice of heater transformer is the main factor determining line regulation, however. I used a Signal #36-6. Rated 18 VCT at 12 A, it is much heavier than needed in the FWCT circuit used. But on the surplus market (searching 20 catalogs) it cost less than the next smaller size available, which was a bit too small.

Screen Regulator

Not so commonly discussed, and of special interest (judging from inquiries) is the screen voltage shunt regulator. Power tetrodes, and especially the 4CX1000A, commonly exhibit negative screen current flow due to secondary emission. Feisty electrons from the cathode hit the screen and knock off more electrons, even more than those arriving. Like, throw one ping-pong ball, forcefully, into a bucket of ping-pong balls, and see a dozen bounce out. To the amp builder (who, in my case at least, disavows knowing anything about what's going on inside the tube) it seems as if current is coming out of the tube. (Current in my shack flows from positive to negative.) This negative screen current flows into the screen supply and tends to increase the screen voltage, which if unchecked will destroy the tube. (The actual source of the negative screen current is the plate supply.)

A series regulator will not suffice to deal with this negative screen current problem; only a shunt regulator will do. VR tubes are traditional, and Zener diodes have been recently in favor. I wanted a fully adjustable supply to enable experimentation with different operating parameters. I also felt that power transistors are inherently more reliable than Zeners. And the transistors give you more watts per dollar. Also, the transistors used operate very

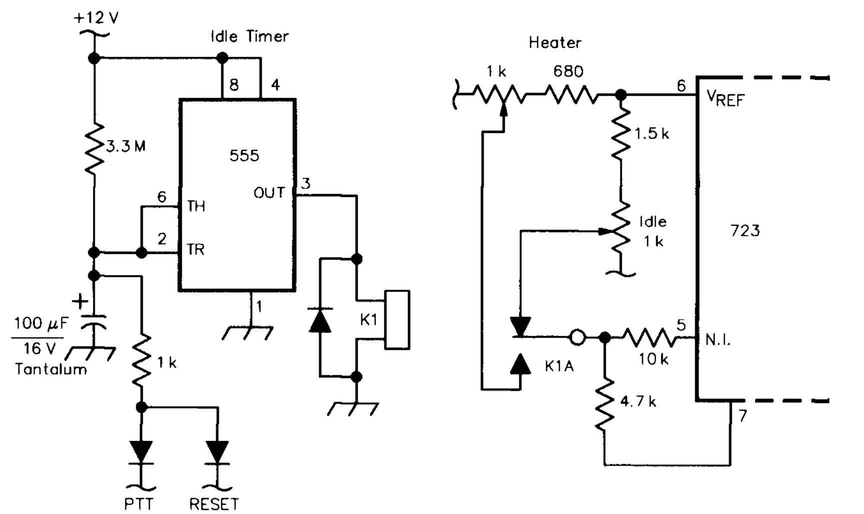


Fig 11—Schematic diagram of the heater-idle circuit. This is a modification of a portion of the heater-regulator circuit in Fig 5. Refer also to the caption for Fig 6.

far from their maximum ratings while Zeners, in this application, typically operate very near their ratings. The shunt transistor regulator was only a bit of extra trouble and has worked flawlessly.

Well, in fact, the first shunt regulator tried, using a 723, didn't work at all! It worked fine on the bench, in all positive and negative current tests, but the shunt transistor shorted when I put the amp in the rack and fired it up. It's best to write about what works, rather than what didn't work, but in this case the story includes a few warnings and explains the reason for some components in the final circuit. I made a half dozen changes, and the second regulator, as shown in Fig 5, performed perfectly from the start. It's hard to say exactly what went wrong with the first circuit, but here are the guesses: oscillation in the 723, possibly triggered by the very jumpy screen current variations during CW, SSB or pulse tuning operation. RF getting into the sensitive 723? (That would explain erratic behavior, but would not be enough by itself to cause the transistor to short out.) Excessive current in the shunt transistor. (In a 5-A transistor?—Note the energy stored in the 22-µF electrolytic capacitor before the 3-kΩ resistor was added.) Puncturing of the mica under the shunt transistor—even two micas. (At 300 V?—What's going on here?—I wish I understood transients better.) Dynatron oscillation? (See page 54 in the reference in Note 3.) I never took a course in electronics, so I can only guess what true failure analysis in an industrial environment would involve: digital storage scopes, chart recorders and a bucket full of transistors (paid for by the company). So, after losing three of the four transistors I had on hand, all I could do was go on hunches and try something a bit different.

The screen regulator that works doesn't use a 723, but merely a single, fairly high-gain transistor as driver for the shunt transistor. A certain amount of gain is necessary, but more than is needed might bring in stability problems. The Zener to the left of the 2N2222A in Fig 5 is merely to provide collector voltage within the transistor ratings; using a high-voltage transistor here would have meant lower gain. The other 15-V Zener is the regulator reference, along with two V_{be} drops in the transistors. Say the reference is then 16.2 V. The output voltage will be this reference multiplied by the ratio set up by the voltage divider at the output, including the screen voltage adjustment pot on the front panel. This ratio having the range 12 to 22, the nominal output voltage is about 200 to 360 V.

There are two details that may be crucial. I used no micas, but mounted the TO220 shunt transistor directly onto a 2×3×1/8-inch aluminum plate, which in turn is mounted on the side wall using ceramic standoff insulators. Second, I added the 3-kΩ, 20-W resistor in the shunt transistor collector lead. This limits the peak (transient?) shunt-transistor current to about 100 mA (at 300 V) and prevents a possible momentary saturated crowbar short to ground. The resistor could be lower valued, and sink more current, but the amp includes an overload circuit set to 30-mA negative screen current, so a regulating range of 100 mA is adequate. Normal operation results in about 20-mA negative screen current peaks during SSB operation. The 0.1-µF capacitor on the collector and the 22-µF capacitor at the output are intended to soften transient pulses which were thought to make the transistor unhappy.

The regulation obtained is only about 1%. This is intentional, as I was most concerned with stability, which is inversely related to regulation. The degree of regulation depends on the gain of the transistors and the resistance of the voltage divider at the output since base current for the first transistor flows through the 120-kΩ resistor. Lowering the divider resistance would improve the regulation, but 1% regulation is more than adequate. It's sometimes difficult, in these cyberdays, to remember that the super-precision available is not always needed—or desired.

From the E = 400-V supply, the R = 5-kΩ (10-W) series resistor limits the forward screen power to $P = E^2/4R$ = 8 W, well within the 12-W rating. Thus no forward screen current overload circuit is needed.

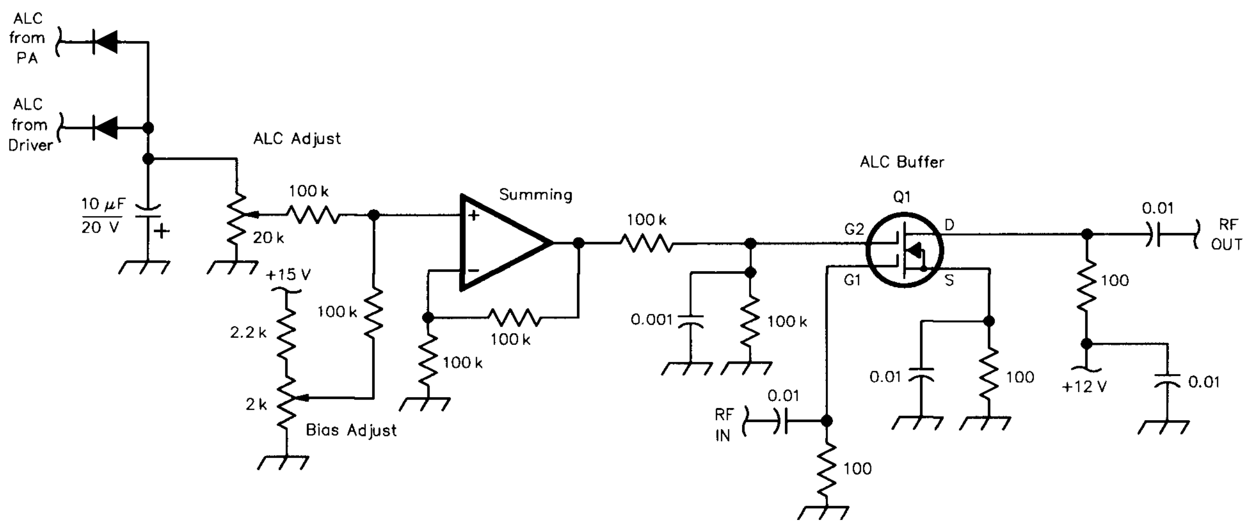


Fig 12—Schematic diagram of an ALC circuit that may be added to a transceiver or transverter. The MOSFET Q1 may be any one of dozens of small-signal RF types (40673, 3N211, ...) often found on the surplus market. The NTE 454 replacement type is available from Hosfelt.[19]

Control Circuits

The warm-up timer in Fig 6 is powered by the +12H rail, only after the air-flow switch, at terminal AIR, is actuated. Several seconds are required for the blower to get up to speed after the line switch is thrown; then the blue light comes on and the timer starts. But only after voltage appears at the heater. This is sensed by the op amp connected to the S+ terminal. So, for example, if the fuse is blown, the timer will not start until after you replace the fuse.

The cool-down latch in Fig 6 is a bit tricky. The basis of operation is the fact that when the line switch is thrown off, the +12-V rail drops more quickly than the +24-V rail (which has minimal load except while transmitting). This throws the latch high and starts the cool-down timer. Since the timer starts in the low state, the discharge pin at the COOL terminal is low, and the cool-down relay K3 in Fig 5 is energized. After about three minutes the timing capacitor charges enough to bring the trigger terminal low and set the 555 high, opening the discharge terminal and allowing the cool-down relay to drop out.

An unexpected anomaly showed up when this simple timer was first tried. Not a very serious defect, but perhaps an amusing incident in the quest for perfection. Here is the situation. After working a few choice DX stations, the band seems dead and you throw the line switch off. Before the cool-down circuit times-out, you hear another DX station, change your mind, and throw the line switch ON again. After allowing the tube to warm-up (see page 8 in "A Luxury Linear"), you work the station. Congratulations! Now you throw the line switch off and are surprised to hear the blower immediately stop! What happened? The cool-down circuit was in COOL mode and timed-out while you were working the new one. That's the reason for the connection to the +24RLY line. What does the cool-down circuit have to do with the coax relays? The +24RLY line resets the cool-down timer (if latched high) the next time you transmit; this was the simplest band-aid solution.

The regulated heater supply, with 10-V at the unregulated point, made over voltage protection (OVP) absolutely essential, to protect against a short-mode failure in the pass transistor Q1 in Fig 5. After hearing of troubles with fold-back and SCR methods of OVP, and considering the various failure modes, an op-amp circuit and a relay seemed to afford the highest reliability. At the bottom of Fig 6, the first op amp acts as a comparator. When the heater voltage exceeds the preset limit, the op-amp goes low and pulls the OVP latch low, removing the ground return for the heater relay coil at point HR in Fig 5. The 10-µF capacitor in the OVP circuit ensures that the OVP latch goes high on start-up when the line switch is thrown ON.

The 2.2-µF capacitor in the overload circuit (Fig 9) forces the overload latch low (normal) on power-up. When low, the latch holds the flash oscillator high and the red light off. I suppose the inverter could have been avoided if, when I got to that point, surprised to find myself standing on my head, I had gone back and redesigned the entire control board. But a low parts count was not a major design goal.

The air-flow switch protects the tube in three ways. Not only does it control the supply voltage (+12H) to the 723 in the heater regulator, and by the same line enable the operate circuit in Fig 7, but it also controls the coil voltage to the heater relay in Fig 5.

Coax Relay Sequencing

VHF operators are especially interested in antenna-relay sequencing devices. In my station (all homebrew), sequencing is included internally in the transceiver, each transverter, each driver amp and each kW amp. This provides the highest level of protection. An MGF-1402 GaAsFET preamp is still working perfectly after ten years with the original transistor. The sequencing circuits used here may be incorporated in other transceivers and transverters for fool-proof coax relay and preamp protection. The sequencing circuits are very simple and much more reliable than many excessively complex systems.

The two op amps shown in the sequencing circuit in Fig 7 use very simple R-C networks to obtain switching delays. Notice that the diodes are reversed. The PTT op amp shifts to an output of about +11 V in transmit. At the coax relay op amp, the diode allows this to charge the capacitor almost instantly, so the coax relay can begin to close. But at the screen relay op amp, the positive control signal must pass through the 68-kΩ resistor, so the screen relay is delayed. At the end of the transmission, the PTT op amp shifts back to an output of about −11 V, and the procedure is reversed.

Keying the amplifier on CW requires special care to avoid any modification of the keying waveform produced by the transceiver. Assuming that the transceiver has the desired keying waveform (my homebrew transceiver has separate internal adjustments for make and break), we want the amplifier to pass this along to the antenna without alteration. The keying circuit at the bottom of Fig 7

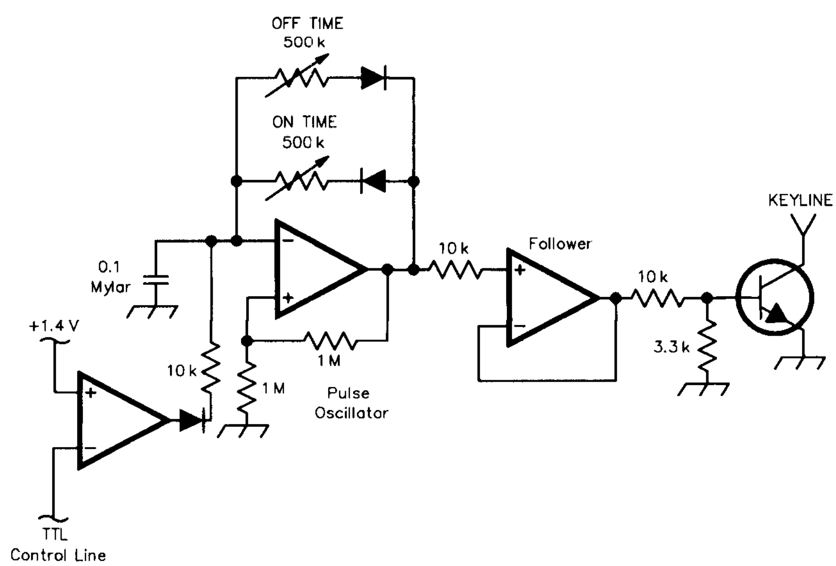


Fig 13—Schematic diagram of the pulse-tuning circuit used for low-duty-cycle tune-up and adjustment. Refer to the caption for Fig 6.

provides for this. The diode allows the key closure signal, a negative output from the first op amp, to almost immediately key the bias circuit (at the KEY2 point), so the amp is up and ready for the dit when the transceiver finally gets around to sending it (about 2 ms later). When the key opens, however, the positive output from the op amp must force its way through the 6.8-kΩ resistor to charge the cap. This allows sufficient time to keep the amp keyed while the dit is decaying. The second op amp, with hysteresis provided by the 1-MΩ feedback resistor, switches sharply when the capacitor crosses the zero potential point. This is a fast-switching delay circuit; it does not produce a keying waveform. It has a square-wave output which encloses the transceiver keying waveform, allowing the transceiver alone to shape the transmitted CW element.

The key sequencing also has a connection to the screen-relay sequencing circuit. This makes the keying dependent on the operate, PTT, sequencing and overload circuits, for an extra bit of protection.

In connecting the amplifier key line to the station, the easiest way to avoid unwanted interaction would be to build an interface circuit that allows the station keyer to separately, but simultaneously, key the transceiver and amplifier. However, for many transceivers it may be possible to simply tie the key lines together. The transceiver schematic must be checked; can it handle 12 V on the keyline? Can an isolating diode be added?

Metering Circuits

This was the really fun part! Imagine: training op amps to do arithmetic! The op amps here are used in three ways: the noninverting amplifier, the inverting summing amplifier with virtual ground and the differential amplifier. These amplifier circuits are described fully in Chapter 8 of the *Handbook*.[7] In the following, refer to Figs 8.44 and 8.46 to 8.49 in the *Handbook*, along with the associated formulas and notation.

The simplest noninverting amplifier used here is the one for HV metering. The meter is to read 5000-V full-scale, and the divider inside the plate compartment (Fig 4) yields a 10,000 to 1 ratio, so 5000 V would produce 0.5 V at the HV2 point in Fig 10. The 10 kΩ resistor in the noninverting (+) input, and the 10 kΩ resistor inside the plate compartment (which is for filtering, in conjunction with feed-through and bypass capacitors not shown on the diagram) have a negligible effect on the circuit, as the op amp input is of very high impedance. Our op amps on the +12/–12 rails have maximum outputs of about +11/–11 V, so we ask for +10 V output at full-scale, using a 10-kΩ meter multiplier resistor and a 1-mA meter. We'll need a gain of 10/0.5 = 20. Arbitrarily choosing 10 kΩ as input resistor R_i, we calculate 190 kΩ for the feedback resistor R_f. I usually choose R_i = 10 kΩ because I have a whole box of 10-kΩ resistors. For R_f, I choose a trimmer at about half the nominal value, and then a fixed resistor, chosen from standard values, to obtain the best range. In this case, a 100-kΩ trimmer and a 150-kΩ fixed resistor yield a range of 150 kΩ to 250 kΩ. That's a fairly good bracketing of the 190-kΩ goal; it doesn't usually work out so well. A 200-kΩ trimpot would not permit sufficient adjustment range, allowing for the tolerances of the circuit components. So omitting the fixed resistor would mean using a 500-kΩ trimpot and having a very touchy adjustment situation.

Plate-current metering is similar. The cathode shunt at the socket (Fig 4), with 1 A of plate current, will produce 0.33 V at point S– in Fig 10.[23] A gain of 10/0.33 = 30 will yield the 10 V we want for the meter with its multiplier. With R_i = 10 kΩ again, we'll need R_f = 290 kΩ. "Shunt" is the traditional term, as if we were to connect a meter directly, but here the shunt merely converts current to voltage, which the op amp amplifies, and the meter multiplier then converts back to current. The 1-μF capacitor provides some meter damping, giving a less wild indication on SSB.

Screen-voltage metering is also similar to the above. So are forward- and reverse-power metering, although the amplification needed for these may depend on the particular construction of the directional coupler. The forward-power meter is peak-indicating. Although very simple, it is extremely useful in conjunction with pulse tuning (see pp 11-12 in "A Luxury Linear" and the "Operation" section below). The diode enables fast attack with a positive signal from the forward power coupler, while the 1-MΩ/1-μF network provides the hold function. The time constant is chosen so that the meter holds long enough for full-power indications under pulse tuning and CW operation, but reacts fast enough to follow tuning adjustments.

Zero-Center Screen Metering

Perhaps more interesting are the zero-center and expanded-scale metering circuits. Zero-center screen-current metering is essential with the 4CX1000A. I could find no zero-center meter on the surplus market to match the others on hand. Finding five similar-looking meters on the surplus market was the hardest part of the whole project. The alert reader will have already noticed that there are actually three different Triplett types (with identical cases) in the cover photo for "A Luxury Linear".

The inverting-summing amplifier with virtual ground is one of the most useful of the op-amp-arithmetic connections; we use it for zero-center screen current metering. The secret is the virtual ground. The noninverting input (+) is really ground, while the op amp with inverse feedback tends to keep the inverting input (–) at the same voltage level as the noninverting, namely zero! So the inverting input is always at 0 V; it acts like a ground. The main advantage of this circuit, compared to the noninverting summing amplifier, is that there is no interaction between the several inputs.

We want a 50-0-50 mA screen meter. The 100-Ω screen-current shunt in Fig 5 will produce –5 V at the –E2 input for 50-mA of positive screen current. Thus we need a gain of –1 to obtain the desired +5 V for half-scale deflection in this inverting circuit. Again with R_i = 10 kΩ, R_f will have a nominal value of 10 kΩ; we use a 5-kΩ trimpot and an 8.2-kΩ fixed resistor.

Now we center the meter. We need only fool the circuit into thinking there is 50 mA flowing. We want an op-amp output of +5 V with no screen current. Using the –12-V rail as an input for this purpose, we need a gain on this branch of +5/–12 = –0.417. With R_f already chosen as nominally 10 kΩ, we calculate R_i = 24 kΩ in this branch; the components shown give a range of 18 kΩ to 28 kΩ. The zero setting hasn't moved a hairline in the two years since the initial adjustment.

Expanded-Scale Heater Metering

The differential amplifier is the circuit of choice for measuring a voltage between two points, neither of which is at ground. Alternatively, the virtual ground in the summing amplifier part of this circuit could have been made virtual S–. But while that would have worked for measuring the voltage, the expanded-scale part of the circuit uses the +12 rail, which is ground-referenced. (The regulation of these rails is essential to the stability of these circuits.) That means another regulator would be needed, referenced to S–. So the differential amplifier is really the simplest solution. The circuit used here in Fig 10 is particularly simple. The heater voltage sensing is at terminals S– and S+; let me call the voltages at these terminals E_1 and E_2, respectively. With all four resistors equal (the value doesn't matter), the output of the differential amplifier is $E_1–E_2$. The differential amplifier therefore simply measures the heater voltage and converts it to a ground-referenced voltage.

The summing amplifier is used to obtain the expanded-scale heater metering, 5.0 to 6.0 V. We want a 1-V change in heater voltage to produce a 10-V change at the op-amp output, for full-scale indication. Thus a gain of –10 will be needed. The differential amplifier has been arranged to invert the heater voltage once, so once more and we're on our feet again. With R_i = 10 kΩ in the measuring branch, we want R_f = 100 kΩ. For an expanded scale indication, we use the expanded scale branch to give the circuit a tendency to indicate –5 V (of course the left meter pin gets in the way); then it will take +5-V input at the measuring branch to indicate a composite zero. The meter has a 1-V full-scale range, so this means a hypothetical –50 V at the op-amp output. Using the +12-V rail for this, we want a branch gain of –50/+12 = –4.17, and we need R_i = 24 kΩ. The individual calculated outputs due to the two input branches are superimposed—they add. Thus the output is $10(E_2–E_1)–50$. The output is zero when the heater voltage $E_2–E_1$ is 5.0, and the output is 10 V when the heater voltage is 6.0.

Adjustment of these circuits is easier than it might seem at first. All adjustments are made with the amp on the bench using small test power supplies to simulate the parameters. Not with high voltage while transmitting! For most tests and adjustments the tube is even cold; a switch turns off the blower, so there is no noise on the bench and the heater is off. In each circuit, first adjust the CAL trimpots (for correct deflection, no matter what part of the scale), and then the CENTER or LEFT trimpots. (I should have put the CAL trimpots at the input—then there would have been no interaction between the CAL and ZERO or LEFT adjustments.)

All the trimpots are at the front edge of the control board. For touch-up adjustments, the amplifier may be slid a few inches out of the rack, leaving all cables attached. The trimpots are then accessible through the top cover vent holes.

Construction

Blower mounting was one of the toughest jobs. The low-noise requirement demands mounting on rubber. The suggestions here are not exactly the way I installed the blower—they are hopefully easier. A good source for material is your local auto parts supplier. Vacuum hose is very thick-walled, with a small ID. Slicing lengthwise through one wall yields a heavy piece of rubber that can be slipped over the edge of the blower outlet. Fig 3 shows that I supported the blower by three screws, with rubber grommets, to the rear panel, but my suggestion is to fabricate a bracket inside the amp and support it from above. The weight of the blower, and a bit of pressure from the bracket, will keep the rubber gasket snug and air-tight.

Inside the grid compartment, across the air inlet, is an RF shield made of copper screening. The air-flow switch is mounted inside the grid compartment; the steel actuating wire on the switch passes through a small hole in the copper screen to the air vane, which is fully inside the blower outlet tube. Alternatively, and more easily, the air flow switch may be mounted on the side of the outlet tube.

After a few clumsy attempts, a very simple method for assembling the input circuit T-match (with insulated above-ground rotors) was found. The key idea is that the two rotors connect together and to the coil (Fig 4 shows the rotor of C2 incorrectly). The two capacitors mount on a piece of one-sided copper circuit board (Fig 2), which is mounted on ceramic insulators. This results in a very low-inductance connection between the two capacitor rotors. The coil connects between the circuit board and a ground lug. The lug is copper; use a small magnet to reject the steel solder lugs in your junk box. The silver-mica blocking capacitor, seemingly redundant, is to protect the tube from loss of bias in the event of a short in C2. The shafts in both grid and plate boxes are of Delrin rod from Small Parts.[16] There might be a better material; there was a recent discussion on the rec.radio.homebrew Usenet Newsgroup about the best materials in RF environments, but I don't remember any conclusive consensus. I do know that there is a glob of melted nylon sitting on my desk as a reminder of the first attempt to connect to the input tuning capacitor shafts.

To wind the ¼-inch tubing for the plate tank without kinking (I made a new coil after the photo!), seal one end in a vise, fill with sand, seal the other end, wind, cut off the ends, and then return the stolen sand to your kid's sandbox.

Construction of the control board entails a certain dilemma. Many projects are essentially experimental; the builder wants to try a few new methods. If one goes through all the trouble of etching a board based on the first draft of the circuit, the many subsequent modifications will shortly turn it into a nightmare. If a different construction method is used, then, when all the final changes have been made, the amplifier is finished and there is no longer a need for an etched board.

For the past seven years I've used wire-wrapping for control boards in all my gear. There are quite a few advantages. Quite dense packing is possible, much denser than ordinary perf-board construction. I even install all the resistors and other small parts in sockets, along with the ICs. This makes it a trivial matter to change a component value, facilitating circuit development. Although it does add a bit to the cost, it can save hours and hours of time. Making a wiring change cannot be said to be easy, working in the maze of wires under the board, but it is possible, clean and neat. It does require some concentration, a small price to pay for having no unsoldering to do. The board is mounted on hinges for easy access to the wire side. I've never seen a wire-wrap connection fail.

All the wire-wrap supplies are available from Digi-Key.[20] Every socket and pin is numbered using a simple matrix scheme, and the numbers are noted on the schematics in the notebooks. Point 237 is pin 7 of U23, the third IC in the second row. Resistor R456 is plugged into the fifth socket in the fourth row, with one lead at pin 6 (by convention, this will be the left or upper end in the schematic). Trimpots can also be fitted onto sockets, if the sockets are of the machined-pin type. Depending on the trimpot type, a touch of solder at each lead may be warranted. The dip relays naturally plug into sockets. A few larger components, such as the coax relay driver and its 5-W base resistor, are soldered to separate wire-wrap pins at the edge of the board (at the bottom in Fig 1). Each (stranded wire) lead to the board is filtered as noted in the caption to Fig 6; the rows of bypass capacitors and RF chokes consume a surprisingly large portion of the board. Each lead to the board passes through two holes before soldering to its wire-wrap pin. This is for strain-relief, so a wire cannot be bent at the point where it is soldered. At certain parts of the amplifier, tie-downs are used for this purpose; Hosfelt has handy stick-on types.[19] DX chasing and contest work require the utmost level of reliability; one broken wire can spoil your whole run.

Operation

Providing suitable drive power is important. Problems can arise when a solid-state driver is used. These "bricks" often exhibit greater IMD (splatter) when operated at reduced output. This will be the case no matter how linear the final amplifier is; it amplifies whatever you feed it. It's just like the old computer cliché, "garbage in, garbage out." It sounds contradictory—a driver operating with less power should produce less splatter. But IMD is relative, and we are to amplify whatever comes out of the driver. One solution would be an attenuator, perhaps built around a dummy load, so the brick may be run at a more linear level. A better solution would be adjusting the bias in the driver. The bricks are usually rated for 100% duty cycle on FM, a steady carrier. SSB and CW operation is much gentler, so the driver idling power may be considerably increased, which should improve IMD performance.

My driver is capable of 200-W output; it's a homebrew conduction-cooled tetrode amplifier with neutralization and 26 dB of gain. As is typical for a class AB_1 tetrode, it is linear at any output level. The transverter maximum output is 2 W, running class A at the output transistor. About 14 dB of gain reduction is needed. This is done in the transverter at the milliwatt level by a resistive panel control in the RF path. The common practice of using high ALC levels to reduce gain often produces IMD (splatter).

Heater Idle Circuit

There are several modes of station operation that call for very long periods—hours and hours—when an amplifier must be ready for near-instant operation, but is rarely used. In my case, with this 2-m amp, the main situation is VHF contest operation (in the sparsely settled Southwest). The contest starts at noon Saturday—hopefully with a big blast on a wide-open 6-m band. There is not much doing on 2 m until around sunset when tropo improves and operators in neighboring states start swinging antennas in all directions. But all afternoon we must be ready on 2; there may be sporadic-E at any moment. And then the same all day Sunday, with the 2-m tubes mostly just sitting and cooking away. A similar situation arises on any summer day when 6 m is open; if the skip is shortening we want to be ready on 2. A more common situation, which would apply to an HF amplifier, involves the DXer who spends almost all the time just listening (as the very best operators do), but must be ready for that new one.

The answer to these problems is the heater idle circuit. This is a simple timer that drops the heater voltage to a specified low level after no transmissions have been made for a specified time. I chose a 12% drop after 5 minutes. Because the heater voltage is regulated, this was easy to do with an IC timer, a DIP relay and a trimpot. In other amplifiers, an IC timer, a relay and a resistor in the filament transformer primary circuit would serve the same purpose.

The idle circuit schematic is shown in Fig 11. If there is no transmission for 5 minutes, the 555 timer switches the 723 regulator in Fig 5 from the panel pot, which sets operating heater voltage, to the trimpot inside that sets the idle voltage. The circuit resets to operating voltage automatically whenever the PTT line (mike button, foot switch or semi-QSK circuit) is keyed, or whenever the reset button on the amplifier front panel is pushed.

How long does it take for the heater to reach operating temperature after reset? I made a number of tests, aiming to determine whether I could forget about the idle circuit, and just grab the mike or key whenever I heard a new grid square, leaving the automatic recovery feature to restore operating heater voltage. The idea (unsubstantiated by any manufacturer or authority) is that the heater loses heat mainly through cathode current. Under this hypothesis, during receive periods the heater gets too hot, hotter than in continuous transmit operation. Thus, it should be possible to maintain operating temperature with less voltage when not transmitting, and full heater voltage would be needed only at the instant a transmission begins.

Does it work? Well, without asking the factory to saw open the tube to investigate, I can only conclude that since the tube has survived all the testing, it works fine. Still, I usually don't wait for the automatic reset. If I hear someone I want to call, I touch the foot switch for half a second to reset the heater voltage. But often I forget to reset manually and the automatic reset circuit works fine.

The tests involved going from the idle condition instantly to full-peak power (pulsed), or full-power CW (dits), to see if full power was instantly achieved. Yes, it was, as quickly as I could read the meter. This power-output test for adequate heater temperature is consistent with tube manufacturers' suggestions for heater voltage adjustment in VHF operation: reduce the heater voltage gradually until the power output drops slightly, then bring it back up a bit. In other words, if you're getting full output, the heater is hot enough. Any more heater voltage and you're just cooking the life out of the poor tube.

Using the heater voltage and current meters, the heater resistance may be calculated. From this the heater temperature may be inferred, relatively, although I don't know the exact relationship. The 4CX1000A is rated nominally at 6.0 V, with advice for lower voltage if adequate, especially on VHF. I operate at 5.8 V (where it draws 9.2 A) and idle at 5.1 V (where it draws 8.4 A). This is a 20% drop in heater power during idle periods, enough to expect a vastly increased tube life. The calculated heater resistance drops from 630 to 607 mΩ.

Since the heater has lower resistance during idle mode, the current will be slightly higher than normal immediately after reset. The time taken for the heater current to drop to normal after reset is another test of the idle-circuit idea. Although difficult to clock, because it happens so quickly, it takes less than 2 seconds.

Note that the heater drops to idle only after 5 minutes without a transmission, not between each transmission during normal operation. And, if you are still worried, you can always reset manually with the mike button, the foot switch or the reset button a few seconds before resuming operation.

ALC for Transverters

For fighting splatter on the ham bands, ALC is the most powerful weapon. The ALC circuit in Fig 8 will produce a negative voltage for driving the ALC-controlled stages in a transceiver or transverter. The R-C network at the follower input prevents keying transients from generating ALC voltage. The pot on the front panel sets the ALC threshold at 0.1 mA of grid current. The panel adjustment may be used for experimentation. The 4CX1000A is rated for zero control-grid dissipation; that is, zero current. However, the spec sheet says a few milliamperes on peaks is okay. I wanted to see if on CW, where IMD is not a consideration, a few milliamps would result in higher efficiency. (I used a 5-mA grid meter initially.) The results: no, there is no improvement in efficiency with higher grid current.

Some rigs (eg, the FT-1000MP) do not have an ALC input line which controls the RF level at the transverter output jack. ALC may be added to a transverter with the circuit shown in Fig 12. The MOSFET buffer stage is designed for unity gain, but this may depend on the individual device. Increasing the drain resistor will increase the output, if necessary. The RF input level should be not more than –16 dBm. The gate 2 bias adjustment is set so that Q1 operates at the knee of its characteristic curve.[24] If the bias is set for maximum gain, the ALC voltage will be forced to rise to a high value before any significant gain reduction is obtained. My transverters have two or three ALC-controlled stages; this means that there is less gain reduction at each stage, and therefore less possibility of ALC-induced IMD. The ALC adjustment in Fig 12 is set so that –5 V applied at either ALC input will produce 20 dB of ALC compression. Excessive ALC may result in IMD. In operation, the transverter gain is adjusted for a maximum of 3 dB of ALC compression, metered on the transceiver panel.

Pulsed Tune-Up

The dit tune-up procedure, with amplifier keying, was described in "A Luxury Linear." In fact, the method used in my shack goes even further. My home-brew transceiver has a built-in pulser, set for a 33% duty cycle. The TUNE switch on the panel automatically shifts the radio into CW, silences the sidetone, hits the PTT line and starts the pulser. So testing at 1500-W PEP output involves only 400 W of average plate dissipation.

The schematic for the pulser, which could be built into a transceiver or as a separate device, is shown in Fig 13. A scope with calibrated time-base is useful for precisely setting the desired pulse rate and duty cycle, but a simple RF monitor scope is sufficient. Merely setting the OFF trimpot at maximum and the ON trimpot at midrange will be adequate.

Improvements

The main improvement I would suggest is in the swinging link mechanism. The simple shaft and insulator method described in the caption to Fig 4 works well enough. However, the link needs to swing only about 30°, and the heavy coax-braid connections make it a bit stiff. In operation, I use the swinging link only as a coarse loading adjustment, so there is no practical problem. Since I haven't touched the swinging link in the past six months, this is one of those situations where improvement is not worth the trouble. But for someone trying this circuit anew, I would suggest some sort of gear drive, for smoother control and finer adjustment.

I have only one other suggestion: build very carefully! Don't lay yourself open to a remark like I got from one of the locals here. All he could say when he saw the new amplifier was, "You got one of the meter labels crooked."

Notes

[21]"A Luxury Linear," *QEX*, May, 1996, p 3-12. (Photos also in *QST*, July 1996, p 19.)

[22]References to Figs 1-10 and Notes 1-20 are to the previous article (see Note 21 above). This article begins with Fig 11 and Note 21.

[23]Correction for "A Luxury Linear," Fig 10: Reverse the ± markings at the inputs of the plate current-metering op amp.

[24]A typical MOSFET characteristic curve is shown as Fig 10 in "A High-Performance AGC System for Home-Brew Transceivers," *QEX*, October 1995, p 12-22.

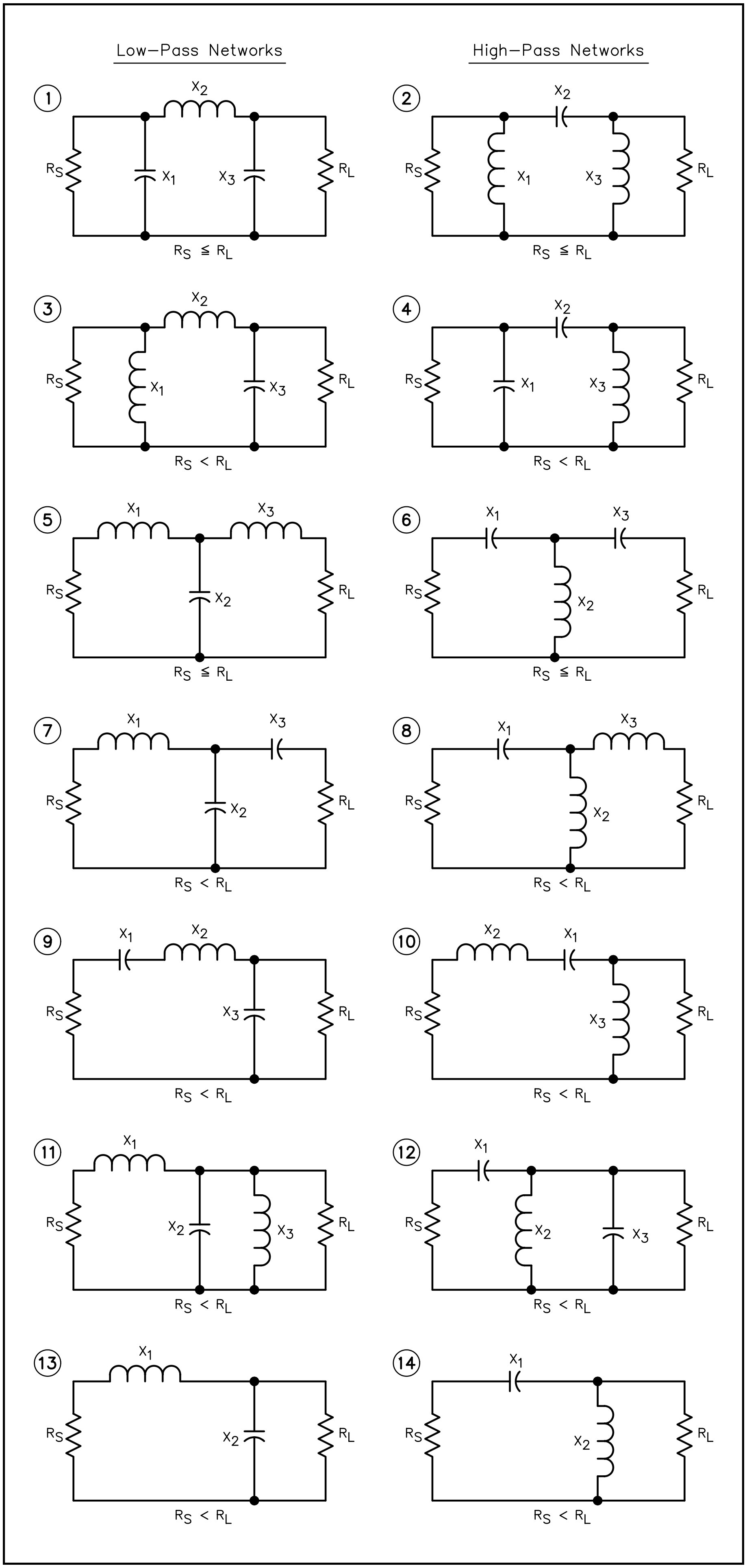
ARRL Handbook CD

Template File

Title:	NB Match
Chapter:	17
Topic:	MATCH.EXE Diagrams

Template contains:

Diagram showing 14 possible network configurations to be analyzed by MATCH.EXE computer program.



This page accompanies the *ARRL Handbook* software package that is available on the *Handbook* CD. This figure shows the 14 possible network configurations used by MATCH.EXE. Refer to this figure and enter the desired network by number when you run the program. Note that low-pass networks have an odd identifying number while high-pass networks have an even identifying number. See the Broadband Transformers file on the Handbook CD-ROM.

Tuned (Resonant) Networks

(excerpted from Chapter 14 of the ARRL Handbook, 2009 and previous editions)

There is a large class of LC networks that utilize resonance at a single frequency to transform impedances over a narrow band. In many applications the circuitry that the network connects to has internal reactances, inductive or capacitive, combined with resistance. We want to absorb these reactances, if possible, to become an integral part of the network design. By looking at the various available network possibilities we can identify those that will do this at one or both ends of the network. Some networks must operate between two different values of resistance, others can also operate between equal resistances. As mentioned before, nearly all networks also allow a choice of selectivity, or Q, where Q is (approximately) the resonant frequency divided by the 3-dB bandwidth.

As a simple example that illustrates the method, consider the generator and load of **Fig 14.58A**. We want to absorb the 20 pF and the 0.1 μH into the network. We use the formulas to calculate L and C for a 500 Ω to 50 Ω L-network, then subtract 20 pF from C and 0.1 μH from L. As a second iteration we can improve the design by considering the resistance of the L that we just found. Suppose it is 2 Ω. We can recalculate new values L′ and C′ for a network from 500 Ω to 52 Ω, as shown in Fig 14.58B.

Further iterations are possible but usually trivial. More complicated networks and more difficult problems can use a computer to expedite absorbing process. Always try to absorb an inductance into a network L and a capacitance into a network C in order to minimize spurious LC resonances and undesired frequency responses. Inductors and capacitors can be combined in series or in parallel as shown in the example. Fig 14.58C shows useful formulas to convert series to parallel and vice versa to help with the designs.

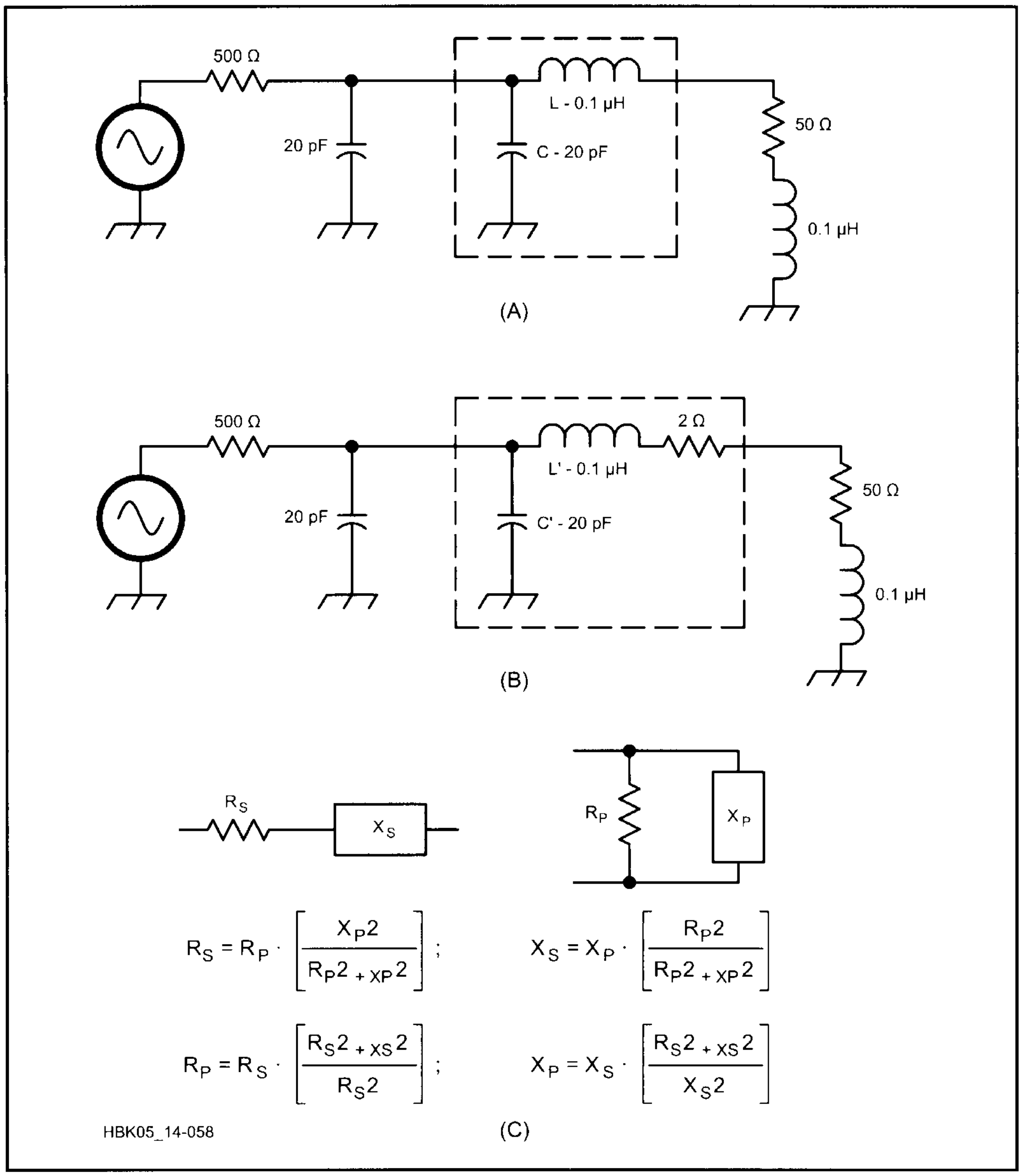


Fig 14.58 — At A, impedance transformation, first iteration. At B, second iteration compensates L and C values for coil resistance. At C, series-parallel conversions.

A set of 14 simple resonant networks, and their equations, is presented in **Fig 14.59**. Note that in these diagrams RS is the low impedance side and RL is the high impedance side and that the X values are calculated in the top-down order given. The program *MATCH.EXE* can perform the calculations.

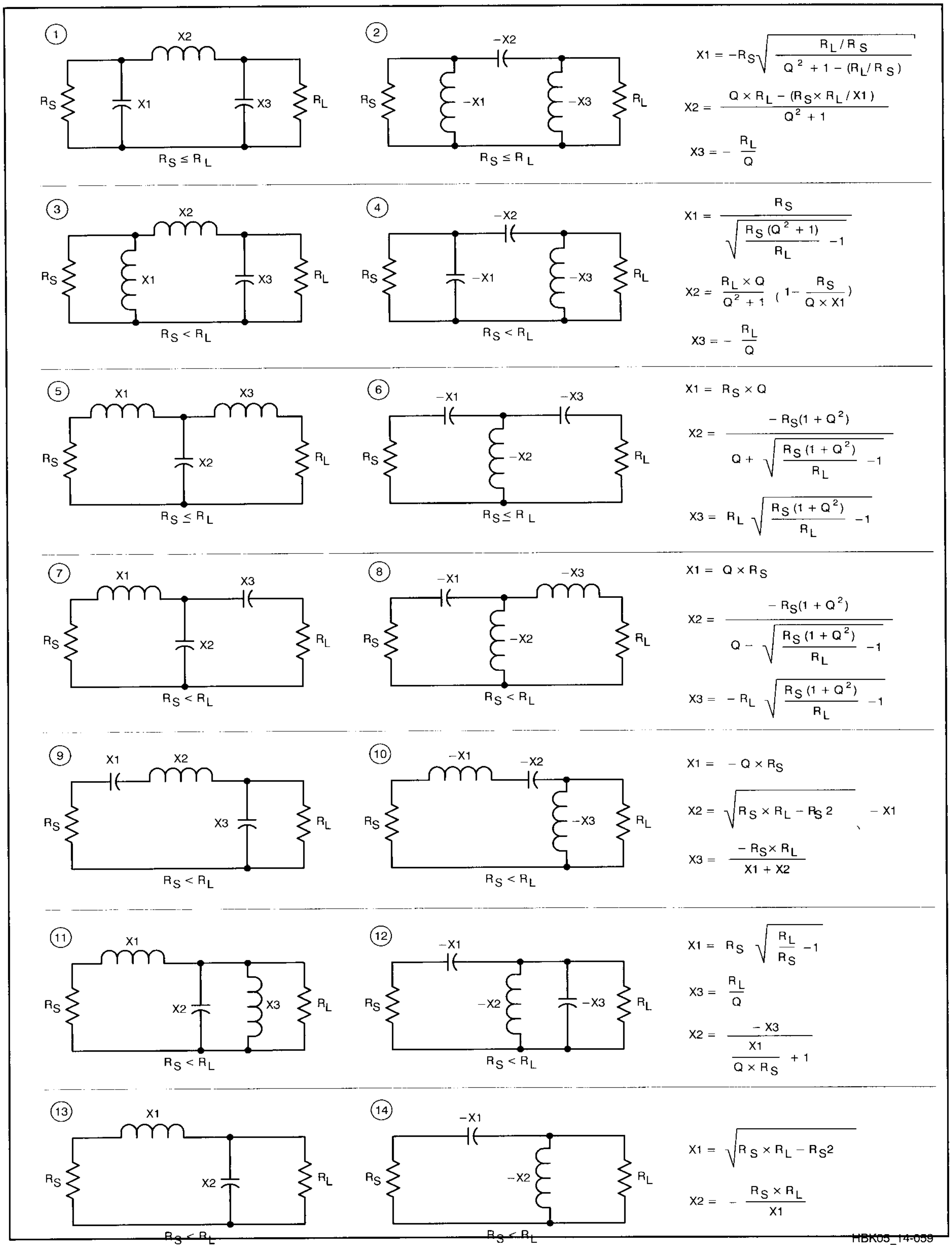


Fig 14.59 — Fourteen impedance transforming networks with their design equations (for lossless components).

Circuit simulation programs can also help a lot with special circuit-design problems and some approaches to resonant network design. It can graph the frequency response, compute insertion loss and also tune the capacitances and inductances across a frequency band. You may select the selectivity (Q) in such programs based on frequency-response requirements. The program can also be trimmed to help realize realistic or standard component values. A math program such as *Mathcad* can also make this a quick and easy process.